Urban development impacts on soil health and function:
A landscape architecture perspective from the Flint Hills Ecoregion.

by

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Abstract

Urban development is increasing worldwide, resulting in a decrease in healthy soil and leading to a loss in associated ecosystem functions. Understanding the impacts of urban development on ecosystem functioning and soil health is vital because healthy soil is essential for biosphere health. Landscape architecture relies heavily on healthy, high-functioning soil for the success of project work and the management of greenspaces to provide vital ecosystem services. Landscape architects are uniquely positioned to transform the landscape, prevent or restore degraded urban spaces, and promote well-functioning greenspace in urban areas, thus improving the ecological and social quality of urban spaces. Understanding the components of soil and how their attributes and interactions affect soil functions is essential to the profession. Understanding the impact of development on soil can help prevent land degradation due to careless design practices. This research sought to understand the effects of urban development and disturbance on soil and assess the potential for urban landscapes to provide similar soil health and function as native grasslands. This research informs readers of the importance of soil health and functions in creating living soils and healthy landscapes. By assessing sites under different land use and management practice in and around Manhattan, Kansas, USA, we researcher evaluated the impact of urban development on soil health using microbial function as the primary indicator. Recent urban development impacted soil nutrient pools influencing microbial function; however, landscape management influenced the range of those impacts. Understanding the implications of soil quality loss via management, urban disturbance, and other interventions should be of interest to landscape architects as these impacts diminish the health of the land and associated flora, fauna, and aquatic resources. Soil health influences the health of

human communities and the sustainability and ecological function of the earth and its ecosystems.

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Acknowledgments

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Chapter 1 - Introduction (Literature Review)

Why Soil is Essential

Ecosystem conservation and climate change are pressing issues for this generation. Humans influence and transform soil's biological, physical, and chemical properties through the process known as anthropogenesis (Soil Science Division Staff, 2017). Human influence has led to degradation at an unprecedented rate, leading to a new geological period known as the Anthropocene (Soil Science Division Staff, 2017). One cause of the change and degradation is the conversion of land to urban conditions. With the increase in global urbanization and 50 percent of the world population living in urban environments, it is essential to understand the effects of urban development on ecosystems and the climate (Lee et al., 2019; Naylo et al., 2019). The urban condition is described as "unique in nature, a realm almost utterly subject to the will and effort of human managers" (Nelson & Lajtha, 2017). Planners and designers are vital as shapers and managers of urban conditions. Landscape architects help foster better environments for people, plants, wildlife, and microorganisms through well-informed plans and designs. Their recognition of their role in combating ecosystem degradation and climate change is becoming more prevalent. It is the duty of landscape architects to be stewards of the environment by carefully considering the impact their projects may have on larger ecological systems and human communities (Grose & Frisby, 2019).

In a world with growing awareness of ecological degradation and adverse climate change impacts, conserving, restoring, and creating living soil is vital. Soil is the foundation for sustaining much of terrestrial and aquatic life on Earth and is critical to the function of the earth's biosphere (Doran & Parkin, 1994). Soil plays a crucial role in food production, resource production, building foundations, cleansing water systems, and the cycling of nutrients that

humans rely on (McBratney et al., 2014; Morel et al., 2004; Scheyer & Hipple, 2005). Soil is also responsible for environmental quality at the local, regional, and worldwide scales (Doran & Parkin, 1994; Doran & Safley, 1997). The most crucial ecosystem functioning for sustaining terrestrial life is found in soil (Young & Crawford, 2004).

A bold and vital fact is that the soil layer covering the earth is the difference between survival and extinction for most terrestrial lifeforms (Doran & Parkin, 1994; Doran & Safley, 1997). With all that soil achieves and provides, it is essential to acknowledge that soil is a non-renewable resource on a human timescale (Doran & Parkin, 1994; Doran & Safley, 1997; Jenny, 1980; Renella, 2020). Living, well-functioning soil may naturally degrade through erosion, fertility loss, acidification, compaction, and carbon loss (McBratney et al., 2014). However, human modification dramatically accelerates degradation. Soil degradation rates can increase at unprecedented rates due to human disturbance (Koch et al., 2013). The loss of soil through landscape disturbance and other urban development will pose a substantial problem in the future if this issue is not understood and addressed (Koch et al., 2013).

As landscape architects, understanding the role of soil in urban environments and the effects of land use, landscape maintenance, and soil disturbance can help inform design decisions and guide land use planning, design implementation, and long-term management (Kays, 2013).

Background

The Basics of Soil

Natural soil (also referred to as native soil) results from five soil-forming factors and, as visually described in Figure 1.1, occurs during four generalized “soil formation” stages. Primary factors include parent material, climate, vegetation, topography, and time—which interactively

influence the formation of soils. The soil is the finished product from the weathering of the parent rock or material (Nelson & Lajtha, 2017). Soil formation timeframes typically range from 100-400 years for every centimeter of topsoil (Doran & Safley, 1997). Soil components include inorganic mineral matter (sand, silt, and clay particles), organic matter, water, gas, and living organisms ranging from microbial organisms to insects (Doran & Parkin, 1994). Together the components of soil create a dynamic living system that plays critical roles in terrestrial ecosystems (Doran & Parkin, 1994; Doran & Safley, 1997).

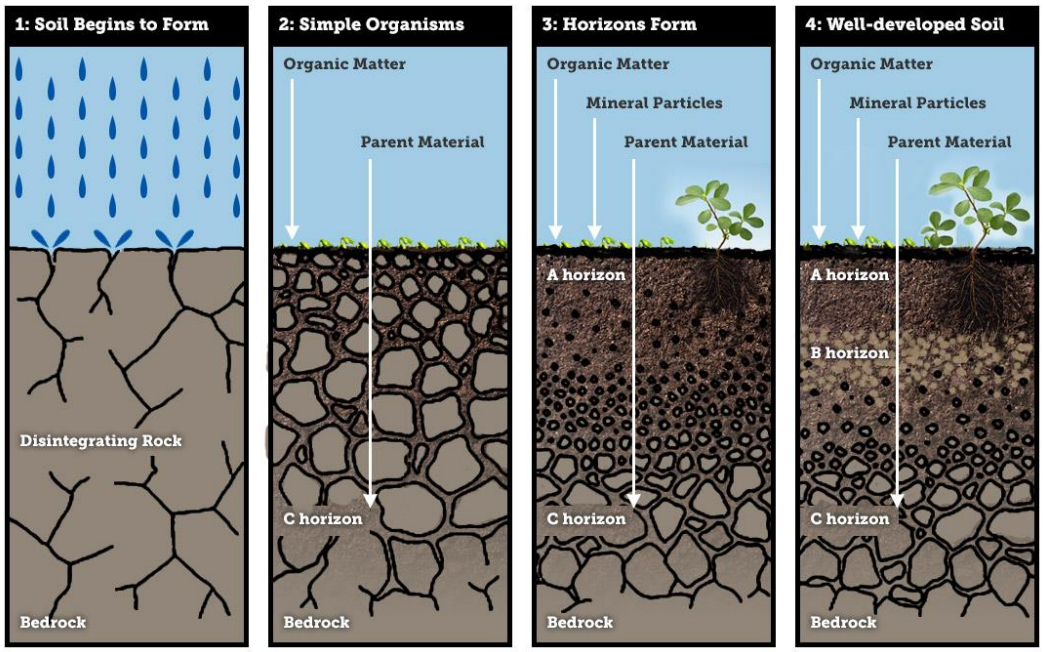

Figure 1. 1 Soil formation processes (WeatherSTEM, 2017).

Soil properties can vary from site to site and from region to region. Important soil attributes are categorized into the physical (bulk density, structure, infiltration, and texture), biological (organic matter, microbial biomass, and biotic activity), and chemical (pH, nutrient content, salt content, etc.) properties of soil (Adhikari & Hartemink, 2016; Doran & Parkin, 1994). As shown in Figure 1.2, soil texture relates to the amounts of sand, silt, loam, and clay in a particular soil or soil sample.

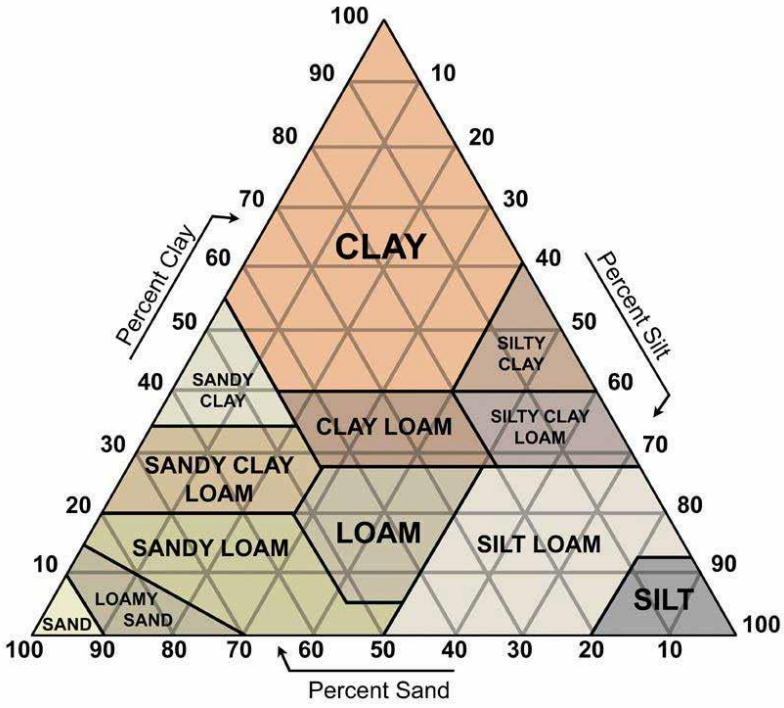

Figure 1. 1 Soil Texture Triangle (Kays, 2013).

Soil Ecosystem Services

Soil properties will affect soil ecosystem services. Ecosystem services are the capacity of natural processes and components to deliver goods and services that fulfill human needs either directly or indirectly (De Groot, 1992). A multitude of ecosystem services are offered by soil and support societal needs, environmental processes, and ecosystems at various scales (Rapport et al., 1997) (Figure 1.3).

Soil is a habitat for microorganisms responsible for maintaining soil biodiversity, decomposition, and nutrient cycling (Adhikari & Hartemink, 2016; Rapport et al., 1997). Soil organisms are also responsible for maintaining biological activities, such as enzymatic activities, which are responsible for nutrient consumption and decomposition in soil (Allison & Vitousek, 2004). Beyond microorganisms, the soil is accountable for many carbon-related processes, such

as nutrient storage, biomass production, carbon sequestration, and respiration (Renella, 2020). Soil also plays a significant role in the water cycle, acting as a water retention system, a water filtering system, and a water infiltration system (McBratney et al., 2014). Soil is thus a vital resource whose function influences the local, regional, and global environmental quality and the ability to maintain terrestrial ecosystems (Doran & Zeiss, 2000).

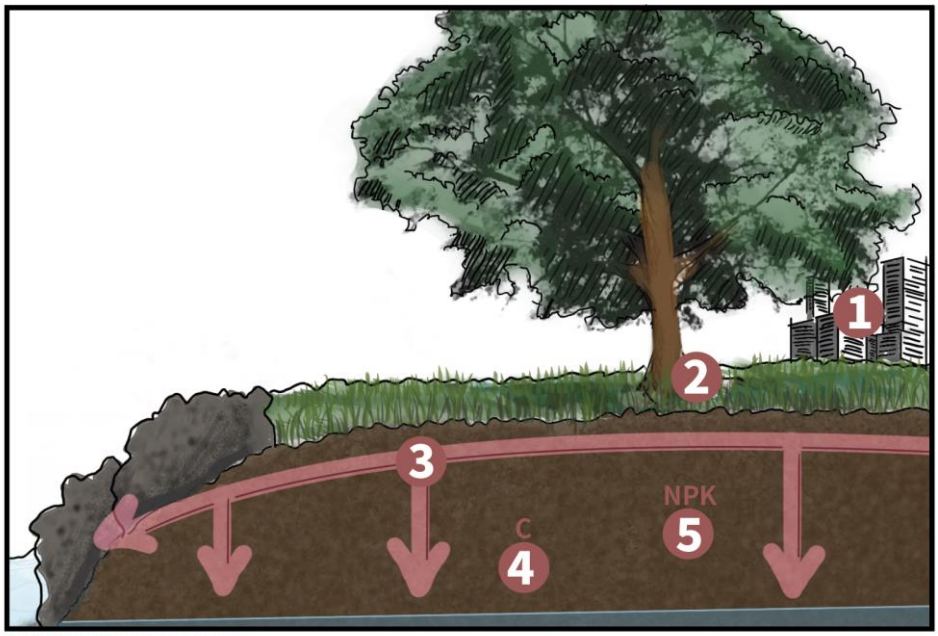

Figure 1.3 Ecosystem services provided by soil (Adapted from Calkins, 2012).

The function of the services soil provides is influenced by soil properties (Eekeren et al., 2010). For example, soil organic matter (SOM) and soil aggregate formation increases soil water holding potential (Chen et al., 2014; Franzluebbers, 2002). SOM also influences a soil's ability to buffer pH and is the main repository of soil carbon (Renella, 2020). Improvements in SOM and carbon can lead to higher water infiltration rates (Brown et al., 2011). Soil properties can be used as soil function and health indicators because of their connectedness to functional processes

and dynamics (Franzluebbers, 2002). Specifically, biological indicators in the soil will be the most sensitive, allowing for the identification of ecological failures long before potential physical and chemical changes in soil (Pankhurst et al., 1997). When considering the changes that urban environments bring to soil properties, we must understand that functional differences in the soil will be present as landscapes are disturbed through urban development.

Soil Quality and Health

Soil quality is determined by a soil's ability to function and its fitness for use (Doran & Parkin, 1994; Doran & Safley, 1997; USDA Natural Resources Conservation Service, 2015). Soil health, while sometimes used interchangeably with soil quality, is a term specifically used to describe soil as a dynamic living system (Doran & Zeiss, 2000). Soil quality is often associated with a soil's fitness for a specific use, whereas soil health is a broader term to describe the overall capacity for soil to function as a system that facilitates biological productivity, supports environmental quality, and maintains user health (Doran & Safley, 1997; Doran & Zeiss, 2000). Soil health is described as "the continued capacity of soil to function as a vital living system, within an ecosystem or land-use boundaries, in ways that sustain biological productivity, promote the quality of air and water environments, and maintain plant, animal and human health" (Doran and Safley 1997, p.8). Soil functional qualities include sustaining biological diversity and processes, regulating water flow, filtration and buffering of organic and inorganic materials, nutrient cycling and storage, and physical stability and support (USDA Natural Resources Conservation Service, 2015).

The USDA NRCS measures soil quality and health by evaluating inherent and dynamic soil properties, known as soil quality indicators. Inherent soil properties are defined as properties that do not change substantially over time and are typically the result of soil-forming factors.

Inherent properties are not management specific. Dynamic soil properties are management-dependent (USDA Natural Resources Conservation Service, 2015) as noted in Figure 1.4.

Soil quality indicators are classified as being in one of three groups: biological (b), chemical (c), and physical (p) (Figure 1.5). Soil quality indicators include water capacity (p), bulk density (p), infiltration (p), organic matter (b), soil electrical conductivity (c), soil enzymes (b), soil nitrate, phosphate, and other nutrients (c), soil pH (c), soil respiration (b), soil structure (p), microbial types and total microbial biomass (b) and soil organic carbon (b) (Pankhurst et al., 1997; Rapport et al., 1997; USDA Natural Resources Conservation Service, 2015).

Figure 1. 2 Soil indicator classification by time scales

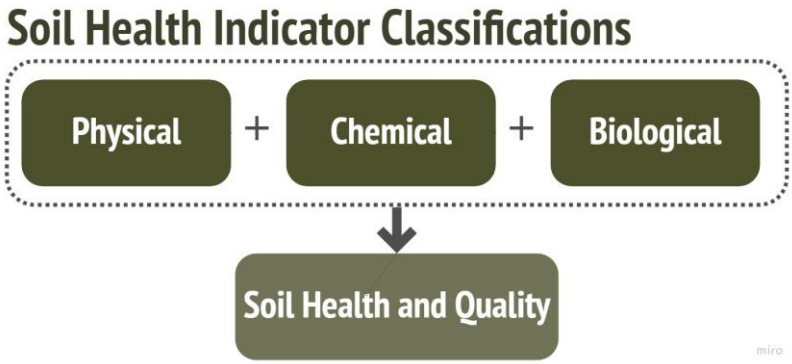

Figure 1. 3 Soil indicator groupings, which together impact soil health and quality.

Soil Carbon

Carbon is the foundation of all life on Earth, and because of this, carbon is considered a part of "natural capital"—providing ecological and economic value to soil (Ghaley et al., 2014). Urban soils, like neighboring natural soils, can act as a carbon sink or carbon storage medium

(Schalenghe & Marsan, 2009). Soil carbon storage helps provide nutrients for vegetation, reduces soil erosion, creates soil aggregates, and increases the biological activity within a soil system (Ghaley et al., 2014). Carbon soil storage and sequestration are essential, especially with an emphasis on mitigating atmospheric carbon's effect on climate change (Koch et al., 2013). It should be noted that soil contains twice as much carbon as Earth's atmosphere, making it just as important as, and more notable than, potential carbon pools such as the atmosphere or ocean (Koch et al., 2013)

Urban soils lose a large capacity for carbon storage and sequestration potential when they are covered by impervious surfaces, reducing the degree to which this surface can be utilized in urban environments (Brown et al., 2011). Carbon storage potential for soils in urban environments depends on more than if and how the soil is covered by vegetation. The quality of the landscape population densities, management histories, topsoil conditions, distance to the urban center, and age of development are important variables (Brown et al., 2011).

Soils in highly disturbed areas or areas recently developed for urbanization show lower carbon storage values than managed landscapes (Brown et al., 2011; Chen et al., 2014). Nevertheless, managed landscapes have demonstrated the ability to support more carbon storage than non-urban soils, which confirms the potential for carbon storage in urban soils with proactive management practices (Pouyat et al., 2006). As such, soil aggregate size plays an influential role in carbon storage in the soil. However, when a site is highly disturbed or compacted, soil aggregates are disrupted into smaller size distributions, causing a decrease in soil carbon (Chen et al., 2014). Biotic disturbances can immediately change soil carbon pools and carbon allocation within an ecosystem (Pickett & Cadenasso, 2008). Disturbances related to

aboveground biomass, the introduction of new species, or disease impacts on urban vegetation and wildlife can impact carbon and nutrient supplies to urban soils (Pickett & Cadenasso, 2008).

Urban carbon pools can be improved by implementing green infrastructure such as living roofs, rain gardens, and bio-swales, enhancing urban stormwater management, infiltration, and storage potential (Brown et al., 2011). Planting urban trees is also a way to improve soil carbon storage due to inputs to the soil from their roots (Chen et al., 2014). Additionally, amending with organic matter (such as plant litter) can supply a carbon source for degraded soil (Beesley, 2012). Lower carbon levels in soil typically indicate less functional soils, whereas higher carbon levels support more resilience (Koch et al., 2013). Carbon is an essential foundation in life and its function; increasing it in our urban environments is vital for our urban systems' future sustainability and function. Techniques to improve soil carbon pools are available, but soil conservation in its existing forms should be preserved if possible. Soils 25 years following development or older contain more carbon than newer soils; this implies at minimum, a 25-year recovery period for soils as a result of construction (Golubiewski, 2006). With soil being a resource that we rely so heavily upon, along with ongoing soil losses and degradation, we cannot afford to wait 25 years or more for soil health to recover.

Soil Microbial Function

Soil microbial functional diversity is any index of the range of ecological processes provided by a microbial community, and the capacity of all organisms in a microbial community to use different resources (Insam et al., 1989). Unlike community or species taxonomic diversity, functional diversity focuses on the overall functions microbial communities provide (Escalas et al., 2019; Insam et al., 1989). Observing microbial functional diversity in soils allows for a better

understanding of the functional roles that microbial communities may have to support overall ecosystem resilience (Escalas et al., 2019; Insam et al., 1989).

The role of microbes is essential in maintaining the function of terrestrial systems, but the specific roles and impact of microbial communities are still being defined (Moscatelli et al., 2018). According to Escalas et al. 2019, microbial communities play a significant role in nearly every biogeochemical process that makes Earth inhabitable. Microbial components in soil and their significance are often overlooked, however, due to their inability to be seen on the landscape by the naked eye and the additional challenge of measuring microbes (Doran & Parkin, 1994). It is important to note that microbial communities play crucial roles in global nutrient and water cycling (Doran & Parkin, 1994; Pankhurst et al., 1997). They help regulate critical processes in the ecosystem, such as primary production, decomposition, nutrient cycling, climate regulation, carbon storage, disease propagation, and pollutant transformation (Escalas et al., 2019; Pankhurst et al., 1997). The wide array of processes controlled by microbial communities is representative of the fact that they are the largest pool of diversity in nature (Escalas et al., 2019).

As landscape architects, we believe that understanding the impact of urban development, land use management, and land use change on soil can significantly grow our interdisciplinary knowledge and enable landscape planning/design decisions to be more ecologically appropriate than many currently implemented landscape architecture projects.

Understanding soil's functional diversity can help us better understand the biological quality and health of soil systems (Hofman et al., 2004). Conserving or re-creating higher functional diversity in soil microbial communities provides a more stable system due to the services offered within living, healthy soils (Hofman et al., 2004). A stable system can indicate a

landscape design project's longer-term success or resilience, which can be assessed for built and designed work and for natural ecosystems. Lower levels of soil microbial diversity can be an indicator of disturbance (Hofman et al., 2004).

Microorganisms account for 80 to 90 % of soil functions (Moscatelli et al., 2018) while only making up ~0.5% of soil mass (Figure 1.6). Microbial function in the soil can be a more sensitive indicator of soil health compared to other indicators of soil such as nutrient levels, soil texture, soil pH, soil temperature, and water content in soils because the microbial function involves the interrelationships between the biological (microbes), chemical (nutrients), and physical properties of soil systems (Nautiyal et al., 2010). Microorganisms are useful indicators to land managers because of their quick response to change (months to years) compared to other indicators, which may not readily change on a shorter-term management timescale (Pankhurst et al., 1997).

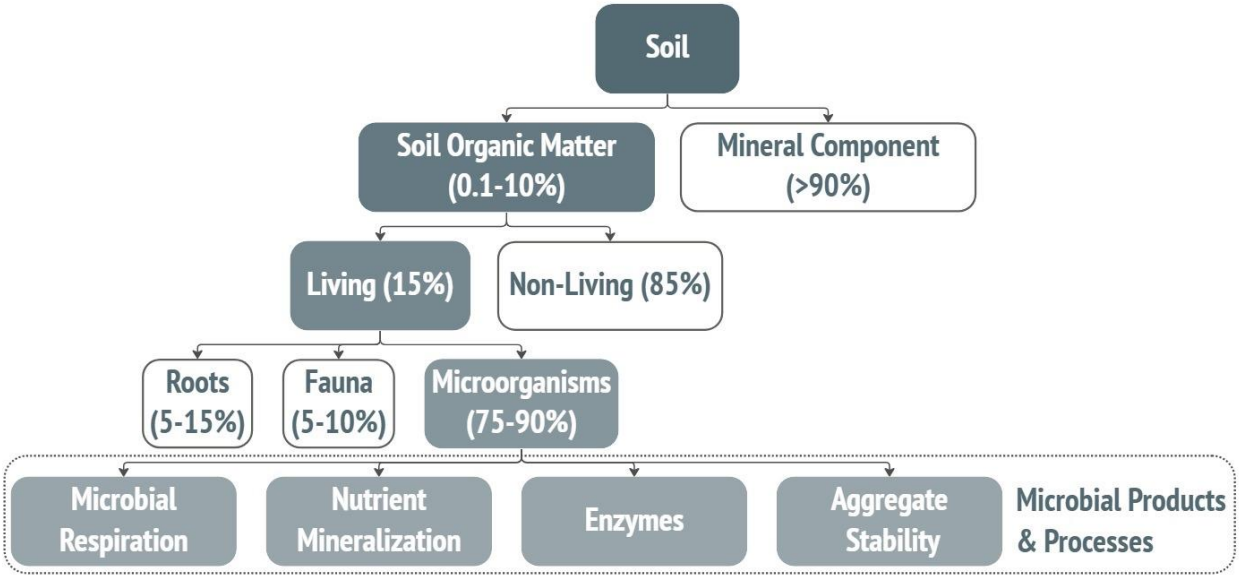

Figure 1. 4 Breakdown of soil components and the role of microbes (derived from Pankurst et al. 1997).

Urban Soils

Urban soils are impacted by human activity and are found in urban and suburban areas or other locations where human activities have created new buildings, roads, parking lots, and other infrastructure (Morel et al., 2004) (Figure 1.7). They can be defined in one of three ways. First, urban soil has a mix that is different from the neighboring natural and agricultural landscapes. The soil mix is modified by human intervention with the import and export of materials and the input of contaminants. Second, soil in parks or gardens may have similarities to agricultural soils, but the land management or use creates a unique profile different from the agricultural soil. Third, soil is modified by construction (and physical urban infrastructure). These soils often lay beneath impervious surfaces (Morel et al., 2004). Soils in urban areas are frequently highly compacted and relatively impervious, leading to increased strain on neighboring systems, especially riparian ecosystems, lakes, ponds, wetlands, and other aquatic areas (Morel et al., 2004; Schalenghe & Marsan, 2009).

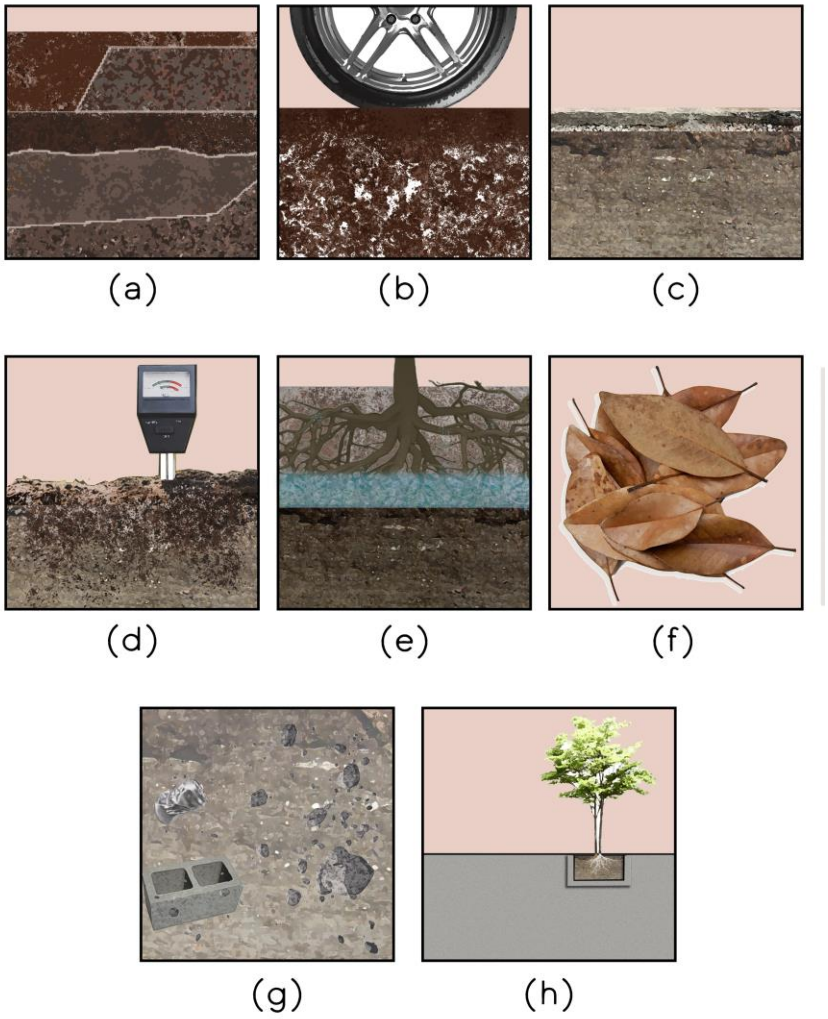

Figure 1. 5 **Urban Soil Characteristics; (a) grade changes caused by cut and fill, (b) compaction and loss of aggregate stability, (c) impervious crust, (d) altered soil pH, (e) poor drainage caused by compaction, (f) nutrient deficiencies, (g) anthropogenic materials (buried rubble and debris), and (h) small soil volumes inadequate for plant growth. These characteristics are detrimental not only to plant growth, but they reduce other natural soil values and benefits as well (Calkins, 2012).**

As with native soils, the basic principles for soil formation are similar in urban environments. However, urban soils are typically significantly altered by human influence. People may change the parent material, with the presence of concrete or other construction materials sometimes becoming primary parent materials. Changing parent material results in changes in the natural weathering process (Morel et al., 2004; Nelson & Lajtha, 2017). Pickett

and Cadenasso recognize that there is novel urban soil creation because of human activity in the urban environment but argue there is also continued soil modification in urban areas because of human activities beyond initial formation (2008) (see Figure 1.8).

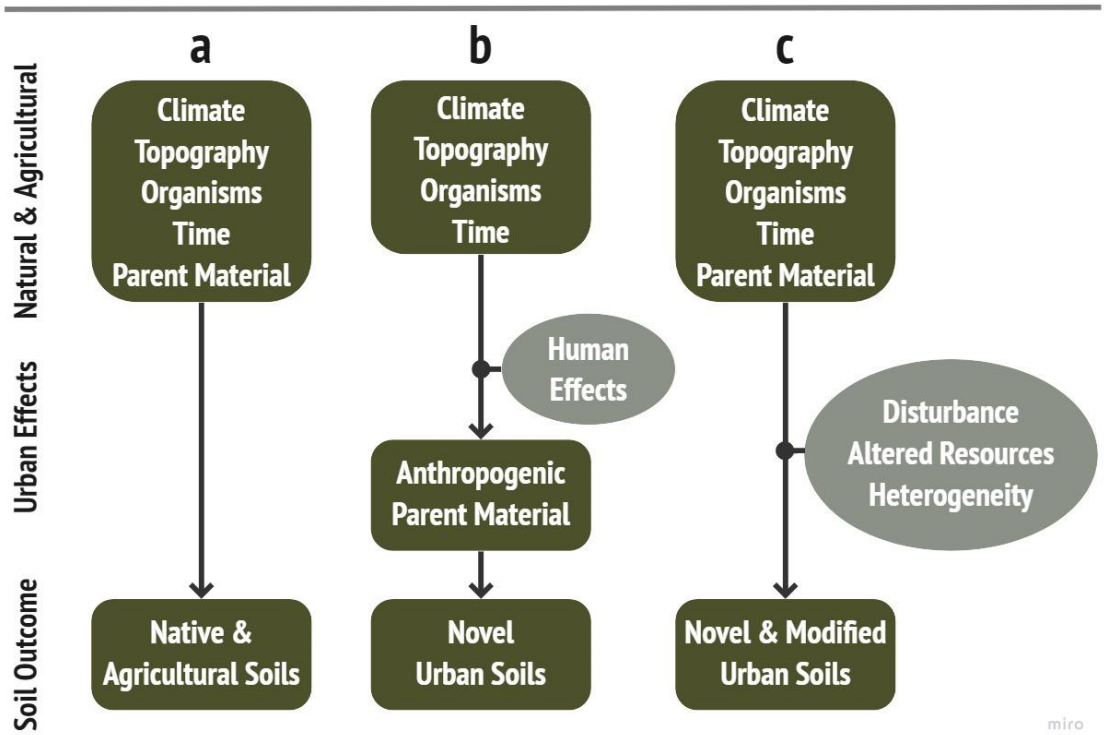

Figure 1. 6 A comparison of formation frameworks of soils and the impact of urbanization. a. Summarizes native and agricultural formation factors. b. Indicates a version of soil formation emphasizing the role of new parent material in forming novel urban soils. c. Indicated that all formation factors are influenced in urban soils, which result in new or modified existing soils in urban environments (Pickett & Cadenasso, 2008).

In urban soils, the effects of soil transportation are an added factor. When moving soil from one site to another, soil layers are often highly manipulated or destroyed, thus changing available nutrients and soil biota. The addition of fertilizer, waste material, trash, or other inputs also changes the nutrient profiles in urban soils (Morel et al., 2004; Nelson & Lajtha, 2017). As a result, urban soils are typically recognized as unique and classified as such. Understanding urban

soil is complex due to the lack of uniformity in soil content and soil profiles or layering (Pouyat et al., 2010).

As a result of disturbance or undesirable soil inputs, urban soils will often have characteristics and properties vastly different from native soils. Urban soils will often have a higher pH than soils in natural ecosystems or agricultural environments due to the influence of concrete and construction inputs (Brown et al., 2011; Naylo et al., 2019). The influence of construction and development disrupts the physical profile of soil, causing urban soil to suffer from compaction (increased bulk density), which leads to lower infiltration rates and lower water holding capacities of soil (Brown et al., 2011; Kumar & Hundal, 2016) (see Figure 1.9). A decrease in soil moisture decreases the activity of the soil microorganisms and can change the carbon and nitrogen processes (Tiemann & Billings, 2011). A notable example is when soil is under water stress it increases the microbes' demand for nitrogen and causes carbon to leave the system faster in the form of respiration (Tiemann & Billings, 2011).

Urban soils, unlike natural soils, are often disconnected from their environments (water, air, or organic inputs), and this disconnect comes from the barriers like sidewalks or sealing that occurs with impervious surfaces (Morel et al., 2004; Schalenghe & Marsan, 2009). Furthermore, with the input of waste materials in urban soils, we see an increase in heavy metal contamination. The contamination leads to limits in biological activity within the soil, changes decomposition rates, and decreases the available organic matter in the soil (Jaworska & Lemanowicz, 2019; Nelson & Lajtha, 2017). All these manipulations to the soil as well as land use changes result in changes in the soil's ability to perform ecosystem services (Zhao et al., 2013).

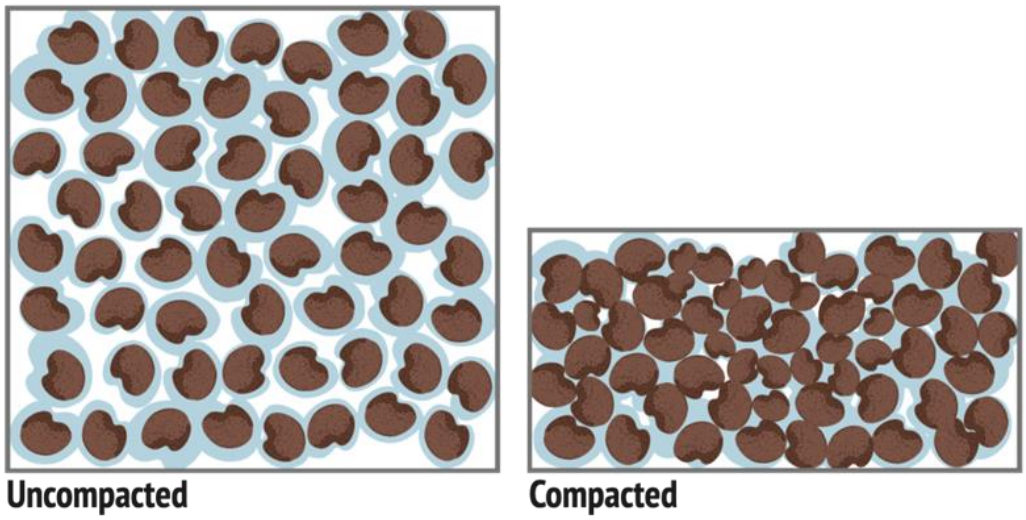

Figure 1. 7 Visualization of soil compaction.

Urban Soil Function

Soil in an urban environment is subject to limited resource availability and high disturbance and modification. As a result, urban soils function differently than those soils found in native or agricultural environments. A primary resource modification that exists in many urban soils is the availability of water. The limit of water infiltration into soils decreases soil moisture content, which can impact other functional capabilities in soil (Pickett & Cadenasso, 2008). These include reduction in organic matter content, biological function, and plant development (Pickett & Cadenasso, 2008). Urban soils are also frequently altered chemically with higher levels of heavy increases in heavy metals such as lead, chromium, copper, and zinc can affect ecosystem processes, such as plant quality and growth as well as microbial community composition and function (Pickett & Cadenasso, 2008; Xie et al., 2016).

Nutrient cycling is an important ecosystem service that supports life on earth by providing the required nutrients to organisms and systems to maintain their function. Notable nutrient cycling processes are nitrogen fixation, decomposition, mineralization, and the

acquisition of phosphorus (Ghaley et al., 2014). Like natural soils, urban soils can perform all these processes. However, a common condition of the urban environment is the change of pH in the soil due to human intervention and contamination. When soil pH is altered, the soil's resource pools of available nutrients change, making it harder for plants and microbes to gain access to the nutrients they require (Lee et al., 2019). Most nutrients in soil are only available to plants and microbes during an optimal pH range, when pH falls out of this optimal range (by increasing or decreasing), microbial community compositions will shift, enzyme activity will decrease, and nutrient uptake by plants it limited (Neina, 2019).

Microbial functioning drives processes such as nutrient cycling. Microbial extracellular enzymes are the primary process that drives complex soil organic matter breakdown into small molecules that are biologically available (Allison & Vitousek, 2004). These processes not only make nutrients and energy available to organisms in the soil, but they also provide the initial steps to key ecological processes such as decomposition and nutrient mineralization (see Figure 1.10). Because soil enzymes support soil functional processes, enzyme activity is a good indicator of the impact of human factors on the soil (Bielinska et al., 2012; Jaworska & Lemanowicz, 2019; Naylo et al., 2019). Knowing this can allow us to assess the impact of landscape architecture projects. Areas that are highly disturbed or under strong negative human influences can be relatively enzymatically inactive. Human influences can include contamination and compaction. Soil nutrient limitation can also be assessed through enzyme activity and by considering that enzyme activity increases when nutrient limitation increases (Allison & Vitousek, 2004).

A decrease in enzymatic activity can also result from the contamination of heavy metals such as Zn, Pb, Cu, and Cd (Bielinska et al., 2012). The presence of these metals limits the

ability of microorganisms to interact with or access nutrients in the soil. Soil pH is another factor influencing microorganisms' ability to interact with nutrients. When soil becomes more alkaline, interactions with water decrease, which reduces the metabolic capabilities of a soil ecosystem, such as nutrient breakdown (Bielinska et al., 2012).

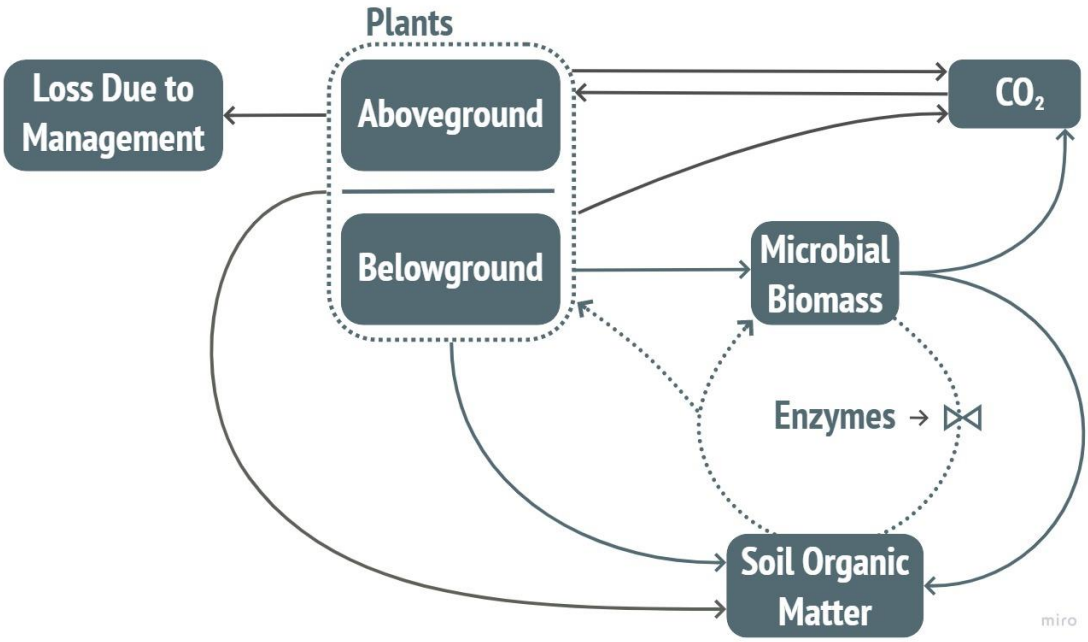

Figure 1. 8 Microbes play a key role in soil organic matter decomposition, driven by enzyme production. As a result, microbes heavily drive the global carbon cycle. Carbon that enters the soil from above and belowground plant production is returned to the atmosphere as CO_2 as a result of respiration by soil microorganisms.

The impacts of management and maintenance

The aboveground removal of biomass by any means (clipping, mowing, or fire) will have an impact on soil (Kitchen et al., 2009), however, management styles differ and will not equally impact soil. Fire, clipping, and mowing are discussed below.

Fire, a common prairie management practice for prairies, has a multitude of environmental impacts, including impacts to soil (Kitchen et al., 2009). When grasslands are burned, there is an increase in CO_2 release into the atmosphere, however, with plant regrowth

carbon is captured through photosynthesis (Gonzalez-Perez et al., 2004). In terms of impacts on soil, fire can have a fertility impact because it can increase the phosphorus and micronutrients available to living organisms by acting a mineralizing agent (DeBano, 1991; Gonzalez-Perez et al., 2004), but can cause a short-term reduction in microbial biomass and change the microbial community composition due to the impacts of fire affecting certain microbes differently (DeBano, 1991; Gonzalez-Perez et al., 2004). Fire also has the ability to increase soil pH (Gonzalez-Perez et al., 2004). SOM can decrease with fire due to the loss of aboveground litter inputs that are burned and displaced from the site; while with the absence of fire, more of the SOM on and within soil will decompose over time (DeBano, 1991).

Clipping, which is the removal of aboveground biomass by cutting grass or other types of vegetation, has been shown to decrease microbial biomass and microbial respiration in soil (Bremer et al., 1998). Clipping also can cause an increase in soil temperature (Bremer et al., 1998). Clipping and mowing in most cases are seen to be similar because they result in similar vegetative impacts, but it should be noted that clipping in this project is seen to be less of a disturbance because it does not use the heavy mowing equipment associated with mowing. Mowing removes aboveground biomass and litter inputs, which can result in a decrease in soil carbon (Kitchen et al., 2009). In research conducted by Kitchen, Blair, and Callaham, there was a greater reduction in soil carbon with mowing than with fire. Root biomass and root carbon and nitrogen concentration also decreased with mowing (Kitchen et al., 2009).

Soil and Landscape Architecture

Landscape architecture is a multifaceted profession. The responsibility of landscape architects lies in the planning, design, management, and promotion of outdoor environments both

built and natural (The American Society of Landscape Architects, n.d.). The environments in which landscape architects work include parks, campuses, plazas, greenspaces, trails, communities, streetscapes, and other open spaces in intensely developed urban cities. Because stewardship of the landscape is a primary responsibility of landscape architects, landscape architects should seek to create a bridge between the environment and human interventions. These efforts involve protecting well-functioning native or naturalized ecosystems and advocating for responsible landscape planning, design, and management. In short, landscape architects should help find and envision solutions to the problems that urban development creates (Grose & Frisby, 2019).

Historically, many landscape architecture projects have focused primarily on the aesthetic and social performance of a place. However, with significant impacts on ecological systems and dramatic climate changes (including intensification of drought and flooding), landscape architecture is moving to provide ecological solutions and integrated, high-quality performance in urban landscape planning, design, and management (American Society of Landscape Architects, 2022). Such initiatives include Sustainable Sites, Landscape Performance research, individual research by firms, and seeking carbon dioxide reduction and carbon sequestration through design. The Sustainable SITES Initiative® is a rating program that evaluates projects based on their suitability in all phases from planning and design to construction and long-term management (Green Buisness Certification Inc., 2023). The goal is to create and implement nature-based solutions to help mitigate the effects of climate change and conserve resources (Green Buisness Certification Inc., 2023). Landscape Performance research facilitated by the Landscape Architecture Foundation provides a collection of research and case studies to advocate and promote sustainable landscape solutions. Their focus is to better understand the

social, environmental, and economic solutions and benefits for specific planning/design projects and to help provide ways to measure the outcomes of a design. Specific to soils, LAF supports research focused on resilience, biodiversity, carbon, and climate (Landscape Architecture Foundation, 2023), all of which are influenced by soils in terrestrial landscapes.

The recent discussion of and movement towards Climate Positive Design (CPD), seeks "to provide a significant contribution to reversing global warming through the exterior built environment" (Climate Positive Design, 2023). This program encourages landscape architects to protect, conserve, restore, and re-create living soils and healthy, well-functioning ecosystems. By being climate positive, the goal is to remove as much atmospheric CO_2 as possible. Pamela Conrad, its founder, started CPD as a way to help find solutions to the climate crisis and plan a more resilient future. The CPD initiative provides tools and resources about how to make an impact wherever possible in the design of outdoor spaces. Specific resources include a design toolkit featuring a section on soil amendment and design strategies.

These combined sustainability, applied research, and climate positive design efforts demonstrate the need and desire of landscape architecture professionals to figure out sustainable solutions to pressing environment issues and problems, which include the protection conservation, restoration, creation, use, and management of soils within the urban environment.

Importance of Soil in the Field of Landscape Architecture

In the field of landscape architecture, soil is the foundation for nearly all project work (Craul, 1999). Landscape architecture relies on the soil to function according to desired parameters for designs to be successful. The chemical, biological, and physical characteristics in soil, and how they interact with one another, will determine a soil's suitability and limitations for planting and land use applications (Craul, 1992). Soil is important to all phases of a project from

landscape and land-use planning to design implementation and long-term maintenance and management (Craul, 1999). Project goals focused on sustainability, carbon sequestration, biodiversity, and sustaining microbial populations (which provide the foundation for all life on earth) require an understanding and willingness to support healthy, living soils (Solano, 2013).

Sustainability is the process of preserving, protecting, or improving the earth's varied resources and ecological systems for future generations of people and other organisms. Ian McHarg and William Marsh called on planners and designers to thoroughly understand regional and local ecological systems, including soil systems, as we engage in land use planning and landscape design (McHarg, 1992 ; Marsh, 2010).

In the process of manipulating sites, providing, or maintaining ecological function is key to accomplishing the goal of sustainability. As noted in the *Sustainable Sites Handbook*, soils are vital to the functioning of ecological processes, and in maintaining or improving the many services ecosystems provide and which are needed to maintain sustainable, resilient urban settings and human-centered developments (Calkins, 2012). Meg Calkins recognizes the slow formation of soil and discusses how the process of development can lead to soil benefits being lost through soil erosion, compaction, relocation, contamination, and overfertilization which result from urban development and land use (2012). It is noted that in urban environments, most soil has been modified or imported (Calkins, 2012). There are, as a result, two essential goals stated for soil management: 1) protecting existing soil with desirable traits, and 2) improving soils that have undesirable traits (Calkins, 2012). These two goals can be addressed through the fields of landscape architecture and land-use planning (working with related professionals) by using careful site assessment and analysis coupled with well-informed landscape design, construction/implementation, maintenance, and management (Calkins, 2012).

How Landscape Architecture Influences Soil

It can be stated that all human influence will result in changes in the biological structure of soils (Urban, 2008). Human-altered soil systems dramatically alter how soils interact with water and how water moves across a landscape (Scheyer & Hipple, 2005). Water movement within the soil is paramount to soil function and soil stability (Scheyer & Hipple, 2005). Water in soil that exists in a built or disturbed environment, such as a construction site or a new landscape development, can be of higher volume due to runoff and this increased volume of flowing water can lead to soil erosion on the surface, sedimentation, and an increase of urban pollutants within streams and other surface waters, and an increased leaching of nutrients in highly permeable soils. The increase in runoff can create hazards via the transportation of fertilizers, pesticides, herbicides, and other chemical treatments to other landscapes and into the local water systems (Scheyer & Hipple, 2005). The applications of such chemicals can also kill microorganisms and insects found within the soil (Urban, 2008). The modification of drainage in the soil can drive soil moisture conditions up or down, which will alter the rate at which soil microbial communities interact with organic matter (Urban, 2008).

Compaction of soil during the development or redevelopment of sites can lead to a decrease in a soil's ability to harmoniously interact with the surrounding environment, including organisms, air, and water (Urban, 2008). The degradation or negative alteration of ecosystem interactions will decrease the ability of organic matter to be distributed properly in the soil. Often, with the change in landscapes via excavation and grading comes a dramatic increase or decrease in soil oxygen levels. An increase in soil oxygen can lead to higher rates of organic matter decomposition in the soil, thus higher carbon loss. Soil altered by stockpiling, reshaping, grading, and transportation all suffer a degree of negative impact to nutrient pools and soil

aggregation (Craul, 1992). On the other hand, soil compaction greatly decreases soil oxygen and water absorption capabilities leading to stress and possibly death of vegetation and microbial life in a soil. Lastly, the change of plant material, removal of dead plant material, or the trimming of trees can lead to a decrease in system resources and nutrients, changing the soil system dynamics (Urban, 2008).

However, in contrast to all of the actual or possible negative impacts that come with the implementation of poorly conceived landscape design projects, there is great potential to protect, conserve, restore and improve site soils. Landscape architects have the ability to provide or increase areas of fertile soils, and to restore soils on site where this is needed and possible. They can specify actions and modifications to increase soil organic matter content and/or soil nutrients, and they can also modify soil structure, nutrient levels, pH, etc. for optimal plant growth and development, while promoting contaminant reduction in soils (Canfield et al., 2018).

Summary

Urban soils and the disturbance to soil as a result of development is only increasing. Realizing the influences of urban development and land use change on soil can influence decisions that maintain soil health and function through wisely-crafted planning/design and management strategies—leading to better urban development and landscape design work. By understanding impacts of development, we can start to mitigate potential negative effects, specify strategies in development for the protection, preservation, conservation, restoration, creation, and management of healthy, living soils on sites, and understand how to utilize long-term sustainable solutions for soils in all planning/design projects.

Soils provide an immense pool of services in urban environments and drive the function of urban ecosystems. By measuring the impacts on urban development on soil health, and the impacts of management across sites, we can start to understand how to best design and implement strategies to promote and sustain well-functioning soils. Landscape architecture as a profession has the unique position to implement and create design solutions to the global problems of soil degradation, starting with urban environments.

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Chapter 2 - The impacts of urban land development and management on soil health and function.

Abstract

Global soil degradation has been influenced in part through the conversion of land to an urban condition. With continually increased urbanization, it is important to understand the effects of urban development on ecosystem function and soil health. Soil is the foundation for sustaining life on earth and is critical to the function of the earth's biosphere. The promotion of green spaces supported by healthy soil can create stronger connections to functional ecosystems for urban residents. This research explored whether urban landscapes, including prairie restorations, can have similar soil health and function to native prairie. To assess this, soils were collected across seven sites, from native grassland to disturbed urban turf, and evaluated for physical, chemical, and biological differences. Soil health and function were quantified by microbial extracellular enzymatic activity, respiration, and biomass. Supporting variables included soil texture, organic matter content, water content, and pH. Urban development and how recently soil disturbance had occurred were shown to impact soil nutrient and organic matter pools and influence microbial function. Because sites range in intensity of development and management, there is a range in the transformation or modification in the soils. Although key differences existed, microbial biomass was not shown to be largely different across sites. However, microbial carbon cycling efficiency differed amongst sites as a result of development and management. Understanding the impacts of soil quality loss through landscape management, disturbance, and other urban development is vital as soil quality loss poses a substantial problem in the future if the issue is not appropriately addressed or managed.

Introduction

Urbanization is increasing worldwide in parallel with human population growth. Urbanization, or urban development, changes the land from a condition in which soils are vegetated and open to infiltration of precipitation, to a condition where most land surfaces are impervious and there is a predominance of buildings, typically in a dense setting (Nelson & Lajtha, 2017). Currently, more than half of the world's population lives in urban environments, and that trend is increasing (projected to be 68 percent by 2050). The global distribution for urban development is not equal (*World Urbanization Prospects: The 2018 Revision*, 2019) with urbanization being greatest in Europe (74.5%), North America (82.2 %), and Latin America (80.7%) as of 2018; however, urban growth in these regions is projected to be ~30 percent from 2018-2050. Other regions of the world have lower urbanization percentages. For example, Africa and Asia are less than 50% urbanized but are projected to grow more rapidly at a growth rate of over 105% (*World Urbanization Prospects: The 2018 Revision*, 2019). With this increased worldwide urbanization comes intensified environmental consequences.

At a local scale, urban development causes disturbance to soils and the life they support. The modification of soils in urban environments results in a heterogeneous soil profile, leading to little consistency in urban soil profiles and their physical and chemical characteristics (Pouyat et al., 2010). The soil profile refers to the vertical section of soil from the surface to the underlying parent material and bedrock (Urban, 2008). Urban soils are considered by some to be disturbed to the point of low health and fertility (Craul, 1992) as a result of intense development. Others expand the definition of urban soils beyond the single criterion of direct disturbance to define urban soils as soils that are altered by urban environmental modifications (Morel et al., 2017; Pouyat et al., 2020). As a result, defining and understanding urban soils is complex.

Urbanized sites range in their intensity of disturbance and urban variable impacts, therefore, cover a range of modification to the soil (Pouyat et al., 2010, 2020). Urban soils are also not affected solely by the disturbance of urbanization, since factors such as subsequent management, intensity, and frequency of use, vegetative cover, and urban climatic changes all influence soil function (Burghart, 2017; Pouyat et al., 2020).

Soil is a crucial foundation for life on Earth, playing a role in food and resource production, building foundations, and water systems (McBratney et al., 2014; Morel et al., 2004; Scheyer & Hipple, 2005), and urbanization disturbance to soil at local and global scales has biosphere impacts. Soil and soil organisms maintain biological activity responsible for nutrient cycling and decomposition of soil organic matter (SOM), which supports soil fertility and plant growth (Adhikari & Hartemink, 2016; Allison & Vitousek, 2004; Zhao et al., 2013). Soil biota are also accountable for carbon (C) and nitrogen (N) cycling processes, such as biomass growth, SOM respiration or CO_2 release, and soil C sequestration (Renella, 2020), having profound impacts on global C cycling. As a result of urban land use change, the ecosystem services provided by soil may be lost (Chen et al., 2014), while at the same time, urbanization and higher population increase demand for food, water, and energy (Morel et al., 2017), posing a serious challenge to future sustainability if the issue is not well understood and addressed (Koch et al., 2013). Climate change also has negative impacts on urban ecosystems, such as heat island effects (increasing temperatures), greenhouse gas emissions, flooding, and the challenge of preserving urban vegetation (Morel et al., 2017). However, urban soils, being the foundation for ecosystems in urban environments, also have the potential to help mitigate negative climate impacts and to provide ecosystem services and support green spaces in cities (Herrmann et al., 2017).

To understand the impacts of urban development and management on soil services, the concept of soil health is useful. Soil health is defined as: “The continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, promote the quality of air and water environments, and maintain plant, animal, and human health” (Doran & Safley, 1997, pg. 8). There are several related concepts that exist to describe soil health, which include soil fertility, soil quality, and soil security (Lehmann et al., 2020). Soil fertility is the soil’s ability to grow crops, food, fuel, and resources for human use (Lehmann et al., 2020). While soil health and soil quality are similar terms (Harris & Bezdicek, 1994), soil quality emphasizes the human uses of soil, valuing soil for its inherent physical, chemical, and biological characteristics that support soil function to maintain processes and grow goods (Doran & Parkin, 1994; Lehmann et al., 2020; Rapport et al., 1997). Soil health focuses on the living system that is soil and on attributes that change at management time scales (Rapport et al., 1997). Soil security conveys the goal of preserving life-sustaining soil worldwide as a common good (Lehmann et al., 2020) and implies that everyone has the right to the benefits and services of healthy soils. This right can be threatened by urban growth and development.

There is potential in urban sites to implement the creation and restoration of native vegetation, such as prairie restoration, and can also serve to improve soil health and function. Although the creation of prairies in urban areas and the influence on soil health has not been well studied, in the restoration of agricultural lands to prairie grasslands there has been notable research that shows a resulting increase in soil health and fertility (Li et al., 2021). Former research has shown in the short term, restoration or creation of prairie land increased soil aggregation, soil organic matter, total N, and nutrient mineralization (Li et al., 2021). Also, the

microbial communities demonstrated higher enzymatic activity, suggesting an increase in decomposition (Li et al., 2021).

Beyond urban development, site-specific management of green spaces also influences soil function and health. The removal of plant aboveground biomass by any means will have substantial impacts on soil nutrient dynamics, since SOM and soil C pools decrease with plant clipping, mowing, or fire (Kitchen et al., 2009). In addition to the loss of dead plant litter supplementing SOM pool, with less plant growth aboveground there tends to be a decrease in the root biomass, which can also lower the soil organic C concentration (Kitchen et al., 2009). Microbial function will control and impact soil nutrients and these interactions as well, soil microbes are responsible for regulating the decomposition of SOM nutrient cycling and making nutrients biologically available to plants and their roots (Escalas et al., 2019; Pankhurst et al., 1997). However, with the removal of plant litter and aboveground and belowground C contributions to the soil, microbial communities receive less SOM to provide energy to sustain biomass and thus less nutrients become available. In contrast to these concerns, some sources state that this removal can also stimulate the allocation of nutrients belowground (Yan et al., 2021). Like urban development, management of urban grass systems range in intensities, from no management beyond mowing, to the use of irrigation, fertilization, and chemicals (Thompson & Kao-Kniffen, 2019).

The objective of this research was to assess the impact of urbanization, vegetative cover, and management on soil health and function. I sought to understand how soil health and microbial function changes under different land cover, vegetation type, and management practices, across a gradient of undeveloped to highly managed urbanized sites. I predicted that (i) urbanized land cover and time since development (or soil disturbance) would have the greatest

impacts on soil health and function, due to the negative impacts of urban development, and that (ii) vegetation type (native tallgrass vs. turfgrass) and maintenance (fire, clipping, and mowing) would influence soil function based on the grass rooting depth, frequency of aboveground biomass removal, and intensity of management. Based on these predictions, I hypothesized a gradient of impact across sampling sites and their functional difference relative to a native tallgrass prairie with undisturbed soil (Figure 2.1).

Site Selection

Sites selected for the study were all located in or near Manhattan, Kansas, USA (39.18°N, 96.57°W): Undeveloped reference prairie sites were located at Konza Prairie Biological Station, eight miles south of Manhattan's town center, while urbanized locations cover a range of management types within city limits (Figure A.1). The selected sites vary in their management (burned annually, clipped annually, mowed annually, or mowed multiple times each month) and land use (urban, created prairie, restored prairie, or native prairie) (Table 2.1) (Table A.1). The managed landscapes at each study site were established at various points in time, ranging from a one-year establishment period before the time of sampling to 50+ years since vegetation was established. At one urban site with native prairie vegetation (Warner Park), the area around the site began urbanizing in 1956; however, the prior site history is unknown. The unique combinations of land use, maintenance, and establishment time were chosen to help better understand the impact of urbanization of native prairie systems, and how the implementation and management of either created or partially restored native prairie systems within urban conditions can help promote and remediate soil health.

Table 2. 1 Sampling locations size, establishment, land use, and management.

Site	Maintenance	Land Use	Vegetative Cover	Establishment	Size (acres)	Irrigated+ Fertilized
Konza Native Prairie*	Annual Burn	Grassland	Tallgrass	--	15.0	N
Konza Restored Prairie	Annual Burn	Grassland	Tallgrass	1997	6.18	N
Warner Park Prairie	Annual Mowing	Urban	Tallgrass	1956	82.0	N
The Meadow (restored prairie)	Annual Clipping	Urban	Tallgrass	2013	0.33	N
Beach Museum Lawn	Frequent Mowing	Urban	Turfgrass	1996	0.28	N
Eisenhower Lawn	Frequent Mowing	Urban	Turfgrass	2004	0.38	Y
Anderson Avenue Lawn	Frequent Mowing	Urban	Turfgrass	2021	1.28	N

*reference site

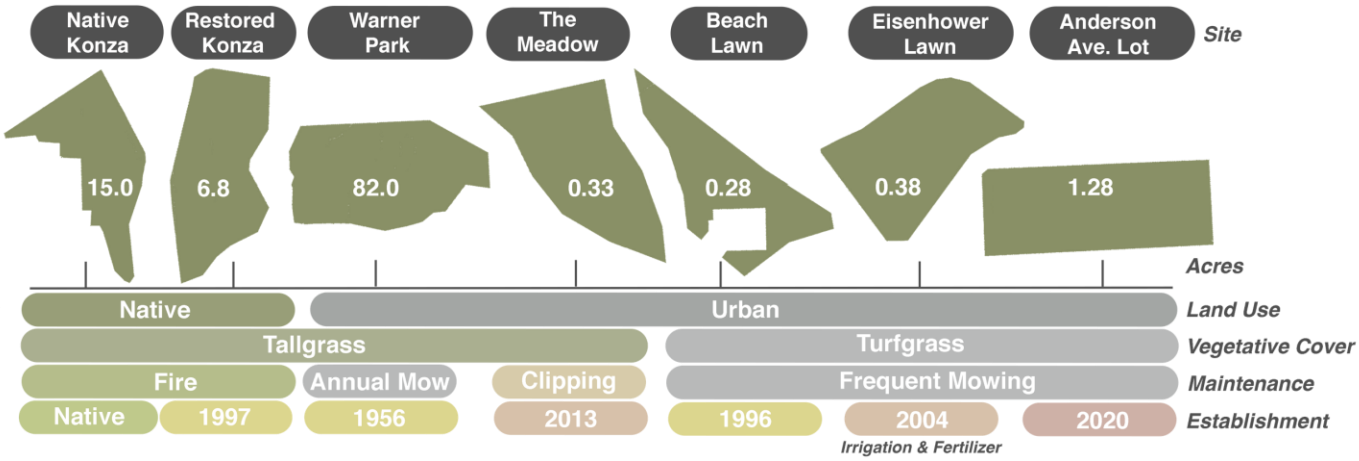

Figure 2. 1 Sampling site summary graphic.

Methods

Soil Sampling

Each of the study sites was sampled using a stratified random sampling method, so that the data remain representative of the heterogeneity within a site, while being easily translated across multiple sites with different areas and configurations (U.S. EPA, 2022). To maintain consistency among sites, a sampling grid of 12m x 12m was placed on all site locations (Figure A.10). The grid allows for sampling methods (sampling area coverage and number of samples) to

remain similar from site to site and amongst time points, even with individual site size variation. Ten cores per site were collected at all sites, with five additional cores taken at random at sites larger than two acres (or 0.81 hectares) to account for greater within-site variability. Soil samples were collected twice during 2022: First, a spring sampling (May 9-13) early in the growing season, and second, a late summer sampling (August 15-18) near the end of the growing season. Soil cores were collected at a depth of 15 cm (or 6 in) and a diameter of 3 cm (or 2 in) using a hammer core. Soil cores were placed in plastic bags and taken to the lab for sieving. Sieving was done using a 4 mm (about 0.16 in) sieve to remove roots and rocks from the soil, while maintaining soil aggregate structures. Following collection and the removal of roots, the soil was stored in the freezer at -20°C until processing. A subset of soil was processed for microbial respiration prior to being frozen (Boone et al., 1999).

Soil Chemical Assessment

For all soil samples at each time point, field soil temperature, electrical conductivity, and soil moisture were measured using the HydraGo Soil Probe (Stevens Water Monitoring Systems, Inc.) immediately adjacent to the soil core points. The probe was lightly pressed into the soil where measurements were instantly read and recorded. Gravimetric water content (GWC) was measured for all soil samples by drying ~5g of field moist soil for a minimum of 48 hours at 105°C in the lab. GWC was calculated by mass loss (Jarrell et al., 1999).

Equation 1 Gravimetric Water Content

$$\theta g = [(g\ moist\ soil) - (g\ dry\ soil)]/(g\ dry\ soil)$$

θg = gravimetric soil content as g H_2O g^{-1} dry soil.

Soil organic matter (SOM) was estimated using a loss on ignition technique (Nelson & Sommers, 1996). SOM was measured after the soil was dried, through combustion of organic matter in the same soil subsample, using a muffle furnace with a temperature of 400°C for three

(3) hours. To prevent rehydration following ignition, soil samples were dried at 105°C for a 24-hour period before SOM measurements were recorded.

Equation 2 Soil Organic Matter

Soil Organic Matter Content (g g^{-1}) = [(g dry soil) − (g combusted soil)]/ (g moist soil)

Soil pH was measured for all individual samples. A 1:2 suspension of field moist soil: DI water was stirred for 30 minutes using a shaker table at a rate of 100 rpm, then rested for 30 minutes and stirred again prior to pH measurement using a pH electrode (Robertson et al., 1999).

Soil total C and N was analyzed using a multiple-sample dry-combustion analyzer (Sollins et al., 1999). A total of ~30 µg of soil was required per sample. The soil was homogenized prior to weighing by grinding the sample to a fine consistency using a soil mill. Soils were weighed into tin capsules and then loaded into an auto sampler with the appropriate standards and blanks, then dropped into a combustion column, and maintained at a constant temperature of 1020°C. The samples were flash combusted in an environment enriched in O_2. The combustion produced CO_2, CO, N, NO, and water. These products passed through a reduction reactor, which removed excess O_2 and reduced N to N_2. The gases, with water and CO_2, passed through magnesium perchlorate to remove water. Lastly, the sample passed through a thermal conductivity detector which gave the signal of the concentrations of C and N present in the sample.

Soil Physical Assessment

Soil texture was determined using a soil hydrometer method (Bouyoucos, 1962). A mass of 50 grams of soil was mixed with 100 ml (about 3.38 oz) of 5% dispersing solution. The mixture was placed in a liter cylinder and diluted to 1000 ml (about 33.81 oz) with deionized water. The suspension of the water and soil mixture was mixed to gain a uniform suspension. A hydrometer was placed in the suspension. The hydrometer reads grams of soil per liter. The first

reading was taken at 40 seconds, and this reading represents the amount of silt and clay suspended. Another reading was taken at 6 hours and 52 minutes to determine the amount of clay in suspension. Temperature and density corrections to readings = + (0.2 unit to the readings of the samples for every 1° F above 67° F) – (0.2 unit for every 1° F below 67° F) – (the density of the blank at each reading).

Equation 3 Soil Texture

% clay = corrected hydrometer reading at 6 hrs, 52 min. x 100/ wt. of sample

% silt = corrected hydrometer reading at 40 sec. x 100/ wt. of sample – % clay

% sand = 100% – % silt – % clay

Bulk density was measured for soil sampled during spring only because it does not change seasonally. A hammer core sampler was used, prior to use a thin-walled plastic liner was placed into the core sampler. The core was hammered into the soil to a depth of 10 cm (about 3.94 in). The liner was removed, and the soil at the base of the sleeve was cut flush. The measured volume of soil was recorded. The soil was removed from the sleeve and placed in oven safe container and dried at 105°C (or 706°F) for 48 hours (Elliott et al., 1999). The final weight was recorded.

Equation 4 Bulk Density

$$Bulk\ density\ (g\ cm^{-3}) = WV$$

W = Oven-dried soil weight in grams V = Volume of core in cm^3

Soil Biological and Functional Assessment

Microbial extracellular enzymatic activity was assessed by measuring the hydrolytic and oxidative enzyme potentials, representing a set enzymes known to indicate nutrient and carbon cycling processes in soils (German et al., 2011; Wallenstein & Weintraub, 2008). Hydrolytic enzyme potential was assessed using fluorometric substrates (methylumbelliferone (MUB) and

methyl-coumarin (MC)) in 96 well plates. Hydrolytic enzyme assays include acid phosphatase (Phos; EC 3.1.3.1, 4-MUB-phosphate), leucyl aminopeptidase (LAP; EC 3.4.11.1, L-leucine-7-amido-4-MC), cellobiohydrolase (CBH; EC 3.2.1.91, 4-MUB-β-D-cellobioside), β-glucosidase (βG; EC 3.2.1.21, 4-MUB-β-D-glucoside), and β-N-acetylglucosaminidase (NAG; EC 3.2.1.14, 4-MUB-N-acetyl-β-D-glucosamine). These assays were processed with a final substrate concentration of 40 µM. All soil assays were processed at room temperature in 50 mM sodium acetate buffer (pH 5) for 2h (βG and Phos), 4h (NAG and CBH), or 18h (LAP). To stop the hydrolytic enzyme assays, solutions in the 96 well plates were increased to pH >8 with an addition of 10 µL 0.5 N NaOH to each well. The fluorescence of hydrolytic substrates was measured using a plate reader with excitation/emissions at 360/450 nm. All assays ran with appropriate blank and quench controls, and final activities were standardized to nmol substrate degraded g^{-1} dry matter. Microbial enzymatic activity ratios are calculated to assess the nutrient limitation across sites. Measured limitation rations include BG: (NAG+LAP) (measuring N-limitation in relation to C), BG: AP (Measuring P-limitation in relation to C), and (NAG+LAP): AP measuring N-limitation in relation to P).

Microbial respiration rates were assessed within two days of sampling. A mass of 25 g of field-moist soil was placed in a mason jar. Each jar was pre-fitted with a rubber septum. The jars were sealed quickly after soil placement, the time was recorded. Samples then rested for 1-3 hours in the dark, allowing for CO_2 accumulation in the jar. Microbial respiration rates (µg CO_2-C g-1 dry soil h-1) and δ13C values were measured using a Picarro G2101-i $13CO_2$ Analyzer (Zeglin & Myrold, 2013).

Microbial biomass was measured using chloroform fumigation (Brookes et al., 1985; Vance et al., 1987) on a subsample of 10 g of field moist soil. The soil sample was fumigated in

a chloroform atmosphere for 24 hours, which denatures cell walls and releases biomass-associated C and N into the soil. Extraction of soluble soil C and N in fumigated and unfumigated soil subsamples was conducted, and the difference between the two was determined and attributed to release from microbial biomass. Dissolved organic carbon (DOC) and inorganic N were extracted by shaking the soil sampling within 40 mL of 0.05 M K_2SO_4 on a rotator shaker for one (1) hour. Values were quantified via combustion and chromatography analysis with a Shimadzu TOC/TLN analyzer (Shimadzu Scientific Instruments, Inc., Columbia, MD, USA). All values are reported as µg C or N g^{-1} dry soil.

Microbial metabolic quotient was calculated utilizing the data collected from both microbial biomass and microbial respiration. To assess metabolic quotient, microbial respiration was quantified per unit of microbial biomass C. Microbial metabolic quotient was a factor used to assess the potential for soils to sequester C and understand the C cycling dynamics of sites (Anderson, 2003; J. Li et al., 2020).

Statistical Analysis

To test the effect of site, growing season, and the interaction between them on soil properties, health, and function, a two-way analysis of variance (ANOVA) model was used. For all ANOVAs, a post-hoc Tukey's test was run to assess which group (per the mean) differed from one another at a significance of 0.01 (99% confidence level). To assess the potential covariation of many measurements, a principal component analysis (PCA) was run for chemical and physical properties together, and biological properties independently. All statistical analysis was conducted in R studio, using version 2022.7.2.576.

Results

Soil Physical Indicators

Bulk Density

Bulk density differed ($P = 2.58^{e-15}$) among the seven research sites (Table 2.2). The bulk density of the Konza Prairie native grassland site was lower than all other sites (1.03 ± 0.08 g/cm^3) (Figure S 2.1). Bulk density across the sites ranged from 1.03 to 1.29 g/cm^3, all sites falling within the optimal range for plant production and root development (<1.60 g/cm^3) (USDA Natural Resources Conservation Service, 2008).

Soil Texture

Anderson Avenue Lawn (30.91 ± 4.99 %) was the lowest in sand percentage (Figure S 2.2). Silt percentage was higher in the native Konza soil (48.13 ± 5.44 %), Warner Park (48.99 ± 4.79 %), and Anderson Avenue (45.18 ± 8.01 %) soils compared to the rest of the sites (Figure S 2.2). Lastly, clay percentage was lower in the native Konza grassland (15.06 ± 3.28 %) and Warner Park (13.65 ± 3.95 %) soils (Figure S 2.2). However, even with differences in particle classes, all sites have the same soil texture, loam, using the USDA soil classification system (Figure 2.2).

Soil Gravimetric Water Content

Gravimetric water content (GWC) differed both among research sites ($F=40.724$, $p < 2^{e-16}$) and between growing seasons ($F=186.946$, $p < 2^{e-16)}$ (Table 2.2). GWC was higher overall ($p < 0.01$) early in the growing season (0.25 ± 0.05 g g^{-1}) compared to late in the growing season (0.18 ± 0.06 g g^{-1}) (Figure S 2.3). Across sites, Eisenhower Lawn had the highest water content late in the growing season (0.25 ± 0.08 g g^{-1}) and was higher (0.32 ± 0.03 g g^{-1}) than all sites,

except for the Konza native grassland (0.29 ± 0.02 g g^{-1}) and the Beach Museum Lawn (0.26 ± 0.03 g g^{-1}), early in the growing season.

Soil Chemical Indicators

Soil Carbon and Nitrogen

Soil total C (TC) did not differ between growing seasons (F=0.552, p = 0.459), but did vary among sites (F=23.756, p $<2^{e-16}$) (Table 2.2). Soil TC was highest in the Konza native grassland soils (3.73 ± 0.42 % TC) and lowest in the Anderson Avenue Lawn soils (1.80 ± 0.23) (Figure 2.3). Similarly, soil total N (TN) did not differ between growing seasons (F=0.361, p = 0.549), but did vary among sites (F=40.205, p $<2^{e-16}$). Soil TN was higher in the Konza native grassland (0.28 ± 0.04 % TN) and Eisenhower Lawn (0.26 ± 0.07 % TN) soils and lowest in the Anderson Avenue Lawn as well (0.12 ± 0.02 % TN) (Figure 2.4).

Soil total C: N differed between seasons (F=13.918, p = 0.00027), being higher early in the growing season (13.60 ± 1.67) compared to later in the growing season (12.89 ± 1.45). C: N was lowest in the Warner Park (12.58 ± 0.76) and Eisenhower Lawn soils (11.83 ± 1.04) early in the growing season and the Warner Park (11.87 ± 0.70) and Eisenhower soils (11.63 ± 2.33) late in the growing season (Figure S 2.4).

Soil organic matter (SOM) was greater later (0.042 ± 0.01 g g^{-1}) in the growing season on average than early (0.039 ± 0.01 g g^{-1}) in the growing season (F=21.855, p $<2^{e-16}$) (Table 2.2). Across sites, Anderson Avenue Lawn had lower SOM than the rest of the sites, in both the early growing season (0.026 ± 0.002g g^{-1}) and late growing season (0.030 ± 0.002 g g^{-1}), following similar trends to TC. The Konza native grassland was highest in organic matter content late in the growing season (0.055 ± 0.006 g g^{-1}) (Figure S 2.5).

Electrical Conductivity

Electrical conductivity (EC) was higher overall early in the growing season (4.15 ± 1.82 dS/m) on average in comparison to late in the growing season (3.31 ± 1.93 dS/m). EC was higher (>4 dS/m) across all sites except for the Konza native grassland (2.73 ± 0.68 dS/m) and Warner Park soils (1.75 ± 0.39 dS/m) early in the growing season (Figure S 2.6). Late in the growing season, Eisenhower Lawn (6.18 ± 2.29 dS/m) and the Konza restored grassland site (5.21 ± 1.15 dS/m) were higher than all other sites. EC across sites ranged from 1.70 dS/m to 6.17 dS/m. According to the USDA, soil with EC > 4 dS/m can indicate soil salinity problems, inhibiting plant production, growth, and microbial activity (USDA Natural Resources Conservation Service, 2011a).

pH

pH did not differ between growing seasons (F=4.710, p = 0.0315) (Table 2.2). Across sites, pH was lowest at the Konza native grassland (6.54 ± 0.31) site and Warner Park (6.33 ± 0.34) (Figure S 2.7). Anderson Avenue Lawn had the highest pH (7.93 ± 0.17). Anderson Avenue Lawn was the only site to fall out of the optimal range for plant growth (pH 6 to 7.5) (USDA Natural Resources Conservation Service, 2011b). Soil pH was within the optimal range for bacteria (pH 5 to 9) at all sites, however, only the Konza native grassland, Warner Park, and Beach Museum sites were within the optimal range for fungi (pH 2 to 7).

Soil Functional Indicators

Microbial Biomass C and N

Microbial biomass C exhibited an interaction between the site and the growing season (F=8.973, p = 2.25^{e-08}) (Table 2.2). Early in the growing season, the highest microbial biomass C was in the Meadow soils (3146.43 ± 851.19 µg g^{-1}) (Figure 2.5). Later in the growing season,

however, there were no site differences. Microbial biomass N was higher in the native Konza (86.57 ± 14.79 μg g^{-1}), restored Konza (80.65 ± 17.59 μg g^{-1}) and Eisenhower Lawn (104.16 ± 44.54) soils in comparison to the Anderson Avenue (54.22 ± 7.41 μg g^{-1}) soils early in the growing season (Figure S 2.8). Late in the growing season, Anderson Avenue Lawn (14.13 ± 8.84 μg g^{-1}) was lowest (22.78 ± 10.74 μg g^{-1}), following early growing season patterns. The ratio of microbial biomass C to microbial biomass N was higher in the Anderson Avenue soils (40.64 ± 8.89) compared to the Beach Museum (25.11 ± 12.40), the Meadow (37.15 ± 6.37), and Warner Park (17.68 ± 6.81) soils early in the growing season (Figure S 2.9). Late in the growing season, there was no difference.

Microbial Respiration Rates

Microbial respiration was higher ($F=151.721$, $p=1.90^{e-15}$) early in the growing season (9.27 ± 0.41 μg CO_2-C h^{-1} kg^{-1}) on average than later in the growing season (8.64 ± 0.48 μg CO_2-C h^{-1} kg^{-1}) (Table 2.2). In the early growing season, microbial respiration was lowest at the Warner Park sampling site (8.70 ± 0.28 μg CO_2-C h^{-1} kg^{-1}) (Figure S 2.10). Late in the growing season, microbial respiration was lowest at Warner Park (8.40 ± 0.33 μg CO_2-C h^{-1} kg^{-1}), the Meadow (8.39 ± 0.34 μg CO_2-C h^{-1} kg^{-1}), and Beach Museum Lawn (8.04 ± 0.49 μg CO_2-C h^{-1} kg^{-1}) sampling sites.

The growing season did not affect the metabolic quotient (qCO_2) ($F=3.403$, $p=0.671$), however, there was an interaction between the site and the growing season ($F=5.252$, $p = 6.10^{e-05}$) (Table 2.2). Early in the growing season, Eisenhower Lawn soils exhibited the highest qCO_2 (12.54 ± 4.86) (Figure 2.6). Late in the growing season, qCO_2 in Anderson Lawn soil (11.27 ± 6.29) was significantly higher than in Konza native grassland (5.23 ± 2.08), Warner Park (3.93 ± 2.12), and Beach Museum soils (4.85 ± 3.76).

Microbial Enzymatic Activity and C: N: P Limitations

Ratios of C-acquiring enzymes to N-acquiring enzymes (ln(βG): ln (NAG+LAP)) were lower on average in the late growing season ($F=10.78$, $p < 2^{e-16}$) (Table 2.2) and lowest in the Konza native grassland (0.64 ± 0.02), Warner Park (0.63 ± 0.02), and Anderson Avenue Lawn soils (0.62 ± 0.03), indicating stronger microbial N limitation at those times and sites (Figure 2.7). Ratios of C-acquiring enzymes to P-acquiring enzymes (ln(βG): ln (AP)) were lower in the Konza native grassland (0.96 ± 0.04) and Warner Park soils (0.94 ± 0.03), indicating stronger P limitation at those locations (Figure 2.8). Ratios of N-acquiring to P-acquiring enzymes (ln (NAG+LAP): ln (AP)) were higher on average ($F=8.607$, $p = 0.004$) late in the growing season and highest in Anderson Avenue Lawn soils both early (1.62 ± 0.007) and late (1.65 ± 0.06) in the growing season, indicating the greatest N limitation in relation to P at those times and locations (Figure 2.9). Overall, the Konza native grassland and Warner Park soils indicated the greatest microbial P limitation in relation to C. In contrast, N limitation is greatest in Anderson Avenue Lawn soils in relation to both C and P.

Individual enzymatic activity was higher on average early in the growing season for AP, βG, CBH, and NAG. LAP was the only enzyme to exhibit lower activity early in the growing season compared to late in the growing season. All activities differed among sites, with season interactions (Table 2.2). AP activity was highest early in the growing season in the Native Konza grassland, and the Warner Park soils (Figure S 2.11). Similarly, LAP was highest at Warner Park than at all sites except the native Konza grassland soil, both early and late in the growing season (Figure S 2.11). Konza native grassland, the Meadow, Beach Museum Lawn, and Eisenhower Lawn soils had higher βG activity than the other sites early in the growing season (Figure S 2.11), while late in the growing season, Native Konza grassland and Anderson Avenue Lawn

soils demonstrated the lowest βG activity. Like βG, CBH had the lowest activity in Anderson Lawn soils in both late and early in the growing season (Figure S 2.11), while the Meadow, the Beach Museum, and Eisenhower Lawn soils had the highest activity during both growing seasons. NAG activity did not differ between seasons and restored Konza soils had the lowest NAG activity compared to all sites except the Meadow.

Summary Results

Principal Component Analysis

A principal component analysis (PC or PCA) of the soil samples was used to assess the covariance among biological variables and another for the physical and chemical variables. PC1 for chemical and physical variables early in the growing season explained 39.7% of the variance and was most strongly correlated with electrical conductivity (EC), percent silt, percent clay, and pH (Table 2.3, Figure S2.12). PC2 explained 24.2% of the variance and was most strongly correlated with the percent sand and gravimetric water content (GWC). Late in the growing season, PC1 explained 35.8% of the variance and was most strongly correlated with percent silt, percent clay, pH, and bulk density. PC2 late in the growing season was most strongly correlated with GWC and EC.

The PCA of biological variables early in the growing season indicated that PC1 explained 30.8% of the total variance and was most strongly correlated with C acquiring enzymatic activity (βG and CBH) and organic matter content (Table 2.3, Figure S2.13), and PC2 explained 21.7% of the variance. It was most strongly correlated with the microbial metabolic quotient, P regulating enzymatic activity (AP) activity, leucyl aminopeptidase (LAP) activity, and total microbial biomass N. Late in the growing season, biological variables PC1 explained 26.6% of the variance and was most strongly correlated with microbial metabolic quotient, microbial

biomass C and N, and organic matter content, and PC2 explained 22.4% of the variance and was most strongly correlated with βG, cellobiohydrolase (CBH), and AP enzymatic activity.

Seasonal Climate

To contextualize annual drivers for precipitation and climate, the seasonal precipitation was compared to the average since 1987, showing that the sampling season in 2022 did not fall out of the average range (Figure S2.14).

Discussion

This study assessed urbanization's effects on soil health and function across a range of sites. I predicted that land cover and time since development (soil disturbance) would have the greatest impact on soil health. Results showed a varied response to this prediction, while overall urban sites had lower organic matter than the native Konza, the function in these soils was equal or greater than the native Konza sites. However, the site assessed following immediate intense disturbance, Anderson Avenue Lawn, demonstrated significantly poorer functioning and nutrient depleted soils.

The second prediction of vegetative cover type and maintenance having an influence on soil was not strongly supported among all sites, but was evidenced at Eisenhower Lawn. Eisenhower Lawn demonstrated high activity and increased organic matter compared to the remaining urban sites. However, most sites did not see significant change based on maintenance (fire, clipping, mowing) and vegetative cover (tallgrass, turfgrass). Instead, seasonal factors such as water content and pH may be responsible.

Site Soil Properties

Although all the sampling sites were local to Manhattan, Kansas, they are under different land use and management regimens, which could lead to long-term changes in the soil character. Chemical and physical properties in soil can influence soil biological function, so to assess the potential management level effects on soil function I needed to account for potential chemical and physical drivers in soil apart from management. Management and disturbance have the potential to influence and change the soil profiles. Due to the selected sites ranging in intensity and duration of the human impact, I expected and saw a range in the transformation or modification in the soils.

The urban condition can influence and increase bulk density through the process of compaction (Nelson & Lajtha, 2017), and our data reflected this phenomenon, as the bulk density of Konza native grassland soil was lower than all other sites. However, all sites fell within the optimal range for plant production, and bulk density was not correlated to other variables, suggesting it did not impair soil biological function. Similarly, soil texture varied somewhat, but all soil texture classifications were the same, even though there were classified differently under the NRCS web soil survey as Reading (Konza native and restored, Beach Museum Lawn), Smolan (Eisenhower), Smolan-Reading (Anderson Avenue, the Meadow) or Geary Silt Loams (Warner Park). The most important potential physical driver of soil function was soil water content. Water content was likely higher earlier in the growing season as a result of higher precipitation and lower temperatures in May compared to August, higher at the Eisenhower site because of irrigation, and higher at the Konza native grassland, likely as a result of the diverse prairie vegetative cover and organic matter content, which assist in processes of water infiltration and aggregate stability, resulting in more consistent soil temperatures and

moisture storage in the soil (Teague et al., 2011). The differences in water content can cause changes in microbial community function (Jangid et al., 2009). Such changes include shifts microbial community composition, microbial biomass, and microbial activity (enzyme activity, respiration, and nutrient decomposition) (Brockett et al., 2012; Geisseler et al., 2011).

Urban soils are often altered by human activity through the presence of concrete and the addition of waste, fertilizer, or other forms of nutrient and chemical inputs (Morel et al., 2004; Nelson & Lajtha, 2017), changing soil properties. Under urban land use, soils often exhibit higher pH (more alkaline) due to the influence of carbonate from concrete and construction materials (Brown et al., 2011; Morel et al., 2004; Naylo et al., 2019). In this study, all urban sites had a higher soil pH than the native Konza grassland site, except Warner Park, which is located on an untilled native prairie surrounded by urban context. The restored Konza prairie soil pH was higher than the native prairie; pH has been documented to increase with the age of restoration (Rosenzweig et al., 2016).

Nutrient Pools

The process of development and the conversion of a natural landscape to a designed and manicured landscape results in some degree of physical disturbance (Pouyat et al., 2010). As a result, soil C and N can be lost, either through the erosion and removal of the topsoil layer when soil is stockpiled or if the soil surface is covered during grading, burying topsoil (Pouyat et al., 2010). Soils in highly disturbed or recently developed areas generally have lower C levels than managed landscapes (Brown et al., 2011; Chen et al., 2014). Older soils contain more C than younger soils following development, meaning there is potential for C to increase as a developed system ages (Golubiewski, 2006). A previous study found that at 25 years following development, soil C levels start to show similar amounts to predevelopment soils, indicating, at

minimum, a quarter-century recovery time frame for disturbed soil (Golubiewski 2006). Anderson Avenue Lawn, the most recently disturbed site (in 2020), had the lowest soil C and N pools, indicating the impacts of the recent removal of housing and regrading of the soil. This site also had the lowest soil microbial biomass N and the lowest biological function of all sites. This recently disturbed site shows the greatest negative effects of urban development on soil health and function. In contrast, the native Konza grassland soil profiles have not been disturbed, preserving their nutrient pools and organic layers, and accordingly had the highest percentage of soil organic matter, C and N.

The magnitude of developmental impact on soil health across the study sites is not linear, however. The restoration site at Konza, the Warner Park prairie, and the Beach Museum Lawn, all of which are at least 25 years old, did not have soil C and N concentrations at the level of the native Konza grassland reference site. This suggests that the organic matter lost through development does not recover quickly and that site-specific management might influence the recovery and inputs of organic matter into soils.

Maintenance or management impacts how that system (plant, soil, and organisms) performs, allocates, and utilizes nutrients. The aboveground management of landscapes can have a substantial impact on belowground dynamics and functioning. Soil C pools can decrease significantly in systems that experience burning, mowing, and/or clipping due to the constraints on root biomass development, which contribute a large portion of soil organic matter, as well as decrease the potential for surface litter inputs (Kitchen et al., 2009). I predicted that the increase in the frequency of mowing and management would have a greater influence on soil organic matter and nutrient storage, however, the sites that were mowed at a higher frequency (multiple times a month) did not exhibit lower nutrient contents than the other sites indicating other

potential drivers for nutrient dynamics in the soil, potentially be driven by soil moisture content, pH, or use of fertilization (as seen at Eisenhower Lawn). The use of fertilization and irrigation can result in an increase in aboveground plant production as well as organic matter allocation into the soil, thus resulting in more fertile soil (Thompson & Kao-Kniffen, 2019). This may explain the soil quality in the Eisenhower Lawn, which are irrigated and fertilized, and have higher organic matter and N content than all sites except the native Konza grassland soils.

Functional Diversity

Enzymatic Activity

Soil microbial extracellular enzymes are responsible for the decomposition of organic matter, which releases plant available nutrients and supports soil fertility. These enzymes break complex organic matter molecules into small molecules that are biologically available (Allison & Vitousek, 2004), making nutrients and energy available to organisms in the soil through the critical ecological process of nutrient mineralization (Bielinska et al., 2012; Jaworska & Lemanowicz, 2019; Naylo et al., 2019). Soil microbial extracellular enzyme activities are dependent on the availability of C, N, and phosphorus (P) in soil. When C, N, or P is limited in soil, microbes will create enzymes to help breakdown more complex compounds in soil to make these elements biologically available to the microbial and plant communities. However, for microbes to function, these elements in the form of organic matter must also be available as forms of energy for microbial activity (Allison & Vitousek, 2004; Zeglin et al., 2007). Also, enzymes function in an optimal pH range, such that, above other variables, soil pH can drive microbial activity dynamics across different sites (Zeglin et al., 2007).

Grassland ecosystems, such as Konza Prairie and Warner Park, are known to be N-limited due to regular fire and high perennial plant retention of N (Rosenzweig et al., 2016).

Restored grassland systems will also exhibit increased N limitation as they age (Rosenzweig et al., 2016). In turn, Konza Prairie and Warner Park soil enzyme activity ratios reflected stronger N limitation in relation to C than other sites, as well as stronger P limitation in relation to C. There was also higher N-acquiring enzyme activity at Anderson Lawn, indicating N limitation; however, soil microorganisms at this site are likely N-limited because of the depleted soil organic matter pool following recent development and disturbance to the soil nutrient pool (Allison & Vitousek, 2004; Koch, 1985). At Anderson Lawn, N was also more limiting than P suggesting an overall relative deficiency of N in the soil, which is also suggested by the total N levels.

Microbial Respiration and Metabolic Activity Quotient

Microbial metabolic quotient (qCO_2) is an indicator of microbial maintenance C demand (microbial C respiration) per unit growth (microbial biomass C) and an index of microbial C use efficiency (J. Li et al., 2020). Microbial respiration reflects the amount of soil microbial activity; however, microbial respiration alone is highly variable and dependent on many factors, including microbial biomass, available C, and water content (Pell et al., 2005).

Across the seven sites, soil microbial respiration was strongly correlated with water content (Figure 2.10). Eisenhower Lawn exhibited the highest microbial respiration later in the growing season, which was also the time point and location with the highest soil moisture, likely due to irrigation. This suggests that irrigation increases microbial activity within the soil, similar to previous studies in which urban turfgrass lawns had much higher soil respiration rates than native grasslands (Kaye et al., 2005). In addition, while microbial biomass C did not differ significantly across sites, the microbial metabolic quotient shows that Eisenhower Lawn (an

urban site, irrigated and fertilized) and Anderson Avenue Lawn (which had housing removed and soil regraded during 2020) sites have lower soil microbial C use efficiency.

Consistent and excess fertilization or de-icing salt use on adjacent sidewalks at Eisenhower Lawn may have caused increased soil EC, as well as potential salt addition to soil via recycled irrigation water that may be high in salt concentration (Calkins, 2012), and previous studies correlate increased EC to increased qCO_2 (Rietz & Haynes, 2003). Higher soil microbial qCO_2 at the Anderson Avenue Lawn may also be due to the recent disturbance to the site. In a previous study, qCO_2 increase was seen as an indicator of microbial stress in the soil as a result of physical disturbance (J. Li et al., 2020; Xu et al., 2017).

Substantial physical disturbance of soil (including regrading and tilling) can lead to changes, including aggregate loss, which results in C instability, inefficient microbial C utilization, and net C loss. The Native Konza Prairie and Warner Park sites, which have not undergone any intense development over the last 50 years, show lower qCO_2, meaning microorganisms are more efficient in their C use (Anderson, 2003; Anderson & Domsch, 2010). Biological succession, or the increase in diversity and biomass over time in a soil ecosystem, results in more efficient microbial communities (Anderson, 2003; J. Li et al., 2020). Greater soil carbon use efficiency is associated with greater carbon sequestration potential (Sinsabaugh et al., 2013), suggesting that the sites that with low soil qCO_2 have greater potential to sequester carbon (Native Konza Prairie and Warner Park Prairie). Comparatively, the sites with high qCO_2 (Eisenhower Lawn and Anderson Lawn) are more likely to be sources of atmospheric CO_2.

Seasonal Drivers

The results of this research show that seasonal drivers play a role in microbial function, and therefore, the timing of soil sampling affects the perceived health of a soil system. Microbial

respiration, enzymatic activity, and microbial communities are influenced by seasonal moisture and soil temperature (Slaughter et al., 2015). Increased temperature and moisture together result in accelerated microbial decomposition due to increased microbial activity (Slaughter et al. 2015), while during the warmer and drier seasons, a decrease in microbial activity due to a decrease in microbial community pools are seen (Slaughter et al., 2015). Seasonal plant growth and belowground root allocation also affect soil biological dynamics because, during the growing seasons, plants compete with soil microbes for nutrients (Kaye & Hart, 1997), thus creating stronger N limitation in the soil.

Understanding that seasonal drivers impact soil microbial structure and function, soil testing should happen multiple times throughout the year to accommodate and assess health under seasonal conditions, or site health assessments should be conducted and compared from consistent testing points from year to year across sites of comparison (always during August for example). Ideally, multi-year and seasonal studies should be completed so that variability in weather patterns can be accounted for and better understood.

Conclusion

This study shows that urbanization has varied effects at different sites due to differences in disturbance intensity and landscape management. An intense and recent disturbance at the Anderson Avenue Lawn site disrupted soil organic matter and nutrient pools, decreasing soil function and resulting in less healthy soil. However, contrary to some definitions of urban soil, many urban sites demonstrated high soil biological function, coming close to that of the undisturbed prairie site at Konza Prairie. Urban soil doesn't mean dead soil: There can be abundant microbial life, organic matter, and nutrients in urban soils, and they can provide similar

ecosystem services to natural soils with the help of restoration and wise soil management. However, despite increased soil organic matter content, inefficient soil microbial function also has the potential to have negative consequences, depending on site management. As seen in the Eisenhower Lawn soil, a highly manicured lawn (frequent mowing, fertilization, and irrigation) can support moderately high soil organic matter. Nevertheless, it also can decrease the efficiency of microbial C use, leading to consequential effects on soil C sequestration potential and CO_2 production. In addition to soil microbial function, microbial community composition and/or plant community changes can be essential to soil health and ecosystem health (as noted in the literature), but this study did not measure those factors.

Importantly, sampling season influences the health of the soil, so sampling time should be standardized or repeated throughout the year or successive years (ideally three years) to reach a representative assessment of soil health. This study shows that urban soils are complex, and that many variables in an urban environment influence soil, therefore soil functions in urban conditions are also variable. Most importantly, this study shows potential for soil health and C sequestration in urban sites if they are valued and managed with soil functions and microbial soil health in mind.

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Tables

Table 2. 1 ANOVA results for soil physical, chemical, and biological characteristics by site and growing season. Values in bold are significant.

Variable	Factors					
	Site		Season		Site*Season	
	(F, P)		(F, P)		(F, P)	
Bulk Density (g mL^{-1})	17.23,	**2.58e-15**				
Sand (%)	9.667,	**4.5e-09**				
Silt (%)	21.17,	**<2e-16**				
Clay (%)	22.08,	**<2e-16**				
Gravimetric Water Content (g g^{-1})	40.724,	**<2e-16**	186.946,	**<2e-16**	4.317,	**0.0005**
Total Carbon (%)	23.756,	**<2e-16**	0.552,	0.459	0.863,	0.524
Total Nitrogen (%)	40.205,	**<2e-16**	0.361,	0.5491	2.526,	0.233
Total C: Total N	14.443,	**5.54e-13**	13.918,	**0.00027**	1.247,	0.285
Organic Matter (g g^{-1})	44.110,	**< 2e-16**	21.855,	**6.41e-06**	8.262,	**9.34e-08**
Electrical Conductivity (ds/m)	33.66,	**< 2e-16**	23.33,	**3.28e-06**	21.78,	**< 2e-16**
pH	63.308,	**<2e-16**	4.71,	0.0315	0.565,	0.758
Microbial Biomass Carbon	4.614,	**0.002**	30.464,	**1.46e-7**	8.973,	**2.25e-08**
Microbial Biomass Nitrogen	5.389,	**1.78e-05**	18.698,	**2.83e-05**	2.908,	0.0104
Microbial C: Microbial N	2.262,	0.041	10.776,	**0.001**	5.593,	**3.06e-05**
Microbial Respiration	17.607,	**1.90e-15**	151.721,	**< 2e-16**	8.527,	**5.38e-08**
Microbial Metabolic Quotient (qCO_2)	6.198,	**7.77e-06**	3.403,	0.671	5.252,	**6.10e-05**
Phosphatase (AP)	25.85,	**< 2e-16**	12.23,	**0.001**	3.73,	**0.002**
β-1,4-glucosidase (βG)	27.78,	**< 2e-16**	29.52,	**2.14e-07**	5.427,	**4.11e-05**
β-N-acetylglucosaminidase (NAG)	11.40,	**1.62e-10**	5.757,	0.176	2.518,	0.024
Cellobiohydrolase (CBH)	45.621,	**< 2e-16**	33.094,	**4.64e-08**	0.809,	0.565
Leucyl aminopeptidase (LAP)	12.146,	**3.82e-11**	1.423,	0.235	1.541,	0.169
βG / AP	29.76,	**<2e-16**	0.007,	0.934	1.006,	0.423
βG / (NAG+LAP)	33.09,	**< 2e-16**	10.78,	**0.001**	1.74,	0.115
(NAG+LAP) / AP	10.358,	**1.28e-09**	8.607,	**0.004**	3.339,	**0.004**

Table 2. 2 Principal Component Analysis (PCA) results. Loading values in bold are the PC driving variables for the PC.

Chemical and Physical Properties							
	PC1 (39.7%)	*PC2 (24.2%)*	*PC3 (15.2%)*		*PC1 (35.8%)*	*PC2 (23.5%)*	*PC3 (20.0%)*
EC	**-0.856**	0.019	-0.245	**% Silt**	**0.882**	-0.119	0.327
% Silt	**0.815**	0.469	-0.112	**pH**	**-0.694**	0.248	0.317
% Clay	**-0.777**	0.364	-0.174	**% Clay**	**-0.693**	0.240	0.554
pH	**-0.710**	0.335	-0.212	**Bulk Density**	**-0.527**	0.436	-0.151
% Sand	-0.226	**-0.881**	0.291	**GWC**	-0.321	**-0.873**	0.012
GWC	-0.006	**-0.664**	-0.563	**EC**	-0.484	**-0.743**	0.231
Bulk Density	-0.475	0.102	**0.718**	**% Sand**	-0.391	-0.084	**0.900**
Biological Properties							
	PC1 (30.8%)	*PC2 (21.7 %)*	*PC3 (16.4%)*		*PC1 (26.6%)*	*PC2 (22.4%)*	*PC3 (15.6%)*
βG	**-0.919**	0.037	0.029	**qCO2**	**-0.800**	0.051	-0.021
CBH	**-0.906**	0.141	-0.008	**MBC**	**0.797**	0.211	0.054
SOM	**-0.687**	0.234	0.146	**SOM**	**0.606**	0.259	-0.283
qCO_2	0.129	**0.735**	0.569	**MBN**	**0.640**	0.261	-0.070
AP	-0.353	**-0.690**	0.473	**βG**	0.275	**-0.844**	0.218
LAP	0.017	**-0.641**	0.368	**CBH**	0.280	**-0.761**	0.368
MBN	-0.395	**0.553**	0.088	**AP**	0.262	**-0.598**	-0.595
MBC	-0.433	-0.192	**-0.823**	**NAG**	-0.349	**-0.433**	-0.409
NAG	-0.392	-0.332	0.292	**LAP**	-0.008	-0.016	**-0.783**
	Early Growing Season				Late Growing Season		

Figures

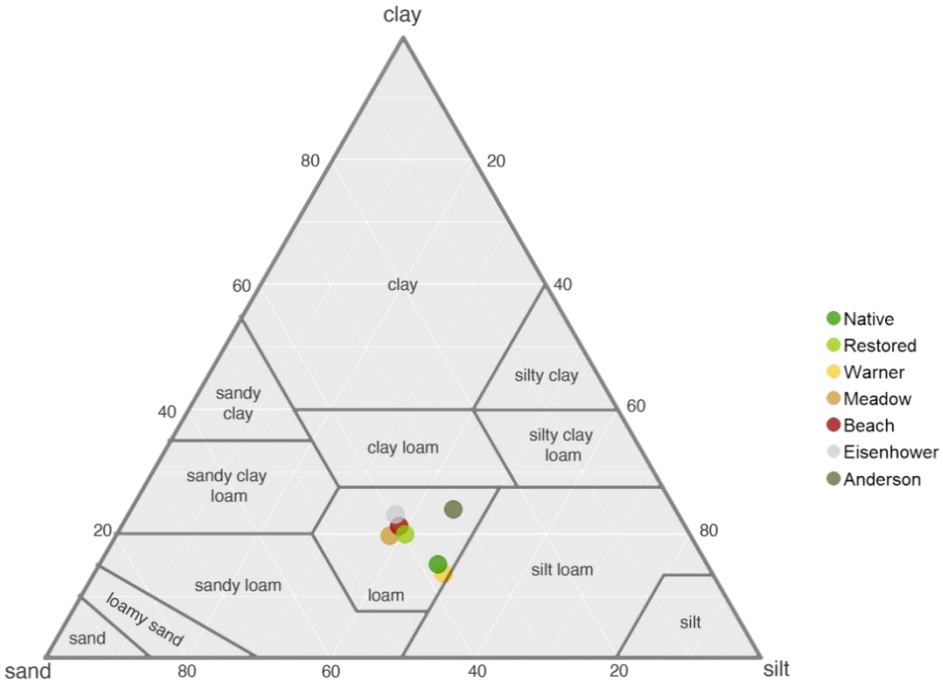

Figure 2. 2 Soil texture classification by site using the USDA soil texture classification triangle.

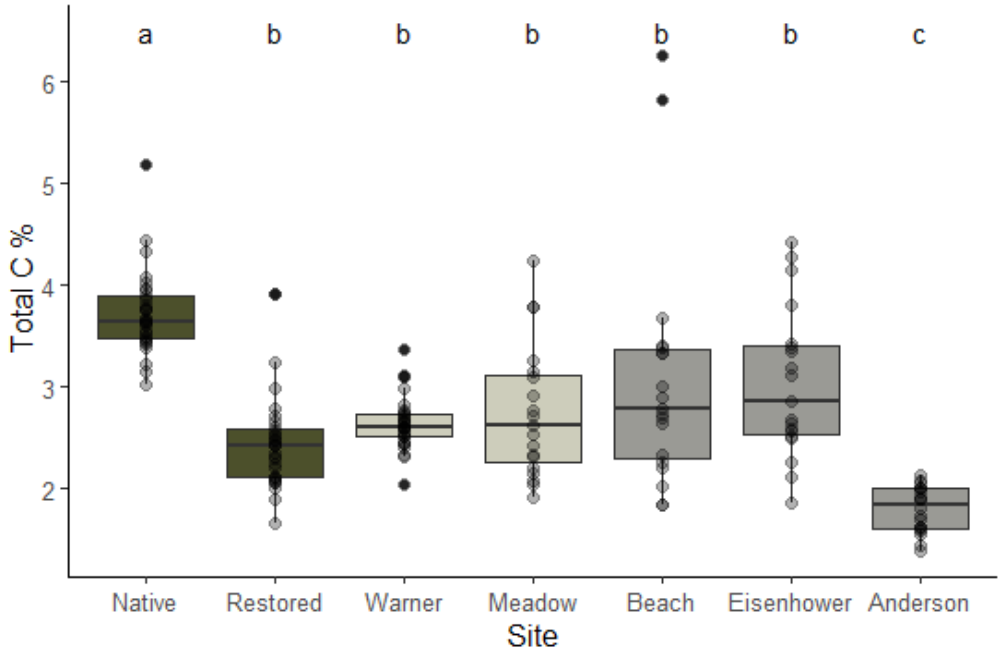

Figure 2. 3 Percent Total C across sites, the seasonal effect not significant. Letters indicate groups for statically different site effects.

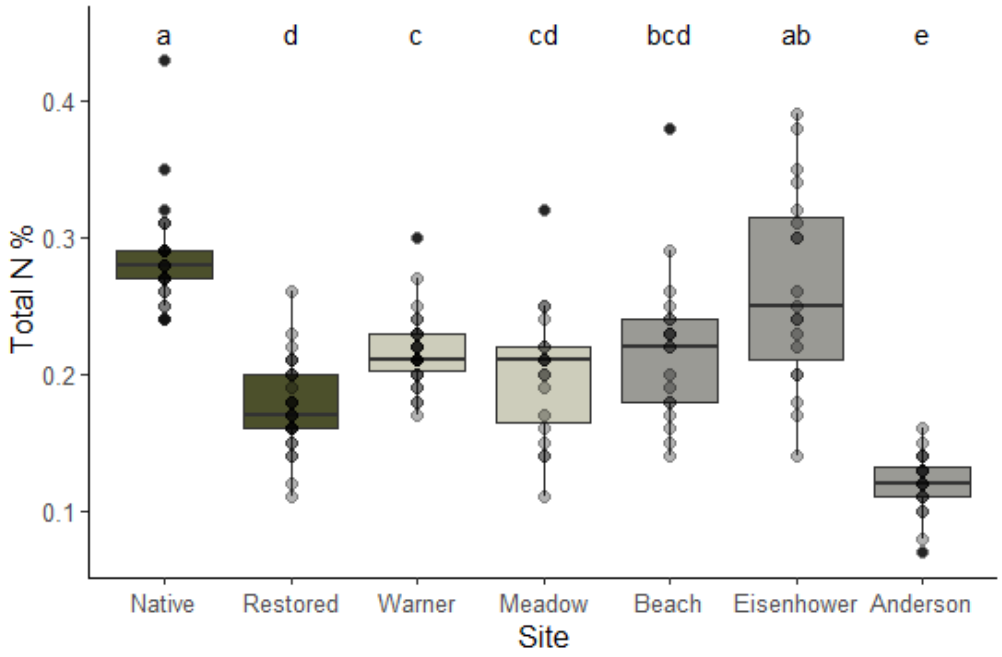

Figure 2. 4 Boxplot of percent Total N across sites, the seasonal effect not significant. Letters indicate groups for statically different site effects.

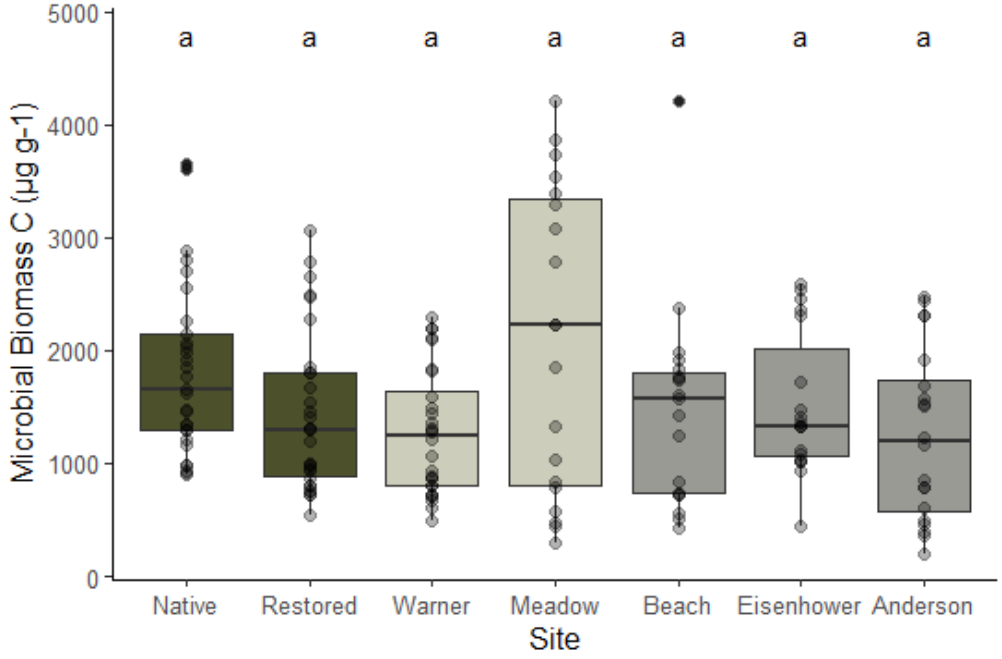

Figure 2. 5 Microbial biomass C (µg g^{-1}) across sites. Seasonal effect significant. Letters indicate groups for statistically different site*season effects.

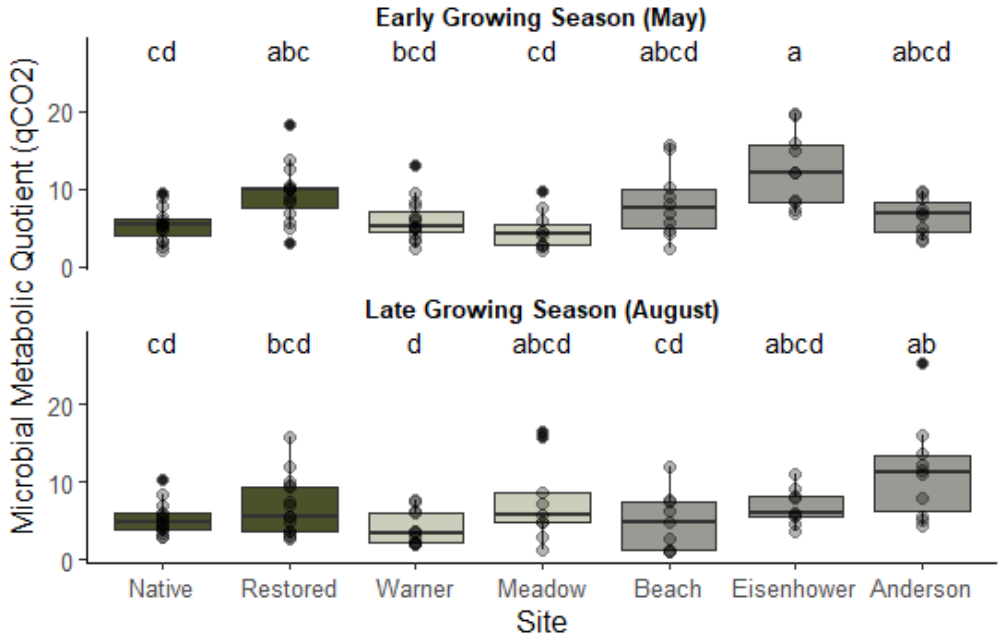

Figure 2. 6 Microbial metabolic quotient (qCO_2). Letters indicate groups for statistically different site effects.

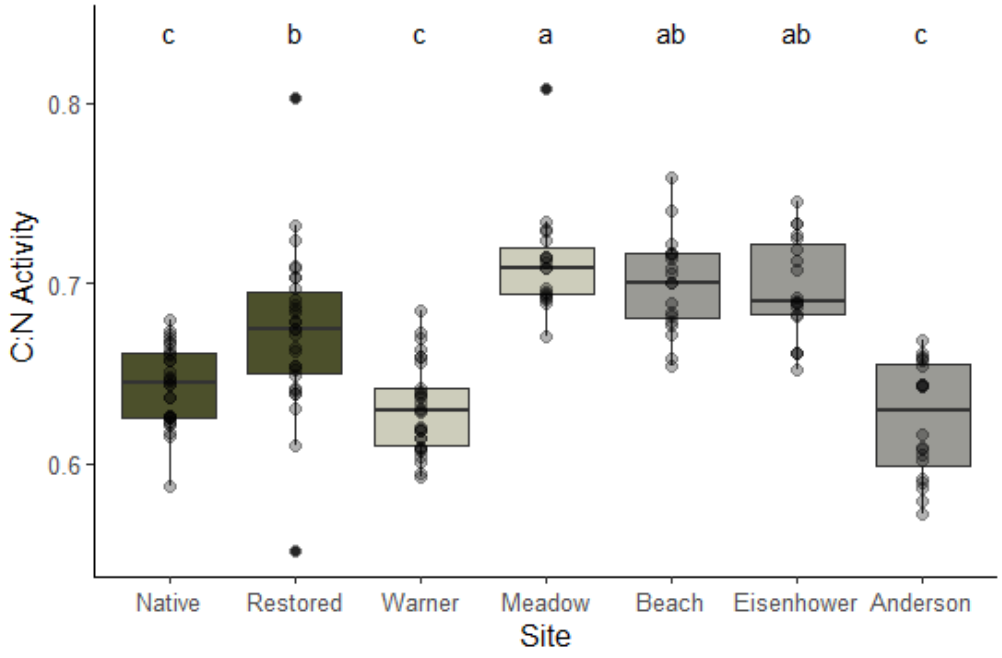

Figure 2. 7 Ratio of C regulating enzymatic activity (BG) to N regulating enzymatic activity (NAG+LAP). The seasonal effect was significant, however, there was no interaction. Letters indicate group for statistically different site effects.

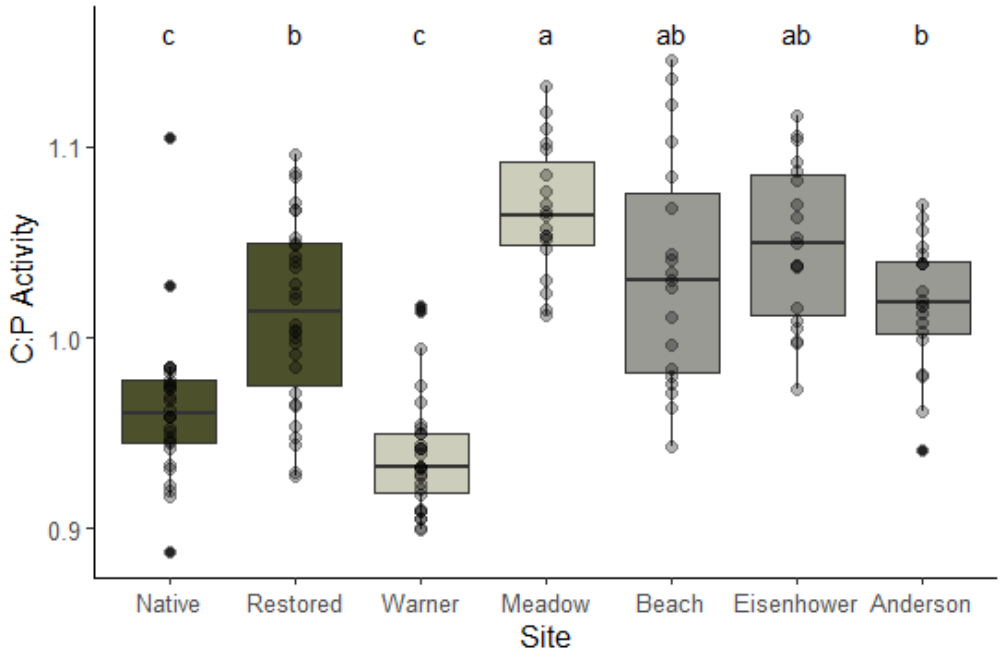

Figure 2. 8 Ratio of C regulating enzymatic activity (BG) to P regulating enzymatic activity (AP). The seasonal effect was not significant. Letters indicate groups for statistically different site effects.

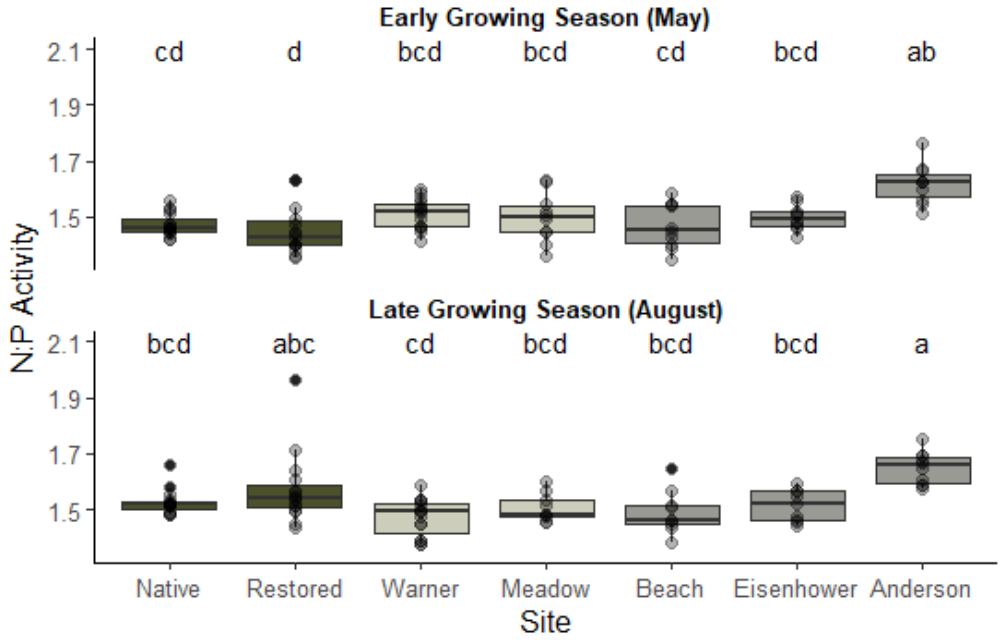

Figure 2. 9 Ratio of N regulating enzymatic activity (NAG+LAP) to P regulating enzymatic activity (AP). The seasonal effect was significant. Letters indicate groups for statistically different site*seasonal effects

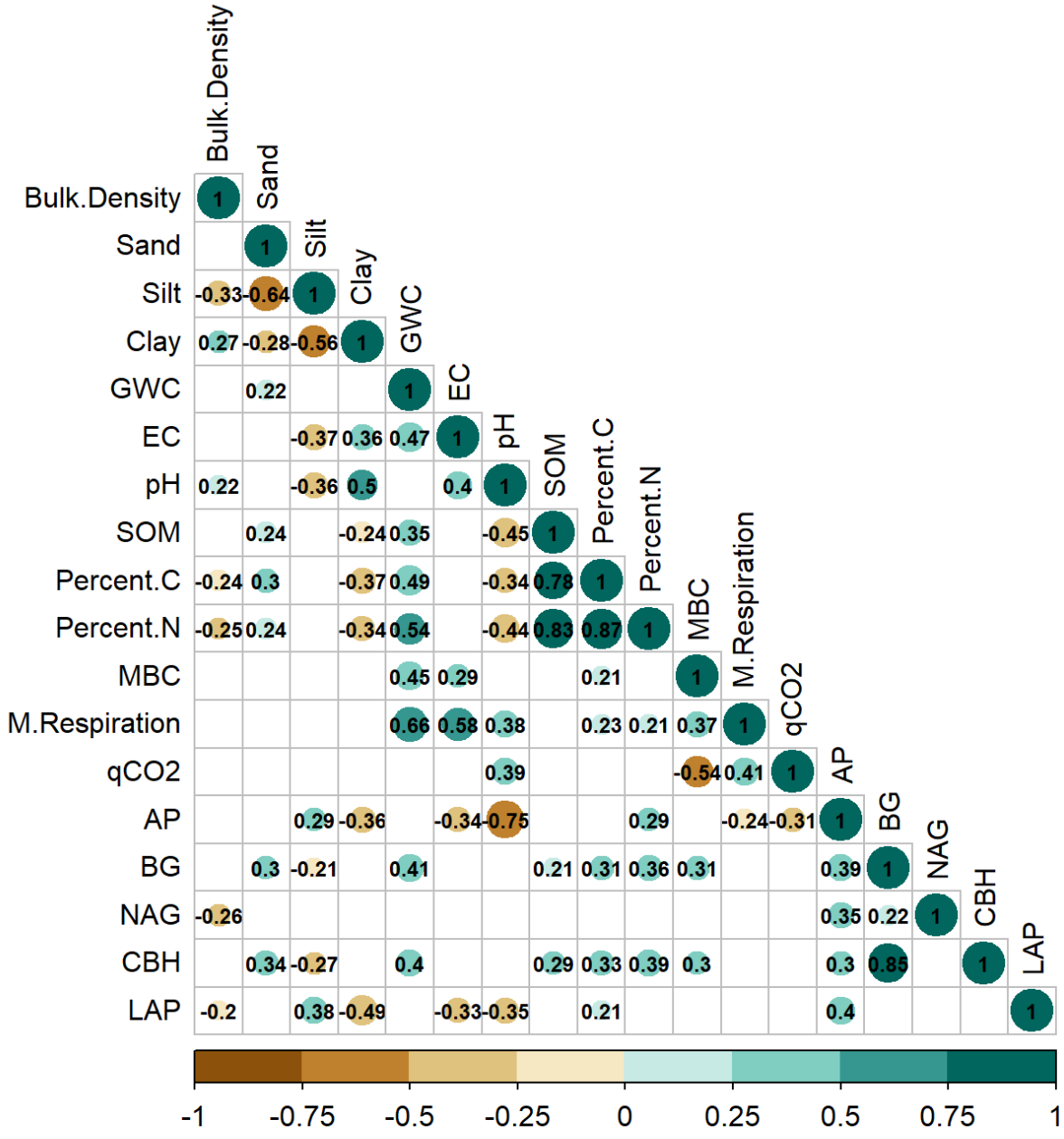

Figure 2. 10 Correlation matrix, blank square represent non-significant correlations.

Supplemental Figures

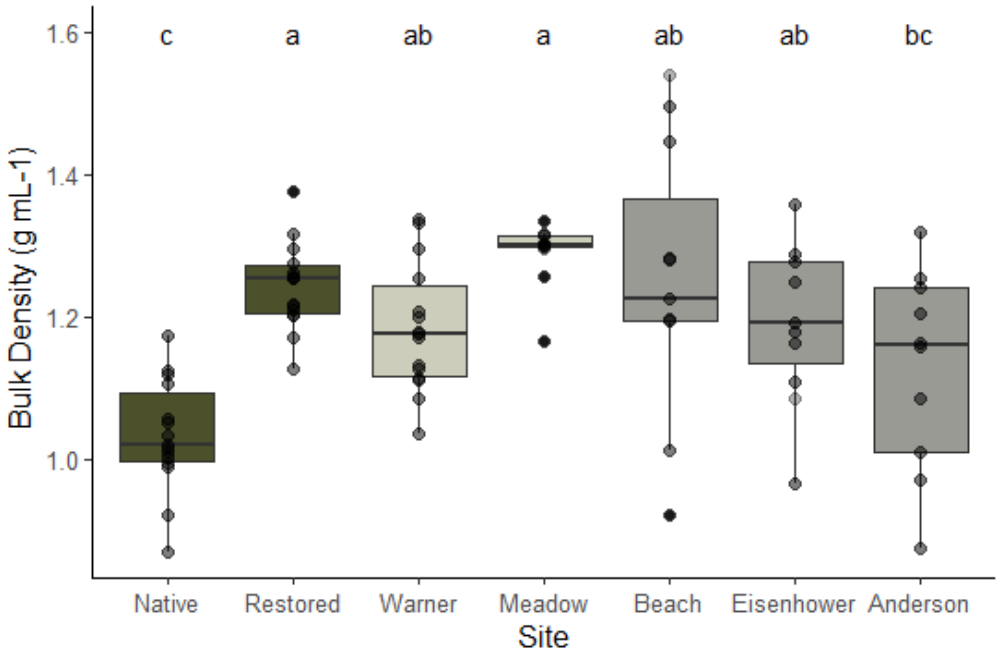

Figure S2. 1 Bulk density for sampling sites. Letters indicate groups for statistically different site effects.

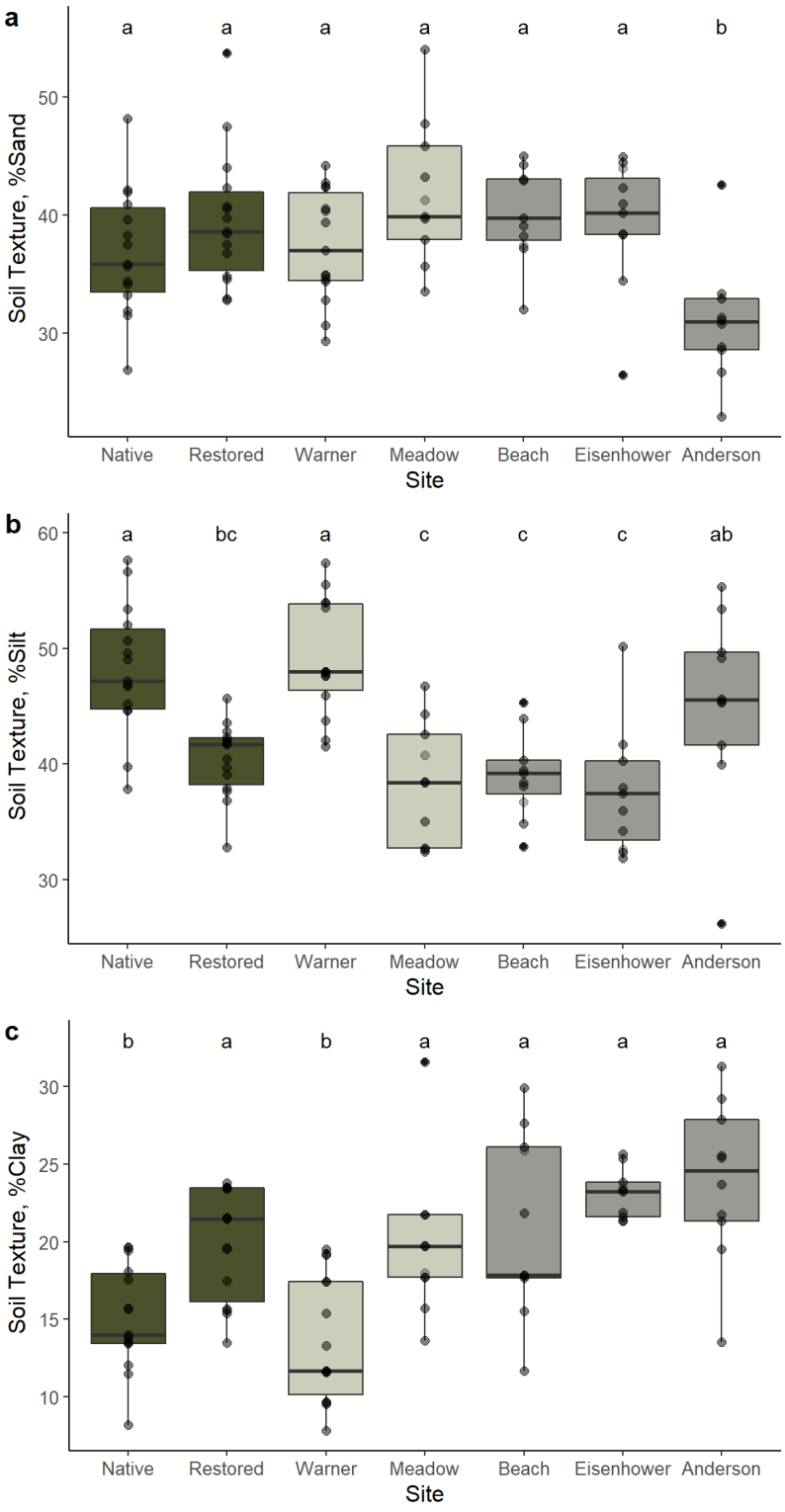

Figure S2. 2 Texture percentages across sampling sites a) percent sand, b) percent silt, c) percent clay. Letters indicate groups for statically different site effects.

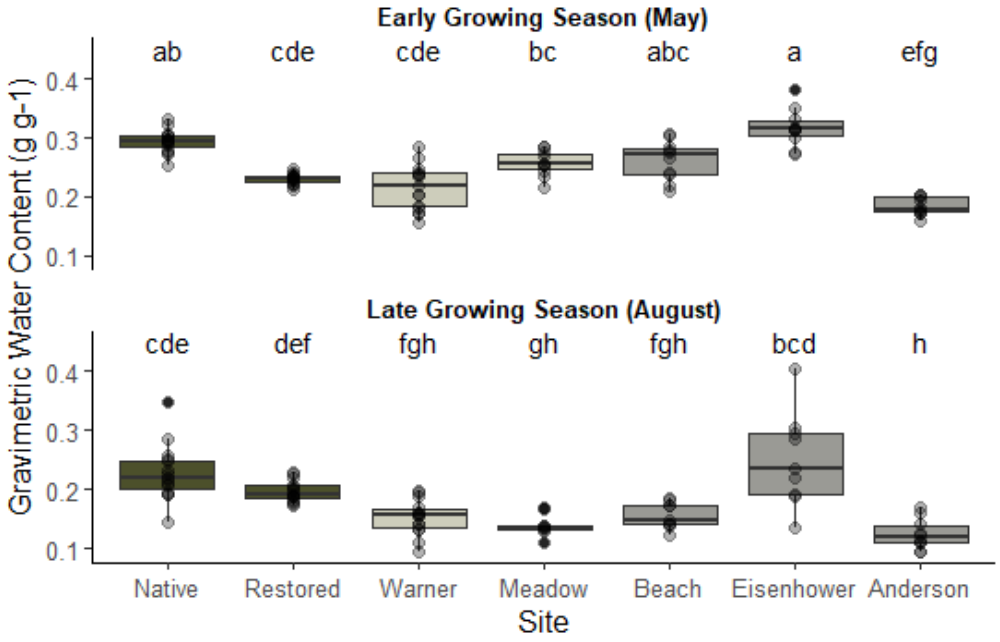

Figure S2. 3 Gravimetric water content (g g^{-1}). The seasonal effect was significant. Letters indicate groups for statistically different site*season effects.

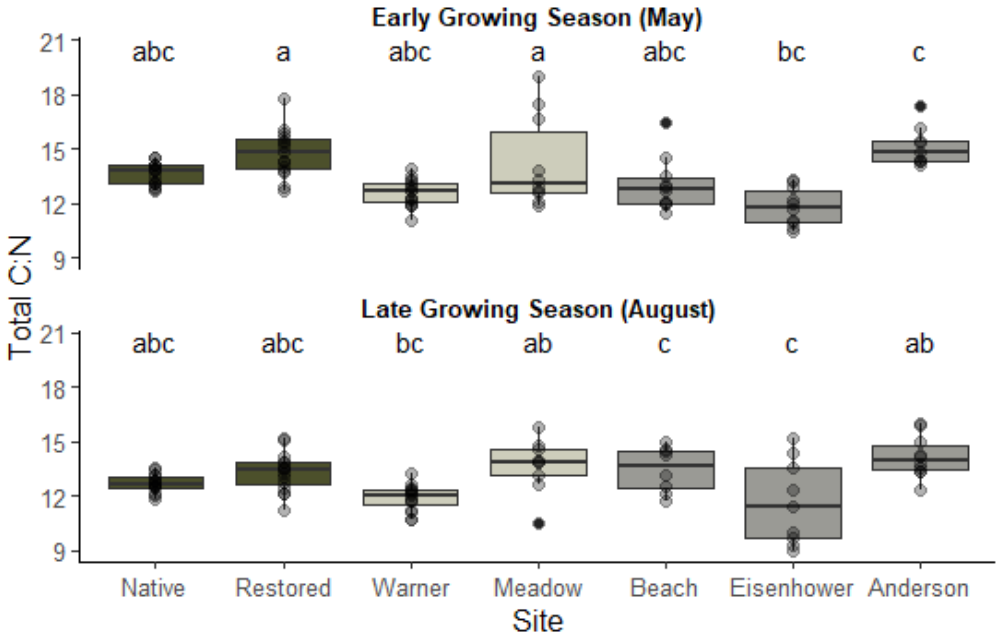

Figure S2. 4 Ratio of percent total C to percent total N across sites. The seasonal effect was significant but there was no interaction. Letters indicate groups for statistically different site effects.

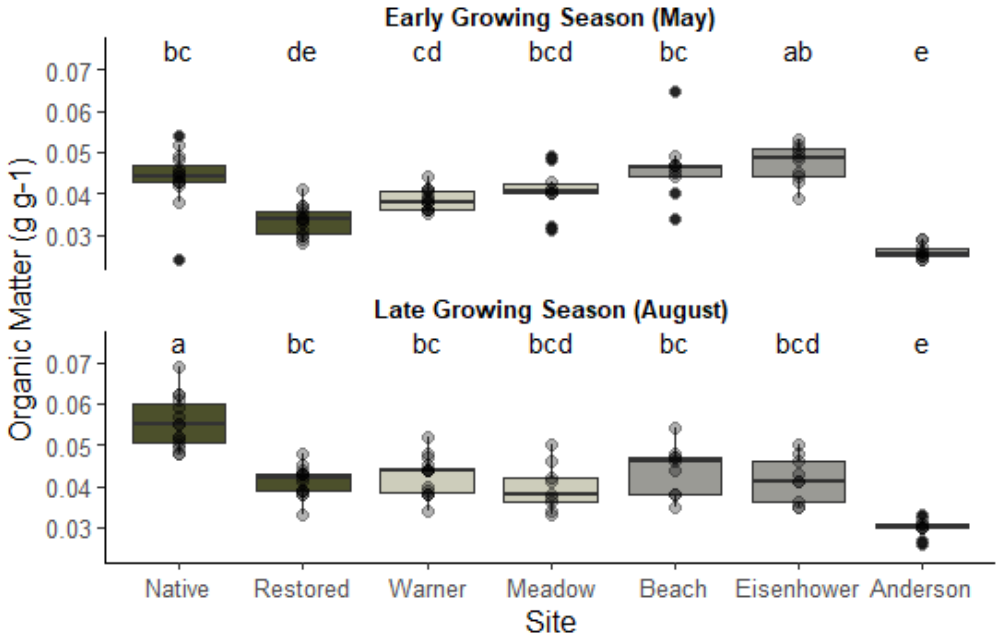

Figure S2. 5 Soil organic matter (g g^{-1}). The seasonal effect was significant. Letters indicate groups for statistically different site*season effects.

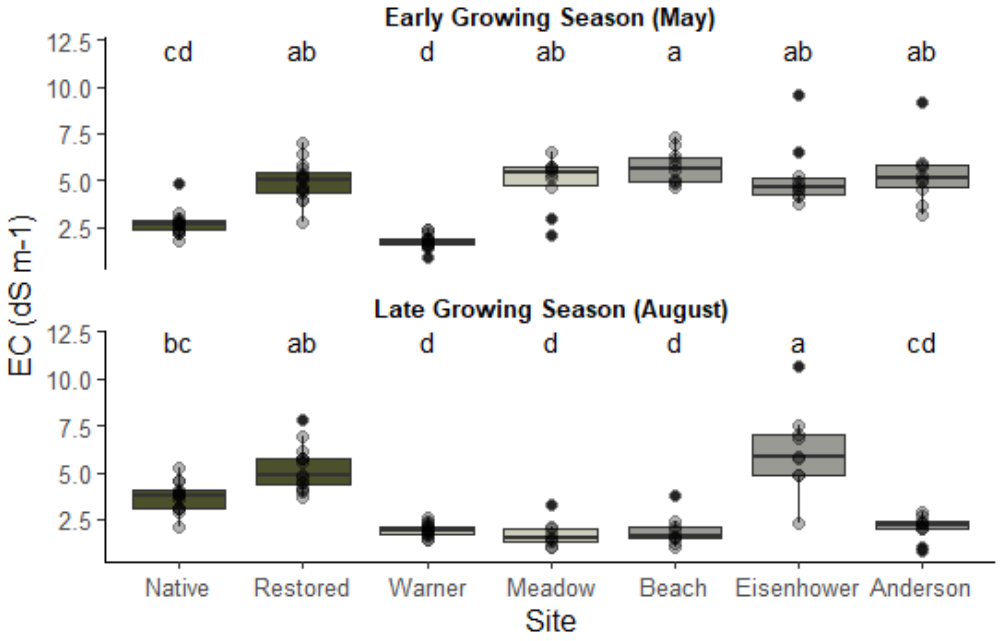

Figure S2. 6 EC (dS m^{-1}) across sites. Seasonal effect was significant. Letters indicate groups for statistically different site*season effects.

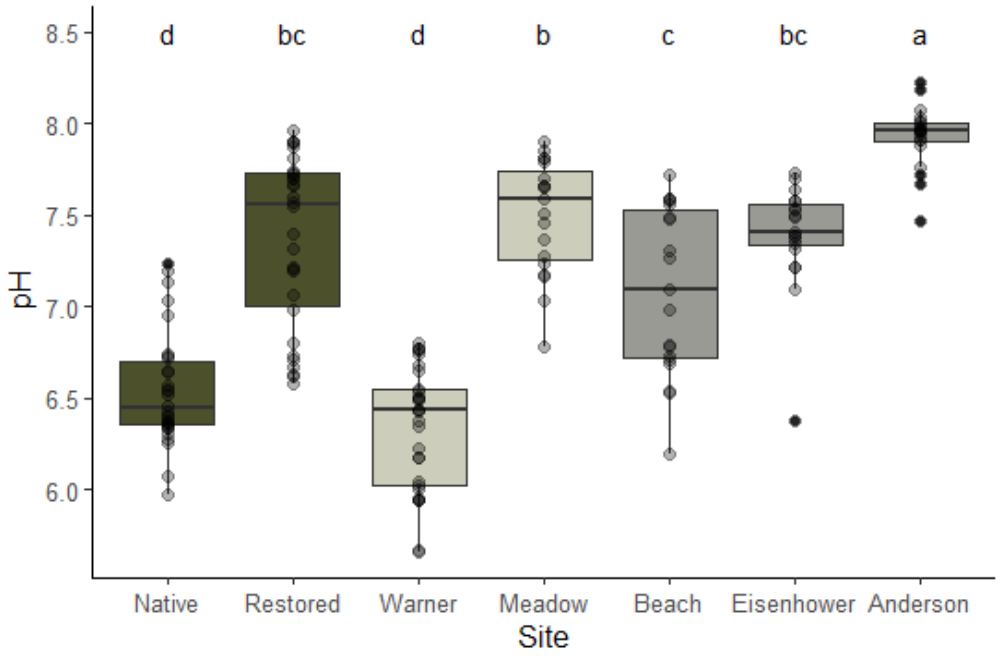

Figure S2. 7 pH across sites. Seasonal effect was not significant. Letters indicate groups for statistically different site effects.

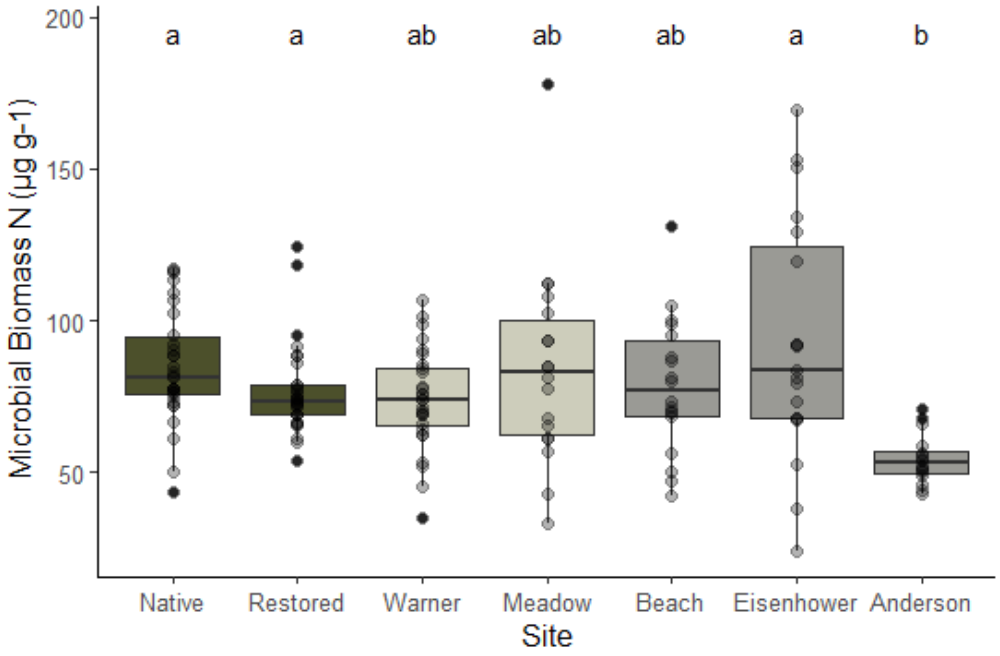

Figure S2. 8 Microbial biomass N (µg g-1) across sites. The seasonal effect was significant, but there was no interaction. Letters indicate groups for statistically different site effects.

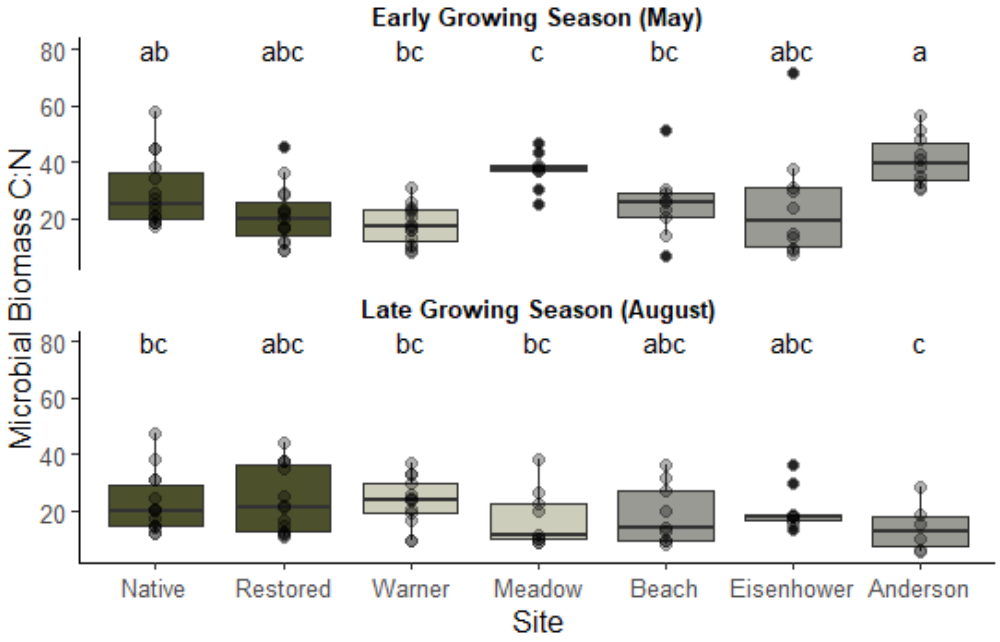

Figure S2. 9 Ratio of microbial biomass C and N across sites. The seasonal effect was significant. Letters indicate groups for statistically different site*seasonal effects.

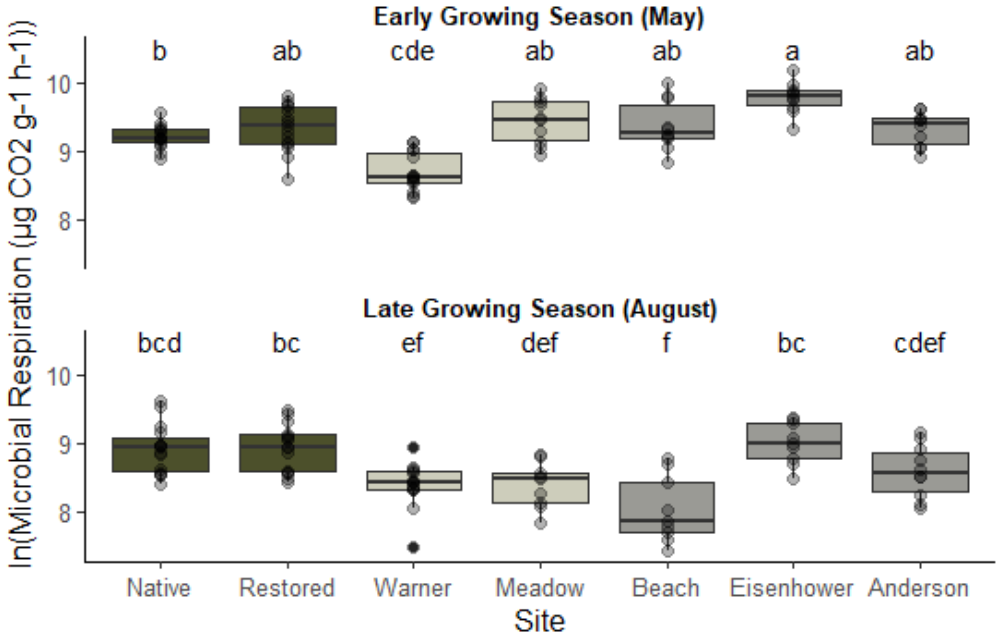

Figure S2. 10 Microbial respiration (µg CO_2 g^{-1} h^{-1}) across sites. The seasonal effect was significant. Letters indicate groups for statistically different site*seasonal effects.

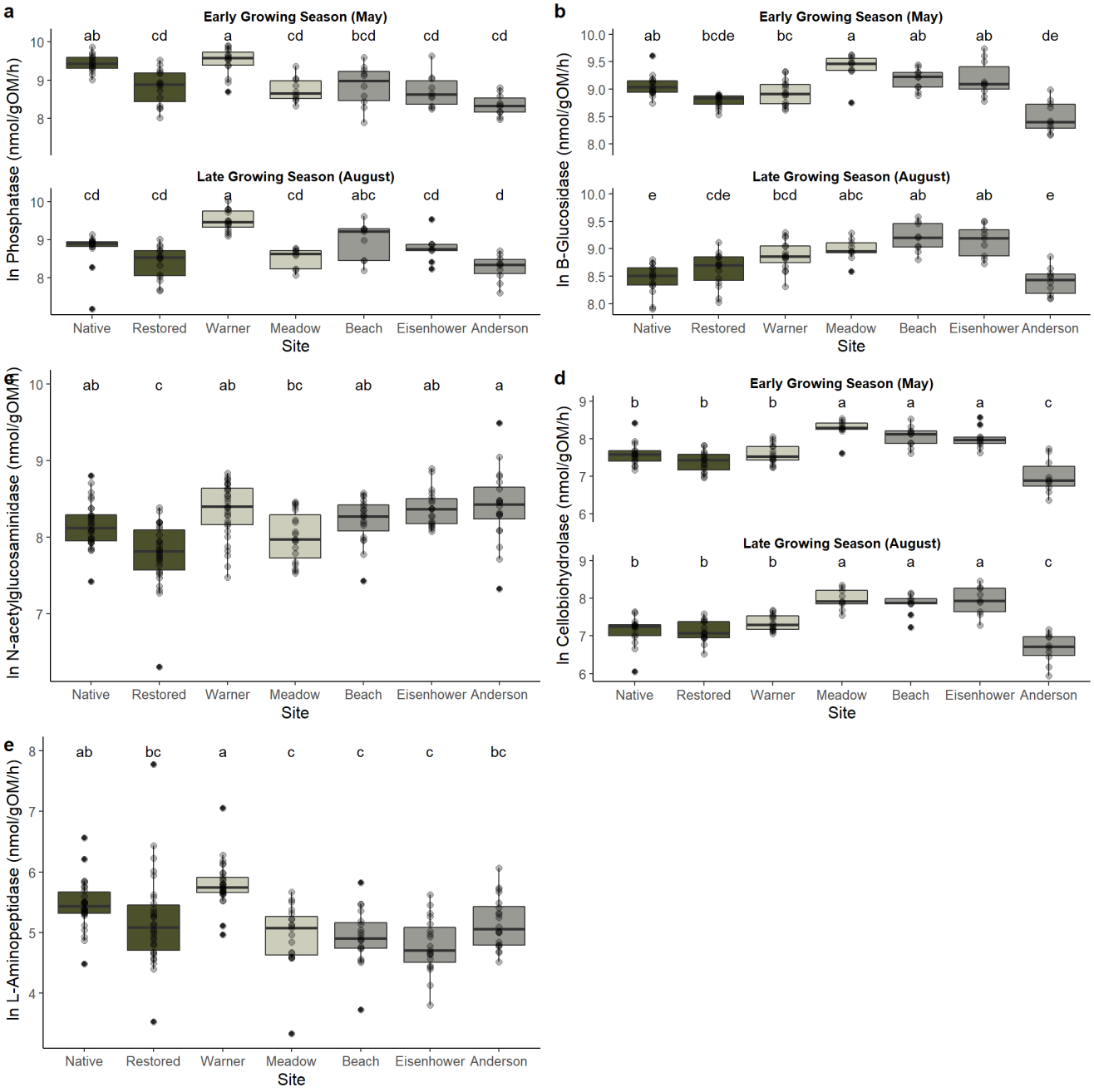

Figure S2. 11 Enzymatic activity (nmol gOM^{-1} h^{-1}) across sites. a) AP activity, the seasonal effect was significant; b) BG activity, the seasonal effect was significant; c) NAG activity; d) CBH activity, the seasonal effect was significant; e) LAP activity, the seasonal effect was significant. Letters indicate groups for statistically different site*seasonal effects.

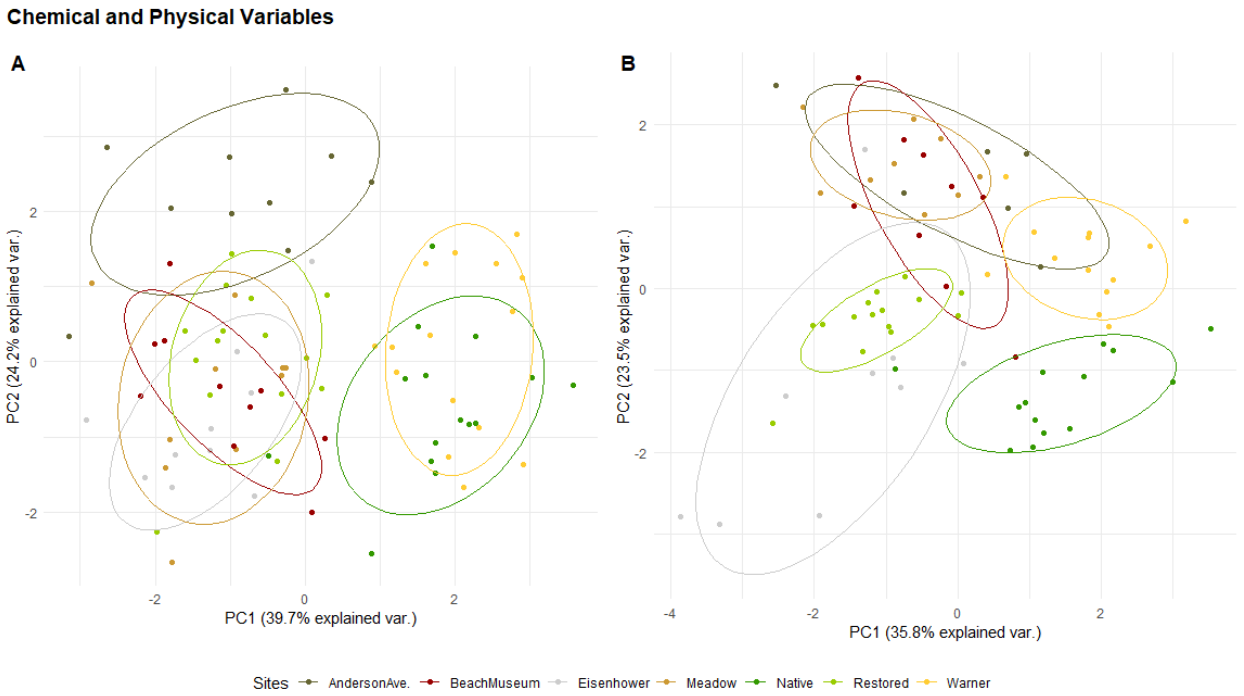

Figure S2. 12 Chemical and physical variables PCA. A) with early growing seasons samples and B) with late growing season samples. Colors represent sites.

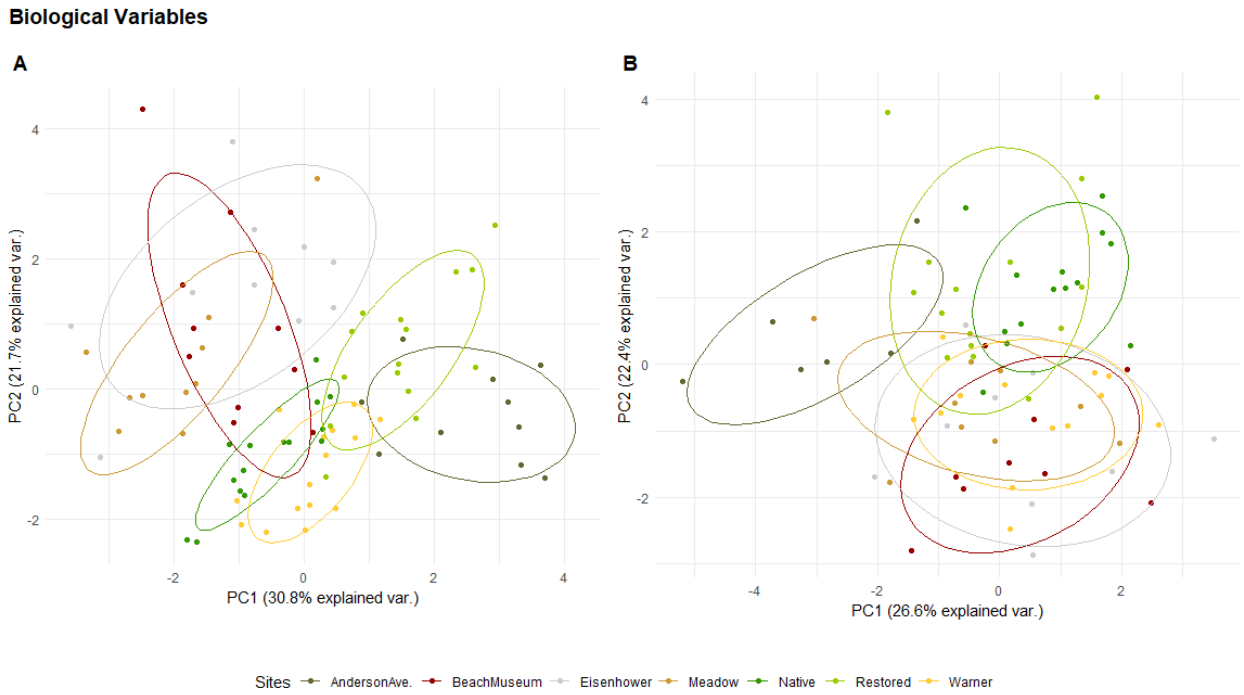

Figure S2. 13 Biological variables PCA. A) with early growing seasons samples and B) with late growing season samples. Colors represent sites.

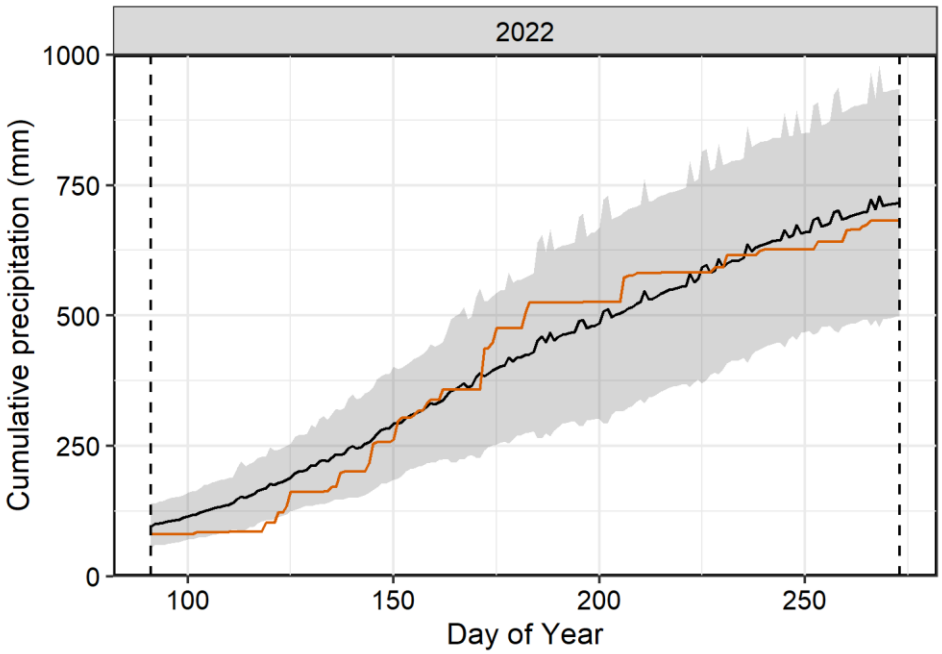

Figure S2. 14 The 2022 precipitation accumulation during the growing season (orange line) compared to the average since 1986 (black line, with grey shaded area representing the 95% confidence interval around the mean).

Chapter 3 - Landscape Architecture and Soil: Current Practices and Important Considerations

Basic needs in soil understanding as a landscape architect

For large complex projects, designers and planners may require the assistance of soil consultants and soil scientists; however, it is the responsibility of the designer or design team to have enough skill and knowledge to be able to evaluate a site and make decisions about the soil on their own (Urban, 2008). To be able to make those necessary decisions, at a minimum, landscape architects must have a basic understanding of the components of soil and the potential impact of development and design on those components and functions of soil in the built, less disturbed, and natural environments.

The components of soil

Soil Texture

Soil texture, also known as particle size distribution, is the proportion and size of the mineral components in soil. Mineral components of soil consist of clay, silt, and sand primarily, but increase in size (known as classes), including gravel, cobble, and boulders (Table 3.1). The proportion of each within a soil determines its textural classification. Soil texture is important as it influences soil moisture, structure, porosity, chemical activity, and biological function. As a landscape architect, it is important to understand the impact and relationship that texture has with other variables in soil (Table 3.2). Although lab testing is the typical route for getting texture on site, an initial test in the field can be made to proximate soil texture by hand (Figure 3.1).

Table 3. 1 Soil Particle Size Classifications, USDA (Craul, 1992).

Soil Material	Diameter (mm)
Clay	**<0.002**
Silt	**0.002-0.05**
Silt, fine	0.002-0.02
Silt, course	0.02-0.05
Sand	**0.05-2.00**
Very fine sand	0.05-0.10
Fine sand	0.10-0.25
Medium sand	0.25-0.50
Coarse sand	0.50-1.00
Very coarse sand	1.00-2.00
Gravel	**2.0-75.0**
Cobbles	**75.0-250.0**
Stones	**250-600**
Boulders	**>600**

Table 3. 2 Soil Characteristics Influenced by Texture (modified from Craul, 1992).

Characteristic	Texture Class			
	Sand	Loam	Silt Loam	Clay
Permeability	Excessive	Good	Fair	Fair to Poor
Available Water	Low	Medium	High	Medium-High
Runoff Potential	Low	Low-Medium	High	Medium-High
Transportability	Low	Medium	High	High
Wind Erodibility	High	Medium	Low	Low
Nutrient Capacity	Low	Medium	Medium	High
Compactibility	Low	Medium	Medium-High	High

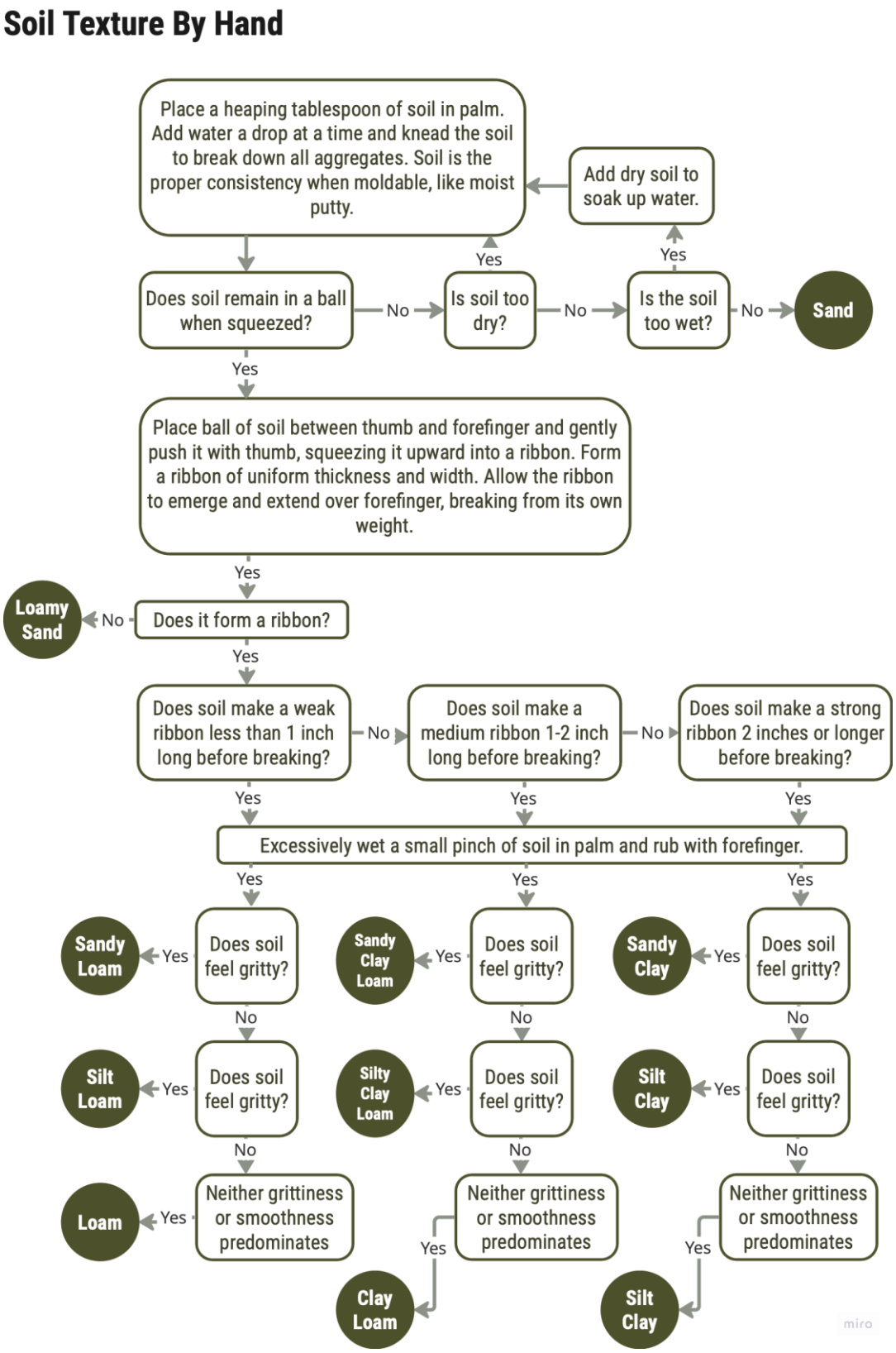

Figure 3. 1 Soil Texture by Feel Test (modified from Thien, 1979).

Structure

Soil structure is the arrangement and aggregate formation of soil mineral particles in the soil, and it influences the amount and distribution of soil pores and as a result, the interactions with air and water in soil (Craul, 1992; Keefer, 2000). There are six types of soil structure found in soil (with two different types being similar functionally), each resulting in different infiltration, plant root penetration capabilities, and gas diffusion rates (Table 3.3).

Table 3. 3 Properties of Soil Structure (adapted from Craul, 1992)

Structure	Properties		
	Infiltration	**Root Penetration**	**Gas Diffusion**
Granular	High	Easy	Favorable
Blocky Subangular Blocky	Decreased	Decreased	Decreased
Columnar Prismatic	Favorable*	Favorable*	Favorable*
Platy	Greatly Reduced	Greatly Reduced	Greatly Reduced

*During soil rewetting, the soil swells and limits water flow and root development.

Bulk Density

Bulk density represents the compactness of soil or soil particles by measuring the weight of soil per unit volume, specifically the oven-dried weight per unit volume (Craul, 1992). The bulk density of the soil will often increase with soil depth (Craul, 1992). Bulk density influences pore space, water availability, and root growth and development (Craul, 1992). Plant roots can

only grow in the pore space available; when that pore space decreases too much as a result of increased bulk density, plants cannot properly develop (Keefer, 2000).

Soil Water

Soil water plays a significant role in soil processes (Craul, 1992, Keefer, 2000). Plants require available water in soil for 1) photosynthesis, 2) nutrient transport in solution via plant roots, 3) translocation of nutrients within plants, 4) plant cooling and transpiration, and 5) keeping plant cells from drying out (Keefer, 2000). Soil water also assists with exchanging and transporting energy and nutrients in soil (Craul, 1992; Keefer, 2000). Lastly, soil water is critical in microbial biochemical processes and soil biomass development.

Macro- and micro-soil pores will control water levels in the soil (Urban, 2008) (Figure 3.2). Macropores are larger, interconnected passageways that assist with water transport to the lower levels of soil (Urban, 2008). Macropores should not hold water for extended periods because they are the main passage for air and oxygen through the soil (Urban, 2008). Micropores are areas in the soil that will store water for longer periods within the structure between small soil particles, where plant roots will uptake water (Urban, 2008). As water drains from the soil, the soil type will go through different states of water saturation, and saturation states and rates are determined by water in the macropores or micropores (see Figure 3.3 and Table 3.4).

Soil water will drain out of the soil with the pull of gravity as water moves through the soil profile and/or by surface runoff when a soil is fully saturated or on sloped terrain and perhaps intersected by a highly compacted soil lens or layer of rock. However, soil water is also lost through direct soil evaporation and through plant uptake and transpiration, also known as evapotranspiration (Urban, 2008), thus making field capacity difficult to measure with precision.

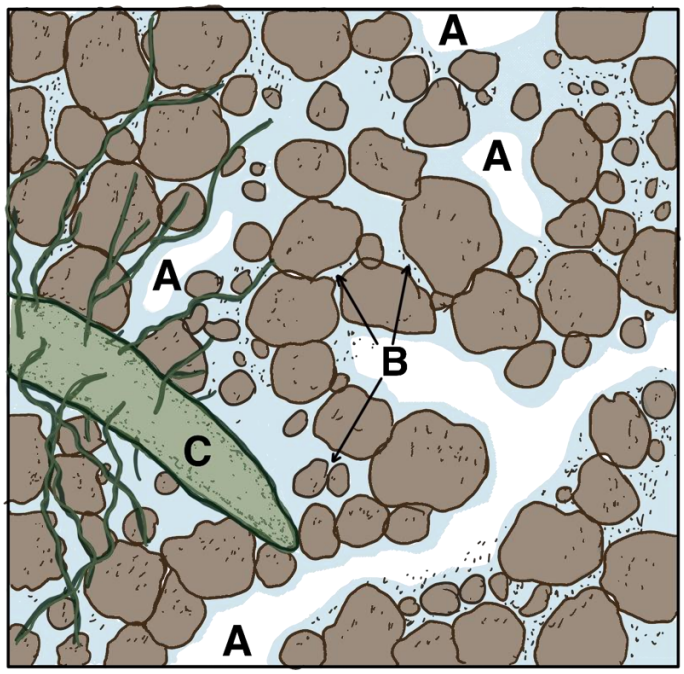

Figure 3. 2 Macropores and Micropores: A) Macropores filled with air after soil returns to field capacity, B) Micropores water films between small particles, C) Root (adapted from Urban, 2008).

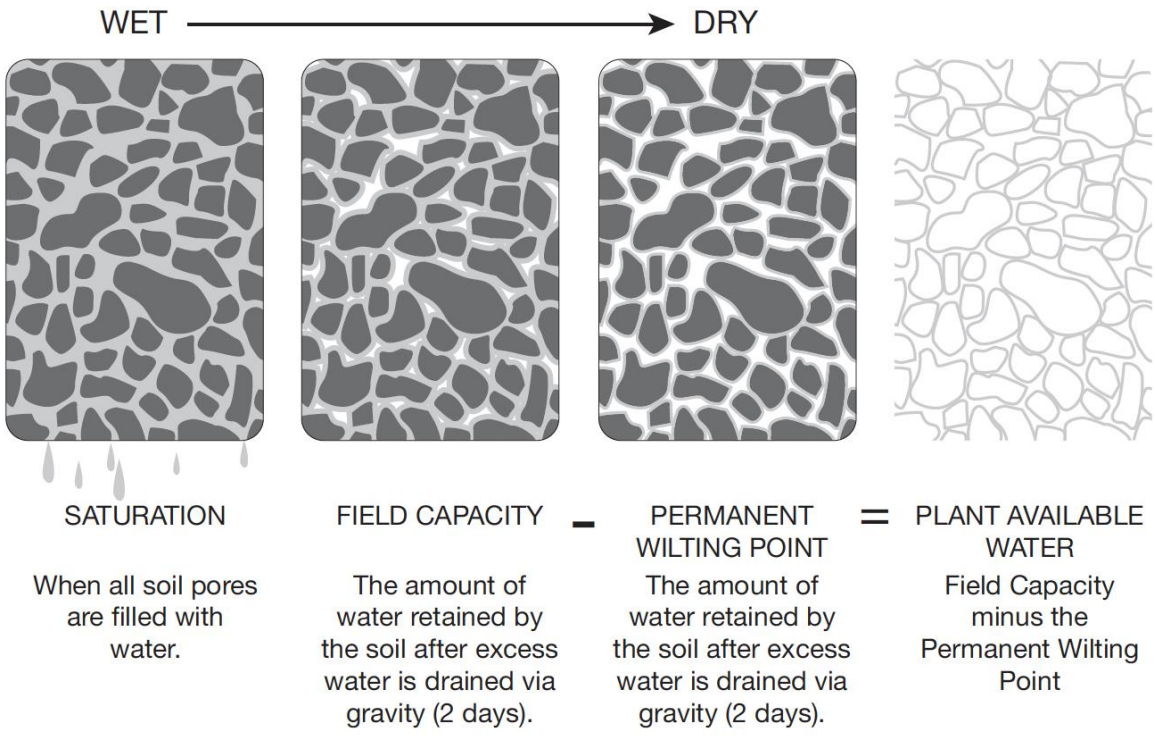

Figure 3. 3 Soil Water Movement and Storage Timeframe Following at Saturation Event (Calkins, 2012).

Table 3. 4 States of Water in Soil (adapted from Urban, 2008).

Terms	Saturation State
Saturated State	Water fills all micropores and macropores.
Field Capacity	Water fills micropores, and this is the amount of water held in the soil after excess water drains via gravity only (making field capacity difficult to measure with precision).
Wilting Point	Roots can no longer take water out of micropores.
Available Water or Water-Holding Capacity	State between field capacity and wilting point.

Color

Soil color is a good indicator of soil parent material and nutrients. Soil color is first defined by the parent material, with common minerals such as quartz, limestone, or feldspar having definingly different color profiles (Urban, 2008). Soil color is created by being coated or stained to appear a certain color as noted in Table 3.5. Iron is a common element that may define a soil's color (e.g., red or gray). Organic matter or humus (decaying plant and animal matter) promotes another defining color for soil, being very dark brown to almost black (Urban, 2008).

Table 3. 5 Soil Color Indicators. Adapted from Urban, 2008.

Soil Color	Indicator of
Black	Soil rich in humus or decayed organic matter
Brown Tones	Soil particles coated in organic matter
Red or Orange	Iron in well-drained soil
Yellow	Iron in slow-draining soils
White	Leached soils (without iron)
Gray	Iron in slow-draining soils or seasonally high water table levels
Blue Gray	Iron in non-draining soils
Mottled Soil	Multicolored soil indicates fluctuating drainage.

Drainage

Soil drainage is classified into three components: runoff, internal drainage, and permeability (Craul, 1992). Soil runoff is the water that moves over the surface of the soil and into the local drainage systems or bodies of water. Runoff occurs when the amount of water exceeds the infiltration capacity of soil. The infiltration of soil is driven by the porosity of the soil, soil structure and surface compaction, and existing moisture content (Craul, 1992). The slope (landform) will strongly influence the rate and volume of runoff (Craul, 1992). Internal drainage in soil is the relative flow of water through the soil profile. The rate of flow into and through soil types is known as soil permeability.

Soil texture, structure, compactness, and depth are used to determine soil drainage classifications from well-drained to poorly drained (Craul, 1992). In soils, when a hardpan or bedrock is reached, there is a restriction on water flow. In these areas, downward drainage of water is prevented, instead, water will flow horizontally along or above the impermeable layer (Keefer, 2000). Hardpans in soils can result in flooding when water in soil fills all the available room above the hardpans (Keefer, 2000). Infiltration rates can be measured in the field using an infiltrometer (Urban, 2008).

Depth

Soil depth can be defined by the “effective root depth” or the depth of soil that allows for root growth (Keefer, 2000). Soil depth is typically the measured distance to the water table or bedrock at the base of a soil profile (Craul, 1992). Depth influences the ability for plants to grow in soil. Shallow soils do not typically promote abundant plant growth due to a lack of space for root development; however, sufficient soil moisture can promote plant growth in shallow soils

(Table 3.6) (Craul, 1992). Soil depth is also relevant information to understand for soil and landscape systems created on built or engineered structures.

Table 3. 6 Soil Depth Classification (per Keefer, 2000).

Classification	Depth (inches)
Very Shallow	< 10
Shallow	10-20
Moderately Deep	20-36
Deep	36 - 60
Very Deep	> 60

Organic Matter and Nutrients

Nutrients required by plants are divided into two groups, micro-nutrients, and macro-nutrients, as shown in Table 3.7 (Craul, 1992; Urban, 2008). Macro-nutrients are utilized at rates in hundreds of pounds per acre compared to micro-nutrients which are utilized in pounds or ounces per acre (Craul, 1992). Most elements required are derived from minerals or soil solids (Craul, 1992). In healthy soils, organic matter typically exists in abundance. Organic matter is critical because it can contain all of the nitrogen used by plants (Craul, 1992).

Organic matter in soil is made up of plant and animal remains in varying stages of decomposition, microbes, and compounds produced by microbes (Keefer, 2000). Organic matter (OM) content can range from 2 to 9 percent in healthy soils, depending on soil type, with sandy soils typically having much less OM than clay soils (Keefer, 2000; Magdoff & van Es 2021). Organic matter in soils gives a good indication of the potential for organic activity in soil (Urban, 2008). Soil OM acts as an energy and nutrient source for microbial organisms and plant roots

(Craul, 1992). It also plays a role in aggregate formation, water movement, structure, aeration, and root development in soil (Craul, 1992).

Soil organic matter (SOM or OM) is influenced by soil temperature and moisture, both of which impact the accumulation and decomposition of OM in the soil (Urban, 2008). When making soil amendments to account for OM deficiencies, there is such thing as too much soil organic matter. Organic matter percentages over 10 percent are unstable (Urban, 2008).

Table 3. 7 Elements Required by Plants (Urban, 2008).

Base Elements	Macro-nutrients	Micro-nutrients
Carbon	Nitrogen	Iron
Hydrogen	Phosphorus	Manganese
Oxygen	Potassium	Boron
	Calcium	Molybdenum
	Magnesium	Copper
	Sulfur	Zinc
		Chlorine
		Cobalt

pH

pH is the measure of hydrogen ion concentration in soil, which can reflect the overall chemical condition of soil (Craul, 1992). Soil pH is connected to the availability of nutrients to plants and can indicate the general character of soil organisms as noted in Figure 3.4 (Craul, 1992).

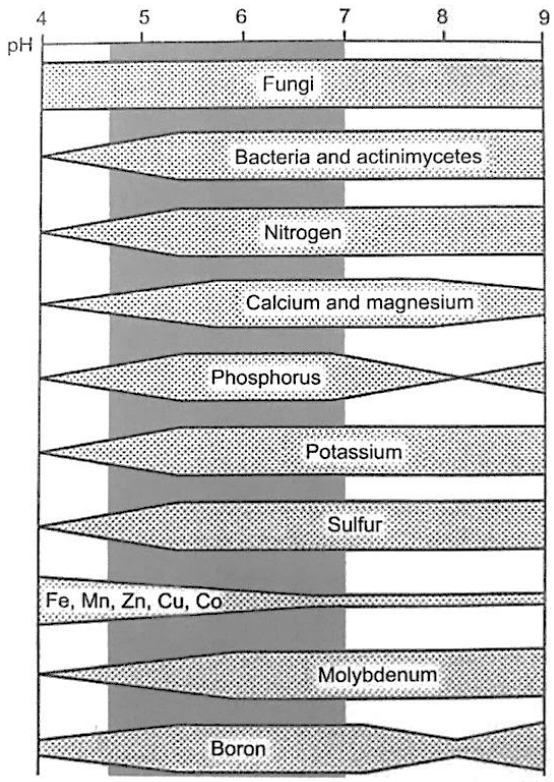

Figure 3. 4 Available Elements with Varying Soil pH. The dark gray column indicates what is generally considered optimal pH for plants (Urban, 2008).

Organisms

Soil organisms range from large animals such as moles and other burrowing mammals, to insects, other small animals, and microscopic organisms (Figure 3.5 & 3.6) (Craul, 1992). Soil can be considered a complex living organism with many organisms living in or on it (Craul, 1992). Soil organisms are connected to soil energy sources and food webs. Microbial organisms in soil play a large role in nutrient decomposition and cycling (Keefer, 2000).

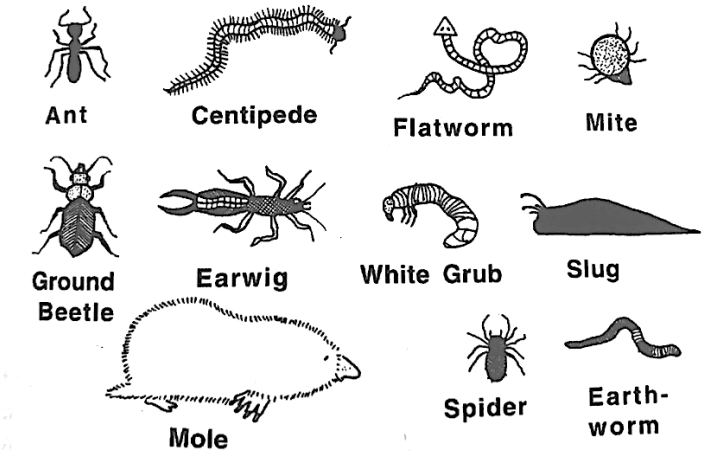

Figure 3. 5 Examples of Small Animals Found in Soil (Keefer, 2000)

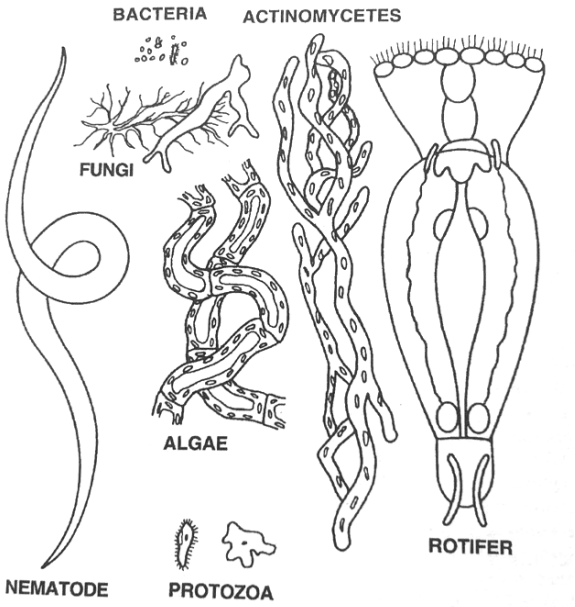

Figure 3. 6 Microscopic Organism Found in Soil (Keefer, 2000).

Getting Soil Information in Practice:

Cost, Ease, Interpretation, and Limitations

NRCS Web Soil Survey

The NRCS (Natural Resources Conservation Service) Web Soil Survey provides site users, engineers, surveyors, and designers with an easy access digital resource for soil maps and data. The NRCS Web Soil Survey is free, documents relevant soil information needed for general (broad-scale) land use and land management decisions (NRCS) and is often used by designers due to its ease of access and interpretation. However, in some urban areas, soils conditions are often not considered or evaluated, or conditions have dramatically changed since the NRCS soil survey was completed (Urban, 2008). Effective urban soil assessment takes place at the site scale, with designers conducting an urban site soil assessment themselves (Urban, 2008) or with the assistance of soil scientists and agronomy experts.

Private or public soil testing labs are frequently used to help determine soil characteristics, including the mineral and nutrient content of sampled soils from a site. On-site soil sampling can be done to better understand the characteristics of soils and may include a range of different tests depending on the nature of the project envisioned. The following page provides examples of soil tests that can be performed as discussed by Barrett Kays in *Planting Soils for Landscape Architectural Projects* (2013). Professional geo-technical reports can also provide detailed soil information, geology, and subsurface hydrology information.

Soil testing costs for various physical, chemical, and biological indicators are shared in Table 3.8 to highlight budget considerations that need to be planned for as planners and designers seek to understand the nature of soils on a particular site.

Recommended On-Site Soil Tests or Sampling for Professional Testing in the Lab

(List from Planting Soils for Landscape Architectural Projects, Kays, 2013)

1) **Basic Soil Testing**
   a) Particle size analysis using hydrometer test,
   b) Soil pH, and
   c) Soil fertility analysis.
2) **Soil Tests for Compacted Soils**
   a) Infiltration rates of surface horizon, and
   b) Saturated hydraulic conductivity using a constant head permeameter.
   c) Particle size analysis of sand and fragments using a sieve test,
   d) Bulk density of each horizon using undisturbed soil core testing, and
   e) Saturated hydraulic conductivity using undisturbed soil core testing.
3) **Soil Tests for Acidic (low pH) Soils**
   a) Cation exchange capacity, and
   b) Base saturation.
4) **Soil Tests for Alkaline (high pH) Soils**
   a) Reaction (pH) of each horizon,
   b) Cation exchange capacity,
   c) Base saturation, and
   d) Soil salinity.
5) **Soil Tests for Saline Soils**
   a) Cation exchange capacity,
   b) Base saturation, and
   c) Soil salinity.
6) **Soil Tests for Wet Sites**
   a) Redoximorphic analysis to determine depth to seasonally-high watertable,
   b) Redoximorphic analysis to determine depth to normal watertable,
   c) Infiltration rates of surface horizon,
   d) Particle size analysis of sand and fragment fractions using sieve test,
   e) Bulk density of each horizon using undisturbed soil core testing,
   f) Vertical saturated hydraulic conductivity using undisturbed soil core testing, and
   g) Horizontal saturated hydraulic conductivity using undisturbed soil core testing.
7) **Soil Tests for Soil Biology**
   a) Soil organic matter,
   b) Nitrogen mineralization, and
   c) Microbe analysis by organism count.
8) **Soil Tests for Stormwater Retention (Water Garden)**
   a) Determination of depth to the restrictive horizon and rock,
   b) Redoximorphic analysis to determine the depth of the seasonally-high watertable,
   c) Redoximorphic analysis to determine the depth to the normal watertable,
   d) Infiltration rates of the surface horizon, and
   e) Saturated hydraulic conductivity using constant head permeameter.

Soil Testing by Indicator

Table 3. 8 Soil indicators and associated soil testing costs (Blum, 2005; Kays, 2013; Koch et al., 2013; Pankhurst et al., 1997)

			Relevance to:				
Indicator	Field or Lab	Potential Cost	Soil Quality	Soil Health	Plant Health	Site Sustain-ability	Built Structure
Physical							
Texture	F/L	$$	+	-	+	+	+
Structure	F	$	+	+	+	+	+
Depth	F	$	+	-	+	+	+
Bulk Density	F/L	$	+	+	+	+	+
Water Holding Capacity		$	+	+	+	+	-
Chemical Indicators							
pH	F/L	$	+	+	+	+	-
Electrical Conductivity	F/L	$	+	+	-	+	-
Cation Exchange Capacity	F/L	$$	+	+	+	+	-
Organic Matter	L	$	+	+	+	+	-
Major Elements	L	$$	+	+	+	+	-
Heavy Metals	L	$$	+	+	+	+	-
Biological Indicators							
Microbial Biomass	L	$$	+	+	+	+	-
Soil respiration	F/L	$	+	+	+	+	-
Enzyme Activity	L	$$	+	+	+	+	-
Soil Biodiversity	L	$$	-	+	+	+	-
Plant Diversity	F/L	$	-	+	+	+	-
Plant Growth	F	$	+	+	+	+	-
Soil Fauna	F/L	$	+	+	+	+	-

$ - Under $10 a sample $$ - Under $50 per sample $$$ >$100

Pricing derived from Kansas State University – Soil Testing Lab; Florida University – Soil Microbial Ecology Extension; University of Missouri – Extension

Influence of planning and design on soil

Soil Preservation

Soil preservation is the practice of keeping healthy soil in place and protected to prevent alteration that would result from excavation, grading, compaction, or other construction impact (Calkins, 2012). Protecting soils has important design implications, requires a project team to consider construction alternatives and construction schedule changes, and may increase or decrease costs. When soil is disturbed, it loses an irreplaceable attribute, the soil structure (Urban, 2008), soil nutrients, and organisms. Designers often assume that importing or re-spreading good soil will result in a restored site, however, it will never be the quality it was before disturbance (Urban, 2008). Thus, the preservation of soil throughout the implementation of designed landscapes is important. Requirements for soil preservation in design projects need to be recorded on the contract document drawings to ensure preservation from the beginning of a construction project (Urban, 2008). Soil preservation and protection require a great effort and commitment to convince landowners and contractors to go the extra mile to preserve soil because compromises will often be requested and may need to be made on a site during the construction process. Importantly, fencing will be required to keep vehicular and persistent foot traffic off of soils and vegetation to be protected during the duration of a construction project.

Successful soil preservation must start with the design phase of a project because preservation and protection goals will impact the location of paving, structures, utilities, grading, planting, and irrigation (Urban, 2008). Strategies for soil preservation or protection include those provided in Table 3.9 and Figure 3.7.

Table 3. 9 Soil Preservation Strategies (Created from Urban, 2008).

1	Sheeting and Shoring	Physical supports are used (or created) to reduce the size and impacts of subsurface excavations.
2	Fencing	Prevents vehicular access into preserved zones and also limits the amount of foot traffic into these areas.
3	Mulch, Mats, and Geotextile	Spreading wood chips, laying mats, and geotextiles over areas to reduce the risks of compaction due to construction work (see Figure 3.8).
4	Preservation of Plants	Serves as an essential barrier for contractors and protects topsoil and subsoil conditions by keeping the soil profile intact.
5	Inspection	Regular and focused site inspections help ensure contractors do not damage areas of interest.
6	Weather	Wet-weather restrictions help prevent the compaction of soils on a project site.

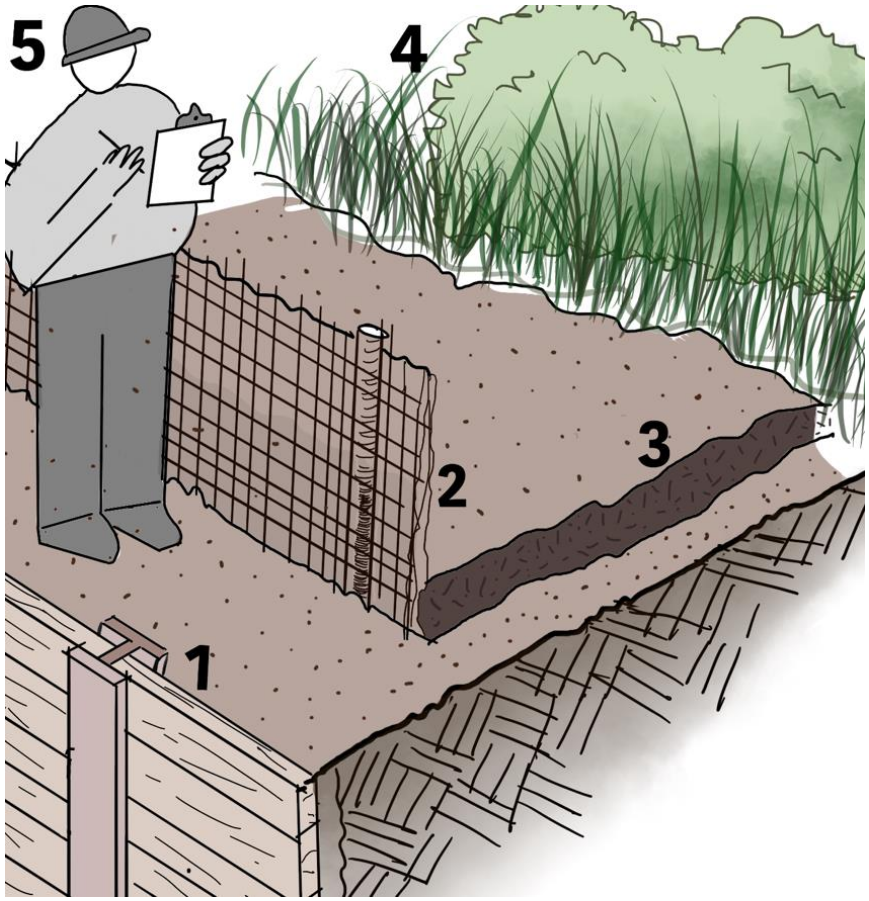

Figure 3. 7 Soil Protection, Numbers shown correspond to Table 3.9 above (adapted from Urban, 2008).

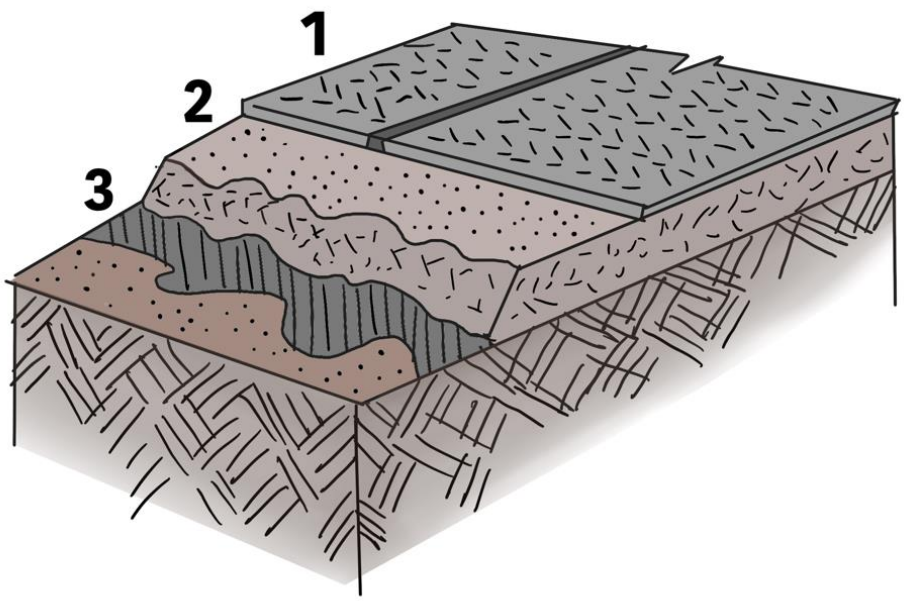

Figure 3. 8 Matting detail 1) AlturnaMATS® or other durable and protective surface covering 2) Six inches of wood chips or mulch, 3) Geotextile fabric (adapted from Urban, 2008).

Handling of soil during development

Topsoil stripping

When soil cannot be preserved on site or needs to be removed due to construction, it will be relocated to another location for reuse. Stripping the topsoil is the first step of most development and construction projects (Craul, 1992). Before stripping, plants, stumps, and large root mats are removed (Urban, 2008). Across a development site, soil is typically stripped to a depth of 12-18 inches (Craul, 1992). The stripped soil is highly disturbed, with little existing structure remaining. The remaining exposed soil layers are at high risk of compaction, are influenced by the water content during the construction, frequently leading to lower infiltration rates and increased soil erosion (Craul, 1992). Because of compaction, the exposed soil layers

require loosening before re-spreading topsoil on top of these layers to prevent severe compaction and allow for root penetration.

Best practices for soil removal and stripping include (source):

1. Herbicide treatment may be warranted prior to stripping if using a particular herbicide is deemed essential to prevent invasive plant development on stockpiled soils. However, herbicides should only be used when other alternatives (namely keeping invasives in check by vegetative competition, removal by hand and/or burn management, or cultivation/tilling) are not available or are not successful. Ideally, use of herbicides will be done in ways that avoid or minimize impacts on living soils and native plants.
2. Grasses and non-woody plants that are not invasive should be mowed, but do not need to be removed.
3. Soil moisture needs to be assessed, and the soil should not be excessively dry or wet when soil stripping happens.
4. If multiple soil horizons require stripping, topsoil (O and A horizons) and subsoil (B, E, and C horizons) should be stripped and stored separately. (See Figure 3.9 for a description of typical soil horizons.)
5. Recommended equipment includes grading machines with large, low-pressure tires or tracks to spread the machine's weight and prevent compaction.

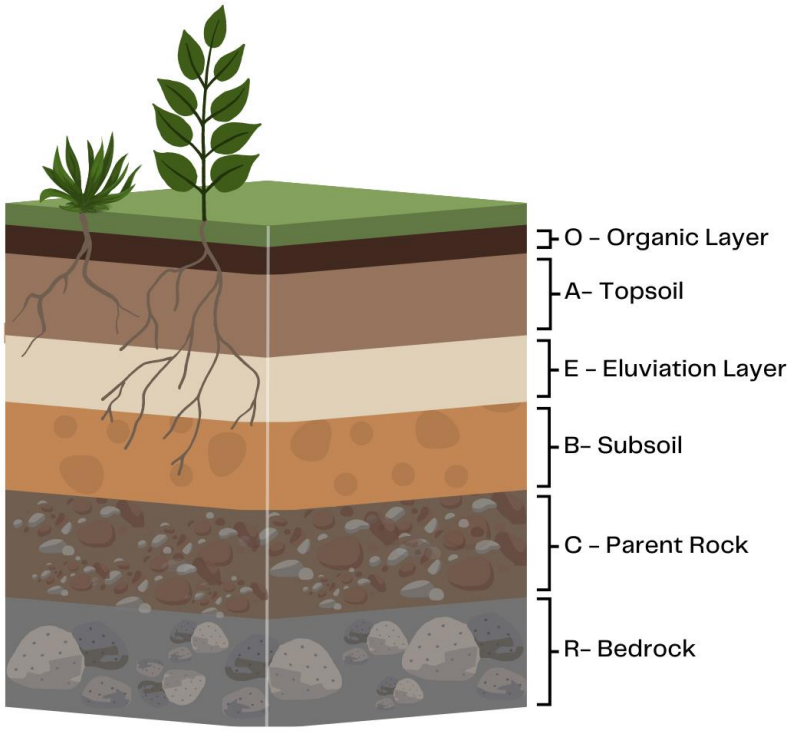

Figure 3. 9 Soil Horizons

Stockpiling

Stockpiling negatively impacts soil (Craul, 1992, Urban, 2008). Some included effects are disturbing soil structure and aggregates, reduction of soil organic matter and C pools, increased compaction, decreasing soil biodiversity, and changing microbial community composition and abundance (Craul, 1992; Urban, 2008; Valliere et al., 2021). Over long periods of stockpiling, nutrients needed to support plant life following re-spreading (Craul, 1992). The longer soils are stockpiled, the longer it will take to reactivate soil's biological function (Urban, 2008). Microbes are also responsible for critical roles in relation to soil function and plant development and diversity. Stockpiling as a result may impact the ability of soil to provide these vital services, compromising the biological potential of topsoil (Valliere et al., 2021). Effects of piling are present in soils stored for one year to 18 months, however, piles two years or older typically show severe impacts (Craul, 1992).

Best practices for soil stockpiling include:

1. Stockpile soil when it is dry (Craul, 1992).
2. Relocate as little soil as possible; storing soil on-site is best (Craul, 1992; Urban, 2008).
3. Pile different soil types separately and reuse for different applications (Figure 3.10).
4. Several small piles are better than large piles. Depth should not be greater than six feet for sandy soils, and four feet for clay soils as per Figure 3.11 (Craul, 1992; Urban, 2008).
5. Storage of soil should be for as short of time as possible (Craul, 1992).
6. Piles should be protected from wind and water erosion by using plant cover, compost or mulch, or a pervious geotextile (Craul, 1992; Urban, 2008). According to Urban (2008) soil should never have an impervious cover for protection (see Figure 3.12).

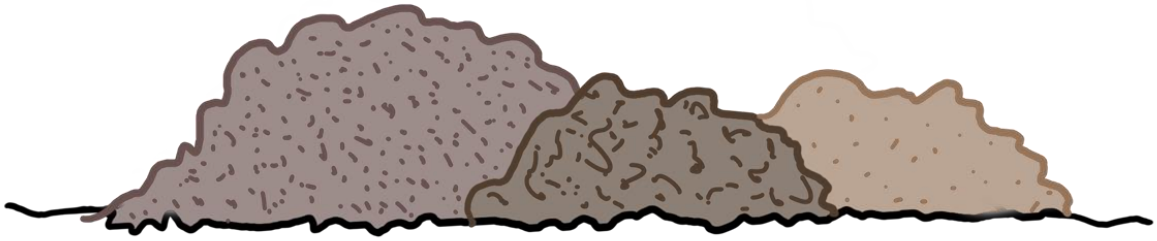

Figure 3. 10 Separate Differing Soil Types (modified from Urban, 2008).

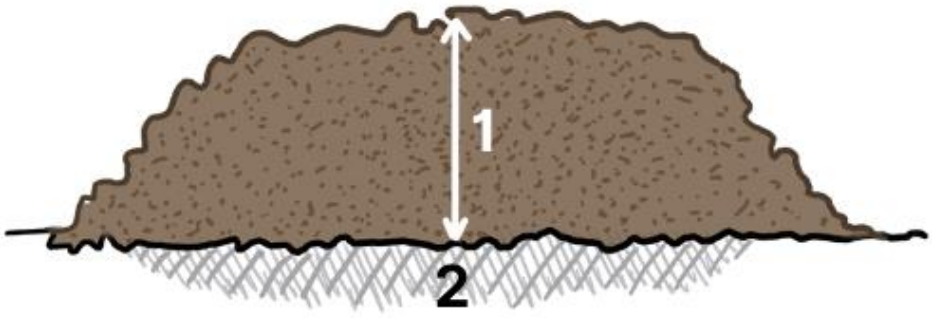

Figure 3. 11 Soil stockpile. 1) Optimum 6 feet for sandy loam, or 4 feet for clay loam. 2) Reduce compaction under storage area when done (modified from Urban, 2008).

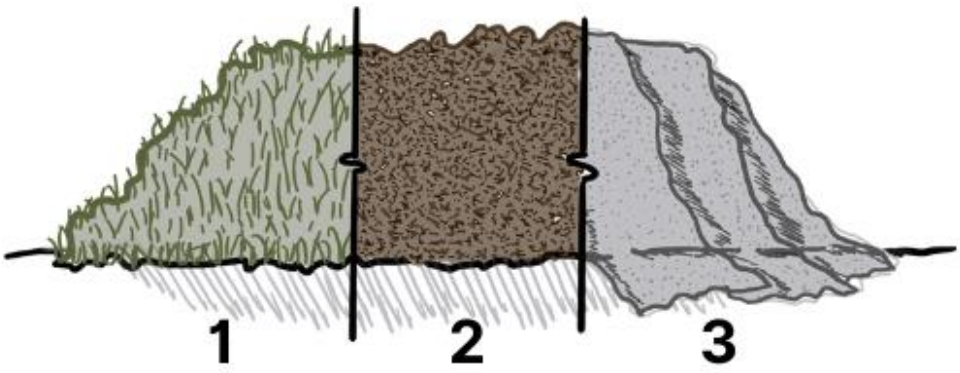

Figure 3. 12 Stockpile protection from wind and erosion. 1) Annual or perennial grass cover, 2) Compost or mulch, 3) Pervious, needle punched geotextile (modified from Urban, 2008).

Re-spreading

Soil re-spreading does not automatically result in healthy soil. Depending on how the soil is stockpiled, the soil will exhibit many changes from its original state (Craul, 1992). Organic matter content, living organisms, and physical character of soil will all be reduced due to the removal, storage, and re-spreading. The soil organisms can take years to reestablish in soil (Craul, 1992). As a result, the following best practices are encouraged.

Best practices for soil re-spreading:

1. Minimize trips with heavy equipment during the re-spreading process (Craul, 1992).
2. Incorporate organic matter while re-spreading to improve drainage, biological function, and introduce structure (Urban, 2008).
3. Based on project goals and site and soil conditions, add nutrients and other amendments to meet specific planting and other project needs.

Grading

Grading results in soil compaction, because constant trips of heavy equipment are required to get a desired soil grading pattern (Craul, 1992), thus stripping macropores in topsoil and

reducing infiltration rates (Kays, 2013). Enforcement of grading during optimal moisture levels in soil (when they are not too wet based on soil type and texture) is a crucial step to limit compaction, however, it is hard to enforce if construction administrators are not on site with contractors whenever they are working. Skilled equipment workers grading during a time of optimal grading moisture level can get the desired grade with minimal trips, resulting in less compaction. In addition, the lighter the equipment used, the better (Craul, 1992). To implement best practices that limit soil compaction, field tests of passes with equipment under different moisture levels are needed to specify and guide grading efforts by contractors and their machine operators (Kays, 2013). In addition, machine operators need to facilitate infiltration of water by roughening soil surfaces and sub-surfaces.

Maintenance

Use of Irrigation

Irrigation is a common maintenance practice in urban systems, and entails a deliberate application of water to soil and plants on a site (Keefer, 2000). Historically, irrigation was used in drier areas and regions where water was a limiting resource, but today, irrigation is used to the point of eliminating water stress, meaning that water is no longer limiting in many urban or developed landscape systems (Keefer, 2000). Because of lack in water limitation, irrigation will promote plant growth and soil organic matter storage (Thompson & Kao-Kniffen, 2019). However, non-essential irrigation is not a sustainable management strategy because water is a resource that is limited and should not be used in excess (Keefer, 2000). Instead, a site design should limit or seek to eliminate the use of long-term irrigation.

Irrigation can result in negative site consequences due to added inputs from irrigation water. To support water conservation rain-harvested water and recycled water are sometimes

used to irrigate a site, however, recycled water may be high in salt content (Calkins, 2012) and lead to other negative impacts to the system. Selecting an appropriate type of irrigation water to be used is very important.

Use of Fertilizers

Fertilization is another common maintenance practice in regularly mowed urban grasslands such as lawns or turf (Thompson and Kao-Kniffin, 2019). With urban development and continued maintenance of systems, there is an inevitable disruption to soil chemical cycling. As a result of development, fertile soil becomes less fertile soil, and organic matter is lost. In some cases, soil is compacted, covered, or impacted by harmful salts and heavy metals by the impacts of urban landscape management systems. With these interventions, soil becomes heavily dependent on human intervention to sustain soil fertility levels (Urban, 2008), thus resulting in even greater or persistent fertilization.

However, the use of fertilizers is controversial. Often fertilizers are used to increase crop yields or for urban lawn aesthetics, neither of which address the long-term health of soils (Urban, 2008). Fertilizer, added to improve soil health, should only be applied if quality data indicates low levels of essential soil nutrients (Urban, 2008) or to jumpstart microorganisms. Fertilization has been shown to increase above-ground biomass and belowground C (Thompson and Kao-Kniffin, 2019). Still, it also has the potential to increase respiration and CO_2 emissions from soil (Gong et al., 2011). The use of fertilization can also decrease soil pH, leading to acidification. The change in pH can impact microbial community dynamics and soil nutrient cycling (Thompson and Kao-Kniffin, 2019).

Recommended is the use and placement of targeted slow release, organic fertilizers and/or compost teas that address the needs of soils and vegetation. Before placement, the first

step is soil testing and establishing the levels of nutrients and elements (chemical composition) in existing or imported soils. Jim Urban states that soil fertilization should never be done without testing the soil's existing biology via a lab bioassay (2008). Fertilizing with necessary nutrients only (based on the soil test) is best, as per Table 3.10 (Calkins, 2012). Designers need to be aware of optimal fertilization application times in the region since placing fertilizer at the wrong time of year can harm existing plants at the site and downstream ecosystems if fertilizers are washed off-site (Calkins, 2012).

Table 3. 10 Examples of Natural/Organic Nutrient Sources (Calkins, 2012).

Plant Nutrient	Natural/ Organic Sources
Nitrogen (N)	Alfalfa, dried blood, cottonseed, feathers, fish, guano, seafood, urine, manure
Phosphorus (P)	Bone meal, bird manure, rock phosphate, vetch
Potassium (K)	Kelp, wood ash, seaweed
Calcium (Ca)	Egg shells, oyster shells
Magnesium (Mg)	Epsom salt (magnesium sulfate)

Liming Soils

Liming is the process of applying ground limestone to raise soil pH. Physical amendments need to be made to the soil to alter soil pH, typically through tillage and pulverization with limestone, as shown in Table 3.11 (Kays, 2013). Ground limestone need to be added and mixed in thoroughly as it does not move into the soil when simply placed on the surface and will only amend surrounding soil particles (Kays, 2013). For best results, lime should be incorporated into the top six inches of the soil (Urban, 2008). However, tillage of soil results in structure, horizon, and nutrient damage so incorporating lime should only be done when this is essential. If plants are present, it is often best to leave the site undisturbed.

Alternative methods include mixing limestone into water and or changing the pH of the irrigation water (Urban, 2008). Before application, lab tests are recommended to determine the amount and length of time required for the amendment to lower the pH (Kays, 2013). However, pH is difficult to change because it is tied to the fundamental configuration of soil, and it is suggested to just choose a plant palette well-suited with the current pH levels (Urban, 2008).

Table 3. 11 Lime amendment specification (Kays, 2013).

	Limestone Specification:
1	Material should contain a minimum of 80% calcium carbonate.
2	A minimum of 99% should pass through a No. 8 sieve, and 75% passing through a No. 60 sieve.
3	Lime in the form of finely ground dolomitic limestone should be used.

Replacing soil

Replacing soil is a solution for specific landscape design projects that do not have the budget, time, or ability to restore existing site soil (Calkins, 2012). However, the transportation of soil has a higher environmental impact, and because of this, the distance for transport should be limited (Calkins, 2012). Using and removing topsoil from an existing green site is also deemed unsustainable (Calkins, 2012). Replacing soil will also change or remove the current organisms and associated soil nutrient pools, if any still exist. There is also the risk of bringing in unwanted materials, organisms, or contaminants if soils are not adequately tested before transportation.

When bringing in soil, simply using soil or topsoil from another site is not good enough. Strategically using soil amendments and restoration in place are best; however, replacing soil can also restore site soil health if, after testing, the soils are deemed unhealthy and/or undesirable

(Kays, 2013, Calkins, 2012). Soils brought in need to be designed and specified professionally. Specifications require soil type and texture (amounts of sand, silt, clay, etc.), organic amendments, pH, soluble salt contents, and chemical analysis (Calkins, 2012).

Current projects in landscape architecture are also exploring ways to create native-like soil on sites. When bringing in new soil, professionals create soil profiles for different landscape design uses (bioswale, meadow, woodland, etc.) to ensure the drainage and soil types suit specific planting types or created ecosystems (Viani, 2022). Landscape architects, soil scientists, and engineers are also going beyond the specification of soils and the placement of these new soils by making sure that the soils that are imported or amended are biologically active soil by incorporating liquid microbiome amendments referred to as a form of compost tea (Viani, 2022). They claim that the use of these amendments creates biologically active soil, which can reduce the need for irrigation and fertilizers, both of which can negatively impact soil systems long term (Viani, 2022). Frequently such designs employ native plant communities adapted to the ecoregion and specific site conditions.

Restoration

Urbanization alters soils drastically and often requires restorative practices to help replenish soils critical functions and ecosystems services (Pavao-Zuckerman, 2008). Restoration in urban areas, however, is not standard across sites; each site will require a unique set of restorative solutions to match the site's needs (Pavao-Zuckerman, 2008). Restoration needs also vary across sites; often, restoration amendments required include amendments to address compaction, pH levels (liming or creating more acidic conditions depending on the intended vegetation), drainage, texture, nutrient availability, and/or biological function (Calkins, 2012).

Reducing or eliminating soil compaction on site is the most common practice to help toward the process of restoration. De-compacting soils can be accomplished one of three ways: 1) physically breaking apart soils, 2) limiting traffic to prevent compaction, and 3) creating conditions for long-term soil structure development by aerating the soil, adding organic matter, and increasing clays in the soil (Calkins, 2012).

Phytoremediation or Phytotechnology

Phytoremediation or phytotechnology is the use of plants to remediate soil and help remove, control, and prevent contaminants in soil (Kennon & Kirkwood, 2015; Todd et al., 2016). Phytoremediation is used to treat brownfield landscapes and can be used to restore vacant lots in urban areas (Todd et al., 2016). It can be a low-cost solution for soil restoration (Figure 3.13). Phytoremediation is an interim solution for contaminated sites before their use for green or public spaces (Todd et al., 2016). Phytoremediation is a fairly young strategy in the field of design but should be considered for sites with highly contaminated soils. Advantages that come with phytoremediation and phytotechnology use are that it is a way to restore soils while keeping soils intact, it is typically low-cost, low-energy, and aesthetically pleasing (Kennen & Kirkwood, 2015). Phytotechnology, when well-understood, can be easily integrated into other design and vegetation plans on site (Kennen & Kirkwood, 2015).

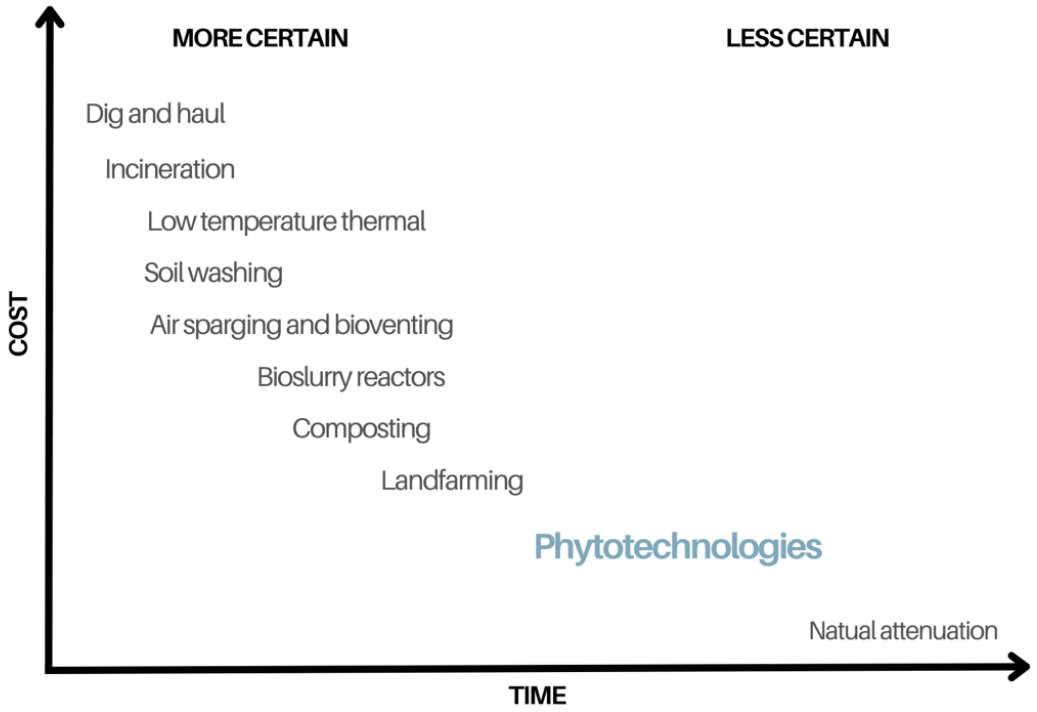

Figure 3. 13 Compared to other remediation options, phytotechnologies can render significant cost savings, but requires longer treatment times and there is a degree of uncertainty will any plant-based system (recreated from Keenen & Kirkwood, 2015).

Steps for the implementation of phytoremediation:

1. Consult a remediation specialist to test the concentrations of contaminants in the soil.
    i) Typical requirements include soil sampling (to understand the extent of potential remediation needs), and documenting groundwater conditions, existing flora and fauna, slopes and microclimate, hydrology, water supply and utilities, site boundaries, and other relevant concerns (Kennen & Kirkwood, 2015),
2. Determine an appropriate mitigation strategy for the site.
3. Define the areas of environmental concern and useable space maps for the site.
4. Enclose (fence off) areas that cannot be utilized or should not be disturbed.

5. Select the appropriate plant species based on the contamination. Ensure that plant selection is based on the specific remediation needs and specify the use of multiple species to minimize a monoculture.
6. Plant primarily grasses, although trees and shrubs can also be utilized.
7. Plant ground covers or use protective mulch to prevent exposed soil surfaces

(Todd et al. 2016).

Phytotechnology has its limits. In some cases, phytotechnology is not possible for the climate or soil conditions, since a site or the soils may be beyond supporting plant life due to infertility or too high of toxicity levels (Kennen & Kirkwood, 2015). Phytoremediation can be costly if plants need to be removed and new ones planted as a strategy for pollutant removal (Kennen & Kirkwood, 2015). Contaminants may not be fully prevented from spreading, and thus they can still be transpired or released, thus causing wildlife and people to be exposed to potentially toxic plants and soils (Kennen & Kirkwood, 2015). There is also an unknown timescale; some remediation is done over five years, while other projects may take more than 50 years (Kennen & Kirkwood, 2015). And, as with all natural and living systems, weather, animals, insects and other variables are not predictable and results can be different than is anticipated (Kennen & Kirkwood, 2015).

Soil potential for site sustainability

Soil health can be synonymous with sustainability (Doran & Zeiss, 2000). Soil health is a primary indicator for sustainable land management practices because of its contribution to plant health, nutrient cycling, and water and air quality (Doran & Zeiss, 2000). Soil quality can, in

some instances, determine the environmental quality of a site and will have a major impact on plant, animal, and human health (Doran & Zeiss, 2000).

Soil as a resource and living system will have a large impact on environmental, social, and economic functions. Soil is a source of raw material (clay, sand, gravel, and minerals), water, and energy (Blum, 2005). On a site scale, soil can promote biomass production, which includes food, raw materials, and renewable energy (Blum, 2005). Soil's contributions to site sustainability include acting as a water filter (in the form of rain gardens, bioswales, vegetated buffers, and constructed wetlands), providing a foundation and essential support for vegetation, enhancing water infiltration and preventing runoff, erosion, and flooding, providing and improving wildlife habitat, sequestering carbon, and reducing maintenance needs (especially long-term irrigation, fertilization, and mowing) (Blum, 2005; *SITES v2 Rating System: For Sustainable Land Design and Development*, 2014) (Figure 3.14).

Soil offers more than ecological benefits; it also acts as a physical basis for human activities such as housing, recreation, and transportation (Blum, 2005). Soil also contains cultural significance, serving as an archive of site history (Blum, 2005).

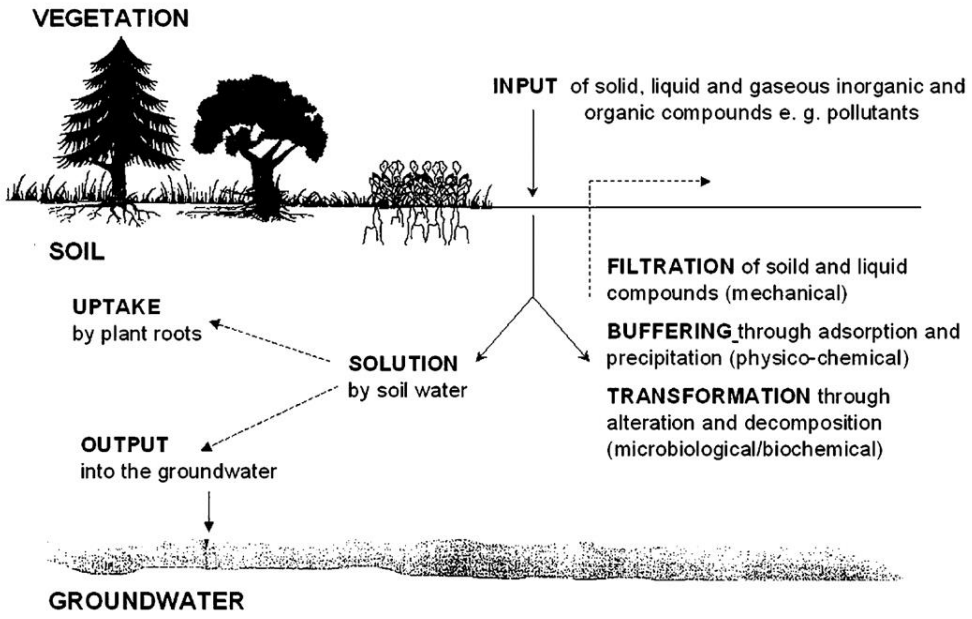

Figure 3. 14 Soil is the System Connecting the Atmosphere, Biosphere, and Hydrosphere (Blum, 2005).

Soil sustainability also relates to the soil site specifications. These specifications include two important components: 1) Reduction of on and off-site environmental impacts by the project. 2) Ease and cost of maintaining the project following completion, minimizing the need for resources long term (water, fertilizer, electricity, and other resource materials) (Craul, 1999).

When designing a site and determining if there is a need or use to preserve, restore, or replace site soils, landscape architects and those they collaborate with need to understand the value and impact of different approaches as well as the sustainability goals for the site. The sustainability potential of soil can help create a more resilient site while also addressing larger (perhaps global) sustainability concerns (Koch et al., 2013) (Table 3.12).

Table 3. 12 Soil functions and their influence on global sustainability challenges (Adapted from Koch et al., 2013).

	Global Sustainability Challenges					
Soil Functions	Food Security	Water Security	Climate Change	Ecosystem Services	Biodiversity Protection	Energy Sustainability
Nutrient Cycling	+	+	+	+	+	+
Water Retention	+	+	+	+	-	+
Biodiversity and habitat creation	-	-	-	+	+	-
Storing, filtering, and transforming compounds	+	+	+	+	+	+
Provision of physical stability and support	+	-	+	+	-	+

Conclusion

Landscape architecture is a profession that relies heavily on the function and health of soil. Understanding the basic elements and their function is the first step in creating successful design, however, the restoration and preservation of soil on a site is critical for long term site success and long-term sustainability. Without healthy soil, there will be excess energy and costs associated with maintaining designs over the short and long term. Soils have the ability to limit or negate the need for common maintenance practices of irrigation and fertilizer if the soils, vegetation, and hydrology fit well with the site and ecoregional context and conditions. Nevertheless, the best practice in site design and implementation is to leave soil undisturbed where this is possible. In many instances, we know that landscape architects are often not hired to leave soils and sites undisturbed, and they will alter the landscape to implement some form of design. Thus, where soil preservation is not possible, being intentional and thoughtful in the soil testing, stripping, storage, and re-spreading across sites is crucial.

The profession is in a position to make smart, thoughtful ecological decisions for the design and development of our cities and should take the steps and strategies to protect, preserve, and restore soils in urban environments. With the world growth and increase in urban development, we must start to see urban soil as a resource that needs protection for the sustainability of our future. Consideration for soil should happen at all phases of a project, which is not a linear process, with each phase or stage informing one another (Calkins, 2012).

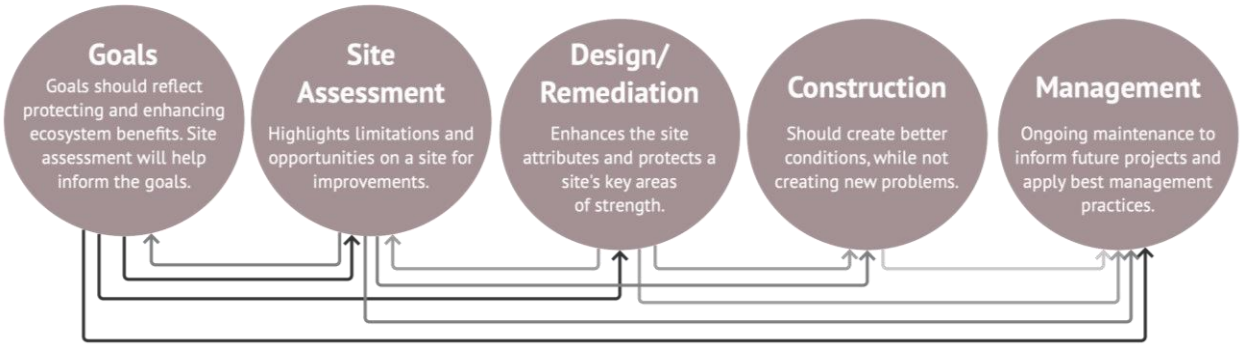

Figure 3. 15 Site design phases (derived from Calkins, 2012).

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Chapter 4 - Overall Conclusions

The overall goal of this thesis was to better understand urban development's impacts on soil health and microbial function and to relate these research findings to landscape architecture. Urban developments and related soil disturbances are increasing worldwide, leading to increased soil degradation in many parts of the world. The degradation of soil results in the loss of soil-provided ecosystem services such as infiltration and water filtration, nutrient cycling, carbon © storage, biomass and plant production, and more.

Nevertheless, urban soils are not dead and completely infertile. There is potential in urban areas to promote and foster healthy, high-functioning soils. In the design and implementation of spaces in urban areas, we can preserve or restore soils through landscape architecture, which relies heavily on healthy soil and well-functioning soil systems for the success and long-term sustainability of implemented designed projects. Disciplines including biology, soil science, agronomy, ecological engineering, construction science, land development, building and landscape construction, landscape management, and related fields have very important roles to play in partnership with landscape architecture and land-use planning to ensure long term health and sustainability of soil (conserved, restored, or created) in cities.

In this study, we directly assessed the effects of urban development and management. We found that urban development and disturbance affect soil health and function, especially in sites with intense and recent disturbances. Soil nutrient pools of all sites decreased in comparison to native grassland, showing disturbance, in any capacity, reduces soil C and nitrogen (N) and that the recovery of a soil system’s C and N takes significant time to regain levels similar to native, undisturbed soils. We also found that management was shown to influence soil health and function, with sites under intensive management (with added irrigation and fertilizer) showing

improved health on site; however, the same site demonstrated less microbial C use efficiency, indicating a lower potential for carbon sequestration.

Future research is needed to understand the direct effects of irrigation and fertilization. The impact of the frequency, duration, application styles, and different types of water (recycled, city, or filtered), and types of fertilizer may vary in their impacts, so having direct studies to address the potential differences in the future is ideal. It is also important, with climate change and the need to sequester carbon, to understand the direct impacts of these management practice on microbial respiration and microbial C utilization to make sure that we are optimizing our landscapes to be C sinks, instead of respiring C back into the atmosphere.

Although this research begins to answer the questions of the effects of urban development and land use management on soil health, the data collected and analyzed has limitations because urban sites are highly variable and soil samples were only taken in May and August during one growing season.

As city sizes differ, the degree of disturbance, contamination, and soil inputs change, and the impacts on the soil will vary. The regions of cities can impact the understanding of urban development and the degree of influence of urbanization, as soils in cities suffer in greater degrees from contamination, climate, and development inputs. This study looked at the effects of urban development in Manhattan, Kansas, and the Flint Hills Ecoregion, USA.

This study was conducted over a period of three months, which leads to a lack of detailed data about site differences and the impacts and dynamics of soil functions over the course of several seasons. Because soil is highly variable the functional differences can be a result of soil moisture and temperature dynamics, and only having a single sampling season limits the validity of data because the conditions of the site can change annually based on the year's precipitation

and climate. Having more sampling points and an increased study period of at least three years would help increase the understanding of the site, management, and climate impacts.

For future studies and next steps, understanding management at a finer scale will be crucial (for example, the amount of runoff and de-icing inputs from neighboring impervious surfaces, irrigation volume and frequency, fertilization volume and frequency, and the amount of biomass removal, etc.). Ideally, sampling directly following the treatment or management event could give the greatest indication of its effects (following mowing, clipping, or fire, or following the application of a fertilizer or herbicide).

To get a greater understanding of microbial processes and differences across sites, it would also be ideal to look at microbial community compositions across varying sites, and also very similar sites under different conditions and in different locations. There may be community dynamics that are driving differences in the soil.

With soil contamination being common in urban sites through the addition of heavy metals, salts, and other contaminants, the presence and quantities of these and other materials, substances, and chemicals, should be measured and analyzed across sites as they could have influence on microbial function and soil health.

Although the soil is crucial when looking at and addressing management and site-level impacts, understanding the impacts on vegetation can give a greater perspective of the effects on whole system C cycling and sequestration across sites. This would require measuring plant biomass, toxin, and nutrient levels, aboveground and belowground plant production, and the responses of different plant species across the selected research sites.

Landscape architecture is a field equipped to address the issue of soil degradation in urban environments, as we are directly involved in the design and implementation of these sites.

With the mantle of urban planning and design comes a responsibility to understand, at minimum, the basics of native and urban soil components and their relationship to site function and vegetative health. Without a basic understanding of soil, we risk implementing harmful and careless designs as professionals. We must be conscious of the impacts of development and design through all project phases. From site analysis, design development, construction, and long-term management, the soil should never be an afterthought. If a soil-conscious design is implemented from the beginning, long-term cost, energy, and management savings will result, creating a greater potential for healthy soil to remain after construction. If soils are tested and evaluated early in projects we can start planning, designing, engineering, and implementing techniques for restoring and creating soils that are best for design success, especially for imported soils and amendments.

With the growth and future study in urban developments and urban soils, there can be an expansion to begin studying soils in designed projects and the influence of the individual project specifications and management practices. Organizations such as the Landscape Architecture Foundation and the Climate Positive Design initiative are bringing more attention to the need to study soils in more detail, and the Sustainable Sites Initiative® is bringing light to the importance of soil (*SITES v2 Rating System: For Sustainable Land Design and Development*, 2014). Practitioners such as James Urban, Johanna Gibbons, Pamela Conrad, Meg Calkins, and others understand their importance to practice (Calkins, 2012; Climate Positive Design, 2023; Gibbons, 2021; Urban, 2008), but it is not enough for a select group of practitioners and organizations to understand the impacts of soil; it is the role of all landscape architects to treat soils as a resource worth protecting and remediating through design.

Overall, the expansion of urban development is inevitable, but the degradation of our soil systems does not have to be. Although this study has found that disturbance impacts soil health, even in the smallest amounts, the health and preservation of soil becoming a primary goal in the field of landscape architecture will help limit the potential degradation across our urban sites. Currently the field of landscape architecture is beginning to implement new practices in the treatment of soil on projects. Understanding the impact of development and the increase in soil compaction in urban environment is the first step, and many landscape architects are already specifying amendments for decompaction and incorporating organic matter to restore soil aggregates (Calkins, 2012; Craul, 1999; Kays, 2013; Urban, 2008; Venhaus, 2012).

Just as recent as November 2022, *Landscape Architecture Magazine* highlighted a 40-acre project whose team undertook and initiated a significant site restoration effort to create and remediate a wide range of soil systems needed on the site. This interdisciplinary landscape architecture and soil science team took the time to detail out at least a dozen distinct soil profiles for specific sites uses and to specify nutrients and the use of microbial compost tea additions to help ensure healthy, biologically functioning soil (Viani, 2022). The project is just one example in the field that can help set the precedent for soil design.

James Urban (www.jamesurban.net/soils-general), Phillip Craul, and Timothy Craul (Craul & Craul 2006) have long sought to emphasize the importance of understanding soil systems and the ways that trees and other plants interact with them in urban settings. Professional landscape architects and soil scientists at firms such as Jeffrey L. Bruce and Company, Pine and Swallow, Biohabitats, and a number of other firms have sought to learn from and build upon the work of earlier soil scientists and broad-and-deep-thinking planners/designers. Let us learn from and with them as we seek to create resilient landscapes and sustainable communities.

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Appendix A - Chapter 2

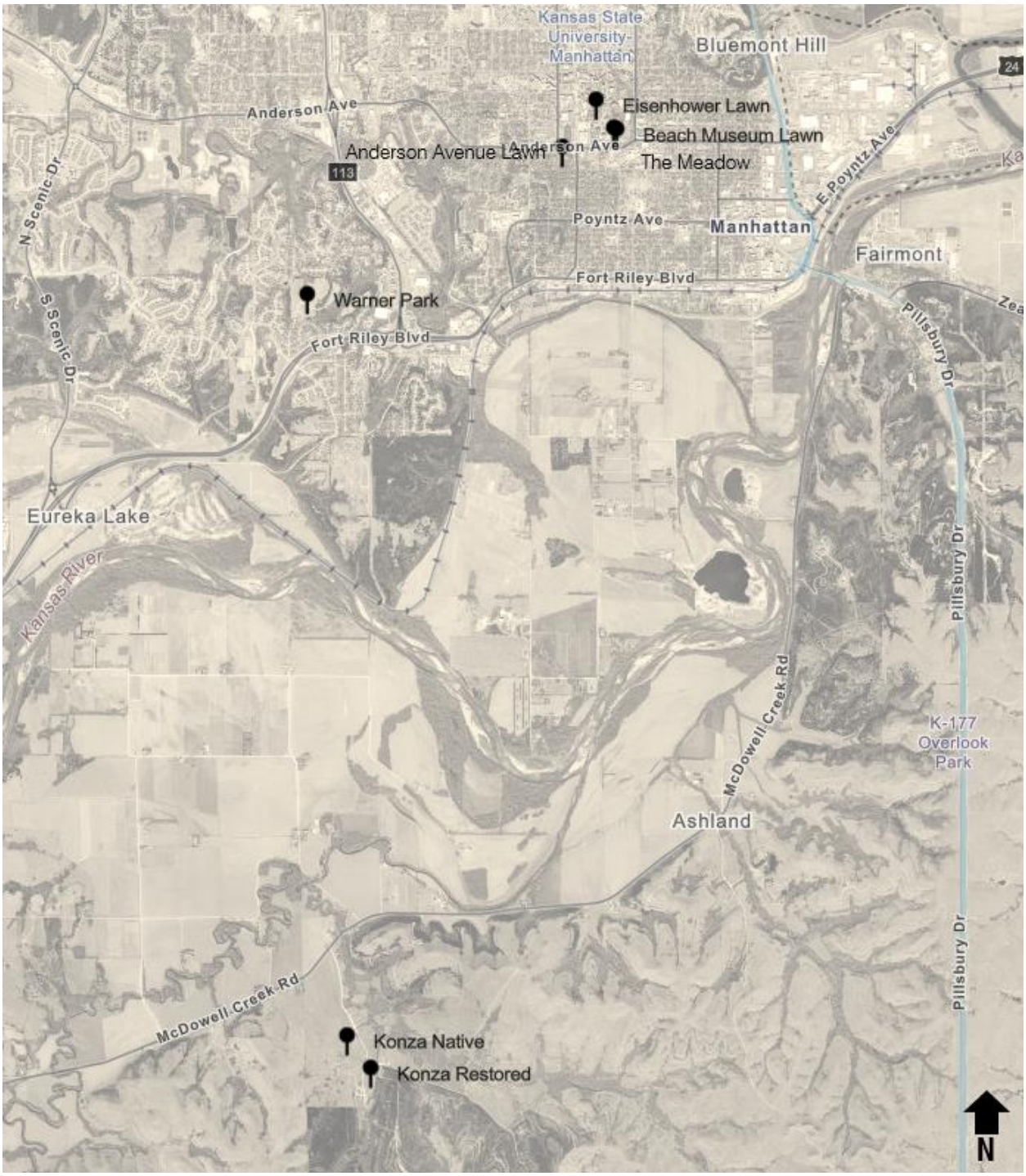

Figure A. 1 Map of sampling sites

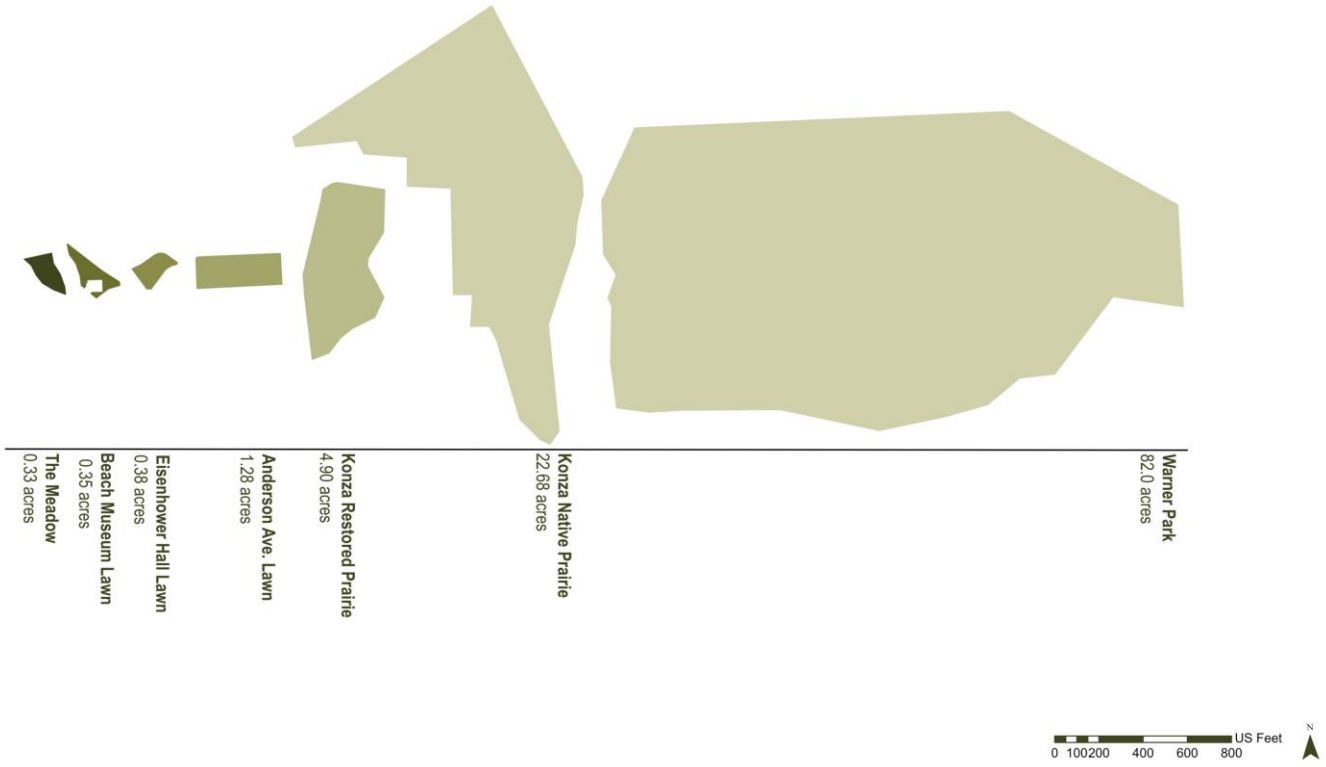

Figure A. 2 Sampling sites size comparisons.

Table A. 1 Site History and Management

Site	History and Establishment Justification	Management
Native Konza	A native, intact plot of Konza prairie	Burned annually in the spring.
Restored Konza	Former agricultural land, restored in 1997.The restoration was reseeded with a conservation reserve prairie seed mix.	Burned annually in the spring.
Warner Park	An intact prairie to our knowledge, however has had significant urban development surrounding it. Established as a city park in 1956.	Mowed annually. Also has mowed pathways for recreation event such as 5k events.
The Meadow K-State	Turf was removed and killed via spray and torch in 2013. Hand seeding was used to establish a native prairie plant selection in the fall of 2013 and irrigated that summer to allow for plant establishment.	Clipped annually and weeded by hand to try and contain invasives.
The Beach Museum Lawn	The establishment of this site was determined following the construction of the Marianna Kistler Beach Museum of Art, which caused disturbance to the surrounding land in 1996.	Mowed frequently.
Eisenhower Lawn	The establishment of 2004 was determined using google imagery to determine the last disturbance which was the implementation of a sidewalk.	Mowed frequently. Irrigated with Manhattan, KS city tap water and frequency based on current ET rates. Turf is fertilized three times a year with granular fertilizer. Turf is treated to control broadleaf weeds with an herbicide.
Anderson Avenue Lawn	Housing was removed July & August 2020.There was no soil brought in, it was filled and graded with existing site soil.	Mowed, as needed.

Figure A. 3 Konza Native Prairie Site

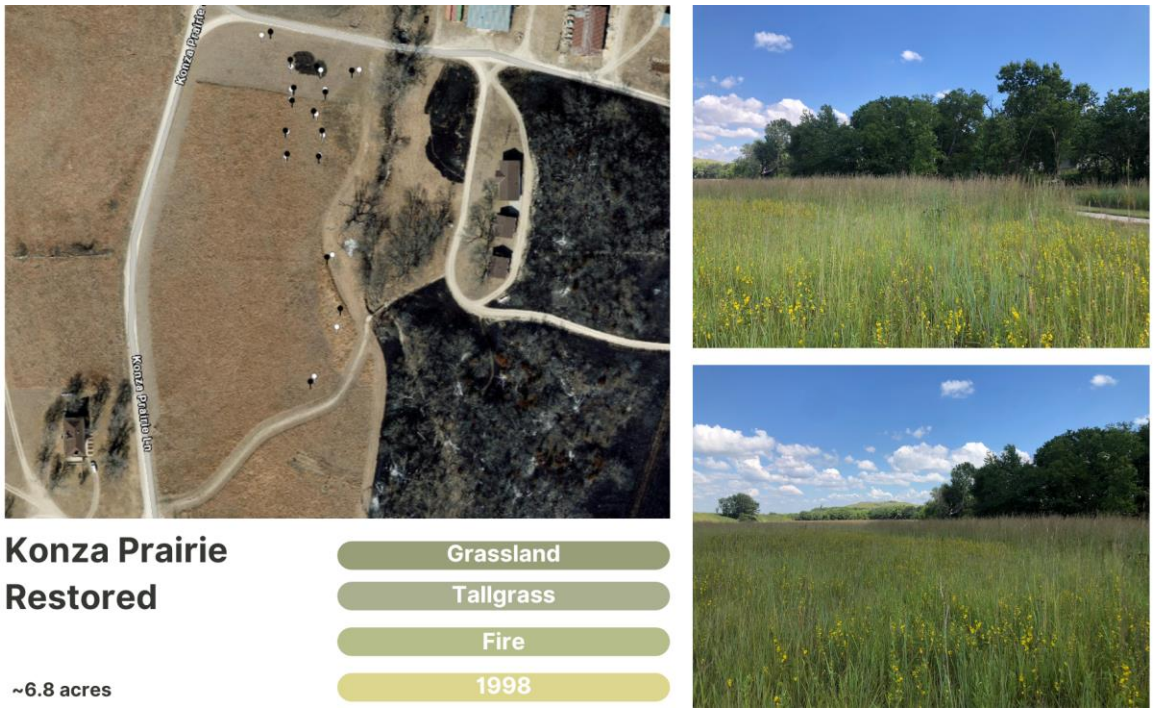

Figure A. 4 Konza Restored Prairie Site

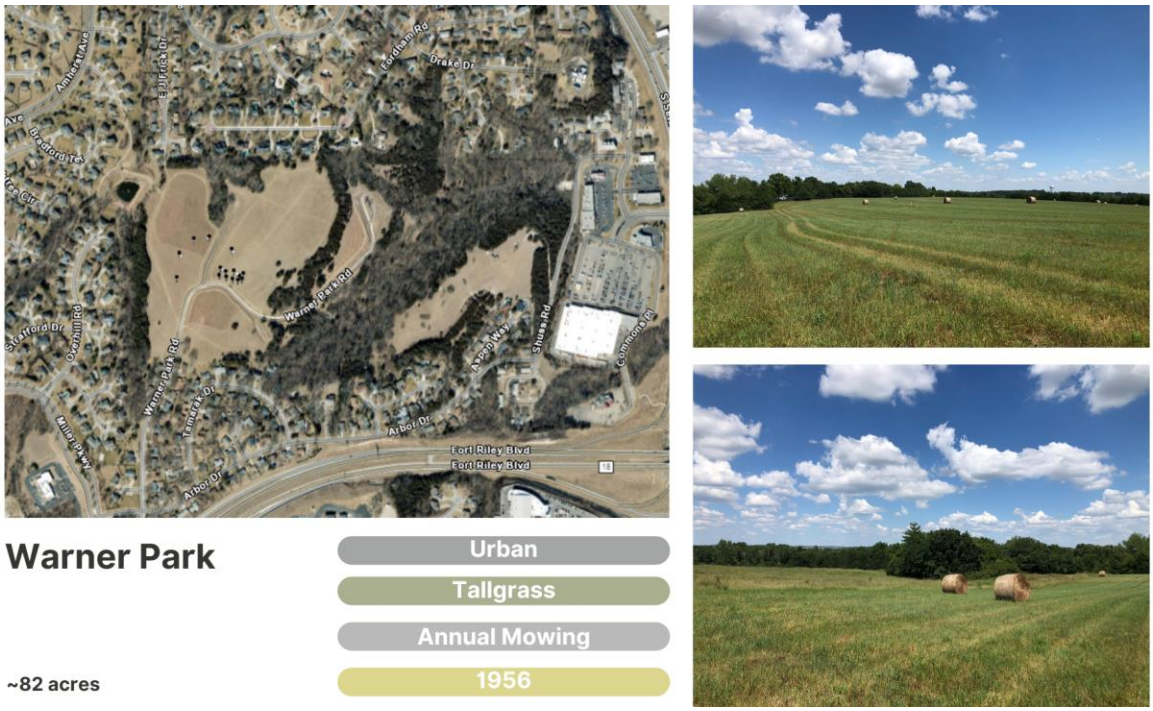

Figure A. 5 Warner Park Site

Figure A. 6 The Meadow Site

Figure A. 7 Beach Museum Lawn Site

Figure A. 8 Eisenhower Lawn Site

Figure A. 9 Anderson Avenue Lawn Site

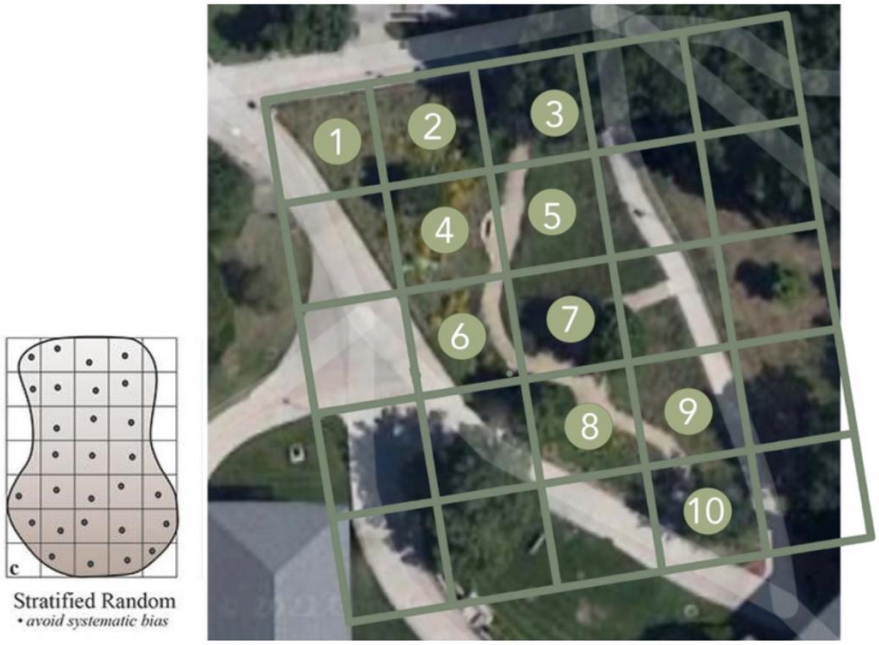

Figure A. 10 Example of stratified sampling on the Meadow site

Figure A. 11 Sampling kit.

Figure A. 12 Soil sample a) Soil sample and sleeve, b) Sample sieved with roots removed.

Figure A. 13 Soil texture in the lab a) Soil dispersion mixer and sodium hexametaphosphate, b) soil slurry mixing, c) Thermometer, hydrometer, and sedimentation cylinder.

Figure A. 14 Microbial biomass a) Weighed samples in beakers for chloroform fumigation, b) soil shaker, c) microbial biomass solution filtering.

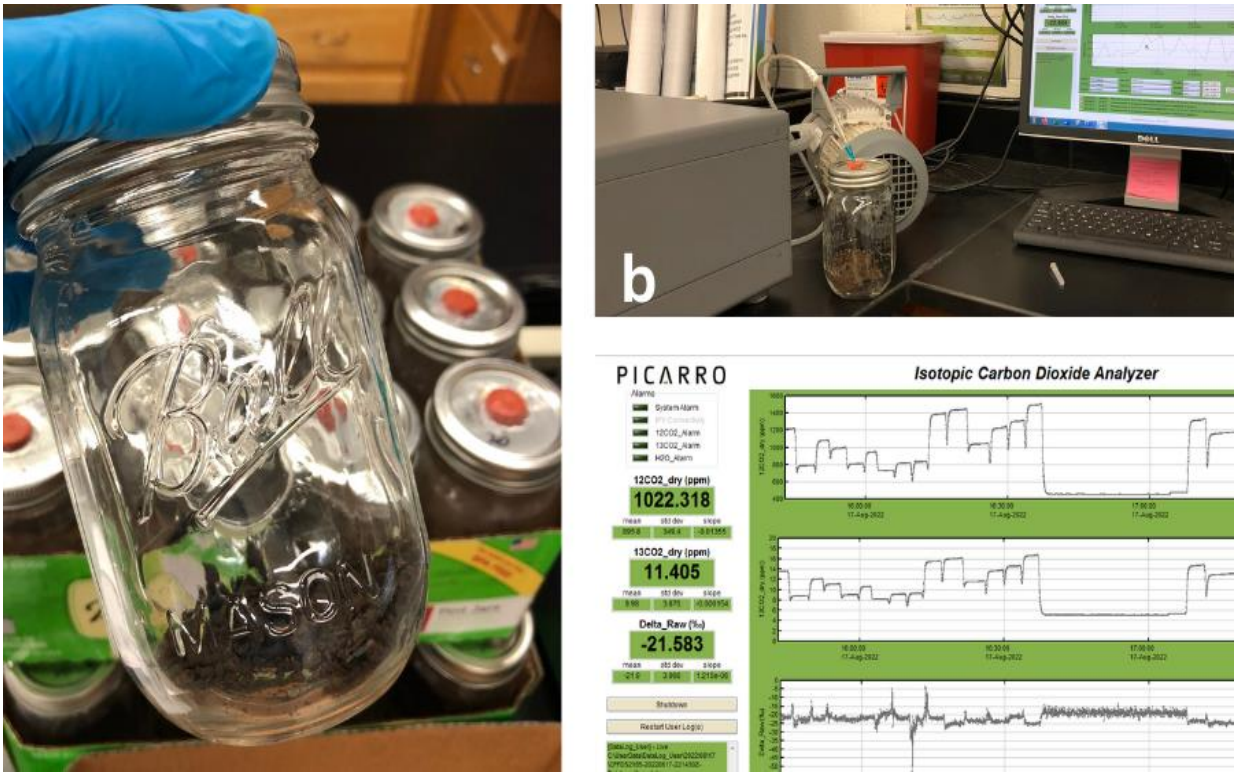

Figure A. 15 Microbial respiration a) Soil sample in the jar, b) Picarro instrument reading the sample, c) A screenshot of the Picarro readings.

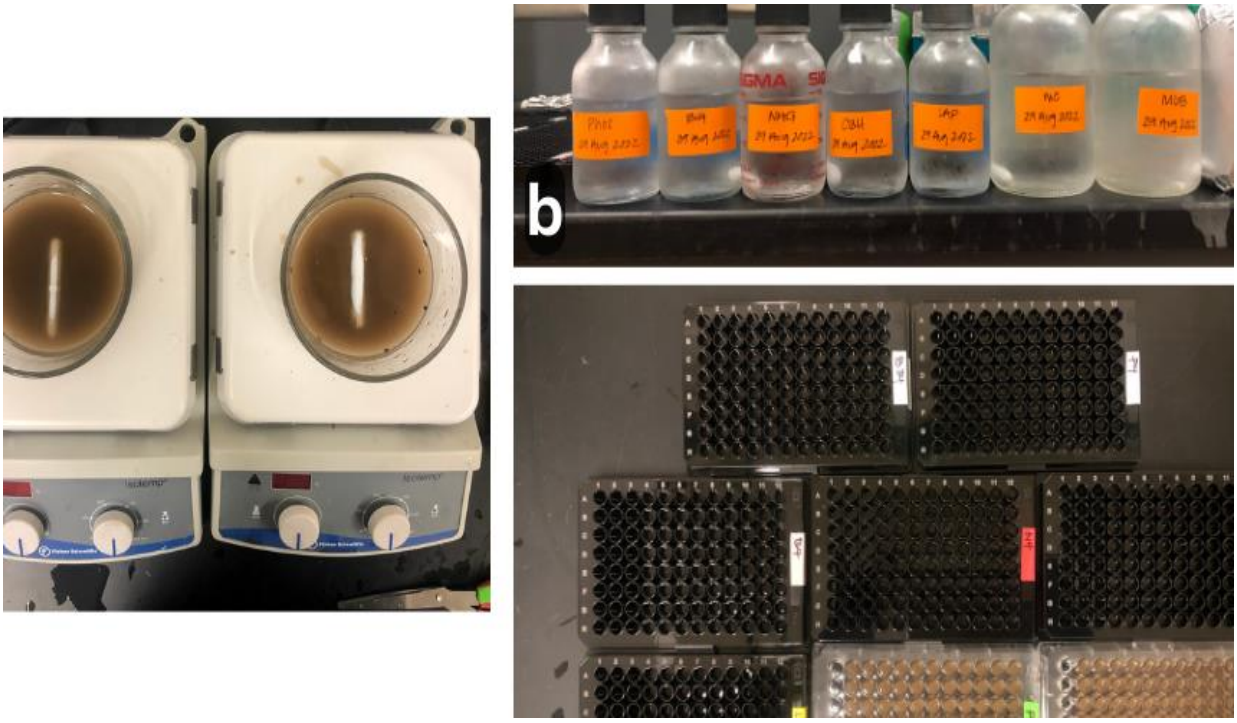

Figure A. 16 Extracellular enzymatic activity a) Soil slurry mixture, b) Enzymes and substrates, c) loaded plates