ABSTRACT

Title of dissertation: PEDOGENESIS IN RAIN GARDENS: THE ROLE OF EARTHWORMS AND OTHER ORGANISMS IN LONG-TERM SOIL DEVELOPMENT

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and Technology

As bioretention comes into widespread use, it has become increasingly important to understand the development of bioretention soils over time. The objective of this research is to investigate the development of bioretention soils and the importance of ecological processes in the performance of rain gardens. The research includes descriptive studies of pre-existing rain garden soil profiles, laboratory experiments quantifying the effect of earthworms on infiltration rates, and a simulation model describing the influence of earthworms and soil organic matter on infiltration. Surveys of several different rain gardens of various ages provide the first detailed descriptions of rain garden soil profiles. The study revealed a great deal of biological activity in rain gardens, and evidence of pedogenesis even in very young sites. The uppermost soil layers were found to be enriched with organic matter, plant roots, and soil organisms. The field sites surveyed showed no signs of clogging due to the trapping of suspended solids carried in stormwater runoff. Some evidence was found of higher than expected infiltration rates at the field sites, which may be attributable to the effects of bioturbation by living organisms.

The ability of earthworms to mitigate the effects of trapped suspended solids on bioretention soils was assessed in the laboratory. Results show that earthworms are capable of maintaining the infiltration rate of bioretention soils, but that their effects have a high degree of variability. This variability is attributed to soil aggregate instability caused by the oversimplification of the ecosystem. Other organisms play a significant role in stabilizing earthworm burrows and casts, and may be essential ingredients in a self-maintaining bioretention ecosystem.

A simulation model of the action of earthworms on soil infiltration rates was developed in order to illustrate the physical processes taking place as a result of earthworm activity. The model was calibrated using data from the field study and microcosm experiment.

This research is intended to provide a first glimpse into the biological processes at work in rain garden soils. The research shows that soil organisms are present in rain gardens, and suggests that their impact on bioretention performance may be significant.

PEDOGENESIS IN RAIN GARDENS: THE ROLE OF EARTHWORMS AND OTHER ORGANISMS IN LONG-TERM SOIL DEVELOPMENT

by

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Dissertation submitted to the Faculty of the Graduate School of the
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Dedication

For my daughters, Evelyn and Violet

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Table of Contents

List of Tables

List of Figures

List of Abbreviations

BSM	Bioretention Soil Medium
CEC	Cation Exchange Capacity
LID	Low Impact Development
SOM	Soil Organic Matter
SS	Suspended Solids
UMCP	University of Maryland, College Park
WNY	Washington Navy Yard
MJES	"Mother" Jones Elementary School
NWHS	Northwestern High School
CBF	Chesapeake Bay Foundation
PP	"Peppercorn Place" (Inglewood Center, III)
CF	Claggett Farm
CC	Chevy Chase Bank
BP	Beltway Plaza
LRH	Laurel Regional Hospital
EPA	Environmental Protection Agency
NOAA	National Oceanic and Atmospheric Administration
NCDC	National Climatic Data Center
PG County	Prince George's County, Maryland
USDA	United States Department of Agriculture

Chapter 1

Introduction and Literature Review

1.1 Background

Bioretention is a new best management practice for the treatment of stormwater runoff from impervious areas such as driveways and parking lots. Bioretention cells (commonly referred to as rain gardens) represent a low-tech treatment option that effectively promotes infiltration, reduces stormwater quantity, and removes heavy metals, nutrients, and other pollutants contained in stormwater runoff (Davis et al., 2001a, 2003). A rain garden is a small planted depression filled with approximately 0.5 to 1 m (2 to 3 ft) of a soil medium engineered to promote infiltration while at the same time providing enough clay and organic matter to promote the breakdown or sorption of pollutants. Runoff flowing into the rain garden is filtered as it percolates through the soil mix. Figure 1.1 shows the configuration of a typical rain garden.

The increasing popularity of rain gardens as stormwater control structures highlights the need for a more thorough understanding of bioretention performance. Rain gardens are essentially planted soil filters, and their performance during a storm event depends on the hydraulic conductivity and pollutant removal capacity of the soil. These soil properties are influenced by the physical effects of storm events as well as the actions of the plants, microbes and soil animals of the rain garden ecosystem. Over time, physical, chemical and biological forces change the composition and structure of the soil, which affects the performance of the rain garden. Thus, the development of bioretention soils over time must be examined if the long-term performance of rain gardens is to be understood.

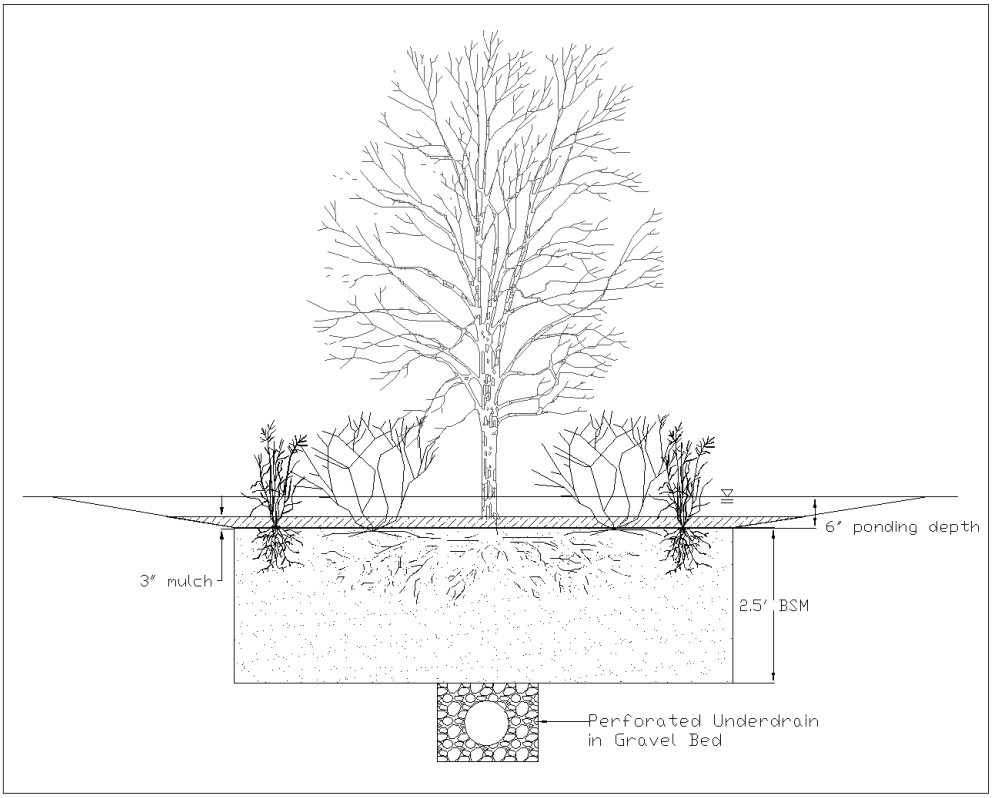


Figure 1.1: Schematic of a typical rain garden, consisting of a 2.5-foot-deep layer of bioretention soil medium (BSM), topped with a 3-inch layer of mulch, planted with a variety of native plants, shrubs and trees. The system is designed to allow a 6-inch ponding depth at the soil surface, and is often outfitted with and underdrain leading to a stormwater discharge.

Many environmental factors can be expected to act on the structures, and these factors may impact their hydraulic performance. For example, suspended solids are a major component of urban stormwater runoff. The fate of suspended solids in rain gardens is not yet well understood, but it is likely that these solids are trapped in the upper layers of the soil (Li and Davis, 2008b,a). Over time, this may lead to clogging of the rain garden, decreasing the infiltration rate.

1.1.1 Pedogenesis

The key to understanding how rain gardens change over time lies in understanding the soil. Thus, it is necessary to examine how soils in general behave, and how they develop over time. This knowledge can then be applied to bioretention soils.

Soil is composed of weathered rock of various sizes, combined with organic matter, and organized into aggregates. Aggregates provide structure to the soil, permitting air and water to enter, and providing habitat for a multitude of organisms. A soil begins as a loose assemblage of weathered rock, which over time undergoes pedogenesis. The first step in the process of pedogenesis is the formation of an A horizon at the soil surface (Figure 1.2). Organic matter begins to accumulate in the upper part of the soil, changing the soil's color and physical properties. The soil develops a characteristic black color due to the presence of dark-colored humic substances. Humus increases the water and nutrient holding capacity of the soil. Sticky organic substances, such as polysaccharides, are produced by a variety of soil organisms, including plant roots, mycorrhizae and bacteria. These organic substances cause soil particles to clump together into spheroidal aggregates. Many of these aggregates are water-stable, and create a stable, porous soil structure. Soil aggregates are also formed in the guts of earthworms. Many earthworms ingest soil, mixing it with organic matter before excreting the mixed matter back into the soil. Earthworm fecal pellets are often water-stable, and in some soils constitute a sizeable fraction of the soil aggregates (Lee and Foster, 1991). Plant roots and macroinvertebrates such as earthworms create macropores, further increasing flow through the soil. Thus, it is biological activity that creates and maintains the permeability of the soil.

Jenny (1941, 1980) proposed that pedogenesis is governed by what he termed the "CLORPT" equation:

$$s = f(cl, o, r, p, t) \tag{1.1}$$

which states that soil properties (s) are a function of climate (cl), organisms (o), topography (r), parent material (p), and time (t). This equation neatly encapsulates the major processes involved in soil pedogenesis. Since it was originally proposed, the exact structure of the CLORPT equation has been the subject of intense debate among soil scientists (Crocker, 1952; Johnson and Watson-Stegner, 1987; Stevens and Walker, 1970; Yaalon, 1975), but the equation's utility as a conceptual model of the main influences on soil development has always been recognized.

Climate. The principal climatic factors influencing soil development are temperature and precipitation (Yaalon, 1983). At higher temperatures, organisms are more active, and therefore have greater influence on soil structure. High temperatures also increase evaporation rates, decreasing the moisture content of the soil. Vegetation is influenced by climate. Even the reaction rates of chemical processes within the soil are increased by increasing temperature. The soil moisture regime plays a major role in soil formation. The balance between precipitation and evapotranspiration determines the flux of water through the soil, redistributing soil particles and leaching soluble materials. Plants and soil organisms require adequate soil moisture in order to flourish. Saturated conditions can occur where there is excess precipitation, and if these saturated conditions persist, oxygen can be depleted in the soil. This causes distinct and dramatic changes in the floral and faunal communities, as well as chemical changes in the soil.

Organisms. Organisms living within and on the surface of a soil produce pronounced changes in the soil profile (Gobat et al., 2003). Plants growing at the soil surface con-

tribute organic matter via litterfall and decay of plant roots. Plant roots exude oxygen and simple sugars, creating a region known as the rhizosphere. The rhizosphere provides critical habitat for bacteria and fungi. Soil animals and microorganisms work together to break down plant litter and incorporate it into the soil matrix. This increase in organic matter changes the structure of the soil. Soil organic matter decreases bulk density, increases water holding capacity, and provides the glue that holds soil aggregates together (Brady and Weil, 2002; Weil et al., 2004). Bioturbation by macroinvertebrates, such as earthworms, as well as burrowing vertebrates, such as moles, aerates and mixes the soil and creates large macropores.

Topography. Rain falling on a slope will tend to run downhill before it has the opportunity to completely infiltrate into the soil. As rain runs off, it removes soil particles, depositing them at the base of the slope. Thus, soils on slopes tend to be drier and have shallower profiles than soils at the bases of slopes.

Parent material. The parent material of a soil acts is baseline from which the soil develops. The parent material determines many of the basic characteristics of the soil. A soil formed from silty loess deposits will be fundamentally different from a soil formed from sandy marine deposits, even if these two soils form under identical climatic and topographic conditions. Sandy soils have much higher hydraulic conductivities than silt or clay soils (Ferguson, 1994), and will therefore leach more rapidly.

The mineral content of soils is also important in their development. For example, a soil formed from limestone will tend to have a high pH, which will effect the composition of the plant community that develops, and will influence the chemical reactions taking place in the soil.

Time. All of the soil processes take place on different time scales, ranging from years to hundreds or even thousands of years. The weathering of rock tends to take thousands of years. Under favorable conditions (generally warm and moist climates), buildup of organic matter can take place over a period of years, and downward migration of clays can occur over several decades (Brady and Weil, 2002; Stevens and Walker, 1970; van Breemen and Buurman, 2002).

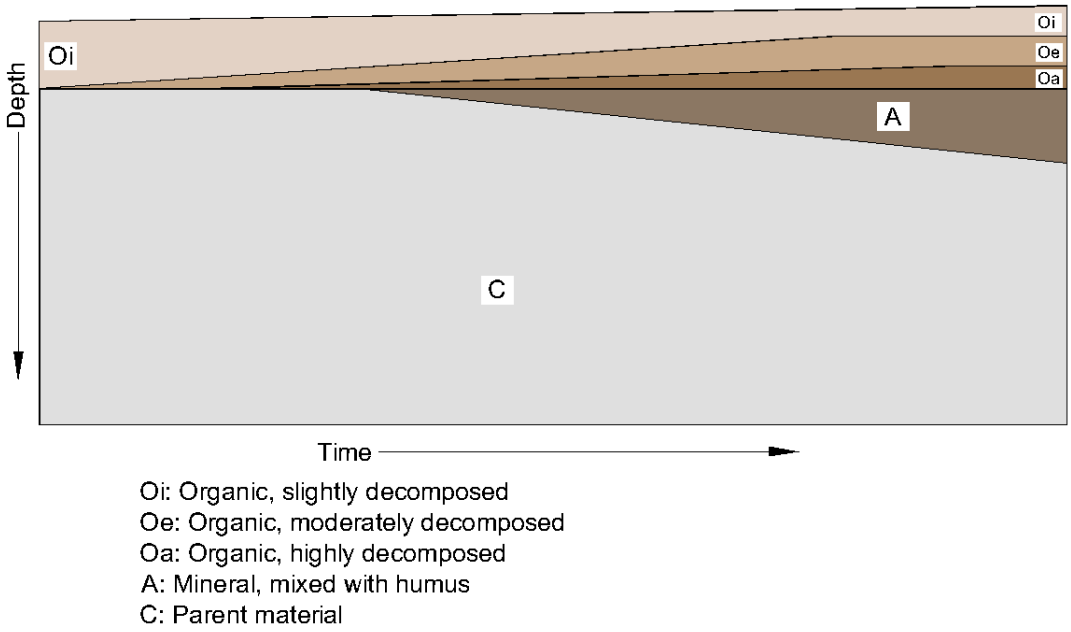


Figure 1.2: Initial stages of pedogenesis, after Brady and Weil (2002). An organic horizon (O) forms at the soil surface, and is gradually broken down and incorporated into the uppermost soil layer, forming an A horizon.

1.1.2 Pedogenesis in rain gardens

The same soil forming factors act on bioretention soils, which begin as a uniform mixture of sand, topsoil and organic matter. Specifications for the bioretention soil medium vary by municipality. One commonly used specification is 50% sand, 30% sandy loam topsoil, and 20% organic matter in the form of mulch or compost by volume, uniformly mixed (LIDC, 2003).

Climate. Rain gardens are often constructed in parking lots or other urban settings, where paved surfaces create microclimates with elevated temperatures (Pickett et al., 2001). These higher temperatures can be expected to accelerate soil formation by increasing the activity of soil organisms. As rain gardens are designed to receive the precipitation falling on an area much larger than the rain garden itself, the effective precipitation on the rain garden is much higher than that of the surrounding area. Bioretention soils are highly permeable, allowing this precipitation to infiltrate quickly through the soil. Anoxic conditions rarely develop. High effective precipitation can be expected to accelerate the leaching of soluble substances and the downward migration of clay particles.

Organisms. Rain gardens are largely devoid of organisms when they are first installed, though the topsoil and organic matter will contain microbes, fungi, seeds, and some meso- and macro-invertebrates. After installation, the rain garden is planted. Over time, invertebrates colonize the soil, and plant root systems develop into dense networks. As the populations of organisms increase, the organic matter content of the upper soil layer can be expected to increase, and a granular structure will develop. These changes should begin almost immediately, and can be expected to have a major impact on the rain garden throughout its operational life. The effect of the rain garden ecosystem on

the bioretention soil is the major focus of this research, and will be discussed in greater detail.

Topography. Rain gardens are located at the bases of largely impervious micro-watersheds. Rain falling on an impervious surface will dislodge fine particles. These particles are carried off by the runoff, and are ultimately deposited in the rain garden. Over time, this deposition of fine particles into the rain garden may clog the soil surface, and may eventually alter the rain garden soil texture.

Parent material. Bioretention soils typically have a very high sand content, and very high hydraulic conductivity, typically 40 – 50 cm/h (Li and Davis, 2008b). Rapid flow of water through the soil accelerates the leaching of soluble materials from the soil, and also limits the soil's water holding capacity, which prevents the development of anoxic conditions during wet periods, but may stress plants during dry periods.

Time. With the high temperatures, high precipitation and high permeability described above, bioretention soils may be expected to develop rapidly.

Over the first few years, an organic (O) horizon would be expected to form at the soil surface, followed by a gradually thickening A horizon just below the soil surface (Figure 1.2). These changes in soil structure will affect the hydraulic properties of the rain garden. The infiltration rate of the bioretention soil is critically important to their proper function. Figure 1.3 illustrates the major factors that influence the drawdown time of a rain garden. The drawdown time, or the time it takes ponded inflow to exit the system, is the most important design parameter of a rain garden. A rain garden must be able to process stormwater efficiently, while holding the stormwater for a sufficient minimum time to remove pollutants. The major external forces that influence the drawdown time are storm characteristics, maintenance procedures, and the initial planting plan. These exter-

nal forces influence the rain garden's internal physical and biological systems, impacting such factors as the soil's porosity, texture, infiltration rate, root biomass, organic matter content, and invertebrate populations.

Storm characteristics, such as intensity, frequency and duration, determine the level of suspended solids loading to the system, the amount of sodium loading from road salts, and the toxic pollutant load that the system must handle. Suspended solids loading directly impacts the infiltration rate of the system by clogging the soil surface. As these solids are incorporated deeper into the soil mix, they decrease the soil's porosity, and gradually change the soil texture. Sodium used in road salts has a direct negative impact on soil structure, decreasing the porosity and infiltration rate of the soil (Ramakrishna and Viraraghavan, 2005). It is also highly toxic to plants and invertebrates, contributing to the system's toxic pollutant load. The porosity and the infiltration rate of the system combine to determine the soil's percolation rate, which, along with the presence or absence of a liner, determines the drawdown time of the rain garden.

The initial planting plan plays an important role in how the biological system develops, and therefore how it responds to storm events. The types of plants used and their spacing determine the root biomass in the soil and the amount of litter falling on the soil surface. Litterfall serves as food for earthworms (as well as other soil-dwelling invertebrates). The earthworm population is also sensitive to the soil texture, preferring loamy soils without excessive sand or clay, and is negatively impacted by the toxic pollutant load. Earthworms create aggregates and biopores, increasing the soil's porosity. Roots create biopores, which increase the soil's porosity, and generate root exudates, which increase soil aggregation. Ants create biopores. Soil organic matter is created through the metabolic activities of earthworms, ants, and other soil organisms, as well as through root exudates.

This organic matter increases soil aggregation both directly and indirectly by serving as a food source for fungal hyphae, which also increase the aggregation of the soil.

Maintenance procedures also impact the functioning of the system. Periodic removal of trapped solids (cake) from the soil surface increases the soil's infiltration rate and porosity, and affects the soil texture by removing fine sand, silt and clay that might otherwise be incorporated into the soil. Removal of plant detritus (litterfall), whether intentional or as a byproduct of rubbish removal, limits the amount of food available to the biological system.

The diagram reveals the links between a rain garden's physical and biological systems. The biological system plays a fundamental role in the maintenance and regeneration of the soil porosity after storm events. This biological system is highly dependent on good initial design and enlightened maintenance to ensure an adequate food supply. Any action that limits the amount of plant litter available limits the carrying capacity of the rain garden. Toxic pollutants carried in stormwater runoff can negatively affect invertebrate populations, but the high capacity of humus to adsorb heavy metals may limit exposure, mitigating this risk.

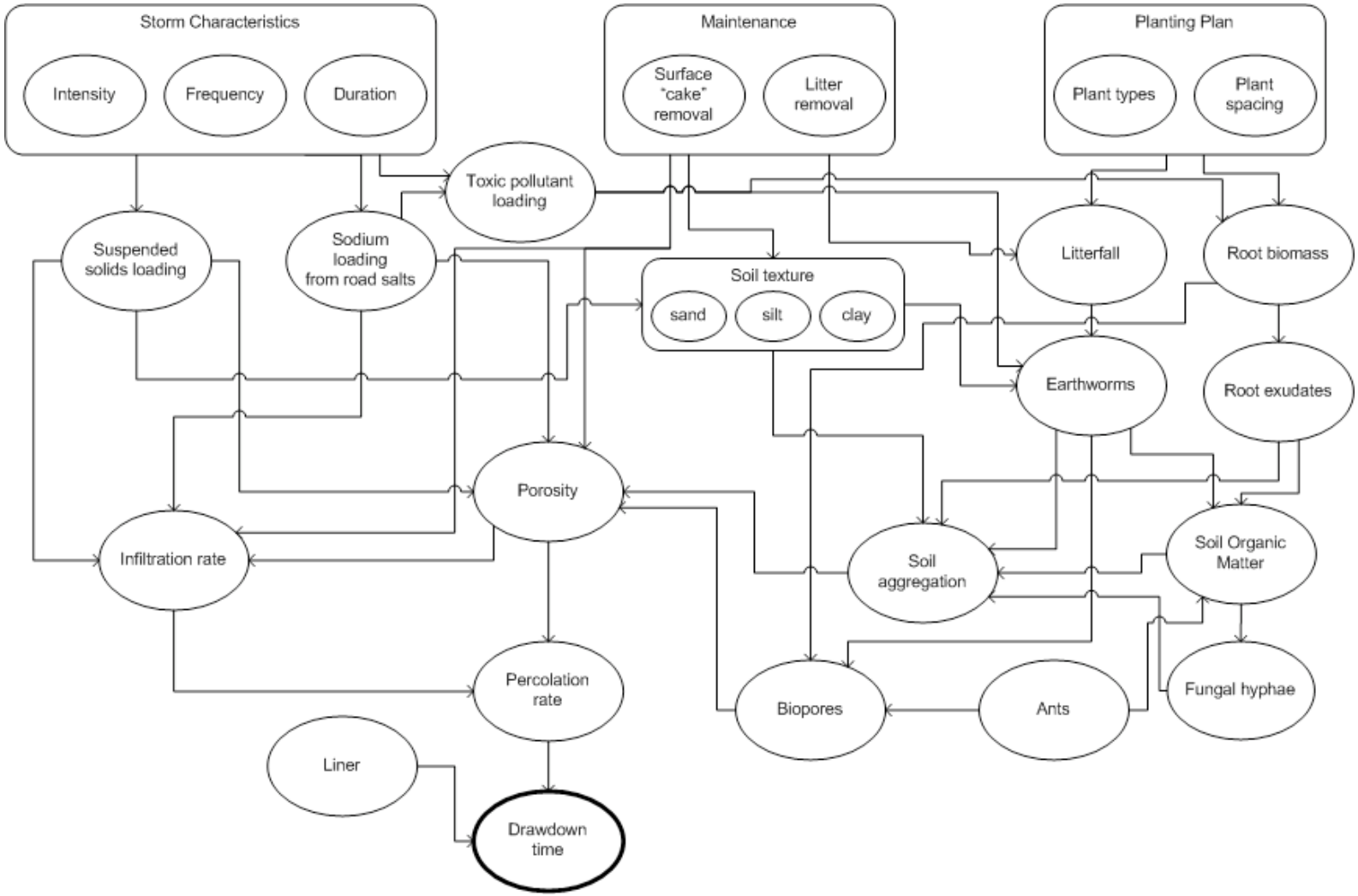


Figure 1.3: Factors influencing the drawdown time of a rain garden.

1.1.3 The role of biology in pedogenesis

Biological activity is the key to the creation and maintenance of aggregates and macropores in the upper soil layers (Six et al., 2004). Organic material in the form of plant litter, decaying roots and animal wastes is gradually broken down and incorporated into the soil. This process is carried out by soil organisms. Soil contains a wide diversity of organisms, ranging in size from mammals, such as prairie dogs and moles, down to microscopic mites and nematodes, all the way to bacteria and viruses. These organisms each inhabit specialized ecological niches, forming a complex soil ecosystem.

The soil fauna are responsible for the modification of soil structure. Macroinvertebrates (earthworms, isopods, millipedes, ants, termites) influence soil structure both through their feeding (incorporating, decomposing and mixing organic matter into the soil) and their burrowing (aeration and mixing). Mesofauna (pot worms, springtails, mites) feed on organic matter and fungal hyphae (Berry et al., 1994). This action breaks down organic matter and mixes it into the soil matrix. Figure 1.4 illustrates a basic rain garden food web, outlining the major organisms likely to be present and their roles in the system.

The process of transforming plant tissue to humus is quite complex and involves the entire soil ecosystem. Leaf litter is produced by plants. This litter is partially decomposed on the soil surface by bacteria and fungi. The partly decayed plant matter is then consumed by shredders, such as earthworms, which break the litter into smaller pieces, mix it with bacteria in their digestive tracts, and deposit this mixture into the soil. Bacteria and fungi then further attack the litter, gradually breaking complex organic substances down into simpler ones. Most of the organic matter that is input into the soil system is consumed by soil organisms. About five percent of the organic matter is converted to

simple compounds, such as polysaccharides, which are extremely important in the formation of soil aggregates (Brady and Weil, 2002). About twenty percent of the organic matter is transformed into the complex, heterogeneous substance known as humus. Humic substances are highly resistant to degradation, colloidal, have a very high cation exchange capacity (CEC), and can bind a large quantity of water (Weil et al., 2004). These traits increase the ability of the soil to retain water and nutrients.

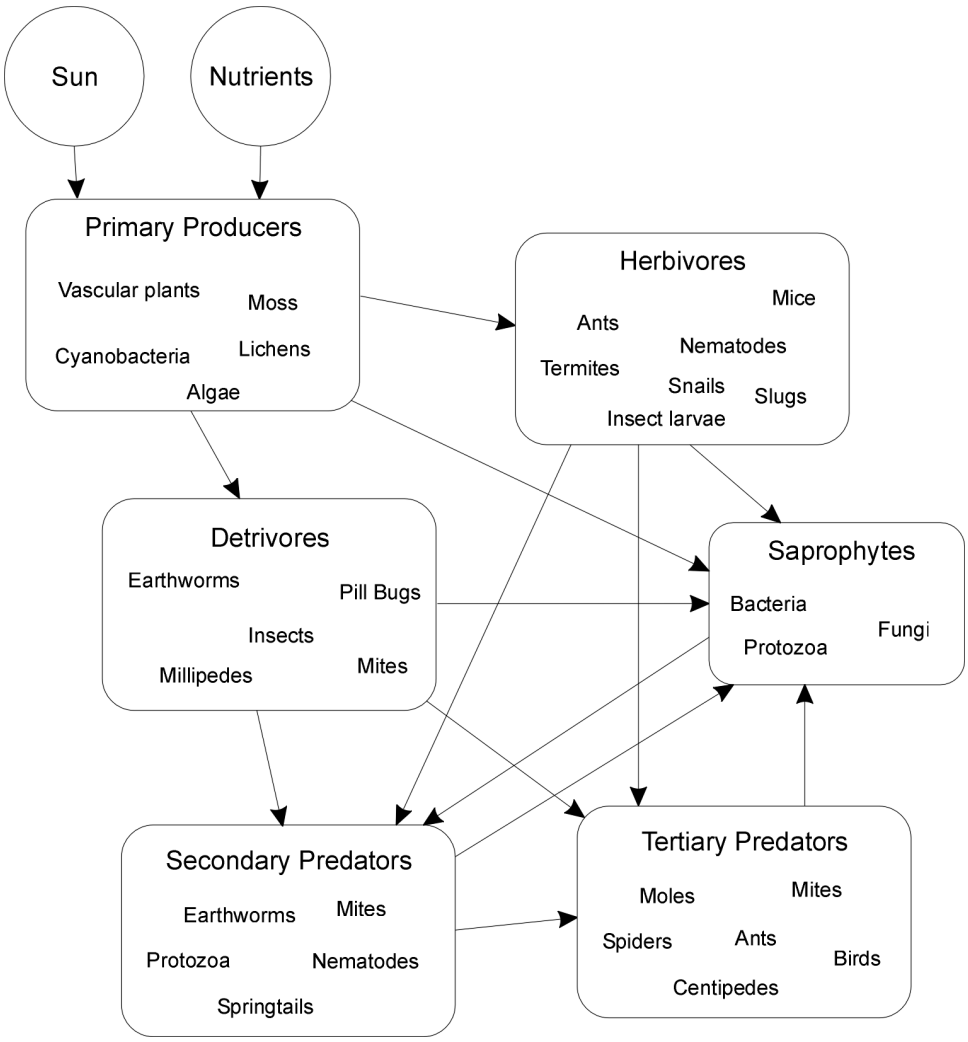


Figure 1.4: A basic terrestrial food web that may be present in rain gardens.

1.1.4 Influence of earthworms on soil structure

While a number of biological factors work together to improve soil structure, earthworms are among the most important (Lee and Foster, 1991; Kretzschmar and Edwards, 2004; Langmaack et al., 1999; Bouché and Al-Addan, 1997; Coleman et al., 2004). In 1881, Charles Darwin recognized that earthworms were responsible for the formation of topsoil (Darwin, 1881). Since then, the effect of earthworms on soil structure has been intensively studied. Several chapters in earthworm ecology and soil science texts are dedicated to the subject (Edwards and Arancon, 2004; van Vliet and Hendrix, 1999; Edwards and Bohlen, 1996; Brady and Weil, 2002). Earthworms can exert significant influence on soil structure, organic matter and nutrient cycling, and other soil organisms (van Vliet and Hendrix, 1999). This influence is carried out in three principle ways:

1. The production of feces (casts) which harden to form stable aggregates.
2. The creation of burrows, which promote infiltration and soil aeration.
3. The incorporation of organic matter into the soil, through burrowing as well as metabolic activities.

Earthworms have been divided into three important ecological groups: epigeic, endogeic and anecic species (Bouché et al., 1977). Epigeic species tend to live on the soil surface, beneath the litter layer. They play a major role in the breakdown of surface litter. Endogeic species inhabit the upper soil horizons. They tend to form horizontal, meandering burrows, and consume organic matter within the soil. Anecic species form long vertical burrows in the soil. These burrows help to aerate the soil and increase infiltration (Lee, 1985). Through their feeding, earthworms incorporate organic matter into the soil. Ingestion of plant litter and soil particles results in the mixing of the soil mineral fraction with organic matter, glueing the two together as earthworm casts. Shaw and Pawluck (1986) examined the effects of different earthworm species on soil structure. Their find-

ings suggest that anecic species play a primary role in transporting organic matter from the surface into the soil. Endogeic species are then responsible for mixing this introduced organic matter throughout the soil.

The effect of earthworms on aggregate stability, or the resistance of aggregates to destruction when subjected to wetting or mechanical stresses, is complex (Six et al., 2004). Some studies have found that earthworms increase aggregate stabilization (Shaw and Pawluck, 1986), while others have found evidence that earthworms can actually destroy soil structure (Schrader and Zhang, 1997). The ultimate effect of earthworms on soil structure seems to be dependent on a multitude of factors specific to the soil and circumstances in question.

The stability of fresh earthworm casts is generally lower than that of the surrounding soil, but stability increases as the casts age over even a few days (Kay and Angers, 1999). Cast stability is believed to derive from the colonization of the cast by fungal hyphae present in the surrounding soil (Lee and Foster, 1991). Soils with high sand contents lack sufficient clay for abiotic aggregation to take place (Oades, 1993). In such soils, aggregation depends on biotic forces, such as the ingestion of soil by macroinvertebrates and the growth and decay of roots. Once created, this structure is stabilized by fungal hyphae, colonies of microorganisms, and metabolic products from the decomposition of higher plants (Oades, 1993). Soils with earthworms commonly have up to 70% pore space (Lee, 1985).

1.1.5 Self-organization and ecological succession

Self-organization is the process by which a developing ecosystem self-selects the assemblage of species best adapted to its particular environmental conditions, or energy

signature. At the most basic level, this process can be seen simply as the survival and persistence of those species which do the best in the given environment. A basic strategy of ecological engineering is to seed a site with as many species as possible, then allow the site to self-organize. Those species which are well-adapted to the site will survive, and those that are not will die out.

Succession is the process of community change in response to environmental changes. Biotic communities change gradually in response to the physical environment. Eventually the ecosystem reaches equilibrium with its energy signature. The community of plants and animals at equilibrium is known as the climax community. In areas where bare ground is generated due to earth-moving, abandonment of agricultural fields, deforestation, fire, or some other disturbance, the plant and animal communities go through a series of successional stages, which follow a predictable general pattern. The area is first colonized by pioneer species, which are typically fast-growing, annual plants and fast-reproducing, opportunistic animal species. This community is gradually replaced by more mature communities, which are characterized by slower-growing, perennial plants and slower- reproducing, more specialized animal species. Eventually, the climax community is reached, and the system is in equilibrium with its environment. The composition of this climax community varies widely depending on the environment or biome; in the eastern United States, the climax community is typically a hardwood forest. In the Midwestern United States, the climax community may be tallgrass prairie. Climax ecosystems are characterized by low productivity and high stability, while immature ecosystems are characterized by high productivity and low stability (Gutierrez and Fey, 1980). Both ecosystems may be of use to engineers, depending on their needs.

1.1.6 Use of microcosms in ecological research

Microcosms are a common experimental unit in ecological research. Use of a microcosm in a laboratory setting permits a level of experimental control that is often impossible to achieve in the field. Most ecosystems of interest are much too large to be manipulated experimentally, so they must either be observed or replicated at a smaller scale. In addition, manipulation of ecosystems in the field can alter the ecosystem in undesirable ways that compromise its function. For example, manipulating the habitat of an endangered species in order to find out what aspects of the habitat the species depends on for survival would be an unacceptable method of conducting research. In such situations, it is sometimes possible to miniaturize the ecosystem and bring it into the controlled environment of the laboratory. Microcosms offer several benefits to ecological researchers:

1. They can be manipulated without fear of compromising the function of a live ecosystem.
2. They can be replicated.
3. Conditions can be controlled.
4. The ecosystem of interest can be simplified to the desired level.

There are, however, limitations to the utility of microcosms, and the practice has come under some criticism. The fundamental issue is whether or not a microcosm can be constructed to accurately mimic the ecosystem of interest. Ecosystems consist of a web of complex interactions, which are usually not fully understood. Microcosms intended to simulate these ecosystems may be lacking essential components. In simplifying an ecosystem to study a limited number of interactions, the system may again be altered to the point where the behavior of the microcosm does not accurately reflect behavior in the real world (Carpenter, 1996). Ecosystems which are very large can be very difficult to simulate at a small scale, because they are dependent on very large processes. Ecosystems

do not exist independently from their surroundings. The flows of energy and material in and out of the system must be accounted for and accurately simulated.

1.2 Summary of Literature Findings and Research

1.2.1 The history of bioretention design

Bioretention was developed in Prince George's County, Maryland in the early 1990s. The design was conceived as a way to promote infiltration of storm water while simultaneously removing pollutants. As engineers have gained experience using rain gardens, the design has evolved. In particular, as researchers have come to understand the importance of the soil medium (Hsieh and Davis, 2005a), the specifications for the soil medium have become more tightly circumscribed. In early rain gardens, a wide range of soil textural classes were deemed acceptable components. For example, at the Beltway Plaza Mall site, constructed in 1997, the bioretention medium specified consisted of five parts topsoil to one part wet loose peat moss or rotted manure (see Appendix A). Acceptable topsoil textures included: loam, sandy loam, clay loam, silt loam, sandy clay loam, or loamy sand. By 2001, The Bioretention Manual, published by Prince Georges County's Department of Environmental Resources (PGCO, 2001), specified a medium consisting of: 50–60% sand, 20–30% leaf compost, and 20–30% topsoil by volume. The topsoil must be loamy sand, sandy loam, or loam, with an infiltration rate higher than 0.5 in/hr. The Low Impact Development Center, in cooperation with the US Environmental Protection Agency, has developed a bioretention specification intended for nationwide use. This specification requires that the Bioretention Soil Mixture (BSM) be composed of : 30% planting soil, 20% shredded 2x hardwood mulch, and 50% sand by volume (LIDC, 2003). The planting soil must be loamy sand or sandy loam. These specifications are the result of hands-on ex-

perience and experimental optimization of the soil medium (Hsieh and Davis, 2005a). In general, it seems that the sand/soil/organic ratio has been settled on, but the source of organic matter shifts between shredded hardwood mulch and leaf compost. This discussion applies principally to variations in design specific to Prince Georges County, Maryland and its environs. Bioretention specifications around the country do not necessarily follow this formula, and can vary widely. For example, Emerson and Travers bioinfiltration traffic island was constructed using a 1:1 mixture of silt and sand, with no organic amendment at all (Emerson and Traver, 2008).

Planting schemes are much less tightly controlled. The selection and placement of plants is left to the landscape designer's discretion, with the recommendation to select native plants that will tolerate variable hydrologic conditions, and will require little maintenance (PGCO, 2001). In The Bioretention Manual (PGCO, 2001), Prince George's County provides a list of suggested species suitable for bioretention in the region.

1.2.2 Bioretention research

Research into the performance of bioretention as a stormwater treatment device is still in its early days. Up until a few years ago, only a handful of papers had been published. More recently, there has been an explosion of interest in the subject, and a corresponding increase in the number of research studies. Table 1.1 is a compilation of the research studies published to date. This research has focused primarily on the pollutant removal performance of bioretention, testing different designs, soil media, and plantings in the laboratory and in the field. A great deal of research has also concerned the hydrologic performance of bioretention (e.g. peak flow reduction).

Researchers have recently begun to turn their attention to the performance of bioretention systems over time. Li and Davis have studied the potential for bioretention systems to become clogged with sediment (Li and Davis, 2008b,a). Emerson and Traver (2008) recently published a four-year study of the hydrologic performance of a bioretention cell. They found seasonal variations in infiltration rate, but no evidence of clogging over time.

The majority of bioretention research has focused on the soil medium. One study (Hong et al., 2006) looked at the effect of mulch on oil and grease removal. Only two studies have looked at rain gardens as ecosystems. Culbertson and Hutchinson (2004) looked at the effect of plant types on performance. Greene et al. (2008), are currently conducting a study that aims to quantify the effect of vegetation (Tallgrass prairie grasses) and earthworms (*L. terrestris*) on hydraulic performance and pollutant removal.

Table 1.1: Summary of bioretention research to date.

Citation	Reporting format	Factors studied
(Davis et al., 2001b)	Journal article	Heavy metals, Nitrogen, Phosphorus
(Davis et al, 2003)	Journal article	Heavy metals
(Kim et al., 2003)	Journal article	Nitrogen
(Culbertson and Hutchinson, 2004)	Conference paper	Nitrogen
(Dietz and Clausen, 2005)	Journal article	Phosphorus, Nitrogen, Heavy metals, Hydrologic performance
(Hsieh and Davis, 2005a)	Journal article	Hydrologic performance, TSS, Oil and grease, Phosphorus, Nitrogen, Heavy metals
(Hsieh and Davis, 2005b)	Journal article	TSS, Oil and grease, Heavy metals, Nitrogen, Phosphorus
(Sharkey and Hunt, 2005)	Conference paper	Nitrogen, Phosphorus, Hydrologic performance
(Davis et al., 2006)	Journal article	Nitrogen, Phosphorus
(Dietz and Clausen, 2006)	Journal article	Nitrogen, Phosphorus, Heavy metals, Hydrologic performance
(Hong et al., 2006)	Journal article	Oil and grease
(Hunt et al., 2006)	Journal article	TSS, Nitrogen, Phosphorus, Heavy metals, Hydrologic performance
(Zhang et al., 2006)	Conference paper	Phosphorus
(Davis, 2007)	Journal article	TSS, Heavy metals, Nitrogen, Phosphorus
(Dougherty et al., 2007)	Conference paper	Nitrogen, Phosphorus, Hydrologic performance
(Hsieh et al., 2007a)	Journal article	Phosphorus, TSS
(Hsieh et al., 2007b)	Journal article	Nitrogen
(UNHSC, 2007)	Annual report	TSS, Nitrogen, Phosphorus, Heavy metals, Hydrologic performance, Oil and grease
(Muthanna et al., 2007a)	Journal article	Heavy metals, TSS, Chloride
(Muthanna et al., 2007b)	Journal article	Heavy metals, Hydrologic performance
(Sun and Davis, 2007)	Journal article	Heavy metals
(Privette and Weeber, 2007, 2008)	Conference papers	Heavy metals, Nitrogen, Phosphorus, Oil and grease, Hydrologic performance
(Rusciano and Obropta, 2007)	Journal article	Fecal coliform, TSS
(Greene et al., 2008)	Conference paper	Earthworms, Vegetation, Hydraulic performance
(Hunt et al., 2008)	Journal article	TSS, Nitrogen, Phosphorus, Heavy metals, BOD, Fecal coliform, Hydrologic performance
(Jones and Hunt, 2008)	Conference paper	Temperature
(Li and Davis, 2008a)	Journal article	Heavy metals
(Li and Davis, 2008b,c)	Journal articles	TSS
(Thompson et al., 2008)	Journal article	Hydraulic performance
(Davis, 2008)	Journal article	Hydrologic performance
(Emerson and Traver, 2008)	Journal article	Hydrologic performance

1.2.3 Use and value of chronosequences

Succession and pedogenesis can be studied either by designing long-term experiments in which a site is observed to undergo the successional changes of interest or by using a space-for-time substitution (Pickett, 1989), in which multiple sites are selected as representatives of the same ecosystem at various stages of development. These sites form what is known as a chronosequence. Chronosequences are used where the process of interest operates over a very long time period, where direct observation is impractical or impossible.

Chronosequences have, for example, been used to study the recovery of ecosystems in areas disturbed by mining. Abandoned open-pit mines and piles of mine spoils present valuable opportunities to observe primary succession and the early stages of pedogenesis. Leisman (1957) studied primary succession on spoil banks from iron mining in Minnesota using a chronosequence. The spoil banks were composed of glacial till, and had been deposited unamended and left to revegetate on their own. Banks were formed over time as the mining operation proceeded, with the oldest bank 51 years old at the time of sampling. The chronosequence consisted of banks at 10-year intervals in time of formation. The plant community composition was surveyed, and soil profiles were studied down to a 15-inch depth. The depth of the A and Ao horizons were measured, and soil samples were taken at multiple depths. These samples were analyzed for: bulk density, particle size distribution, pH, organic carbon, and total Kjeldahl nitrogen. Young sites were found to be dominated by herbaceous weed species, then, as the sites aged, this community tended to be supplanted by a poplar woodland with a mixed herbaceous/grass understory. A few sites, however, were never colonized by woody species, and retained their grassland character. The chronosequence showed a uniform increase in the thickness of the Ao

horizon to 0.5 in after 51 years. Depth to the A horizon increased monotonically from zero to 1-inch over the first 20 years, but thereafter increased more quickly on sites dominated by herbaceous vegetation than on sites dominated by woody vegetation. No evidence was found of B horizon development, which would have been evidenced by downward migration of silt and clay particles. Organic matter content started out very low, and gradually increased over time, from 0.08% at 2 years to 1.26% at 51 years at the 1-inch depth. Total nitrogen also increased over time. The soil was very sandy (69% sand, on average).

Frouz et al. (2001) compared pedogenesis and soil biota in two chronosequences of coal mine spoils. One site was afforested with conifers, which produced little decomposable litter, and one afforested with deciduous trees, which produced a much thicker and more habitable litter layer. Both sites showed increasing organic matter over time. Both sites also showed increasing density and species richness of invertebrates over time, though there were differences in patterns of development.

Kangas (1979) used a chronosequence to study succession on spoil mounds from phosphate mining. The chronosequence consisted of eight sites, ranging from 1 to 50 years in age. Vegetation surveys were conducted at the sites. Soil organic matter was measured, and ants were collected. Percent cover, tree height, litter weight, soil organic matter, and ant nest density all increased with age.

Foster and Tilman (2000) studied succession in a chronosequence of 23 abandoned fields, then re-surveyed the plant communities at the sites 14 years later, in order to test the validity of the chronosequence. They found that the chronosequence accurately showed a deceleration of compositional change over time. Newly abandoned fields were dominated by fast-growing annuals, which were gradually displaced by slower-growing

perennials. The follow-up survey did not show the increase in species richness over time suggested by the chronosequence, though the authors postulate that this may have been due to weather-related perturbations rather than the inapplicability of the chronosequence (implying that the chronosequence was actually more accurate than the long-term study in measuring long-term successional trajectories).

It is important to be aware that the quality of the data generated using a chronosequence will only be as good as the sites which have been selected. Sites must be as similar as possible. Ideally, time is the only difference between sites. Practically, this is never the case, so it is up to the researcher's judgement to decide which differences are significant enough to influence the site's development. Pickett (1989) examines the use of chronosequences as an alternative to long-term ecological studies. He concludes that space-for-time substitution is useful where general trends are sought. Space-for-time studies can reveal averages, but may not reflect conditions at a particular site. Stevens and Walker (1970) contend that all chronosequence studies fail in one way or another to control for all soil forming factors apart from time, but assert that even flawed chronosequences can be useful for making qualitative comparisons.

1.2.4 Pedogenesis in abandoned farmland and reclaimed mines

The effects of ecological development on pedogenesis are most readily observed in the regeneration of disturbed soils. Abandoned farmland and mine spoils are common places where physically degraded soils are deserted and allowed to revert to natural habitat. Scullion and Malik (2000) conducted a 9-year study of the influence of earthworms on soil development on coal mine spoils. They found that earthworm inputs increased the creation of stable soil aggregates.

Hoogerkamp et al. (1983) inoculated abandoned pastures with earthworms, and observed their effect on the soil profiles over a decade. They found that after about three years, earthworms had incorporated surface residues into the soil, and an A horizon had begun to develop. After nine years, the A horizon had increased in thickness to 5-8 cm.

Roberts et al. (1988b,a) conducted experiments to compare pedogenesis on mine spoils topped with topsoil to those where the soils were amended with organic material (sawdust and sewage sludge). All plots were mulched and hydroseeded with tall fescue (*Festuca arundinacea*). Soil samples were taken at various depths up to 30 cm every year for three years. Soil profiles were analyzed to a depth of 1 m after 1 and 3 years. Within 1 year, A horizons were distinguishable in all plots. After three years, A horizons were more developed, and AC and C1 horizons were observable. The authors note that soil structure development was concentrated in root zones. A horizons were thicker in the topsoiled and organically-amended plots, and thinner in the control plots (4 cm for control, 7 cm for topsoil and sawdust, and 14 cm for sludge). Soil organic matter was observed to increase over time in all plots, though the increase was significant only in the controls, due to the higher background organic matter levels in the treatments.

Gonzalez-Sangregorio et al. (1991) studied pedogenesis in lignite mine spoils over the first three years. The soils were plowed, limed, fertilized, hydroseeded with grasses and legumes, and mulched at the beginning of the experiment. Organic carbon content was observed to increase over time.

1.2.5 Earthworms and pedogenesis

Shaw and Pawluck (1986) demonstrated the ability of earthworms to produce well-aggregated, granular soil structures from unstructured soils. Scullion and Malik (2000)

introduced earthworms to physically degraded coal mine spoils. They found that earthworms increased the formation of stable soil aggregates. Bouché and Al-Addan (1997) demonstrated a correlation between earthworm populations and soil infiltration rates. Blanchart (1992) measured the ability of earthworms to aggregate sieved soils. He found that *M. anomala* exerted a strong influence on soil structure, forming 60% of the soil into aggregates after 30 months.

The beneficial effect of earthworms on soil permeability has been demonstrated by a number of laboratory and field studies. Bouché and Al-Addan (1997) conducted field surveys at seventeen sites in France. The sites displayed a variety of soil types and earthworm species. They found a correlation between infiltration rates and earthworm biomass. Lachnicht et al. (1997) conducted a field experiment in which an agricultural field was subdivided and subjected to three treatments: reduced earthworms, unaltered earthworms, and supplemented earthworms. After several weeks, they found a significantly greater number of macropores in the treatment with supplemental earthworms, but no significant difference in infiltration rates between the treatments.

Urbánek and Doležal (1992) compared the extent of earthworm burrows to infiltration rates of agricultural soils. They found a positive relationship between the extent of earthworm burrows and infiltration rate, and conclude that earthworm burrowing plays a critical role in the maintenance of soil porosity in soils where subsurface drainage has been employed. Joschko et al. (1992) conducted soil column experiments comparing the saturated hydraulic conductivity of soil columns with and without earthworms. They found that the columns with earthworms had higher infiltration rates than did the controls.

Microcosms have been used extensively to study the burrowing behavior of earthworms, and the effect of earthworm burrowing on soil macroporosity and hydraulic con-

ductivity. Capowiez (Capowiez, 2000; Capowiez and Belzunces, 2001; Capowiez et al., 2001) used microcosms to study the burrowing behavior of two earthworm species of different ecological types (anecic and endogeic). Gupta et al. (2001) used microcosms to assess the effect on macroporosity and potential for preferential flow through the burrows of three earthworm species.

Shaw and Pawluck (1986) conducted a microcosm study to assess the ability of earthworms to create structure in different soil textures. After a year, the soil fabric of the sandy loam control (no earthworms) consisted of individual mineral grains coated with clays and organics. In the treatment containing endogeic species, the matrix at the soil surface consisted of mineral grains coated with matrix material so that bridges formed between the grains. In the treatments containing anecic species (*L. terrestris*), the sandy loam soil showed few fecal deposits on the soil surface, in contrast to the other soil types (silty clay loam and clay loam), which showed greater numbers of fecal deposits on the soil surface. In the treatment containing both endogeic and anecic species, the surface soil of the sandy loam consisted of units of densely packed matrix material fused into aggregates. In other words, a more granular surface soil structure was present in the column containing a diverse assembly of earthworm ecotypes. The authors hypothesize that this is due to the synergistic effect of the activities characteristic of the two ecotypes: anecic species feed at the surface, adding organic matter to the soil matrix. Endogeic species then feed within the soil, incorporating this organic matter subsidy into the soil matrix, increasing the granularity of the soil structure.

Ponder et al. (2000) tested the ability of earthworms to reduce soil compaction in microcosms. Using a loamy soil and the species *Diplocardia ornata*, they found that the

earthworms were able to significantly reduce the bulk density of compacted microcosms after three months.

In a review of studies of earthworm populations on reclaimed lands, Curry and Cotton (1983) found that *A. caliginosa*, *A. chlorotica*, and *L. rubellus* tend to be the most successful early colonizers in European mine spoils. These are endogeic and epigeic species, which inhabit the soil surface and upper layers of the soil, respectively. They tend to have high reproductive rates. They found that anecic species, such as *L. terrestris*, tend to take longer to colonize sites. This is due in part to their low reproductive rates.

1.3 Goals of This Study

The objective of this research is to investigate the importance of ecological processes in the long-term performance of rain gardens. The research cataloged variations between rain garden soils of different ages, with emphasis on soil ecosystem development. The influence of earthworms on infiltration rates was quantified, and the potential use of earthworms to regenerate clogged soils was investigated. The knowledge gained by this investigation will allow the development of more informed maintenance procedures for rain gardens. This will allow the stormwater management community to better ensure reliable water quality and quantity performance for the lifetime of a rain garden.

In order to develop new recommendations for rain garden maintenance, it is first necessary to understand how rain garden soils will behave over time. Current engineering design of rain gardens assumes that the soil mix installed will remain largely unchanged for the lifetime of the cell. The only development anticipated is the accumulation of a sediment layer on the soil surface, which may need to be removed periodically. The principles of pedogenesis as understood by soil science suggest that these assumptions are

inadequate. Once installed, a rain garden should evolve in a manner similar to a degraded soil in any other setting. That is, plants and soil animals will colonize the soil, and will systematically change the soil structure. This research is intended to explore the rain garden soil system. The research is divided into three components:

1. descriptive studies of pre-existing rain garden soil profiles,
2. laboratory experiments quantifying the effect of earthworms on infiltration rates, and
3. a simulation model describing the influence of earthworms and soil organic matter on soil porosity and surface crust thickness.

Field surveys of several different rain gardens of various ages provide the first detailed descriptions of rain garden soil profiles. While differences in design and life histories between rain gardens will likely confound direct comparison, it is expected that general patterns of rain garden pedogenesis will emerge from the data set.

A detailed investigation of the influence of earthworms on soil infiltration rates was be performed in the laboratory. Soil columns provided a controlled environment that allowed the effects of earthworms to be isolated from other factors which may also affect infiltration rates. The use of microcosms allowed multiple replicates to be constructed. These microcosms were used to test the hypothesis that bioretention soils containing earthworms have higher infiltration rates than bioretention soils lacking earthworms. This provides a quantitative assessment of a direct impact of soil ecological development on rain garden performance.

A simulation model of the action of earthworms on infiltration was developed. The purpose of the model is to illustrate the physical processes taking place as a result of earthworm activity. The model was developed using data from the field study and the microcosm experiment. Emphasis was given to the potential role of crusting on the soil surface and pore dynamics within the soil on the rain garden's storage capacity.

This research is intended to provide a first glimpse into the biological processes at work in rain garden soils. The three components, taken together, show that soil organisms are present in rain gardens, and explore their potential impact on bioretention performance.

Chapter 2

Field Study

2.1 Introduction

Ten existing rain gardens of various ages were surveyed. The purpose of the surveys was to assess the level of biological activity in the rain gardens, and to characterize their soil profiles. The data collected include: earthworm quantity, species, and size, soil organic matter, soil particle size distribution, root biomass, macroinvertebrate abundance and species richness, and infiltration rate.

These data yield a chronosequence showing the evolution of biological activity and soil profiles over time. While comparison between research sites is complicated by differences in design and history, these data provide a valuable glimpse into processes working at a much larger time scale than are practical to study experimentally.

2.1.1 Background on field sites

Ten existing rain gardens were selected for assessment. They were selected to represent a wide range of rain garden ages and design styles, in order to get a sense of the full spectrum of rain gardens currently in use. Rain gardens ranged in age from one year to ten years. Figure 2.1 shows the locations of the research sites. All were located in the Washington, DC metro area, most in Prince George's County, Maryland. Greater detail on the sites is included as Appendix A.

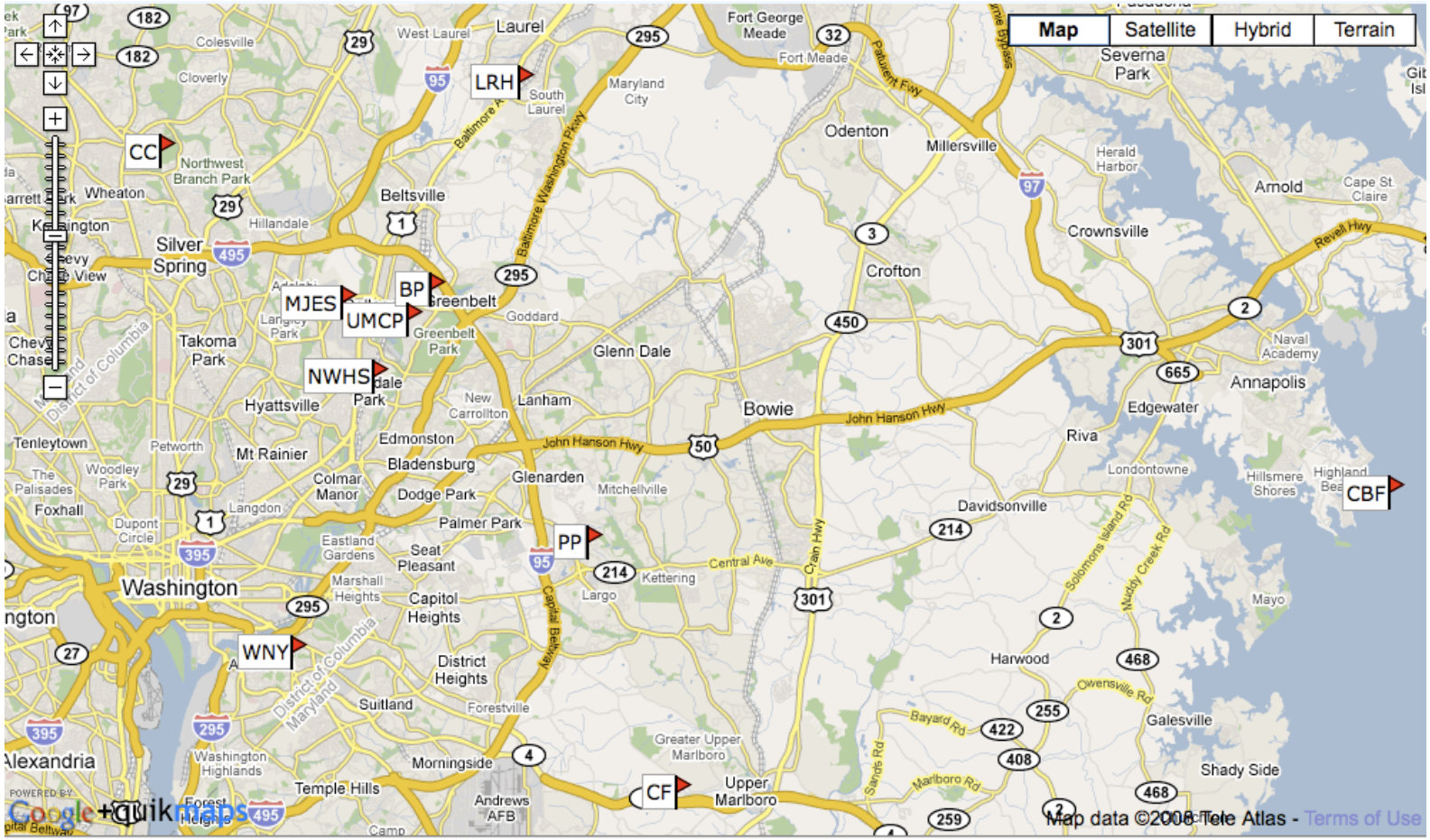


Figure 2.1: Locations of field sites (Quikmaps - http://www.quikmaps.com).

2.1.1.1 University of Maryland (UMCP)

The UMCP site is located on the College Park campus of the University of Maryland, at the end of parking lot PP1, on the south side of the Comcast Center. This rain garden was constructed in 2004, and was sampled in the summer of 2005, making the rain garden 1 year old at the time of sampling. It is a component of a Low Impact Development (LID) retrofit of the Comcast Center parking areas, which included several rain gardens. The cell is in the floodplain of Campus Creek, and was overtopped during a storm event in 2004. The flooding deposited a layer of fine material on the cell surface, which caused the death of many of the original plantings. At the time of sampling, the cell was sparsely covered by herbaceous vegetation, as shown in Figure 2.2. Figure 2.3 shows the shape and location of the site in context. The approximate sampling locations are indicated.

Figure 2.2: Photo of UMCP site.

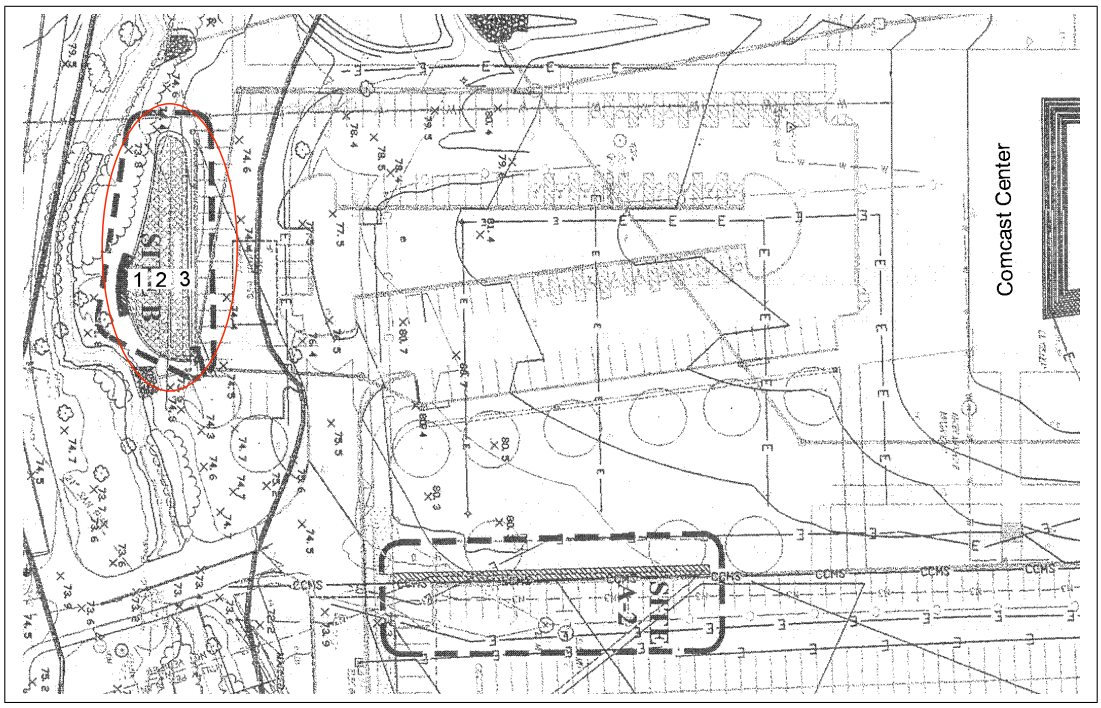


Figure 2.3: UMCP site planview (source: UMCP Department of Facilities Planning). The rain garden of interest is circled, and the sampling locations (1,2, and 3) are indicated.

2.1.1.2 Washington Navy Yard (WNY)

The WNY site is located in the Washington Navy Yard in Washington, DC, in the parking lot of Building 166, south of the O Street visitor center and east of the visitor parking garage. This rain garden was constructed in 2002, and was sampled in the summer of 2004, making the rain garden 2 years old at the time of sampling. It is one component of an LID retrofit of this parking lot, which included several rain gardens and a section of permeable pavement. At the time of sampling, the cell was sparsely planted with small shrubs (red chokeberry, *Aronia arbutifolia*), and the soil surface was covered with mulch, as shown in Figure 2.4. The cell is lined with concrete on the bottom and sides, and is equipped with an underdrain. Maintenance consists of annual removal of mulch and trapped sediment from the soil surface. Figure 2.5 shows the shape and location of the site in context. The approximate sampling locations are indicated.

Figure 2.4: Photo of WNY site.

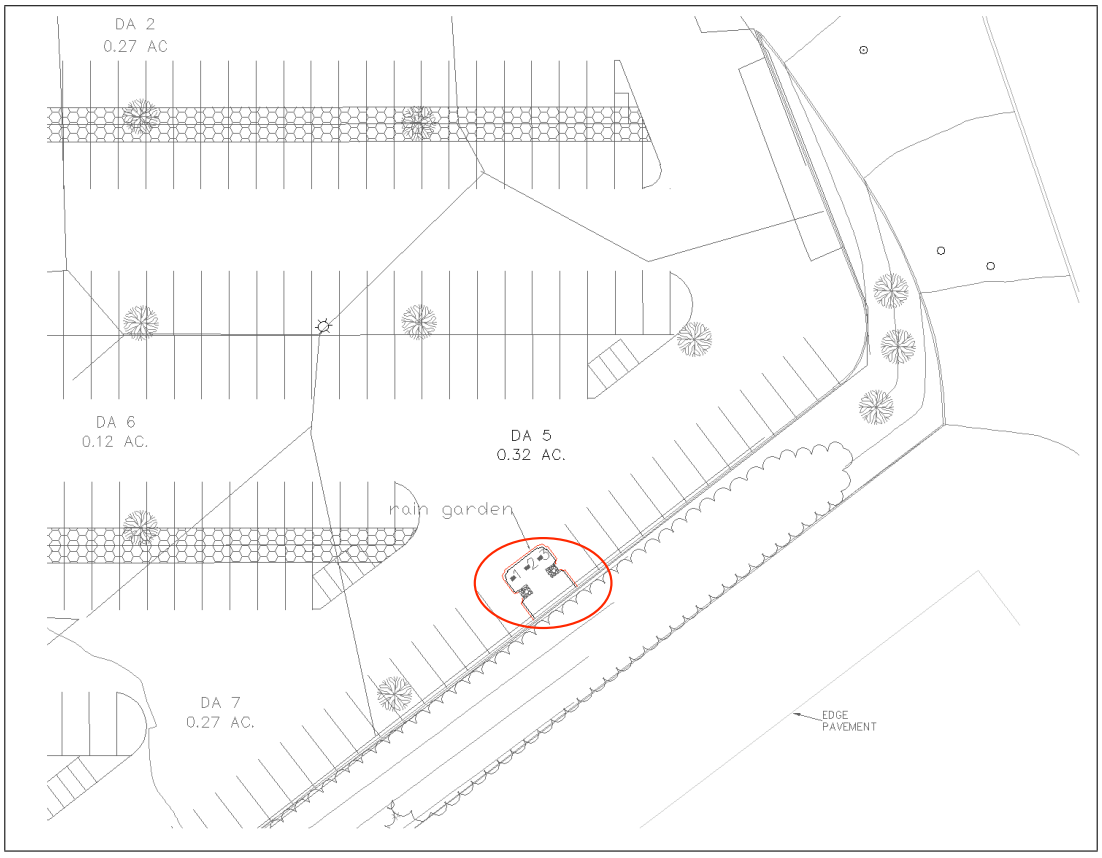


Figure 2.5: WNY site planview (source: The Low Impact Development Center, Inc.). The rain garden of interest is circled, and the sampling locations (1,2, and 3) are indicated.

2.1.1.3 Mary Harris "Mother" Jones Elementary School (MJES)

The MJES site is located at Mary Harris "Mother" Jones Elementary School in Adelphi, Maryland. The rain garden sampled is located directly in front of the school, between the first and second rows of parking spaces. The rain garden was constructed in 2002, and was sampled in the summer of 2005, making the rain garden 3 years old at the time of sampling. At the time of sampling, the cell was densely vegetated with a wide variety of herbaceous plants, shrubs, and small trees, as shown in Figure 2.6. The soil was covered with a layer of mulch. Figure 2.7 shows the shape and location of the site in context. The approximate sampling locations are indicated.

Figure 2.6: Photo of MJES site.

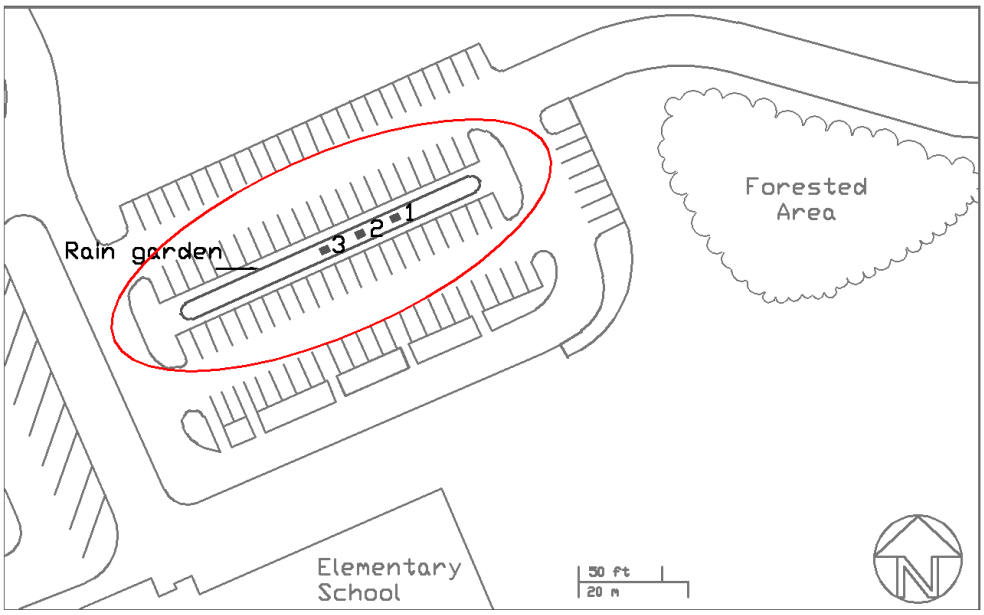


Figure 2.7: MJES site planview. The rain garden of interest is circled, and the sampling locations (1,2, and 3) are indicated.

2.1.1.4 Chesapeake Bay Foundation Headquarters (CBF)

The CBF site is located at the Philip Merrill Environmental Center in Annapolis, MD, in the parking lot on the north side of the building entrance. The rain garden was constructed in 2001 and was sampled in the summer of 2005, making the rain garden 4 years old at the time of sampling. The surrounding parking lot is paved with gravel rather than asphalt. At the time of sampling, the cell was densely populated with small trees, shrubs, and herbaceous vegetation, as shown in Figure 2.8. The soil was covered with a thick litter layer. Figure 2.9 shows the shape and location of the site in context. The approximate sampling locations are indicated.

Figure 2.8: Photo of CBF site.

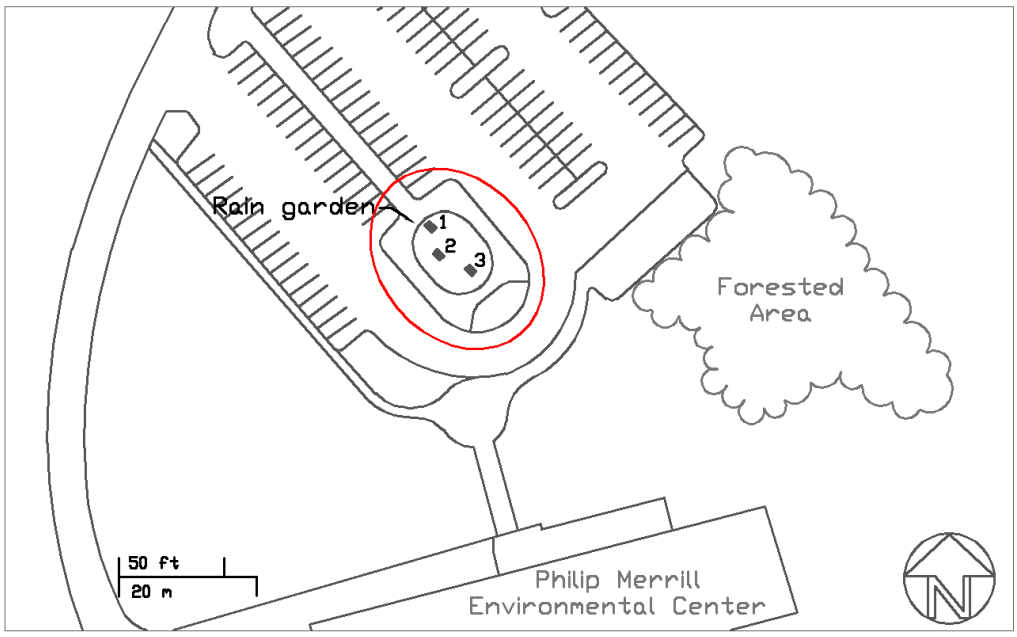


Figure 2.9: CBF site planview. The rain garden of interest is circled, and the sampling locations (1,2, and 3) are indicated.

2.1.1.5 Northwestern High School (NWHS)

The NWHS site is located at Northwestern High School in Hyattsville, MD, directly in front of the school, between the driveway and the first row of parking spaces. This rain garden was constructed in 1999, and was sampled in the summer of 2004, making the rain garden 5 years old at the time of sampling. It is a component of an LID retrofit of the entire parking lot, which included several rain gardens. At the time of sampling, the cell was densely vegetated with a wide variety of herbaceous plants, shrubs, and small trees, as shown in Figure 2.10. The soil was covered with a thin litter layer. Figure 2.11 shows the shape and location of the site in context. The approximate sampling locations are indicated.

Figure 2.10: Photo of NWHS site.

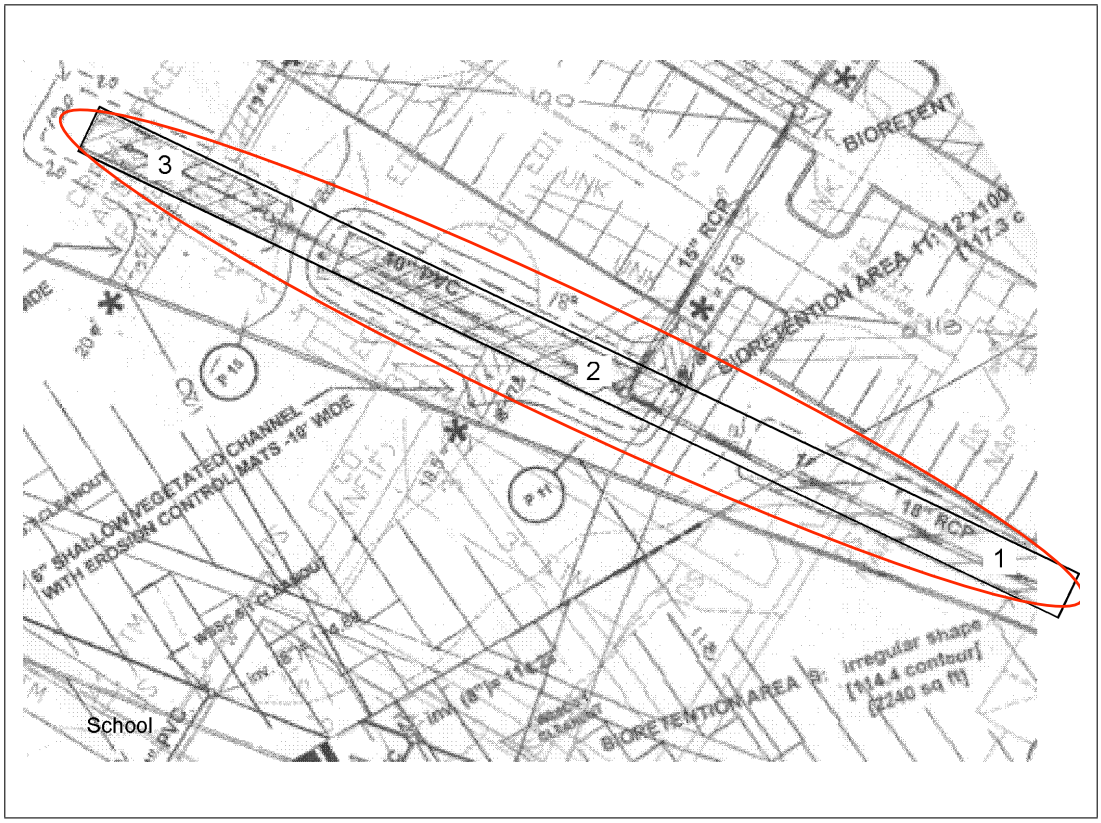


Figure 2.11: NWHS site planview (source: Prince George's County Public Schools). The rain garden of interest is circled, and the sampling locations (1,2, and 3) are indicated.

2.1.1.6 Inglewood Center III (PP)

The PP site is located at Inglewood Center III, 9400 Peppercorn Place, Upper Marlboro, MD. The rain garden sampled is located on the north side of the building, between the driveway and the parking lot. The rain garden was constructed in 1999, and was sampled in the summer of 2004, making it 5 years old at the time of sampling. At the time of sampling, the cell was densely populated with herbaceous vegetation, with the exception of a bare area directly in front of the overflow inlet, as shown in Figure 2.12. The soil surface was covered with a thick mulch layer. Figure 2.13 shows the shape and location of the site in context. The approximate sampling locations are indicated.

Figure 2.12: Photo of PP site.

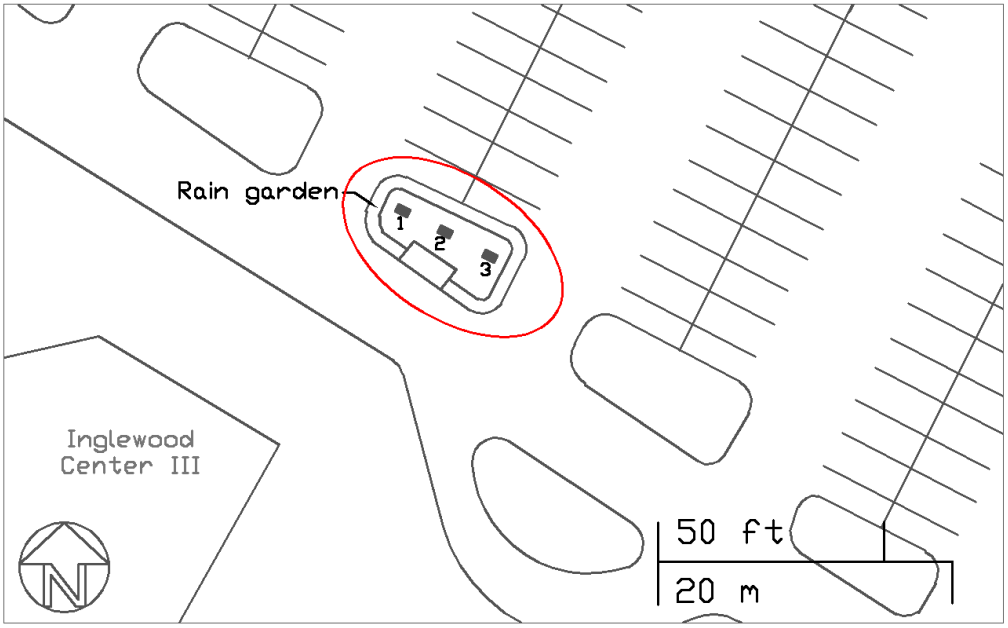


Figure 2.13: PP site planview. The rain garden of interest is circled, and the sampling locations (1,2, and 3) are indicated.

2.1.1.7 Claggett Farm (CF)

The CF site is located on Claggett Farm in Upper Marlboro, MD. This rain garden was constructed in 1999, and was sampled in the summer of 2005, making the rain garden 6 years old at the time of sampling. The rain garden at this site is unique in several respects. It is located alongside a barn, whose roof constitutes the entire drainage area of the rain garden. In addition, this rain garden was constructed using only unamended, in-situ soil. The soil was aerated to a depth of one foot, then bordered by wooden planks. At the time of sampling, the rain garden was dominated by a dense stand of goldenrod (*Solidago spp.*) and an unidentified shrub, as shown in Figure 2.14. Figure 2.15 shows the shape and location of the site in context. The approximate sampling locations are indicated.

Figure 2.14: Photo of CF site.

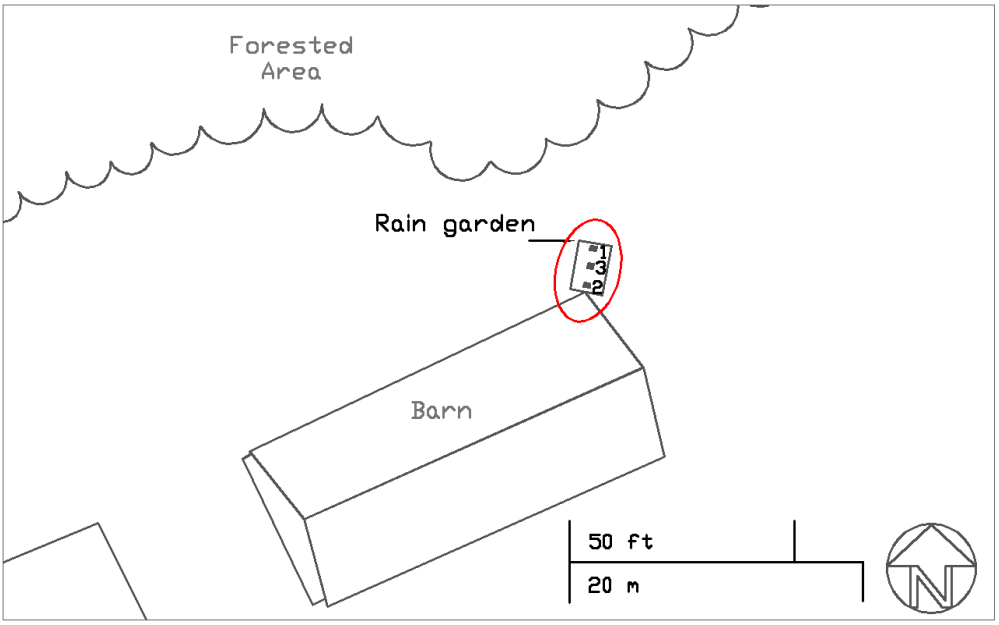


Figure 2.15: CF site planview. The rain garden of interest is circled, and the sampling locations (1,2, and 3) are indicated.

2.1.1.8 Chevy Chase Bank (CC)

The CC site is located at the Glenmont Branch of Chevy Chase Bank, on Randolph Road in Silver Spring, MD. The rain garden sampled is located between the parking lot and the bank drive-thru on the west side of the bank building. The rain garden was constructed in 1998, and was sampled in the summer of 2005, making the rain garden 7 years old at the time of sampling. At the time of sampling, the cell was very densely populated with ornamental grasses and shrubs, and the soil was covered with a thick mulch layer, as shown in Figure 2.16. Figure 2.17 shows the shape and location of the site in context. The approximate sampling locations are indicated.

Figure 2.16: Photo of CC site.

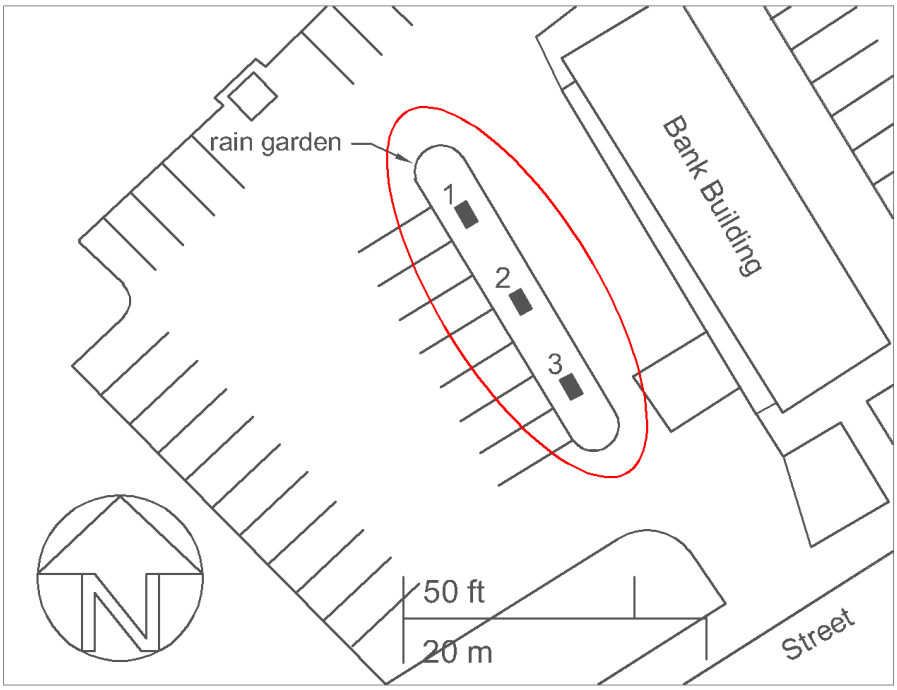


Figure 2.17: CC site planview. The rain garden of interest is circled, and the sampling locations (1,2, and 3) are indicated.

2.1.1.9 Beltway Plaza Mall (BP)

The BP site is located behind the Beltway Plaza Mall in Greenbelt, MD. This rain garden was constructed in 1997, and was sampled in the summer of 2004, making the rain garden 7 years old at the time of sampling. A series of rain garden retrofits have been constructed in this parking lot over the years, starting in 1993. The cell is planted with small trees (mainly *Acer rubrum*), and is densely colonized by a variety of herbaceous plants, as shown in Figure 2.18. The rain garden is mowed every fall, and then the plants are allowed to regenerate over the following year. Figure 2.19 shows the shape and location of the site in context. The approximate sampling locations are indicated.

Figure 2.18: Photo of BP site.

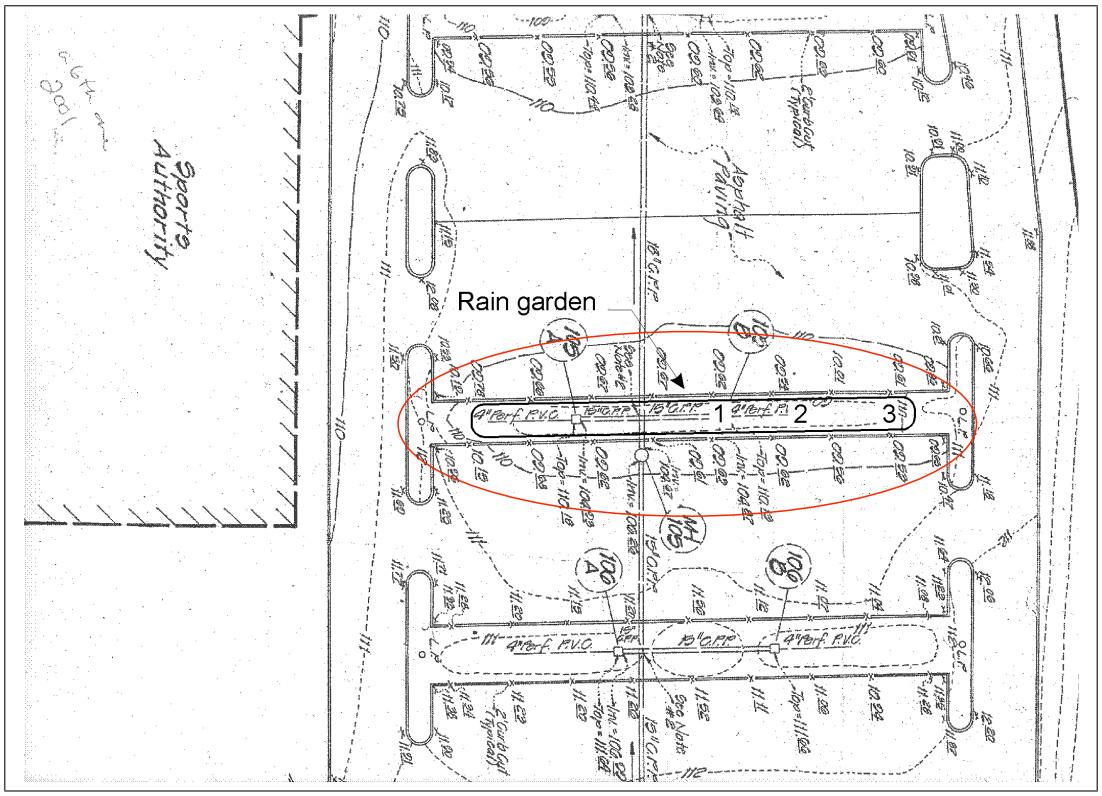


Figure 2.19: BP site planview (source: Beltway Plaza Developers). The rain garden of interest is circled, and the sampling locations (1,2, and 3) are indicated.

2.1.1.10 Laurel Regional Hospital (LRH)

The LRH site is located at Laurel Regional Hospital in Laurel, MD, to the north of the Emergency entrance, between a service road and a small parking lot. It was constructed in 1994, and was sampled in the summer of 2004, making the rain garden 10 years old at the time of sampling. It is one of several rain gardens on the site, and one of the oldest rain gardens in existence. At the time of sampling, the cell contained a stand of well-established trees, with an understory dominated by large shrubs, as shown in Figure 2.20. The soil surface was covered by a thin litter layer beneath the vegetation. Figure 2.21 shows the shape and location of the site in context. The approximate sampling locations are indicated.

Figure 2.20: Photo of LRH site.

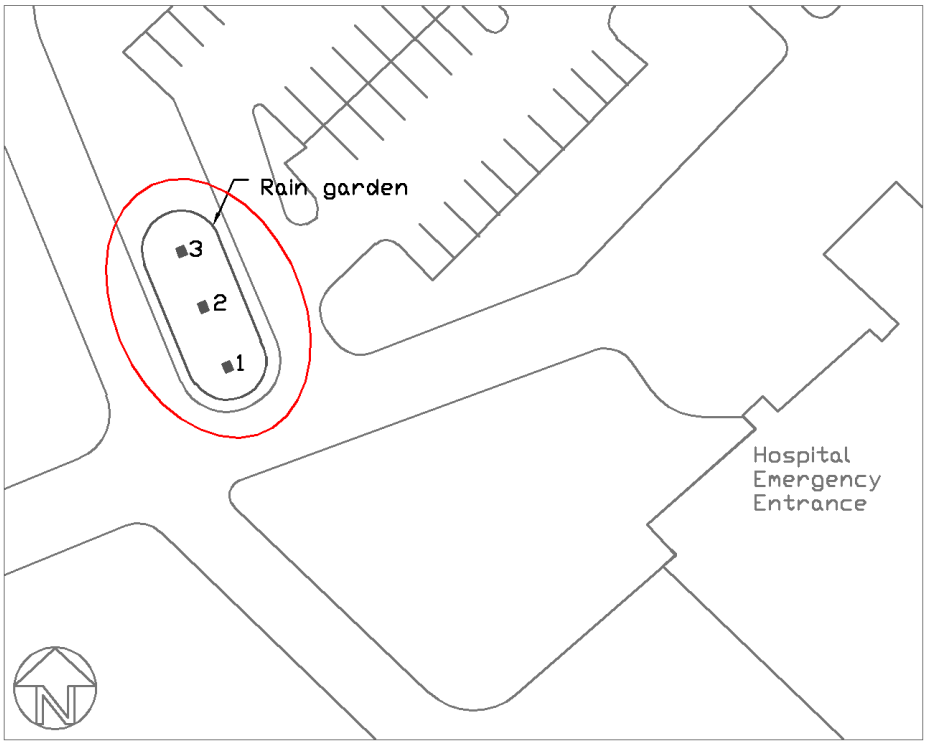


Figure 2.21: LRH site planview. The rain garden of interest is circled, and the sampling locations (1,2, and 3) are indicated.

2.2 Methodology

2.2.1 Field sampling

The sites were sampled during the summers of 2004–2006. Each site was sampled once, at three locations. The sampling locations were spaced evenly along a transect spanning the length of the rain garden. At each location, the litter layer was removed, and plants were clipped at the soil surface. A 20 cm x 30 cm hole was dug, and the first 10 cm of soil was removed. This material was hand sorted. Plant roots were collected. Earthworm lengths were recorded. Representatives of different earthworm species were then sedated in a weak ethanol solution, and preserved in 4% formalin solution for later identification. Other macroscopic invertebrates were tallied and returned to the rain garden. Soil animals were classified into easily identifiable taxa (see Table 2.1). The volume of the removed soil was recorded. Approximately 1 liter of soil was removed for laboratory analysis. The procedure was repeated for the soil from 10–20 cm depth, and from 20–30 cm depth. The major features of the soil profile were recorded, including thicknesses, textures and colors of identifiable layers. Soil colors were described using a Munsell soil color chart. Texture was estimated by feel. The residual soil was then returned to the pit.

At a later date, the infiltration rate of some of the rain gardens was measured using a double ring infiltrometer (ASTM, 2003). The infiltration rate was measured at two to three locations spaced evenly along the same transect used in the soil sampling. A level site was selected that had not been disturbed by the initial soil sampling, and the soil surface was cleared of mulch and plant litter. Plants were clipped at the soil surface, but the roots were not disturbed. Two concentric rings, of 12 in and 24 in diameters, were driven into the soil using a brace and a sledgehammer. When the progress of the rings

Table 2.1: Common and scientific names of animal taxa.

COMMON NAME	SCIENTIFIC NAME
Earthworms	Oligochaeta: Lumbricidae
Beetles	Coleoptera
Common white grubs	Coleoptera: Scarabaeidae larvae
Snts	Hymenoptera: Formicidae
Centipedes	Myriapoda: Chilopoda
Millipedes	Myriapoda: Diplopoda
Potworms	Oligochaeta: Enchytraeidae
Pill bugs	Crustacea: Isopoda
Spiders	Arachnida: Araneae
Springtails	Hexapoda: Collembola
Slugs and snails	Mollusca: Gastropoda
Fly larvae	Hexapoda: Diptera larvae
Mites	Arachnida: Acari
Other insect larvae	Insecta

was impeded by large roots, a machete was inserted into the ground alongside the rings to sever the roots. Great care was taken to minimize disturbance of the soil. The outer ring was driven to a depth of 6 inches, and the inner ring was driven to a depth of 2–4 inches. The inner ring and annular space were filled with water to a depth of 3 inches. Water was added to both spaces as needed in order to maintain a constant head. The volume of water added to the inner ring was measured at regular intervals. Measurements were taken until the volume of water added per unit time reached equilibrium. The experiment was continued for one hour at equilibrium. The incremental infiltration velocity was calculated as follows:

$$I = \frac{\Delta V}{A \Delta t} \tag{2.1}$$

where:

I = inner ring incremental infiltration velocity (cm/h)

ΔV = volume of liquid used to maintain constant head in inner ring (cm^3)

A = internal area of inner ring (cm^2), and

Δt = timer interval (h).

The final infiltration rate of the soil was calculated by taking the average of the incremental infiltration velocity of the final three measurements.

2.2.2 Laboratory analysis

Plant roots were washed, and live roots were separated from dead. Live roots were characterized by flexibility, light-colored interior, with no signs of decay. Roots considered dead were dark throughout, brittle, or decayed. The live roots were dried overnight in a 70°C oven, then weighed. To estimate the mass of very fine roots, all visible root fragments were removed from a 100 mL soil subsample. The roots were washed, oven dried at 70°C, and weighed. The weight of this subsample was then multiplied by the measured volume of removed soil to give the total mass of fine roots. Soil organic matter, SOM, was measured using the loss-on-ignition method (ASTM, 2000). The soil sample was oven dried at 70°C. A 6 g subsample was crushed and sieved using a #10 (2mm) mesh sieve. The subsample was weighed, then ashed at 400°C for four hours. The ashed sample was weighed, and the SOM was calculated using the formula:

$$\%\ organic\ matter = \frac{mass\ (oven\text{-}dried) - \ mass\ (ashed)}{mass\ (oven\text{-}dried)} \times 100\% \tag{2.2}$$

Particle size distribution was measured using the hydrometer method and dry sieving. Samples with more than 10% organic matter were first oxidized using a 6% hydrogen peroxide solution. Details of the procedures followed are included in Appendix B. The resulting particle size distribution curve was used to calculate the coefficient of uniformity

(d_{60}/d_{10}), where d_{60} and d_{10} are the soil particle diameters for which 60% and 10% of the mass of a soil sample is finer, respectively.

A taxonomic guide to earthworms commonly found in Maryland (Csuzdi and Slávecz, 2003; Reynolds, 1974) was developed by compiling descriptions from a number of sources (Baker and Barrett, 1994; Eaton, 1942; Fender and McKey-Fender, 1990; Gates, 1937, 1958, 1972a,b, 1973, 1974; James, 1990; Lee, 1959; Reynolds et al., 1974; Schwert, 1990; Sims et al., 1999; Worm Watch Canada, 2002). This key is included as Appendix C. The preserved earthworm samples were examined using a dissecting microscope. Earthworms were identified as completely as possible by external features using the key. The extent to which the earthworm samples were identifiable depended upon their maturity, and on the presence or absence of unique identifying features. Non-clitellate (immature) specimens lack many identifying features, and can rarely be identified, even to genus.

2.3 Results

The data presented here are average values for the three locations sampled at each of the sites. Results are reported as mean ± standard deviation. Complete data for all samples taken at each of the sites are included as Appendix D.

2.3.1 University of Maryland (UMCP)

A summary of the data collected at UMCP is presented in Table 2.2. An average of 4.3 ± 2.5 earthworms were collected from the uppermost soil layer. No earthworms were found below 10 cm. Mean earthworm size was 2.6 ± 0.7 cm. Root biomass was highest in the upper and lower soil layers (0.71 ± 0.20 g and 0.73 ± 0.69 g, respectively, averaging 1.74 ± 0.89 g for the entire depth). Soil organic matter was highest at the surface

(2.91 ± 0.33%), decreasing with depth to 1.44 ± 0.03% at the 20–30 cm depth. The soil texture was sand throughout, averaging 91.0 ± 1.2% sand, 4.6 ± 0.9% silt, and 3.8 ± 0.3% clay. The particle size distribution is presented graphically in Figure 2.22. A coefficient of uniformity of 10 was measured throughout the site. A total of 5 animal taxa were collected, all from the uppermost soil layer. The composition of the animal community is presented in Figure 2.23. The UMCP animal community is dominated by earthworms (Lumbricidae), followed by beetles (Coleoptera). Individual grubs, ants, millipedes and spiders were also collected. Nine of the collected earthworms were identified as *Diplocardia singularis* (see Appendix D). The distribution of major soil animal groups with depth is shown in Figure 2.24. The major groups were found only in the uppermost soil layers.

Table 2.2: Summary of data collected at UMCP, averaged. *indicates a parameter for which values are summed over the sampling depth rather than averaged. †Layers where no earthworms were found are not included in the calculation of the average earthworm size.

	Depth			
	0–10 cm	10–20 cm	20–30 cm	Entire Depth Profile
Earthworms (#s)	4.3 ± 2.5	0	0	4.3 ± 2.5*
Earthworm Size (cm)	2.6 ± 0.7	0	0	2.6 ± 0.7†
Root Biomass (g)	0.71 ± 0.20	0.30 ± 0.15	0.73 ± 0.69	1.74 ± 0.89*
Soil Organic Matter (%)	2.91 ± 0.33	1.53 ± 0.05	1.44 ± 0.03	2.05 ± 0.25
Soil Textural Classification	Sand	Sand	Sand	Sand
Sand Content (%)	89.4 ± 2.4	92.6 ± 1.7	92.0 ± 0.7	91.0 ± 1.2
Silt Content (%)	6.1 ± 2.9	4.6 ± 0.8	4.4 ± 0.9	4.6 ± 0.9
Clay Content (%)	4.5 ± 0.6	2.9 ± 1.0	3.6 ± 0.3	3.8 ± 0.3
d_{60} (mm)	0.5	1	1	n/a
d_{10} (mm)	0.05	0.1	0.1	n/a
Coefficient of Uniformity (d_{60}/d_{10})	10	10	10	n/a
Soil Animals (#s, includes earthworms)	7 ± 4	0	0	7 ± 4 *
Total Number of Taxa (not averaged)	5	0	0	5*

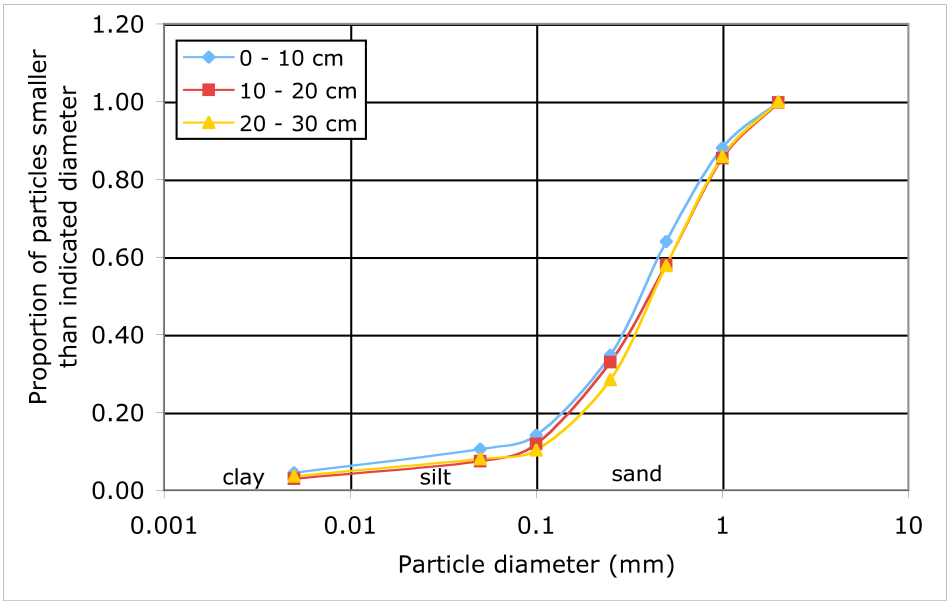


Figure 2.22: UMCP particle size distribution.

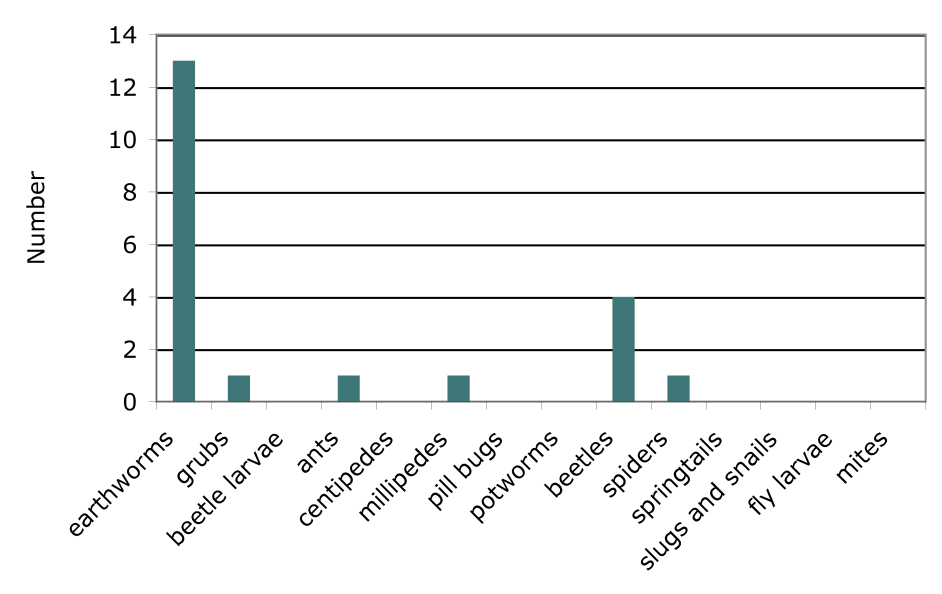


Figure 2.23: UMCP animal diversity. Total number of individuals of major invertebrate taxa found over entire site.

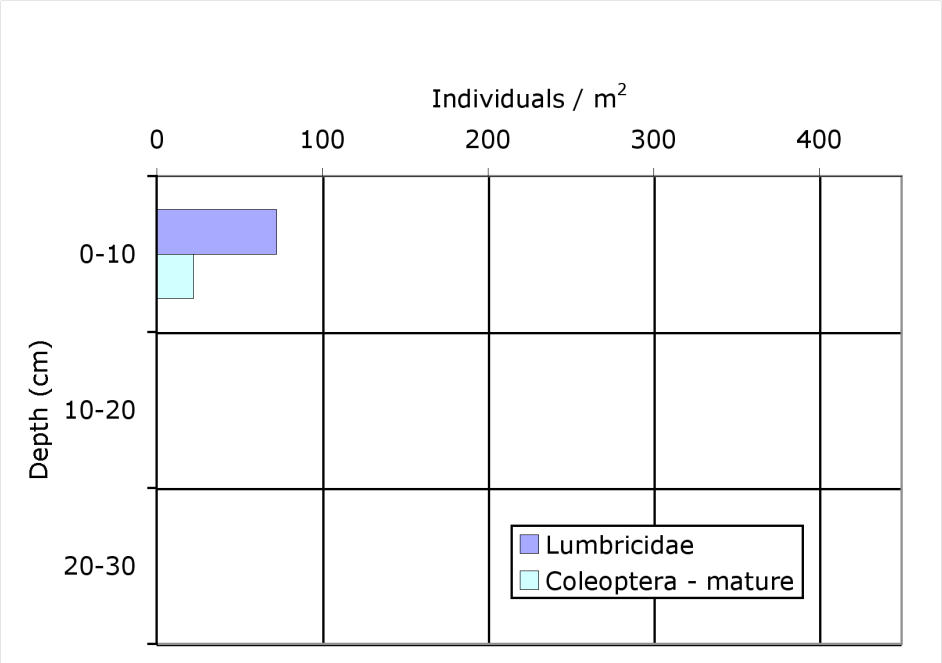


Figure 2.24: UMCP animal depth profile, showing the variation in density with depth of the most abundant macroinvertebrate taxa.

2.3.2 Washington Navy Yard (WNY)

A summary of the data collected at WNY is presented in Table 2.3. An average of 4.0 ± 5.3 earthworms were collected from the uppermost soil layer. 1.7 ± 2.1 earthworms were collected from the 10–20 cm depth. No earthworms were found below 10 cm. Mean earthworm size was 5.0 ± 0.8 cm. Root biomass was lowest in the uppermost layer (2.74 ± 2.23 g), increasing in the middle and lower layers (3.50 ± 3.42 g and 3.49 ± 3.78 g, respectively). The total root biomass over the entire sampling depth was 9.73 ± 9.18 g. Soil organic matter was highest at the surface (6.28 ± 1.82%), decreasing with depth to 2.05 ± 0.19% at the 20–30 cm depth. The soil texture was sandy loam throughout, averaging 71.3 ± 3.4% sand, 21.3 ± 5.7% silt, and 7.4 ± 2.8% clay. The particle size distribution is presented graphically in Figure 2.25. A coefficient of uniformity of 10 was measured at the 0–10 and 10–20 cm depths, and a coefficient of uniformity of 100 was measured at the 20–30 cm depth. A total of 2 animal taxa were collected. Animals were found at the upper and middle soil layers. The composition of the animal community is presented in Figure 2.26. The WNY animal community is dominated by grubs (Coleoptera: Scarabaeidae larvae), followed by earthworms (Lumbricidae). No other animals were found. None of the collected earthworms were identified (see Appendix D). The distribution of major soil animal groups with depth is shown in Figure 2.27. The major groups were found primarily in the upper soil layer, and at lower densities in the middle layer. None were found in the lower layer.

Table 2.3: Summary of data collected at WNY, averaged. *indicates a parameter for which values are summed over the sampling depth rather than averaged. †Layers where no earthworms were found are not included in the calculation of the average earthworm size.

	Depth			
	0–10 cm	10–20 cm	20–30 cm	Entire Depth Profile
Earthworms (#s)	4.0 ± 5.3	1.7 ± 2.1	0	5.7 ± 7.4*
Earthworm Size (cm)	5.0 ± 0.8	0	0	5.0 ± 0.8†
Root Biomass (g)	2.74 ± 2.23	3.50 ± 3.42	3.49 ± 3.78	9.73 ± 9.18*
Soil Organic Matter (%)	6.28 ± 1.82	2.34 ± 0.16	2.05 ± 0.19	3.56 ± 0.62
Soil Textural Classification	Sandy Loam	Sandy Loam	Sandy Loam	Sandy Loam
Sand Content (%)	71.6 ± 3.5	72.0 ± 3.9	70.2 ± 4.5	71.3 ± 3.4
Silt Content (%)	23.0 ± 2.9	21.2 ± 5.0	19.8 ± 11.1	21.3 ± 5.7
Clay Content (%)	5.3 ± 1.3	6.8 ± 1.4	10.0 ± 6.8	7.4 ± 2.8
d_{60} (mm)	0.5	0.5	0.5	n/a
d_{10} (mm)	0.05	0.05	0.005	n/a
Coefficient of Uniformity (d_{60}/d_{10})	10	10	100	n/a
Soil Animals (#s, includes earthworms)	11± 4	2 ± 2	0	14 ± 5*
Total Number of Taxa (not averaged)	2	2	0	2*

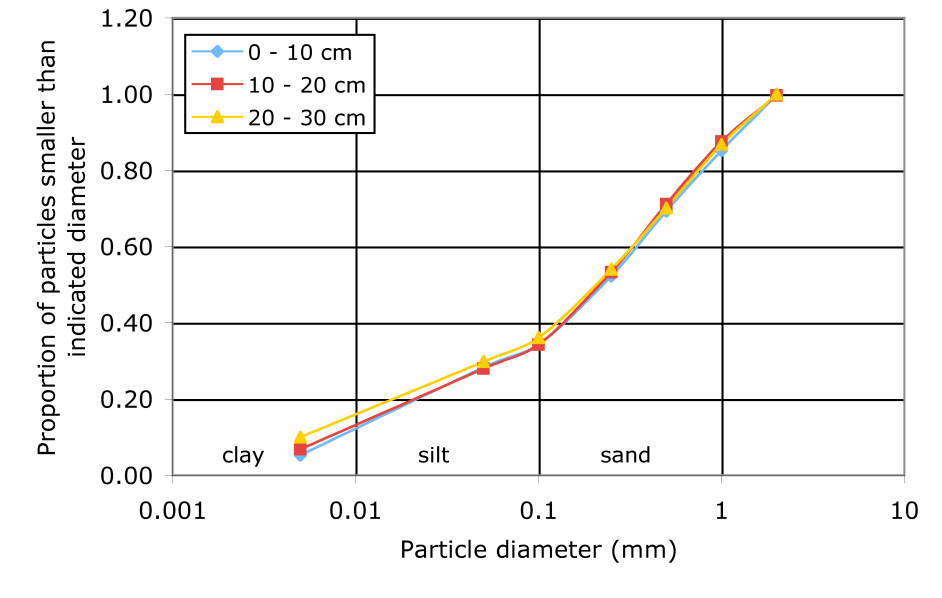


Figure 2.25: WNY particle size distribution.

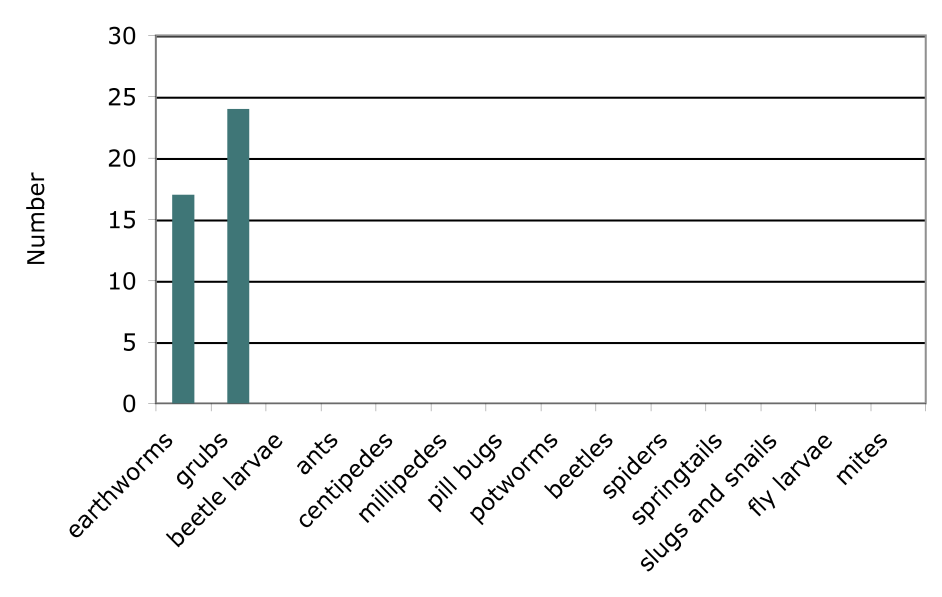


Figure 2.26: WNY animal diversity. Total number of individuals of major invertebrate taxa found over entire site.

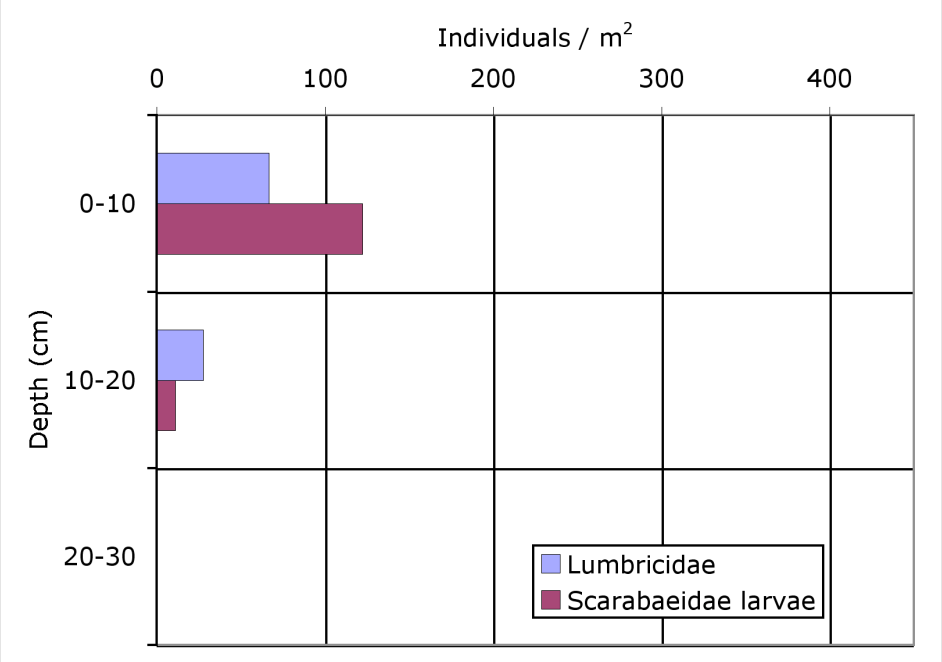


Figure 2.27: WNY animal depth profile, showing the variation in density with depth of the most abundant macroinvertebrate taxa.

2.3.3 "Mother" Jones Elementary School (MJES)

A summary of the data collected at MJES is presented in Table 2.4. An average of 45.2 ± 65.9 earthworms were collected from the uppermost soil layer. 2.5 ± 4.3 earthworms were collected from the 10–20 cm depth. Only 0.7 ± 1.2 earthworms were found below 20 cm. A very large number of small earthworms (121) were found in the upper soil layer at one sampling location. Mean earthworm size was 3.1 ± 1.1 cm. Root biomass was 1.62 ± 0.74 g in the upper and middle layers, increasing slightly to 2.08 ± 2.97 g in the lower layer. Total root biomass for the entire soil depth was 5.33 ± 4.18 g. Soil organic matter was highest at the surface (17.53 ± 14.15%), decreasing with depth to 2.09 ± 1.60% at the 20–30 cm depth. The average soil texture was sandy loam at all depths, averaging 65.8 ± 21.3% sand, 19.7 ± 12.4% silt, and 14.5 ± 8.9% clay. The particle size distribution is presented graphically in Figure 2.28, and shows considerable variability between sampling locations (see Appendix D). A coefficient of uniformity of 50 was measured at all depths. A total of 12 animal taxa were collected. Animals were found primarily in the upper soil layer, but also occurred in the middle and lower soil layers. The composition of the animal community is presented in Figure 2.29. The MJES animal community is dominated by grubs (Coleoptera: Scarabaeidae larvae), followed by earthworms (Lumbricidae). Potworms (Enchytraeidae) and springtails (Collembola) were found in moderate numbers. Grubs, other beetle larvae, ants, centipedes, millipedes, spiders, slugs and snails were collected in much lower numbers. Representatives of *Allolobophora chlorotica*, *Bimastos parvus*, *Pheretima spp.*, and *Lumbricus spp.* were identified among the collected earthworms (see Appendix D). The distribution of major soil animal groups with depth is shown in Figure 2.30. The major groups were found primarily in the upper soil layer. Animal densities decreased with depth.

Table 2.4: Summary of data collected at MJES, averaged. *indicates a parameter for which values are summed over the sampling depth rather than averaged. †Layers where no earthworms were found are not included in the calculation of the average earthworm size.

	Depth			
	0–10 cm	10–20 cm	20–30 cm	Entire Depth Profile
Earthworms (#s)	45.2 ± 65.9	2.5 ± 4.3	0.7 ± 1.2	48.3 ± 71.4*
Earthworm Size (cm)	4.3 ± 2.1	2.1	3.0	3.1 ± 1.1 †
Root Biomass (g)	1.62 ± 0.74	1.62 ± 1.40	2.08 ± 2.97	5.33 ± 4.18*
Soil Organic Matter (%)	17.53 ± 14.15	2.31 ± 1.70	2.09 ± 1.60	7.31 ± 5.75
Soil Textural Classification	Sandy Loam	Sandy Loam	Sandy Loam	Sandy Loam
Sand Content (%)	57.2 ± 18.9	71.3 ± 21.7	68.8 ± 23.8	65.8 ± 21.3
Silt Content (%)	28.8 ± 14.3	14.5 ± 11.5	15.8 ± 12.6	19.7 ± 12.4
Clay Content (%)	14.0 ± 5.3	14.2 ± 10.3	15.4 ± 11.5	14.5 ± 8.9
d_{60} (mm)	0.25	0.25	0.25	n/a
d_{10} (mm)	0.005	0.005	0.005	n/a
Coefficient of Uniformity (d_{60}/d_{10})	50	50	50	n/a
Soil Animals (#s, includes earthworms)	73 ± 84	4 ± 6	1 ± 1	78 ± 90*
Total Number of Taxa (not averaged)	11	4	1	12*

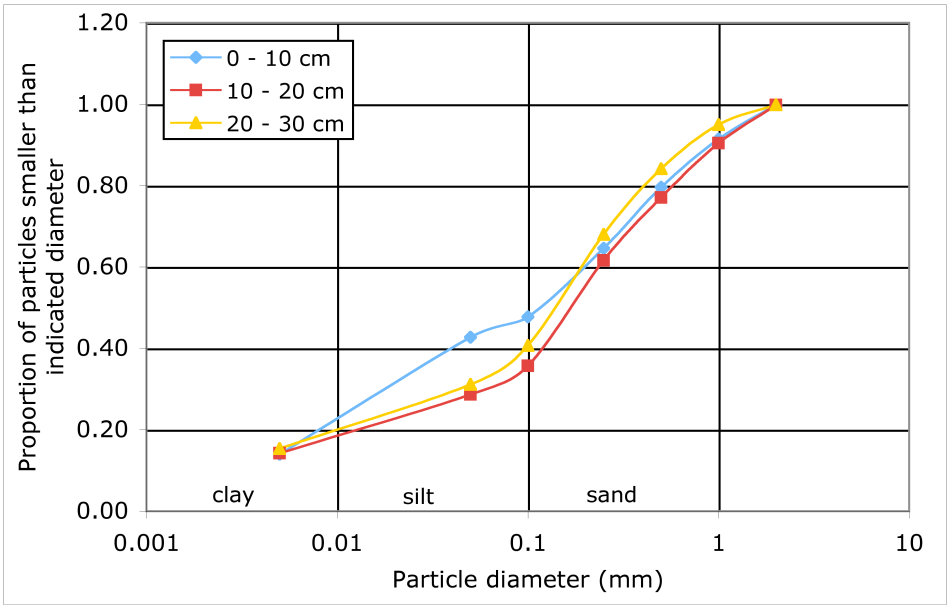


Figure 2.28: MJES particle size distribution.

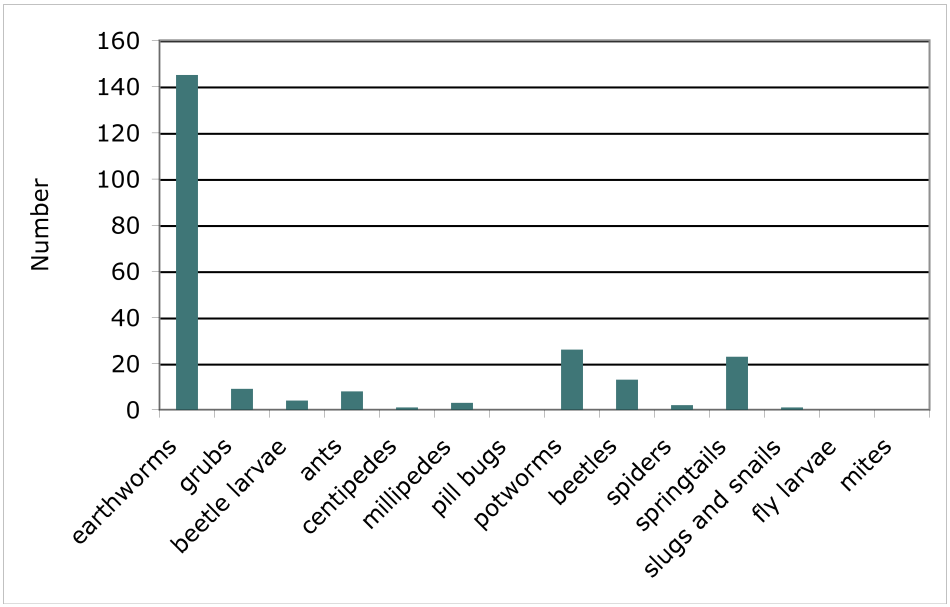


Figure 2.29: MJES animal diversity. Total number of individuals of major invertebrate taxa found over entire site.

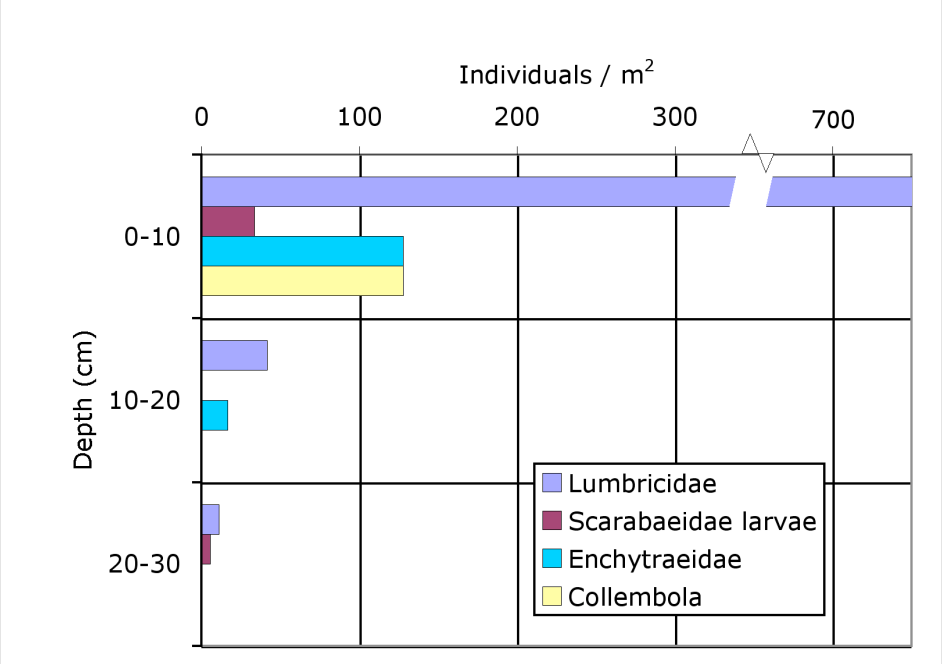


Figure 2.30: MJES animal depth profile, showing the variation in density with depth of the most abundant macroinvertebrate taxa.

2.3.4 Chesapeake Bay Foundation Headquarters (CBF)

A summary of the data collected at CBF is presented in Table 2.5. An average of 14.0 ± 8.5 earthworms were collected from the uppermost soil layer. 1.3 ± 1.2 earthworms were collected from the 10–20 cm depth. Only 0.3 ± 0.6 earthworms were found below 20 cm. Mean earthworm size was 2.7 ± 1.9 cm. Root biomass was highest in the uppermost soil layer (10.10 ± 7.18 g), decreasing sharply in the middle and lower layers to 1.86 ± 0.49 g and 0.89 ± 0.61 g, respectively. Soil organic matter was very low throughout, and similar at all depths (upper: 2.68 ± 0.66%, middle: 2.69 ± 0.33%, lower: 2.83 ± 0.17%). The average soil texture was sandy clay loam at all depths, averaging 61.0 ± 0.9% sand, 16.5 ± 0.6% silt, and 22.5 ± 1.3% clay. The particle size distribution is presented graphically in Figure 2.31. A coefficient of uniformity of 50 was measured at all depths. A total of 11 animal taxa were collected. Animals were found primarily in the upper soil layer, but also occurred in the middle and lower soil layers. The composition of the animal community is presented in Figure 2.32. The CBF animal community is dominated by earthworms (Lumbricidae) and pill bugs (Isopoda). Beetles (Coleoptera) were found in moderate numbers. Beetle larvae, ants, centipedes, millipedes, potworms, spiders, and springtails were collected in much lower numbers. The majority of the earthworms collected at CBF were identified as *Apporectodea caliginosa* (see Appendix D). One representative of *Pheretima diffringens* was also identified. The distribution of major soil animal groups with depth is shown in Figure 2.33. Lumbricid density declined with depth. Isopods and Coleoptera occurred primarily in the uppermost soil layer, though one Coleoptera individual was found in the middle soil layer.

Table 2.5: Summary of data collected at CBF, averaged. *indicates a parameter for which values are summed over the sampling depth rather than averaged. † Layers where no earthworms were found are not included in the calculation of the average earthworm size.

	Depth			
	0–10 cm	10–20 cm	20–30 cm	Entire Depth Profile
Earthworms (#s)	14.0 ± 8.5	1.3 ± 1.2	0.3 ± 0.6	15.7 ± 9.7*
Earthworm Size (cm)	2.3 ± 0.3	4.8 ± 3.9	1.0	2.7 ± 1.9†
Root Biomass (g)	10.10 ± 7.18	1.86 ± 0.49	0.89 ± 0.61	12.85 ± 8.18*
Soil Organic Matter (%)	2.68 ± 0.66	2.69 ± 0.33	2.83 ± 0.17	2.74 ± 0.36
Soil Textural Classification	Sandy Clay Loam	Sandy Clay Loam	Sandy Clay Loam	Sandy Clay Loam
Sand Content (%)	61.0 ± 1.4	60.8 ± 1.0	61.3 ± 0.6	61.0 ± 0.9
Silt Content (%)	15.1 ± 1.6	17.1 ± 0.6	17.2 ± 1.0	16.5 ± 0.6
Clay Content (%)	23.9 ± 2.0	22.1 ± 1.2	21.5 ± 1.5	22.5 ± 1.3
d_{60} (mm)	0.25	0.25	0.25	na
d_{10} (mm)	0.005	0.005	0.005	na
Coefficient of Uniformity (d_{60}/d_{10})	50	50	50	na
Soil Animals (#s, includes earthworms)	44 ± 18	2 ± 2	0 ± 1	46 ± 16*
Total Number of Taxa (not averaged)	10	3	1	11*

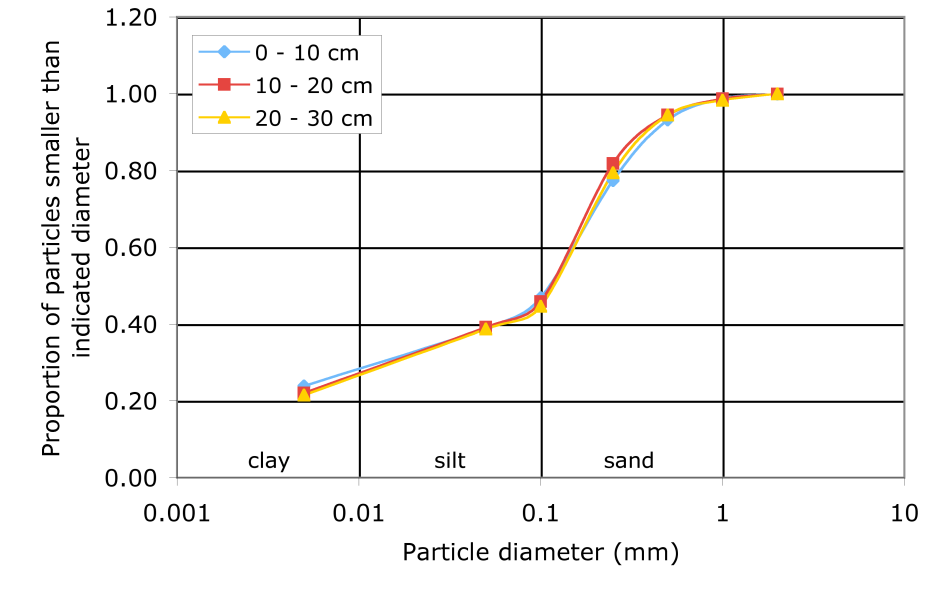


Figure 2.31: CBF particle size distribution.

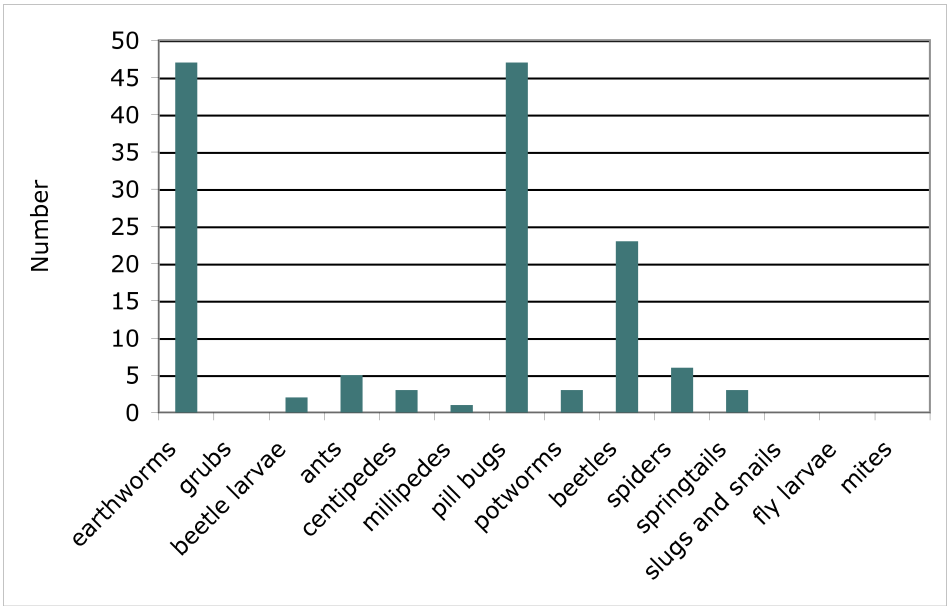


Figure 2.32: CBF animal diversity. Total number of individuals of major invertebrate taxa found over entire site.

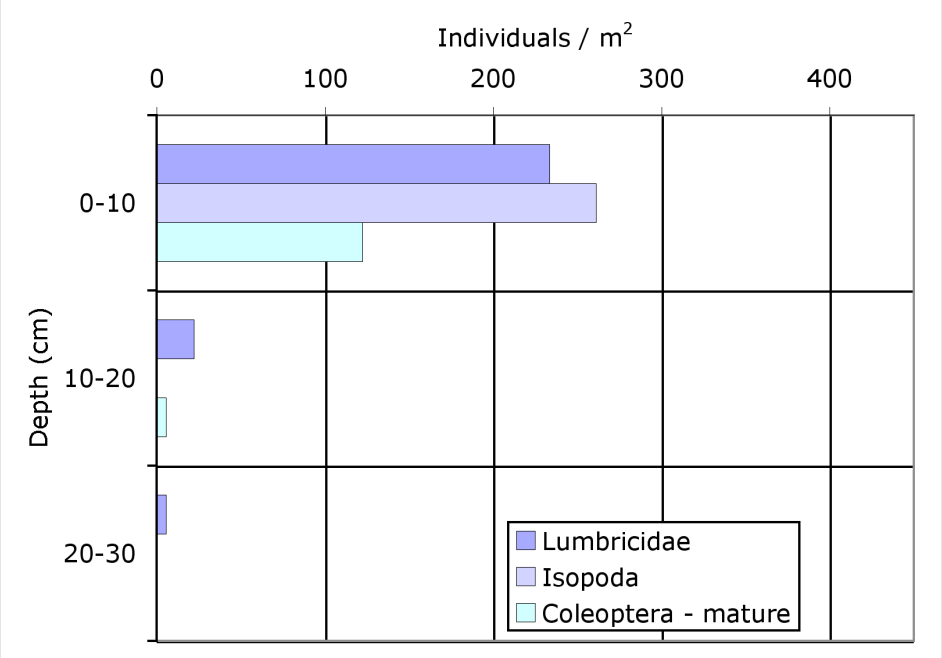


Figure 2.33: CBF animal depth profile, showing the variation in density with depth of the most abundant macroinvertebrate taxa.

2.3.5 Northwestern High School (NWHS)

A summary of the data collected at NWHS is presented in Table 2.6. An average of 18.0 ± 27.8 earthworms were collected from the uppermost soil layer. 9.3 ± 16.2 earthworms were collected from the 10–20 cm depth. 1.3 ± 2.3 earthworms were found below 20 cm. Mean earthworm size was 2.3 ± 0.6 cm. Root biomass was highest in the uppermost soil layer (7.58 ± 5.41 g), decreasing sharply to 1.43 ± 0.12 g in the middle layer, and 1.22 ± 0.59 g in the lower layer. Total root biomass for the entire sampling depth was 10.22 ± 5.09 g. Soil organic matter was highest in the upper layer (4.39 ± 1.11%), decreasing to 2.81 ± 0.69% in the lower layer. Soil texture showed some variability with depth, with the middle layer exhibiting the finest texture. When averaged over the entire depth, the soil had loamy texture, averaging 51.4 ± 4.0% sand, 34.2 ± 1.0% silt, and 14.4 ± 3.7% clay. The particle size distribution is presented graphically in Figure 2.34. A coefficient of uniformity of 50 was measured in the upper and lower layers, and a coefficient of uniformity of 20 was measured in the middle layer. A total of 11 animal taxa were collected. Animals were found primarily in the upper and middle soil layers, but also occurred in the lower layer. The composition of the animal community is presented in Figure 2.35. The NWHS animal community is dominated by earthworms (Lumbricidae). Potworms (Enchytraeidae) were found in moderate numbers. Grubs, other beetle larvae, ants, centipedes, millipedes, pill bugs, beetles, spiders, and springtails were collected in much lower numbers. None of the collected earthworms could be identified (see Appendix D). The distribution of major soil animal groups with depth is shown in Figure 2.36. The densities of both Lumbricidae and Enchytraeidae were highest in the uppermost soil layer and decreased with depth.

Table 2.6: Summary of data collected at NWHS, averaged. *indicates a parameter for which values are summed over the sampling depth rather than averaged. †Layers where no earthworms were found are not included in the calculation of the average earthworm size.

	Depth			
	0–10 cm	10–20 cm	20–30 cm	Entire Depth Profile
Earthworms (#s)	18.0 ± 27.8	9.3 ± 16.2	1.3 ± 2.3	28.7 ± 46.2*
Earthworm Size (cm)	2.9 ± 1.2	1.9	2.0	2.3 ± 0.6 †
Root Biomass (g)	7.58 ± 5.41	1.43 ± 0.12	1.22 ± 0.59	10.22 ± 5.09*
Soil Organic Matter (%)	4.39 ± 1.11	3.59 ± 0.41	2.81 ± 0.69	3.60 ± 0.25
Soil Textural Classification	Sandy Loam	Loam	Sandy Loam	Loam
Sand Content (%)	53.1 ± 4.0	43.4 ± 7.5	57.8 ± 9.3	51.4 ± 4.0
Silt Content (%)	33.0 ± 1.5	40.0 ± 8.1	29.6 ± 5.1	34.2 ± 1.0
Clay Content (%)	14.0 ± 3.3	16.6 ± 3.2	12.6 ± 4.6	14.4 ± 3.7
d_{60} (mm)	0.25	0.1	0.25	n/a
d_{10} (mm)	0.005	0.005	0.005	n/a
Coefficient of Uniformity (d_{60}/d_{10})	50	20	50	n/a
Soil Animals (#s, includes earthworms)	40 ± 37	22 ± 16	12 ± 16	74 ± 46*
Total Number of Taxa (not averaged)	9	7	2	11*

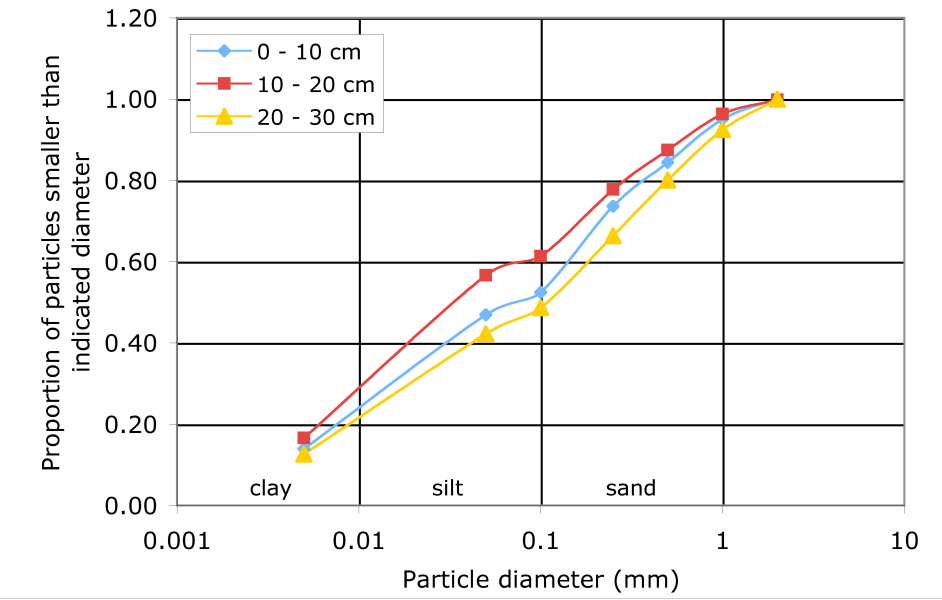


Figure 2.34: NWHS particle size distribution.

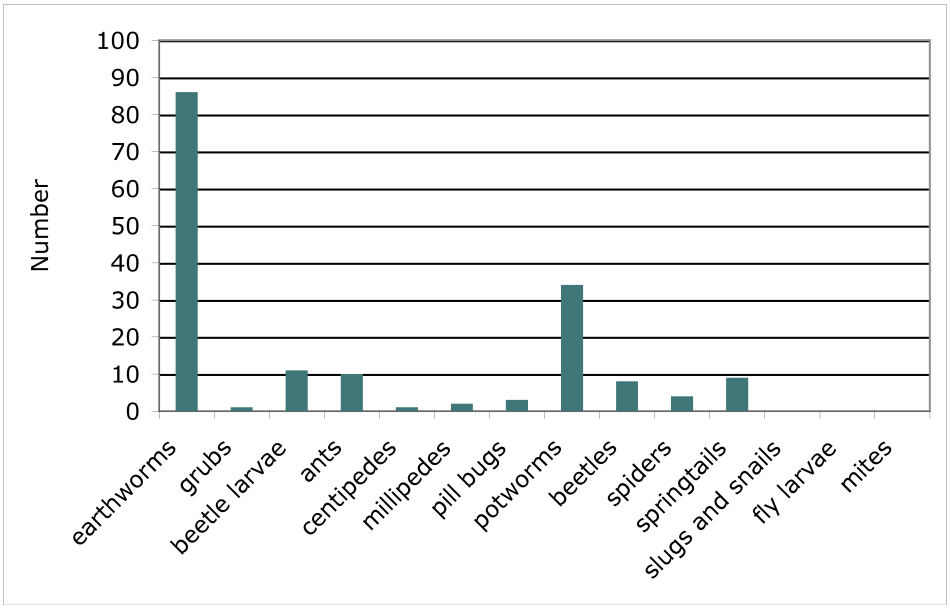


Figure 2.35: NWHS animal diversity. Total number of individuals of major invertebrate taxa found over entire site.

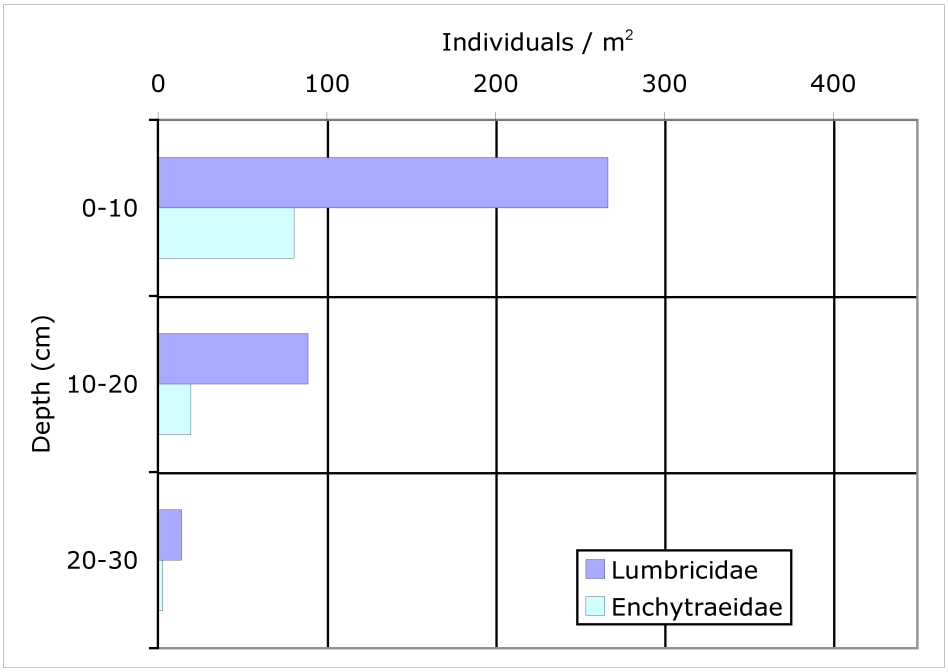


Figure 2.36: NWHS animal depth profile, showing the variation in density with depth of the most abundant macroinvertebrate taxa.

2.3.6 Inglewood Center III (PP)

A summary of the data collected at PP is presented in Table 2.7. An average of 4.2 ± 2.5 earthworms were collected from the uppermost soil layer. 0.7 ± 0.6 earthworms were collected from the 10–20 cm depth. 0.3 ± 0.6 earthworms were found below 20 cm. Mean earthworm size was 5.9 ± 2.8 cm, increasing from 3.5 ± 0.5 cm in the uppermost layer to 5.9 ± 2.8 cm in the lower layer. Root biomass was highest in the upper soil layer (1.92 ± 1.30 g), decreasing to 1.02 ± 0.53 g in the middle layer and 0.64 ± 0.17 g in the lower layer. The total root biomass for the entire sampling depth was 3.58 ± 1.78 g. Soil organic matter was very high in the upper layer (17.90 ± 9.31%), decreasing to 3.75 ± 1.69% in the lower layer. Soil texture became sandier with depth, ranging from sandy loam in the upper layer to sand in the lower layer. When averaged over the entire depth, the soil had 82.3 ± 3.0% sand, 8.1 ± 2.0% silt, and 9.6 ± 1.6% clay. The particle size distribution is presented graphically in Figure 2.37. A coefficient of uniformity of 50 was measured in the upper layer, and a coefficient of uniformity of 10 was measured in the middle and lower layers. A total of 9 animal taxa were collected. Animals were found primarily in the upper soil layers, but also occurred in the middle and lower layers. The composition of the animal community is presented in Figure 2.38. The PP animal community is dominated by grubs (Scarabaeidae larvae). Earthworms (Lumbricidae) were found in moderate numbers. Other beetle larvae, ants, pill bugs, potworms, beetles, spiders, and springtails were collected in much lower numbers. Representatives of *Dendrodrilus rubidus*, *Apporectodea caliginosa* and *Octolasion tyrtaeum* were identified among the collected earthworms (see Appendix D). The distribution of major soil animal groups with depth is shown in Figure 2.39. The densities of both Lumbricidae and Scarabaeidae larvae were highest in the uppermost soil layer and decreased with depth.

Table 2.7: Summary of data collected at PP, averaged. *indicates a parameter for which values are summed over the sampling depth rather than averaged. †Layers where no earthworms were found are not included in the average.

	Depth			
	0–10 cm	10–20 cm	20–30 cm	Entire Depth Profile
Earthworms (#s)	4.2 ± 2.5	0.7 ± 0.6	0.3 ± 0.6	5.2 ± 2.8*
Earthworm Size (cm)	3.5 ± 0.5	5.3 ± 2.5	9.0	5.9 ± 2.8 †
Root Biomass (g)	1.92 ± 1.30	1.02 ± 0.53	0.64 ± 0.17	3.58 ± 1.78*
Soil Organic Matter (%)	17.90 ± 9.31	8.27 ± 4.69	3.75 ± 1.69	9.98 ± 5.16
Soil Textural Classification	Sandy Loam	Loamy Sand	Sand	Loamy Sand
Sand Content (%)	70.5 ± 8.1	86.6 ± 2.4	89.7 ± 2.3	82.3 ± 3.0
Silt Content (%)	13.0 ± 4.6	6.8 ± 4.4	4.4 ± 3.0	8.1 ± 2.0
Clay Content (%)	16.5 ± 3.6	6.6 ± 2.0	5.9 ± 2.4	9.6 ± 1.6
d_{60} (mm)	0.25	0.5	0.5	n/a
d_{10} (mm)	0.005	0.05	0.05	n/a
Coefficient of Uniformity (d_{60}/d_{10})	50	10	10	n/a
Soil Animals (#s, including earthworms)	19 ± 10	2 ± 1	0 ± 1	22 ± 9*
Total Number of Taxa (not averaged)	9	3	1	9*

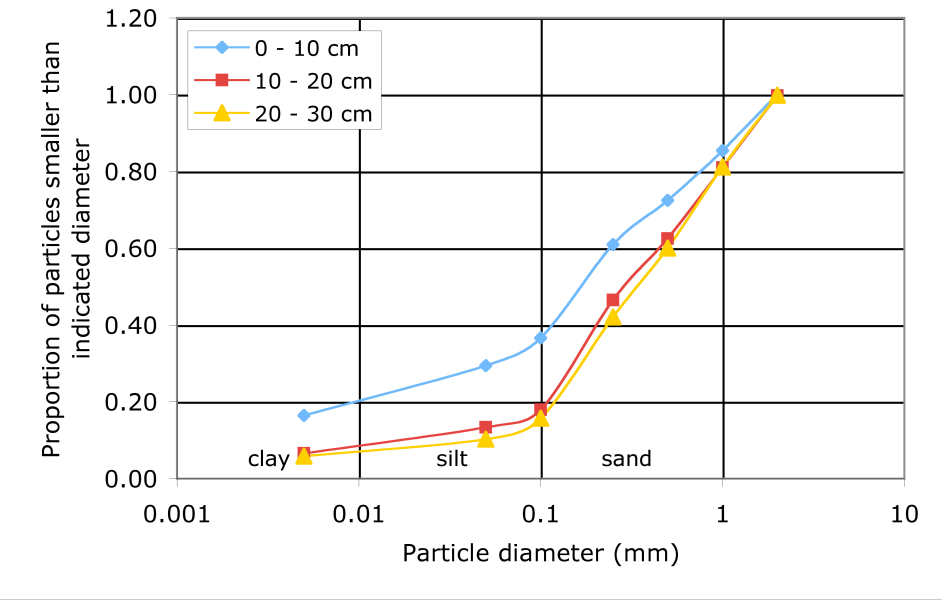


Figure 2.37: PP particle size distribution.

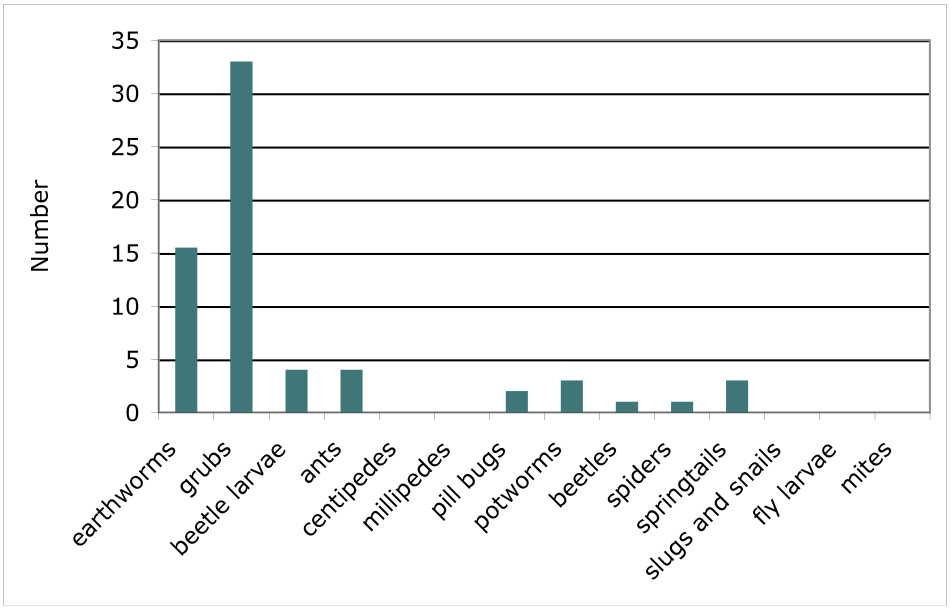


Figure 2.38: PP animal diversity. Total number of individuals of major invertebrate taxa found over entire site.

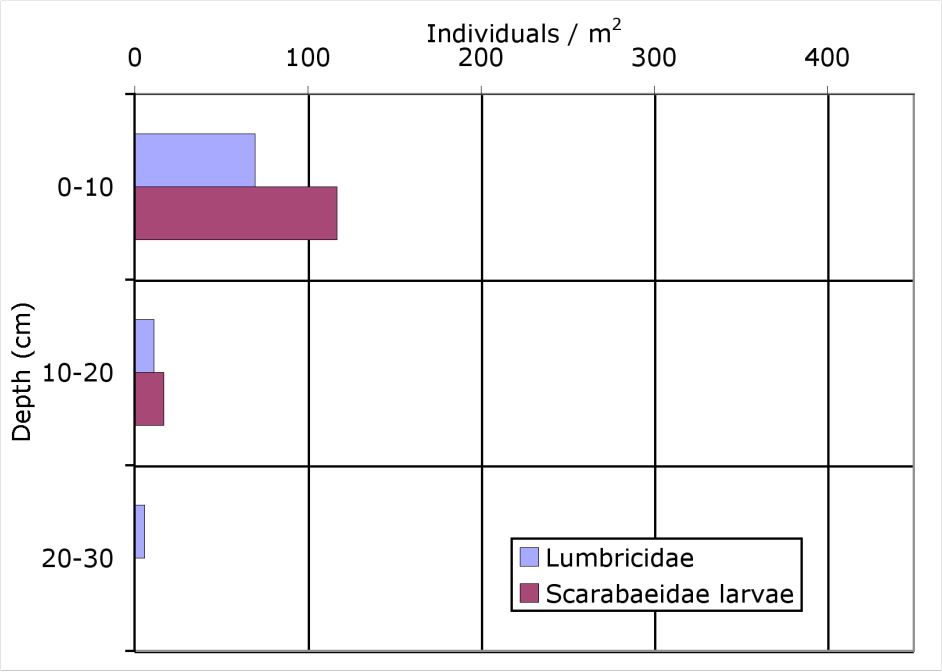


Figure 2.39: PP animal depth profile, showing the variation in density with depth of the most abundant macroinvertebrate taxa.

2.3.7 Claggett Farm (CF)

A summary of the data collected at CF is presented in Table 2.8. No earthworms were collected from the uppermost soil layer. 3.7 ± 4.6 earthworms were collected from the 10–20 cm depth. 1.7 ± 2.9 earthworms were found below 20 cm. Sampling was performed in late summer, after a prolonged dry period, and all earthworms collected were aestivating. Mean earthworm size was 4.6 cm. Root biomass was highest in the uppermost layer (21.97 ± 12.97 g), decreasing sharply to 8.47 ± 3.12 g in the middle layer, and 2.25 ± 1.30 g in the lower layer. Total root biomass for the entire sampling depth was 32.69 ± 16.68 g. Soil organic matter was highest in the upper layer (5.59 ± 0.28%), decreasing to 2.49 ± 0.39% in the lower layer. Soil texture was sandy loam at all depths, averaging 66.9 ± 1.6% sand, 17.8 ± 0.6% silt, and 15.4 ± 1.0% clay. The particle size distribution is presented graphically in Figure 2.40. A coefficient of uniformity of 50 was measured in the upper and middle layers, and a coefficient of uniformity of 20 was measured in the lower layers. A total of 10 animal taxa were collected. Animals were found primarily in the upper soil layers, but also occurred in the middle and lower layers. The composition of the animal community is presented in Figure 2.41. The CF animal community is dominated by ants (Formicidae). Earthworms (Lumbricidae) and beetles (Coleoptera) were found in moderate numbers. Grubs, other beetle larvae, centipedes, millipedes, pill bugs, spiders, and springtails were collected in much lower numbers. Four *Allolobophora chlorotica* were identified among the collected earthworms (see Appendix D). The distribution of major soil animal groups with depth is shown in Figure 2.42. A large number of ants (Formicidae) were collected, with the highest density occurring in the upper soil layer, and with decreasing density with depth. Coleoptera were found only in the uppermost soil layer. Interestingly, earthworms (Lumbricidae) were found only in

the middle and lower soil layers. No earthworms were found in the upper soil layer. This is consistent with the dry conditions encountered at this site, as earthworms tend to move deeper into the soil to avoid dessication.

Table 2.8: Summary of data collected at CF, averaged. *indicates a parameter for which values are summed over the sampling depth rather than averaged. †Layers where no earthworms were found are not included in the average.

	Depth			
	0–10 cm	10–20 cm	20–30 cm	Entire Depth Profile
Earthworms (#s)	0	3.7 ± 4.6	1.7 ± 2.9	5.3 ± 4.0*
Earthworm Size (cm)	0	4.6 ± 1.5	4.6 ± 0	4.6 ± 0
Root Biomass (g)	21.97 ± 12.97	8.47 ± 3.12	2.25 ± 1.30	32.69 ± 16.68*
Soil Organic Matter (%)	5.59 ± 0.28	3.75 ± 0.33	2.49 ± 0.39	3.94 ± 0.33
Soil Textural Classification	Sandy Loam	Sandy Loam	Sandy Loam	Sandy Loam
Sand Content (%)	70.0 ± 2.5	67.6 ± 2.6	63.0 ± 1.9	66.9 ± 1.6
Silt Content (%)	17.5 ± 0.8	18.4 ± 1.5	17.4 ± 0.6	17.8 ± 0.6
Clay Content (%)	12.5 ± 1.9	14.0 ± 2.1	19.6 ± 2.2	15.4 ± 1.0
d_{60} (mm)	0.25	0.25	0.1	n/a
d_{10} (mm)	0.005	0.005	0.005	n/a
Coefficient of Uniformity (d_{60}/d_{10})	50	50	20	n/a
Soil Animals (#s, includes earthworms)	34 ± 12	22 ± 16	14 ± 16	70 ± 24*
Total Number of Taxa (not averaged)	6	7	2	10*

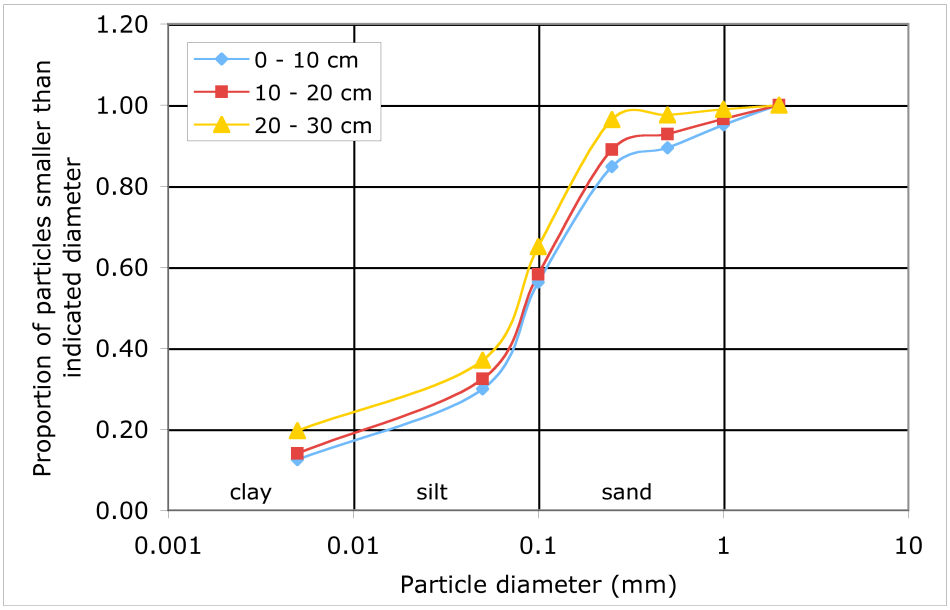


Figure 2.40: CF particle size distribution.

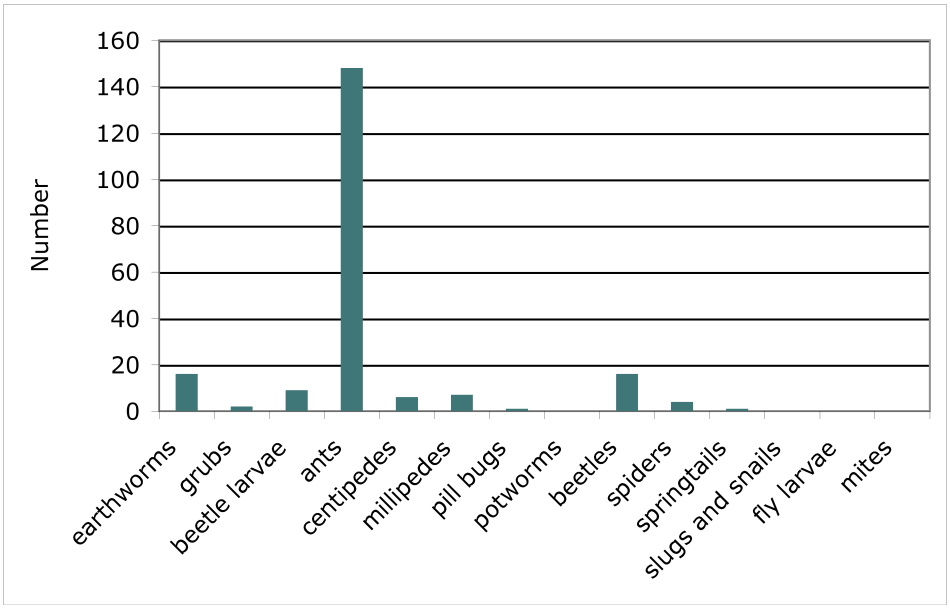


Figure 2.41: CF animal diversity. Total number of individuals of major invertebrate taxa found over entire site.

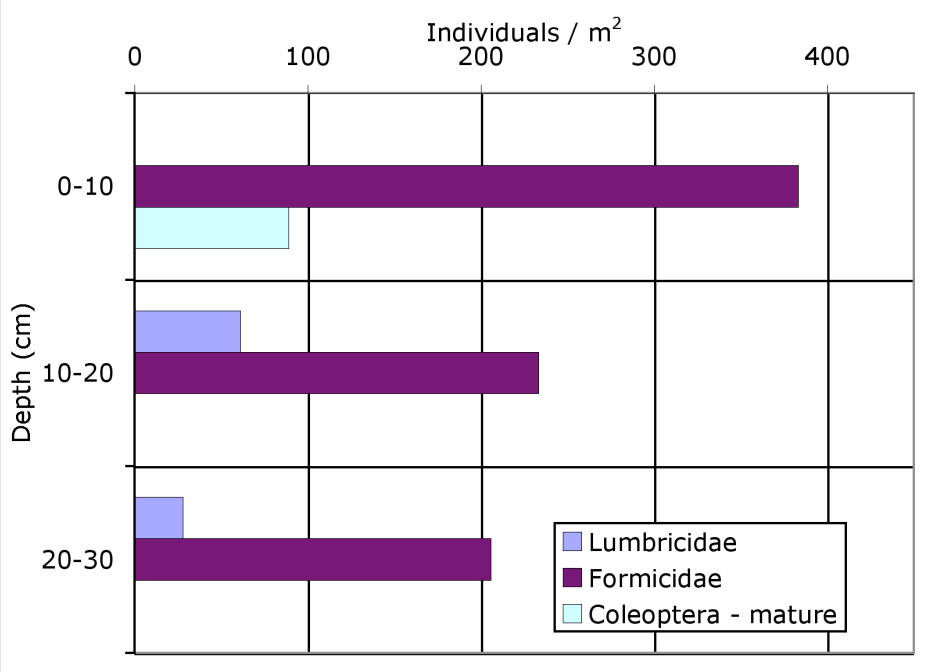


Figure 2.42: CF animal depth profile, showing the variation in density with depth of the most abundant macroinvertebrate taxa.

2.3.8 Chevy Chase Bank (CC)

A summary of the data collected at CC is presented in Table 2.9. An average of 10.2 ± 9.2 earthworms were collected from the uppermost soil layer, 10.0 ± 10.4 from the 10–20 cm depth, and 7.7 ± 8.0 below 20 cm. Mean earthworm size was 2.7 ± 0.7 cm. Root biomass was highest in the uppermost soil layer (26.04 ± 14.65 g), decreasing to 19.30 ± 18.30 g in the middle layer and 11.15 ± 15.32 g in the lower layer. Soil organic matter was very high in the upper layer (30.13 ± 11.42%), decreasing to 10.06 ± 11.02% in the lower layer. Soil texture was sandy loam at all depths, averaging 66.1 ± 25.2% sand, 25.3 ± 16.8% silt, and 8.6 ± 8.4% clay. The particle size distribution is presented graphically in Figure 2.43. A coefficient of uniformity of 50 was measured in all layers. A total of 12 animal taxa were collected. Animals were found primarily in the upper and middle soil layers, but also occurred in the lower layer. The composition of the animal community is presented in Figure 2.44. The CC animal community is dominated by earthworms (Lumbricidae). Ants (Formicidae) and centipedes (Chilopoda) were found in moderate numbers. Grubs, other beetle larvae, pill bugs, potworms, spiders, springtails, snails and slugs, and mites were collected in much lower numbers. The majority of the earthworms collected were identified to be *Pheretima spp.* (see Appendix D). The distribution of major soil animal groups with depth is shown in Figure 2.45. Earthworms (Lumbricidae) were found at nearly equal densities in the upper and middle soil layers, and a lower density in the lower layer. Formicidae were found only in the upper and middle layers. Chilopods were found at all layers, with density decreasing with depth.

Table 2.9: Summary of data collected at CC, averaged. *indicates a parameter for which values are summed over the sampling depth rather than averaged. †Layers where no earthworms were found are not included in the average.

	Depth			
	0–10 cm	10–20 cm	20–30 cm	Entire Depth Profile
Earthworms (#s)	10.2 ± 9.2	10.0 ± 10.4	7.7 ± 8.0	27.8 ± 27.0*
Earthworm Size (cm)	2.7 ± 1.4	1.9 ± 0.8	3.4 ± 1.3	2.7 ± 0.7†
Root Biomass (g)	26.04 ± 14.65	19.30 ± 18.30	11.15 ± 15.32	56.49 ± 15.08*
Soil Organic Matter (%)	30.13 ± 11.42	16.37 ± 14.19	10.06 ± 11.02	18.85 ± 11.89
Soil Textural Classification	Sandy Loam	Sandy Loam	Sandy Loam	Sandy Loam
Sand Content (%)	62.4 ± 16.8	53.9 ± 25.1	64.5 ± 25.6	66.1 ± 25.2
Silt Content (%)	31.0 ± 11.4	36.1 ± 20.4	24.6 ± 18.5	25.3 ± 16.8
Clay Content (%)	6.5 ± 5.5	10.0 ± 6.0	10.8 ± 7.4	8.6 ± 8.4
d_{60} (mm)	0.25	0.25	0.25	n/a
d_{10} (mm)	0.05	0.005	0.005	n/a
Coefficient of Uniformity (d_{60}/d_{10})	5	50	50	n/a
Soil Animals (#s, includes earthworms)	23 ± 22	18 ± 17	11 ± 15	52 ± 54*
Total Number of Taxa (not averaged)	8	9	4	12*

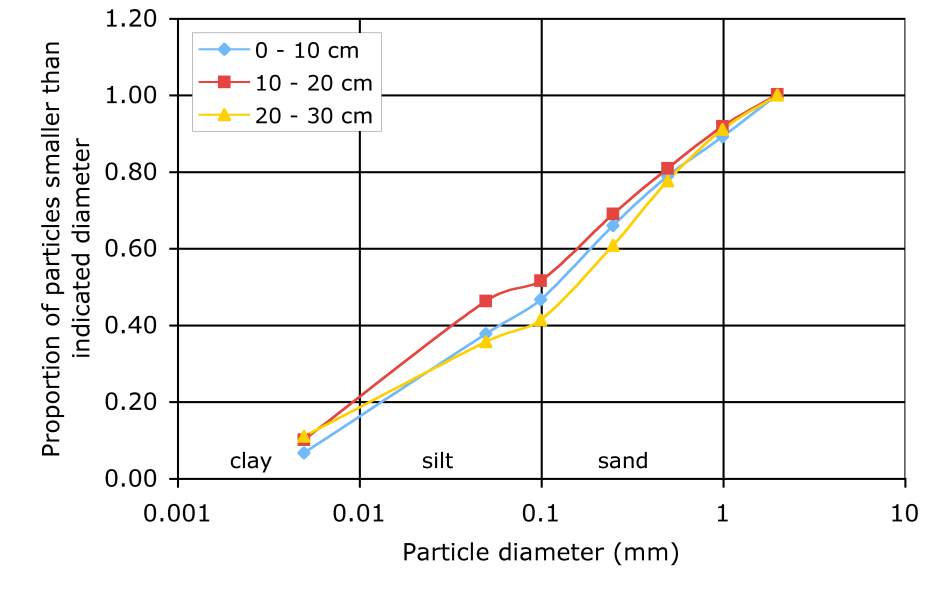


Figure 2.43: CC particle size distribution.

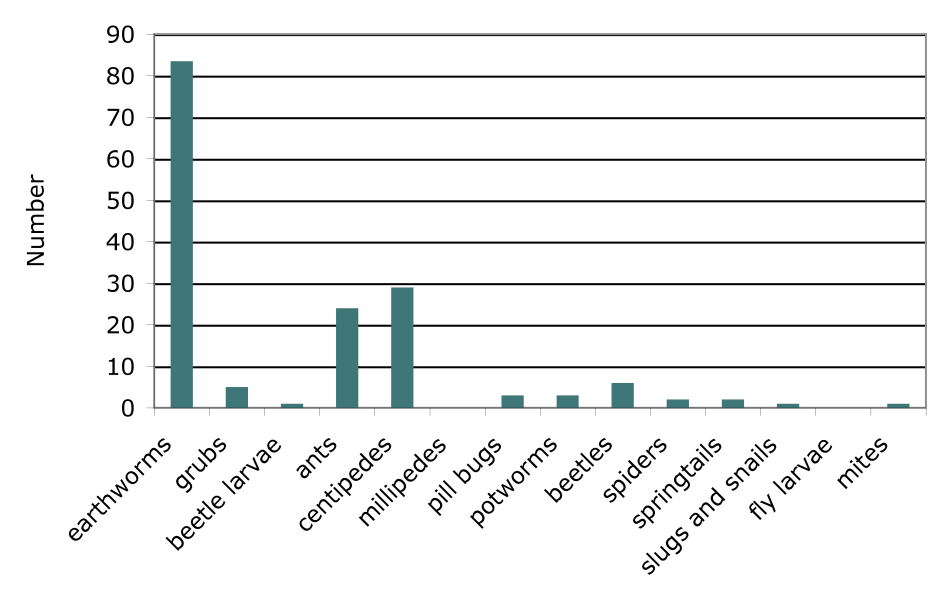


Figure 2.44: CC animal diversity. Total number of individuals of major invertebrate taxa found over entire site.

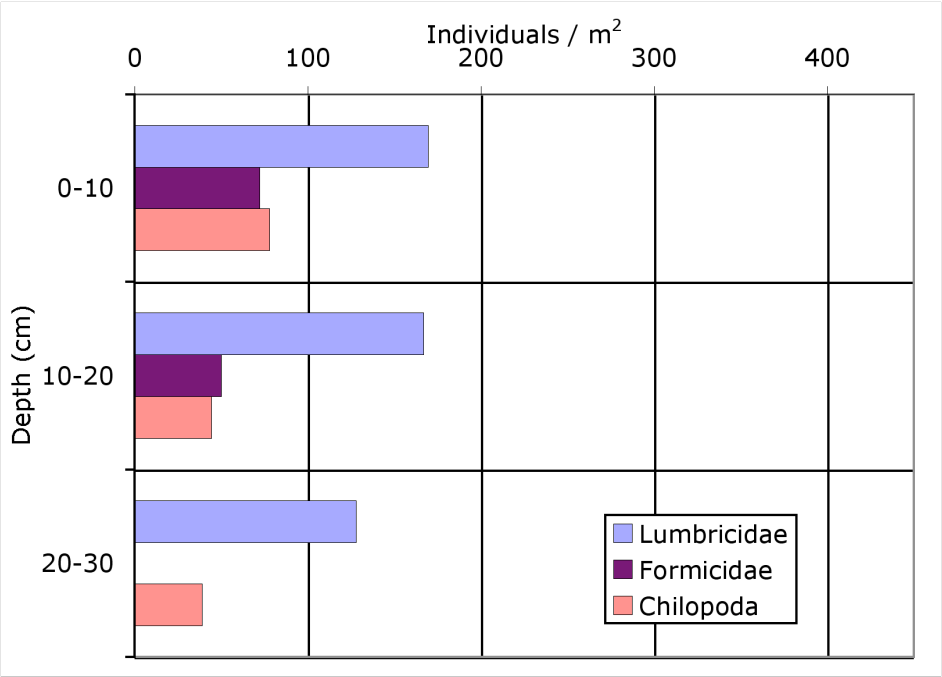


Figure 2.45: CC animal depth profile, showing the variation in density with depth of the most abundant macroinvertebrate taxa.

2.3.9 Beltway Plaza Mall (BP)

A summary of the data collected at BP is presented in Table 2.10. An average of 19.5 ± 12.3 earthworms were collected from the uppermost soil layer, 4.0 ± 4.6 from the 10–20 cm depth, and 0.7 ± 0.6 below 20 cm. Mean earthworm size was 3.8 cm. Root biomass was highest in the uppermost soil layer (19.08 ± 11.44 g), decreasing to 7.12 ± 2.16 g in the middle layer and 2.98 ± 2.15 g in the lower layer. Total root biomass for the entire sampling depth was 29.18 ± 11.49 g. Soil organic matter was highest in the upper layer (9.50 ± 3.89%), decreasing to 2.92 ± 0.08% and 3.03 ± 1.18% in the middle and lower layers, respectively. Soil texture was sandy clay loam in the upper and middle layers and loam in the lower layer, averaging 53.0 ± 6.6% sand, 23.5 ± 2.8% silt, and 23.4 ± 4.3% clay over the entire sampling depth. The particle size distribution is presented graphically in Figure 2.46. A coefficient of uniformity of 50 was measured in the upper and middle layers, and a coefficient of uniformity of 20 was measured in the lower layer. A total of 6 animal taxa were collected. Animals were found primarily in the upper soil layer, but also occurred in the middle and lower layers. The composition of the animal community is presented in Figure 2.47. The BP animal community is dominated by earthworms (Lumbricidae). Ants, centipedes, millipedes, pill bugs, and beetles were collected in much lower numbers. Representatives of *Eisenia fetida*, *Lumbricus sp.*, and *Pheretima sp.* were identified among the collected earthworms (see Appendix D). The distribution of major soil animal groups with depth is shown in Figure 2.48. Earthworms (Lumbricidae) were found at all depths, with density decreasing with depth. Formicidae were found in the upper and middle layers, and at a higher density in the middle layer than in the upper layer. Chilopoda and Coleoptera were found only in the upper soil layer.

Table 2.10: Summary of data collected at BP, averaged. *indicates a parameter for which values are summed over the sampling depth rather than averaged. †estimated.

	Depth			
	0–10 cm	10–20 cm	20–30 cm	Entire Depth Profile
Earthworms (#s)	19.5 ± 12.3	4.0 ± 4.6	0.7 ± 0.6	24.2 ± 15.1*
Earthworm Size (cm)	3.8 ± 0.0	3.8 ± 0.0	3.8 ± 0.0	3.8 ± 0.0 †
Root Biomass (g)	19.08 ± 11.44	7.12 ± 2.16	2.98 ± 2.15	29.18 ± 11.49*
Soil Organic Matter (%)	9.50 ± 3.89	2.92 ± 0.08	3.03 ± 1.18	5.15 ± 0.96
Soil Textural Classification	Sandy Clay Loam	Sandy Clay Loam	Loam	Sandy Clay Loam
Sand Content (%)	62.2 ± 9.7	54.4 ± 1.0	42.5 ± 13.8	53.0 ± 6.6
Silt Content (%)	16.2 ± 5.0	22.8 ± 1.5	31.5 ± 9.2	23.5 ± 2.8
Clay Content (%)	21.6 ± 4.8	22.7 ± 1.3	26.0 ± 6.9	23.4 ± 4.3
d_{60} (mm)	0.25	0.25	0.1	n/a
d_{10} (mm)	0.005	0.005	0.005	n/a
Coefficient of Uniformity (d_{60}/d_{10})	50	50	20	n/a
Soil Animals (#s, includes earthworms)	24 ± 12	6 ± 2	1 ± 1	30 ± 12*
Total Number of Taxa (not averaged)	6	2	1	6*

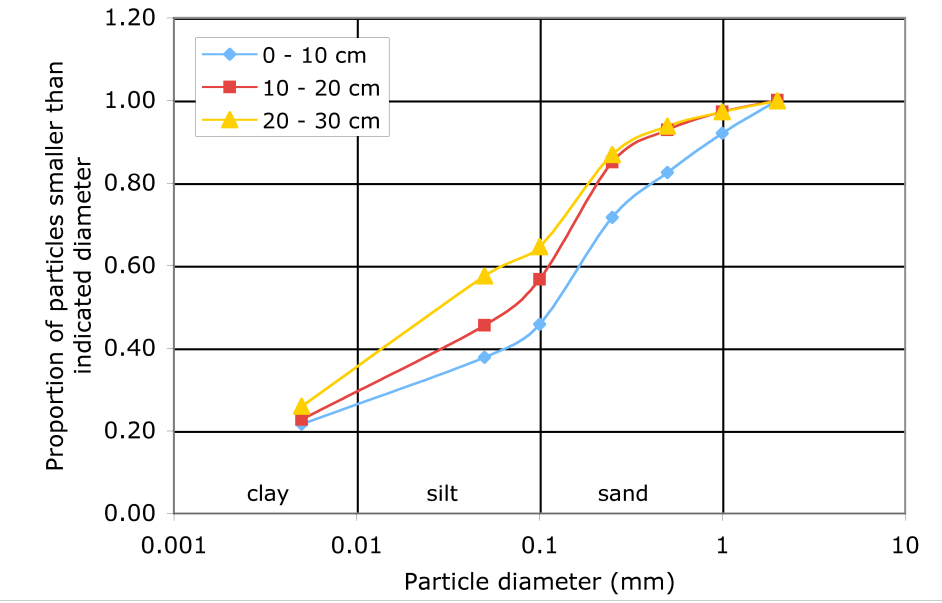


Figure 2.46: BP particle size distribution.

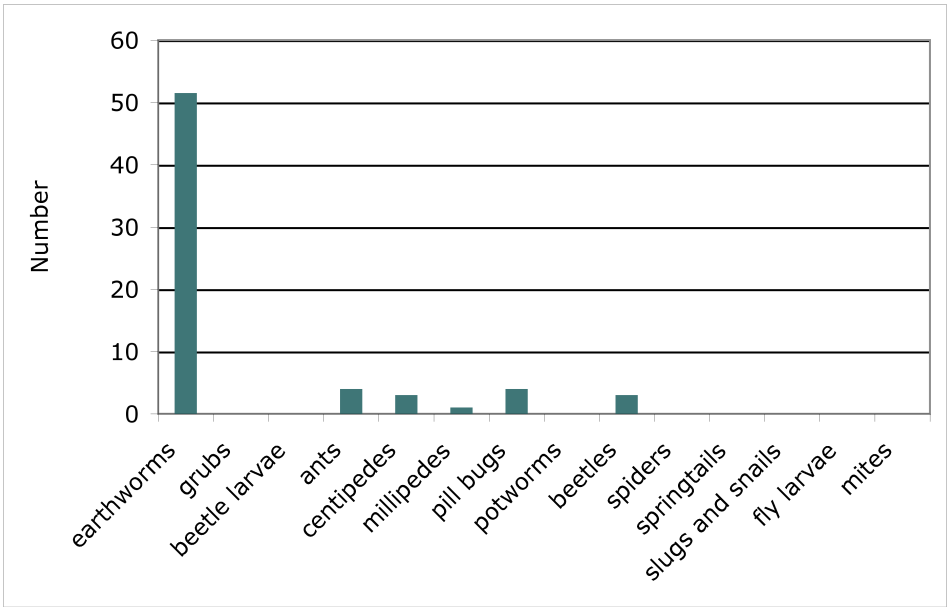


Figure 2.47: BP animal diversity. Total number of individuals of major invertebrate taxa found over entire site.

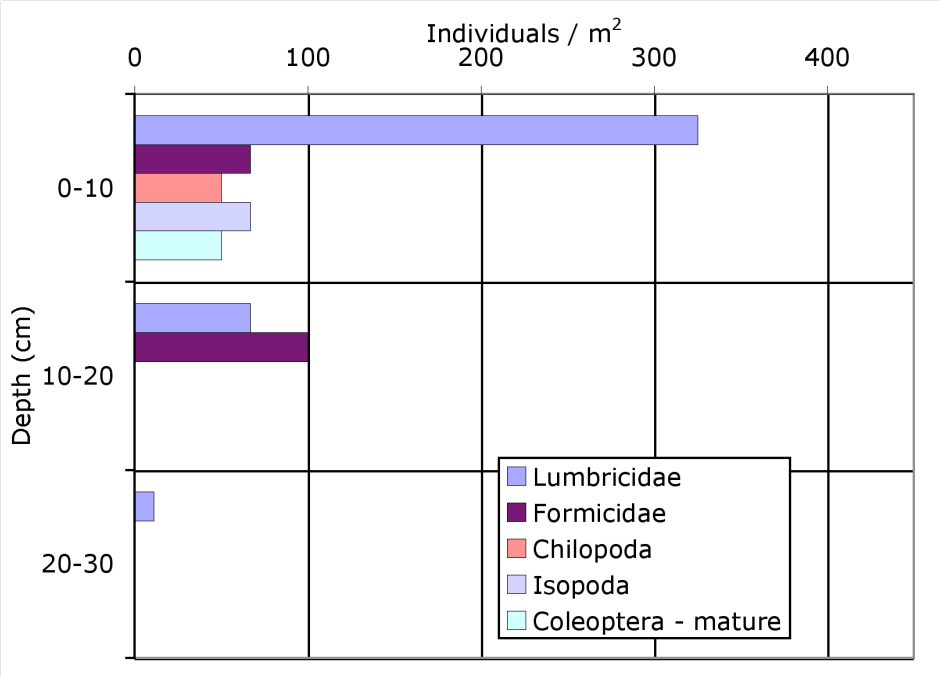


Figure 2.48: BP animal depth profile, showing the variation in density with depth of the most abundant macroinvertebrate taxa.

2.3.10 Laurel Regional Hospital (LRH)

A summary of the data collected at LRH is presented in Table 2.11. An average of 13.7 ± 0.7 earthworms were collected from the uppermost soil layer, 4.2 ± 3.3 from the 10–20 cm depth, and 3.8 ± 3.8 below 20 cm. Mean earthworm size was 4.0 ± 0.3 cm. Root biomass was highest in the uppermost layer (7.74 ± 6.05 g), decreasing to 5.04 ± 5.01 g in the middle layer and 0.95 ± 0.85 g in the lower layer. The total root biomass for the entire sampling depth was 13.73 ± 11.69 g. Soil organic matter was highest in the upper layer (5.96 ± 2.11%), decreasing to 2.13 ± 0.20% in the lower layer. Soil texture was sandy loam in the upper layer and loam in the middle and lower layers, averaging 46.4 ± 14.4% sand, 33.3 ± 14.5% silt, and 20.3 ± 4.1% clay over the entire sampling depth. The particle size distribution is presented graphically in Figure 2.49. A coefficient of uniformity of 50 was measured in the upper layer, and a coefficient of uniformity of 20 was measured in the middle and lower layers. A total of 10 animal taxa were collected. Animals were found primarily in the upper soil layer, but also occurred in the middle and lower layers. The composition of the animal community is presented in Figure 2.50. The LRH animal community is dominated by earthworms (Lumbricidae). Grubs, other beetle larvae, ants, centipedes, millipedes, pill bugs, beetles, slugs and snails, and fly larvae were collected in much lower numbers. The majority of the earthworms collected were of indeterminate *Lumbricus sp.* Representatives of *Lumbricus rubellus*, and *Apporectodea caliginosa* were also identified (see Appendix D). The distribution of major soil animal groups with depth is shown in Figure 2.51. Earthworms (Lumbricidae) were found at all depths, with density decreasing with depth. Isopoda were found only in the upper soil layer.

Table 2.11: Summary of data collected at LRH, averaged. *indicates a parameter for which values are summed over the sampling depth rather than averaged. †Layers where no earthworms were found are not included in the average.

	Depth			
	0–10 cm	10–20 cm	20–30 cm	Entire Depth Profile
Earthworms (#s)	13.7 ± 0.7	4.2 ± 3.3	3.8 ± 3.8	21.7 ± 6.5*
Earthworm Size (cm)	4.2 ± 0.8	3.6 ± 0.8	4.1 ± 0.9	4.0 ± 0.3†
Root Biomass (g)	7.74 ± 6.05	5.04 ± 5.01	0.95 ± 0.85	13.73 ± 11.69*
Soil Organic Matter (%)	5.96 ± 2.11	3.36 ± 0.94	2.13 ± 0.20	3.82 ± 1.00
Soil Textural Classification	Sandy Loam	Loam	Loam	Loam
Sand Content (%)	52.7 ± 14.2	45.7 ± 14.6	40.8 ± 18.4	46.4 ± 14.4
Silt Content (%)	29.3 ± 14.5	31.2 ± 13.0	39.4 ± 18.0	33.3 ± 14.5
Clay Content (%)	18.0 ± 1.9	23.1 ± 14.1	19.8 ± 0.4	20.3 ± 4.1
d_{60} (mm)	0.25	0.1	0.1	n/a
d_{10} (mm)	0.005	0.005	0.005	n/a
Coefficient of Uniformity (d_{60}/d_{10})	50	20	20	n/a
Soil Animals (#s, includes earthworms)	17 ± 4	4 ± 4	3 ± 3	24 ± 10*
Total Number of Taxa (not averaged)	9	4	1	10*

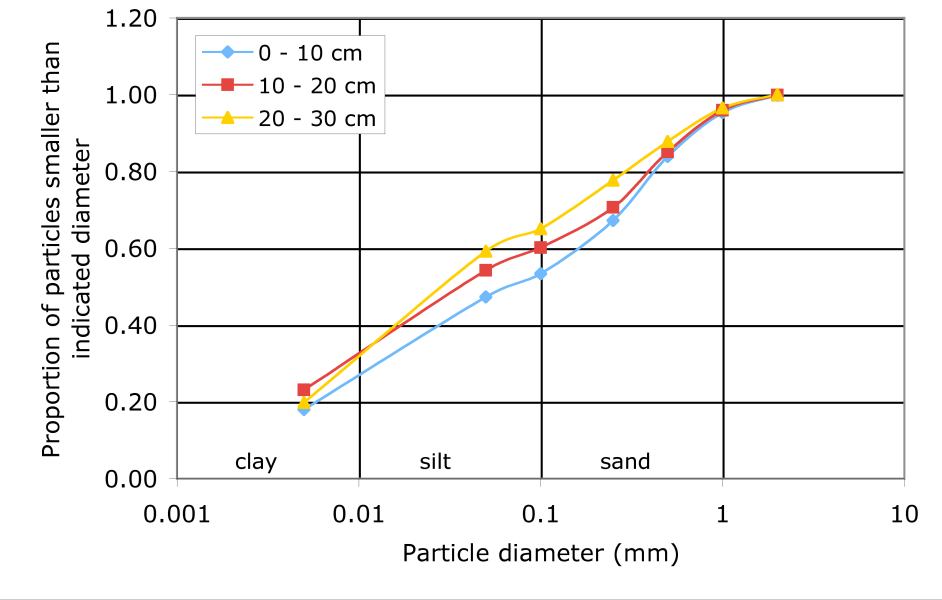


Figure 2.49: LRH particle size distribution.

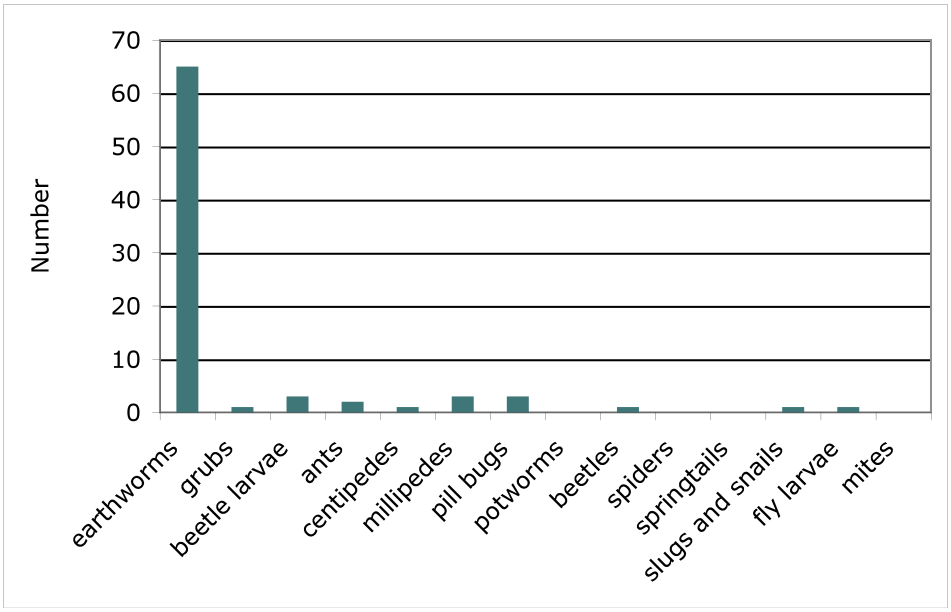


Figure 2.50: LRH animal diversity. Total number of individuals of major invertebrate taxa found over entire site.

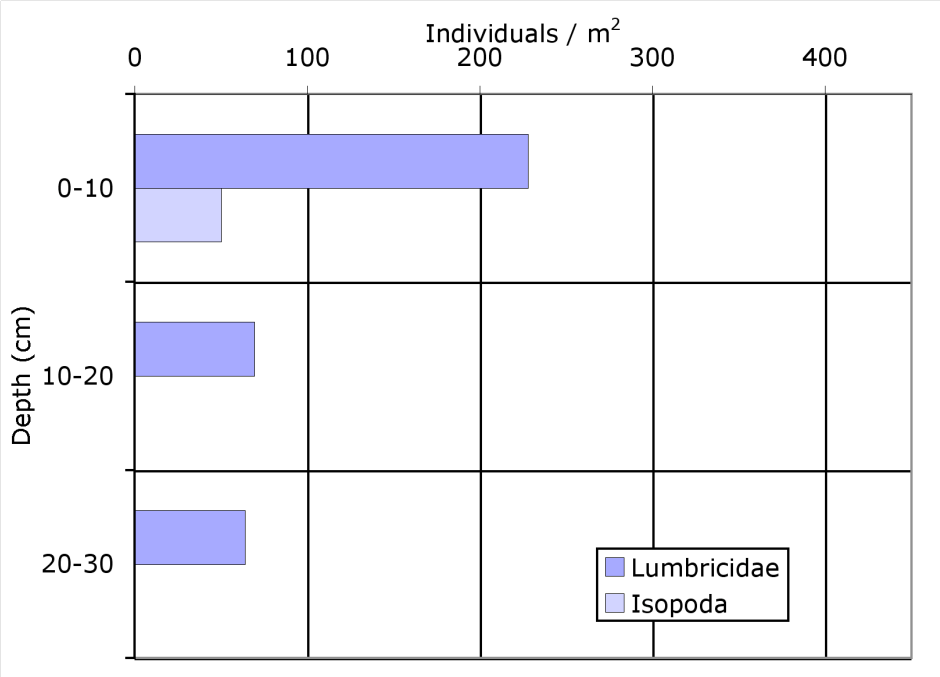


Figure 2.51: LRH animal depth profile, showing the variation in density with depth of the most abundant macroinvertebrate taxa.

2.3.11 Results of infiltration tests

Infiltration tests were performed at three rain garden sites, using a double-ring infiltrometer. Results are compared to the infiltration rate that would be expected given the soil textures measured at each of the field sites (Appendix D). The expected infiltration rate was estimated using published values for the saturated hydraulic conductivities of the soil textures found at each of the sites (Rawls et al., 1982). These published values were derived by taking the means of a large set of published and unpublished saturated hydraulic conductivity measurements for each of the USDA soil textural classifications. Under saturated conditions, the infiltration rate is approximately equal to the saturated hydraulic conductivity. For vertical flow through a layered soil, the effective saturated hydraulic conductivity, K_e, is given by:

$$K_e = \frac{\sum_{i=1}^{n} L_i}{\sum_{i=1}^{n} \frac{L_i}{K_i}} \tag{2.3}$$

where L_i = layer height, and

K_i = layer saturated hydraulic conductivity (Hillel, 1998).

The results of infiltration testing at the BP site are presented in Table 2.12. The infiltration rate was measured at three locations, and ranged from a high of 18.4 cm/h to a low of 1.6 cm/h. The average infiltration rate was 8.2 ± 8.9 cm/h. The effective saturated hydraulic conductivity that would be expected given the measured soil texture is 0.5 cm/h. The results of infiltration testing at the LRH site are given in Table 2.13. The infiltration rate was measured at three locations, and ranged from a high of 12.7 cm/h to a low of 3.0 cm/h. The average infiltration rate was 8.3 ± 4.9 cm/h. The effective saturated hydraulic conductivity that would be expected given the measured soil texture is 1.4 cm/h. The infiltration rate was measured at two locations at the NWHS site. The

results of these tests are given in Table 2.14. The measured infiltration rate ranged from a high of 10.6 cm/h to a low of 0.2 cm/h. The average measured infiltration rate was 5.4 ± 7.4 cm/h. The effective saturated hydraulic conductivity that would be expected given the measured soil texture is 1.7 cm/h.

Table 2.12: Results of infiltration testing at BP site. Infiltration rate was measured at three locations. Average infiltration rate is reported as mean ± standard deviation, and is compared to the predicted infiltration rate of the soil given it's measured texture, using values from Rawls et al. (1982).

Site	Infiltration Rate (cm/h)
1	18.4
2	1.6
3	4.6
Average Infiltration Rate (cm/h)	8.2 ± 9
Predicted Infiltration Rate (cm/h)	0.5

Table 2.13: Results of infiltration testing at LRH site. Infiltration rate was measured at three locations. Average infiltration rate is reported as mean ± standard deviation, and is compared to the predicted infiltration rate of the soil given it's measured texture, using values from Rawls et al. (1982).

Site	Infiltration Rate (cm/h)
1	12.7
2	9.0
3	3.0
Average Infiltration Rate (cm/h)	8.3 ± 4.9
Predicted Infiltration Rate (cm/h)	1.4

Table 2.14: Results of infiltration testing at NWHS site. Infiltration rate was measured at two locations. Average infiltration rate is reported as mean ± standard deviation, and is compared to the predicted infiltration rate of the soil given it's measured texture, using values from Rawls et al. (1982).

Site	Infiltration Rate (cm/h)
1	10.6
2	0.2
Average Infiltration Rate (cm/h)	5.4 ± 7.4
Predicted Infiltration Rate (cm/h)	1.7

2.4 Discussion

The field surveys were intended to assess the extent of biological activity in the soil, to collect baseline soil physical data, and to look for evidence of pedogenesis in existing rain gardens.

2.4.1 Extent of biological activity

2.4.1.1 Root systems

The extent of the root systems present in these rain gardens is an important measure of the level of biological activity in the soil. Roots are the backbone of the soil ecosystem, playing vital structural and functional roles (Six et al., 2004). As they grow and die back, roots create void space in the soil. Root exudates glue soil particles together into aggregates. Root cells slough off and die back, providing a major source of organic matter for micro- and mesofauna (Gobat et al., 2003). The area immediately surrounding each root (about 2 mm thick), called the rhizosphere, provides an oxygen and nutrient rich habitat for microorganisms, especially bacteria, which are responsible for many of the important chemical reactions taking place in the soil, such as nitrification. Roots form mutualistic associations with mycorrhizal fungi. These fungi grow into large networks of fine hyphae extending deeply into the soil. This improves the plant's nutrient absorption, and provides structure and stability to the soil. Roots also act as organisms, consuming oxygen, water and nutrients from the soil.

As young plants establish themselves, they put a great deal of energy into developing their root systems (Brady and Weil, 2002). Root biomass can therefore be expected to increase quickly with the age of the rain garden. Figure 2.52 shows the root biomass measured at each of the field sites. The trend toward increasing root biomass with age is

not monotonic, but the data suggest that older rain gardens tend to have greater biomass than younger rain gardens. This analysis is of course somewhat confounded by variations in vegetation between sites.

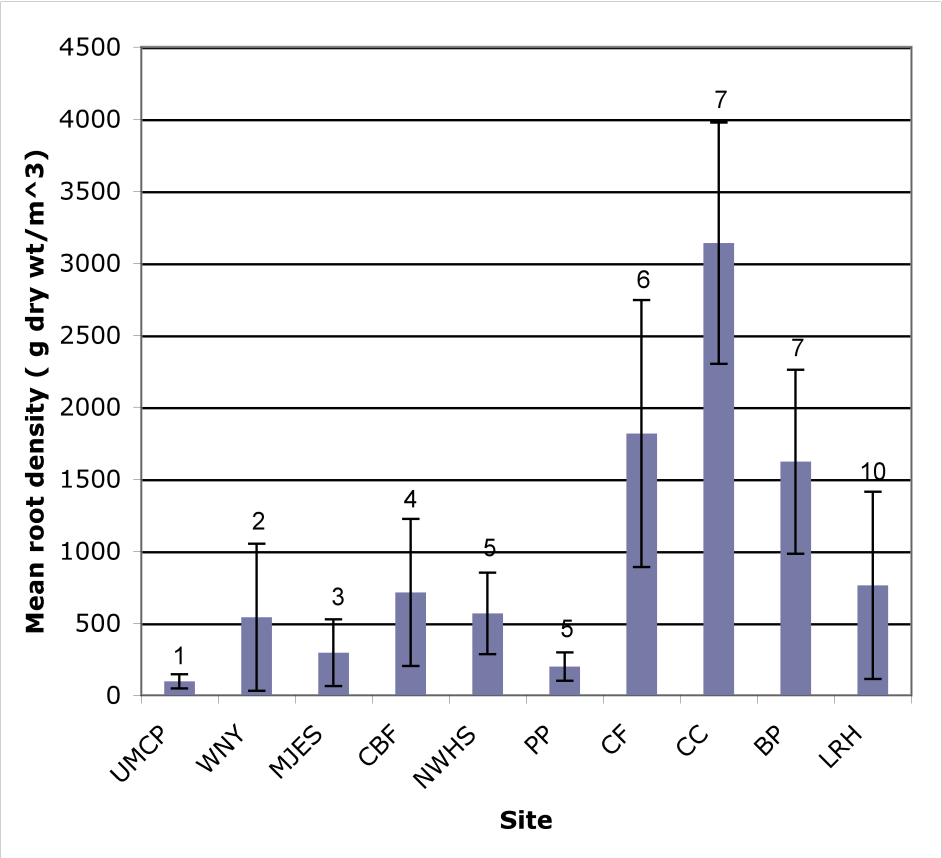


Figure 2.52: Mean root density for all research sites. Error bars represent the standard deviation between sampling locations. Numbers above each column indicate the age of the rain garden in years at the time of sampling.

2.4.1.2 Soil animals

This study has revealed the basic structure of the soil community. A robust community of fauna was found. Each of the fauna found can be expected to play a role in the development of the soil. These roles are described in Table 2.15. The first step of pedogenesis, the development of an organically-enriched A horizon, is fundamentally a biological process. Plant litter falls on the soil surface. Millipedes, pillbugs, ants and earthworms fragment this litter, mix it with bacteria in their guts, and incorporate this inoculated plant material into the soil matrix. Earthworms, potworms, springtails, and mites consume this pre-digested plant material, further fragmenting it, and further boosting bacterial and fungal activity. Bacteria and fungi complete the process of humification, converting this decayed plant material into stable humus. Predators, such as centipedes, spiders, and some ants, regulate invertebrate populations, preventing explosive growth of a population, which would lead to collapse. Invertebrates act as earth-movers as well. Burrowing animals, such as earthworms, ants, beetle larvae, mix soil layers, incorporate organic matter into the soil, aerate the soil, improve infiltration, and create and destroy aggregates. Earthworms, snails and slugs exude mucilages which act to glue soil particles together. Figure 2.53 shows the relative numbers of taxa found at each site.

Table 2.15: The roles of major invertebrate taxa in the soil ecosystem (Gobat et al., 2003; Hole, 1981)

Taxon	Role
Earthworms (Lumbricidae)	Create voids Mix soil layers Create and destroy soil aggregates Distribute bacteria throughout soil Fragment organic matter Mix surface residues into soil Consume organic matter
Potworms (Enchytraeidae)	Create voids Stimulate bacteria and fungi Consume organic matter
Beetles (Coleoptera)	Larvae create voids Larvae consume plant roots Adults consume plants, animal wastes, carrion, other invertebrates
Ants (Formicidae)	Create voids Mix soil layers Consume plants, microarthropods
Millipedes (Diplopoda)	Create voids Fragment plant litter
Springtails (Collembola)	Consume fungi Fragment and mix of organic matter Regulate microbial populations
Slugs and Snails (Gastropoda)	Exude mucus that helps glue soil particles together Consume decaying organic matter, fresh plant material, and carrion
Fly larvae (Diptera)	Fragment plant litter Consume carrion Consume vertebrate waste
Pillbugs (Isopods)	Fragment plant litter Mix soil Bury organic matter
Mites (Acari)	Fragment organic matter mix organic matter throughout soil Regulate microbial populations
Centipedes (Chilopoda)	Feed on other invertebrates - control populations
Spiders (Araneae)	Feed on other invertebrates - control populations

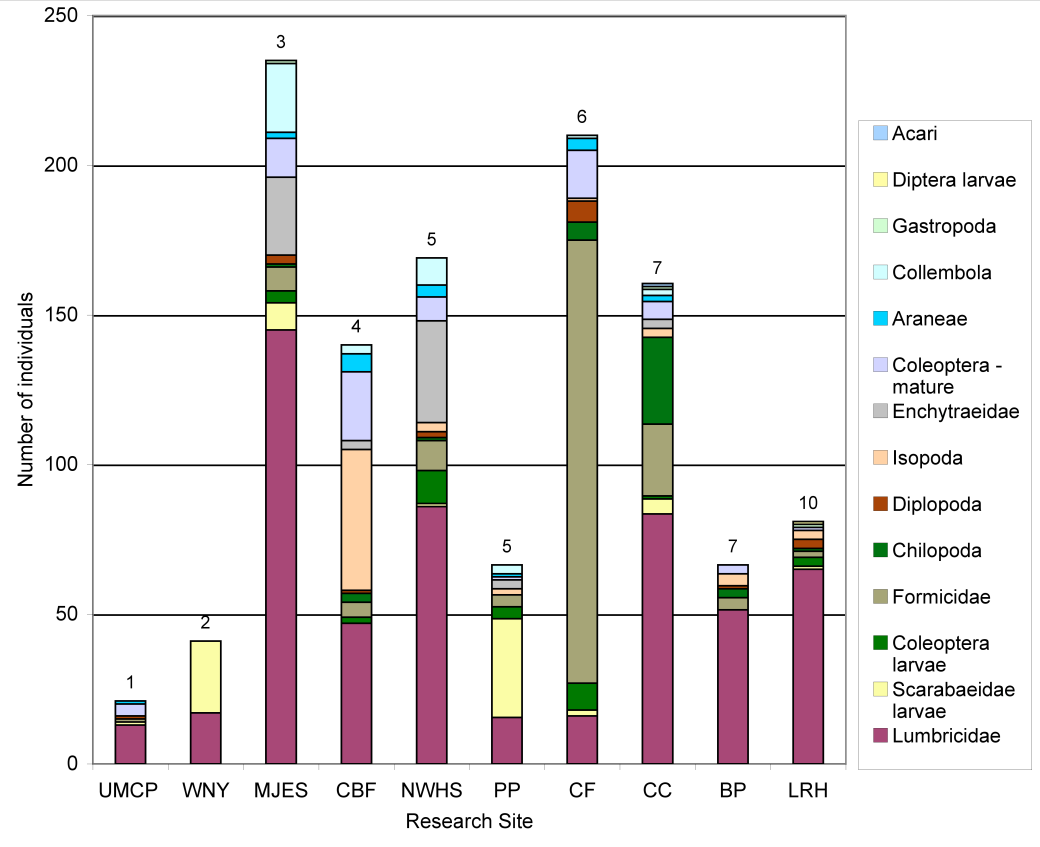


Figure 2.53: Soil animals found at each of the research sites, reported as total numbers of individuals tallied over the entire site. Numbers above each column indicate the age of the rain garden in years at the time of sampling.

2.4.1.3 Earthworms

Earthworms were found at all ten sites. Even the youngest site, UMCP, which had only been in operation for one year, and had the sandiest soil, had earthworms. In fact, earthworms are the only soil animal that was observed at all sites. Figure 2.54 shows the numbers of earthworms counted at each of the sites, and compares these values to reported earthworm densities for a comparable natural system, an old pasture (109–646 individuals/m^2)(Edwards and Bohlen, 1996). All earthworm densities were close to this range, with four sites within the range, four sites slightly below the range, and one site above it. These data show that earthworms are colonizing rain gardens, and reach densities similar to other natural areas. Sites where earthworm populations are lower may be showing the influence of many factors, such as the age of the rain garden, sand content of the soil mix, soil moisture regime, or proximity to existing earthworm populations. These factors are discussed in more detail in Sections 2.4.3 and 2.4.4.

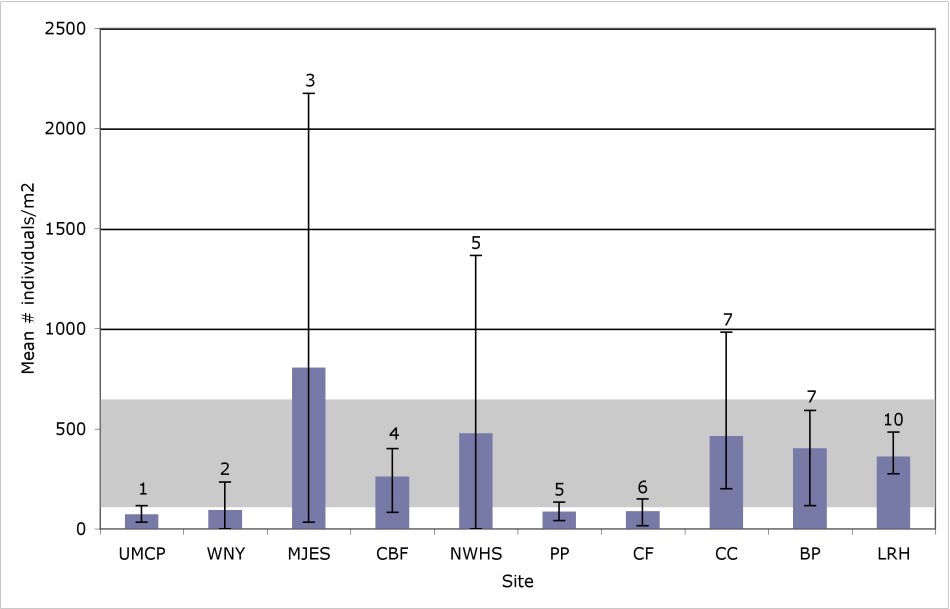


Figure 2.54: Mean earthworm density for each of the field sites sampled. Error bars represent the maximum and minimum measured values. The shaded area represents reported earthworm densities for old pasture (109–646 individuals/m^2) (Edwards and Bohlen, 1996).

2.4.1.4 Soil organic matter enrichment

The average organic content of the upper soil layer (0–10 cm) of each of the sites is shown in Figure 2.55. The expected organic matter content of a "typical" bioretention soil medium using 50% sand, 20% topsoil, and 30% compost by volume was calculated for comparison purposes. Assuming the following dry bulk densities: sand, 1.5–2.0 g/cm^3 (Brady and Weil, 2002); sandy loam topsoil, 1.3–1.5 g/cm^3 (Brady and Weil, 2002); compost, 0.3–0.4 g/cm^3 (Glancey and Hoffman, 1996); and BSM, 1.27–1.32 g/cm^3 (Thompson et al., 2008), the compost content of this mixture is 7–9% by weight. The organic matter content of compost can vary widely, from 30–65% on a dry weight basis (CSPMA, 1996). This would yield a soil mix with 2–6% organic matter. Six of the ten sites sampled showed organic matter levels within this range. One site (BP) had a slightly elevated organic matter content, and three sites (MJES, PP and CC) had much higher organic matter content.

SOM was measured by the loss-on-ignition method (ASTM, 2000), which measures the total organic matter fraction smaller than 2 mm in diameter. This method, therefore, does not include large, undecomposed organic matter fragments. Bioretention soil media sometimes use shredded hardwood mulch as an organic matter source, and much of this organic matter would be excluded from the measurement. This is appropriate, as organic matter pieces this large do not play the same role as smaller, more decomposed organic matter fractions. In addition, the method does not distinguish between small, undecomposed particles and the more active, humified organic matter fractions, which are of interest due to their prominent role in the maintenance of soil structure and their strong affinity for cations (Brady and Weil, 2002; Weil et al., 2003). Measurement of this active fraction falls to future researchers. Some sites did contain a great deal of hardwood

mulch, which had often degraded sufficiently to create a lot of very small mulch pieces. This tended to drive up the measured organic matter content. Indeed, the three sites with elevated organic content, MJES, CC, and PP, were observed to have a lot of mulch incorporated into the upper soil layers.

Different specifications were used in the construction of many of these sites, but these specifications were not available for all sites. All available data on the research sites is included as Appendix A. At Beltway Plaza, the specification called for five parts topsoil to one part peat moss or rotted manure. Peat moss typically contains 80% organic matter (CSPMA, 1996), which would yield a soil medium with 13% organic matter, a higher value than the average measured content of 9.5%. Unfortunately, soil testing data for the soil medium installed at this site is not available, so it is impossible to say whether the organic matter content of the soils has increased or decreased over time.

2.4.2 Baseline physical data

2.4.2.1 Soil texture

Current specifications for bioretention soil mix (PGCO, 2001; LIDC, 2003) specify that the mix shall contain 50% sand, 20% sandy loam topsoil, and 30% compost or shredded hardwood mulch. This would yield a soil texture of 83.7–96.7% sand, 0–14.3% silt, and 0–5.7% clay. Of the ten sites sampled, only UMCP was within these specifications, though PP was very close. All other sites had lower sand and higher silt and clay contents.

The cause of this discrepancy could not be determined definitively, because testing data are not available for the soils used in the construction of the cells. Indeed, even specifications were unavailable for most of the sites. We do know that Prince George's County's bioretention specifications have evolved over time, requiring greater quantities of

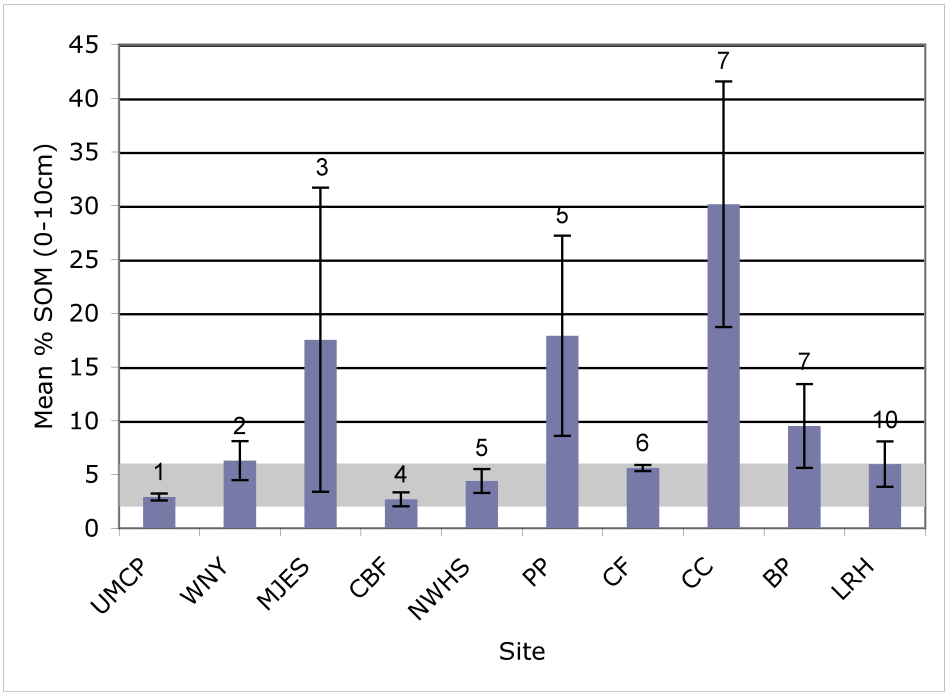


Figure 2.55: Mean upper layer % SOM for all sites. Error bars show standard deviations. The shaded area represents the expected organic matter content of a typical BSM soil medium (2–6%).

Table 2.16: Average soil texture for each of the research sites.

Site	Sand (%)	Silt (%)	Clay (%)	Textural Classification
UMCP	91.0 ± 1.2	4.6 ± 0.9	3.8 ± 0.3	Sand
WNY	71.3 ± 3.4	21.3 ± 5.7	7.4 ± 2.8	Sandy Loam
MJES	65.8 ± 21.3	19.7 ± 12.4	14.5 ± 8.9	Sandy Loam
CBF	61.0 ± 0.9	16.5 ± 0.6	22.5 ± 1.3	Sandy Clay Loam
NWHS	51.4 ± 4.0	34.2 ± 1.0	14.4 ± 3.7	Loam
PP	82.3 ± 3.0	8.1 ± 2.0	9.6 ± 1.6	Loamy Sand
CF	66.9 ± 1.6	17.8 ± 0.6	15.4 ± 1.0	Sandy Loam
CC	66.1 ± 25.2	25.3 ± 16.8	8.6 ± 8.4	Sandy Loam
BP	53.0 ± 6.6	23.5 ± 2.8	23.4 ± 4.3	Sandy Clay Loam
LRH	46.4 ± 14.4	33.3 ± 14.5	20.3 ± 4.1	Loam

sand in the soil mix. Beltway Plaza Mall's plans specified five parts topsoil to one part wet loose peat moss or rotted manure. The topsoil could be: loam, sandy loam, clay loam, silt loam, sandy clay loam, or loamy sand (see Appendix A). In contrast, the current Prince

George's County bioretention specifications, which were used in the construction of the UMCP cell, specify a soil mix that is 50% sand, 30% sandy loam topsoil, and 20% organic material in the form of compost or shredded hardwood mulch (see UMCP site details, Appendix A). Differences in the particle size distribution of the original soil mix could account for the differences in soil textures measured in this study. It is also possible that we are seeing the effect of years of enrichment of the system with fine material carried in by stormwater.

At several sites, large clods of soil with high clay content were found in the deeper soil layers. The origin of these clods is unknown, though it is likely that they are unmixed components of the original soil used in construction. Mottling and gleying were observed in many of these clods, indicating the presence of reducing conditions in these microsites. These clods could be providing a location for denitrification and other chemical reactions that require anaerobic conditions.

2.4.2.2 Infiltration rate

At the three sites where the infiltration rate was measured, the measured infiltration rate greatly exceeded the infiltration rate that would be expected given the particle size distribution of the soil (Figure 2.56). This is an expected result of the presence of biological actors in the soil, one of whose effects is to increase soil porosity through burrowing and the creation of aggregates. This measurement highlights the value of biological activity in the successful operation of bioretention systems.

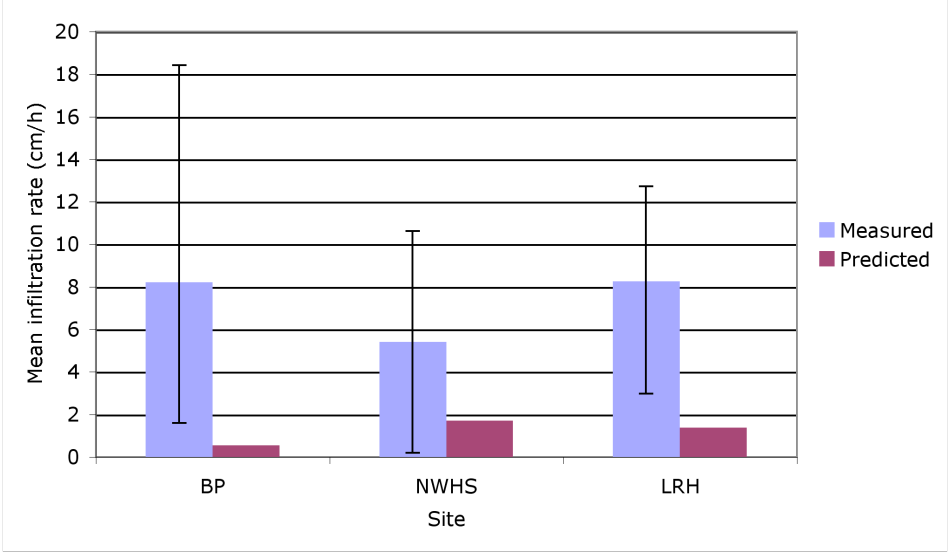


Figure 2.56: Comparison of measured versus predicted infiltration rates for the sites sampled. The measured value is the mean, and the error bars represent the maximum and minimum measured values. Predicted values represent the effective infiltration rate for the soil textures measured onsite, based on Rawls et al. (1982).

2.4.2.3 Evidence of pedogenesis

When treated as a chronosequence, the ten field sites yield a picture of the development of a rain garden over a decade. In these first ten years, we see the beginnings of pedogenesis, with the gradual formation of an A horizon, enriched with organic matter. Figure 2.57 shows the gradual development of an enriched organic layer in the uppermost soil layer (0–10 cm) over time. The profiles show both a shift toward higher organic matter in the upper layer and a shift toward a steeper gradient of organic matter between the upper and lower soil layers. A very similar pattern was seen by Leisman (1957) in a chronosequence on abandoned mine spoil banks in Minnesota (Figure 2.58).

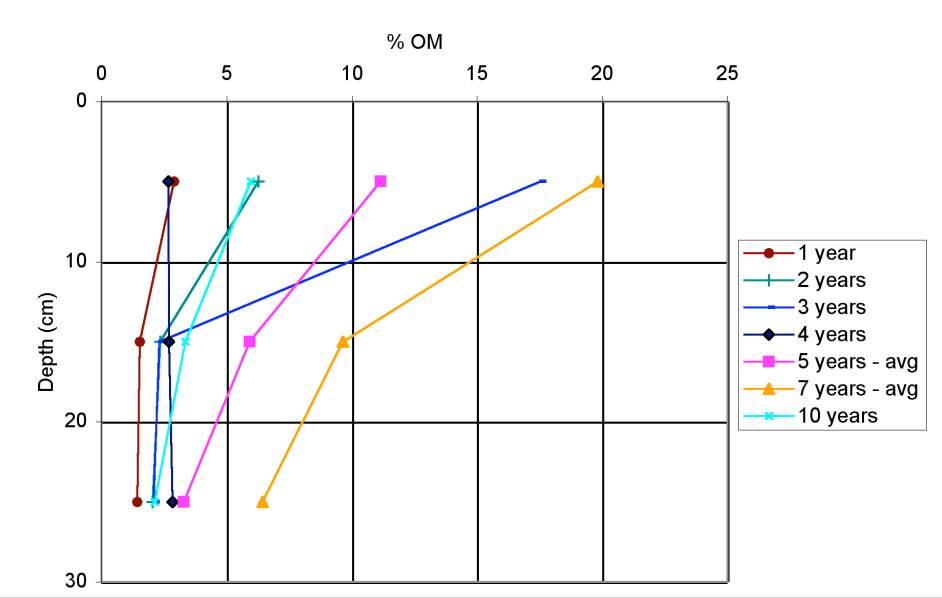


Figure 2.57: Soil organic matter profile development over time. Data series are plotted with organic matter increasing to the right, and depth increasing downward, so that the soil surface is at the top of the chart. The 5-year profile was derived by averaging data from the CBF and NWHS sites. The 7-year profile was derived by averaging data from the CC and BP sites.

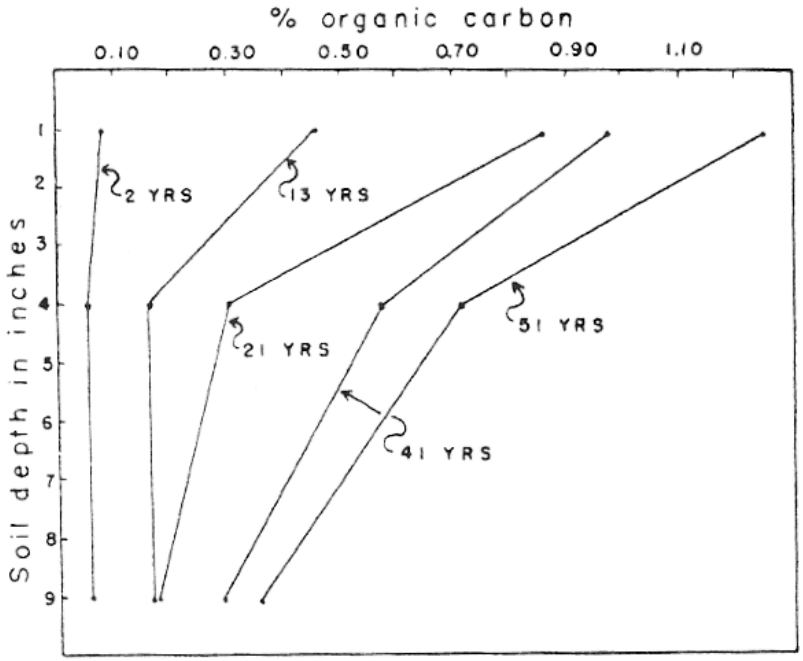


Figure 2.58: Organic carbon profile development in a mine spoil chronosequence (Leisman, 1957).

Organic matter in the uppermost soil layer (0–10 cm) appears to increase slightly over time, but the coefficient of correlation ($R^2 = 0.0475$), as shown in Figure 2.59, is not high enough to declare that this relationship definitively exists. It is worth noting that the extremely high organic matter content of the CC site is likely an artifact of the presence of a very large amount of mulch mixed into the soil, rather than to decomposed organic matter that has been incorporated into the soil matrix.

2.4.2.4 Changes in root biomass over time

The sequence appears to show an increase in root biomass over time, though the coefficient of correlation ($R^2 = 0.27$), as shown in Figure 2.60, is not high enough to state that

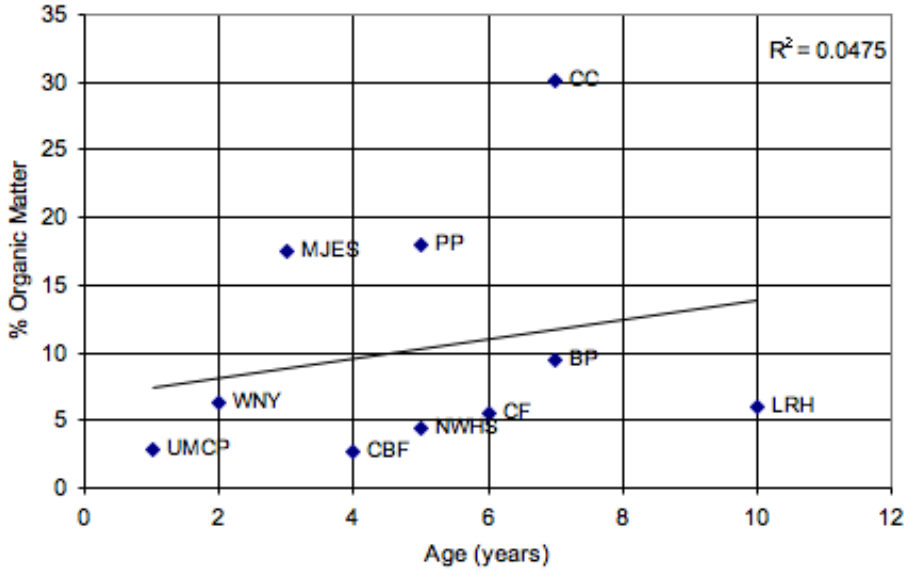


Figure 2.59: Soil organic matter in uppermost 10 cm versus age.

such a correlation definitively exists. Root biomass increases as plants become established, therefore root biomass is expected to increase over the first years after planting.

Here again, Figure 2.61 reveals a shift to the right with the age of the rain garden. The diagram shows the gradual formation of a gradient with depth, with the greatest root biomass in the topsoil, and decreasing at deeper soil levels. This is an expected result, corresponding to declining oxygen levels at greater soil depths.

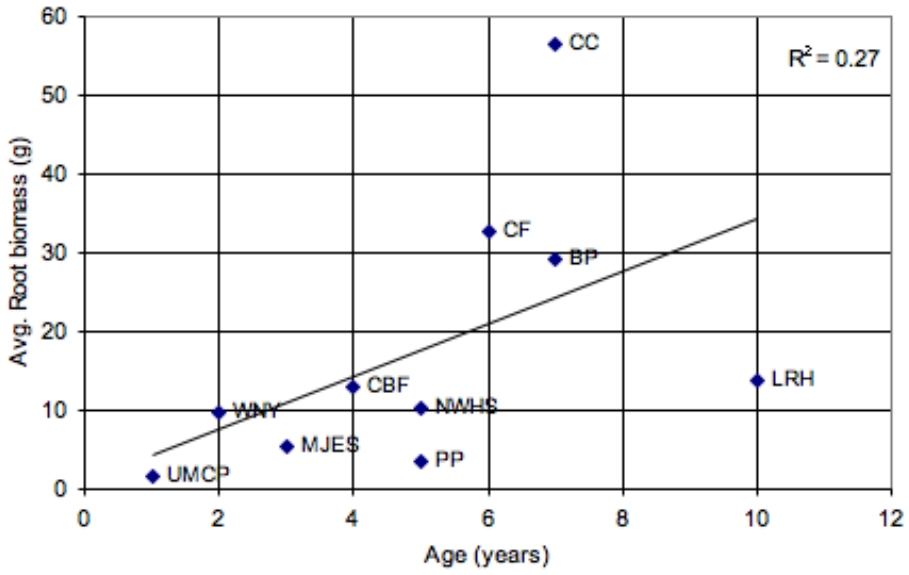


Figure 2.60: Root biomass versus age.

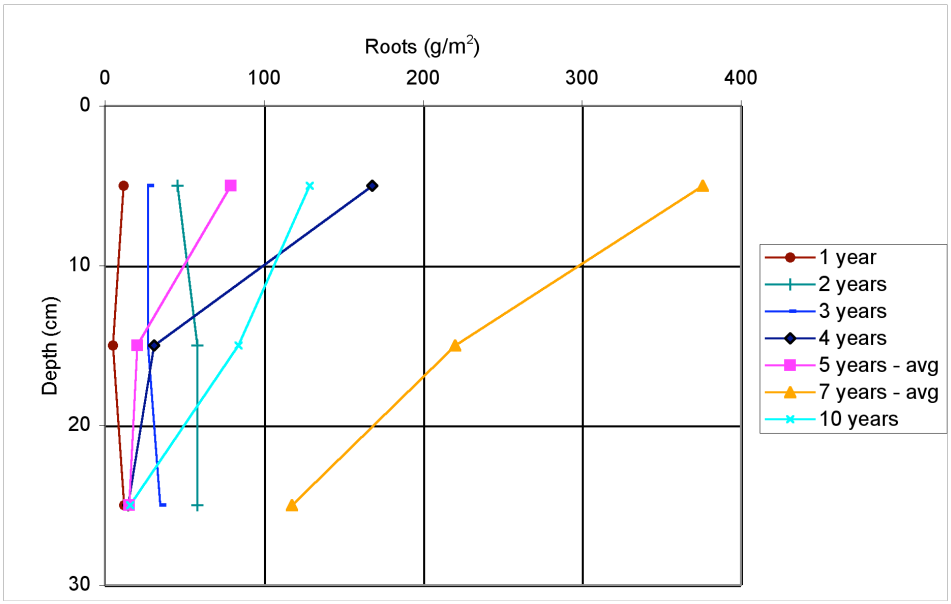


Figure 2.61: Root profile development over time. Data series are plotted with root biomass increasing to the right, and depth increasing downward, so that the soil surface is at the top of the chart. The 5-year profile was derived by averaging data from the CBF and NWHS sites. The 7-year profile was derived by averaging data from the CC and BP sites.

2.4.2.5 Changes in earthworm abundance over time

Figure 2.62 shows no correlation between earthworm abundance and rain garden age ($R^2 = 0$). Figure 2.63 suggests an increase in earthworm abundance over time at all depths, with greater increases in the uppermost soil layer. This is consistent with the gradual colonization of the sites by earthworms washed in from surrounding natural areas. Note the MJES had many more earthworms than any of the other sites. The reason for this is unknown.

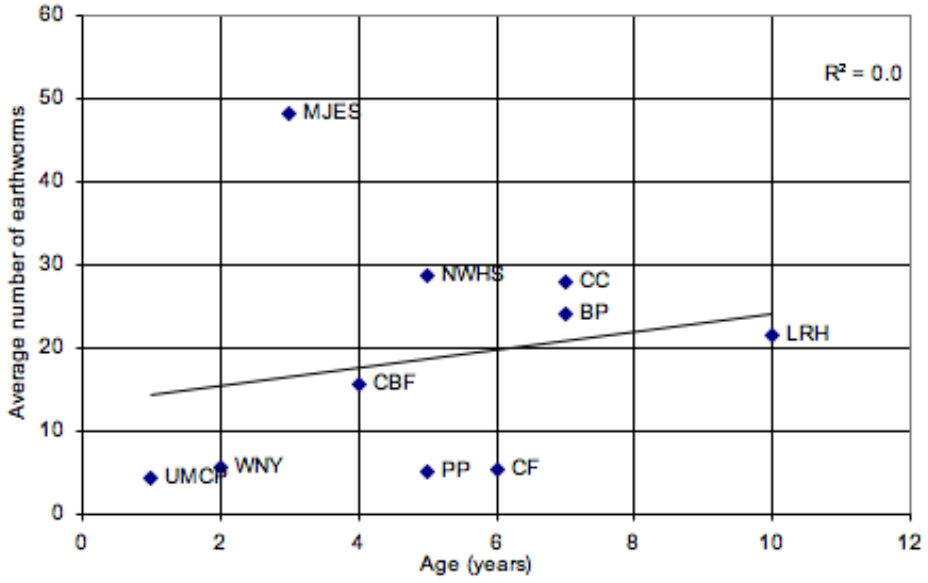


Figure 2.62: Earthworm abundance versus age.

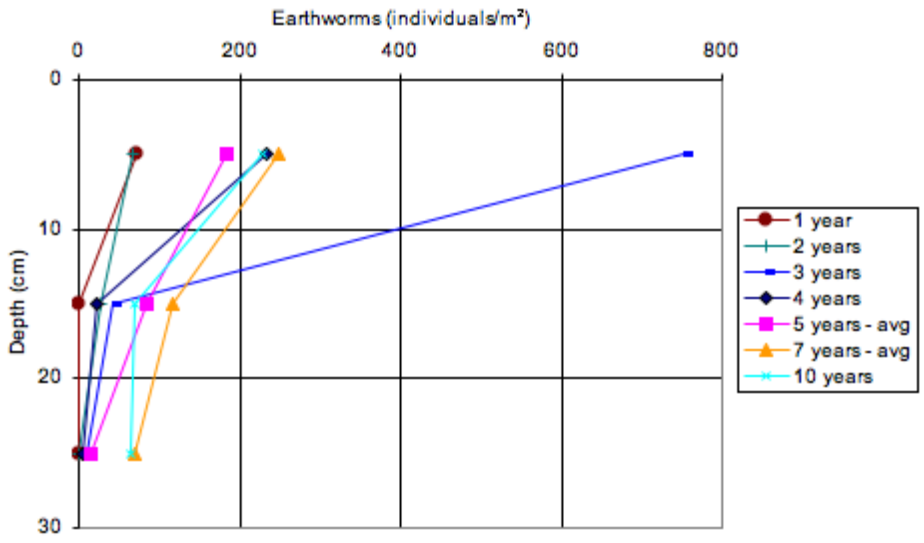


Figure 2.63: Earthworm profile development over time. Data series are plotted with earthworms increasing to the right, and depth increasing downward, so that the soil surface is at the top of the chart. The 5-year profile was derived by averaging data from the CBF and NWHS sites. The 7-year profile was derived by averaging data from the CC and BP sites.

2.4.2.6 Colonization by soil animals

Table 2.17 summarizes how the depth at which taxa were found varied with the age of the rain garden sampled. At one year, macroinvertebrates were confined to the uppermost soil layer. After two years, they had spread to the 10–20 cm depth. After three years, they had spread through the entire 30 cm sampling depth. All sites showed higher numbers of macroinvertebrates in the upper soil layers. Increasing species richness and density are expected patterns of the gradual colonization of a newly disturbed site. Earthworms had colonized all sites, including the youngest site, UMCP, which had only been in operation for one year. This suggests that earthworms may be an important pioneer species in the rain garden ecosystem.

Table 2.17: Variation in total number of soil animals counted and number of different animal taxa encountered at each sampling depth with age. Where two rain gardens are of the same age, the results are averaged. Partial animal counts are the result of severing of earthworms during sampling.

		Depth		
Age	Site(s)	0-10 cm	10-20 cm	20-30 cm
1 year	UMCP	21 animals 5 taxa	–	–
2 years	WNY	34 animals 2 taxa	7 animals 2 taxa	–
3 years	MJES	219.5 animals 11 taxa	12.5 animals 4 taxa	3 animals 1 taxon
4 years	NWHS, CBF	126 animals 9.5 taxa	36.5 animals 5 taxa	18 animals 1.5 taxa
5 years	PP	57 animals 9 taxa	7 animals 3 taxa	1 animal 1 taxon
6 years	CF	102 animals 6 taxa	66 animals 7 taxa	41 animals 2 taxa
7 years	CC, BP	70 animals 7 taxa	35.5 animals 5.5 taxa	18 animals 2.5 taxa
10 years	LRH	50 animals 9 taxa	13 animals 4 taxa	10 animals 1 taxon

2.4.3 Confounding factors

Variations in the histories of these sites make them an imperfect chronosequence. They differ in many respects, some of which may influence organic matter, root biomass, and animal populations to a greater degree than the passage of time. The most important of these factors are: variations in soil texture, differences in plant cover, differences in the litter/mulch layer, and variations in the proximity to natural areas.

2.4.3.1 Effect of soil texture on earthworm populations

It is well known that earthworms dislike very sandy soils (Curry, 1998). This is thought to be due in part to the abrasive effects of sands on their soft bodies. Figure 2.64 suggests an inverse relationship exists between earthworm abundance and the sand content of the soil, though the coefficient of correlation ($R^2 = 0.3$) is not high enough to make such a statement definitively. This may be due to the presence of MJES as an outlier.

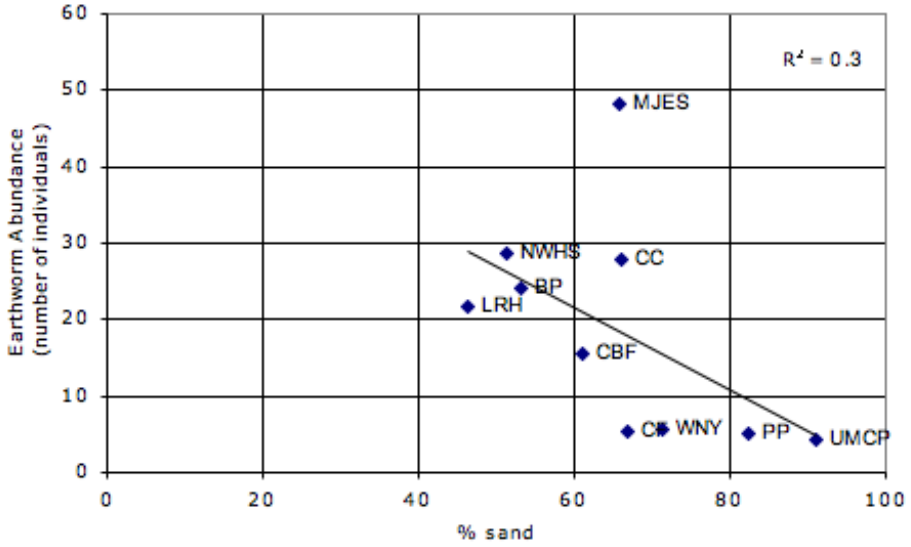


Figure 2.64: Relationship between earthworm abundance and sand content.

2.4.3.2 Effect of plant cover and litter layer

The type and extent of plant cover can be expected to have a major influence on many aspects of the biology of the rain garden. Plant cover will determine to a large extent the root biomass that can be expected to develop over time. It will also determine the amount of plant litter than will accumulate on the rain garden surface, contributing to the organic content of the soil. The type of plants present can affect soil animals, as the litter produced may be more or less easily broken down. For example, earthworms tend to dislike leaves containing high levels of tannin, such as spruce, oak, and beech (Edwards and Bohlen, 1996). Dominance by one of these species could depress earthworm populations. The type and thickness of the litter layer can directly effect soil animal populations. In addition to serving as a food source, the litter layer provides shelter for surface-dwelling organisms, and protects the soil surface from temperature extremes.

2.4.3.3 Proximity to natural habitat

Rain gardens are not inoculated with soil organisms when they are constructed, so any invertebrates that establish themselves within the soil must have either been accidentally introduced with the soil mix, or must have colonized from nearby natural areas. Therefore, the proximity of a rain garden to such a natural area might be an important factor in determining how quickly it will be colonized by soil invertebrates, and may also determine which animals are likely to be introduced.

2.4.3.4 Effect of management

Various management schedules could have an influence on biological development. For example, mowing, sediment removal and mulch replacement, use of pesticides and

herbicides within the watershed, use of road salts within the watershed, would be expected to impact both plant and animal populations. Unfortunately, detailed data on the management of these sites are unavailable.

2.4.4 Sources of error in animal sampling

Sampling of soil-dwelling macroinvertebrates is notoriously difficult to perform accurately (Southwood and Henderson, 2000). A number of factors could have influenced the survey results. Environmental factors, such as time of year, temperature on the sampling date, and the antecedent weather conditions, may have influenced macroinvertebrate populations at the time of sampling. In addition, the sampling method used, while appropriate for assessing the earthworm population, does not give an accurate population estimate for all taxa. Many of the very small soil animals, such as springtails, were probably missed during hand sorting. For this reason, animal numbers should be used only for comparison between these sites and not for comparison with other studies. Many soil animals are likely to have escaped during the sampling process.

2.4.4.1 Time of year

Soil macroinvertebrates can be expected to be at different stages of their life cycles at different times of year. All samples were taken during the warmer months, between May and October, but populations at the beginning of the season could differ substantially from populations at the end of the season. Figure 2.65 compares the number of animals found at each site with the month during which sampling took place. The data show a tendency toward higher numbers of animals found at the end of the summer than at the beginning of the summer. Earthworm populations seem to peak in midsummer.

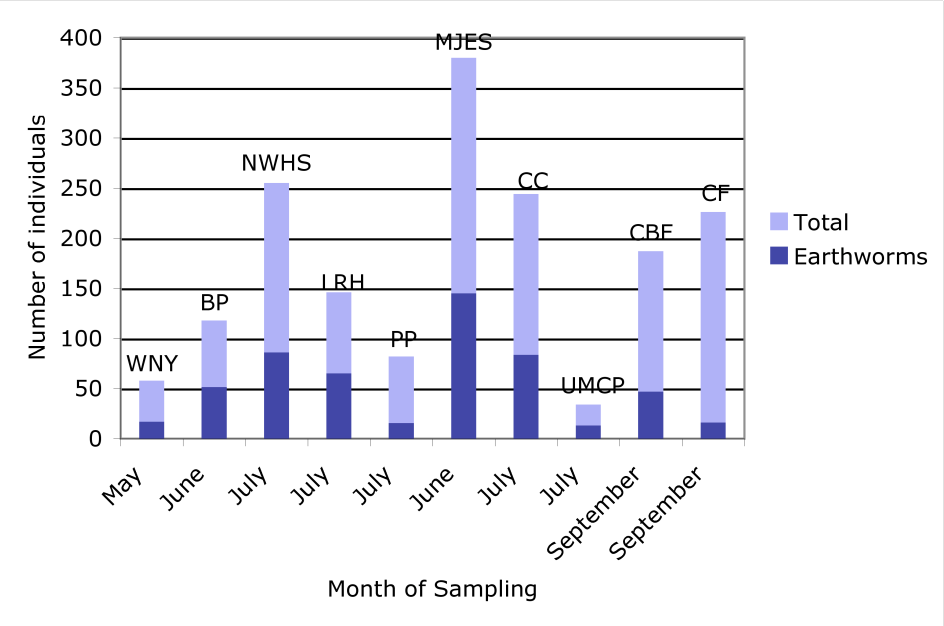


Figure 2.65: Effect of month of sampling on earthworms and total number of soil animals detected.

2.4.4.2 Outdoor temperature

High ambient temperatures could have caused variations in the number of animals found. Animals could have retreated to cooler spots, either deeper in the soil, or elsewhere in the rain garden (under trees, for example). This would result in a decrease in the number of animals found with increasing temperature. Figure 2.66 reveals no such pattern on declining animal numbers with increasing temperature. In fact, if anything, the data tend toward higher numbers of animals detected at higher temperatures.

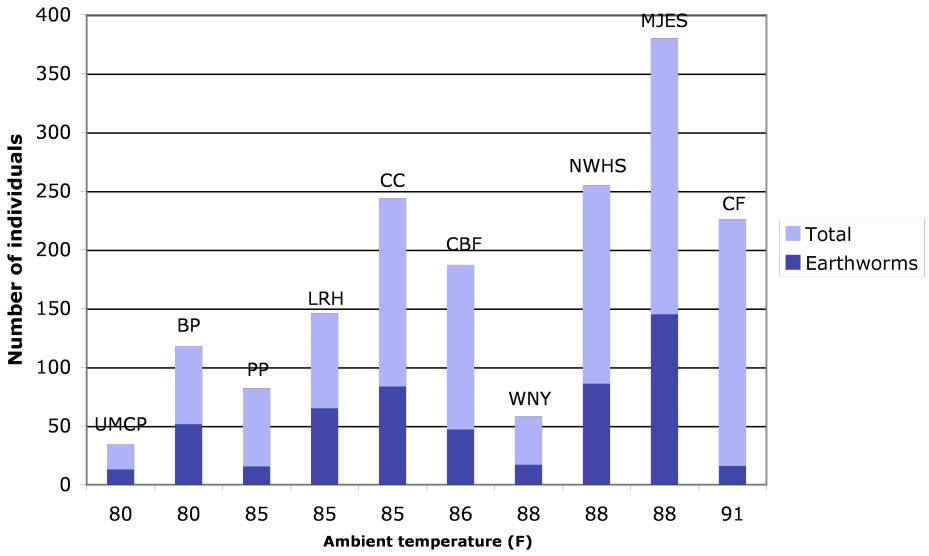


Figure 2.66: Effect of ambient temperature on earthworms and total numbers of soil animals detected. Ambient temperature is the daily maximum temperature recorded at the nearest NOAA weather station (Beltsville, MD).

2.4.4.3 Antecedent weather conditions

As soil invertebrates are dependent on water and oxygen for their survival, weather conditions in the week prior to sampling might influence the number of animals found. During droughts, earthworms tend to aestivate, curling up into a tight ball, often inside a soil aggregate. This makes their detection difficult. Many other animals will die off if no water is available. However, too much rain could also depress animal populations by limiting the amount of available oxygen in the soil. Therefore, we would expect to see lower numbers of earthworms and other animals after particularly wet or dry periods. Interestingly, Figure 2.67 shows a different pattern, possibly even the inverse of what is expected. The highest animal counts occurred after the driest periods. This may suggest that animals are better able to survive lack of water than lack of oxygen, or it may be a coincidence only, caused by some other factor.

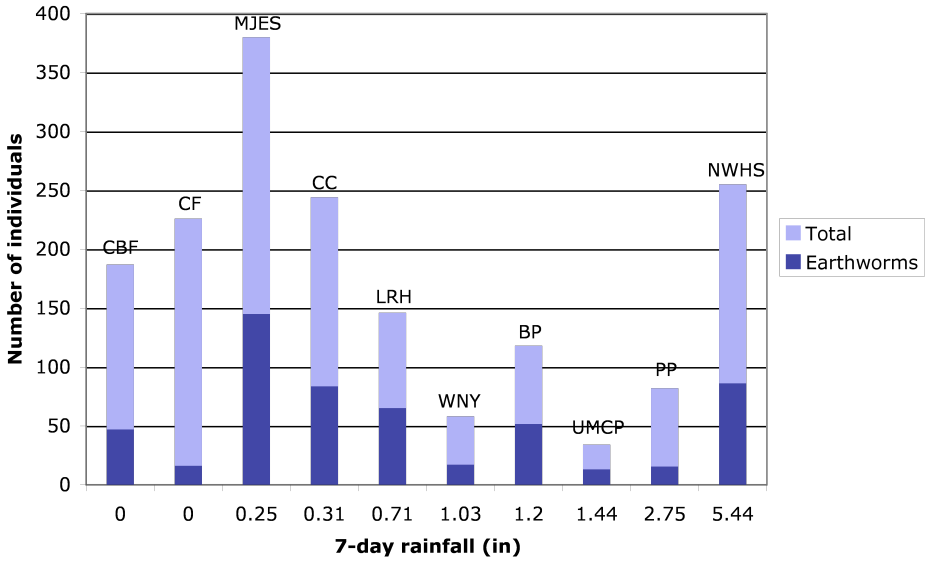


Figure 2.67: Effect of precipitation on numbers of earthworms and other soil animals detected. 7-day rainfall totals are those recorded at the nearest NOAA weather station (Beltsville, MD).

2.4.5 Infiltration tests

Infiltration tests were conducted on only three of the ten research sites. Infiltration testing on all sites were not attempted due to time constraints and concerns about the reliability of the data. The infiltration tests were performed using a double-ring infiltrometer, which proved to be unsuitable to the soil conditions encountered in a rain garden. Double-ring infiltrometers are best used in sites with little root biomass, and where the rings can be driven into the ground using hydraulic equipment (ASTM, 2003). Bioretention cells are not accessible to hydraulic equipment, such as truck jacks, because the surrounding soil must not be compacted. Therefore, the rings must be driven in by hand using a sledgehammer. Bioretention cells are heavily vegetated, and many of the older sites contain tree and shrub species. Roots more than 1 cm in diameter are common. These cannot be severed by the rings as they are driven into the soil. Where the rings encountered large roots, the roots were cut through by pushing a machete down alongside the rings. This added to the disturbance of the surrounding soil, which could have lead to inaccurate measurements.

Bioretention cells are constructed with a thick (commonly 3-inch) mulch layer at the soil surface. Over time, this mulch layer breaks down and is incorporated into the soil surface. This poses a particular difficulty in using the double ring infiltrometer, as the mulch surface must be removed in order to drive the rings in to the ground, but the mulch layer does not end abruptly, but rather mulch pieces become incorporated into the upper soil layers. The driving of the rings is easily halted by hitting a large mulch piece. The data shows wide variability in infiltration rates between tests at the same site, but it is impossible to say whether this is the result of spatial heterogeneity or inaccuracy due to the inapplicability of the measurement technique to the site conditions.

2.4.6 Diversity among rain gardens

This study reveals the wide diversity in what we refer to as a rain garden; there are huge differences in the soils, vegetation, animals, designs and watersheds. Age was expected to be the primary driver of differences between the sites. Factors were expected to change steadily over time, with higher organic matter, roots and animal populations at older sites. This study found a great deal of variation between sites, suggesting that other factors are at least as important as time in determining the level of biological activity at a given site.

2.4.6.1 Differences in history, location

Unfortunately, data on the original site designs were often unavailable. The oldest site for which as-built plans were available was the Beltway Plaza Mall (BP) site (see Appendix A). The rain garden that was sampled was constructed on this site in 1997. The bioretention specification contained in these plans allows a wide range of soil textures to be used in the bioretention mixture. No sand was to be added, and the mix was 5 parts soil to 1 part organic matter, which is much less than the 3:2 mix currently specified.

Differences in land use within watershed would affect runoff composition. The dominant land use within the watersheds of the sampling sites are given in Table 2.18. The unpaved parking lot at the Chesapeake Bay Foundation (CBF) might be expected to produce more sediment, but less runoff overall due to increased infiltration over the parking surface. The runoff coming from the roof at Claggett Farm (CF) would carry pollutants from atmospheric deposition only, and would not contain the same mix of pollutants related to automobiles, such as oil and grease, and heavy metals from tire wear. Reduced

heavy metal loading at Claggett Farm could be expected to provide better habitat for soil animals.

Table 2.18: Land use within the watersheds of sampling locations.

Site	Watershed Land Use
UMCP	paved parking lot
WNY	paved parking lot
MJES	paved parking lot
CBF	unpaved parking lot
NWHS	paved parking lot
PP	paved parking lot
CF	roof
CC	paved parking lot
BP	paved parking lot
LRH	paved parking lot

As shown in Figure 2.68, the sites show a significant decrease in sand content with the age of the rain garden ($R^2 = 0.5$). Unfortunately, we lack sufficient historical data to discern whether this trend is due to changes in the soil specifications or to inflow of additional silt and clay in the form of suspended solids. It is likely that both play a role, though changes in soil specifications are probably the primary driving force.

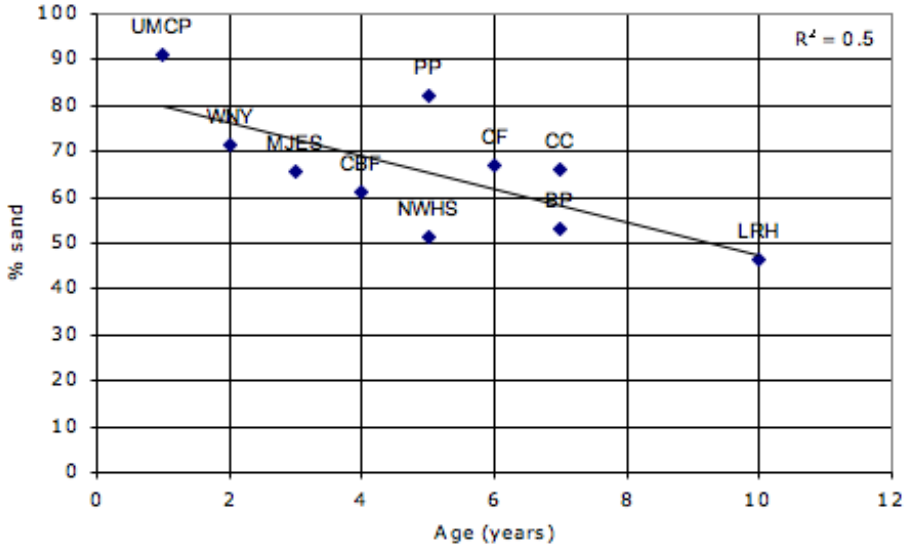


Figure 2.68: Changes in sand content with rain garden age.

2.5 Summary

1. Biological activity is ubiquitous in rain garden soils.
2. Rain gardens begin to undergo pedogenesis immediately after installation.
3. Rain gardens develop a characteristic soil profile with exponentially decreasing biological activity with depth.
4. No evidence of clogging due to normal operation was found.
5. Earthworms were found at all field sites.
6. Earthworms occurred at densities similar to fallow pastures.
7. Representatives of thirteen major soil-dwelling invertebrate taxa were found.
8. Earthworms and other soil invertebrates rapidly colonize rain gardens in spite of their physical isolation.
9. Some rain gardens showed higher than expected infiltration rates.
10. Substantial differences in particle size distribution were found between rain gardens of different ages, with newer sites containing more sand and less clay and silt.
11. Older rain gardens tend to have higher root biomass than younger rain gardens.
12. Many sites had lower soil organic matter than would be expected from the typical bioretention soil medium.
13. Assessment of long-term rain garden development is hampered by the scarcity of original design documents and soil testing data.

Chapter 3

Microcosm Study

3.1 Introduction

A microcosm study was performed to evaluate the effect of earthworms on the saturated hydraulic conductivity of soil columns subjected to simulated storm events. Eighteen soil columns were divided into three treatment groups. The treatments were designed to test the ability of earthworms to maintain the hydraulic conductivity of a soil column subjected to sediment loading, and to improve the saturated hydraulic conductivity of a soil column that is already clogged with sediment. The initial saturated hydraulic conductivity of the columns was measured, then the columns were subjected to simulated storm events for six months. The final saturated hydraulic conductivity was measured at the end of the experiment, and earthworm survivorship was assessed. The change in hydraulic conductivity over the course of the experiment within each treatment group was evaluated, and the initial and final hydraulic conductivities of the treatment groups were compared. An earlier study was performed to test the ability of earthworms to survive in bioretention soil media (BSM). The results of this study are included as Appendix E.

3.2 Methods

Eighteen rain garden microcosms were constructed using 24-inch lengths of 4-inch diameter PETG (polyethylene terepthalate glycol). These were divided into three treatment groups of six columns each: the Control group, without earthworms; Treatment 1, with earthworms; and Treatment 2, with earthworms and an added sediment layer at

the surface. Treatments were assigned according to a stratified randomized design, with the columns arranged into groups of three (Table 3.1). This was intended to eliminate potential sources of systematic error, such as differences in temperature across the room where the columns were set up.

Table 3.1: Treatment assignments for microcosms showing stratified randomized experimental design.

Column #	Treatment	Abbreviation
1	Control	C
2	Worms	T1
3	Worms + sediment	T2
4	Worms + sediment	T2
5	Control	C
6	Worms	T1
7	Control	C
8	Worms + sediment	T2
9	Worms	T1
10	Worms + sediment	T2
11	Control	C
12	Worms	T1
13	Worms + sediment	T2
14	Worms	T1
15	Control	C
16	Control	C
17	Worms + sediment	T2
18	Worms	T1

Earthworms were collected by hand digging from a rain garden in Beltway Plaza Mall in Greenbelt, MD, and from a residential yard in Takoma Park, MD. Additional adult *Lumbricus terrestris* were obtained by mail order (Carolina Biological Supply). The collected earthworms were classified by size and coloration, but were all juveniles, and were therefore not identifiable. They were collected just below the soil surface, and were likely endogeic species, which burrow horizontally through the topsoil. *L. terrestris*, an anecic species, were added in order to increase the range of earthworm ecotypes present in the microcosms.

The columns were constructed on November 4, 2005. Each column rested on a funnel filled with #57 washed stone gravel, as shown in Figure 3.1. The column was filled to a 45 cm depth with a variant of the standard bioretention soil medium (BSM): 50% sand, 30% sandy loam topsoil, 10% compost, and 10% shredded hardwood mulch by volume (LIDC, 2003; PGCO, 2001). The BSM was tamped down by hand. Each of the treatment columns was inoculated with:

- 1 "rain garden" earthworm hatchling, unpigmented, length < 3 cm,
- 1 medium pink "rain garden" earthworm, length 3–7 cm, and
- 3–4 pink "Takoma Park" worms, with lengths ranging from 2–7 cm.

The earthworms were allocated in such a way as to balance out the total length of earthworms added (i.e. one large worm = two small worms). The earthworms were placed on the soil surface in the Treatment 1 and Treatment 2 columns. The Treatment 1 and Control columns were then topped with a 3 cm depth of moistened shredded hardwood mulch. Treatment 2 was topped with 150 g of manufactured sediment, creating a 1-cm-deep sediment layer. This was then covered with 3 cm of moistened shredded hardwood mulch. Sediment was created by passing BSM through a 0.6 mm (#30) mesh sieve, in a manner similar to Hsieh and Davis (2005a). The sediment was intended to represent trapped suspended solids.

Particle size analysis was performed using hydrometer and sieve tests as described in A.1.9. The results are shown in Tables 3.2 and 3.4.

Three adult *L. terrestris* were added to each of the Treatment 1 and 2 columns on December 15, 2005, following the completion of the initial tests, as they were expected to quickly construct deep burrows, which would have a significant effect on the soil saturated hydraulic conductivity. These earthworms were placed on the soil surface, under the mulch layer.

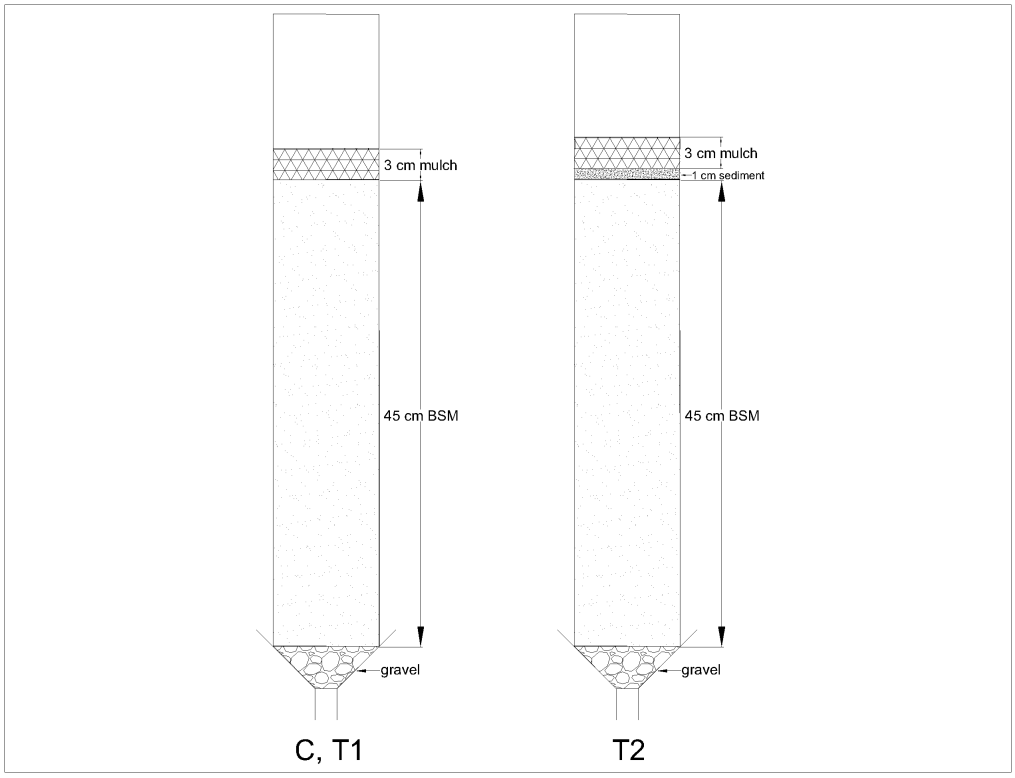


Figure 3.1: Diagram showing microcosm setup.

Table 3.2: Particle size distribution for bioretention soil mix.

Particle Size	Percentage
sand	93.2%
silt	4.0%
clay	2.8%
d_{60}	0.50 mm
d_{10}	0.25 mm
Coefficient of uniformity, d_{60}/d_{10}	2
USDA textural classification	sand

3.2.1 Infiltration testing

The saturated hydraulic conductivity of the columns was measured using a constant head infiltration setup (Figure 3.2). As equipment constraints allowed testing of

Table 3.3: Particle Size Distribution of manufactured sediment.

Particle Size	Percentage
sand	88.4%
silt	6.5%
clay	5.1%
d_{60}	0.50 mm
d_{10}	0.05 mm
Coefficient of Uniformity, d_{60}/d_{10}	10
USDA Textural class	loamy sand

only one column at a time, the columns were tested sequentially by column number. Initial tests were performed between 11/6/05 and 12/14/05. Final tests were performed between 6/19/06 and 7/6/06. A constant water depth of 10 cm above the soil surface was established, and the soil was allowed to saturate for one hour. Then, for the next six hours, the volume of water exiting the base of the funnel was collected and measured every hour to yield the flow rate per hour. The tests were conducted for six hours in order to ensure that the columns were completely saturated, and that the measured infiltration rate would reach steady state. These hourly values were then averaged to determine flow rate of the column. Saturated hydraulic conductivity, K_s, was calculated by applying Darcy's Law in the following form (Hillel, 1998):

$$K_s = \frac{QL}{Ah} \tag{3.1}$$

where Q = effluent flow rate (cm/h)

L = soil height (cm)

A = column cross-sectional area (cm^2), and

h = head (cm).

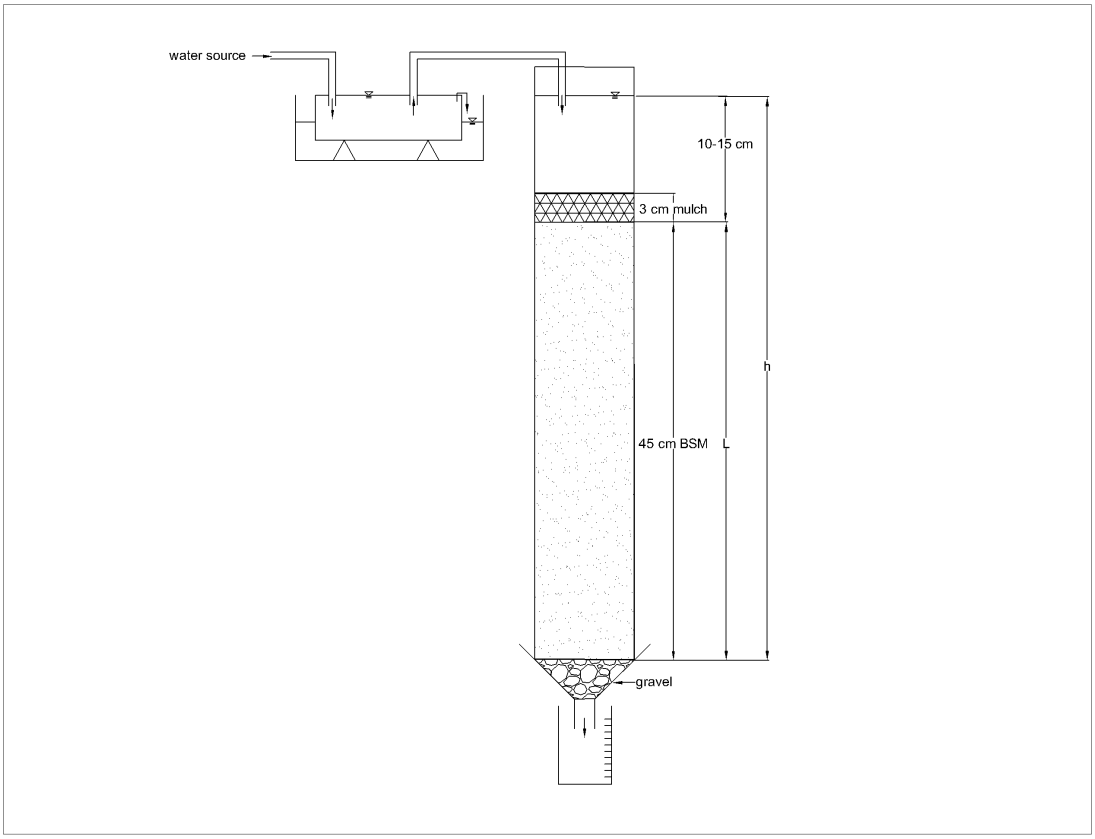


Figure 3.2: Diagram of setup to establish constant head for infiltration testing.

3.2.2 Earthworm feeding

The earthworms were fed a variety of seasonally available foods. During the winter and early spring, the earthworms were fed assorted decaying leaves, primarily cherry (*Prunus sp.*). These were supplemented with cornmeal in order to avoid any possibility of malnutrition affecting survivorship. Partially decayed leaves were collected outdoors, soaked in tap water for three hours to soften, then roughly chopped. In late spring and early summer, the earthworms were fed assorted fresh wild greens, supplemented with cornmeal. Greens were collected outdoors, then roughly chopped. Greens included Kentucky Bluegrass (*Poa pratensis*), white clover (*Trifolium repens*), dandelion (*Taraxacum officinale*) and plantain (*Plantago major*). Additional cornmeal and leaves were added when they had been consumed in one or more of the columns. In total, the treatment columns received 8.0 g of wet chopped decayed leaves, 3.0 g of chopped fresh greens, and 4.0 g of cornmeal. No foods were added to the Control columns, to avoid the possibility of artificially clogging the columns with unconsumed plant litter or mold growth.

3.2.3 Storm simulations

Storm simulations were designed to approximate a typical rainfall for May-October in Prince George's County, MD. This six-month period was selected because earthworms are most active during late spring, summer, and early fall. The microcosms were intended to represent unit elements of a rain garden. Ponding during simulated storms was intended to reflect the ponding occurring in rain gardens during storm events. In order to obtain representative values, 30-year rainfall averages published by the National Climatic Data Center for the nearest weather station (Baltimore, MD) were used (NCDC, 2003).

Table 3.4: 30-year rainfall averages for Baltimore, MD (NCDC, 2003).

Month	Precipitation (in)	# of Rainy Days
May	3.89	11
June	3.43	10
July	3.85	9
August	3.74	9
September	3.98	8
October	3.16	8

It was assumed that the theoretical rain garden would drain a 1-acre paved parking lot (CN = 98). The size of the theoretical rain garden was calculated following the sizing procedure described in Low-Impact Development Hydrologic Analysis (PGCO, 2000). The calculations are presented below.

Given:

Site area: 1 acre = 43,560 ft^2

Existing CN: 98 (pavement)

Proposed CN: 60 (woods, fair condition, Hydrologic Soil Group B soils)

Design storm: Type II, 1-inch over 24 hours

Solution:

Using Appendix A in PGCO (2000), total storage volume required using retention storage = 0.8 inches over the entire site.

Storage volume required = 43,560 ft^2 × 0.8 in = 2,900 ft^3

Depth of bioretention soil = 2.5 ft

Bioretention soil porosity (ideal) = 0.5

Ponding depth = 0.5 ft

Effective storage depth = soil depth × porosity + ponding depth = 1.75 ft

Size of bioretention cell required (rain garden area) = volume required ÷ storage depth
= 1657.14 ft

Each column represented a unit volume within this rain garden.

The historic rainfall data contained in Table 3.5 was converted into a stormwater dosing schedule for the columns by the following calculations. Assume equal rainfall for each storm in a given month.

$$Rainfall = \frac{Total\ Precipitation}{Number\ of\ Storms} \tag{3.2}$$

$$Runoff\ Volume = \ Rainfall \times Watershed\ Area \tag{3.3}$$

$$Ponding\ Depth = \frac{Runoff\ Volume}{Rain\ Garden\ Area} \tag{3.4}$$

$$Storm\ Volume = \ Ponding\ Depth \times Column\ Surface\ Area \tag{3.5}$$

Revision to Storm Schedule. It was important to avoid waterlogging the columns to the extent that anoxic conditions developed, which would have killed the earthworms. At the end of month four, it was apparent that the soil columns were not drying sufficiently between storms. The storm volume used for months 5 and 6 was reduced to 2.00 L (see Table 3.6), but the suspended solids (SS) added with each storm event was held steady at

Table 3.5: Design storm frequencies, based on 30-year rainfall averages for Baltimore, MD (NCDC, 2003).

Real Month	Real Dates	Data Month	Days in Data Month	# Storms	Storm Frequency (days)
1	12/15/05-1/14/06	May	31	10	2.8
2	1/15/06-2/13/06	June	30	10	3
3	2/14/06-3/17/06	July	31	9	3
4	3/18/06-4/17/06	August	31	9	3.4
5	4/18/06-5/17/06	September	30	8	3.75
6	5/18/06-6/17/06	October	31	8	3.9

Table 3.6: Design storm volumes, based on 30-year rainfall averages for Baltimore, MD (NCDC, 2003). Storm volumes for months 5 and 6 were reduced to 2.00 L per storm.

Real Month	Real Dates	Data Month	Storm Volume Scheduled (L)	Storm Volume Actual (L)
1	12/15/05-1/14/06	May	1.91	1.91
2	1/15/06 2/13/06	June	1.85	1.85
3	2/14/06 3/17/06	July	2.31	2.31
4	3/18/06 4/17/06	August	2.25	2.25
5	4/18/06 5/17/06	September	2.69	2.00
6	5/18/06 6/17/06	October	2.14	2.00

3.0 g, as discussed below, in order to avoid changing the total SS input over the course of the experiment.

3.2.3.1 Suspended solids loading

In order to maximize the potential for clogging over the 6-month experiment, sufficient solids were added to potentially create a 1-cm sediment layer. 3.0 g of SS were added to each column during every storm event, yielding a total of 165.0 g over the course of the experiment. The SS concentration of the simulated runoff ranged between 1,100 mg/L and 1,600 mg/L, an order of magnitude higher than typical values for urban runoff,

which are typically on the order of 150 mg/L (Hsieh and Davis, 2005a; Kadlec and Knight, 1996).

To ensure that the entire SS load was added with each storm event, the solids were not mixed with the water, but rather sprinkled on the column surface prior to the addition of the water. A thin plastic shield was placed over the surface after the solids were added but prior to wetting in order to minimize the disturbance of the soil surface. This film was removed as soon as all of the water had been added to the column, so that the natural filtration of the solids by the soil would not be impeded.

Solids were manufactured in two batches. The first batch was the same as the sediment placed in the Treatment 2 columns during setup, created by passing BSM through a 0.6 mm (#30) sieve. The second batch was manufactured at a later date by the same method, using the BSM used in the soil columns, combined with waste soil collected from the sampled rain gardens. The addition of waste soil was intended to increase the silt and clay content of the sediment. The second batch was used from day 79 (3/3/06) through the end of the experiment. The particle size distributions of the two batches are given in Table 3.7.

Table 3.7: Particle size distribution for manufactured suspended solids (SS).

	First Batch	Second Batch
Sand	88.4%	78.5%
Silt	6.5%	13.1%
Clay	5.1%	8.4%
d_{60}	0.5 mm	0.25 mm
d_{10}	0.05 mm	0.05 mm
Coefficient of Uniformity, d_{60}/d_{10}	10	5
USDA textural classification	loamy sand	loamy sand

3.2.3.2 Statistical analyses

The mean, standard deviation and variance of the initial and final saturated hydraulic conductivity (K_s) were calculated for each of the treatment groups. A two-tailed paired Student's t-test was used to examine the change in K_s over time within each of the treatment groups. In a paired t-test, the population of interest is the difference between a pair of measurements ($D = K_{sf} - K_{si}$). In this case, the paired measurements are the initial and final K_s for each column. Student's t-test requires that the population of interest be normally distributed or approximately normally distributed, that samples are randomly selected from the populations of interest, and that the pairs of observations are independent.

Null hypothesis: mean initial K_s equals the mean final K_s (H_0: $D = 0$, $K_{si} = K_{sf}$).

Alternative hypothesis: mean initial K_s does not equal the mean final K_s (H_a: $D \neq 0$, $K_{si} \neq K_{sf}$).

If Student's t-test yields a significant result, then the null hypothesis is rejected, and it can be concluded with a high degree of confidence that the mean values of the populations being compared differ. Student's t-test is sensitive to outliers and extreme skewness, but is reasonably accurate for data sets that are approximately normally distributed (Ott and Longnecker, 2001). Outliers and skewness were assessed visually by examination of quantile comparison plots generated using the R statistical software package (R Development Core Team, http:\\www.r-project.org). A normally distributed data set will appear as a straight line. If the data set deviates far from this line, either by forming a more curved line (evidence of skewness) or by the presence of data points falling far from the

line (outliers), then this is evidence that the data are far from normally distributed, and the t-test is not appropriate.

One-way analysis of variance (ANOVA) was employed to compare the saturated hydraulic conductivities of the treatment groups at the beginning and end of the experiment. ANOVA relies on the comparison of the variance between treatment groups to the variance within treatment groups. The higher the ratio, the more likely that a significant difference exists between treatment groups.

Null hypothesis: K_s is the same for all treatments (H_0: $K_{sC} = K_{sT1} = K_{sT2}$)

Alternative hypothesis: K_s differs between one or more treatments.

ANOVA requires that: (1) each of the populations is approximately normally distributed, (2) each of the sets of measurements is an independent random sample from its population, and (3) the populations must have equal variances. Normality of the populations was established prior to conducting Students t-tests. Homogeneity of variance is assessed using Levine's Test:

Null hypothesis: variances are equal (H_0: $\sigma_C^2 = \sigma_{T1}^2 = \sigma_{T2}^2$)

Alternative hypothesis: variances are not all equal.

All tests were performed using the R statistical software program (R Development Core Team, http:\\www.r-project.org).

3.3 Results

3.3.1 Control

Table 3.8 and Figure 3.3 illustrate the test results for the control group. The average hydraulic conductivity for the group decreased from 84 ± 12 cm/h at the beginning of

the experiment to 60 ± 11 cm/h at the end of the experiment. Hydraulic conductivity decreased for all columns in the group.

Table 3.8: Results of saturated hydraulic conductivity tests for Control group. Average values are presented as mean ± standard deviation.

Column	Initial K_s (cm/h)	Final K_s (cm/h)	Change (cm/h)
1	76	45	-31
5	83	66	-16
7	106	55	-51
11	74	55	-18
15	86	76	-10
16	82	61	-20
Average	84 ± 12	60 ± 11	-24 ± 15

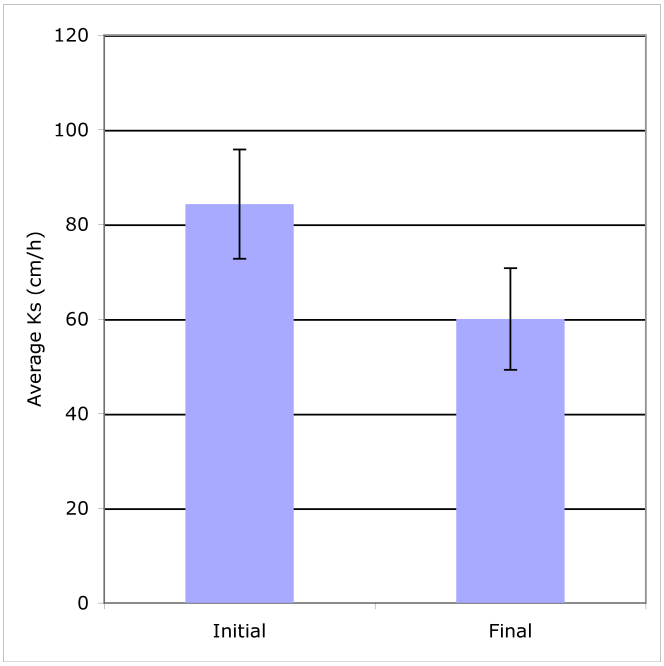


Figure 3.3: Average saturated hydraulic conductivity for Control group. Error bars indicate the standard deviation from the mean. Average initial saturated hydraulic conductivity was 84 ± 12 cm/h. Average final saturated hydraulic conductivity was 60 ± 11 cm/h.

A paired Students t-test was performed to compare the initial saturated hydraulic conductivity (K_s) to the final K_s of the Control group. Examination of the quantile-quantile plot (Figure 3.4), shows that the data does not deviate far from a normal distribution, therefore, the t-test is applicable. Results of the t-test are presented in Table 3.9. The p-value <0.05, therefore there was a significant change in K_s over time for the Control group.

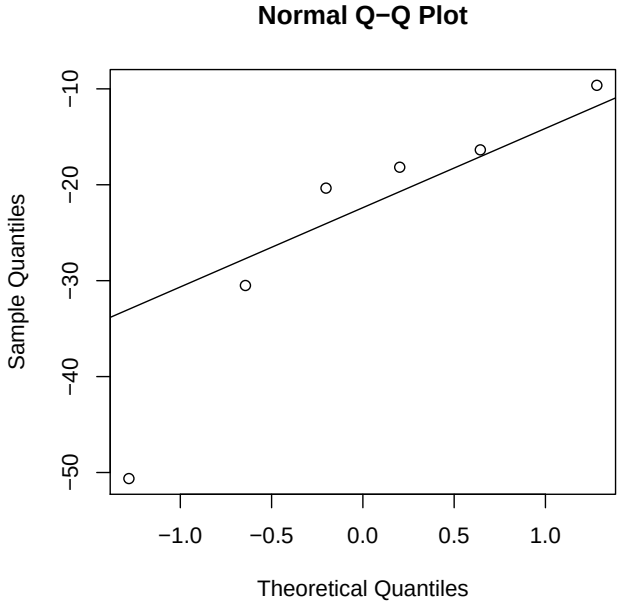


Figure 3.4: Quantile-quantile plot of Control group change. The straight line represents a normal distribution. Visual inspection of the data set suggests that the data fall closely enough to the normal line to be treated as normally distributed.

Table 3.9: Two-sided paired t-test of Control group change.

Null hypothesis	degrees of freedom	T	p-value	Confidence level	Significant?
$H_0 : K_{sfin} = K_{sinit}$	5	4.1	0.01	95%	YES

3.3.2 Treatment 1

Table 3.10 and Figure 3.5 illustrate the test results for the Treatment 1 group. The average hydraulic conductivity for the group decreased from 78 ± 14 cm/h at the beginning of the experiment to 69 ± 28 cm/h at the end of the experiment. There was a high degree of variability in the final saturated hydraulic conductivity, ranging from 34 cm/h for Column 6 to 114 cm/h for Column 2.

Table 3.10: Results of saturated hydraulic conductivity tests for Treatment 1 group. Average values are presented as mean ± standard deviation.

Column	Initial K_s (cm/h)	Final K_s (cm/h)	Change (cm/h)
2	80	114	34
6	64	34	-31
9	77	47	-31
12	80	81	1
14	103	65	-38
18	65	72	7
Average	78 ± 14	69 ± 28	-10 ± 28

Examination of the quantile-quantile plot (Figure 3.6) shows that the data set does not deviate far from a normal distribution. Therefore the t-test is applicable. Results of the t-test are presented in Table 3.11. P-value >> 0.05, therefore the null hypothesis is not rejected. The average saturated hydraulic conductivity of the T1 treatments did not significantly decrease over time.

Table 3.11: Two-sided paired t-test of Treatment 1.

Null hypothesis	degrees of freedom	T	p-value	Confidence level	Significant?
$H_0 : K_{sfin} = K_{sinit}$	5	8.2	0.45	95%	NO

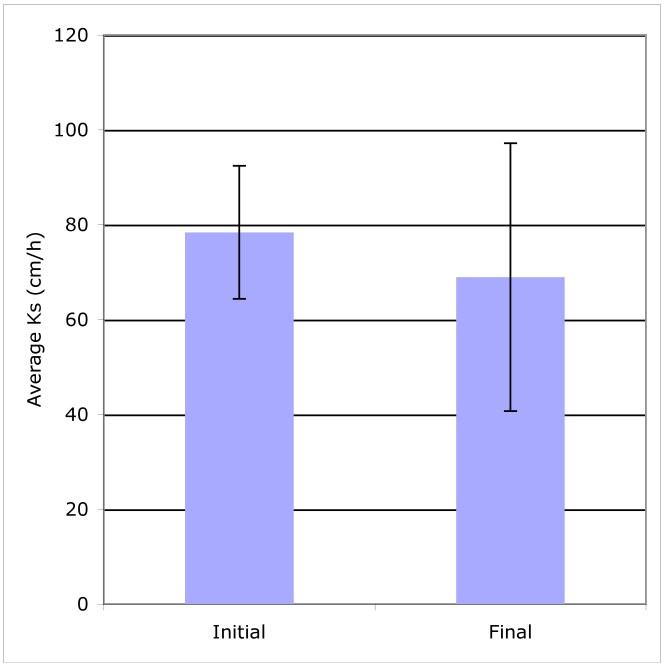


Figure 3.5: Average saturated hydraulic conductivity for Treatment 1 group. Error bars indicate the standard deviation from the mean. Average initial saturated hydraulic conductivity was 78 ± 14 cm/h. Average final saturated hydraulic conductivity was 69 ± 28 cm/h.

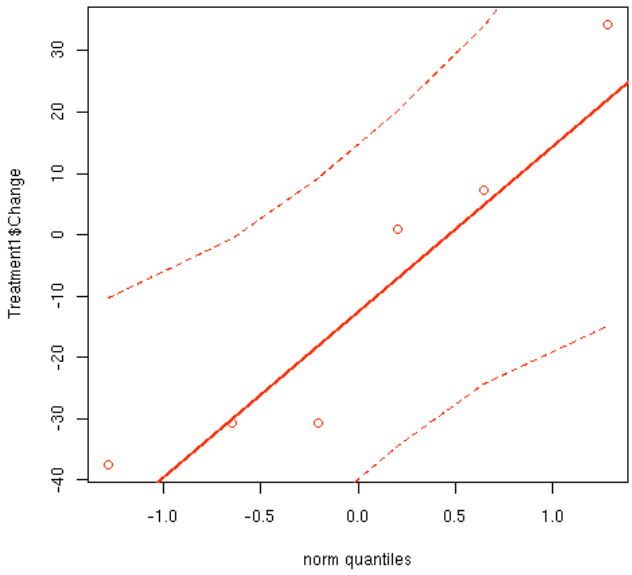


Figure 3.6: Quantile-quantile plot of Treatment 1 change. The straight line represents a normal distribution. Visual inspection of the data set suggests that the data Visual inspection of the data set suggests that the data fall closely enough to the normal line to be treated as normally distributed.

3.3.3 Treatment 2

Table 3.12 and Figure3.7 illustrate the test results for the Treatment 2 group. The average saturated hydraulic conductivity for the group decreased from 71 ± 19 cm/h at the beginning of the experiment to 61 ± 12 cm/h at the end of the experiment. There was a high degree of variability in the final hydraulic conductivity, though less than that observed in the Treatment 1 group. Final saturated hydraulic conductivity ranged from 47 cm/h for Column 17 to 80 cm/h for Column 3. Saturated hydraulic conductivity increased in three of the columns (Columns 3, 4, and 8), and decreased in three of the columns (Columns 10, 13, and 17).

Table 3.12: Results of saturated hydraulic conductivity tests for Treatment 2 group. Average values are presented as mean ± standard deviation.

Column	Initial K_s (cm/h)	Final K_s (cm/h)	Change (cm/h)
3	50	80	31
4	54	56	2
8	58	63	6
10	82	64	-18
13	92	54	-39
17	87	47	-40
Average	71 ± 19	61 ± 12	-10 ± 28

Examination of the quantile-quantile plot (Figure 3.8) shows that the data does not deviate far from normality, so the t-test is applicable. Results of the t-test are presented in Table 3.13. P-value >> 0.05, therefore there is no significant difference between initial and final average K_s for Treatment 2.

Table 3.13: Two-sided paired t-test of Treatment 2.

Null hypothesis	degrees of freedom	T	p-value	Confidence level	Significant?
$H_0 : K_{sfin} = K_{sinit}$	5	0.9	0.42	95%	NO

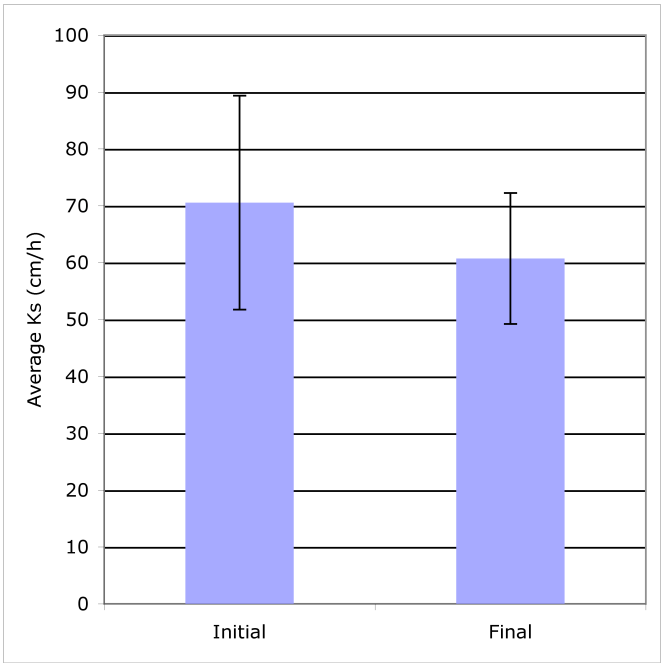


Figure 3.7: Average saturated hydraulic conductivity for Treatment 2 group. Error bars indicate the standard deviation from the mean. Average initial saturated hydraulic conductivity was 71 ± 19 cm/h. Average final saturated hydraulic conductivity was 61 ± 12 cm/h.

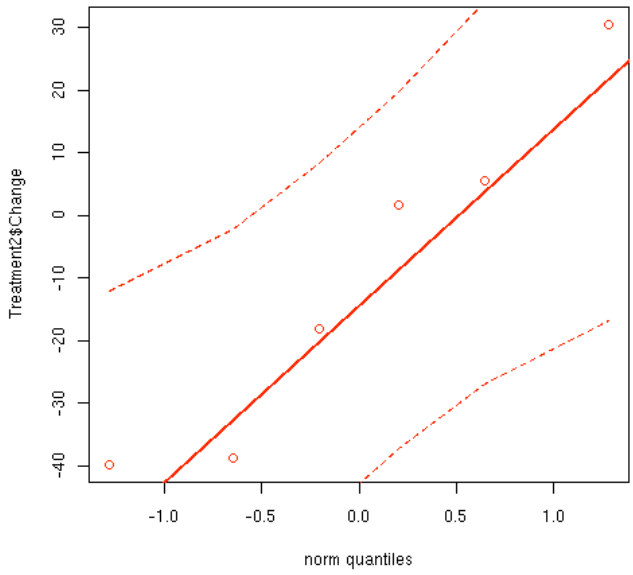


Figure 3.8: Quantile-quantile plot for Treatment 2. The straight line represents a normal distribution. Visual inspection of the data set suggests that the data Visual inspection of the data set suggests that the data fall closely enough to the normal line to be treated as normally distributed.

3.3.4 Effect of treatments

The average initial and final hydraulic conductivities were compared between treatment groups in order to discern what effect if any the addition of earthworms may have had on hydraulic conductivity. Table 3.14 shows the mean and variance of initial K_s for the treatment groups. Mean initial K_s values were similar for the three groups (Control: 84 cm/h, Treatment 1: 78 cm/h, Treatment 2: 71 cm/h). One-way analysis of variance (ANOVA) was performed to compare the initial values between treatments. As ANOVA requires that the treatment groups have homogeneity variances, Levine's test was performed to ensure the homogeneity of variances, and therefore the applicability of the ANOVA test. Results of Levine's test are presented in Table 3.15. The dataset fails Levine's test, therefore the variances are homogeneous, and the ANOVA test is applicable.

Results of the ANOVA test are presented in Table 3.16. We fail to reject the null hypothesis. Therefore, there is no significant difference among the initial saturated hydraulic conductivities of the three treatment groups. This suggests that the inclusion of a 1 cm artificial sediment layer in Treatment 2 had no measurable effect on the saturated hydraulic conductivity of the soil columns in this treatment group.

Table 3.14: Mean and variance of initial saturated hydraulic conductivity for each of the treatment groups.

Treatment	Mean K_s (cm/h)	Variance (cm^2/h^2)
Control	84	130
Treatment 1	78	200
Treatment 2	71	350

Table 3.17 shows the mean and variance of final K_s for the treatment groups. Mean final K_s values were similar for the three groups (Control: 60 cm/h, Treatment 1: 69 cm/h, Treatment 2: 61 cm/h). One-way analysis of variance (ANOVA) was performed

Table 3.15: Levine's test for homogeneity of variance for initial saturated hydraulic conductivity.

Null hypothesis	Degrees of freedom	F-value	p-value	Confidence level	Significant?
$H_0 : \sigma_C = \sigma_{T1} = \sigma_{T2}$	2	2.5	0.12	95%	NO

Table 3.16: Analysis of variance for initial saturated hydraulic conductivity.

Null hypothesis	Sum of Squares	F-value	p-value	Confidence level	Significant?
$H_0 : K_{sC} = K_{sT1} = K_{sT2}$	595.2	1.3	0.31	95%	NO

to compare the initial values between treatments. Levine's test was performed to ensure the homogeneity of variances, and therefore the applicability of the ANOVA test. Results of Levine's test are presented in Table 3.18. Visual inspection of the variance in final K_s (Table 3.17) suggest that final variances may not be homogeneous, but Levine's test yields a p-value of 0.14, which is greater than 0.05. The dataset fails Levine's test, therefore variances are homogeneous, and the ANOVA test is applicable.

Results of the ANOVA test are presented in Table 3.19. We fail to reject the null hypothesis. There is no significant difference in final saturated hydraulic conductivities between the three treatment groups. Therefore, the presence of earthworms had no measurable effect on the saturated hydraulic conductivities of the soil columns.

Table 3.17: Mean and variance of final saturated hydraulic conductivity for each of the treatment groups.

Treatment	Mean K_s (cm/h)	Variance (cm^2/h^2)
Control	60	120
Treatment 1	69	800
Treatment 2	61	130

Table 3.18: Levine's test for homogeneity of variance for final saturated hydraulic conductivity.

Null hypothesis	Degrees of freedom	F-value	p-value	Confidence level	Significant?
$H_0 : \sigma_C = \sigma_{T1} = \sigma_{T2}$	2	2.3	0.14	95%	NO

Table 3.19: Analysis of variance for final saturated hydraulic conductivity.

Null hypothesis	Sum of Squares	F-value	p-value	Confidence level	Significant?
$H_0 : K_{sC} = K_{sT1} = K_{sT2}$	303.4	0.42	0.66	95%	NO

3.3.5 Earthworm survivorship

After the completion of the final infiltration tests, the soil columns were disassembled, and earthworms were removed from the soil and tallied. Large worms were removed by sieving the soil sample through a 2 mm (#10) sieve. Hatchlings and cocoons were removed by wet sieving through a 0.6 mm (#30) sieve. Detailed tallies of the number and size of each of the earthworm types are included in Appendix F. Summaries are presented in Figures 3.9 and 3.10.

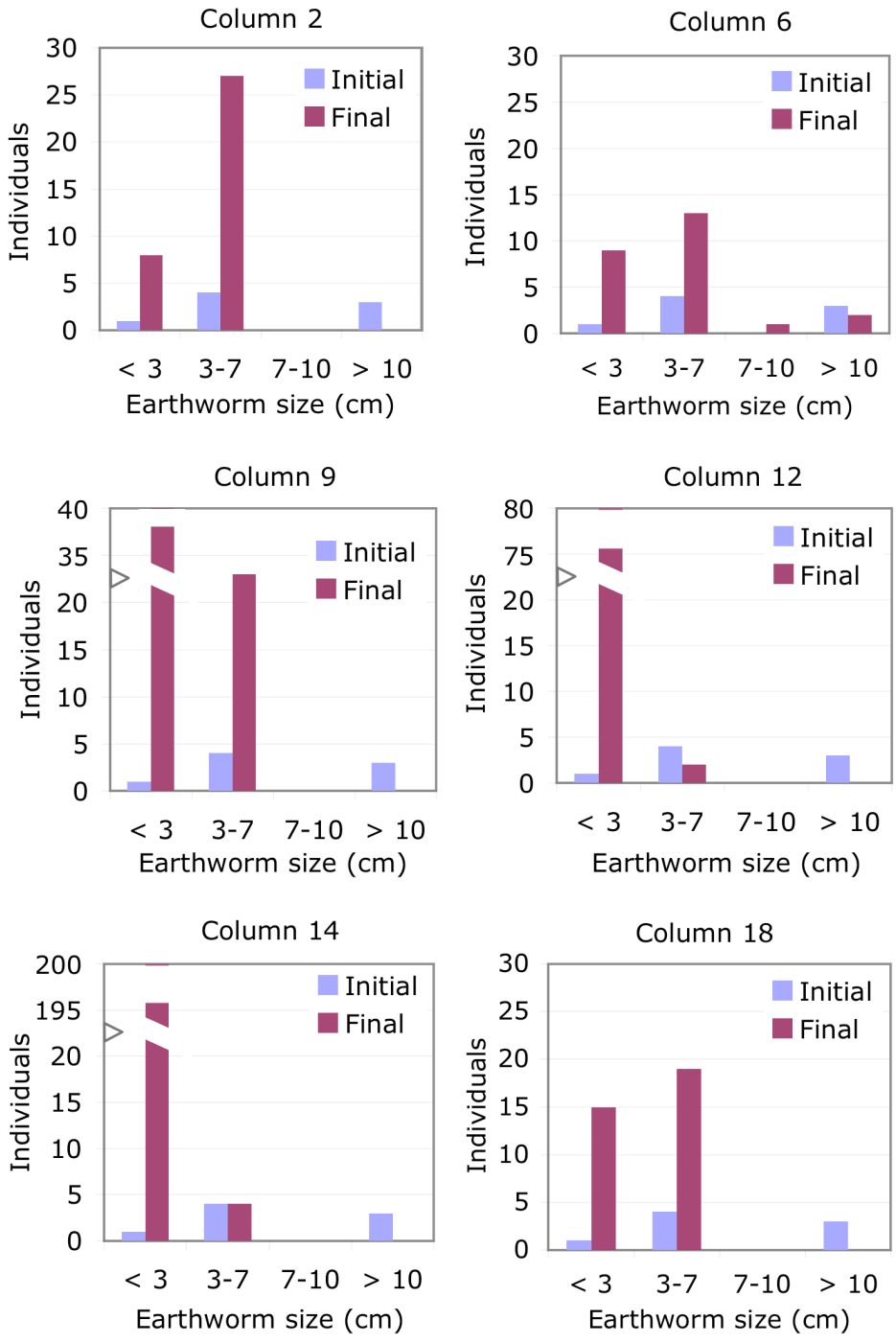


Figure 3.9: Changes in earthworm size distribution over time for Treatment 1 group.

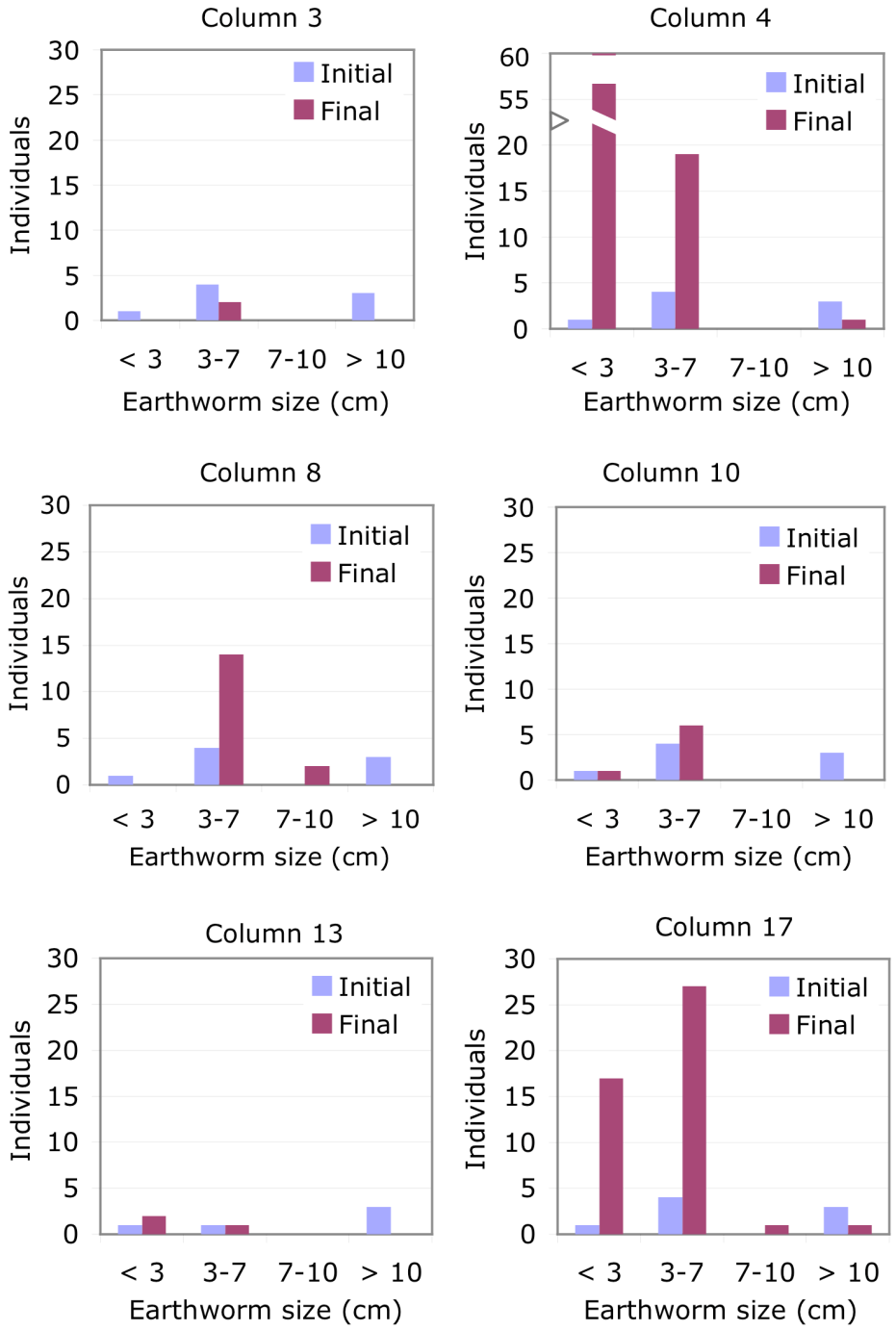


Figure 3.10: Changes in earthworm size distribution over time for Treatment 2 group.

3.4 Discussion

The only group to show a significant decrease in saturated hydraulic conductivity over the course of the experiment was the Control group, which contained no earthworms. In other words, the Control group clogged. On average, the columns with earthworms did not clog, and were able to maintain their saturated hydraulic conductivities over the course of the experiment. There was no significant difference in final saturated hydraulic conductivities between treatment groups, however. This may be explained in part by the high degree of variability in saturated hydraulic conductivity between columns where earthworms were present. Variance increased over the course of the experiment for the Treatment 1 group, but decreased for the Treatment 2 group, and stayed approximately the same for the Control group (Table 3.20). The initial and final K_s for all treatment groups is shown in Figure 3.11.

Table 3.20: Comparison of variance in initial and final saturated hydraulic conductivity among treatment groups.

Treatment	Variance in initial K_s (cm^2/h^2)	Variance in final K_s (cm^2/h^2)
Control	130	120
Treatment 1	200	800
Treatment 2	350	130

Some evidence of pore instability in the treated columns was found. The infiltration rate was observed to decrease over the course of the six-hour infiltration test for all columns, whether or not they contained earthworms (see Figure 3.12, Figure 3.13, and Figure 3.14), but the decreases were more pronounced in columns containing earthworms. The gradual decrease in infiltration rate observed in all columns has been noted by other researchers (Thompson et al., 2008), who found that sandy engineered bioretention soils were susceptible to compaction as a result of wetting and the weight of the

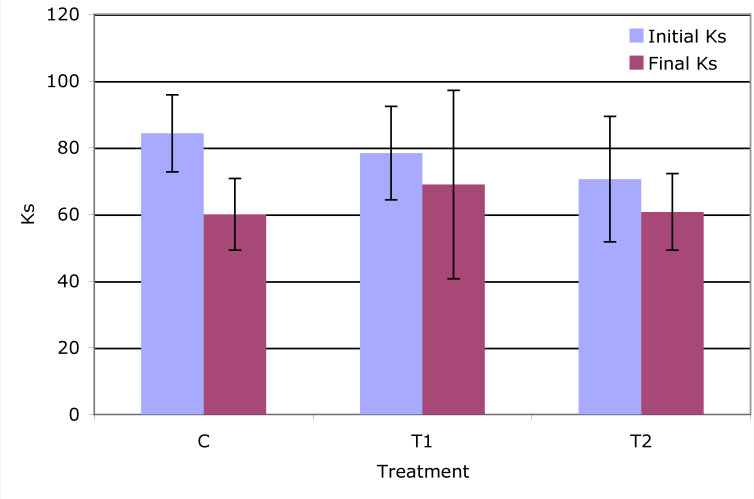


Figure 3.11: Comparison of initial and final K_s for all treatment groups. The error bars represent the standard deviation from the mean.

ponded water occurring during infiltration tests. The same effects would likely be seen during storm events, where the soil became saturated and ponded conditions developed. Indeed, Dougherty et al. (2007) observed evidence of compaction over the first six months of operation in two newly constructed rain gardens. Hillel (1998) notes that soil infiltrability generally decreases monotonically as water flows through a soil. In addition to the expected decrease due to the development of saturated conditions (resulting in a decreasing matric suction gradient), decreasing infiltrability is also sometimes attributable to the gradual deterioration of the soil structure (Hillel, 1998).

Final saturated hydraulic conductivities for all columns in the Control group were lower than initial saturated hydraulic conductivities. Final saturated hydraulic conductivities for treatment columns were more variable. Many soil columns containing earthworms showed initially high infiltration rates, which decreased dramatically over the course of the six-hour infiltration tests (Figure 3.13 and Figure 3.14). This is likely due to the gradual disintegration of surface aggregates and the collapse of biopores. The destruction of

earthworm casts on the soil surface was observed during the simulated storms, but casts quickly reappeared after storms, indicating the presence of active earthworms.

Biopores and aggregates created by earthworms may have been unstable due to several factors. Three key factors have been identified:

1. low clay content of the BSM
2. lack of fungal hyphae (oversimplification of the ecosystem), and
3. persistent wet conditions.

The BSM contained 93.2% sand, 4% silt, and only 2.8% clay (Table 3.2). Clay plays an important role in stabilizing pores and aggregates within the soil matrix. Chemical bonds between clay and organic matter are critical to binding soil aggregates together (Schrader and Zhang, 1997). According to Oades (1993), a soil must have at least 15% clay in order to form aggregates, in the absence of significant biological activity. A soil with so little clay will not be able to retain any structure created by earthworms.

In an effort to isolate the effect of earthworms on soil structure, all other biological actors were excluded from the soil columns. In sandy soils, aggregates are stabilized by plant roots, fungal hyphae, microbial colonies, and the metabolic products of plant decay (Forster, 1990). The microcosms lacked these components. Fungal hyphae play a particularly prominent role in aggregation of sand particles, which are only weakly joined by microbial colonies or their metabolic products (Six et al., 2004). Hyphae grow and form a sticky mesh around aggregates, protecting soil structure (Oades, 1993). This highlights the importance of the entire soil ecosystem in the creation and persistence of soil macropores. Earthworms can create macropores, but without the stabilizing effect of fungal hyphae, the macropores quickly collapse. Fungal hyphae are also responsible for stabilizing earthworm casts, which are weak when freshly deposited, but strengthen after

a few days, as they are colonized by fungal hyphae (Lee and Foster, 1991). The columns had relatively low organic matter, and lacked bacteria, fungal hyphae or plant roots, which would have stabilized the soil structure created by the earthworms.

The stability of earthworm casts is increased by drying (Oades, 1993). Over the course of the experiment, the columns were subjected to frequent storm events, with little opportunity for drying between storms. Drying was further impeded by the small surface area of the columns, combined with the artificial moisture barrier of the columns themselves. In a real rain garden, moisture would wick away from the rain garden into the surrounding soil. Water uptake by plants and higher evaporation due to increased sunlight and air movement would also increase drying in a field setting. Several studies have shown that fresh, moist casts are less stable than uningested soil (Barois et al., 1993; Schrader and Zhang, 1997). Casts need to dry and age in order to stabilize. In our artificially wet system, the aggregates never had the opportunity to dry out. Without clay, fungal hyphae, roots, or the opportunity to dry out, the casts and burrows formed by the earthworms were likely very unstable.

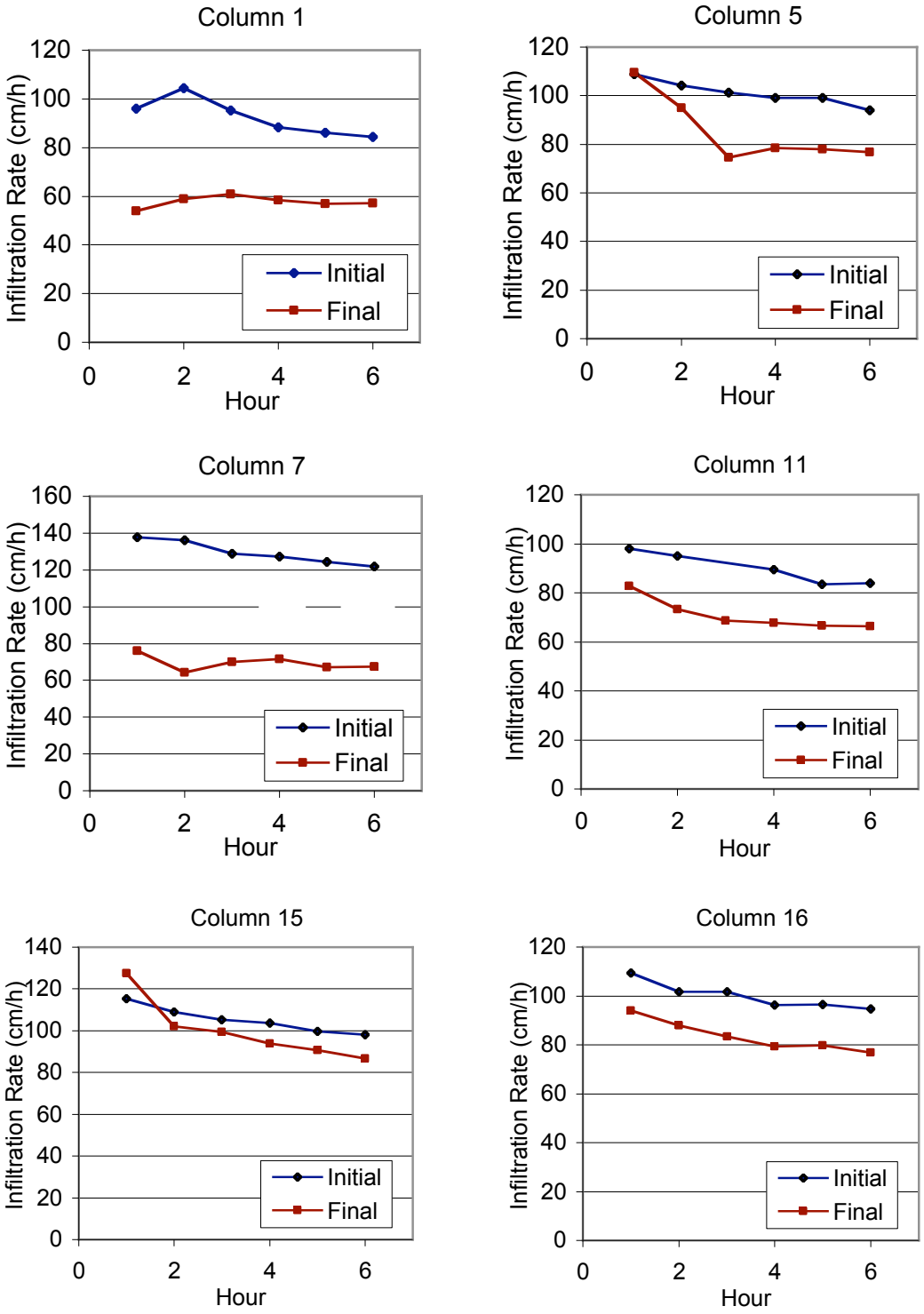


Figure 3.12: Results of initial and final infiltration tests for Control group showing declining infiltration rates over the course of the tests.

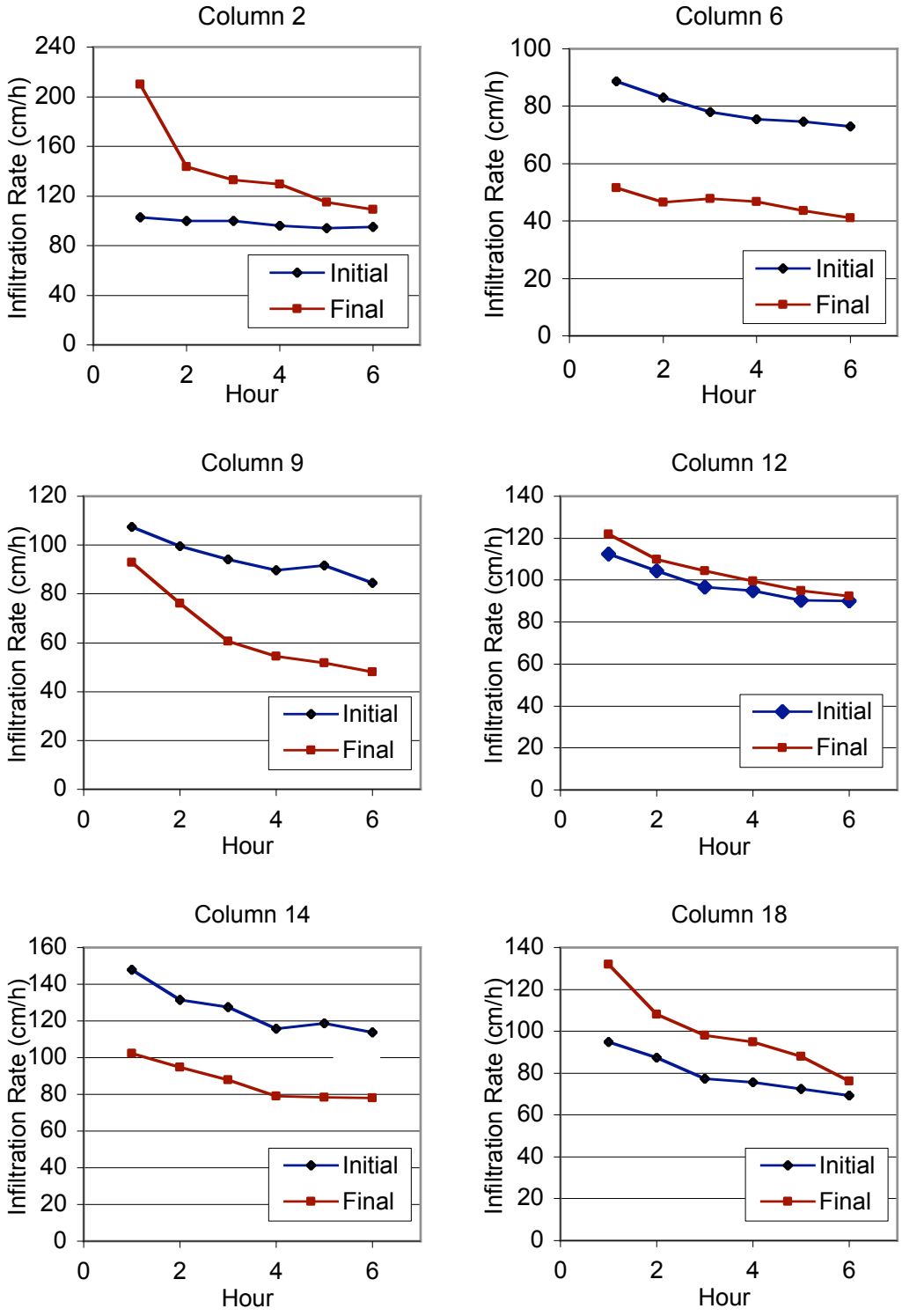


Figure 3.13: Results of initial and final infiltration tests for Treatment 1 group showing declining infiltration rates over the course of the tests.

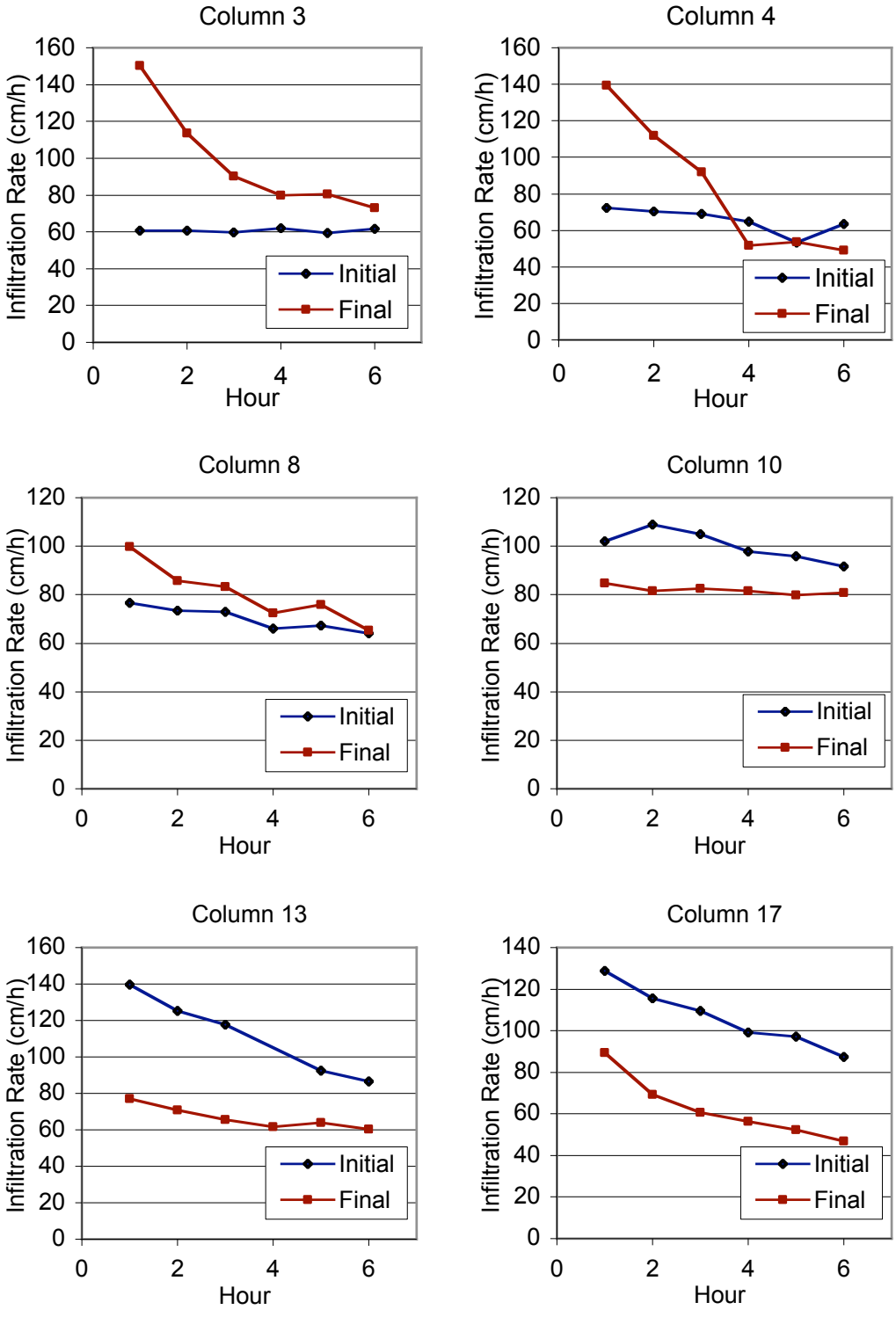


Figure 3.14: Results of initial and final infiltration tests for Treatment 2 group showing decreasing infiltration rates over the course of the tests.

3.4.1 Sources of error

Three major sources of error have been identified: (1) earthworm mortality, (2) error introduced by the initial saturated hydraulic conductivity testing schedule, and (3) insufficiently large sample size. Earthworm mortality may have been a major factor in the high variance observed between treatment columns. The final assessment of earthworm survivorship at the end of the experiment showed dramatic changes in the columns earthworm populations over the course of the experiment. Figure 3.15 compares the number of surviving earthworms to the final K_s for each column, but finds that there is no correlation between the two ($R^2 = 0$). The majority of the earthworms in the columns were immature, and quite small in size. Very small earthworms would not be expected to have any effect on hydraulic conductivity, as immature earthworms have little effect on macroporosity (Francis and Fraser, 1998).

Figure 3.16 compares the number of surviving adult *L. terrestris* to the final K_s, and finds that there is an inverse relationship ($R^2 = 0.4$). *L. terrestris* tend to construct large, deep burrows, which may have proved to be unstable, as discussed above. Another possibility is that the presence of these earthworms in their burrows impeded flow through these large biopores during storm events. These results suggest that under these experimental conditions, earthworm burrowing was as often bad for infiltration as it was good. The burrowing activity of the earthworms may have actually caused compaction in some cases. Depending on a multitude of factors which are not yet completely understood, earthworms can act as either compacting or decompacting agents in the soil system (Six et al., 2004).

Due to equipment constraints, initial infiltration tests were performed on one column at a time. The columns were constructed, and earthworms were added, on November 4,

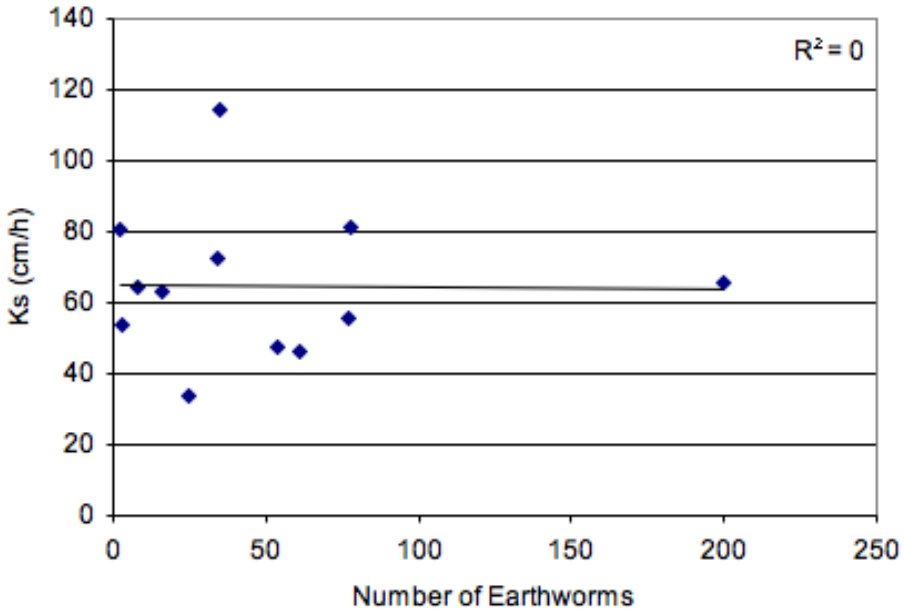


Figure 3.15: Final K_s versus total number of earthworms.

2005. The initial infiltration tests were conducted between November 6 and December 14. Final infiltration tests were performed on two columns at a time. The delay in sampling the columns in the Control and Treatment 1 groups had no effect on their measured saturated hydraulic conductivity (Figure 3.17, Figure 3.18). However, there is a significant increase in the saturated hydraulic conductivity of the Treatment 2 columns over time ($R^2 = 0.70$, as shown in Figure 3.19. This is likely due to the effect of the introduced earthworms on the sediment layer. Indeed, these figures show that the first measurement taken from the Treatment 2 group is much lower than the Control and Treatment 1 groups, but that the final measurement taken from the Treatment 2 group is similar to the Control and Treatment 1 groups. It appears that the earthworms began to substantially alter the sediment layer in the Treatment 2 columns immediately after they were introduced, even before the initial measurements were taken. Therefore, the average initial K_s for

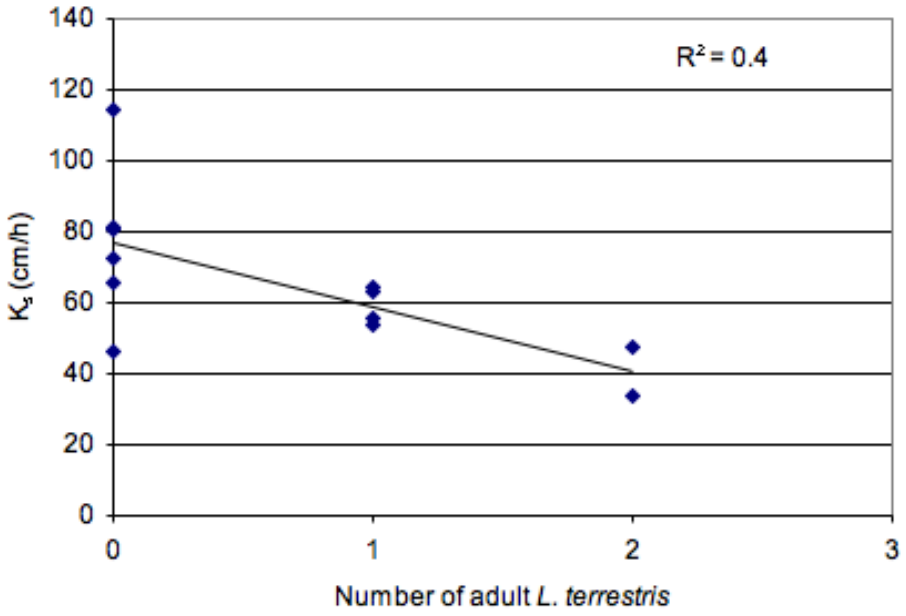


Figure 3.16: Final K_s versus number of surviving adult *L. terrestris*.

the Treatment 2 group does not accurately reflect the K_s of the columns as they were constructed, with a 1 cm sediment layer on top of the BSM. The effect of delay on the measured K_s for the final infiltration tests is harder to interpret. Figures 3.20 to 3.22 show an increase in K_s over time for the Control group, no change over time for the Treatment 1 group, and decreasing K_s over time for the Treatment 2 group. No underlying cause for these trends could be identified.

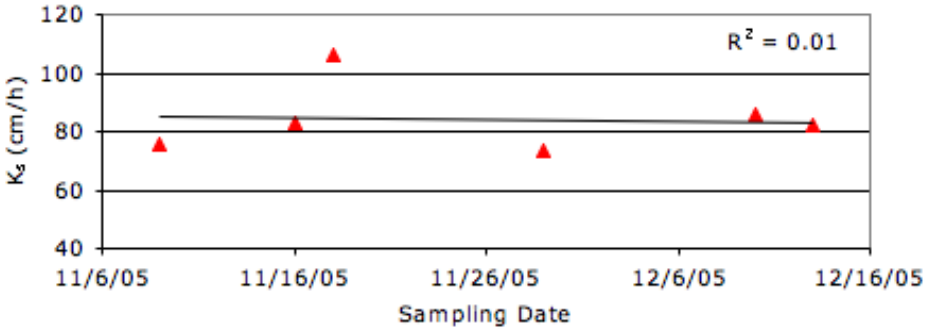


Figure 3.17: Initial K_s of Control group versus sampling date.

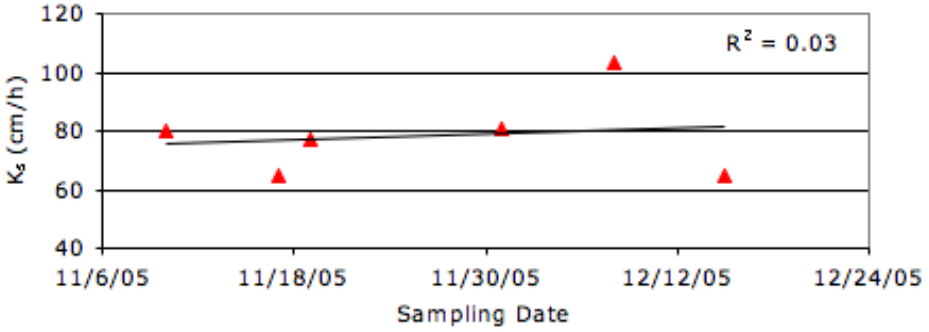


Figure 3.18: Initial K_s of Treatment 1 group versus sampling date.

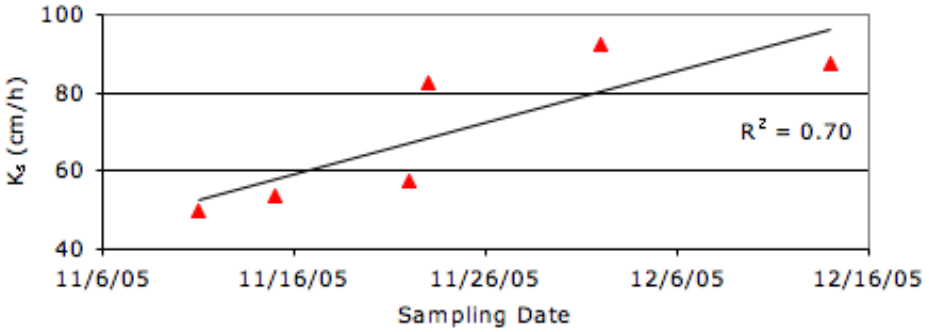


Figure 3.19: Initial K_s of Treatment 2 group versus sampling date.

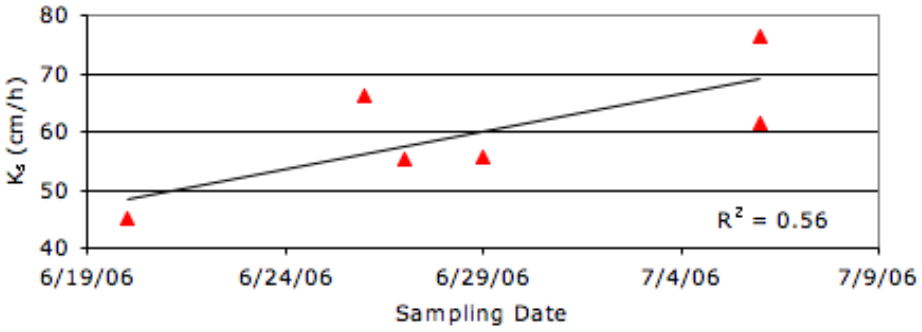


Figure 3.20: Final K_s of Control group versus sampling date.

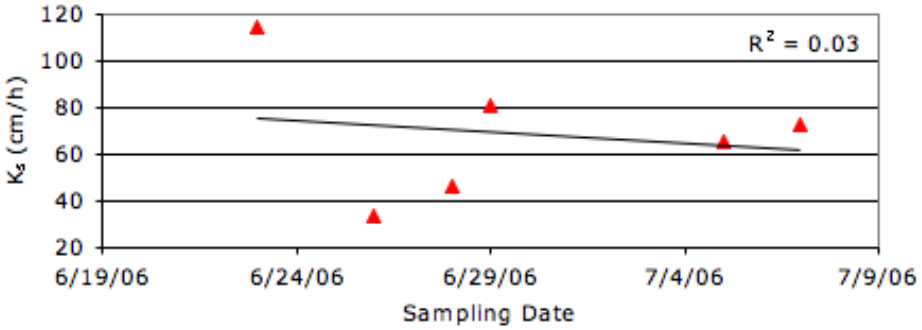


Figure 3.21: Final K_s of Treatment 1 group versus sampling date.

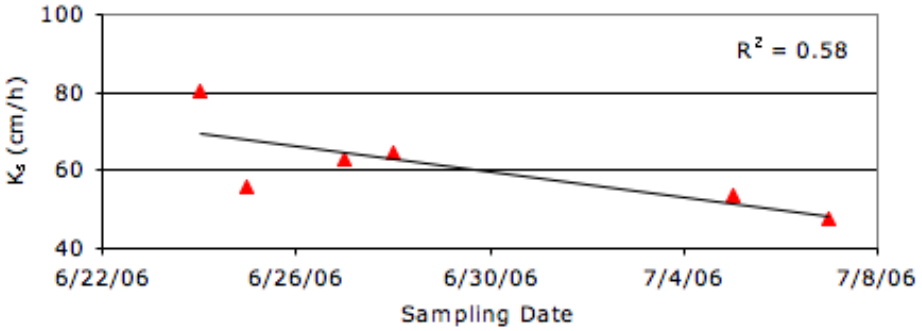


Figure 3.22: Final K_s of Treatment 2 group versus sampling date.

The analysis is significantly limited by the small number of replicates in each of the treatment groups. Given the measured variance, the sample size required to have 95% confidence that the measured sample mean equals the true population mean plus or minus 5 cm/h is calculated by applying the formula:

$$n = \frac{(1.96)^2\sigma^2}{5^2} \tag{3.6}$$

(Ott and Longnecker, 2001), where σ^2 is the highest measured variance. The variance in the measured final K_s for the Treatment 1 group was 800 cm^2/h^2. Each treatment would need to have 123 replicates in order to compensate for this high variance. In this experiment, each treatment had only six replicates. This complicates interpretation of the results, because (a) there is significant potential for error in the prediction of the true population mean, and (b) it is difficult to determine whether or not the data sets are truly normally distributed, and thus which statistical tests are appropriate.

3.4.2 Comparison to Li and Davis (2008b)

Li and Davis (2008b) conducted a column study similar in many respects to this one, but did not include earthworms in their experiment. The purpose of their study was to determine what potential incoming sediment had to clog bioretention media, and whether sediment would be deposited at the soil surface or deeper in the soil matrix. Li and Davis used bioretention soil media of very similar composition to the medium used in this study, except that their medium used mulch to provide organic matter, while this study used a combination of mulch and compost. The particle size distributions of the media are nearly identical (Table 3.21). Several storm events were simulated using a series of suspensions of varying particle size distributions. The "sand" suspension was closest to the SS used in this study (Table 3.22). The resulting changes in the columns' hydraulic conductivity

were compared. Filter cake thickness was measured as well. The researchers found that incoming sediment was primarily deposited on the soil surface, forming a cake. This cake significantly reduced the flow rate of water through the soil column. The researchers investigated the effectiveness of removal of the cake and uppermost soil layer in restoring the columns hydraulic conductivity, finding that removal could restore some but not all of the original hydraulic conductivity, and that the benefit of increasing the depth of soil removal was marginal. Table 3.23 compares Li and Davis' results to the results of the current study. Li and Davis observed a significant loss in hydraulic conductivity as a result of solids loading, as did the Control group in this experiment. The columns containing earthworms did not experience significant clogging. This suggests the potential utility of earthworms in maintaining the hydraulic conductivity of bioretention cells.

Table 3.21: Comparison of bioretention soil medium used in this study to Li and Davis (2008b).

Characteristic	Ayers	Li and Davis (2008b)
Sand (%)	93.2	96 - >98
Silt (%)	4.0	<2–4
Clay (%)	2.8	<2–4
Soil texture	Sand	Sand

Table 3.22: Comparison of simulated suspended solids used in this study to Li and Davis (2008b).

Characteristic	Ayers	Li and Davis (2008b)
Sand (%)	78.5–88.4	>99
Silt (%)	6.5–13.1	<1
Clay (%)	5.1–8.4	<1
Soil texture	Loamy Sand	Sand

Table 3.23: Comparison of experimental results with Li and Davis (2008b). Average values are reported as mean ± standard deviation.

	Control	Treatment 1	Treatment 2	Li and Davis (2008b)
initial hydraulic conductivity (cm/h)	84 ± 12	78 ± 14	71 ± 19	55
final hydraulic conductivity (cm/h)	60 ± 11	69 ± 28	61 ± 12	7
total solids loading (kg/m^2)	20.2	20.2	38.6	6.4
TSS texture	Loamy Sand	Loamy Sand	Loamy Sand	Sand
TSS loading rate (mg/L)	1,299–2,222	1,299–2,222	1,299–2,222	35–1,729

3.5 Summary

1. Soil columns without earthworms showed a significant decrease in saturated hydraulic conductivity over the course of the experiment.
2. Soil columns with earthworms did not show a significant decrease in saturated hydraulic conductivity.
3. Earthworm activity was not significantly impeded by the inclusion of an initial sediment cake at the soil surface.
4. The saturated hydraulic conductivities of soil columns with earthworms had a high variance, which may be attributable to pore instability.
5. High pore instability may be attributable to the absence of plant roots and fungal hyphae in the soil columns.
6. High earthworm mortality was observed in the soil columns.
7. Earthworm populations showed a shift from adults to hatchlings over the course of the experiment.

Chapter 4

Model

4.1 Introduction

The RAINGARDEN model was developed in order to study the influence of earthworm growth and soil organic matter on the hydraulic performance of a rain garden. Hydraulic performance is assessed in terms of soil porosity, which limits the stormwater detention capacity of the soil, and by the thickness of a surface sediment layer, which limits the available volume for detention on the rain garden surface. Factors influencing the creation, destruction, and stability of pore space are included.

Soil organic matter serves to improve the stability of pore space and as a food source for earthworms. Earthworms play a dual role, increasing pore space and reducing the thickness of the sediment layer. Storm events deposit sediment at the soil surface, and destroy soil pores. Litterfall serves as an external source of organic matter. Emphasis is given to earthworms because of their well-known roles in maintaining soil structure in agricultural and other soil types. Earthworms increase soil porosity both by the creation of macropores through their burrowing and by the aggregation of soil particles through their metabolic processes (Edwards, 1998; Lee, 1985). Ultimately, soil animals such as earthworms may be able to be used as elements of design for the ecological engineering of bioretention cells. An earlier version of the RAINGARDEN model is described in Ayers and Kangas (2004). The RAINGARDEN model is a conceptual, or synthetic model, and is intended to begin the description of mechanisms within the soil affecting system performance. The model is developed using real values from the literature and other parts

of this research, and illustrates the dynamics of soil physical parameters in response to biological activity. At this point, the model serves as a conceptual illustration of the processes believed to be at work in rain gardens. It has not been subjected to sensitivity analysis, calibration or validation.

4.1.1 The energy systems language

The energy systems language (also referred to as energy circuit language) was developed by H.T. Odum in the 1950s and 60s (Odum, 1971; Brown, 2004). It is a systematic method of creating diagrammatic models of systems, which is commonly used in the fields of ecological engineering and systems ecology. The energy systems language is used to visualize systems and to describe them mathematically. Every symbol used is mathematically defined (Figure 4.1). Drawing a diagram is equivalent to writing a set of differential equations. A system is defined, and the components of interest and the relationships between them are drawn.

The principle advantage of the energy systems approach is that the act of drawing the diagram yields a model based on fundamental physical, chemical and biological relationships between the model components. Ecosystems tend to be very complex, and thus quite difficult to study. The energy systems language forces the modeler to distill the system to its essentials, choosing only a few key variables and interactions to focus on.

The first step in the simulation is to draw a detailed energy systems diagram. A boundary is defined, delineating the system of interest. The relevant inputs, state variables and interactions are identified. The diagram then yields a set of differential equations describing the system dynamics. These equations are generated using the method described in Odum (1971).

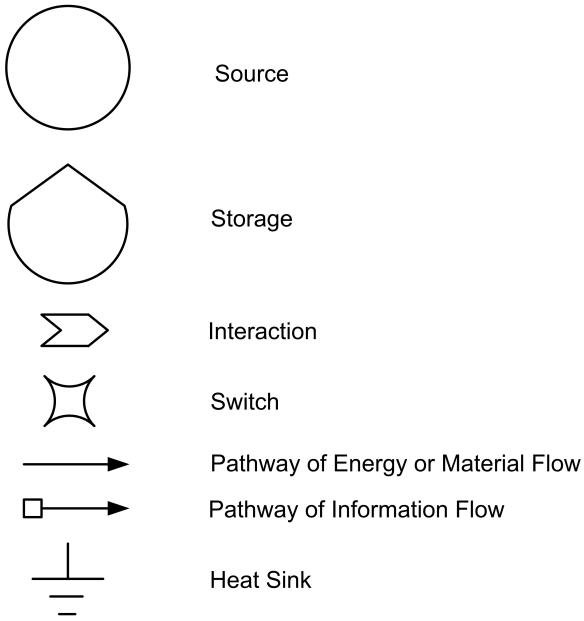


Figure 4.1: Symbols used in the energy systems language.

4.1.2 RAINGARDEN model

Sources:

L = SOM inputs from litter fall (g)

I = water flowing into raingarden (L)

D = sediment carried in by water (g)

Storages:

S = soil mass (g)

O = soil organic matter mass (g)

W = number of earthworms (individuals)

V = void space (L)

H = pore water (L)

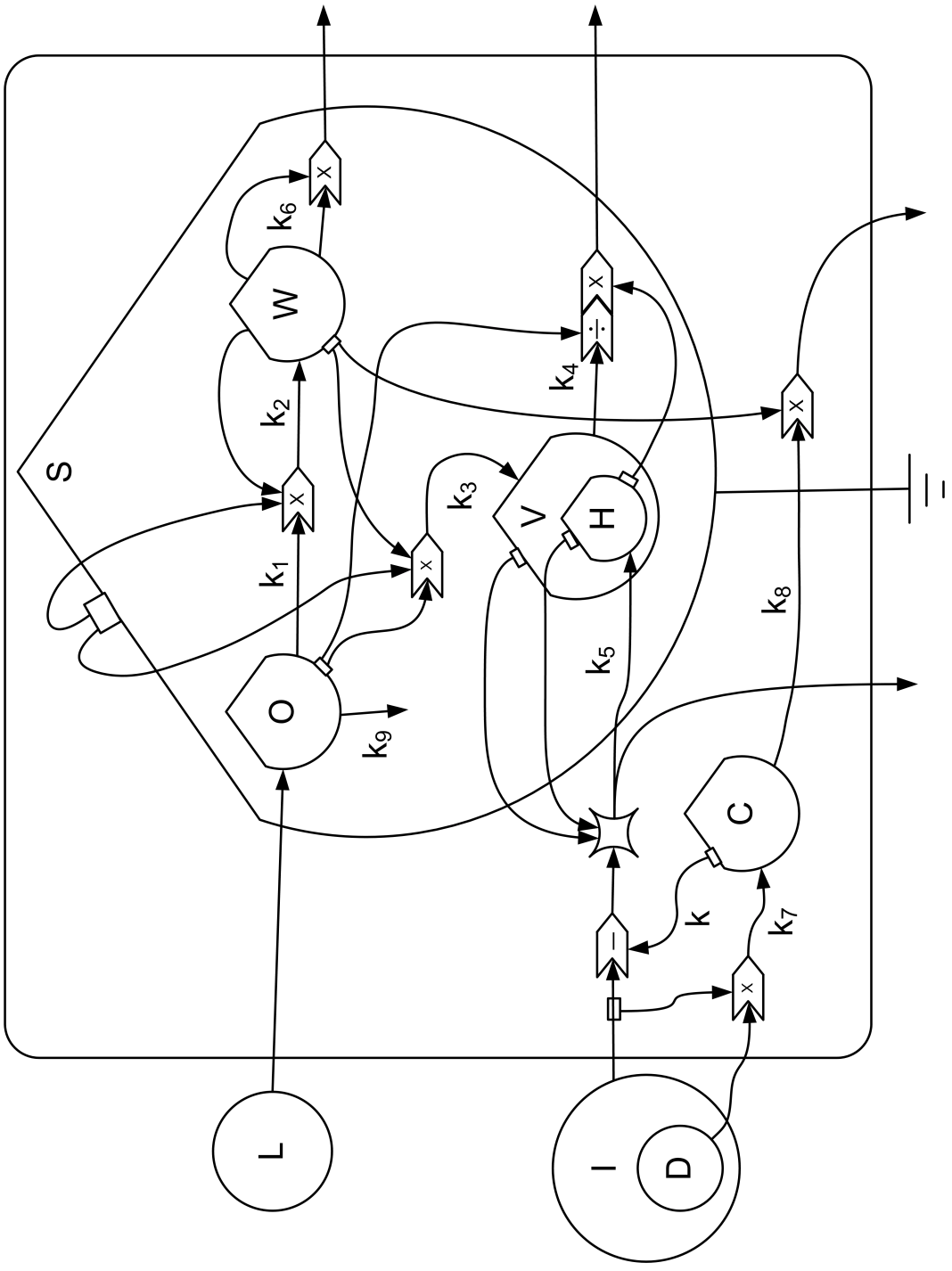


Figure 4.2: Energy systems diagram of simulation model RAINGARDEN.

C = surface crust thickness (cm)

Flows:

$J_1 = k_1 \times S \times O \times W$ = SOM consumed by earthworms (g/d)

$J_2 = k_2 \times S \times O \times W$ = worm growth (individuals/d)

$J_3 = k_6 \times W^2$ = worm death (individuals/d)

$J_4 = k_3 \times S \times O \times W$ = creation of voids due to earthworm burrowing (L/d)

$J_5 = k_4 \times \frac{H}{O}$ = loss of void space due to wetting (L/d)

J_6 = [IF V >H] I $\times$ (1-k $\times$ C) = water entering voids (L/d)

$J_7 = k_5 \times H$= water exiting voids (L/d)

$J_8 = k_7 \times I \times D$ = deposition to crust (cm/d)

$J_9 = k_8 \times C \times W$ = loss of crust due to earthworm burrowing (cm/d)

$J_{10} = k_9 \times O$ = loss of organic matter due to microbial degradation (g/d)

K through k_8 are rate constants applied to the associated flows.

Plant litter (L), is the only source of organic matter to the system. In the model, plant litter adds directly to the organic content (O) of the soil (S). Organic matter is lost through consumption by earthworms (W) and decay. The earthworm population increases through consumption of organic matter, and decreases by death. The rate of organic matter consumption by earthworms is dependent on the earthworm population, and is therefore represented by a feedback loop. The rate of earthworm death is proportional to the square of the earthworm population, producing logistic decay. This simplification of the rain garden ecosystem is necessary in order to produce a model of manageable complexity. In reality, plant litter (L) would create an organic layer at the soil surface, which would then eventually be decomposed by soil animals and incorporated into the

soil matrix, gradually increasing organic matter (O). In addition, earthworms (W) are assumed to use soil organic matter (O) as a food source. This is also a simplification of a complex process, in which earthworms of different ecotypes feed on different substances in different regions of the soil. For example, anecic species, such as *L. terrestris*, ingest plant litter from the soil surface, but only digest the bacteria living on the litter, not the plant material itself. Chapter 1 discusses these processes in greater detail.

The primary factor of interest in the model is the ability of the rain garden to store runoff (I) during storm events, and to discharge this stored runoff into the groundwater between storm events. This capacity is a function of the available pore space (V), and of the thickness of the surface crust (C). In this model, the surface crust limits storage capacity by decreasing the ponding volume available. The effects of the surface crust and changing soil porosity on the rate of stormwater infiltration into the rain garden are not included in the model. The amount of water that can be held within the soil (H) is limited to the available pore space, minus the amount of water exfiltrated from the system. The available pore space is a function of organic matter and earthworm population, and is limited to the soil volume (S). Pore space is lost as a result of wetting, but this loss is retarded by the stabilizing effect of the organic matter. Surface crust grows as a result of the deposition of suspended solids (D), and is destroyed by bioturbation by earthworms. The model does not capture all processes at work within the soil, but does illustrate some key relationships, and highlights the critical role of the soil biology in the maintenance of the systems hydraulic performance.

The energy systems diagram shown in Figure 4.2 was converted to a set of differential equations using the method described in Odum (1971):

$$\frac{dO}{dt} = L - k_1 SOW - k_9 O \tag{4.1}$$

$$\frac{dW}{dt} = k_2 SOW - k_6 W^2 \tag{4.2}$$

$$\frac{dV}{dt} = k_3 SOW - k_4 \frac{H}{O} \tag{4.3}$$

$$\frac{dH}{dt} = IF(I(1-kC) > (V - H + k_5 H))THEN(V - H + k_5 H)ELSE(I(1-kC)) \tag{4.4}$$

$$\frac{dC}{dt} = k_7 ID - k_8 CW \tag{4.5}$$

Where O = soil organic matter content, expressed as total mass,

L = litterfall

S = soil volume,

W = total mass of earthworms in soil,

V = total volume of soil void space (porosity),

H = total volume of water held in soil pores,

C = thickness of surface crust (clogging layer),

I = inflow into raingarden (vol), and

D = suspended solids carried in inflow.

A computer model was constructed to solve this set of equations numerically using STELLA^{TM}software (version 5.1.1, High Performance Systems, Inc., Hanover, New Hampshire). Numerical values for the model inputs, flows and storages were obtained from a wide array of sources, including published papers and, where appropriate, values obtained from the field study that is a part of this research. In particular, the soil organic matter content and earthworm population values were derived directly from the average values for all of the field sites, and the exfiltration rate was derived from the hydraulic conductivity of the columns in the microcosm experiment. Detailed derivations of these values are included in Appendix G. The values are given in Table 4.1. These values were then used to calculate the coefficients in Equations 4.1 to 4.5. These are given in Table 4.2. For the purpose of the calculation of coefficients, an assumption was made that the model was at a steady state in which all state variables remained constant. Each model run was continued for 1500 days, with the model iterating once per day. The initial values for the model runs were the values listed in Table 4.1 except where otherwise noted. A runoff hydrograph (I) was derived from precipitation data taken from a NOAA weather station in Beltsville, MD (NCDC, 2008) using the SCS Method (McCuen, 2005). The calculation is included in Appendix G.

Table 4.1: Numerical values for the inputs, state variables, and flows in the RAINGARDEN model. Detailed derivations appear in Appendix G.

Parameter	Description	Value	Source
L	SOM inputs due to litter fall and root decay	2.05 g/m^2/d	steady state assumption
I	water flowing into rain garden	0.162 m^3	(McCuen, 2005)
D	sediment carried in by water	8.9 x 10^{-3} cm/m^3	(Li and Davis, 2008b)
S	soil volume	1 m^3	assumed
O	soil organic matter mass	9.15 x 10^4 g	field study
W	number of earthworms	310.7 individuals	field study
V	void space	0.5 m^3	(Brady and Weil, 2002)
H	pore water	0.08 m^3	(Brady and Weil, 2002)
C	surface crust thickness	0.4 cm	(Li, 2007)
J_1	SOM consumed by earthworms	2.05 g/d	(Binet and Trehen, 1992; Satchell, 1967)
J_2	worm growth rate	0.38 individuals/d	(Lakhani and Satchell, 1970)
J_3	worm death	0.38 individuals/d	steady state assumption
J_4	creation of voids due to earthworm burrowing	3.915 x 10^{-4} m^3/d	(Bastardie et al., 2003; Guild, 1955)
J_5	loss of void space due to wetting	3.915 x 10^{-4} m^3/d	steady state assumption
J_6	water entering voids	0.158 m^3/d	assumed
J_7	water exiting voids	2.45 m^3/d	microcosm experiment
J_8	deposition to crust	3.46 x 10^{-4} cm/d	(Li and Davis, 2008b)
J_9	loss of crust due to earthworm burrowing	3.46 x 10^{-4} cm/d	steady state assumption
J_{10}	rate of microbial decay of OM	0 g/d	assumed

Table 4.2: Values of coefficients in model equations.

Coefficient	Value	units
k	6.60 x 10^{-2}	cm^{-1}
k_1	7.21 x 10^{-8}	$m^{-3}ind^{-1}d^{-1}$
k_2	1.34 x 10^{-8}	$m^{-3}g^{-1}d^{-1}$
k_3	1.38 x 10^{-11}	$g^{-1}ind^{-1}d^{-1}$
k_4	447.78	gd^{-1}
k_5	30.625	d^{-1}
k_6	3.94 x 10^{-6}	$ind^{-1}d^{-1}$
k_7	0.24	$m^{-3}d^{-1}$
k_8	2.78 x 10^{-6}	$ind^{-1}d^{-1}$
k_9	0	d^{-1}

4.2 Results and Discussion

4.2.1 Model run 1: organic matter (O) and earthworms (W) held constant

Earthworm population and soil organic matter are held constant in the steady state scenario. Crust thickness gradually decreases as a result of earthworm activity, despite intermittent inputs of suspended solids (Figure 4.3). Figure 4.4 shows void space gradually increasing over time, as earthworms burrow within the soil, and the soil organic matter preserves this structure. During storm events in which the runoff volume exceeds the empty pore space in the soil, only a portion of the inflowing water is stored as pore water within the void space. The excess can be assumed to be discharged through an overflow.

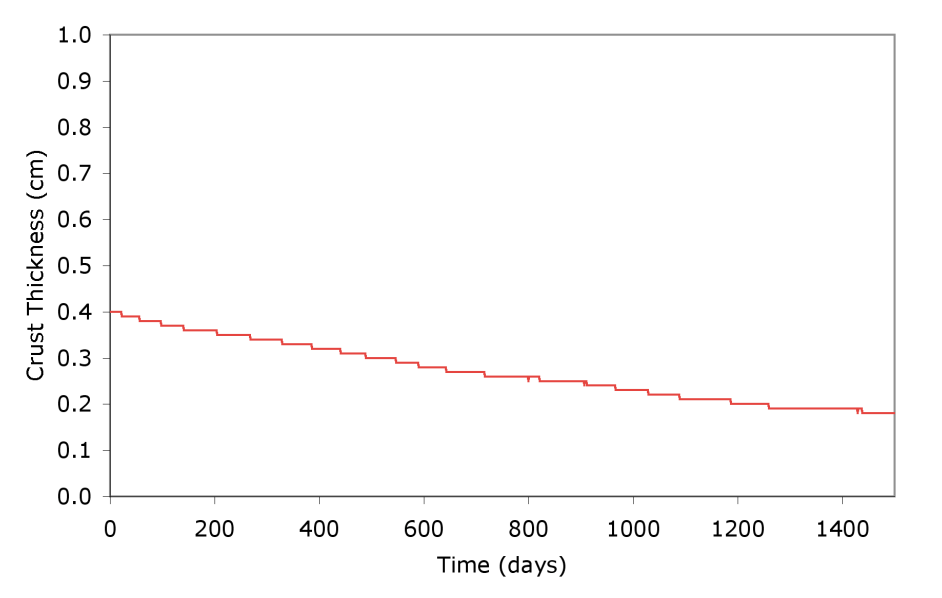


Figure 4.3: Standard run: crust thickness (C) over 1500 days.

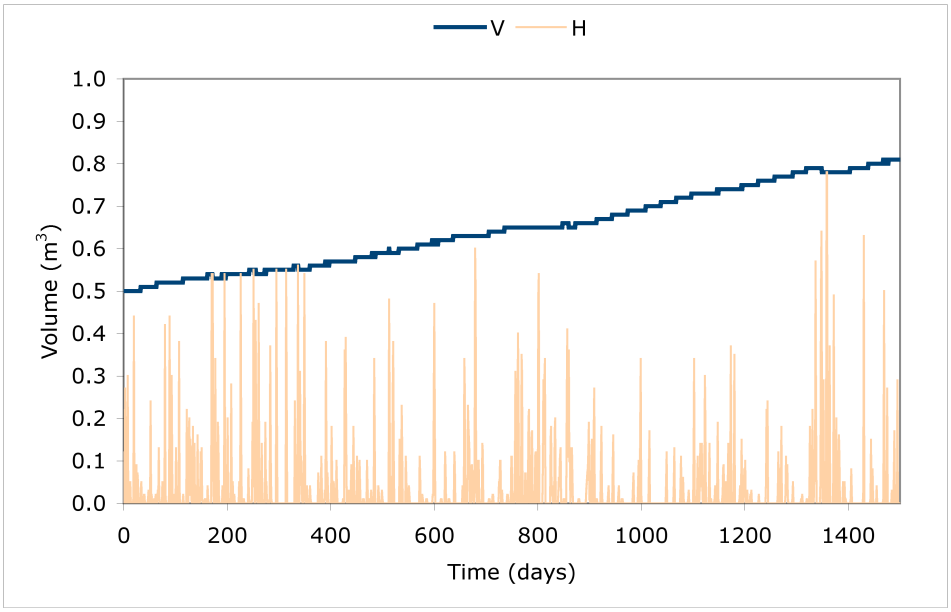


Figure 4.4: Standard run: void space (V) and pore water (H) over 1500 days.

4.2.2 Model run 2: no earthworms (W = 0)

A model run with the initial earthworm population set to zero illustrates the beneficial effect of earthworms within the system. Results are presented graphically in Figure 4.5, Figure 4.6, and Figure 4.7. Organic matter increases linearly, as it has a constant input of plant litter, but no source of decay. Void space is gradually lost in spite of the added stability provided by increased organic matter, since there are no earthworms to regenerate lost void space. Crust thickness increases with each storm event. This simulation makes clear the critical role of earthworms in the maintenance of a rain garden's hydraulic performance.

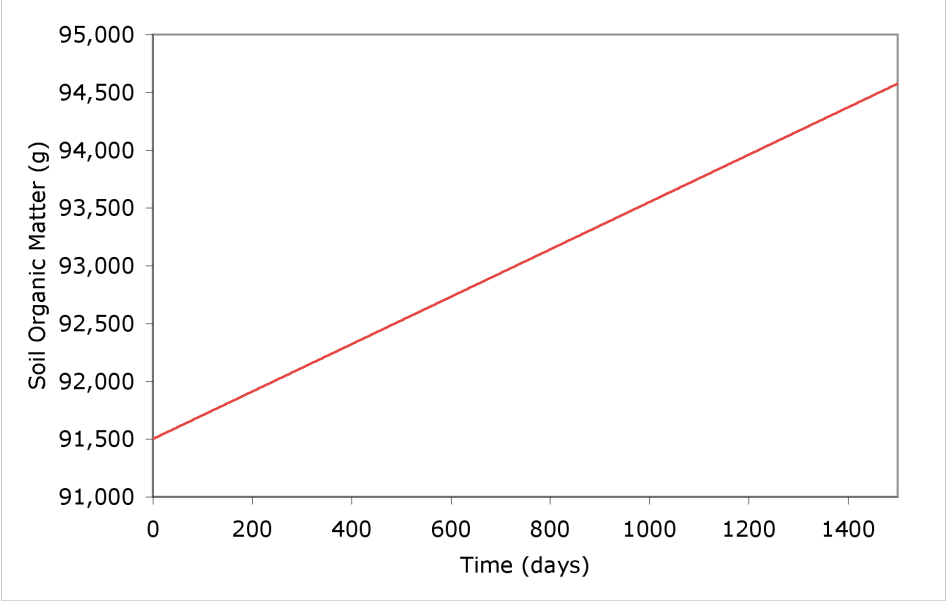


Figure 4.5: Soil organic matter (O) in a system without earthworms over 1500 days.

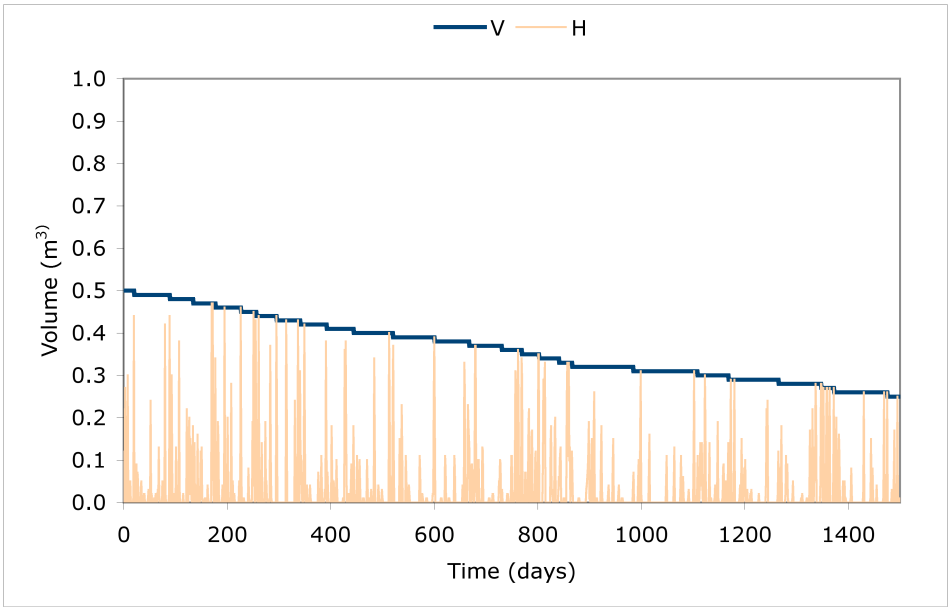


Figure 4.6: Pore space (V) and pore water (H) in a system without earthworms over 1500 days.

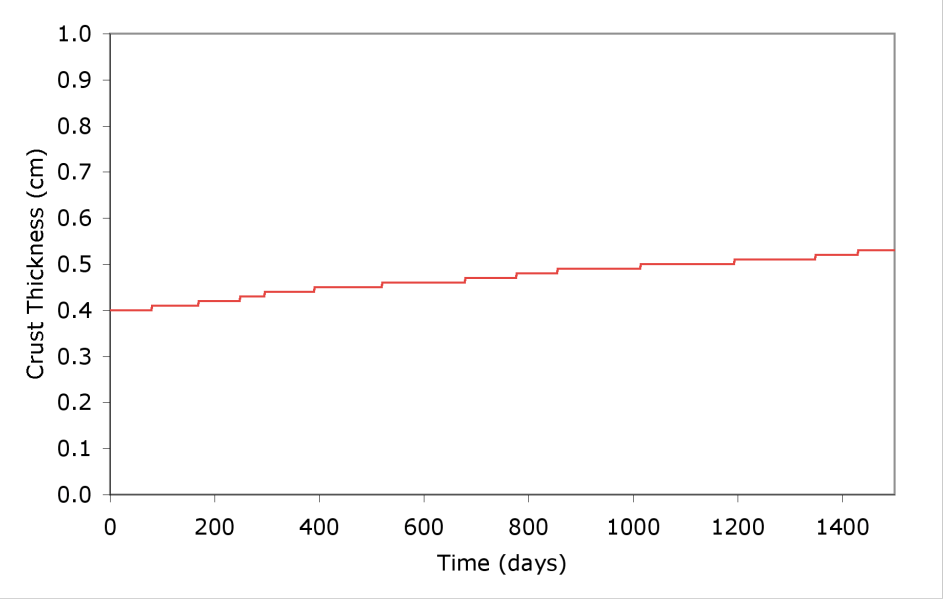


Figure 4.7: Crust thickness (C) in a system without earthworms over 1500 days.

4.2.3 Model run 3: less cohesive organic matter (increased k_4 from 448.35 to 5,000)

Organic matter also plays an important role in the maintenance of soil porosity. The cohesiveness of organic matter, represented in the model by the inverse of the k_4 constant, is primarily responsible for the resistance of void space to deterioration by inflowing stormwater. When k_4 is increased, void space rapidly deteriorates (Figure 4.8). This situation is similar to that observed in the microcosm study of Chapter 3, in which biopores created by earthworms collapsed as a result of wetting during the final infiltration tests.

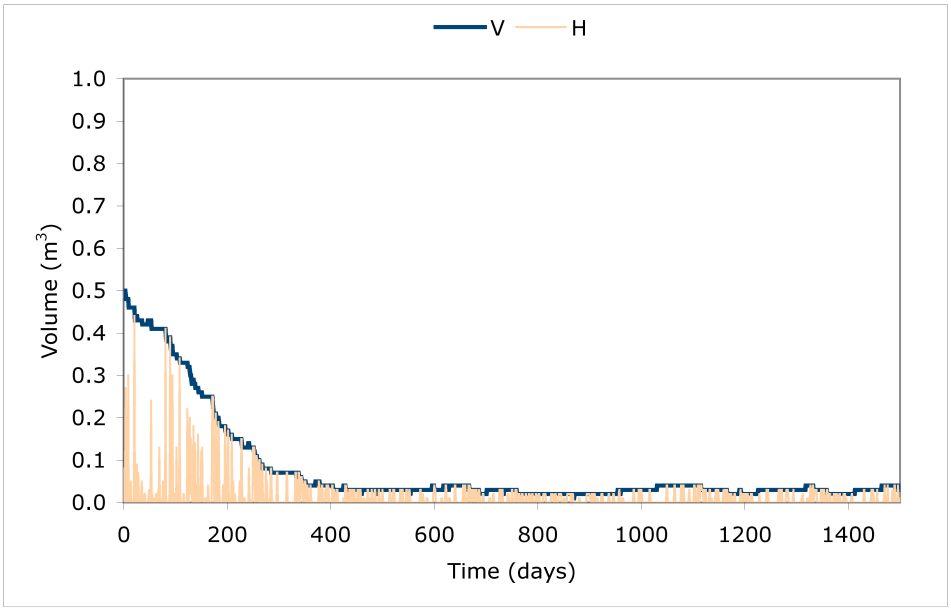


Figure 4.8: Loss of porosity (V) over 1500 days in a system where organic matter is less cohesive.

4.3 Summary

These model runs illustrate the role that earthworms and soil organic matter may play in the maintenance of the hydraulic function of the rain garden. In the model, earthworms prevent the formation of a surface crust that would inhibit infiltration, and burrow through the soil, creating void space, which is stabilized by soil organic matter. In the future, the model will be rigorously tested and validated.

Chapter 5

Conclusions

This research is the first to describe the ecosystems that are present in rain gardens. Because the designers of rain gardens usually conceive of them primarily as physical and chemical systems for the retention, infiltration and removal of pollutants from stormwater, little consideration is given to the biological system. Bacteria are assumed to be important to the degradation of pollutants, but the role of higher plants and animals has not been sufficiently explored. The field study reveals a robust invertebrate community within the soil. Earthworms were found at all sites, and representatives of twelve other invertebrate taxa were observed.

Rain gardens were found to undergo pedogenesis, changing their soil structure and composition in response to increasing biological activity. In the first years after construction, the uppermost soil layer begins to become enriched with organic matter, plant roots, and soil organisms. The soil profile develops a characteristic pattern of decreasing biological activity with depth. This pattern is an emergent property of rain garden soils, resulting from the cumulative effects of lower level processes, such as the metabolic activities of earthworms and other invertebrates. In this way, rain gardens self-organize from a planted depression filled with a simple mixture of topsoil, sand and mulch or compost into a complex soil ecosystem.

The field sites surveyed showed no signs of clogging due to the trapping of suspended solids carried in stormwater runoff. Some evidence was found of higher than expected

infiltration rates at the field sites, which may be attributable to the effects of bioturbation and of the formation of a granular soil structure.

Earthworms act to regenerate soil porosity and bury deposited sediment between storms. This "ecological service" is crucial to the sustained performance of a rain garden over its operational life. It is critical, however, to recognize that earthworms do not and cannot act in isolation. Many different components of the rain garden ecosystem work together to sustain the earthworm population and to stabilize the biopores and aggregates that earthworms create. The microcosm experiment found that earthworms were able to maintain the infiltration rate of a soil column subjected to simulated storms over a six-month period. Soil columns lacking earthworms showed decreased infiltration rates after six months. However, the variance of the final infiltration rate measurement of the treatment groups was much higher than that of the control group, suggesting that the effects of earthworms operating in isolation could be unpredictable. Without fungal hyphae or plant roots to stabilize the structure created by the earthworms, pores were vulnerable to collapse during storm events.

Shedding light on the complex web of relationships between a rain garden's physical and biological systems is the central theme of this study. Some, though by no means all, of these relationships were identified in Figure 1.3. The simulation model explores the relationships between five of these factors in detail (see Figure 5.1). Data taken from the field and microcosm studies were used in conjunction with data from the literature to create a simplified but realistic representation of the way in which earthworms and soil organic matter work together to maintain a rain garden's soil structure. In the model, litterfall serves as the direct source of organic matter to the soil. Organic matter acts both as a food source for earthworms and as a stabilizer, limiting the destructive effect of

storms on soil porosity. Earthworms increase soil porosity and decrease the thickness of the surface crust of solids deposited during storm events. Model runs illustrate the importance of earthworms and organic matter in the prevention of clogging in rain gardens.

Li and Davis (2008b) conducted a field observation of a rain garden in Washington DC. They measured the total suspended solids (TSS) loading to the rain garden over several storm events, and calculated that the rain garden would likely clog after 1 to 2 years. However, while the researchers observed a small surface layer of sediment at the entrance zone of the rain garden, they did not observe widespread clogging of the media during their 1.5-year monitoring period. The authors speculate that the vegetation and fauna present at the site may play a role in preventing the development of a sediment layer at the soil surface. Similar conditions were observed at the rain gardens evaluated in the current study. The only site observed to have a surface sediment layer was UMCP, the youngest. This layer was not produced by sediment carried in by runoff, but rather by deposition during one very large storm event, in which a creek adjacent to the rain garden overtopped the facility, depositing a large quantity of sediment. The soil surfaces of the other nine sites did not have apparent surface sediment layers. The surfaces of most were covered with a layer of mulch or plant litter. In the rare instances where the surface of the soil was bare, there was no pronounced difference in soil texture between the soil surface and deeper soil layers. Thus, this study lends support to Li and Davis suggestion that biological activity in rain gardens may play a critical role in the prevention of clogging by incoming sediment.

In summary, this study finds that:

1. Biological activity is ubiquitous in rain gardens.

2. Rain gardens develop a characteristic soil profile of exponentially decreasing biological activity with depth.

3. No evidence of clogging due to normal operation was found.

4. Earthworms may prevent clogging caused by trapped solids.

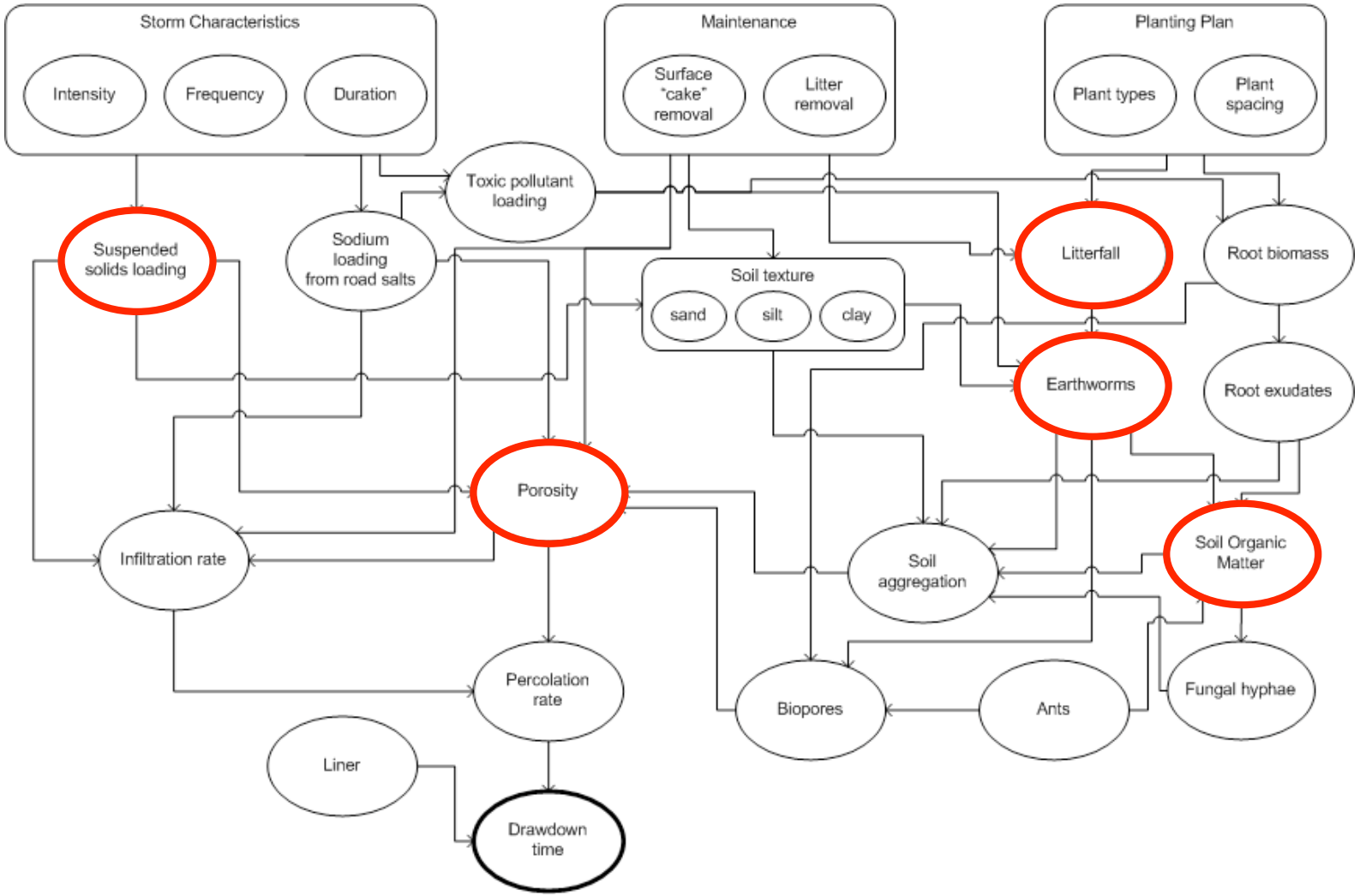


Figure 5.1: Factors influencing the drawdown time of a rain garden, with emphasis on those factors included in the simulation model.

5.1 Implications for Rain Garden Design

This study has yielded an improved understanding of and appreciation for the living organisms present in rain gardens. This new knowledge gives rise to several recommendations for rain garden design and maintenance. These recommendations will improve the value of rain gardens as habitat for desirable organisms, and exploit the innate abilities of the natural system to improve rain garden performance.

5.1.1 Design with self-organization in mind

Rain gardens are living systems, and their capacity to self-organize in response to external forces must be taken into account in their design. Designers often fail to anticipate the changes that will be brought about by the activities of the organisms that will colonize the system. These changes include bioturbation and the enrichment of the soil with organic matter. The trajectory of pedogenesis within rain gardens is of inherent interest to engineers, who must anticipate how structures they design will perform throughout their operational lives. Changes in the soil structure and composition may impact infiltration rates and pollutant removal performance. For example, the gradual formation of a granular soil structure in the topsoil may lead to increasing infiltration rates. The enrichment of the soil with organic matter may improve pollutant removal. On the other hand, earthworm burrowing and plant root growth may create undesirable preferential flow paths that hamper the pollutant removal performance of the rain garden.

5.1.2 Limit pesticide use in the rain garden and its watershed

Earthworms are very susceptible to pesticides, as are other soil animals. These animals are critical to the soil development. Each soil organism plays a role in the complex

conversion of plant detritus into humus. Soil animals colonizing the rain garden are valuable, and care must be taken to avoid harming them. Pesticide use in the rain garden and its watershed should be strictly controlled. Nonetheless, on occasion a particularly destructive "pest" will invade the system, and may destroy more rain garden plants than is desirable. In such a case, it would be preferable to use a targeted approach, such as Integrated Pest Management, rather than a broad-spectrum insecticide, in order to limit the impact on more desirable species.

5.1.3 Avoid disturbance of topsoil and mulch

The field surveys revealed that the majority of the biological activity occurring in the rain garden occurs at the soil surface. This is where the soil organisms break down the litter layer at the soil surface and incorporate it into the soil matrix. If a rain garden becomes clogged, the temptation will be to remove the mulch and upper soil layers. Disturbance of these layers will destroy the soil ecosystem, along with its beneficial effects. All of the soil structure that has developed, as well as all of the highly decomposed humic material with which the soil has been enriched, and which has a high cation exchange capacity, and therefore very high affinity for most pollutants found in stormwater, is removed. Therefore care should be taken to avoid disturbance of the soil unless absolutely necessary. Mulch may be added, but decayed mulch should not be removed. The same natural processes that create and maintain soil porosity in natural soils are at work in rain garden soils. With proper management, these processes can be exploited to maintain the infiltration rate of the rain garden over the long term.

5.1.4 Limit the sand content of the Bioretention Soil Medium (BSM)

In designing bioretention cells, it is tempting to use a very high sand content, in order to maximize the infiltration rate of the soil mix. The need to balance the intrinsic permeability of sand with the superior pollutant removal capacity of clay and organic matter has been recognized by other researchers (Hsieh and Davis, 2005a). Very sandy soils create additional problems for rain garden biota. Sand does not hold water or nutrients well, and can create an inhospitable environment for rain garden plants and soil animals. In particular, earthworms can find sand to be a difficult medium in which to thrive. The microcosm experiment revealed another potential pitfall of using too much sand: sand does not hold a macropore structure very well, which limits the infiltration rate of the soil to the permeability of the medium. Earthworms and plant roots may create pores, but in an unstable soil, this structure will be destroyed every time it rains. In fact, the microcosm experiment results suggest that burrowing of anecic species in very sandy soils might actually promote compaction, as their burrows may be unstable if the soil lacks sufficient clay. There is a potential for these burrows to be stabilized by a well-developed network of fungal hyphae, but further research will need to be done to support this hypothesis. The microcosm experiment suggests that the sand content of the current specification may be too high to take full advantage of the macropore-creating ability of resident earthworms. It is interesting to note that all of the sites surveyed appeared to be in good working order, though the infiltration rate was measured directly at only three of ten sites. The soil texture at these sites varied greatly. If further investigation reveals that the older sites, which contain much higher clay contents, function as well as the newer, sandier rain gardens, then this would suggest that the soil structure created by the soil organisms may indeed play a critical role in the promotion of infiltration in rain gardens. If a robust soil

ecosystem can create a stable, granular soil structure that infiltrates well, then this may permit use of a soil with a higher clay content, which may enhance pollutant removal.

5.1.5 Consider seeding rain gardens with earthworms

Given the importance of earthworms to the maintenance of hydraulic conductivity in rain gardens, it may be worthwhile to consider introducing earthworms into the system during construction. However, the appropriate earthworm species are not easily available commercially. Earthworms used in vermiculture, *Eisenia fetida*, are a surface dwelling, endogeic species, and do not burrow into the soil. They are therefore not appropriate to this application. Earthworms used as fishing bait are relatively easy to obtain in season, but are of mixed species. Canadian night crawlers, *Lumbricus terrestris*, are harvested in the wild. European night crawlers, *Eisenia hortensis*, and African night crawlers, *Eudrilus eugeniae*, are farmed, and are becoming increasingly popular as fishing bait. All three are non-native species, though *Lumbricus terrestris* is ubiquitous in many parts of the United States. It is generally best to avoid introducing non-native species where possible to avoid unintentionally introducing invasive pests.

A better approach might be to inoculate a newly constructed rain garden with a small amount of topsoil collected from a nearby habitat. This soil would contain representatives of the local earthworm population, as well as other invertebrates, bacteria, fungi, and the seeds of local plants, all of which are beneficial to the rain garden. The soil should be collected from a habitat similar to a rain garden, such as a meadow or abandoned lot, or from another rain garden in the vicinity. The soil should be transferred immediately from the source habitat to the rain garden, to minimize invertebrate mortality due to

dessication, and should be installed intact. A small amount of soil, perhaps one to three cubic feet, would likely be sufficient to inoculate a typical rain garden.

5.1.6 Consider seeding rain gardens with mycorrhizal fungi

This study theorizes that mycorrhizal fungi play a critical role in the stabilization of soil pores and aggregates. They form a fine, sticky mesh that spreads throughout the soil, holding soil particles in place. This role has not yet been observed or quantified in rain gardens, but is well known in other soil systems. Mycorrhizal fungi inoculants are available commercially from a number of mail-order suppliers, and are commonly used to improve plant growth. Inoculating rain gardens with mycorrhizal fungi during construction may improve soil permeability by stabilizing the soil structure, and improve plant establishment at the same time.

5.1.7 Plant densely

A wide variety of planting schemes have been employed in rain gardens. Some are planted with a dense cover of native, fast-growing annuals, and others are planted in a more ornamental fashion, with isolated shrubs surrounded by mulch. Plant roots create biopores, oxygenate the soil, provide a food source, exude sticky substances that bind soil aggregates, and provide microsites for bacterial degradation of pollutants. Therefore, rain gardens can be expected to perform best when densely rather than sparsely planted. In addition, densely planted native annuals will ensure a steady supply of plant litter, the primary food source for the soil ecosystem.

5.1.8 Mow to encourage high productivity

Over time, rain gardens can be expected to undergo succession, where fast-growing annuals are gradually overtaken by slower-growing perennials. Fast-growing plants offer a number of advantages to the rain garden designer. Their high productivity means higher root growth, higher plant litter deposition, and faster take-up of nutrients carried into the rain garden in stormwater runoff. In order to maintain this early successional stage, rain gardens should be mowed periodically. Mowing will kill slow growing perennials, and will stimulate the growth of fast growing annuals.

5.2 Suggestions for future research

This research represents a major step in opening the "black box" which is the rain garden ecosystem. Completing this picture, and gaining an understanding of precisely how this ecosystem affects rain garden performance are tasks that must be left to future researchers. Biological activity can be expected to affect both hydrologic function and pollutant removal. The effects of management strategies, such as mowing, pesticide application, and mulch replacement, on the rain garden ecosystem should be explored. The types of plants used in rain gardens may affect their performance. Planting the rain garden with highly productive early successional species may help to establish a highly productive ecosystem, in which take-up of nutrients and creation of biopores and soil organic matter are maximized. Some of the rain gardens installed at the University of Maryland are instrumented in such a way as to allow detailed analysis of hydraulic and pollutant removal performance, and could be useful in assessing the affects of biological activity.

Comprehensive measurements of the infiltration rates of a great number of established rain gardens would be of great value in understanding their performance over the

long term. The instrument most commonly used to measure infiltration, the double ring infiltrometer, is not well-suited for use at these sites. The double ring infiltrometer is designed for use on agricultural fields, where thick roots are rare. Rain gardens are full of thick roots, especially when they are planted with shrubs and perennials. The use of an alternative technique not requiring disturbance of the soil might prove more successful.

The role of fungal hyphae in the stabilization of soil structure should be explored. The microcosm experiment could be repeated, this time including fungi.

Design experiments based on the variance measured in this study. When this research was initiated, very little was known about the variability of different parameters within or among rain gardens. Now that some of these values have been measured, it is possible to calculate the number of samples and/or replicates that would be required to obtain statistically significant measurements.

Examine the potential negative impacts of the use of sodium chloride deicers in the rain garden watershed. Sodium chloride is known negative impacts on terrestrial and freshwater ecosystems (Ramakrishna and Viraraghavan, 2005). The capture of sodium ions in the rain garden soil may have destructive effects, including the dispersal of soil aggregates, and toxicity to plants and animals.

Most of the testing of rain gardens has been performed on the east coast of the United States. Rain garden performance should be tested in other areas of the country and the world. Differences in soil properties, particularly the presence of expansive clays, may require design modifications.

A note of caution. When exploring the role of ecological factors in the performance of a system, it is tempting to take a reductionist approach, attempting to measure the impact of each component individually. Scientists and engineers seek linear, causal rela-

tionships that are quantifiable and predictable. Unfortunately, this approach often fails when applied to ecological systems, where components interact synergistically, and the whole is something more than the sum of its parts. Even this study fell into this trap in attempting to isolate the effect of earthworms on infiltration rates in the microcosm study described in Chapter 3. In the microcosm study, the earthworms created pores, but lacked the support system they would have had in a natural ecosystem. In a natural soil, the pores would have been stabilized by fungal hyphae and the soil would have been glued together by organic matter. A more robust microcosm experiment would contain a soil ecosystem of sufficient complexity to reflect the behavior of the system. This is part of a major question in ecology, namely how to capture the richness and complexity of an ecosystem in a controlled laboratory setting.

Engineering a living system is a challenging task, requiring an understanding of both the physical requirements to be met and the ways in which the system will behave and evolve over time. This study is an attempt to integrate ecology and soil science with civil engineering. Rain gardens are a new kind of ecosystem, and are not yet well understood. Revealing the functioning of the rain garden ecosystem will necessarily be an iterative process, with each new discovery raising new questions.

Appendix A

Additional Background on Field Sites

A.1 University of Maryland (UMCP)

Address: University of Maryland, College Park, MD 20742

Data source: UMCP Department of Facilities Planning

Table A.1: UMCP Bioretention Specification

Bioretention soil mix	50% sand 30% topsoil, sandy loam or finer 20% shredded 2x hardwood mulch
mulch depth	3 inches
underdrains	6" perforated pipe
cell dimensions	3,000 sf
drainage area	not available
ponding depth	not available
soil depth	not available

Table A.2: UMCP Planting Plan

Trees	*Betula nigra* (river birch)
Shrubs	*Aronia arbutifolia* (red chokeberry)
Herbaceous	*Eupatorium fistulosum* (joe pye weed) *Lobelia siphilitica* 'blue selection' (blue lobelia) *Aster novae-angeliae* (New England aster) *Solidago rugosa* (goldenrod)

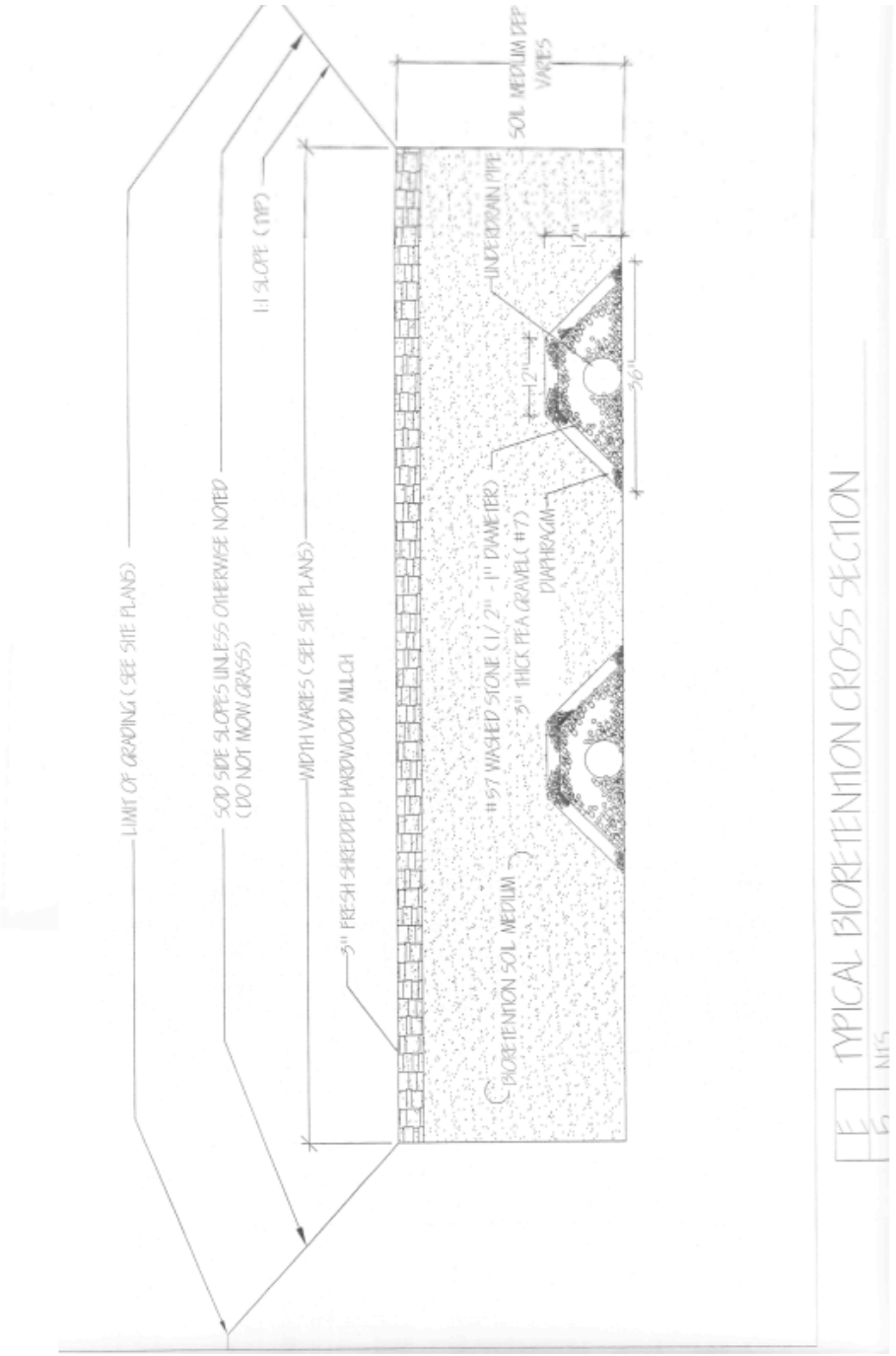


Figure A.1: UMCP construction detail (Source: UMCP Department of Facilities Planning).

A.1.1 Washington Navy Yard (WNY)

Address: 1014 N Street, SE, Washington, DC 20374

Data Source: The Low Impact Development Center Inc.

Table A.3: WNY Bioretention Specification

Bioretention soil mix	50% sand, conforming to ASTM c144-97 30% topsoil conforming to ASTM D5268-92, modified, clay content less than 10%, organic content less than 20% 20% shredded 2x hardwood mulch
soil depth	not available
ponding depth	not available
mulch depth	3 inches
underdrains	4" perforated pipe
cell dimensions	225 sf
drainage area	0.32 ac

Table A.4: WNY Planting Plan

Trees	not available
Shrubs	not available
Herbaceous	not available

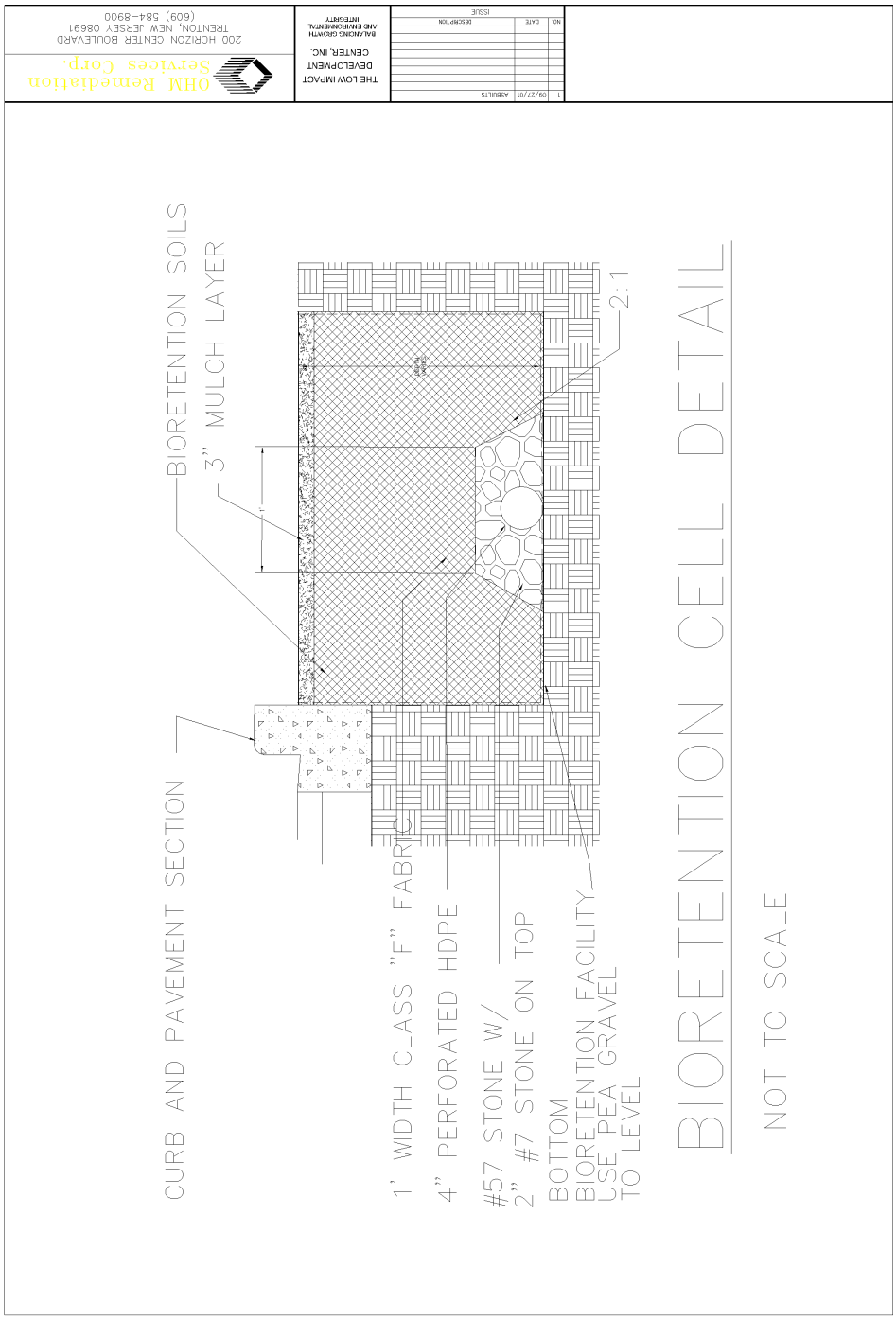


Figure A.2: WNY construction detail (Source: The Low Impact Development Center Inc.).

A.1.2 Mary Harris "Mother" Jones Elementary School (MJES)

Address: 2405 Tecumseh Street, Adelphi, MD 20783

Data Source: Prince George's County Department of Environmental Resources (DER) (PGCO, 2004b)

Table A.5: MJES Bioretention Specification

Bioretention soil mix	50% sand 25% topsoil 25% compost
soil depth	1.5 ft, with 1.5 ft stone retention area underneath
ponding depth	6 inches
mulch depth	3 inches
underdrains	6" perforated pipe
cell dimensions	800 sf
drainage area	not available

Table A.6: MJES Planting Plan

Trees	not available
Shrubs	not available
Herbaceous	not available

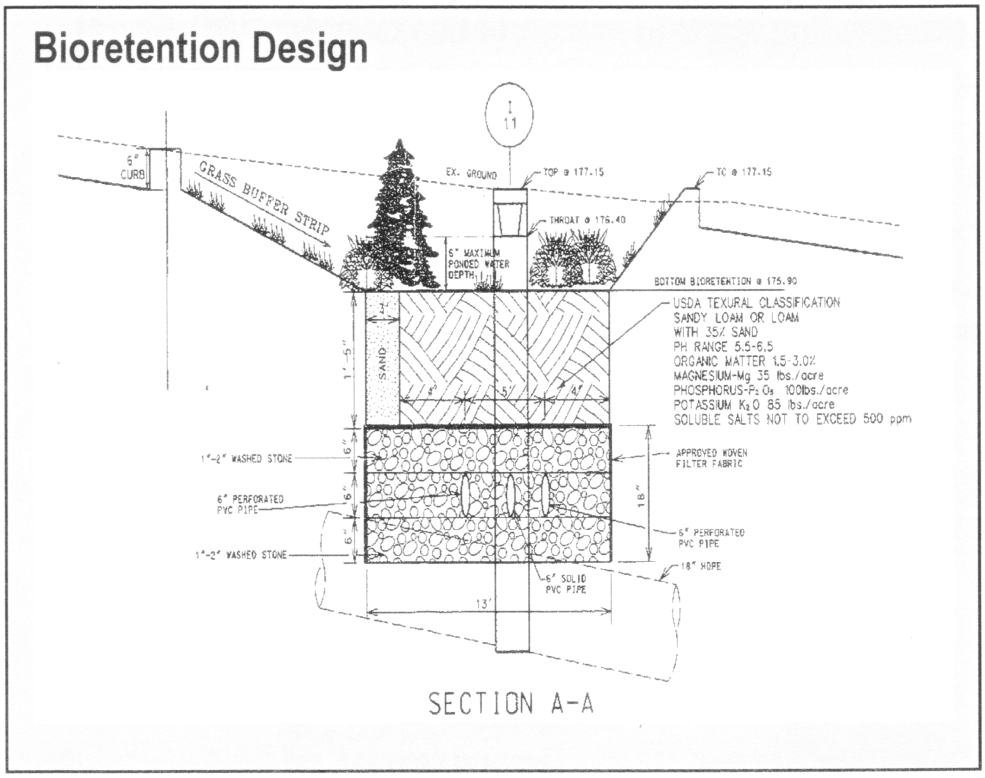


Figure A.3: MJES construction detail (PGCO, 2004b).

A.1.3 Chesapeake Bay Foundation Headquarters (CBF)

Address: Philip Merrill Environmental Center, 6 Herndon Avenue, Annapolis, MD 21403

No information available

A.1.4 Northwestern High School (NWHS)

Address: 7000 Adelphi Road, Hyattsville, MD 20782

Data Sources: Prince George's County DER (PGCO, 2004c), construction plans obtained from Prince George's County Schools, Hyattsville, MD

Table A.7: NWHS Bioretention Specification

Bioretention soil mix	50% sand 25% topsoil (35–60% sand, 30–55% silt, 5–10% clay) 25% compost
soil depth	2.6 ft
ponding depth	5 inches
mulch depth	3 inches
underdrains	6" perforated pipe
cell area	4040 sf
drainage area	3.17 acres, mostly paved

Table A.8: NWHS Planting Plan

Trees	*Quercus palustris* (pin oak) *Acer rubrum* (red maple) *Koelreuteria paniculata* (golden rain tree)
Shrubs	*Ilex glabra* 'Shamrock' (inkberry 'Shamrock') *Fothergilla gardenii* (Fothergilla) *Aesculus parviflora* (Bottlebrush buckeye) *Ilex verticillata* 'Sparkleberry' (winterberry 'Sparkleberry')
Herbaceous	*Hemerocallis sp.* (Hyperion daylily) *Iris kaempfera* (Japanese bearded iris) *Liatris spicata* (Blazing star) *Vernonia noveboracensis* (New York ironweed) *Lobelia cardinalis* (Cardinal flower) *Saccharrum ravenne* (Plume grass) *Narcissus sp.* 'Mount Hood' (Mount Hood daffodils) *Aster novae-angliae* (New England aster) *Verbena hastata* (Blue vervain) *Eupatorium dubium* (Joe pye weed) *Rudbeckia* 'Goldsurm' (Black-eyed susan) *Kosteletzkya virginica* (Seashore mallow) *Pennisetum alopecuroides* (Fountain grass)

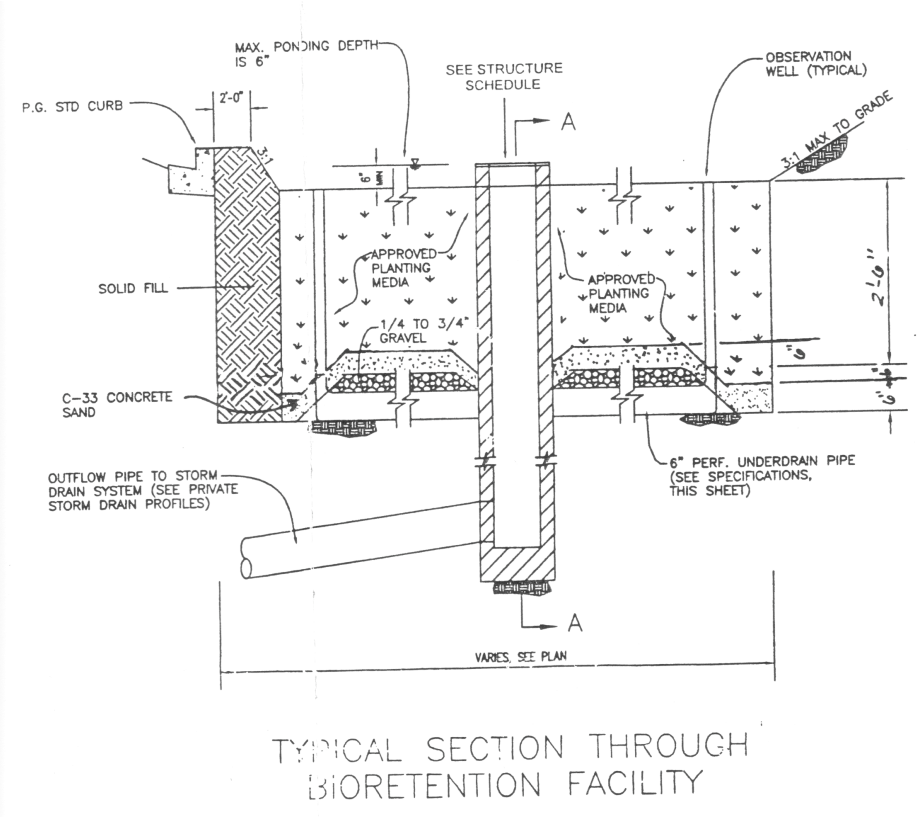


Figure A.4: NWHS construction detail (Source: Prince George's County Schools)

A.1.5 Inglewood Center III (PP)

Address: 9400 Peppercorn Place, Upper Marlboro, MD 20774

Data Sources: Prince George's County DER (PGCO, 2004a)

Table A.9: PP Bioretention Specification

Bioretention soil mix	70% sand 30% compost
soil depth	2 ft over 1 ft stone retention area
ponding depth	6 inches
mulch depth	3 inches
underdrains	not available
cell area	324 sf
drainage area	not available

Table A.10: PP Planting Plan

Trees	not available
Shrubs	not available
Herbaceous	not available

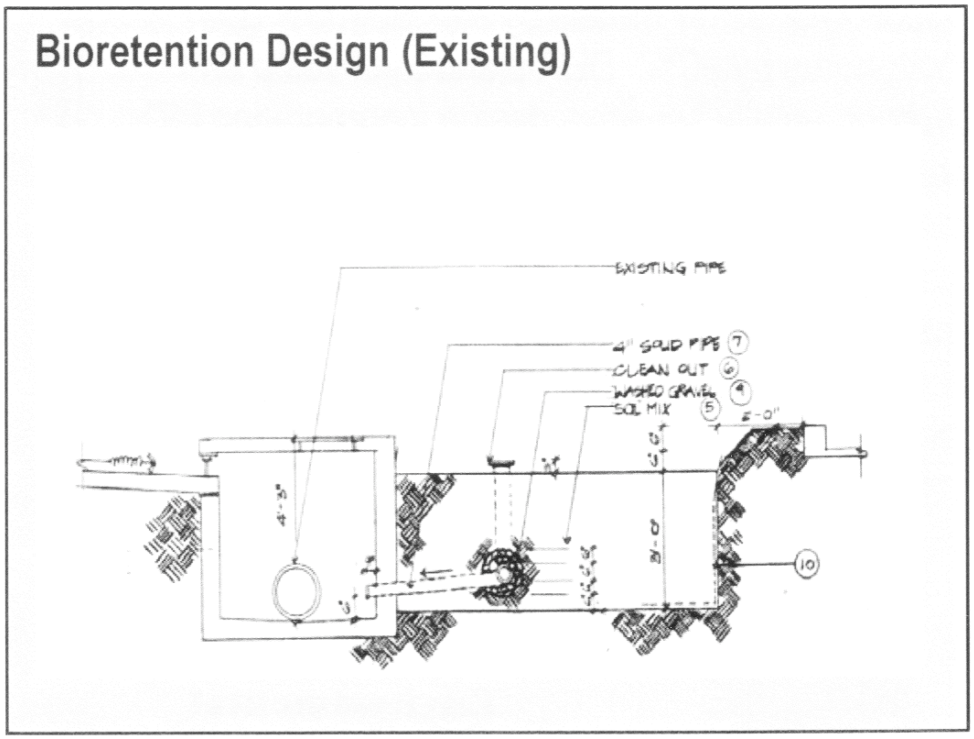


Figure A.5: PP construction detail (PGCO, 2004a).

A.1.6 Claggett Farm (CF)

Address: 11904 Old Marlboro Pike, Upper Marlboro, MD 20772

Data Source: Chesapeake Bay Foundation (CBF, 2005)

Table A.11: CF Bioretention Specification

Bioretention soil mix	not available
soil depth	not available
ponding depth	not available
mulch depth	not available
underdrains	not available
cell area	77 sf
drainage area	1125 sf

Table A.12: CF Planting Plan

Trees	not available
Shrubs	not available
Herbaceous	not available

A.1.7 Chevy Chase Bank (CC)

Address: 2315 Randolph Road, Silver Spring, MD 20902

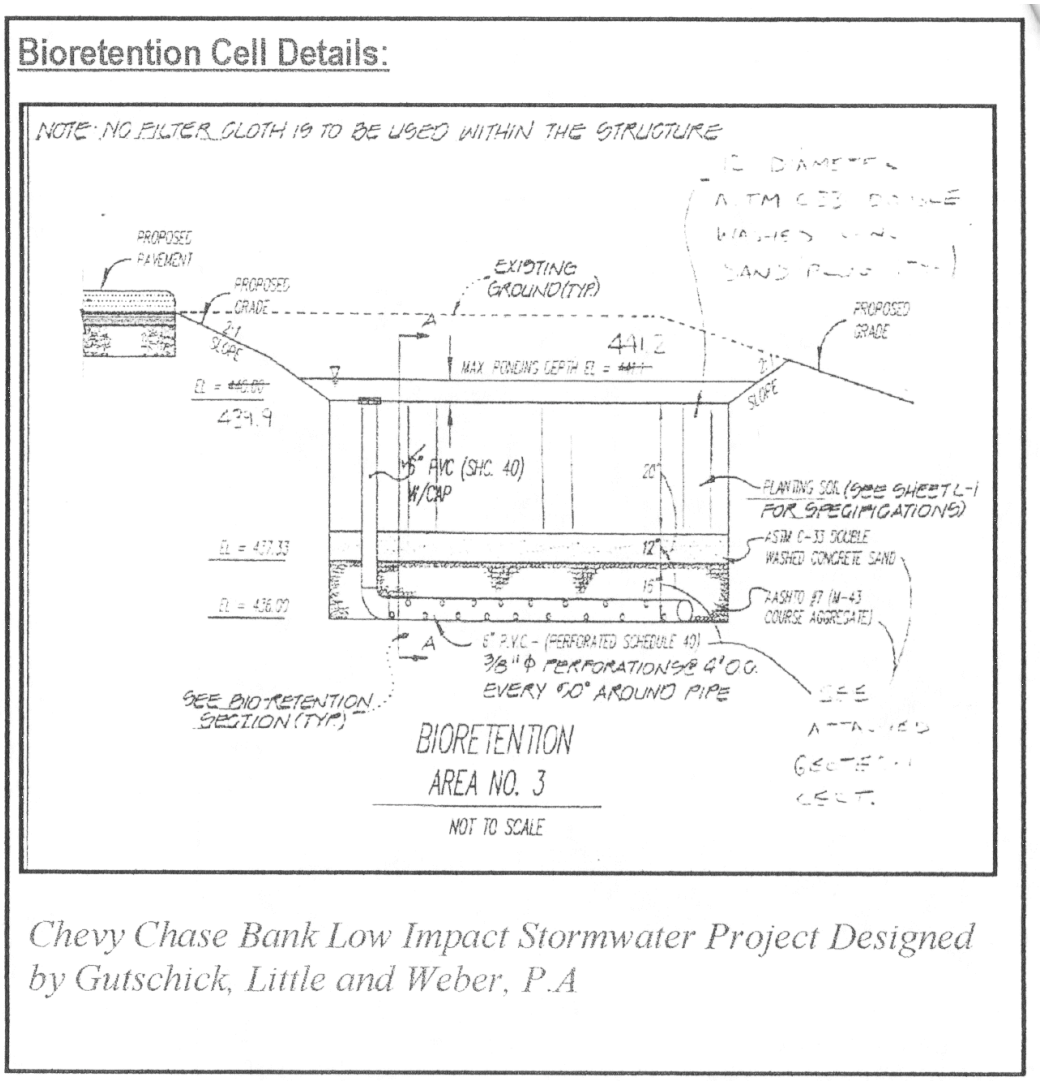
Data Source: Montgomery County Department of Environmental Protection (MCDEP, 2004)

Table A.13: CC Bioretention Specification

Bioretention soil mix	not available
soil depth	22 inches
ponding depth	not available
mulch depth	not available
underdrains	6" perforated pipe
cell area	134 sf
drainage area	5,750 sf (4,850 sf impervious)

Table A.14: CC Planting Plan

Trees	not available
Shrubs	not available
Herbaceous	not available



Chevy Chase Bank Low Impact Stormwater Project Designed by Gutschick, Little and Weber, P.A

Figure A.6: CC construction detail (MCDEP, 2004)

A.1.8 Beltway Plaza Mall (BP)

Address: 6000 Greenbelt Road, Greenbelt, MD 20770

Data Source: Beltway Plaza Developers

Table A.15: BP Bioretention Specification

Bioretention soil mix	5 parts topsoil[1] 1 part wet loose peat moss or rotted manure
soil depth	36 inches
ponding depth	12 inches
mulch depth	3 inches
underdrains	4" perforated pipe
cell area	1,300 sf
drainage area	0.5 acres, paved

Table A.16: BP Planting Plan

Trees	*Liquidambar styraciflua* (sweet gum) *Cornus stoloniferia* (red twig dogwood)
Shrubs	*Ilex glabra* (inkberry) *Myrica pennsylvanica* (Northern bayberry) *Juniperus conferta* (shore juniper)
Herbaceous	*Spartina pectinata* (cord grass) *Scirpus cyperinus* (woolgrass) *Lythrum salicaria* (loosestrife) *Panicum virgatum* 'Rotstrahlbusch' (red switch grass) *Hemerocallis fulva* (wild daylily)

[1]Topsoil specs: loam, sandy loam, clay loam, silt loam, sandy clay loam, or loamy sand

Figure A.7: BP construction detail (Source: Beltway Plaza Developers)

A.1.9 Laurel Regional Hospital

Address: 7300 Van Dusen Road, Laurel, MD 20707

No information available

Appendix B

Soil Testing Procedures

B.1 Procedure for Hydrometer Test

Adapted from Weil (1998)

B.1.1 Equipment

- 1 L cylinder with stopper
- 1 hydrometer (ASTM 151H)
- #10, #200 sieves
- 250 mL beaker
- thermometer
- wash bottle
- dropper
- scale
- electric blender with metal cup
- hot plate or Bunsen burner
- drying oven
- 6% hydrogen peroxide
- 10% Calgon solution, $(NaPO_3)_6$
- amyl alcohol
- distilled water

B.1.2 Procedure

1. Collect an air-dried soil sample
2. Pass through #10 sieve
3. On a separate sample, determine soil moisture content
4. Determine texture by feel

5. Weigh out soil into a 250 mL beaker. If coarser than sandy loam, use 100 g. If sandy loam or finer, use 50 g
6. If organic matter content is greater than 5%, oxidize sample:
   (a) Add 100 mL of 6% hydrogen peroxide to beaker
   (b) Mix well and allow to stand overnight
   (c) Warm gently in a water bath until reaction subsides (control frothing by adding 2 drops of amyl alcohol)
   (d) Cool for a few minutes
   (e) After reaction has subsided, boil for 5 minutes (not to dryness)
   (f) Cool completely
7. Add 100 mL distilled water and 25 mL 10% Calgon solution to the beaker
8. Stir well for 5 minutes. For clayey soils, allow mixture to stand overnight.
9. Using distilled water from a wash bottle, completely transfer the contents of the beaker to a metal blender cup. Fill the cup no more than 1/3 full using distilled water.
10. Place metal cup on blender. If coarse soil is used, blend for 5 minutes. If fine soil is used, blend for 10 minutes.
11. Transfer contents of blender cup completely to a Bouyoucos cylinder.
12. Fill cylinder partway with distilled water.
13. Insert hydrometer, and fill cylinder to 600 mL mark with distilled water.
14. Remove hydrometer
15. Stopper the cylinder. Rotate end over end for about 1 minute (ten times).
16. Immediately stand the cylinder on the bench and start a stop watch. Quickly insert the hydrometer. If a froth is present at the surface, add a few drops of amyl alcohol.
17. Read the hydrometer at 40, 50, 60, 70 and 80 seconds.
18. Plot readings on Figure B.1. Draw a straight line through the readings. Record the value at which the line intersects the heavy reference line.
19. Remove the hydrometer and measure the temperature of the suspension.
20. After 7 hours, take another hydrometer reading and temperature measurement.
21. Pour contents of cylinder through a 200-mesh sieve. Wash sieve until water runs clear.
22. Oven dry sand retained on sieve at 158°F (70°C) for 4 hours, and store for sieve analysis.
23. Fill cylinder with 25 mL of 10% Calgon solution an enough distilled water to make up 1 L.
24. Take hydrometer and temperature readings.

B.1.3 Hydrometer test data sheet

Soil ID:	Date:
Texture by feel:	
Air-dried mass, m_a (g):	
Moisture content: 1.5% (assumed)	
Oven-dried mass, $m_o = m_a - m_a \times 0.015$ (g) =	
Organic Matter Content:	>10% : yes / no
Oxidized: yes / no	
Notes on oxidation:	

Start Time:
Initial Temperature (°C):
Composite Correction Factor, ccf:

ccf = -0.1575 × T + 6.57

Timer	Hydrometer Reading	Corrected Reading (Reading ccf)	Mass in suspension (g)
40 sec			
50 sec			
60 sec			
70 sec			
80 sec			

mass in suspension = corrected hydrometer reading
Plot values on chart in Figure B.1

End Time (+7 hours):		
End Temperature (°C):		
Composite Correction Factor, ccf:		
Hydrometer Reading	Corrected Reading (Reading ccf)	Mass in suspension (g)

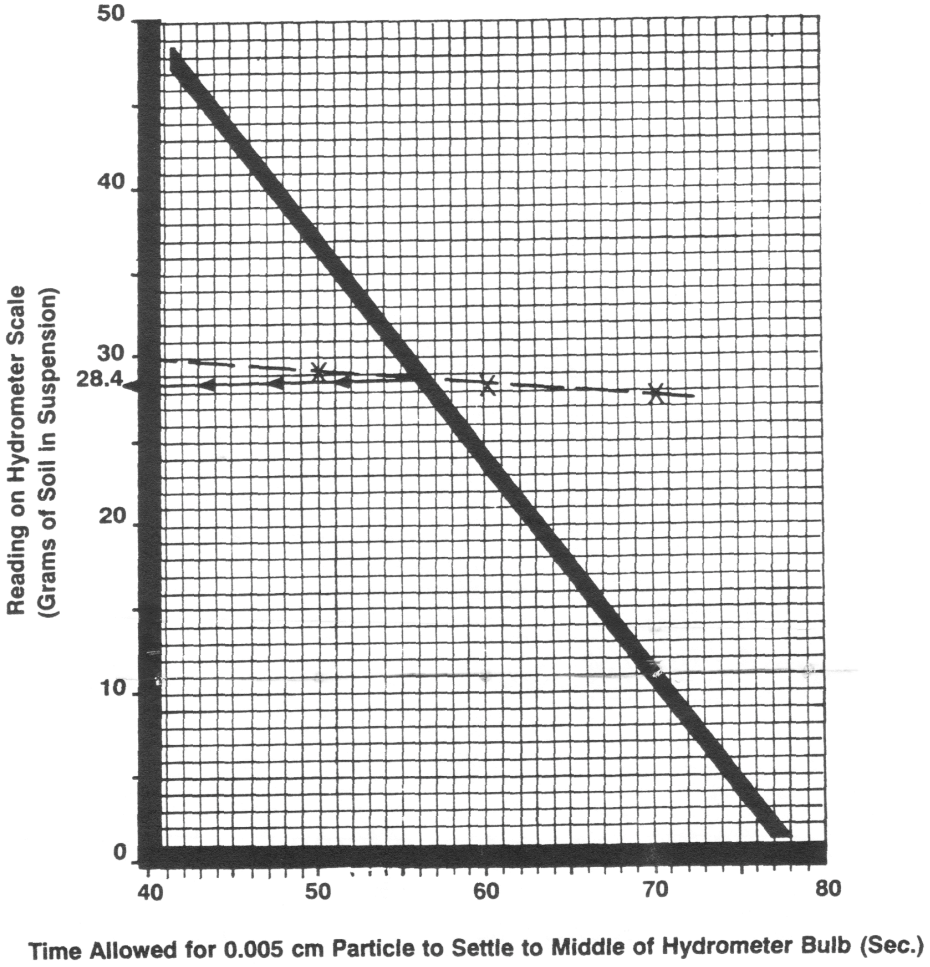


Figure B.1: Graph to determine silt and clay content. Plot 5 readings (40, 50, 60, 70 and 80 sec). Use value corresponding to the intersection of you plot with heavy diagonal line (Weil, 1998).

Initial Y-intercept (silt and clay) (g):
% silt and clay = corrected reading / O.D. sample mass (g) * 100 =
% sand = 100 - % silt and clay =
final mass in suspension (clay) (g):
% clay = corrected reading / O.D. sample mass (g) * 100 =
% silt = % silt and clay - % clay =

% sand:
% silt:
% clay:
Textural designation:

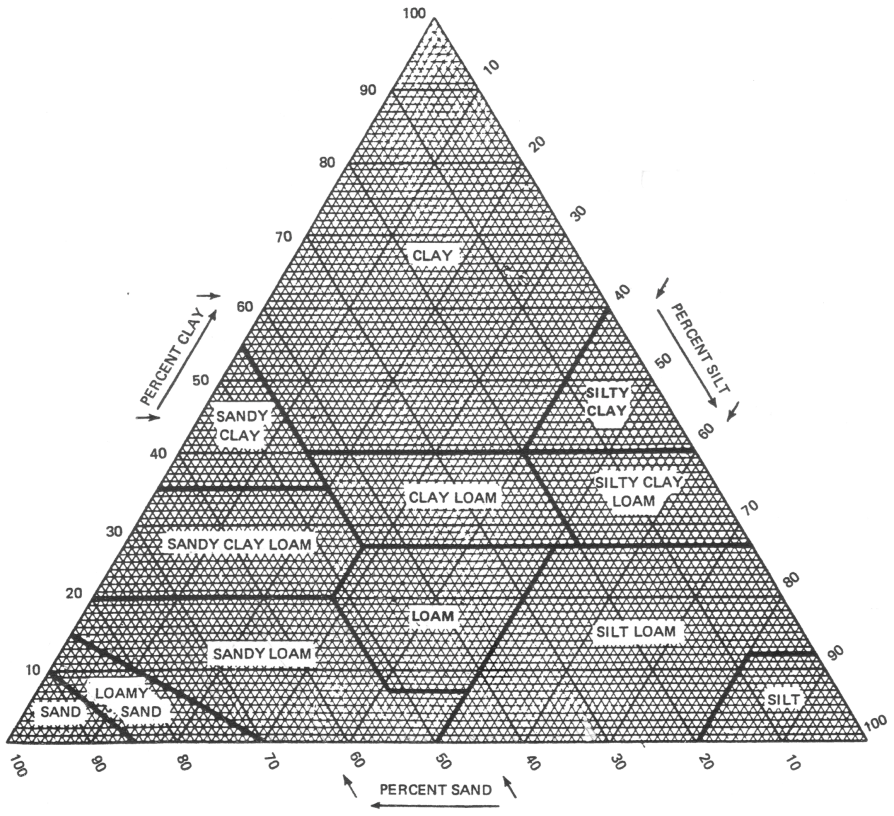


Figure 3.3 USDA Textural Classes. Read the percent sand, silt and clay in the direction indicated by the respective small arrows.

Figure B.2: USDA textural triangle (Weil, 1998).

B.2 Procedure for Sieve Testing of Soil Samples

B.2.1 Equipment

- stackable sieves: #4, #10, #20, #40, #60, #100, #140, #200
- cap and bottom pan for sieves
- mechanical shaker
- drying oven
- scale
- 250 mL beaker
- wash bottle
- distilled water

B.2.2 Procedure

1. Measure out enough soil so that about 500 g of will remain after removing silt and clay fractions. Record mass.
2. Wash soil on a #200 sieve (with tap water) until water runs clear.
3. Wash soil retained on #200 sieve into an evaporating dish using distilled water. Oven-dry dish at 110°C.
4. After oven-drying, weigh soil and subtract mass of evaporating dish.
5. Assemble stack of dry and clean sieves, with a bottom pan.
6. Pour soil into top sieve, then shake mechanically for about 15 minutes.
7. Weigh the soil retained on each of the sieves.

Appendix C

Taxonomic Key to the Earthworms of Maryland

1. Setae closely paired 2
– Setae widely paired 25
– Setae equidistant 28
– Setae perichaetine 29

2 (1). Prostomium epilobic 3
– Prostomium tanylobic 22

3 (2). Clitellum annular 4
– Clitellum saddle-shaped 5

4 (3). Dorsal color unpigmented . . . . . *Bimastos heimburgeri*, *Microscolex dubius*, *Bimastos palustris*
– Dorsal color white . . . . . *Bimastos palustris*
– Dorsal color blue . . . . . *Bimastos palustris*
– Dorsal color grey . . . . . *Eisenia rosea*, *Bimastos palustris*
– Dorsal color pink . . . . . *Eisenia rosea*, *Bimastos palustris*
– Dorsal color reddish . . . *Bimastos palustris*, *Bimastos heimburgeri*, *Bimastos tumidus*
– Dorsal color reddish violet . . . . . *Bimastos palustris*
– Dorsal color violet . . . . . *Bimastos palustris*
– Dorsal color slate . . . . . *Bimastos palustris*
– Dorsal color dark reddish brown . . . . . *Bimastos heimburgeri*, *Bimastos tumidus*, *Bimastos palustris*
– Dorsal color red-brown in transverse bands . . . . . *Bimastos palustris*
– Dorsal color brown . . . . . *Bimastos heimburgeri*, *Bimastos palustris*
– Dorsal color yellowish brown . . . . . *Bimastos palustris*
– Dorsal color yellowish green . . . . . *Bimastos palustris*
– Dorsal color dark green . . . . . *Bimastos palustris*
– Dorsal color iridescent . . . . . *Bimastos palustris*

5 (3). Dorsal color unpigmented 6
– Dorsal color white 8
– Dorsal color blue . . . . . *Octolasion tyrtaeum*
– Dorsal color grey 9
– Dorsal color pink 11
– Dorsal color reddish 12
– Dorsal color reddish violet 17
– Dorsal color violet . . . . . *Eisenoides lonnbergi*
– Dorsal color slate . . . . . *Eisenoides lonnbergi*
– Dorsal color dark reddish brown 18
– Dorsal color red-brown in transverse bands . . . . . *Eisenia fetida*
– Dorsal color brown 19
– Dorsal color yellowish brown . . . . . *Aporrectodea longa*
– Dorsal color yellowish green . . . . . *Allolobophora chlorotica*
– Dorsal color dark green 21

6 (5). Tuberculata pubertatis indistinct . . . . . *Bimastos heimburgeri*
– Tuberculata pubertatis sucker-like papillae 7

– Tuberculata pubertatis ridge-like . . . . . *Aporrectodea caliginosa turgida*, *Aporrectodea caliginosa trapezoides*
– Tuberculata pubertatis bipartite . . . . . *Aporrectodea caliginosa turgida*
– Tuberculata pubertatis tripartite . . . . . *Aporrectodea caliginosa trapezoides*
– Tuberculata pubertatis triangular . . . . . *Aporrectodea calignosa tuberculata*
– Tuberculata pubertatis bilboate . . . . . *Aporrectodea caliginosa turgida*
– Tuberculata pubertatis crescentic . . . . . *Aporrectodea caliginosa turgida*

7 (6). Setae (aa:ab:bc:cd:dd) 4.5:1.5:3:1:15; tuberculata pubertatis two pairs . . . . . *Aporrectodea caliginosa trapezoides*
– Setae (aa:ab:bc:cd:dd) 13:1.5:6:1:25; tuberculata pubertatis three pairs . . . . . *Allolobophora chlorotica*

8 (5). Spermathecal pores above setal line c; tuberculata pubertatis narrow strip; setae (aa:ab:bc:cd:dd) 3.3: 1.6: 1.3: 1.0: 7.3 . . . . . *Octolasion tyrtaeum*
– Spermathecal pores between setal lines cd; tuberculata pubertatis triangular; setae (aa:ab:bc:cd:dd) 4.5:1.5:3:1:15 . . . . . *Aporrectodea calignosa tuberculata*

9 (5). Spermathecal pores above setal line c . . . . . *Octolasion tyrtaeum*
– Spermathecal pores between setal lines cd 10

10 (9). Tuberculata pubertatis indistinct . . . . . *Eisenia rosea*
– Tuberculata pubertatis sucker-like papillae . . . . . *Eisenia rosea*
– Tuberculata pubertatis elliptical . . . . . *Eisenia rosea*
– Tuberculata pubertatis oval . . . . . *Eisenia rosea*
– Tuberculata pubertatis saucer-like . . . . . *Eisenia rosea*
– Tuberculata pubertatis narrow strip . . . . . *Eisenia rosea*
– Tuberculata pubertatis broad, rectangular . . . . . *Eisenia rosea*
– Tuberculata pubertatis ridge-like . . . *Eisenia rosea*, *Aporrectodea caliginosa turgida*
– Tuberculata pubertatis bipartite . . . *Aporrectodea caliginosa turgida*, *Eisenia rosea*
– Tuberculata pubertatis tripartite . . . . . *Eisenia rosea*
– Tuberculata pubertatis triangular . . . . . *Eisenia rosea*, *Aporrectodea calignosa tuberculata*
– Tuberculata pubertatis bilboate . . . . *Aporrectodea caliginosa turgida*, *Eisenia rosea*
– Tuberculata pubertatis crescentic . . . *Eisenia rosea*, *Aporrectodea caliginosa turgida*

11 (5). First dorsal pore 3/4 . . . . . *Eisenia fetida*, *Eisenia rosea*
– First dorsal pore 4/5 . . . . . *Eisenia rosea*, *Eisenia fetida*
– First dorsal pore 5/6 . . . . . *Eisenia rosea*
– First dorsal pore 6/7 . . . . . *Eisenia rosea*
– First dorsal pore 7/8 . . . . . *Eisenia rosea*
– First dorsal pore 8/9 . . . . . *Eisenia rosea*
– First dorsal pore 9/10 . . . . . *Eisenia rosea*
– First dorsal pore 10/11 . . . . . *Eisenia rosea*
– First dorsal pore 11/12 . . . . . *Eisenia rosea*
– First dorsal pore 12/13 . . . . . *Aporrectodea caliginosa turgida*, *Eisenia rosea*
– First dorsal pore 13/14 . . . . . *Aporrectodea caliginosa turgida*, *Eisenia rosea*
– First dorsal pore 14/15 . . . . . *Eisenia rosea*

12 (5). Spermathecal pores absent 13
– Spermathecal pores two pairs 15
– Spermathecal pores three pairs 16

13 (12). Tuberculata pubertatis indistinct 14
– Tuberculata pubertatis sucker-like papillae . . . . *Aporrectodea caliginosa trapezoides*

– Tuberculata pubertatis ridge-like . . . . . *Aporrectodea caliginosa trapezoides*
– Tuberculata pubertatis tripartite . . . . . *Aporrectodea caliginosa trapezoides*
14 (13). Male pores inconspicuous . . . . . *Bimastos heimburgeri*
– Male pores with small tumescences . . . . . *Bimastos heimburgeri*, *Bimastos parvus*
– Male pores with moderate tumescences . . . *Bimastos tumidus*, *Bimastos heimburgeri*
– Male pores with large tumescences . . . . . *Bimastos heimburgeri*
– Male pores confined to a single segment . . . . . *Bimastos heimburgeri*
– Male pores large . . . . . *Bimastos heimburgeri*
– Male pores paired . . . . . *Bimastos heimburgeri*
15 (12). Setae (aa:ab:bc:cd:dd) 4: 1: 4: 1: 16 . . . . . *Eisenia fetida*
– Setae (aa:ab:bc:cd:dd) 4.5:1.5:3:1:15 . . . . . *Aporrectodea caliginosa trapezoides*
16 (12). Spermathecal pores between setal lines cd . . . . . *Aporrectodea caliginosa trapezoides*
– Spermathecal pores setal line d . . . . . *Eisenoides carolinensis*
17 (5). Ventral color unpigmented; spermathecal pores two pairs; tuberculata pubertatis narrow strip; male pores paired . . . . . *Eisenia fetida*
– Ventral color yellowish; spermathecal pores absent; tuberculata pubertatis indistinct; male pores with small tumescences . . . . . *Bimastos parvus*
18 (5). Tuberculata pubertatis indistinct . . . *Bimastos heimburgeri*, *Bimastos tumidus*
– Tuberculata pubertatis sucker-like papillae . . . . *Aporrectodea caliginosa trapezoides*
– Tuberculata pubertatis oval . . . . . *Aporrectodea longa*
– Tuberculata pubertatis ridge-like . . . . . *Aporrectodea caliginosa trapezoides*
– Tuberculata pubertatis tripartite . . . . . *Aporrectodea caliginosa trapezoides*
19 (5). Spermathecal pores absent; tuberculata pubertatis indistinct . . . . . *Bimastos heimburgeri*
– Spermathecal pores two pairs; tuberculata pubertatis narrow strip 20
20 (19). Posterior square; setae (aa:ab:bc:cd:dd) 3: 1: 3: 1: 6 . . . . *Eiseniella tetraedra*
– Posterior trapezoidal; setae (aa:ab:bc:cd:dd) 4: 1: 4: 1: 16 . . . . . *Eisenia fetida*
21 (5). Posterior depressed dorso-ventrally; spermathecal pores three pairs; tuberculata pubertatis sucker-like papillae; setae (aa:ab:bc:cd:dd) 13:1.5:6:1:25 . . . . . *Allolobophora chlorotica*
– Posterior square; spermathecal pores two pairs; tuberculata pubertatis narrow strip; setae (aa:ab:bc:cd:dd) 3: 1: 3: 1: 6 . . . . . *Eiseniella tetraedra*
22 (2). Tuberculata pubertatis indistinct . . . *Bimastos heimburgeri*, *Bimastos palustris*
– Tuberculata pubertatis saucer-like . . . . . *Lumbricus friendi*
– Tuberculata pubertatis narrow strip 23
– Tuberculata pubertatis broad, rectangular . . . . . *Lumbricus rubellus*
– Tuberculata pubertatis ridge-like 24
23 (22). Spermathecal pores setal line c; setae (aa:ab:bc:cd:dd) 5: 1.2: 5: 1: 20 . . . . . *Lumbricus castaneus*
– Spermathecal pores setal line d; setae (aa:ab:bc:cd:dd) 7: 1.5: 6: 1: 22 . . . . . *Lumbricus friendi*
24 (22). Spermathecal pores between setal lines cd; setae (aa:ab:bc:cd:dd) 6: 1.3: 5: 1: 22 . . . . . *Lumbricus terrestris*
– Spermathecal pores setal line d; setae (aa:ab:bc:cd:dd) 7: 1.5: 6: 1: 22 . . . . . *Lumbricus friendi*
25 (1). Clitellum annular . . . . . *Diplocardia singularis*, *Microscolex dubius*, *Bimastos heimburgeri*, *Bimastos palustris*

– Clitellum saddle-shaped 26
26 (25). Tuberculata pubertatis indistinct .... *Bimastos heimburgeri*, *Bimastos parvus*
– Tuberculata pubertatis narrow strip 27
– Tuberculata pubertatis broad, rectangular ..... *Dendrodrilus rubidus*
27 (26). Setae (aa:ab:bc:cd:dd) 2: 1: 2: 1: 12; posterior cylindrical .....
..... *Dendrodrilus rubidus*
– Setae (aa:ab:bc:cd:dd) 3.3: 1.6: 1.3: 1.0: 7.3; posterior octagonal .....
..... *Octolasion tyrtaeum*
28 (1). Clitellum annular; ventral color unpigmented ..... *Microscolex dubius*
– Clitellum saddle-shaped; ventral color reddish ..... *Dendrobaena octaedra*
29 (1). Spermathecal pores absent 30
– Spermathecal pores two pairs 32
– Spermathecal pores three pairs 33
30 (29). Unusual features fuzzy ..... *Pheretima agrestis*, *Pheretima diffringens*
– Unusual features white flecks 31
– Unusual features brown flecks ..... *Pheretima diffringens*
– Unusual features bulbous head ..... *Pheretima diffringens*
31 (30). Ventral color unpigmented ..... *Microscolex dubius*
– Ventral color reddish ..... *Pheretima diffringens*
– Ventral color same as dorsal color ..... *Pheretima diffringens*
32 (29). Unusual features fuzzy ..... *Pheretima agrestis*
– Unusual features white flecks ..... *Microscolex dubius*
33 (29). Unusual features fuzzy ..... *Pheretima hupeiensis*, *Pheretima agrestis*
– Unusual features white flecks ..... *Microscolex dubius*, *Pheretima hupeiensis*
– Unusual features brown flecks ..... *Pheretima hupeiensis*
– Unusual features bulbous head ..... *Pheretima hupeiensis*

This key was generated using DELTA (DEscriptive Language for TAxonomy, by IntKey). The taxonomic descriptions included in this key were compiled from a number of sources (Baker and Barrett, 1994; Eaton, 1942; Fender and McKey-Fender, 1990; Gates, 1937, 1958, 1972a,b, 1973, 1974; James, 1990; Lee, 1959; Reynolds et al., 1974; Schwert, 1990; Sims et al., 1999; Worm Watch Canada, 2002). The earthworms included in this key are those identified by Reynolds (1974) and Csuzdi and Slávecz (2003) as occurring in Maryland. The key includes only external features. In some cases, the data included in the key are insufficient to distinguish between closely related species.

Appendix D

Raw Field Data

D.1 University of Maryland (UMCP)

Sampling Date: July 29, 2005

Age at sampling: 1 year

Table D.1: UMCP Earthworms - number of individuals and sum of lengths

	Location		
Depth	1	2	3
0-10 cm	7 worms, 22.5 cm	2 worms, 5.5 cm	4 worms, 7.0 cm
10-20 cm	0 worms	0 worms	0 worms
20-30 cm	0 worms	0 worms	0 worms

Table D.2: UMCP Root biomass, air-dried

	Location		
Depth	1	2	3
0-10 cm	0.49 g	0.88 g	0.77 g
10-20 cm	0.18 g	0.46 g	0.26 g
20-30 cm	0.75 g	1.42 g	0.03 g

Table D.3: UMCP Soil organic matter content

	Location		
Depth	1	2	3
0-10 cm	3.19%	2.98%	2.55%
10-20 cm	sample was lost prior to testing	1.50%	1.57%
20-30 cm	1.46%	1.44%	1.40%

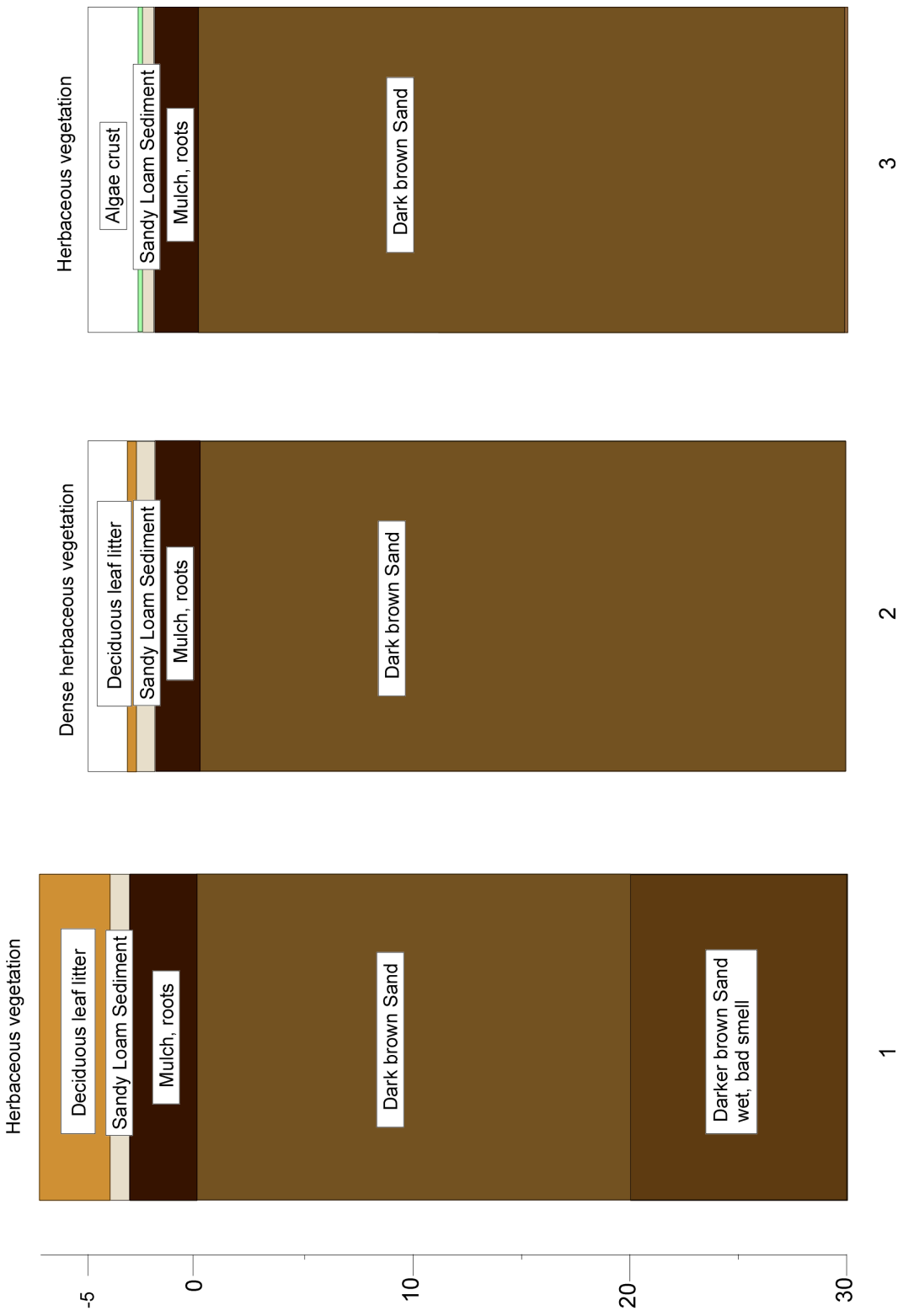


Figure D.1: UMCP soil profile.

Table D.4: UMCP Soil texture

Depth	Location		
	1	2	3
0-10 cm	Sand 88.3% sand 7.3% silt 4.3% clay	Sand 87.7% sand 8.2% silt 4.0% clay	Sand 92.1% sand 2.8% silt 5.1% clay
10-20 cm	sample was lost prior to testing	Sand 91.4% sand 5.1% silt 3.6% clay	Sand 93.8% sand 4.0% silt 2.2% clay
20-30 cm	Sand 92.0% sand 4.1% silt 3.9% clay	Sand 92.6% sand 3.8% silt 3.6% clay	Sand 91.3% sand 5.4% silt 3.3% clay

Table D.5: UMCP Soil invertebrates total tally for entire site.

Common name	Scientific name	Number of individuals
adult beetles	Coleoptera	4
beetle larvae	Coleoptera larvae	-
common white grubs	Coleoptera: Scarabaeidae larvae	1
ants	Hymenoptera: Formicidae	1
centipedes	Myriapoda: Chilopoda	-
millipedes	Myriapoda: Diplopoda	1
potworms	Oligochaeta: Enchytraeidae	-
pill bugs	Crustacea: Isopoda	-
spiders	Arachnida: Araneae	1
springtails	Hexapoda: Collembola	-
slugs and snails	Mollusca: Gastropoda	-
fly larvae	Hexapoda: Diptera larvae	-
mites	Arachnida: Acari	-

Table D.6: UMCP Earthworm species identified.

Earthworm species	Number identified
Diplocardia singularis	9

D.2 Washington Navy Yard (WNY)

Sampling Date: May 13, 2004

Age at sampling: 2 years

Table D.7: WNY Earthworms - number of individuals and sum of lengths

	Location		
Depth	1	2	3
0-10 cm	10 worms, 55.8 cm	0 worms	2 worms, 8.9 cm
10-20 cm	4 worms, 19.1 cm	0 worms	1 worm, 3.8 cm
20-30 cm	0 worms	0 worms	0 worms

Table D.8: WNY Root biomass, air-dried

	Location		
Depth	1	2	3
0-10 cm	3.88 g	4.18 g	0.17 g
10-20 cm	3.38 g	6.97 g	0.14 g
20-30 cm	2.96 g	7.51 g	0 g

Table D.9: WNY Soil organic matter content

	Location		
Depth	1	2	3
0-10 cm	8.26%	4.67%	5.90%
10-20 cm	2.35%	2.49%	2.18%
20-30 cm	2.16%	2.16%	1.83%

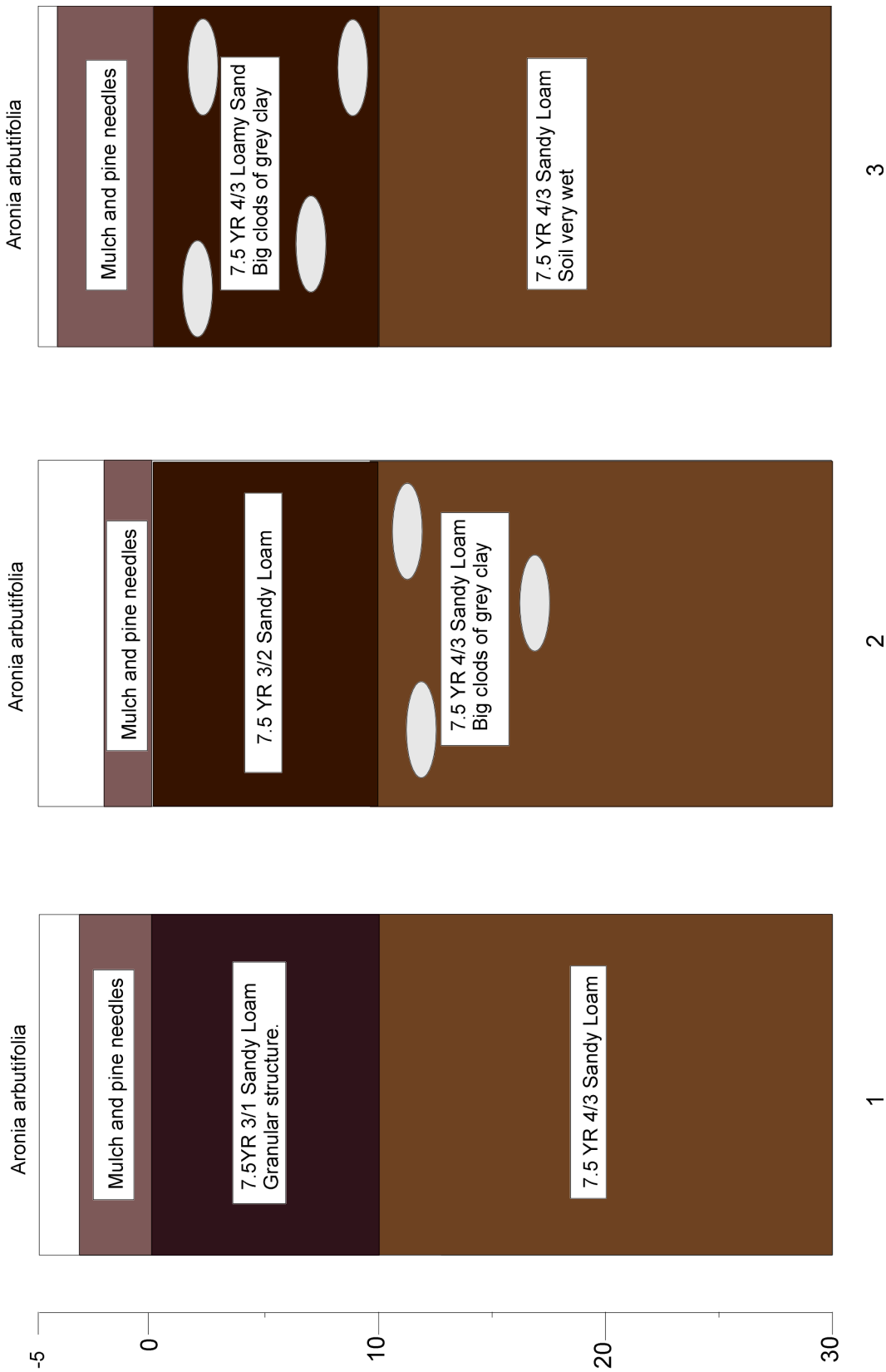


Figure D.2: WNY soil profile.

Table D.10: WNY Soil texture

Depth	Location		
	1	2	3
0-10 cm	Sandy loam 68.1% sand 26.4% silt 5.4% clay	Sandy loam 71.8% sand 21.7% silt 6.5% clay	Loamy sand 75.0% sand 21.0% silt 3.9% clay
10-20 cm	Sandy loam 67.9% sand 26.8% silt 5.2% clay	Sandy loam 75.6% sand 17.1% silt 7.3% clay	Sandy loam 72.4% sand 19.7% silt 7.9% clay
20-30 cm	Sandy loam 66.5% sand 26.8% silt 6.7% clay	Sandy loam 75.2% sand 7.0% silt 17.8% clay	Sandy loam 68.9% sand 25.6% silt 5.5% clay

Table D.11: WNY Soil invertebrates total tally for entire site.

Common name	Scientific name	Number of individuals
adult beetles	Coleoptera	-
beetle larvae	Coleoptera larvae	-
common white grubs	Coleoptera: Scarabaeidae larvae	24
ants	Hymenoptera: Formicidae	-
centipedes	Myriapoda: Chilopoda	-
millipedes	Myriapoda: Diplopoda	-
potworms	Oligochaeta: Enchytraeidae	-
pill bugs	Crustacea: Isopoda	-
spiders	Arachnida: Araneae	-
springtails	Hexapoda: Collembola	-
slugs and snails	Mollusca: Gastropoda	-
fly larvae	Hexapoda: Diptera larvae	-
mites	Arachnida: Acari	-

Table D.12: WNY Earthworm species identified.

Earthworm species	Number identified
none identified	

D.3 "Mother" Jones Elementary School (MJES)

Sampling Date: June 16, 2005

Age at sampling: 3 years

Table D.13: MJES Earthworms - number of individuals and sum of lengths

Depth	Location		
	1	2	3
0-10 cm	121 worms, 353.5 cm	12.5 worms, 83.0 cm	2 worms, 6.5 cm
10-20 cm	7.5 worms, 15.5 cm	0 worms	0 worms
20-30 cm	2 worms, 6.0 cm	0 worms	0 worms

Table D.14: MJES Root biomass, air-dried

Depth	Location		
	1	2	3
0-10 cm	1.35 g	1.06 g	2.46 g
10-20 cm	2.77 g	0.07 g	2.03 g
20-30 cm	5.51 g	0.16 g	0.58 g

Table D.15: MJES Soil organic matter content

Depth	Location		
	1	2	3
0-10 cm	30.87%	2.69%	19.02%
10-20 cm	3.52%	0.37%	3.04%
20-30 cm	3.00%	0.24%	3.03%

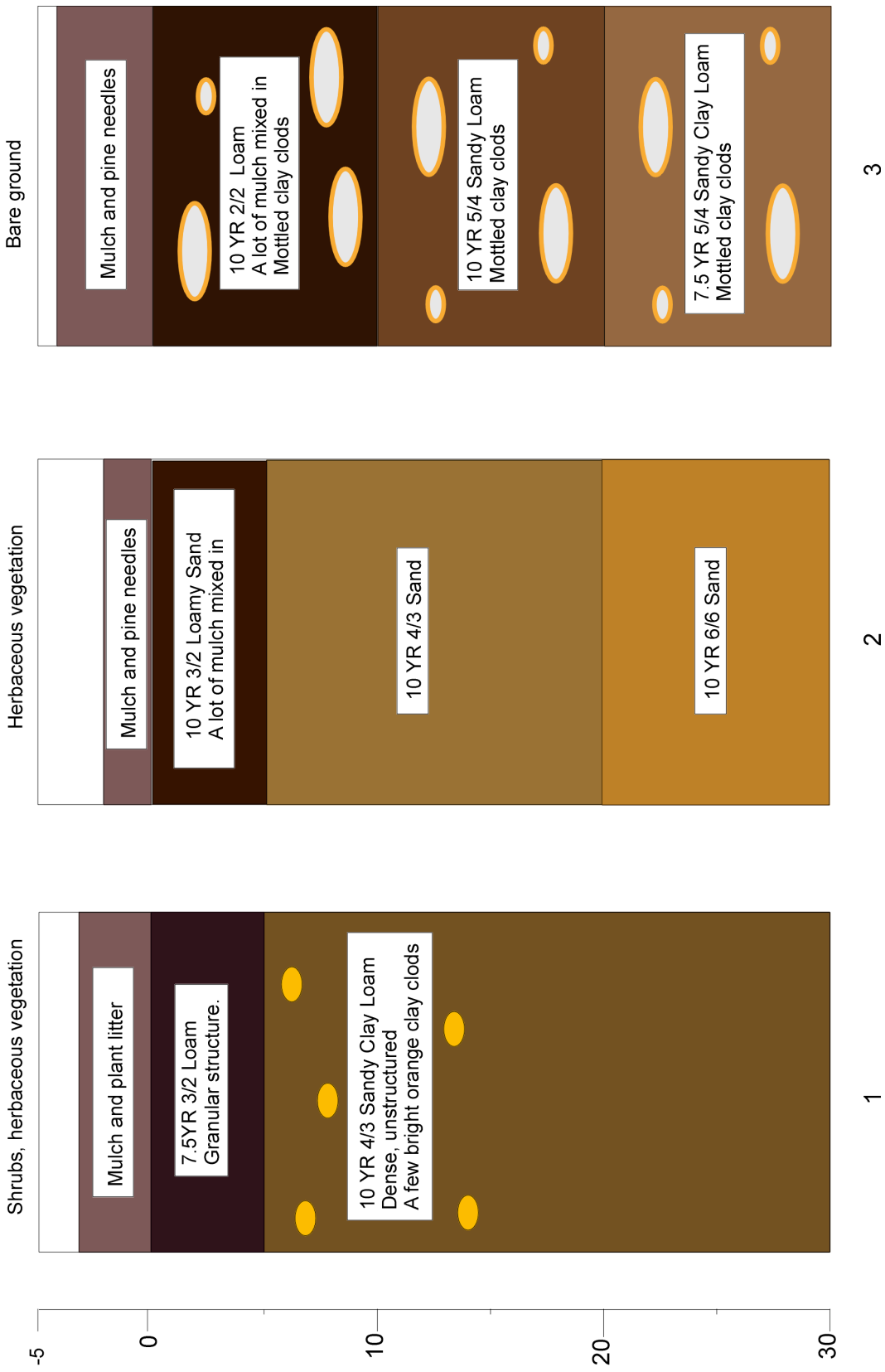


Figure D.3: MJES soil profile.

Table D.16: MJES Soil texture

Depth	Location		
	1	2	3
0-10 cm	Loam 43.1% sand 41.3% silt 15.6% clay	Loamy sand 78.7% sand 13.2% silt 8.1% clay	Loam 49.9% sand 31.8% silt 18.3% clay
10-20 cm	Sandy Clay Loam 57.2% sand 21.2% silt 21.6% clay	Sand 96.3% sand 1.2% silt 2.5% clay	Sandy Loam 60.4% sand 21.0% silt 18.6% clay
20-30 cm	Sandy Clay Loam 57.2% sand 19.9% silt 22.9% clay	Sand 96.2% sand 1.6% silt 2.2% clay	Sandy Clay Loam 53.1% sand 25.8% silt 21.1% clay

Table D.17: MJES Soil invertebrates total tally for entire site.

Common name	Scientific name	Number of individuals
adult beetles	Coleoptera	13
beetle larvae	Coleoptera larvae	4
common white grubs	Coleoptera: Scarabaeidae larvae	9
ants	Hymenoptera: Formicidae	8
centipedes	Myriapoda: Chilopoda	1
millipedes	Myriapoda: Diplopoda	3
potworms	Oligochaeta: Enchytraeidae	26
pill bugs	Crustacea: Isopoda	-
spiders	Arachnida: Araneae	2
springtails	Hexapoda: Collembola	23
slugs and snails	Mollusca: Gastropoda	1
fly larvae	Hexapoda: Diptera larvae	-
mites	Arachnida: Acari	-

Table D.18: MJES Earthworm species identified.

Earthworm species	Number identified
Allolobophora chlorotica	2
Bimastos parvus	1
Pheretima spp.	14

D.4 Chesapeake Bay Foundation Headquarters (CBF)

Sampling Date: September 14, 2005

Age at sampling:4 years

Table D.19: CBF Earthworms - number of individuals and sum of lengths

	Location		
Depth	1	2	3
0-10 cm	22 worms, 53.0 cm	5 worms, 13.0 cm	15 worms, 29.5 cm
10-20 cm	2 worms, 15.0 cm	0 worms	2 worms, 4.0 cm
20-30 cm	0 worms	0 worms	1 worm, 1.0 cm

Table D.20: CBF Root biomass, air-dried

	Location		
Depth	1	2	3
0-10 cm	8.05 g	4.17 g	18.09 g
10-20 cm	2.01 g	1.31 g	2.25 g
20-30 cm	0.50 g	0.58 g	1.59 g

Table D.21: CBF Soil organic matter content

	Location		
Depth	1	2	3
0-10 cm	.41%	2.52%	2.12%
10-20 cm	3.07%	2.45%	2.56%
20-30 cm	2.95%	2.91%	2.65%

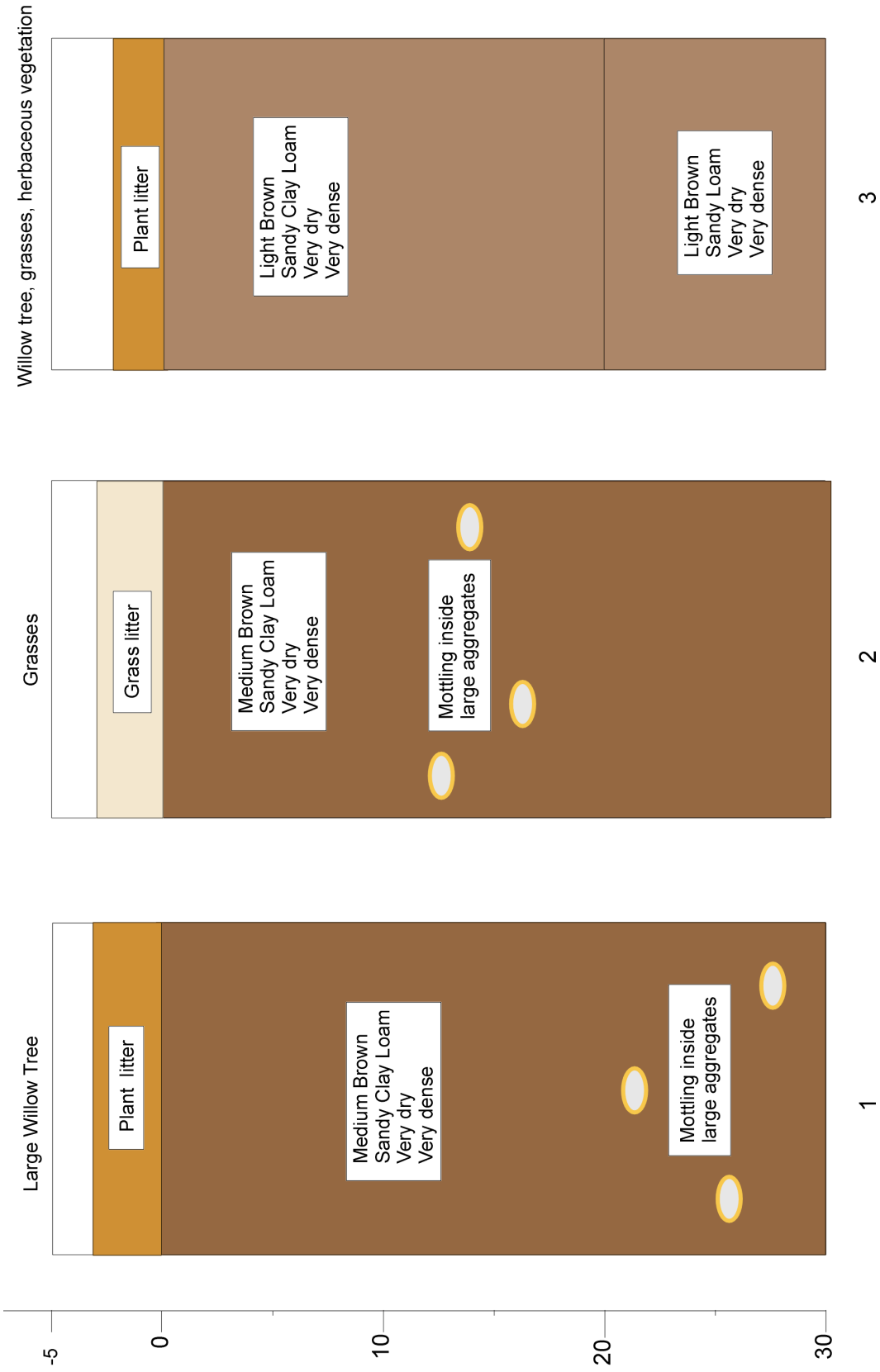


Figure D.4: CBF soil profile.

Table D.22: CBF Soil texture

Depth	Location		
	1	2	3
0-10 cm	Sandy Clay Loam 60.6% sand 16.9% silt 22.5% clay	Sandy Clay Loam 59.8% sand 14.0% silt 26.2% clay	Sandy Clay Loam 62.6% sand 14.5% silt 22.9% clay
10-20 cm	Sandy Clay Loam 61.8% sand 17.5% silt 20.7% clay	Sandy Clay Loam 59.8% sand 17.4% silt 22.8% clay	Sandy Clay Loam 60.8% sand 16.5% silt 22.7% clay
20-30 cm	Sandy Clay Loam 61.4% sand 16.9% silt 21.7% clay	Sandy Clay Loam 60.6% sand 16.5% silt 22.9% clay	Sandy Loam 61.8% sand 18.3% silt 19.9% clay

Table D.23: CBF Soil invertebrates total tally for entire site.

Common name	Scientific name	Number of individuals
adult beetles	Coleoptera	23
beetle larvae	Coleoptera larvae	1
common white grubs	Coleoptera: Scarabaeidae larvae	-
ants	Hymenoptera: Formicidae	5
centipedes	Myriapoda: Chilopoda	3
millipedes	Myriapoda: Diplopoda	1
potworms	Oligochaeta: Enchytraeidae	3
pill bugs	Crustacea: Isopoda	47
spiders	Arachnida: Araneae	6
springtails	Hexapoda: Collembola	3
slugs and snails	Mollusca: Gastropoda	-
fly larvae	Hexapoda: Diptera larvae	-
mites	Arachnida: Acari	-
insect larvae	Insecta	1

Table D.24: CBF Earthworm species identified.

Earthworm species	Number identified
Apporectodea caliginosa	46
Pheretima diffringens	1

D.5 Northwestern High School (NWHS)

Sampling Date: July 7, 2004

Age at sampling: 5 years

Table D.25: NWHS Earthworms - number of individuals and sum of lengths

	Location		
Depth	1	2	3
0-10 cm	50 worms, 102.5 cm	0 worms	4 worms, 15.0 cm
10-20 cm	28 worms, 52.5 cm	0 worms	0 worms
20-30 cm	4 worms, 4.0 cm	0 worms	0 worms

Table D.26: NWHS Root biomass, air-dried

	Location		
Depth	1	2	3
0-10 cm	4.81 g	13.82 g	4.11 g
10-20 cm	1.35 g	1.56 g	1.38 g
20-30 cm	1.05 g	0.73 g	1.87 g

Table D.27: NWHS Soil organic matter content

	Location		
Depth	1	2	3
0-10 cm	5.4 %	4.56%	3.20%
10-20 cm	4.03%	3.20%	3.54%
20-30 cm	2.01%	3.21%	3.21%

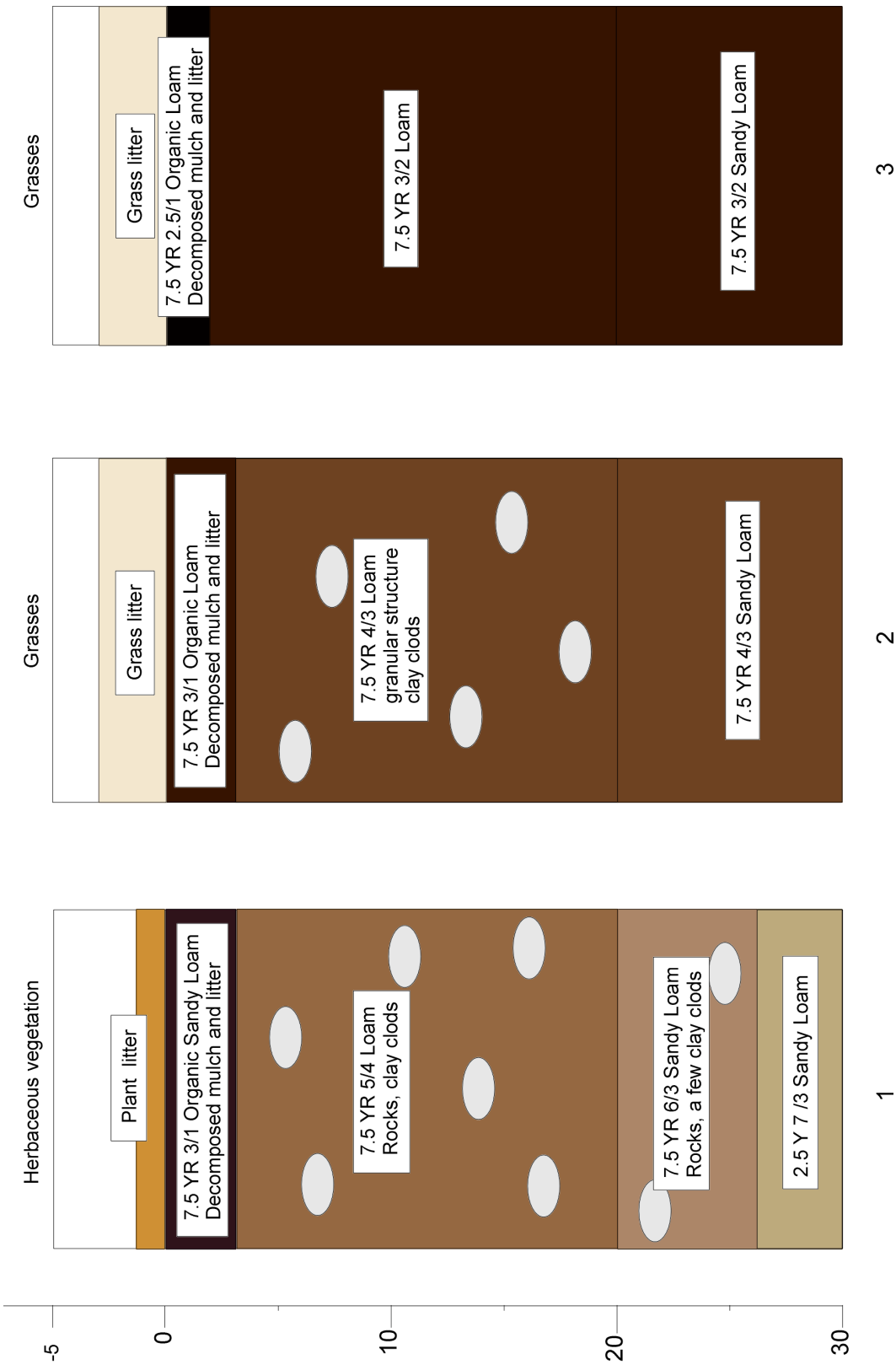


Figure D.5: NWHS soil profile.

Table D.28: NWHS Soil texture

Depth	Location		
	1	2	3
0-10 cm	Sandy loam 57.6% sand 32.1% silt 10.3% clay	Loam 51.3% sand 32.1% silt 16.6% clay	Loam 50.3% sand 34.7% silt 15.0% clay
10-20 cm	Loam 40.1% sand 46.7% silt 13.2% clay	Loam 38.1% sand 42.4% silt 19.5% clay	Loam 51.9% sand 31.0% silt 17.1% clay
20-30 cm	Sandy loam 68.5% sand 24.0% silt 7.5% clay	Sandy loam 52.7% sand 30.9% silt 16.4% clay	Sandy loam 52.1% sand 33.9% silt 14.0% clay

Table D.29: NWHS Soil invertebrates total tally for entire site.

Common name	Scientific name	Number of individuals
adult beetles	Coleoptera	8
beetle larvae	Coleoptera larvae	11
common white grubs	Coleoptera: Scarabaeidae larvae	1
ants	Hymenoptera: Formicidae	10
centipedes	Myriapoda: Chilopoda	1
millipedes	Myriapoda: Diplopoda	2
potworms	Oligochaeta: Enchytraeidae	34
pill bugs	Crustacea: Isopoda	3
spiders	Arachnida: Araneae	4
springtails	Hexapoda: Collembola	9
slugs and snails	Mollusca: Gastropoda	-
fly larvae	Hexapoda: Diptera larvae	-
mites	Arachnida: Acari	-

Table D.30: NWHS Earthworm species identified.

Earthworm species	Number identified
none	

D.6 Inglewood Center III (PP)

Sampling Date: July 29, 2004

Age at sampling: 5 years

Table D.31: PP Earthworms - number of individuals and sum of lengths

	Location		
Depth	1	2	3
0-10 cm	7 worms, 26.5 cm	3 worms, 11.5 cm	2.5 worms, 7.5 cm
10-20 cm	1 worm, 3.5 cm	1 worm, 7.0 cm	0 worms
20-30 cm	0 worms	1 worm, 9.0 cm	0 worms

Table D.32: PP Root biomass, air-dried

	Location		
Depth	1	2	3
0-10 cm	3.15 g	0.56 g	2.06 g
10-20 cm	1.57 g	0.51 g	0.98 g
20-30 cm	0.69 g	0.79 g	0.45 g

Table D.33: PP Soil organic matter content

	Location		
Depth	1	2	3
0-10 cm	16.27%	9.52%	27.92%
10-20 cm	5.89%	5.25%	13.68%
20-30 cm	2.69%	2.86%	5.70%

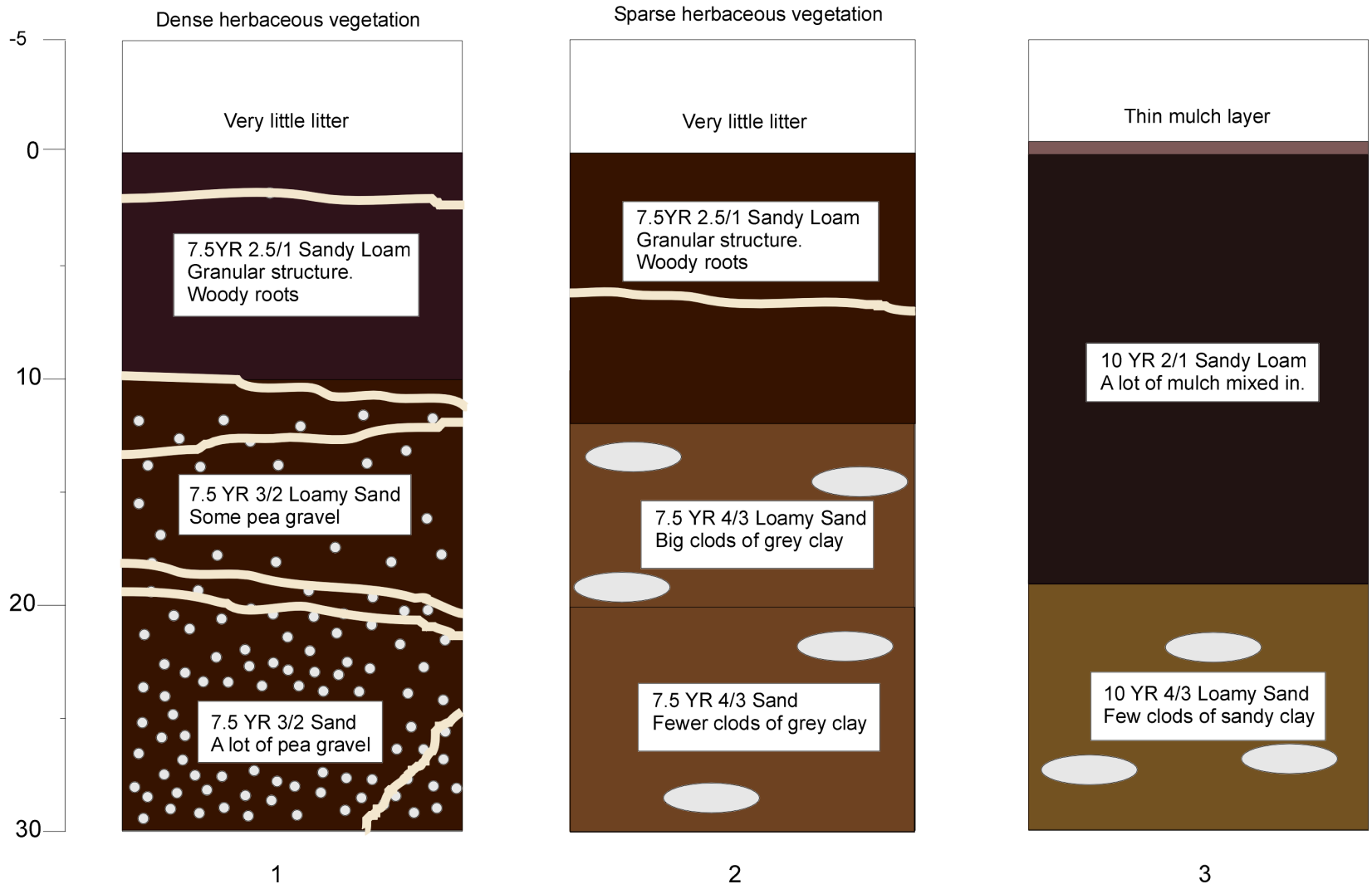


Figure D.6: PP soil profile.

Table D.34: PP Soil texture

Depth	Location		
	1	2	3
0-10 cm	Sandy Loam 62.9% sand 17. 5% silt 19.6% clay	Sandy loam 79.1% sand 8.3% silt 12.6% clay	Sandy loam 69.6% sand 13.2% silt 17.2% clay
10-20 cm	Loamy sand 83.8% sand 11.9% silt 4.3% clay	Loamy sand 88.1% sand 4.3% silt 7.6% clay	Loamy sand 87.8% sand 4.2% silt 7.9% clay
20-30 cm	Sand 92.2% sand 1.5% silt 6.3% clay	Sand 89.2% sand 7.5% silt 3.3% clay	Loamy sand 87.8% sand 4.2% silt 8.0% clay

Table D.35: PP Soil invertebrates total tally for entire site.

Common name	Scientific name	Number of individuals
adult beetles	Coleoptera	1
beetle larvae	Coleoptera larvae	4
common white grubs	Coleoptera: Scarabaeidae larvae	33
ants	Hymenoptera: Formicidae	4
centipedes	Myriapoda: Chilopoda	-
millipedes	Myriapoda: Diplopoda	-
potworms	Oligochaeta: Enchytraeidae	3
pill bugs	Crustacea: Isopoda	2
spiders	Arachnida: Araneae	1
springtails	Hexapoda: Collembola	3
slugs and snails	Mollusca: Gastropoda	-
fly larvae	Hexapoda: Diptera larvae	-
mites	Arachnida: Acari	-

Table D.36: PP Earthworm species identified.

Earthworm species	Number identified
Dendrodrilus rubidus	1
Apporectodea caliginosa	1

D.7 Claggett Farm (CF)

Sampling Date: September 16, 2005

Age at sampling: 6 years

Table D.37: CF Earthworms - number of individuals and sum of lengths

	Location		
Depth	1	2	3
0-10 cm	0 worms	0 worms	0 worms
10-20 cm	1 worm, 5.0 cm	9 worms, 53.5 cm	1 worm, 3.0 cm
20-30 cm	0 worms	0 worms	5 worms, 23.0 cm

Table D.38: CF Root biomass, air-dried

	Location		
Depth	1	2	3
0-10 cm	26.52 g	7.35 g	32.06 g
10-20 cm	11.37 g	5.16 g	8.88 g
20-30 cm	3.55 g	0.95 g	2.25 g

Table D.39: CF Soil organic matter content

	Location		
Depth	1	2	3
0-10 cm	5.90%	5.36%	5.51%
10-20 cm	4.09%	3.44%	3.71%
20-30 cm	2.93%	2.17%	2.38%

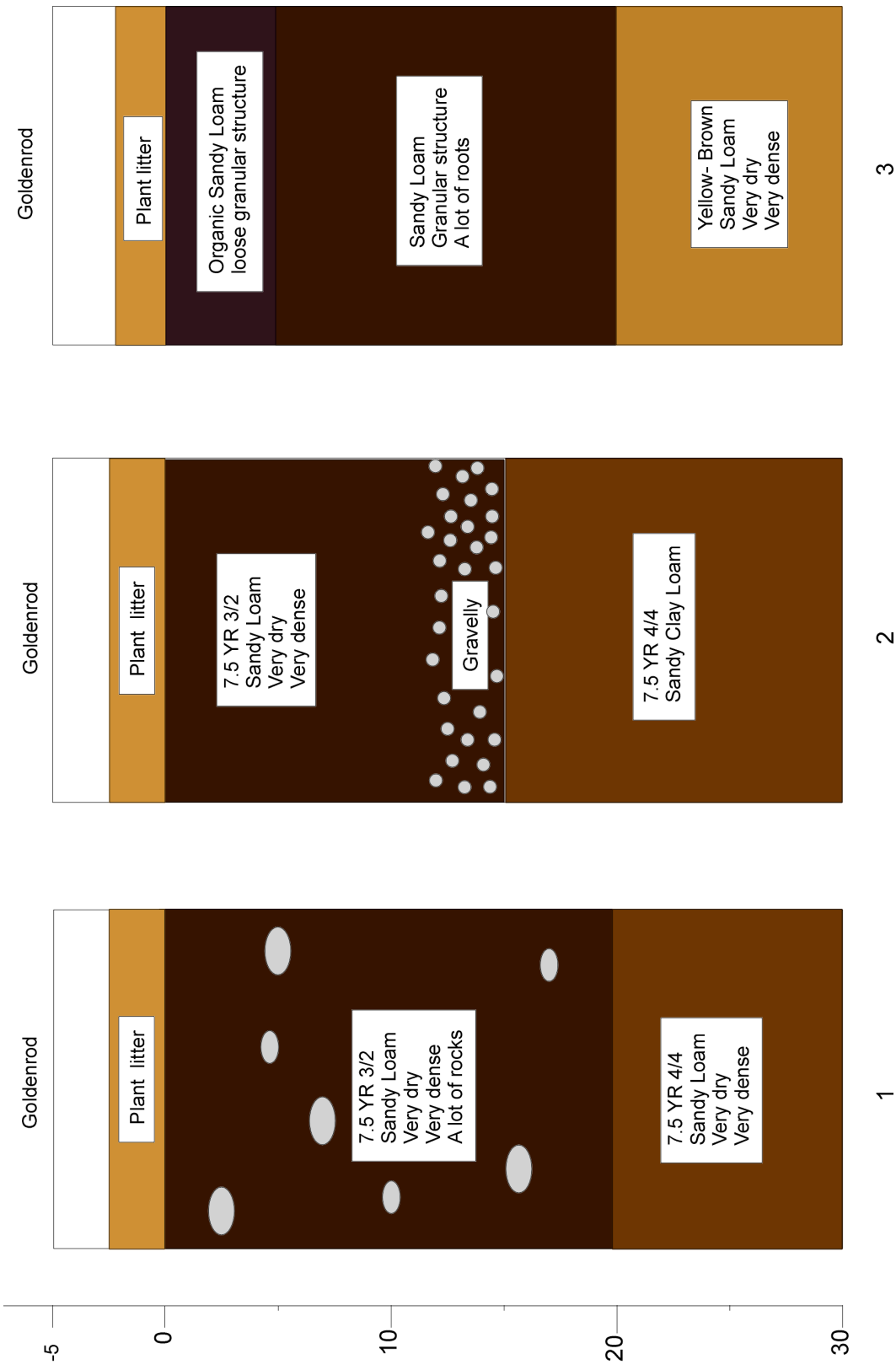


Figure D.7: CF soil profile.

Table D.40: CF Soil texture

Depth	Location		
	1	2	3
0-10 cm	Sandy Loam 72.6% sand 16.6% silt 10.8% clay	Sandy Loam 67.5% sand 18.0% silt 14.5% clay	Sandy Loam 69.9% sand 17.9% silt 12.1% clay
10-20 cm	Sandy Loam 70.2% sand 16.8% silt 13.0% clay	Sandy Loam 67.5% sand 19.8% silt 12.7% clay	Sandy Loam 65.1% sand 18.5% silt 16.4% clay
20-30 cm	Sandy Loam 62.8% sand 18.0% silt 19.2% clay	Sandy Clay Loam 61.2% sand 16.8% silt 22.0% clay	Sandy Loam 64.9% sand 17.4% silt 17.7% clay

Table D.41: CF Soil invertebrates total tally for entire site.

Common name	Scientific name	Number of individuals
adult beetles	Coleoptera	16
beetle larvae	Coleoptera larvae	9
common white grubs	Coleoptera: Scarabaeidae larvae	-
ants	Hymenoptera: Formicidae	148
centipedes	Myriapoda: Chilopoda	-
millipedes	Myriapoda: Diplopoda	7
potworms	Oligochaeta: Enchytraeidae	-
pill bugs	Crustacea: Isopoda	1
spiders	Arachnida: Araneae	4
springtails	Hexapoda: Collembola	1
slugs and snails	Mollusca: Gastropoda	-
fly larvae	Hexapoda: Diptera larvae	-
mites	Arachnida: Acari	-
insect larvae	Insecta	2

Table D.42: CF Earthworm species identified.

Earthworm species	Number identified
Allolobophora chlorotica	4

D.8 Chevy Chase Bank (CC)

Sampling Date: July 7, 2005

Age at sampling: 7 years

Table D.43: CC Earthworms - number of individuals and sum of lengths

Depth	Location		
	1	2	3
0-10 cm	20.5 worms, 46.5 cm	7 worms, 11.0 cm	3 worms, 13.0 cm
10-20 cm	22 worms, 33.0 cm	4 worms, 5.5 cm	4 worms, 13.0 cm
20-30 cm	16.5 worms, 31.0 cm	1 worm, 4.0 cm	5.5 worms, 24.0 cm

Table D.44: CC Root biomass, air-dried

Depth	Location		
	1	2	3
0-10 cm	9.25 g	32.65 g	36.22 g
10-20 cm	14.18 g	39.62 g	4.10 g
20-30 cm	28.77 g	0.99 g	3.69 g

Table D.45: CC Soil organic matter content

Depth	Location		
	1	2	3
0-10 cm	42.54%	27.80%	20.05%
10-20 cm	32.74%	7.53%	8.83%
20-30 cm	22.46%	1.36%	6.35%

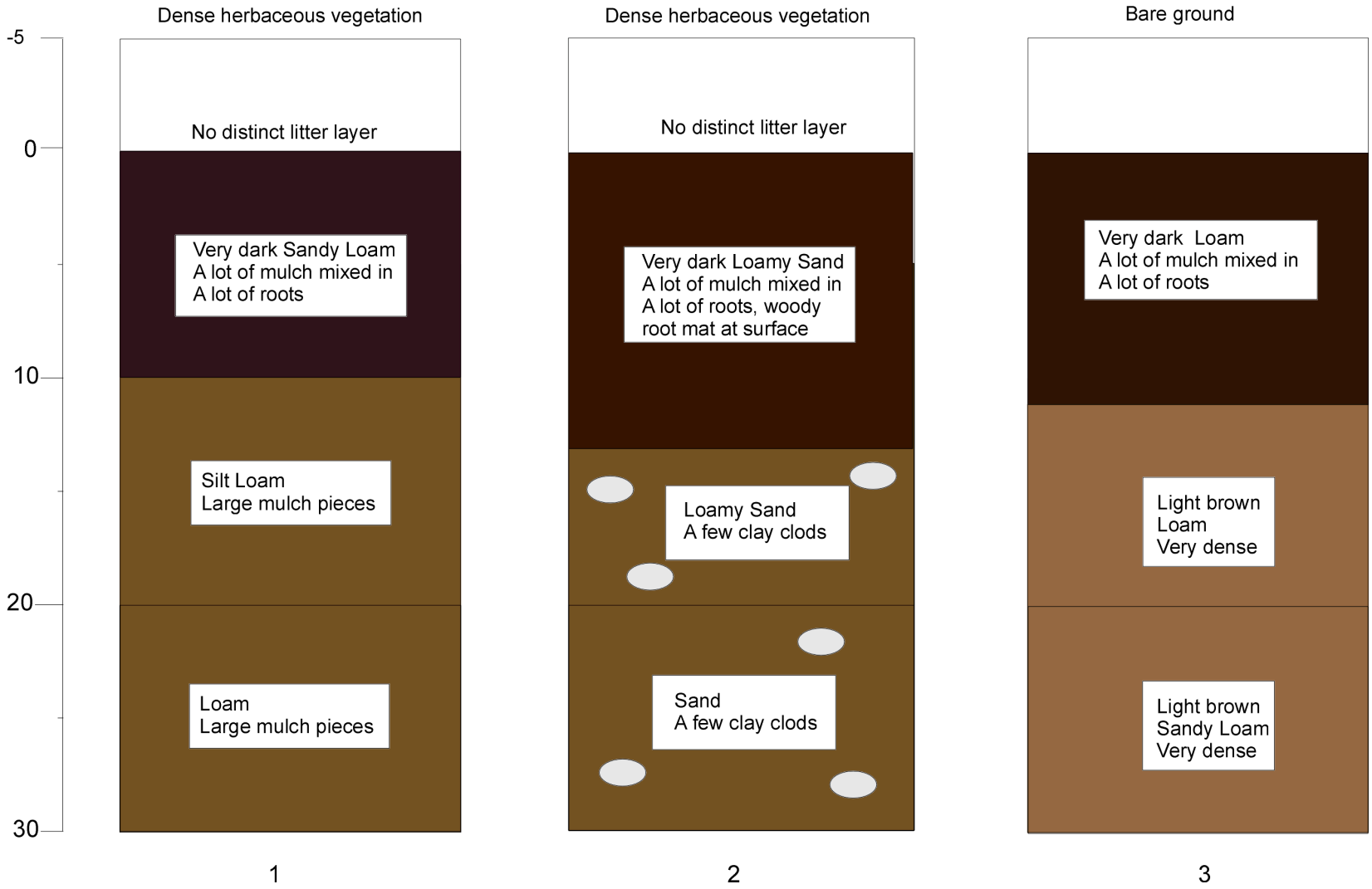


Figure D.8: CC soil profile.

Table D.46: CC Soil texture

Depth	Location		
	1	2	3
0-10 cm	Sandy Loam 67.0% sand 28.3% silt 4.6% clay	Loamy Sand 76.4% sand 21.3% silt 2.3% clay	Loam 43.8% sand 43.5% silt 12.7% clay
10-20 cm 11.6% clay	Silt Loam 32.3% sand 56.1% silt 3.3% clay	Loamy Sand 81.4% sand 15.3% silt 15.0% clay	Loam 48.0% sand 37.0% silt
20-30 cm	Loam 46.7% sand 39.1% silt 14.2% clay	Sand 93.8% sand 3.8% silt 2.4% clay	Sandy Loam 53.1% sand 31.0% silt 15.9% clay

Table D.47: CC Soil invertebrates total tally for entire site.

Common name	Scientific name	Number of individuals
adult beetles	Coleoptera	6
beetle larvae	Coleoptera larvae	1
common white grubs	Coleoptera: Scarabaeidae larvae	5
ants	Hymenoptera: Formicidae	22
centipedes	Myriapoda: Chilopoda	29
millipedes	Myriapoda: Diplopoda	-
potworms	Oligochaeta: Enchytraeidae	3
pill bugs	Crustacea: Isopoda	3
spiders	Arachnida: Araneae	2
springtails	Hexapoda: Collembola	1
slugs and snails	Mollusca: Gastropoda	1
fly larvae	Hexapoda: Diptera larvae	-
mites	Arachnida: Acari	1

Table D.48: CC Earthworm species identified.

Earthworm species	Number identified
Pheretima sp.	29

D.9 Beltway Plaza Mall (BP)

Sampling Date: July 28, 2004

Age at sampling: 7 years

Table D.49: BP Earthworms - number of individuals and sum of lengths

Depth	Location		
	1	2	3
0-10 cm	20 worms, 75.9 cm	31.5 worms, 119.6 cm	7 worms, 26.0 cm
10-20 cm	9 worms, 34.2 cm	3 worms, 11.4 cm	0 worms
20-30 cm	1 worm, 3.8 cm	1 worm, 3.8 cm	0 worms

Table D.50: BP Root biomass, air-dried

Depth	Location		
	1	2	3
0-10 cm	13.44 g	32.24 g	11.55 g
10-20 cm	9.60 g	5.63 g	6.12 g
20-30 cm	4.93 g	3.35 g	0.67 g

Table D.51: BP Soil organic matter content

Depth	Location		
	1	2	3
0-10 cm	12.62%	10.75%	5.14%
10-20 cm	3.02%	2.87%	2.88%
20-30 cm	2.52%	2.19%	4.38%

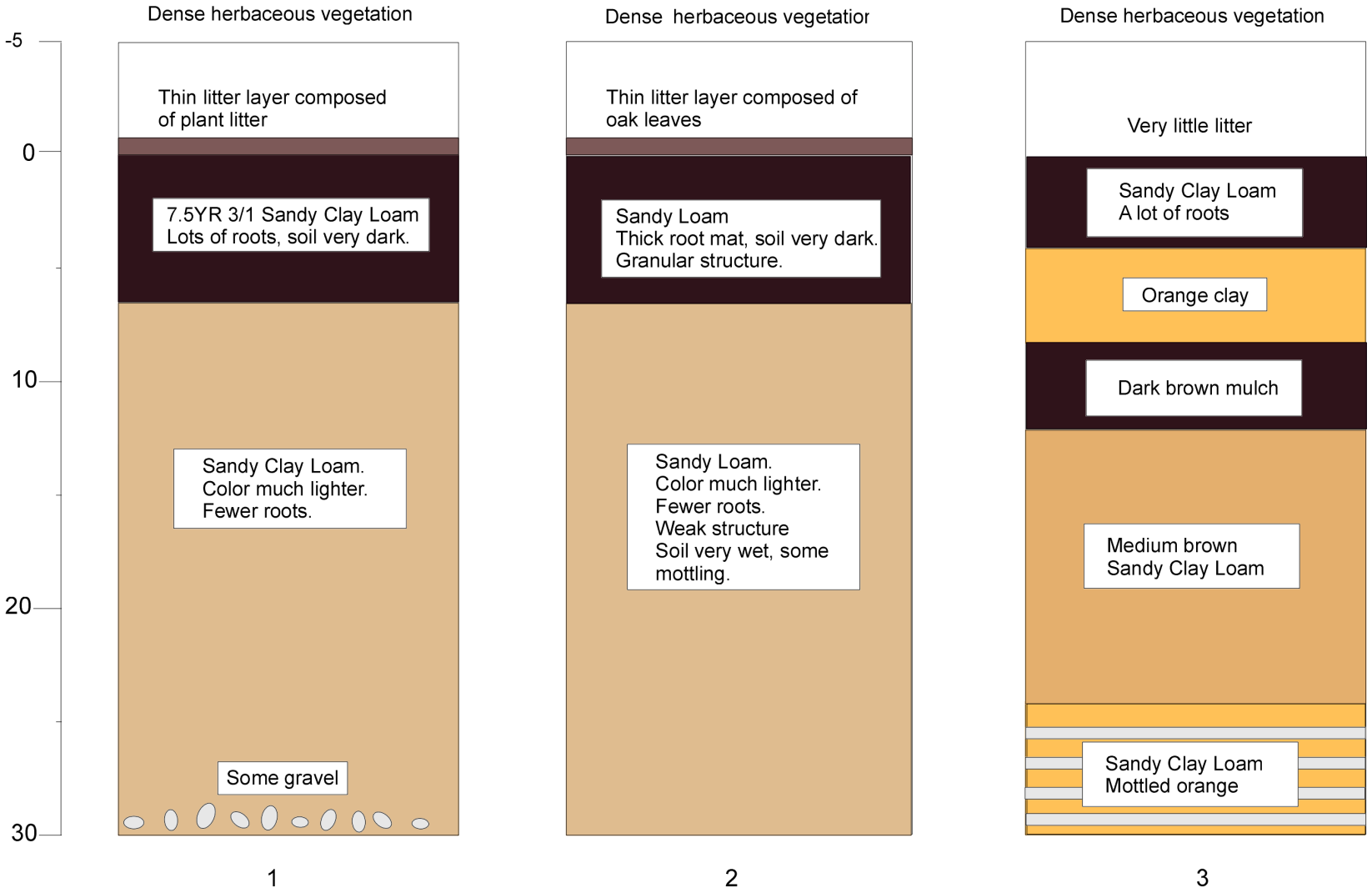


Figure D.9: BP soil profile.

Table D.52: BP Soil texture

Depth	Location		
	1	2	3
0-10 cm	Sandy clay loam 60.0% sand 17.9% silt 22.1% clay	Sandy loam 72.8% sand 10.6% silt 16.6% clay	Sandy clay loam 53.7% sand 20.1% silt 26.2% clay
10-20 cm	Sandy clay loam 53.3% sand 24.0% silt 22.7% clay	Sandy clay loam 55.1% sand 23.4% silt 21.5% clay	Sandy clay loam 54.9% sand 21.1% silt 24.0% clay
20-30 cm	Sandy clay loam 55.1% sand 21.1% silt 23.8% clay	Loam 44.8% sand 34.9% silt 20.4% clay	Clay loam 27.7% sand 38.6% silt 33.7% clay

Table D.53: BP Soil invertebrates total tally for entire site.

Common name	Scientific name	Number of individuals
adult beetles	Coleoptera	3
beetle larvae	Coleoptera larvae	-
common white grubs	Coleoptera: Scarabaeidae larvae	-
ants	Hymenoptera: Formicidae	4
centipedes	Myriapoda: Chilopoda	3
millipedes	Myriapoda: Diplopoda	1
potworms	Oligochaeta: Enchytraeidae	-
pill bugs	Crustacea: Isopoda	4
spiders	Arachnida: Araneae	-
springtails	Hexapoda: Collembola	-
slugs and snails	Mollusca: Gastropoda	-
fly larvae	Hexapoda: Diptera larvae	-
mites	Arachnida: Acari	-

Table D.54: BP Earthworm species identified.

Earthworm species	Number identified
Eisenia fetida	4
Lumbricus sp.	5
Pheretima sp.	3

D.10 Laurel Regional Hospital (LRH)

Sampling Date: July 20, 2004

Age at sampling: 10 years

Table D.55: LRH Earthworms - number of individuals and sum of lengths

	Location		
Depth	1	2	3
0-10 cm	13.5 worms, 67.5 cm	13 worms, 44.0 cm	14.5 worms, 63.0 cm
10-20 cm	8 worms, 34.5 cm	2.5 worms, 7.0 cm	worms, 7.5 cm
20-30 cm	7.5 worms, 35.5 cm	4 worms, 14.0 cm	0 worms

Table D.56: LRH Root biomass, air-dried

	Location		
Depth	1	2	3
0-10 cm	12.46 g	0.92 g	9.84 g
10-20 cm	10.24 g	0.25 g	4.64 g
20-30 cm	1.86 g	0.17 g	0.82 g

Table D.57: LRH Soil organic matter content

	Location		
Depth	1	2	3
0-10 cm	3.86%	8.08%	5.94%
10-20 cm	3.18%	4.38%	2.52%
20-30 cm	2.02%	2.36%	2.02%

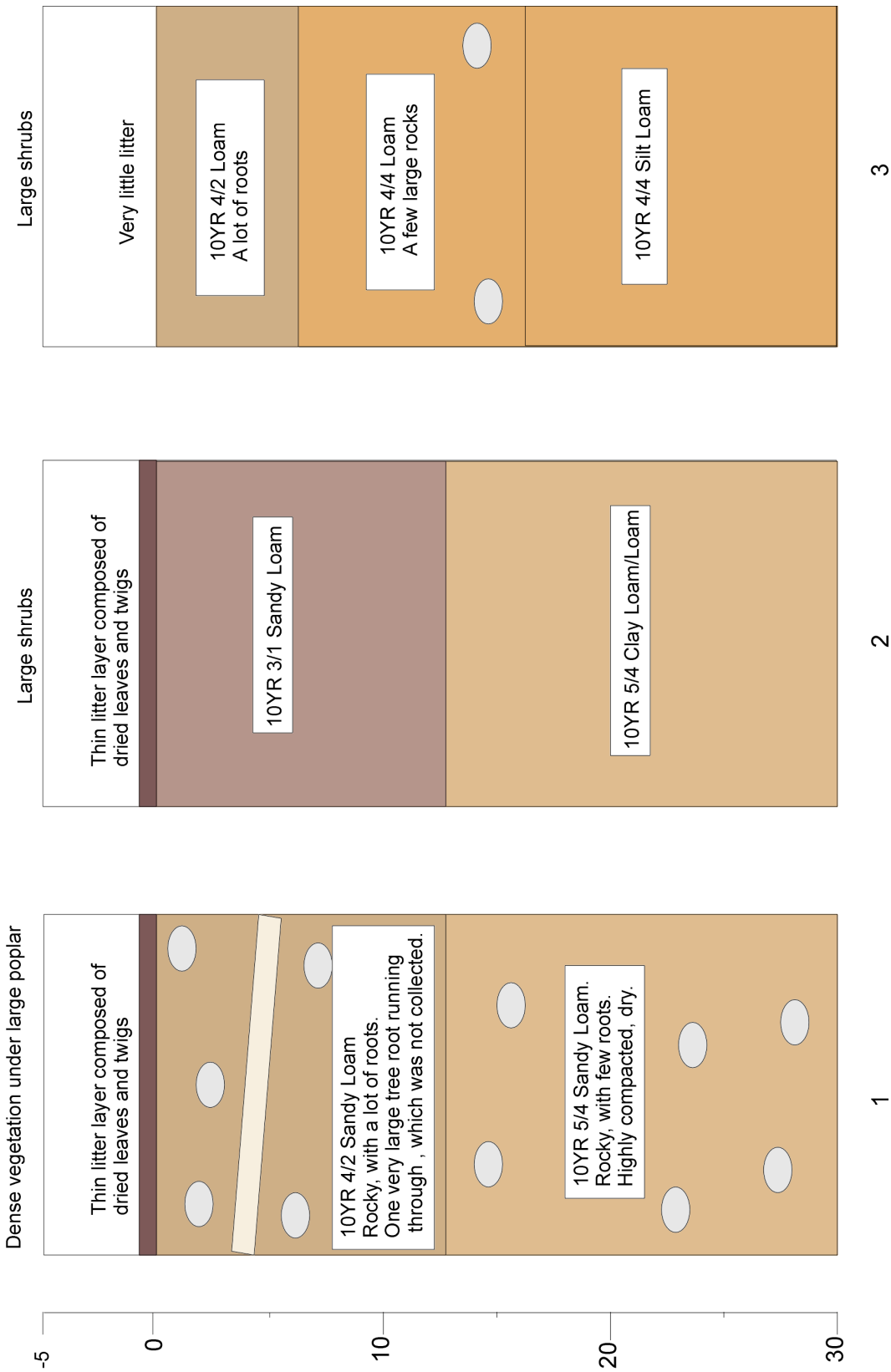


Figure D.10: LRH soil profile.

Table D.58: LRH Soil texture

Depth	Location		
	1	2	3
0-10 cm	Sandy loam 59.2% sand 20.7% silt 20.1% clay	Sandy loam 62.4% sand 21.2% silt 16.4% clay	Loam 36.4% sand 46.0% silt 17.5% clay
10-20 cm	Sandy loam 62.4% sand 25.4% silt 12.1% clay	Clay loam 39.0% sand 22.0% silt 39.0% clay	Loam 35.6% sand 46.1% silt 18.2% clay
20-30 cm	Sandy loam 59.4% sand 21.1% silt 19.5% clay	Loam 40.3% sand 40.1% silt 19.6% clay	Silt loam 22.6% sand 57.1% silt 20.3% clay

Table D.59: LRH Soil invertebrates.

Common name	Scientific name	Number of individuals
adult beetles	Coleoptera	1
beetle larvae	Coleoptera larvae	3
common white grubs	Coleoptera: Scarabaeidae larvae	1
ants	Hymenoptera: Formicidae	2
centipedes	Myriapoda: Chilopoda	1
millipedes	Myriapoda: Diplopoda	3
potworms	Oligochaeta: Enchytraeidae	-
pill bugs	Crustacea: Isopoda	3
spiders	Arachnida: Araneae	-
springtails	Hexapoda: Collembola	-
slugs and snails	Mollusca: Gastropoda	1
fly larvae	Hexapoda: Diptera larvae	1
mites	Arachnida: Acari	-

Table D.60: LRH Earthworm species identified.

Earthworm species	Number identified
Lumbricus rubellus	2
other *Lumbricus spp.*	25
Aporrectodea caliginosa	3

Appendix E

Microcosm Pilot Project

Short-term (1-month) microcosm experiments were conducted in Fall 2004 in order to assess earthworm survivorship in bioretention soil media with variable sand content. Earthworms survived in all three treatments. The experiment was conducted with the assistance of students enrolled in NRMT 470 (Heidi McMillen, Nicholas Regalia, Laura Senkowsky, Katie Struder, and Kyle Wagner). The results of this study were presented in poster form at the 2005 meeting of the American Ecological Engineering Society (AEES) in Columbus, Ohio.

Eighteen soil columns were constructed from 4-inch diameter clear plastic tubing. Each soil column was about 24 inches tall. A funnel was placed over the base of the tubing to allow drainage but prevent the soil from falling out. Three treatments were used:

Treatment 1: 50% sand, 30% sandy loam topsoil, 10% shredded hardwood mulch, 10% compost.

Treatment 2: 25% sand, 55% sandy loam topsoil, 10% shredded hardwood mulch, 10% compost.

Treatment 3: 80% sandy loam topsoil, 10% shredded hardwood mulch, 10% compost

Earthworms were collected from a previously sampled rain garden at Beltway Plaza Mall. Three soil columns for each treatment were inoculated with three large and two small earthworms, which were not identified. 100 mL of composted manure was added to each column to provide food for the worms. Each column was topped with 2–3 cm

of hardwood mulch. The columns were kept moist throughout the experiment. After 4 weeks, the columns were disassembled, and the surviving earthworms were retrieved. 66.7% of the earthworms in Treatment 1 and Treatment 2 survived (Figure E.1). 60% of the earthworms in Treatment 3 survived. The lower survivorship in the 0% sand columns may be explained by the development of low-oxygen conditions within the soil.

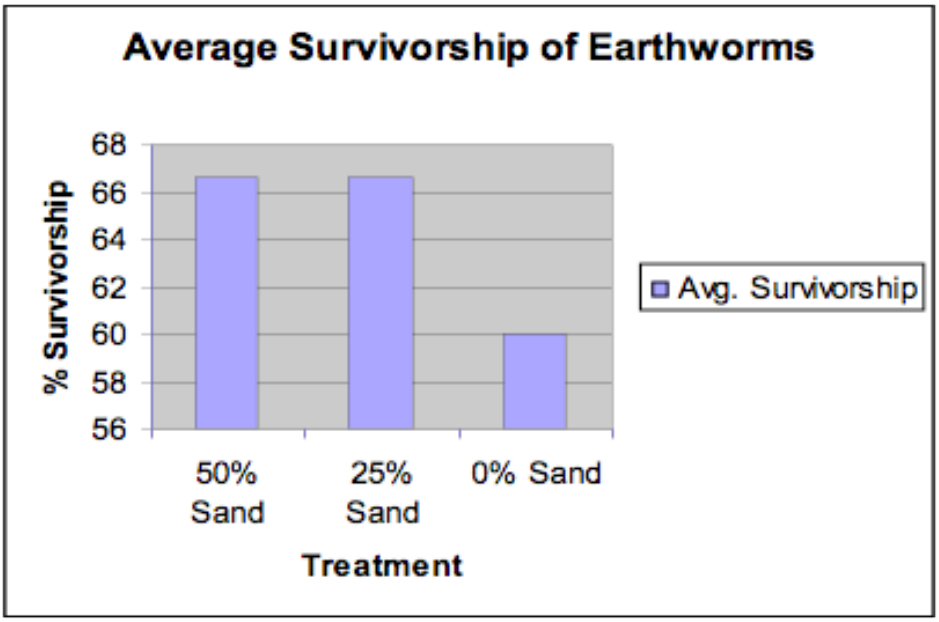


Figure E.1: Survivorship of earthworms in media of varying sand content.

Appendix F

Detailed Earthworm Survivorship Data for Microcosm Experiment

Table F.1: Column 2, Treatment 1

Initial earthworm size distribution	
Category	Number
small unpigmented juveniles, < 3 cm	1
medium unpigmented juveniles, 3–7 cm	4
large adult *L. terrestris*, > 10 cm	3
Final earthworm size distribution	
Category	Number
small unpigmented juveniles, < 3 cm	8
medium unpigmented juveniles, 3–7 cm	27

Table F.2: Column 3, Treatment 2

Initial earthworm size distribution	
Category	Number
small unpigmented juveniles, < 3 cm	1
medium unpigmented juveniles, 3–7 cm	4
large adult *L. terrestris*, > 10 cm	3
Final earthworm size distribution	
Category	Number
medium unpigmented juveniles, 3–7 cm	1
medium unpigmented adult, 3–7 cm	1

Table F.3: Column 4, Treatment 2

Initial earthworm size distribution	
Category	Number
small unpigmented juveniles, < 3 cm	1
medium unpigmented juveniles, 3–7 cm	4
large adult *L. terrestris*, > 10 cm	3
Final earthworm size distribution	
Category	Number
small unpigmented juveniles, < 3 cm	57
medium unpigmented juveniles, 3–7 cm	16
medium unpigmented adult, 3–7 cm	1
medium adult violet/greenish, 3–7 cm	2
large adult *L. terrestris*, > 10 cm	1
cocoons	2

Table F.4: Column 6, Treatment 1

Initial earthworm size distribution	
Category	Number
small unpigmented juveniles, < 3 cm	1
medium unpigmented juveniles, 3–7 cm	4
large adult *L. terrestris*, > 10 cm	3
Final earthworm size distribution	
Category	Number
small unpigmented juveniles, < 3 cm	1
medium unpigmented juveniles, 3–7 cm	4
medium unpigmented adult, 3–7 cm	1
small *L. terrestris* juveniles, < 3 cm	8
medium *L. terrestris* juveniles, 3–7 cm	9
large adult *L. terrestris*, > 10 cm	2

Table F.5: Column 8, Treatment 2

Initial earthworm size distribution	
Category	Number
small unpigmented juveniles, < 3 cm	1
medium unpigmented juveniles, 3–7 cm	4
large adult *L. terrestris*, > 10 cm	3
Final earthworm size distribution	
Category	Number
medium unpigmented juveniles, 3–7 cm	11
large unpigmented adult, 7–10 cm	1
medium green adult	1
medium *L. terrestris* juveniles, 3–7 cm	2
large adult *L. terrestris*, 7–10 cm	1
cocoons	1

Table F.6: Column 9, Treatment 1

Initial earthworm size distribution	
Category	Number
small unpigmented juveniles, < 3 cm	1
medium unpigmented juveniles, 3–7 cm	4
large adult *L. terrestris*, > 10 cm	3
Final earthworm size distribution	
Category	Number
small unpigmented juveniles, < 3 cm	25
medium unpigmented juveniles, 3–7 cm	16
medium unpigmented adults, 3–7 cm	2
small *L. terrestris* juveniles, < 3 cm	13
medium *L. terrestris* juveniles, 3–7 cm	5

Table F.7: Column 10, Treatment 2

Initial earthworm size distribution	
Category	Number
small unpigmented juveniles, < 3 cm	1
medium unpigmented juveniles, 3–7 cm	4
large adult *L. terrestris*, > 10 cm	3
Final earthworm size distribution	
Category	Number
small red juveniles, < 3 cm	1
medium red juveniles, 3–7 cm	2
medium unpigmented juveniles, 3–7 cm	3
medium unpigmented adults, 3–7 cm	1
cocoons	2

Table F.8: Column 12, Treatment 1

Initial earthworm size distribution	
Category	Number
small unpigmented juveniles, < 3 cm	1
medium unpigmented juveniles, 3–7 cm	4
large adult *L. terrestris*, > 10 cm	3
Final earthworm size distribution	
Category	Number
small unpigmented juveniles, < 3 cm	73
medium unpigmented juveniles, 3–7 cm	1
small juvenile *L. terrestris*, < 3 cm	3
medium juvenile *L. terrestris*, 3–7 cm	1
cocoons	14

Table F.9: Column 13, Treatment 2

Initial earthworm size distribution	
Category	Number
small unpigmented juveniles, < 3 cm	1
medium *L. terrestris* juveniles, 3–7 cm	1
large adult *L. terrestris*, > 10 cm	3
Final earthworm size distribution	
Category	Number
small unpigmented juveniles, < 3 cm	2
medium *L. terrestris* juveniles, 3–7 cm	1
cocoons	1

Table F.10: Column 14, Treatment 1

Initial earthworm size distribution	
Category	Number
small unpigmented juveniles, < 3 cm	1
medium unpigmented juveniles, 3–7 cm	4
large adult *L. terrestris*, > 10 cm	3
Final earthworm size distribution	
Category	Number
small unpigmented juveniles, < 3 cm	188
medium unpigmented juveniles, 3–7 cm	1
small juvenile *L. terrestris*, < 3 cm	8
medium juvenile *L. terrestris*, 3–7 cm	2
medium grey adult, 3–7 cm	1
cocoons	5

Table F.11: Column 17, Treatment 2

Initial earthworm size distribution	
Category	Number
small unpigmented juveniles, < 3 cm	1
medium unpigmented juveniles, 3–7 cm	4
large adult *L. terrestris*, > 10 cm	3
Final earthworm size distribution	
Category	Number
small unpigmented juveniles, < 3 cm	14
medium unpigmented juveniles, 3–7 cm	17
large grey adult, 7–10 cm	1
small juvenile *L. terrestris*, < 3 cm	3
medium juvenile *L. terrestris*, 3–7 cm	9
medium adult *Lumbricus sp.*, 3–7 cm	1
large adult *L. terrestris*, > 10 cm	1
cocoons	8

Table F.12: Column 18, Treatment 1

Initial earthworm size distribution	
Category	Number
small unpigmented juveniles, < 3 cm	1
medium unpigmented juveniles, 3–7 cm	4
large adult *L. terrestris*, > 10 cm	3
Final earthworm size distribution	
Category	Number
small unpigmented juveniles, < 3 cm	15
medium unpigmented juveniles, 3–7 cm	13
medium *L. terrestris* juveniles, 3–7 cm	6
large adult *L. terrestris*, > 10 cm	14

Appendix G

RAINGARDEN Model Development

G.1 State Variables

S: soil volume

S = 1 m^3

Derivation: assumed unit volume

O: soil organic matter

O = 9.15 x 10^4 g

Derivation: average value for all field samples from field survey

Average SOM = 6.% (by dry weight)

Convert to mass:

Bulk density of BSM = 1.5 g/cm^3 (typical value for a cultivated sand or sandy loam (Brady and Weil, 2002))

Total soil mass = soil volume × bulk density = 1.5 g/cm^3 × 1 m^3 × 10^6 cm^3/m^3 = 1.5 x 10^6 g

Mass of organic matter = total soil mass × % SOM = 1.5 x 10^6 g × 0.061 = 9.15 x 10^4 g

W: earthworms (number of individuals)

W = 310.7 individuals

Derivation: average value for all field samples from field survey

Average number of worms = 18.64 individuals for the entire sampled depth (30 cm) of

each 20 x 30 cm sampling area. Assuming that there are no earthworms deeper than 30 cm, convert to number per unit volume:

Number of worms in unit volume = 18.64 ÷ 600 cm^2 ×10,000 cm^2/m^2 × 1 m^3 = 310.7 individuals

V: void space

V = 0.5 m^3

Derivation: pore volume for an ideal soil = 50% of total soil volume (Brady and Weil, 2002)

Void space = 50% × total soil volume, S = 50% × 1 m^3 = 0.5 m^3

H: pore water

H = 0.08 m^3/d

Derivation:

For a sand/loamy sand at field capacity, water content = 8% of soil volume (Brady and Weil, 2002)

Volume of water held in pores at field capacity = 8% × total soil volume, S = 8% x 1 m^3 = 0.08 m^3

C: crust thickness

C = 0.4 cm

Derivation: average thickness for column tests subjected to continuous loading using kaolin as suspended solids in Table 5-1 of (Li, 2007)

G.2 Forcing Functions

I: Inflow Volume

I = 0.162 m^3 Derivation: based on the SCS Method of runoff estimation (McCuen, 2005)

Rainfall depth, P = 1/2”

Watershed area: raingarden area = 20:1

Watershed area, A = 20 m^2

CN = 98 (assume a paved surface)

Retention, S = (1000) / (CN 10) = 0.20

Runoff depth, Q = $(P - 0.2S)^2$ / (P + 0.8S) = 0.32” = 0.0081 m

Runoff volume, I = Q × A = 20 × 0.0081 = 0.162 m^3

D: TSS

D = 0.13 g/L (Li and Davis, 2008b)

expressed as incoming thickness in cm per L of inflowing runoff:

D = TSS / bulk density / area

Assuming TSS is kaolin as in Li and Davis (2008b), bulk density of kaolin = 1.46 g/cm^3 (average value of oven-dried surface-weathered and sedimentary kaolin samples, Table 1-A, Baumann and Keller (1975))

D = 0.13 g/L × (103 L/m^3) / (1.46 g/cm^3) / 104 cm^2

= 8.9 x 10^{-3} cm/m^3 of runoff

L: litterfall

L = 2.05 g/d

Derivation: at steady state, L = J_1 - J_{10}

G.3 Flows

$J_1 = k_1SOW$

J_1: earthworm assimilation rate

J_1 = 2.05 g/d

Derivation:

Earthworm biomass increases by 10% over 85 days (Binet and Trehen, 1992)

Growth rate = rate of assimilation of organic matter (feeding rate is not important, as most is egested back into the soil)

Growth rate = 0.1 g/g ÷ 85 days = 1.18 x 10^{-3}g/g/d

Assimilation rate = growth rate × number of earthworms × average size of adult *L. terrestris*)

Assimilation rate = 1.18e^{-3}g/g/d × 5.6 g/ ind (Satchell, 1967) × (310.7 ind) = 2.05 g/d

$J_2 = k_2SOW$

J_2: rate of earthworm reproduction

J_2 = 0.38 ind/d

Derivation:

Earthworm growth rate: .33–.56 g new worms ÷ g existing worms/yr (Lakhani and Satchell, 1970)

average = .45g/g/yr × 310.7 ind ÷ 365 d = 0.38 ind/d

$J_3 = k_6WW$

J_3: rate of earthworm death

$J_3 = 0.38$ ind/d

Derivation: $J_2 = J_3$ at steady state

$J_4 = k_3SOW$

J_4: rate of void creation by earthworm burrowing

$J_4 = 3.915$ x 10^{-4} m^3/d

Derivation: 2.5 cm/d/ind (average length of burrow created per day, (Bastardie et al., 2003) $\times$ $\pi(0.8 \text{ cm} \div 2)^2$ (average burrow diameter, Guild (1955)) $\times$ 310.7 ind

$= 391.5$ cm^3/d $\times$ 1 $m^3/10^6$ $cm^3 = 3.915$ x 10^{-4} m^3/d

$J_5 = k_4VH/O$

J_5: rate of void collapse due to wetting

$J_5 = 3.915$ x 10^{-4} m^3/d

Derivation: at steady state, $J_5 = J_4$

$J_6 = I(1\text{-}kC)$

J_6: infiltration rate

$J_6 = 0.158$ m^3/d

Derivation: at $kC_{max} = 1$

$C_{max} = 6" = 15.24$ cm (assumes entire ponding depth is filled)

$k = 1/ C_{max} = 0.066$ cm^{-1}

$J_6 = (0.162\ m^3) \times (1-(0.066\ cm^{-1}) \times (0.4\ cm)) = 0.158\ m^3/d$

$J_7 = k_5H$

J_7: exfiltration rate

$J_7 = 2.45\ m^3/d$

Derivation: based on results of microcosm experiment. Average initial exfiltration rate, control group $= 10.22\ cm/h \times 1/100\ m/cm \times 24\ h/d \times 1\ m^2$ (surface area) $= 2.45\ m^3/d$

$J_8 = k_7DI$

J_8: rate of crust growth (cm/d)

$J_8 = 3.46 \times 10^{-4}\ cm/d$

24% of TSS is captured at the soil surface (Li and Davis, 2008b)

Crust growth rate $= 0.24 \times D \times I = 0.24 \times (8.9 \times 10^{-3}\ cm/m^3) \times (0.162\ m^3)$

$= 3.46 \times 10^{-4}\ cm$

$J_9 = k_8CW$

J_9: rate of crust removal by earthworms

$J_9 = 3.46 \times 10^{-4}\ cm$

Derivation: At steady state, assume $J_8 = J_9$

$J_{10} = k_9O$

J_{10}: rate of microbial degradation of organic matter

$J_{10} = 0$

Derivation: assumed for simplicity

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