LANDSCAPE DESIGN *FOR* CARBON SEQUESTRATION

A framework for design, installation, and management of complex adaptive landscapes for carbon sequestration

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FOR
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Abstract

Landscape architects have the potential to contribute to climate change mitigation through natural climate solutions that sequester carbon in ecosystems. However, landscape architects lack resources on how to design landscapes for carbon sequestration and, in particular, soil carbon sequestration. I address these gaps by translating and interpreting the scientific literature to create an actionable framework for landscape architects. The framework consists of principles, strategies, and actions for design, installation, and management of landscapes for carbon sequestration. A key recommendation is that increasing the functional diversity of plants increases the potential carbon sequestration of the landscape by increasing its productivity and resilience. Additionally, plant functional diversity supports the soil microbial ecosystem, which is key to long-term soil carbon storage. This framework emphasizes that designing landscapes for carbon sequestration should prioritize belowground carbon dynamics and the functioning of the whole landscape system.

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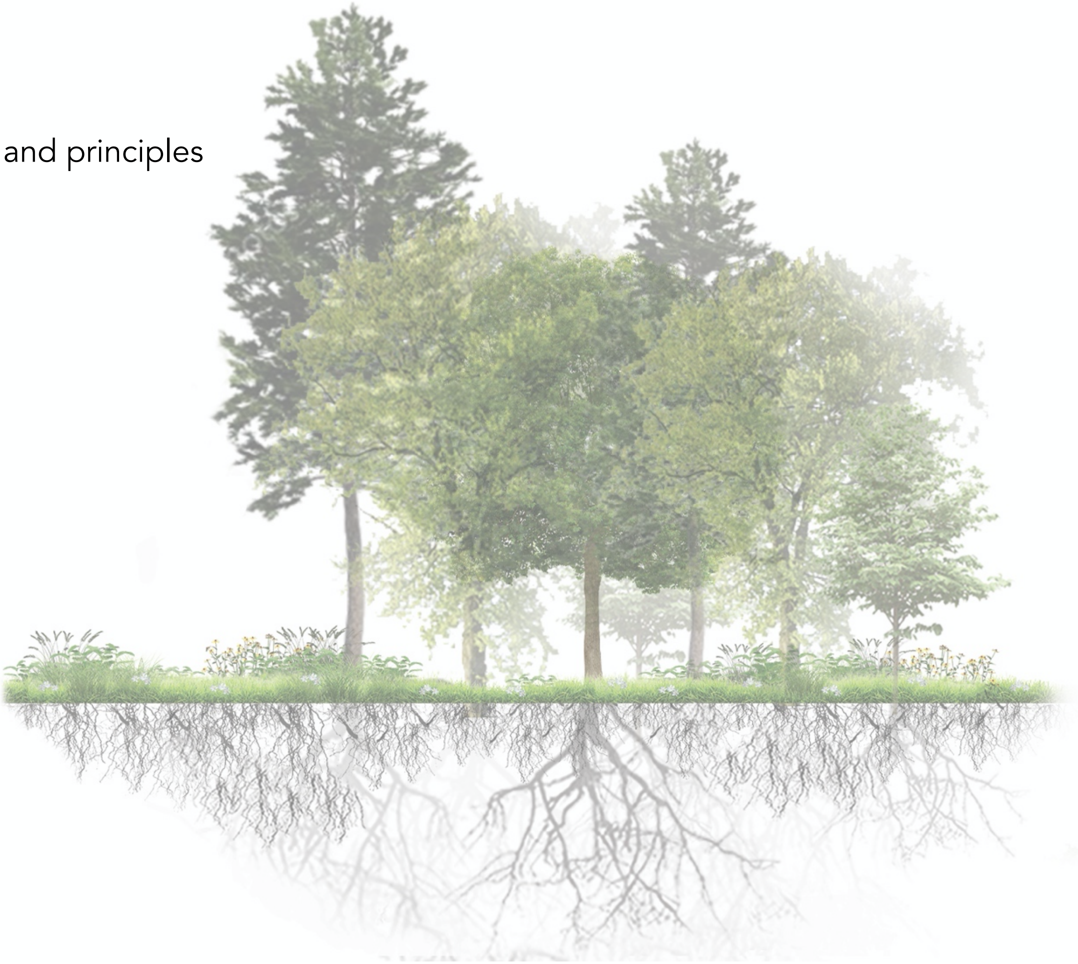
Part One

Introduction, background, and principles



Chapter 1 Introduction

Climate change is widely acknowledged to threaten the well-being of human and natural systems. Primary direct causes of climate change are the release of greenhouse gas emissions into the atmosphere from consumption of fossil fuels, as well as land uses that release natural stores of carbon from ecosystems. The scientific consensus is that we need to avoid warming the planet by more than 1.5 degrees to avoid a jump in catastrophic impacts. At this point, cutting emissions is not enough to keep warming under 1.5 degrees; removing carbon dioxide from the atmosphere is necessary (Minx et al. 2018; IPCC 2018). Many of the technologies being explored for carbon dioxide removal require large amounts of energy or land, which would negatively impact habitat or food production. These technologies are also not feasible because they have yet to be developed and are not ready for implementation (Minx et al. 2018; Boysen et al. 2017).

Natural Climate Solutions, or the sequestration of carbon in natural systems, is the only currently feasible solution with positive co-benefits for human and natural systems (Minx et al. 2018; Boysen et al. 2017). Natural Climate Solutions have potential to mitigate up to 21% of US emissions each year (Fargione et al. 2018). In the context of natural climate solutions, "**carbon sequestration**" in this project refers to the biological process where plants take carbon dioxide out of the atmosphere through photosynthesis, store the carbon in their tissues, and send carbon through roots to the soil, where it can be stored long-term.

Restoring natural systems that sequester carbon can help mitigate climate change as well as address the on-going destabilization of natural systems. Human civilization depends on the life-support services of the world's natural ecosystems that provide supply and filtration of fresh water, nutrient cycling, control of pests and disease, habitat for plants and animals that provide food and medicine, and regulation of regional and global climate. The same factors that are contributing to climate change–the on-going exploitation and destruction of natural systems and overconsumption of natural resources–are undermining these life-support services. Natural Climate Solutions are important because they can restore these critical services of natural systems in addition to helping mitigate climate change. Natural Climate Solutions are being studied and implemented in various fields such as forestry or agriculture but are not yet a large area of study or action for the field of landscape architecture. This may be due to the complexity of the science of carbon sequestration, lack of research on carbon sequestration in urban areas, difficulty in scaling up the impact of site-scale decisions, and lack of policy and funding for projects. Landscape architects can help mitigate climate change and address the destabilization of natural systems by designing landscapes that sequester carbon.

Project Goals and Methodology

How should landscape architects approach the design of landscapes for carbon sequestration? The purpose of this project is not to give quantifiable targets for maximizing carbon sequestration, but explore how designers can increase potential carbon sequestration as a co-benefit along with other design goals in a project. The scope of this project is the design of vegetated landscapes and plant communities, and does not address the design or sustainability of hardscapes and other structures included in landscape architecture. There are two main goals for this project:

1) Inform designers about key the drivers and processes of plant and soil carbon sequestration
2) Provide a framework of recommendations to guide design, installation, and management of landscapes for increased carbon sequestration potential.

The methodology (Figure 1.1) consists of a review of the current literature, primarily focused on connections among plant traits, soil life, and carbon sequestration; the interpretation of the literature in terms meaningful to design practice; and the formulation of a framework for design, installation, and management of landscapes to increase long-term carbon sequestration.

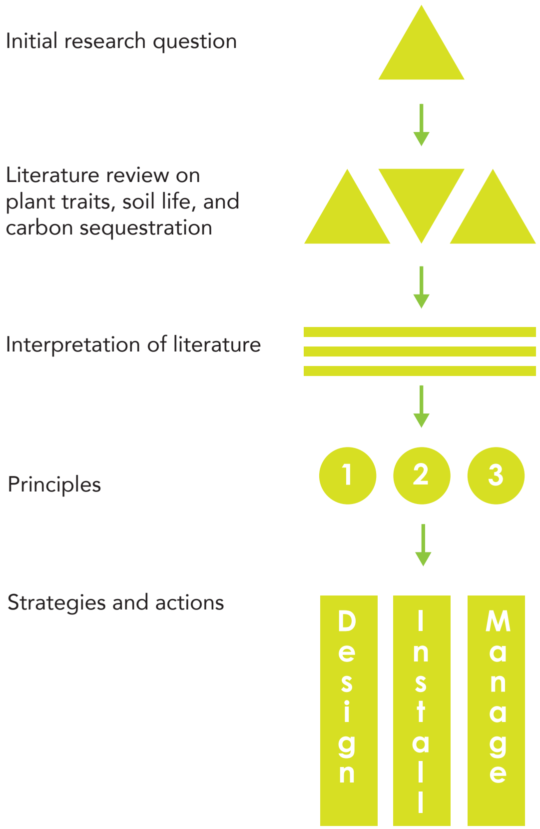


Figure 1.1 Methodology

The scientific literature on carbon sequestration is changing rapidly, dramatically altering our understanding of its processes and potential. Through literature review, I examined how plant traits, plant diversity, soil microbial communities, soil health, and management practices impacted above and below ground carbon sequestration. I also reviewed literature on ecological planting design and investigated which activities of landscape architects support or diminish carbon sequestration. To help guide my process and assess whether I was on the right track, I informally spoke to several experts in landscape architecture and soil biology who provided important guidance on the state of carbon sequestration knowledge.

The main outcome of my research is *the translation and interpretation of the literature to create an actionable framework for landscape architects to sequester carbon in their projects*. The framework consists of three key principles that are threaded through sets of strategies and actions for design, installation, and management of landscapes for carbon sequestration (Figure 1.2).

Significance and Potential

Although it is common for landscape architects to incorporate sustainability and consider climate change in their projects, implementation of natural climate solutions has yet to become widespread in the field. The Climate Positive Design Challenge, of the design firm CMG landscape architecture, is shifting this through the Pathfinder app, a carbon calculator to guide design and management of landscapes. Although these tools are a step in the right direction, currently there are not resources available for landscape architects on how to design and choose plants for increased *soil* carbon sequestration based on scientific evidence. Tools available to landscape architects, such as the Pathfinder app and the i-Tree software, only incorporate estimations of potential sequestration in biomass (above and belowground live plant parts); they do not address potential carbon sequestration in the soil (Conrad 2019; McPherson 1999). This gap exists because it is not feasible to quantify the amount of carbon that specific plants send into the soil (see Chapter 3 for further discussion). This project addresses this gap and this limitation by providing principles and strategies to guide design for biomass *and* soil carbon sequestration through incorporating an understanding of whole-ecosystem above and belowground dynamics.

It is clear from the literature that to design effectively for carbon sequestration in general, one needs to incorporate soil carbon sequestration. Most ecosystems in temperate climates have more carbon belowground than above ground. Additionally, there is more carbon in the soil than in the world's vegetation and atmosphere combined (Lehmann and Kleber 2015).

The potential for urban landscapes and urban soils to sequester carbon and mitigate climate change could substantial. Residential ornamental landscapes have potential to be net carbon sinks (Jo and Mcpherson 1995) and have been measured to contain amounts of carbon comparable to the carbon storage in forests (Whittinghill et al. 2014). Urban soils are estimated to store three times more carbon than urban trees (Pouyat et al. 2006; Nowak et al. 2013). Some studies have shown that soil carbon stocks are increased when agricultural land is urbanized (Liu et al. 2018; Vasenev et al. 2018). Although some urban landscape systems may be net emitters of carbon, such as lawns and urban forests, implementing more sustainable maintenance practices and lifecycle management of trees can shift the systems to being carbon sinks (Mcpherson et al. 2014). Although more research is needed to demonstrate that urban soil carbon sequestration can be significant to global carbon dynamics (Amundson and Biardeau 2018), improved management of urban soils for carbon sequestration carries many co-benefits for urban ecosystem services and public awareness.

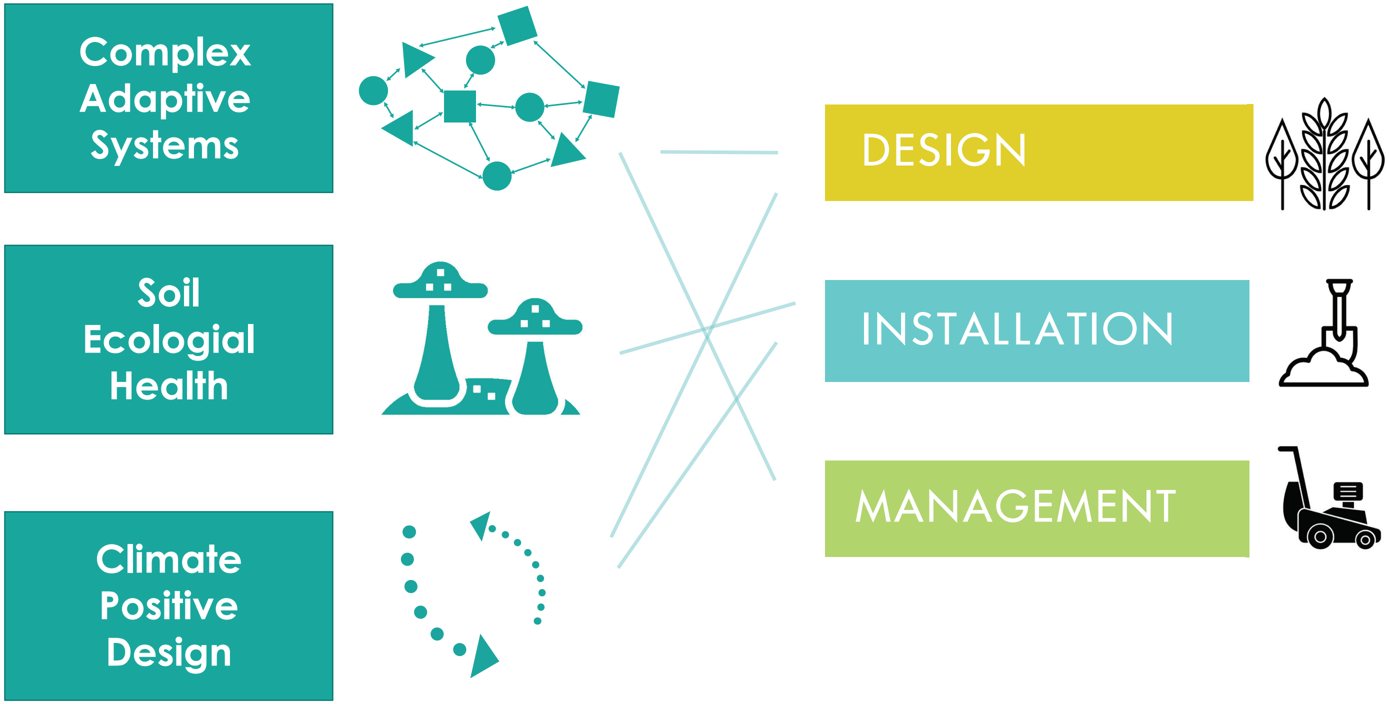


Figure 1.2 Project framework

Project Overview

Part one includes Chapters 1 and 2, which frame and review background knowledge to inform design applications in part two. **Part two** applies the principles developed in Chapter 2 to the framework of strategies and actions described in chapters 3-5, and concludes with policy recommendations and discussion in Chapter 6.

~ Part 1 ~

Chapter 1: Introduction presents the project scope and significance.

Chapter 2: Background and Principles explains the three principles of the framework: Complex Adaptive Systems, Soil Ecological Health, and Climate Positive Design. The section on Soil Ecological Health reviews the process of carbon sequestration and important components such as soil microbial ecosystems.

~ Part 2 ~

Chapter 3: Strategies for Design includes strategies and actions to guide design decisions for carbon sequestering landscapes, with an emphasis on how to select a palette of plants.

Chapter 4: Strategies for Installation presents strategies and actions for protecting soil health and reducing emissions in the installation of landscapes.

Chapter 5: Strategies for Management reviews the concept of adaptive management and relates it to the principle of complex adaptive systems; then follow with recommended strategies and actions to enhance diversity, protect soil life, and reduce emissions through management of landscapes.

Chapter 6: Final Thoughts discusses how the framework for landscape carbon sequestration could be applied to existing landscape architecture programs and inform policy.

Chapter 2 Background and Principles

This chapter includes three principles that guide the framework of strategies presented in Part Two of the project: 1) Complex Adaptive Systems, 2) Soil Ecological Health, and 3) Climate Positive Design (Figure 2.1). Through discussing each principle I will also review important background knowledge necessary for implementing the principles through landscape design.

Figure 2.1 The three principles

Principle 1: Complex Adaptive Systems

Incorporating selected characteristics of complex adaptive systems helps designers increase the efficiency, resilience, and health of the whole landscape system, which can translate to increased carbon sequestration. This section starts with key characteristics of complex adaptive systems, then reviews concepts of plant functional traits and diversity, and finally discusses how these concepts relate to carbon sequestration.

Characteristics of Complex Adaptive Systems

What is a complex system? A **system** can be defined as an assemblage of **components** linked together by regular action or interdependence (Lovelock 2000). A system is also distinct from the surrounding environment. An ecological system, or **ecosystem**, is an assemblage of organisms or groups of organisms that regularly interact through competition, symbiosis, trophic food webs, or sharing resources. An ecosystem is **complex**, not simple or random. Simple systems have easily predictable order and behavior: once you know the pattern of relationships among objects, you can predict the placement of the other objects (Figure 2.2). A random collection of objects, on the other hand, has no order and is unpredictable. In the middle, is a complex arrangement–there is a discernable non-random pattern, but it is difficult to predict. Thus, a **complex system** is an assemblage of components linked by regular interactions that form patterns, but are difficult to predict.

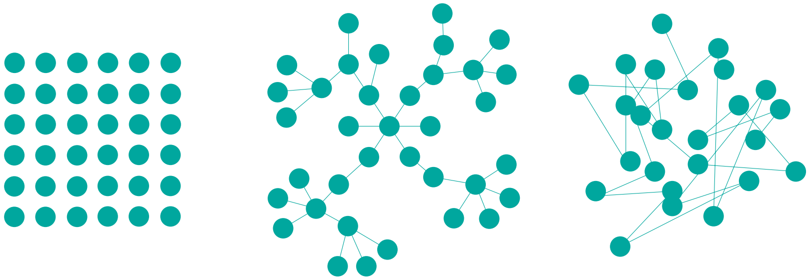


Figure 2.2 Simple, complex, and random patterns (adapted from Anand et al. 2010)

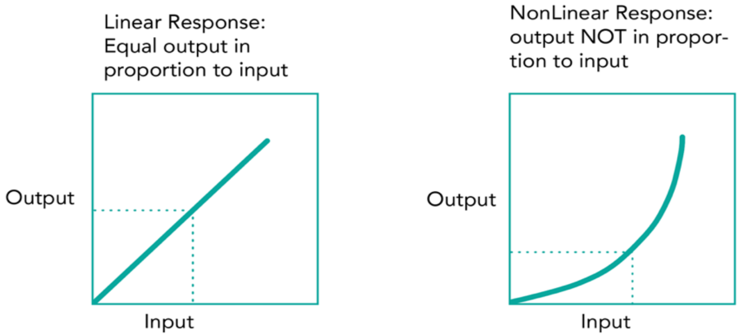


Figure 2.3 Linear vs nonlinear responses

One reason complex systems are difficult to predict is they have simultaneous interactive processes that lead to **nonlinear responses** to changes in the behavior of components or in the environment (Figure 2.3). A linear response, as in a simple system, is directly proportional to the input. A nonlinear response is not proportional to the input. Because complex systems typically include dynamical nonlinear responses due to multiple interacting processes, there is often a time lag before an impact or disturbance produces a noticeable response or effect. For example, if construction impacts an oak tree's root system, the tree may not show any signs of decline for years because it is a complex adaptive system.

Dynamical nonlinear responses are the result of complex interactions and feedback loops among system components (Levin 1998). **Feedback loops** happen when an action by one component affects the system **state** (structure and functioning), which in turn affects multiple components. Feedbacks can be negative or positive. **Positive feedback** is where the system response amplifies the input, accelerating change to the system (Figure 2.4). For example, climate change causes arctic sea ice to melt, which results in more darker-colored ocean surface that absorbs more heat

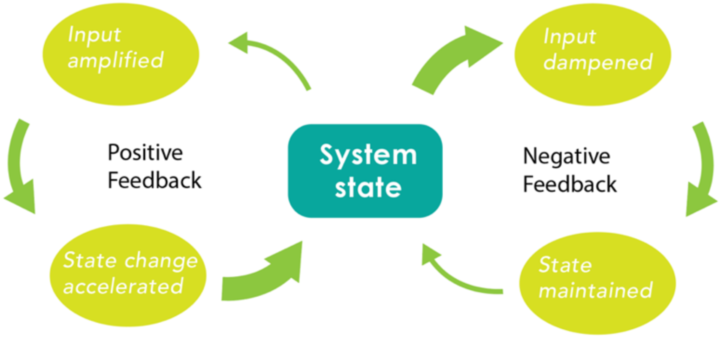


Figure 2.4 Positive and negative feedbacks (adapted from The Met Office)

from the sun, accelerating climate change. **Negative feedbacks** dampen the input, buffering the system from the potential effect and maintaining the current system state (Gunderson 2000). An example of negative feedback is the carbon sequestration of forests that dampens the warming of climate change by decreasing the greenhouse gases in the atmosphere. Complexity in a system tends to increase its capacity for negative feedbacks that help maintain the system state (Levin et al. 2013; Simard et al. 2012; Ryan et al. 2007).

Complex Adaptive Systems may be defined as systems where "macroscopic system properties such as trophic structure, diversity–productivity relationships, and patterns of nutrient flux emerge from interactions among components, and may feed back to influence the subsequent development of those interactions" (Levin 1998). Complex adaptive systems have a fundamental capacity to self-organize. **Self-organization** is the set of processes where the components in a system interact and respond with nonlinear feedbacks such that assemblages or patterns **emerge** on a higher scale (Figure 2.5) These patterns emerging from self-organization mean that a complex adaptive system cannot be understood by analyzing its components in isolation. The whole is more than the sum of the parts (Ryan et al. 2017).

The capacity of **complex *adaptive* systems** to self-organize allows the system to adapt to changing conditions. A group of organisms that work together to maintain favorable systemic conditions can use resources more efficiently and are likely to be more resilient against systemic change. **Resilience** refers the amount of disturbance a system can absorb before changing state (Gunderson 2000). **Interconnection** in a system increases its resilience by providing more

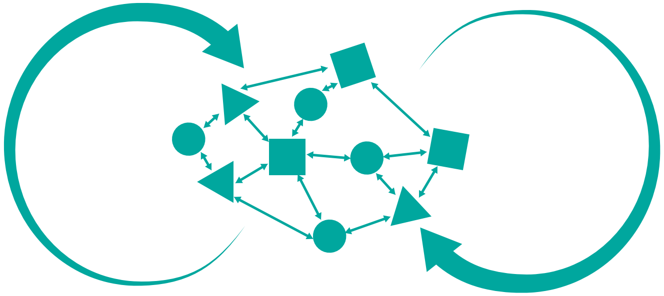


Figure 2.5 Self-organization through feedbacks

avenues for feedbacks to occur. For example, a tree with roots in a symbiotic relationship with fungi (*called* ***mycorrhizae****-see page 46*), will better acquire nutrients from the soil, while the fungi will receive carbon for energy from the tree. The tree and fungi together as a system will use the resources in the environment more efficiently. The tree roots and fungi also work together to stabilize the soil against erosion, which will help protect nutrients in the soil in case of extreme wind or flooding–meaning increased resilience. Many root-fungi interconnections allow more sharing of resources and more avenues for nonlinear responses that buffer the system against disturbances (Simard et al. 2012).

Complex systems exist as an aggregation of smaller systems and as a subsystem of larger systems. This **nestedness** contributes to the occurrence of complex interactions and nonlinear feedbacks (Figure 2.6). Collective action on a smaller scale affects higher scales and the emergent properties feedback to affect the smaller scale. An "ecosystem" is an abstract concept not fixed to particular scale (Pickett and Cadenasso 2002), but existing in a hierarchy of interconnected, nested systems. The development of hierarchical organization is "natural consequence of the self-organization of any complex system"(Levin 1998). A larger system, like a forest, contains smaller systems, like plant communities, that contain smaller microbial ecosystems. Designers should analyze multiple scales of systems to understand the complex dynamics of a landscape (Pulliam and Johnson 2002). Looking at a finer grain scale, such as testing for soil health, offers more detail about the system functioning. At a larger scale, fewer details are observable, but larger trends that may affect the system over time will be clearer (Levin 1992). For example, examining the watershed of a site over a year may reveal that a large amount of polluted runoff washes through the site after the first storm of the season. Then the designer can implement stormwater infrastructure and educate the neighborhood about protecting the watershed.

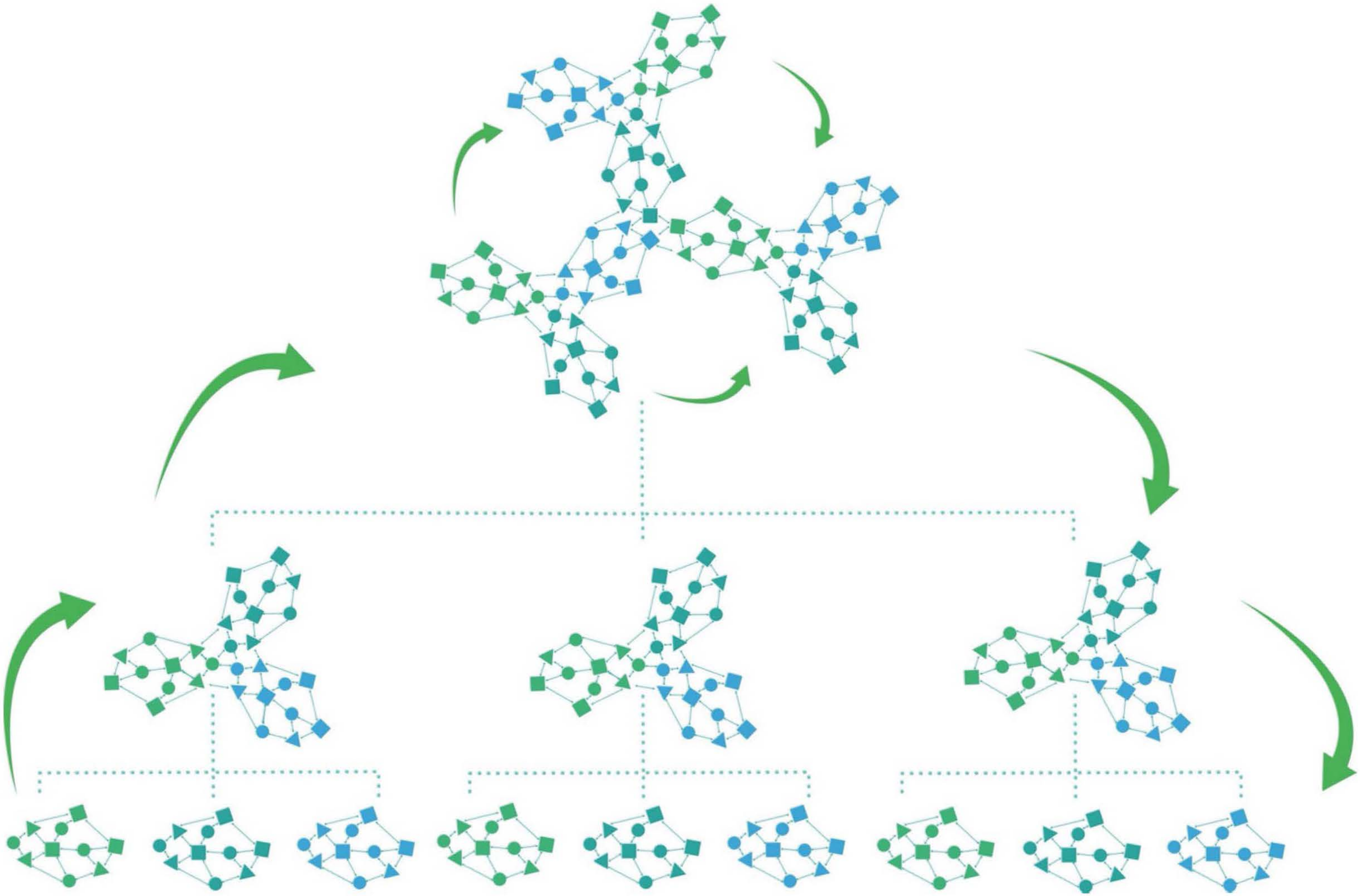


Figure 2.6 A complex adaptive system as a hierarchy of nested systems

Plant Functional Traits and Diversity

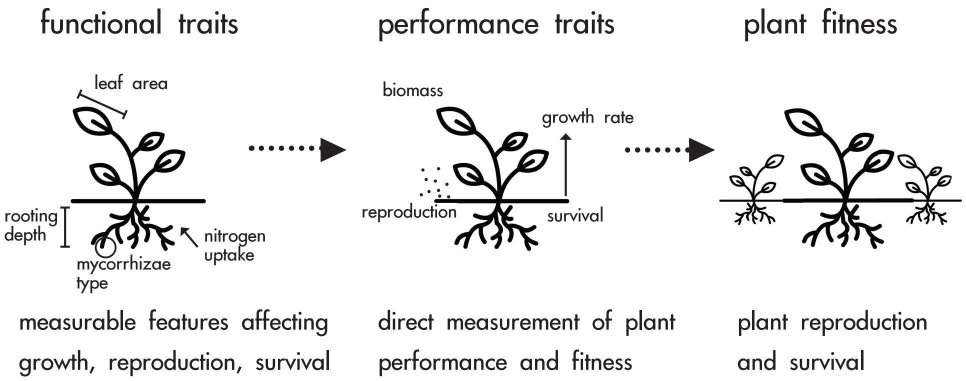


Figure 2.7 Functional and performance plant traits (Violle et al. 2007).

Functional diversity is a key characteristic of complex adaptive systems important for designing landscapes for carbon sequestration; but first I will review plant traits, plant life history strategies, and measures of diversity.

A **plant trait** can be defined as any independently measurable feature of a plant (Garnier et al. 2016). Plant traits affect a plant's performance, which affect its fitness, or how well it survives and reproduces in a particular environment. Plant traits can be categorized as functional traits and performance traits (Figure 2.7). **Performance traits** are direct measurements of an entire plant's performance, such as its size, survival rates, or seed production. **Functional traits** are plant characteristics such as its growth form or internal processes that indirectly affect a plant's fitness through their effects on whole-plant performance traits (Violle et al. 2007). For example, a plant with a functional trait of large leaf area, will photosynthesize more carbon and have energy to grow faster (a performance trait), then will have increased fitness.

Plants evolve different traits depending on the amount of disturbance or stress from the environment. A disturbance refers to an event that disrupts ecosystem structure by damaging plants, or by changing resource availability or the physical environment (Pickett and White 1985).

Stress refers to environmental factors that limit plant performance (growth, reproduction, survival) such as lack of light, water, nutrients, like in deserts or alpine environments. Plants have a limited amount of resources available to them to put into their adaptation and survival strategies. The life history strategies of plants exist along a spectrum between focusing on resource acquisition or resource conservation. Plants that put energy into strategies for acquiring resources, such as fast growth, experience a tradeoff and have less energy for conserving those resources in well-protected tissues (Conti and Diaz 2015).

The ecologist J. P. Grime developed a theory for categorizing plants according to their **life history strategies** and position along the resource acquisition-conservation spectrum. Plants are organized into three categories based on their traits evolved in response to a particular environment: competitors, stress-tolerators, and ruderals (Figure 2.8). **Competitor** plants are adapted to a very fertile environment with low stress and low disturbance. Many plants like fertile environments so plants need to have competitive characteristics to survive. **Stress-tolerator** plants have traits such as smaller leaves to adapt to a high stress environment like a sandy and windy beach or alpine environment. **Ruderal** or pioneer plants come in after a disturbance, grow quickly and produce a lot of seeds (Grime 1977). Some plants have a combination of these strategies. Competitor plants and ruderal plants are closer to the resource acquisition end of the spectrum, and stress-tolerator plants are closer to the conservation end of the spectrum. Plants can be categorized into these groups because of this tradeoff between strategies.

Diversity is an important component of complex adaptive systems and carbon sequestering landscapes. The three measures of diversity I will discuss in this project are species diversity, phylogenetic diversity, and functional diversity. First, it is important to note that **diversity**, as in **species diversity**, refers not just to the number of species present, but also the evenness of their distribution. **Phylogenetic** diversity means that the group of organisms are as least related to each other as possible (*discussed further in Chapter 3*). Species diversity and phylogenetic diversity are important because they influence functional diversity (Milcu et al. 2014).

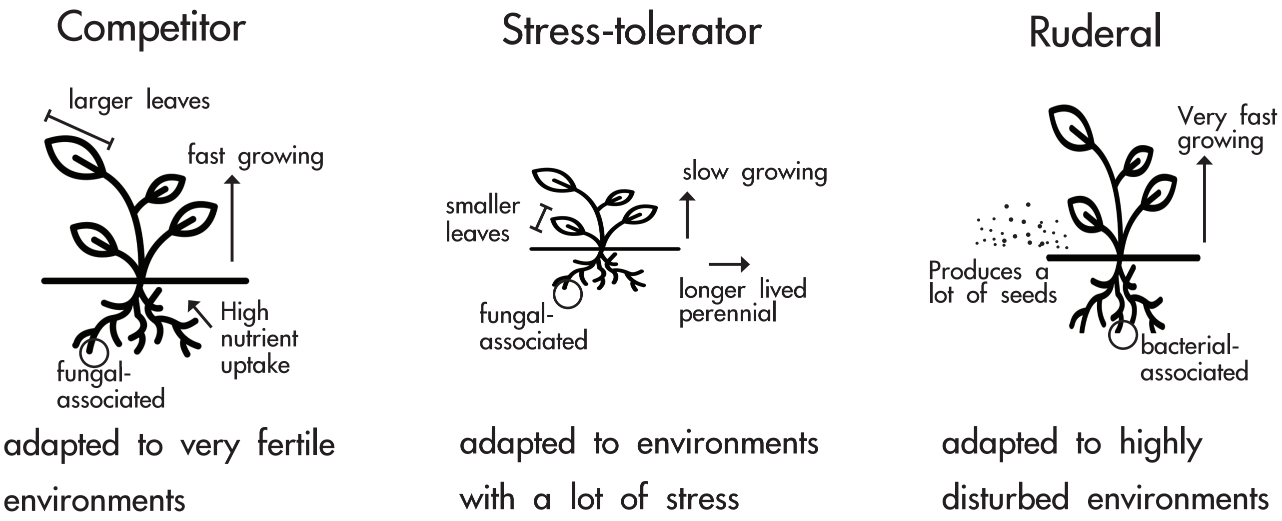


Figure 2.8 Categories of Grime’s plant life history strategies (Grime 1977)

Functional diversity is a diversity of functional traits or functional types (Figure 2.9). It can also be thought of as the degree of variation in traits among organisms in a community (Garnier et al. 2016).

Figure 2.9 Functional diversity

There are two hypothesis that explain how plant functional traits and diversity impact ecosystem functionality: the dominance hypothesis and the niche-complementarity hypothesis. **The dominance hypothesis** states that the traits of the dominant plant species most strongly effect the functioning of the ecosystem. **The niche-complementarity hypothesis** explains ecosystem functioning as primarily influenced by the combination of species with different functional traits using resources in a complementary manner (Garnier et al. 2016). When plant species with different functional traits occupy different niches in the system, there is less overlap in their use of resources including light, water, and nutrients (Figure 2.10).

These two hypotheses are not mutually exclusive and one may better explain dynamics than the other depending on the ecosystem and situation (Conti and Diaz 2012). Both hypotheses can explain how plant functional traits influence carbon sequestration in ecosystems. While increasing the height of plants can increase carbon sequestration through affecting that particular dominant plant trait (Conti and Diaz 2012), specific combinations of plant functional traits (such as grasses and legumes together) can increase belowground carbon storage (Yang et al. 2019)

Figure 2.10 Functional diversity facilitates filling of niches

Niche-complementarity–the differentiation of niches occupied by functionally different organisms–can "translate to enhanced ecosystem functioning" (Garnier et al. 2016). For example, in a disturbed grassland, a ruderal plant like red clover may spread quickly to fill in gaps and add nitrogen to the soil through its symbiotic relationships with bacteria in its roots. While a competitive plant, like a perennial grass, may take advantage of the extra nitrogen to grow a more extensive system of fine roots that help the soil hold on to nutrients, which benefits the clover. Together, when plants like the clover and the grass fill different functional roles, the whole system can use resources more efficiently and become more **productive**–the plants make more use of sunlight water and nutrients to do more photosynthesis, take in more carbon from the atmosphere, store more carbon in biomass, and send more carbon belowground to the soil.

Functional diversity in ecosystems facilitates self-organization of complementary types that function together to increase the system's resilience (Gunderson 2000). Some components of a system are more critical than others to maintain functioning. Critical ecosystem processes are generally mediated by a small functional group of species that act as a keystone species, such as groups of microbes that fix nitrogen in the soil (Levin 1998). A functional diversity of organisms in an ecosystem fill important roles and even overlap in roles (**functional redundancy**) that keep a system functioning in the event of a disturbance, thus enhancing system resilience (Gunderson 2000).

For example, if a community of trees in a park woodland have functional diversity, a disease that affects one species will be less likely to wipe out all the tree species, leaving the critical role of the trees to provide canopy-level habitat structure intact. If there is one species that is especially critical to ecological functioning, such as oak trees, multiple individuals of that species are important to create functional redundancy for the resilience of the whole system. Designers can create functional diversity and redundancy to enhance system resiliency by including multiple individuals of key plant species along with a functional diversity of plant species (Gunderson 2000, Levin et al. 2013). To synthesize the important takeaways from this first principle, characteristics of complex adaptive systems, especially functional diversity, support increased system efficiency and resiliency, which can translate to increased carbon storage in the ecosystem (Gunderson 2000; Garnier et al. 2016; Conti and Diaz 2015).

Increasing functional diversity can contribute to increased system efficiency through filling different functional niches that allow the system to better take advantage of available resources (Garnier et al. 2016. A system that uses resources more efficiently can be more productive and sequester more carbon in biomass and soil (Conti and Diaz 2015). A system with functionally diverse components can self-organize to fill important roles and adapt to changing conditions, allowing larger patterns to take place such as negative feedbacks that maintain the current system state, thus contributing to system resiliency (Figure 2.11). A more resilient system is important for carbon sequestration because a system that is more likely to maintain functioning over time will better protect stores of carbon in plant biomass and soil (Gunderson 2000; Levin et al. 2013; Conti and Diaz 2015). Carbon sequestration can be conceived of as an emergent property arising from the complex interactions of organisms in ecosystems. Strategies and actions for designers to increase carbon sequestration in landscapes through designing for plant functional diversity are presented in Chapter 3.

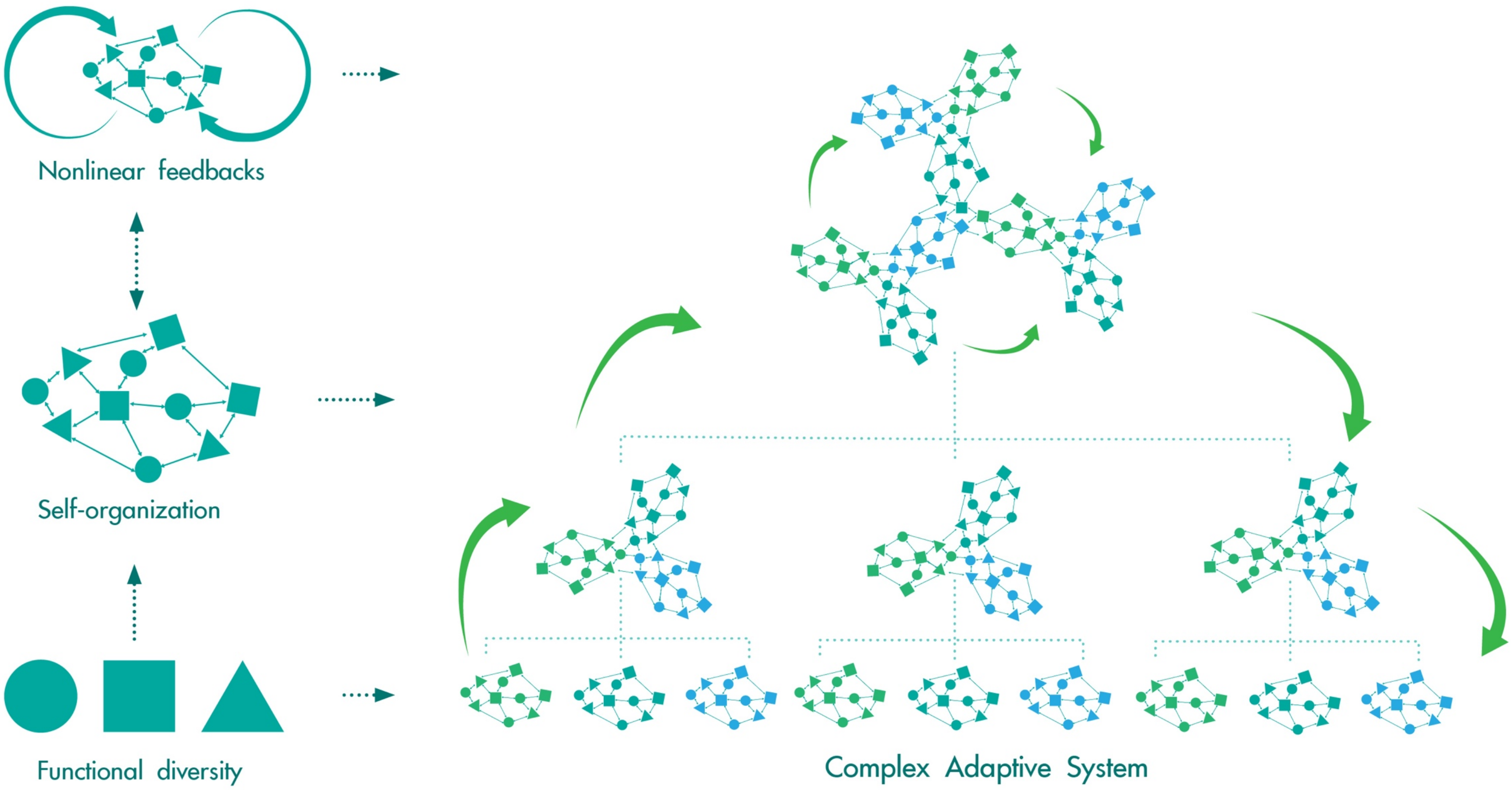


Figure 2.11 Functional diversity is fundamental to complex adaptive systems

The characteristics of complex adaptive systems can lead to more ecosystem efficiency, productivity, and resiliency; which together with soil ecological health, lead to increased potential carbon sequestration and storage and reduced emissions, thus Climate Positive Design (Figure 2.12).

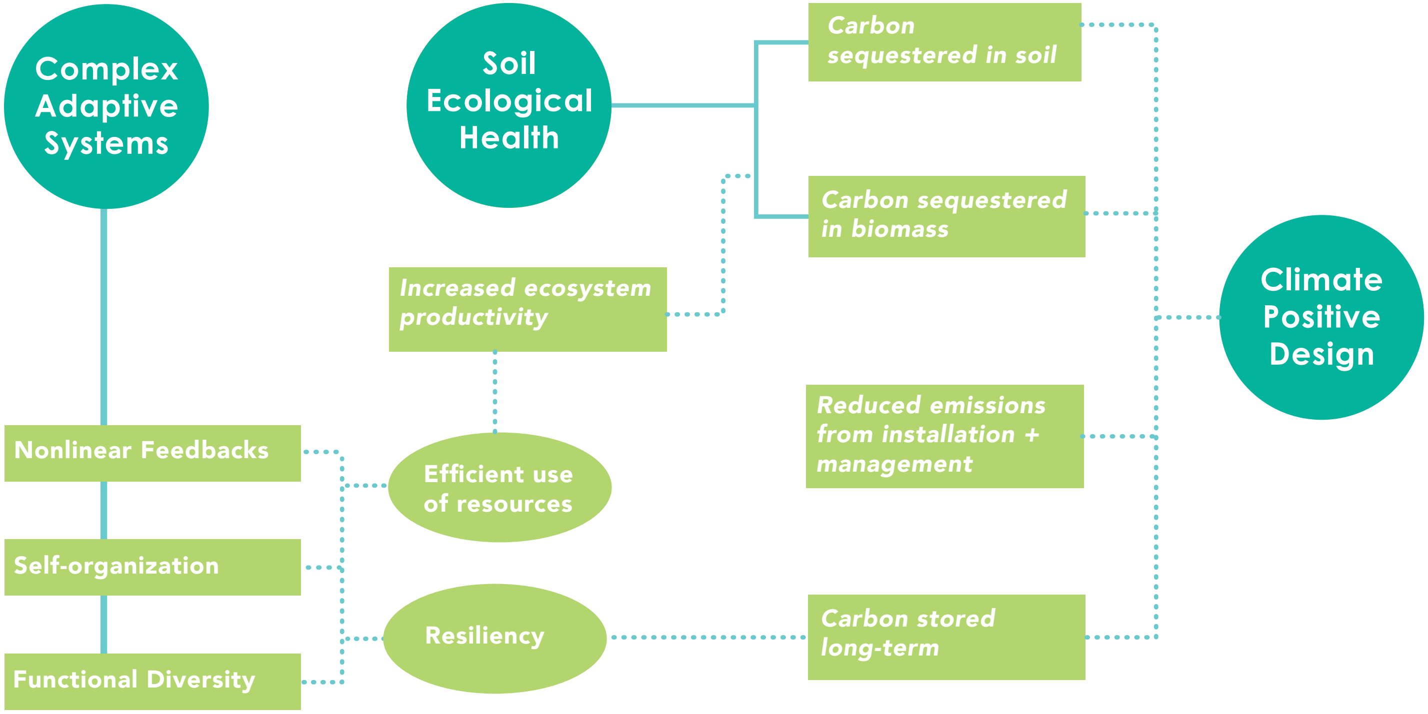


Figure 2.12 The principles of Complex Adaptive Systems and Soil Ecological Health support Climate Positive Design

Principle 2: Soil Ecological Health

Landscape design for carbon sequestration should prioritize soil ecological health. The global pool of carbon in the soil is three times the amount of carbon in the atmosphere or global vegetation. The proportions of carbon stored above and below ground, and the typical residence time of soil carbon, vary by climatic zone but it is clear that soil carbon is important in terrestrial ecosystems across the globe (Sayer et al. 2019; Trumbore 1993; Malhi et al. 1999). Soils are "now in the frontline of global environmental change" and understanding ecological dynamics of soils is critical to addressing climate change (Schmidt et al. 2011).

Supporting soil ecological health and soil carbon sequestration has important co-benefits for plant and ecological health of the whole landscape. Soil organic matter is critical for functioning of ecosystems, retaining nutrients, trapping pollutants, protecting water quality, and supporting plant productivity (Lehmann and Kleber 2015). I will first discuss the process of carbon sequestration, the role of plants, stabilization and storage of soil carbon, and review the types of life in the soil. Then I will discuss how soil microbes, especially mycorrhizal fungi are important to carbon sequestration.

Plant Carbon sequestration is the process where plants take carbon out of the atmosphere through photosynthesis, incorporate the carbon into aboveground biomass (shoots) and belowground biomass (roots), and facilitate the formation of organic matter and carbon storage in the soil through microbial activity (Figure 2.13). Carbon is transferred into the soil from plants through roots and also through plant litter on the soil surface. Soil microbes decompose plant litter and feed off the carbon from roots. Other soil organisms consume the microbes and their products and the carbon cycles through the soil food web. As the carbon is processed by soil organisms, plant litter is broken down into organic matter, releasing nutrients available for plant growth. Carbon is also released back to the atmosphere due to respiration during decomposition.

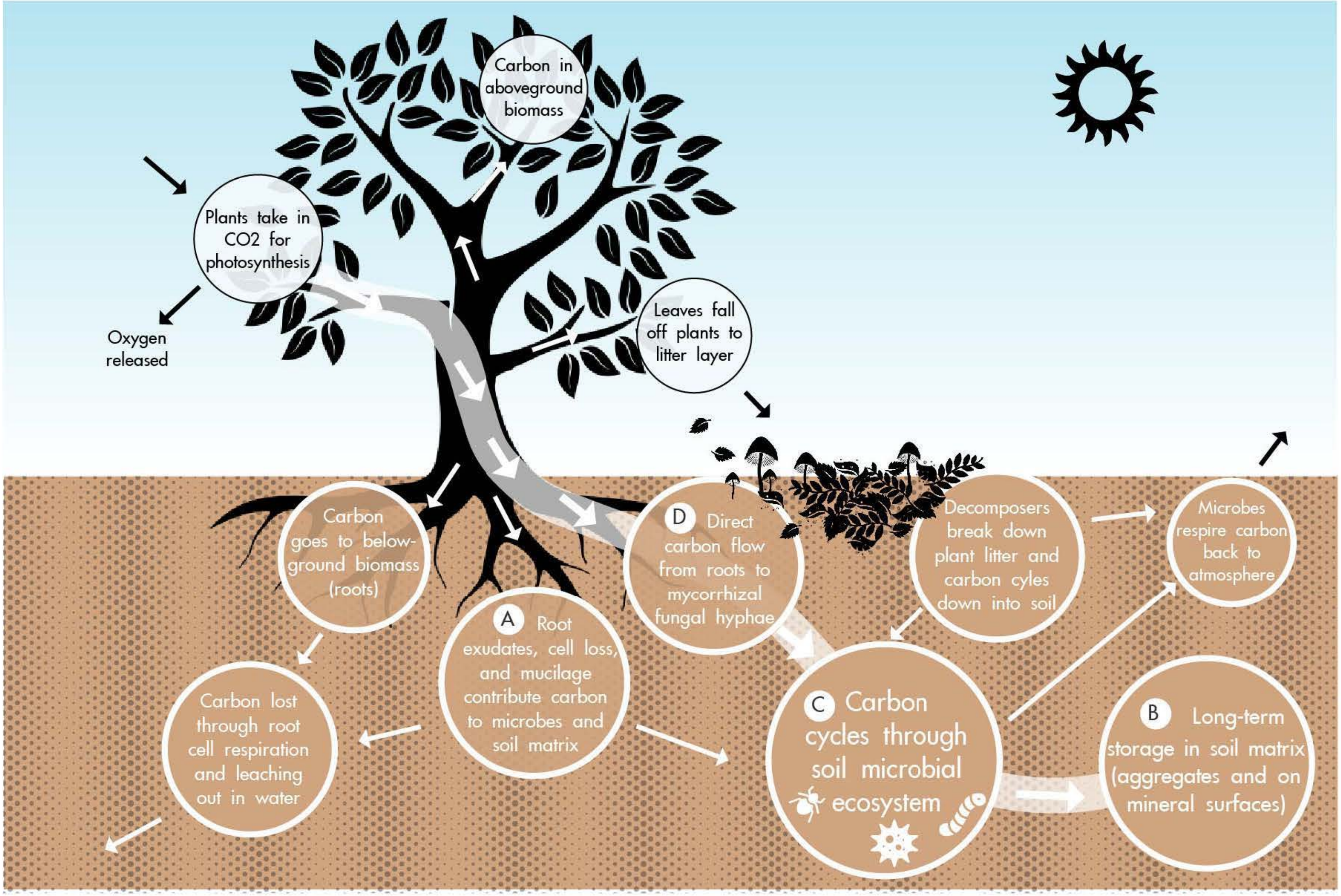


Figure 2.13 Process of carbon sequestration: plants and soil microbial communities are essential to long-term soil carbon storage

As microbes and plants grow through the soil, they secrete various compounds that help the soil bind together in **aggregates**, or tiny clumps. These aggregates physically protect carbon in organic matter from further decomposition, preventing the release of the carbon through microbial respiration, and facilitating long-term carbon storage. Organic matter also can be **adsorbed**, or bonded to surfaces of minerals where it can also be protected long-term from degradation and release (Dignac et al. 2017). In summary, plants play a central role in the contribution and stabilization of carbon in the soil, while organisms in the soil food web are also essential to the cycling of nutrients and formation of aggregates to store carbon long-term belowground (Kallenbach et al. 2016; Dignac et al. 2017; Schmidt et al. 2011). The more soil organisms can form complex, self-organizing systems, the more they can work together to sequester carbon.

Plants and Soil Ecological Health

Plants are essential to soil ecological health because they supply carbon through their roots that supports the microbial ecosystem and they protect the soil from erosion (Dignac et al. 2017; Jones et al. 2009). A healthy soil microbial ecosystem holds more nutrients and makes them available to plants, supporting plant health and productivity. How does carbon get transferred from plants to the soil? How much carbon is transferred? How does plant coverage and plant diversity impact soil life and soil health?

Roots release carbon into the soil through death of root cells, direct flow to symbionts from living roots, root exudates, mucilage, and release of gases (Figure 2.13 A). The flow of carbon between roots and soil is actually bi-directional. The recapture of carbon by plants may happen as part of the plant absorbing nutrients, may regulate the growth of microbes, or be absorbed as part of signaling between plants (Jones et al. 2009).

How do plants allocate the carbon they fix from the atmosphere? How much goes belowground to the soil? One estimate is that plants send an average of 40% of carbon belowground to roots and soil; about 50% of that is retained in root biomass, 33% returned to atmosphere as cellular respiration, and 12% is retained in the soil (Jones et al. 2009). But in reality, the amount of carbon allocated belowground varies widely: it can be less than 10% in croplands, around 60% in native grasslands, and around 20% in forests in temperate zones (Jackson et al. 2017).

Roots are surrounded by a gelatinous layer of mucus or mucilage. This helps the root by protecting it from toxins, pathogens, and water loss. It also reduces friction against soil particles to facilitate the movement and growth of the root through the soil. The mucilage contributes to carbon sequestration by helping to bind aggregates together, promoting soil aeration and stability of carbon in soil aggregates. The mucilage itself contains carbon that is consumed by soil organisms and is a source of carbon that may end up stabilized in aggregates (Jones et al. 2009).

Recent research has found that root exudates are more important than aboveground inputs in supporting a slow cycling of carbon that leads to more stable stores (Sokol et al. 2019). Root inputs are about five times more likely to be stabilized as soil organic carbon than aboveground inputs (Jackson et al. 2017). Root inputs have also been found to be 2-13 times more efficient than litter inputs in forming both slow-cycling mineral-stabilized carbon and fast-cycling organic carbon. The chemical composition of roots and their exudates, and their location deeper in the soil profile than litter is attributable to their efficiency in forming stable SOC. Deeper soil profiles have more microbially-derived mineral carbon than at shallower depths (Jackson et al. 2017). This increased efficiency of root inputs facilitates more carbon being stabilized and stored in the soil (Sokol et al. 2019). Because of the importance of the root to soil carbon pathway, designers should prioritize covering soil with plants; more plant coverage means there are more roots in the soil and results in more carbon stored in the soil. Plants also protect the soil from exposure to air and heat can oxidize (burn up) carbon. Islands of shrubs planted in seas of mulch do not store as much carbon as continuous plant cover (*see chapter 5 page*). Planting designs that facilitate faster establishment and more stable plant communities can store more carbon.

Diverse plant communities have more diverse inputs to the soil, creating more varied microclimate conditions that support more active and abundant soil microbial communities (Lange et al. 2015). A more diverse and abundant soil microbial community contributes more to carbon storage (Johnson, Ellington, and Eaton 2015). Increased plant diversity can lead to an increase the diversity of arbuscular mycorrhizal fungi species (Weisser et al. 2017). Increased plant functional diversity has been shown to correspond with an increase in complexity of belowground communities (Milcu et al. 2013). Higher plant diversity can also increase the amount of carbon roots send to soil microbial communities, which increases both microbial activity and carbon storage (Faucon 2017). Importantly, high levels of soil carbon can provide a positive feedback to plant species richness and productivity by increasing soil water-holding capacity and sustaining soil fertility, thus creating a self-sustaining process that enhances carbon storage (Chen et al. 2018).

Stabilization and Storage of Soil Carbon

It was originally thought that as organic matter decomposed, more complex molecules were formed by the actions of soil microbes until a substance called humus was created (called humification). Humus was thought to be composed of large, complex molecules that were resistant to decomposition, making humus the largest and most stable pool of organic matter in the soil (Lehmann and Kleber 2015). It turns out that these complex molecules were thought to exist because of the extraction methods used to study them. Scientists were using inaccurate extraction methods to measure the decomposition rates of different compounds. From this method of analysis came the idea that more complex chemical compounds, such as the lignin in plant litter took longer to decompose and contributed more to long-term soil carbon storage. However, studies using novel in situ methods have found that the complex molecules thought to make up humus don’t actually exist in the field. In addition, molecules thought to persist for long-term in soil, such as lignin, may actually decompose in the short-term and other compounds thought to be quickly decomposed, such as sugars, can persist for decades (Schmidt et al. 2011; Lehmann and Kleber 2015).

Now it is understood that initial decomposition rates of plant materials can't be linked to whether that carbon persists in the soil for the long-term, and that more complex chemical compounds don't necessarily take longer to break down. The chemical quality of plant litter does not alone determine the rate of decomposition of the plant material (Reynolds et al. 2017). This means that the chemical nature of organic matter doesn't determine how long the carbon stays stored in the soil (Schmidt et al. 2011).

Unfortunately, popular literature still refers to the process of humification as the primary process for carbon to become stored long-term in the soil. Soil organic matter exists in the soil more as a spectrum of states of decay starting from the fragmentation of plant litter to the waste products of microbes (Lehmann and Kleber 2015). There is no magic transition point where organic matter "becomes" humus and is stored long-term. Stability of carbon in the soil depends not on the chemical nature of organic matter, but on the properties of the surrounding physical and biological environment, and the physical arrangement of soil mineral particles. The persistence of organic matter in the soil depends on climate, water availability, the characteristics of the soil microbial community, and chemical characteristics of soil such as acidity and reactivity of mineral surfaces (Schmidt et al. 2011).

We know understand that for carbon in organic matter to stay stored in the soil, it needs to be physically protected from decomposition by being included in aggregates or being adsorbed, or bonded, to mineral surfaces (Figure 2.13 B). Adsorption of organic matter to mineral surfaces is accomplished through a variety of chemical bonds such as anion/cation exchange, van der Waals forces, hydrogen bonding and hydrophobic interactions (Frey et al. 2019; Dignac et al. 2017). Soil aggregates are also critical to protecting organic matter from decomposition and are formed by plant roots and fungal hyphae acting as a scaffold, while the mucus or glue-like substances excreted by plant roots and microbes holds aggregates together (Figure 2.14).

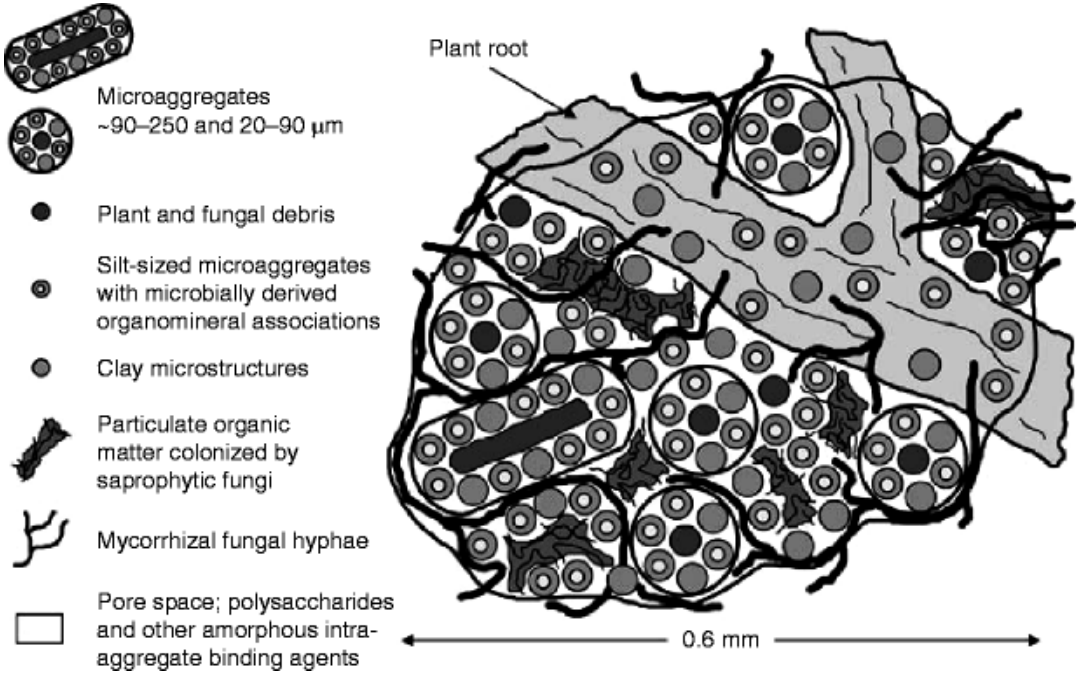


Figure 2.14 Structure of soil aggregates is held together by roots and fungal hyphae (image source: Chevallier et al. 2011)

Soil Life and Role of Microbes in Carbon Sequestration

In healthy soil ecosystems, an abundance and diversity of life is constantly feeding off each other and each other's waste, cycling and processing carbon and nutrients. The **soil food web** is the ecological community of organisms that interact in the soil (see Figure 2.15). A healthy soil food web has co-benefits for plant and ecosystem health through improving nutrient availability, water filtration, water holding capacity, water infiltration, and decreasing compaction of soil (Ingham 1999).

At the bottom of the soil food web are microbes like fungi and bacteria that form **soil microbial communities** and digest carbon in plant material for energy (Figure 2.13 C). Then there is a multitude of microorganisms such as protozoa, nematodes, and microscopic arthropods that feed of bacteria, fungi, and each other. Soil microorganisms are not evenly spread out throughout the soil. They are concentrated in the top soil horizons, in the area directly around roots (the rhizosphere).

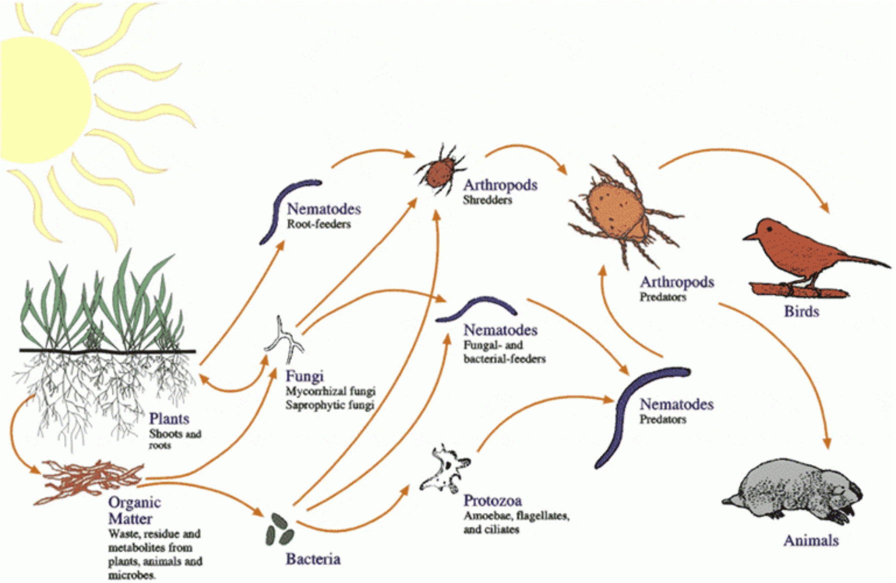


Figure 2.15 The Soil Food Web (image source: Ingham 1999)

Within the soil matrix, microorganisms occupy diverse pockets of pore space and layers of water in between mineral particles (Schmidt et al. 2011). 1 gram of soil can hold up to 1 billion bacteria representing 1 million species and 1 million fungi representing 10,000 species (Dignac et al. 2017). At the "top" of the soil food web are macrofauna such as millipedes, insects, and moles. Some of these organisms are **ecosystem engineers,** like earthworms and ants, whose activities of borrowing and feeding have a significant structural influence on the soil environment. All of these organisms interacting in a community are important for sustaining the ecosystem services of healthy soil such as nutrient cycling, water holding capacity, and carbon sequestration (Ingham 1999, Dignac et al. 2017).

Microbes are now understood to be essential to soil carbon storage. In the past, it was thought that a dominant pathway for carbon sequestration was direct inputs from plants. The idea was that plant roots deposited carbon directly into the soil through root exudates where it would be stored long-term in organic matter (the complex "humus" discussed earlier). For a long time the difficulty of studying soil ecosystems, because they are underground and invisible, has stood in the way of understanding a lot of the interactions of plants and microbes, and the mechanisms behind soil carbon sequestration. However, recent studies using new molecular tools of analysis suggest that organic matter first processed by microbes may be a more important pathway of carbon sequestration than carbon directly deposited by plants. A study of soil organic matter indicated that the accumulated organic matter was first processed by microbes, and that the microbial community was a stronger driver of soil organic matter development than soil mineral structure (Kallenbach et al. 2016).

Importance of Mycorrhizal Fungi for Carbon Sequestration

Both fungi and bacteria are essential components of the soil ecosystem and necessary for carbon sequestration and many other ecosystem functions or services. However, fungi play a particularly important role in soil carbon sequestration.

First, some basics about fungi. The mushrooms we all know are the fruiting bodies of an underground **mycelium**, or mass, of **hyphae** (Figure 2.16). Fungal hyphae are long once-celled strands that grow through the soil and can fuse to each other. The main types of fungi in the soil are decomposer fungi, which break down plant litter, parasitic fungi, and mycorrhizal fungi. **Mycorrhizae** are root structures that are a symbiotic association between plant roots and fungi in which the plant provides carbon compounds to the fungi for energy and the fungi sends nutrients back to the plant. Fungal hyphae are able to transfer carbon and nutrients very rapidly, increasing efficiency of plant nutrient uptake. (Chapin 2011). The hyphae of **mycorrhizal fungi** can form a continuous network, called the **mycorrhizal network** or **mycelial network**, between roots of different tree individuals; trees use this network to send signals and transfer nutrients to each other (Simard et al. 2012) (Figure 2.17). Plants evolved alongside their mycorrhizal fungi partners and over 90% of plant species have mycorrhizal associations (Feijin et al. 2018).

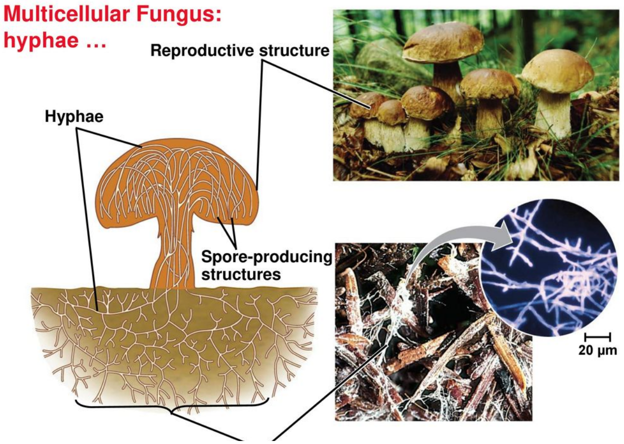


Figure 2.16 Basic structures of fungi (image source: Campbell 1994)

There are multiple types of mycorrhizal fungi, but the two most common types are **Arbuscular mycorrhizae** and **Ectomycorrhizae. Arbuscular mycorrhizal (AM)** fungi associate with most plant species and its hyphae form a symbiosis with plants by penetrating inside plant root cells (Figure 2.18). Ectomycorrhizal fungi occur with a smaller number of ecologically significant plant species such as oaks, pines, and willows. Ectomycorrhizal fungal hyphae form a sheath around plant root cells and have other functional differences from arbuscular mycorrhizal fungi.

Figure 2.17 Plant roots and mycorrhizal fungi form a network in the soil

Transfer of carbon from plants to mycorrhizal fungi is a significant and important pathway of carbon into the soil (Figure 2.13 D). The amount of carbon that plants send to mycorrhizal fungi depends on environmental factors such as climate, nutrient availability, and successional stage of the ecosystem. As mycorrhizal fungi grow through the soil, they forage for patches of nutrient-rich organic matter, transporting carbon and nutrients through the mycelial network, and depositing carbon into nutrient-deficient soil pores, where it can be protected from microbial decomposition. Mycorrhizal fungi contribute to carbon sequestration in the soil through three significant mechanisms: releasing hyphae exudates, the accumulation of dead biomass, and contributing to formation and stabilization of soil aggregates (Frey et al. 2019).

It was previously thought that plant root exudates were the primary pathway for carbon to be transferred from roots into the soil, but recent research shows that mycorrhizal fungi also release exudates. A significant portion of carbon from plants is transferred directly to mycorrhizal fungi and then released as mycorrhizal fungi exudates instead of directly released from roots. AM fungi colonize roots above or upstream of root tips or hairs, such that they intercept and divert root exudates from being released through root tips. Fungi release exudates for many reasons including to stimulate other microbes to release enzymes to mine organic matter for nutrients such as N and P (Stimulating growth of other microbes to decay organic matter however may contribute

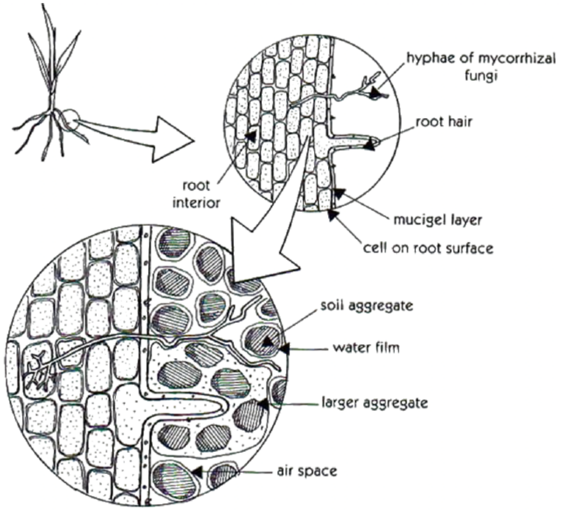


Figure 2.18 Arbuscular mycorrhizal fungi penetrates plant root cells (image source: Magdoff 1993)

to release of carbon). As mycorrhizal fungi grow, the exudates they release may be deposited into aggregates or adsorbed to mineral surfaces where the carbon in the exudates will be stabilized long-term. (Frey et al. 2019)

Mycorrhizal fungi invest carbon they receive from plants in constructing more biomass as they grow. In some systems, mycorrhizal fungi biomass accounts for a large proportion of the microbial biomass in the soil. As living fungi respire, the carbon in their biomass may be released as free carbon into the soil. Organisms such as nematodes or mites may feed off the hyphae and consume the carbon. When fungal hyphae dies, then the dead fungal biomass or **necromass** becomes a store of carbon in the soil. Mycorrhizal fungi hyphae live for days to months, and this frequent growth and death of hyphae, or "turnover", results in large amounts of organic matter from the necromass accumulating in the soil. This process is one of the most dominant pathways for carbon contributed from plants to be stabilized in the soil (Jones et al 2009; Frey et al. 2019).

Mycorrhizal fungi have been shown to be directly linked to the formation of aggregates that protect soil carbon from degradation (Frey et al. 2019). High densities of mycorrhizal fungi hyphae help form and stabilize aggregates. As hyphae grow they physically entangle and trap particles in the network. Hyphae exudates also help glue together soil particles to form aggregates (Dignac et al. 2017). One study found a linear relationship between AM hyphal abundance and soil aggregation. Following 6 years of fungicide treatments, a reduction in mycorrhizal fungi hyphae networks was highly correlated with a reduction in carbon storage (Wilson et al. 2009).

It is critical for designers to nurture and protect soil microbial life to support soil carbon sequestration. See Chapters 3-5 for strategies and actions that designers can take to improve and protect soil ecological health.

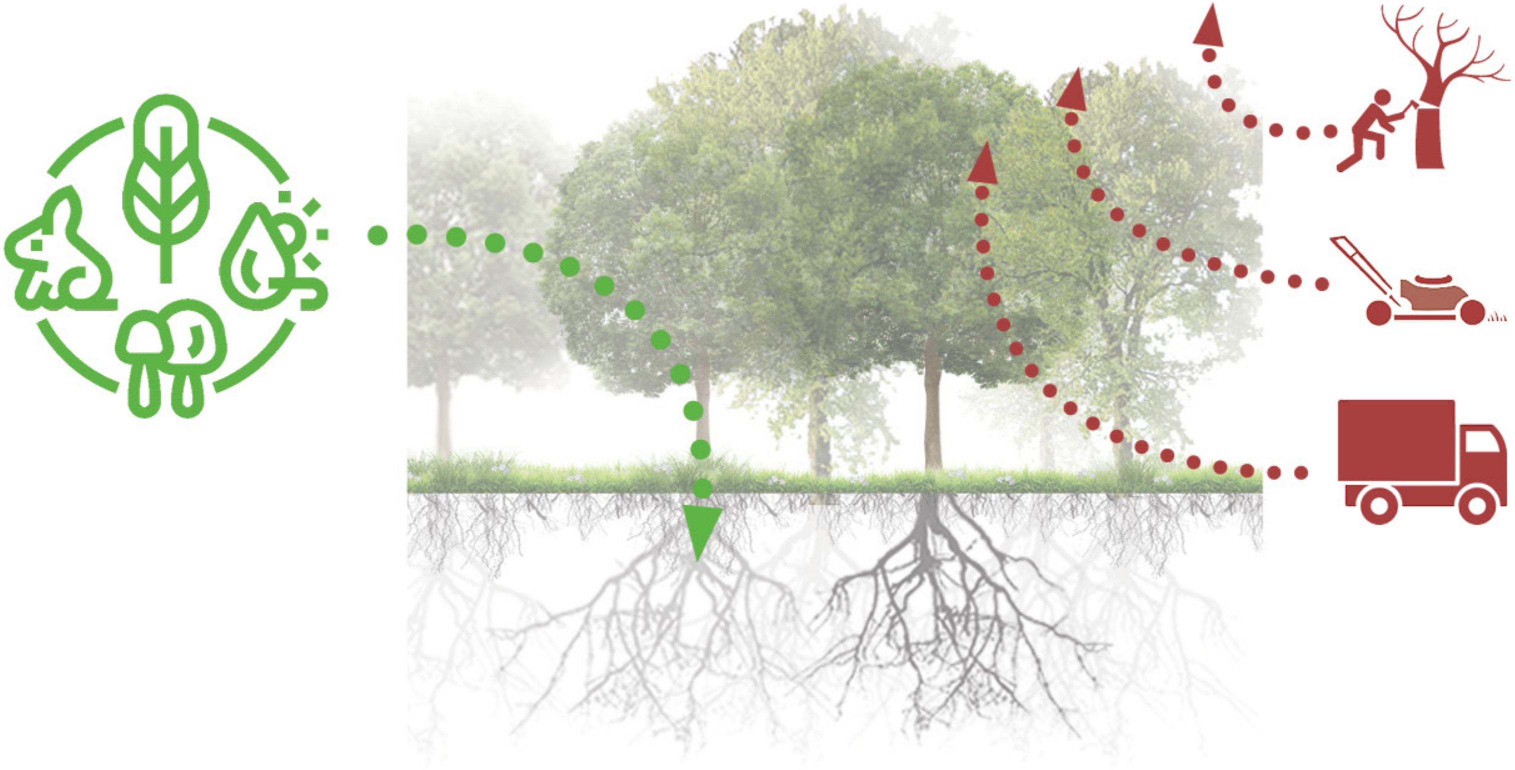


Figure 2.19 Climate Positive Design

Principle 3: Climate Positive Design

Climate Positive Design can be an effective organizing principle for the design of carbon-sequestering landscapes (Figure 2.19). All landscapes are complex adaptive systems that interact with the surrounding environment through energy exchange in the form of water, carbon, nutrients, and the movement of organisms and materials. For a landscape to sequester carbon from the atmosphere in a way that mitigates climate change, the flux of carbon in and out of the system needs to be net positive–meaning more carbon is sequestered in biomass and soil than is lost from the system due to respiration and emissions. Landscapes are not only drawing carbon down through photosynthesis, but also are releasing carbon back through cellular respiration of plants, microbes, and other organisms. Disturbances such as fire or tilling soil release carbon from biomass and soil. In addition to these "natural" sources of emissions, construction and maintenance of landscapes also releases emissions from production and transportation of materials, and gas-powered maintenance machines (Whittinghill et al. 2014). Many landscapes are designed and managed by humans; human activities should be conceptualized as part of the whole landscape system, especially when considering carbon fluxes. Otherwise, these activities may cancel out the benefit to the climate of the landscape's carbon sequestration capacity.

Many landscape architecture projects result in such high emissions from construction and maintenance that the landscape never sequesters enough carbon to make up for its own impact. The resource-intensive maintenance practices of urban forests may lead to more carbon emitted than the landscape absorbs in the course of a year (McPherson et al. 2014; Whittinghill et al. 2014).

Pamela Conrad, at CMG landscape architecture, started the Climate Positive Design Challenge to encourage landscape architects to increase the carbon sequestration potential of their projects. The challenge is hosted on a website that also includes a tool called Pathfinder that lets landscape architects roughly calculate or visualize the years a project may take to become climate positive–that is to start net sequestering carbon. To use the tool, designers can add up the potential sequestration by vegetation planned in the project, subtract emissions associated with use of construction materials such as concrete, and also subtract emissions associated with maintenance. A score card is generated that reports on how long the project will take to become net climate positive. The website also offers resources such as a design toolkit to assist with climate positive design. The challenge aims for park landscapes to become climate positive in 5 years and for plaza type projects to be positive in 20 years. Pamela Conrad and CMG landscape architecture calculated that if all landscape architects practiced Climate Positive Design, the field of landscape architecture could sequester 1 gigaton of carbon, enough to be in the top 80 solutions for climate change listed by Project Drawdown (Conrad 2019).

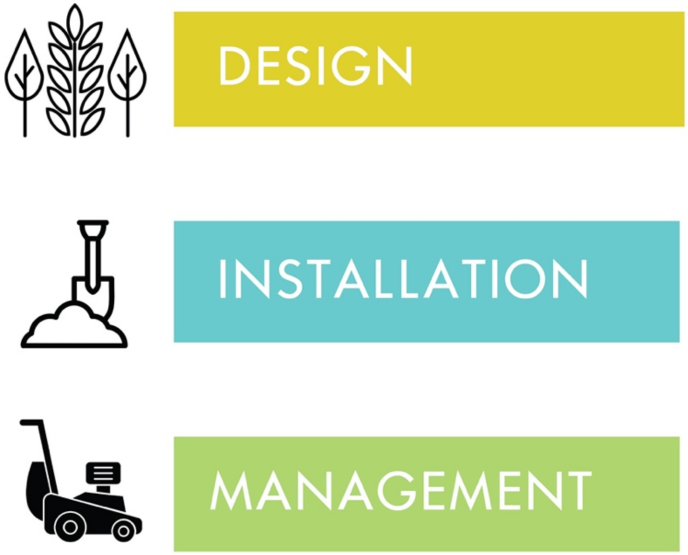
Climate Positive Design is an important principle for designing carbon sequestering landscapes because it zooms out to look at the net impact of the landscape as a human and natural complex system. To practice Climate Positive Design, a designer can apply strategies in part two such as increasing carbon input to the system by increasing biomass, productivity, and diversity of vegetation, or by adding soil amendments to support soil ecological health. Simultaneously, the designer needs to protect that carbon from leaving the system by keeping the soil covered with plants and returning pruned material to the site. Then the designer needs to reduce emissions associated with construction materials and maintenance of the landscape.

Chapters 3, 4, and 5 will provide in-depth strategies and actions for how to practice climate positive design. By tracking these inputs and outputs of carbon associated with the landscape system, designers can do their best to make sure that the whole system will be net sequestering carbon from the atmosphere–actually mitigating climate change. Designers can use the pathfinder app on the Climate Positive Design website to roughly estimate these inputs and outputs in the project.

Climate Positive Design is useful to understand the big picture, but to really design a carbon sequestering landscape, it is important to apply the previous principles of complex adaptive systems and soil ecological health to build an efficient and resilient whole landscape system. Incorporating key characteristics of complex adaptive systems into designs can support more resilient landscapes that also use resources more efficiently, contributing to enhanced carbon sequestration and storage. Putting together enhanced ecosystem carbon sequestration and storage, with actions to reduce emissions, creates a climate positive design approach that will have a net benefit for regulation of global climate.

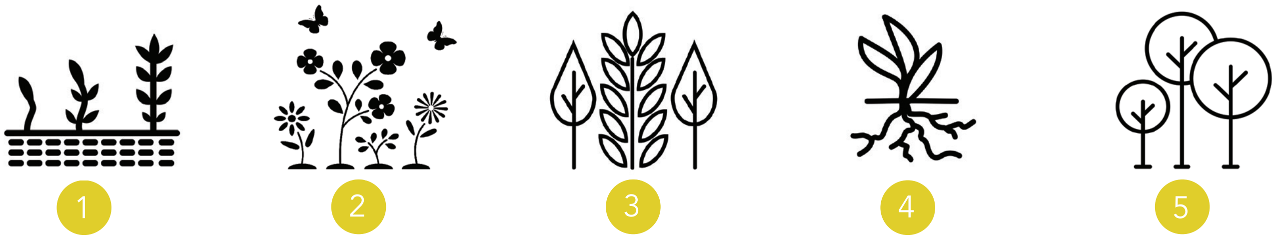
Part Two

Chapters 3, 4, and 5 are structured around strategies and actions to guide design, installation, and maintenance for carbon sequestering landscapes. They are not exhaustive lists of the actions could be taken to increase carbon sequestration for a net climate benefit but are a selection of recommendations that are most important based on my research and experience in the field. I devote more time to discussing concepts or actions that are underrecognized relative to their importance, and less time discussing topics that are straight-forward or more commonly understood. The recommendations are intended to be applicable to a wide variety of situations, but which strategies and actions are appropriate to implement varies widely on the physical, ecological, and social situation of the landscape at a particular site.



Chapter 3 Strategies for Design

The framework I've developed consists of five strategies, with suggested actions, to guide design of complex adaptive landscapes for increased carbon sequestration in both plant biomass and in the soil. The strategies build on the three key principles from Chapter 2 and are based on my literature review on plant traits, soil ecology, and carbon sequestration.



Introduction

Landscape design for carbon sequestration should incorporate carbon flows in both plant biomass and in soil. In temperate climates, there is more carbon belowground in the soil than in aboveground biomass in most ecosystems (Cavallaro et al. 2018). Additionally, carbon in the soil is more likely to be stored long-term than carbon aboveground (Dass et al. 2018). From my research, it is not feasible to quantify and rank plant species according to their *soil carbon sequestration* potential. This is because the ecological interactions and feedbacks between plants and soil are so complex. The amount of carbon that plants send belowground is highly variable depending on the climate, soil type, soil ecological health, and other environmental and ecological factors (Frey et al. 2019). Data exists for average rates of root exudation for particular plants, however it is not clear whether higher rates directly result in more carbon storage (Jackson et al. 2017). Although a significant amount of carbon from plants may be sent directly to mycorrhizal fungi, there are not estimates of that for specific plants. There are only a very few averages for particular ecosystems, because it is so difficult to study mycorrhizal fungi (Frey et al. 2019). Although designers can't rank plants by their soil carbon sequestration potential, due to complex plant-soil feedbacks, designers *can* choose plants based on their potential to *work together* as a carbon-sequestering designed ecosystem.

The strategies are based on literature review connecting specific plant traits to increased carbon sequestration, and functional diversity to whole ecosystem effects. Plant functional traits effect soil properties such as structural stability, nutrient availability, and soil carbon sequestration (Faucon et al. 2017). Including plants with traits such as deeper roots or more fibrous roots can directly increase carbon sequestration (Rillig et al. 2015; Demenois et al. 2018). Plant functional traits can affect whole ecosystem properties through the two hypotheses discussed in Chapter 2: the Niche-Complementarity hypothesis and the Dominance hypothesis (Garnier et al. 2016). Plant functional traits also affect how the ecological community self-organizes to maintain the system structure, which can feedback to affect the plant survival (thus, a complex adaptive system) (Gunderson 2000; Garnier et al. 2016; Conti and Diaz 2015). The strategies and actions are formulated to increase the potential carbon input by photosynthesis and create a diverse and efficient system that cycles carbon down into long-term storage in the soil, keeping it from release.

Strategy 1 gives examples of actions that directly support carbon sequestration in biomass, although increasing functional diversity also increases biomass sequestration. Strategy 2 discusses how other measures of diversity support functional diversity and resilience. Strategies 3 and 4 concern how to directly add more functional diversity by including a mix of plant sizes, habits, and life history strategies. Strategy 5 suggests methods of arranging plants to support functional diversity and resilience.

Designers should incorporate all strategies into the landscape design, but not all actions will be appropriate for every situation. Which actions are appropriate depends on the target ecosystem or vegetation type and the overall design goals. . Most of the strategies and actions are applicable to most climate zones and landscape types, but not all. For example, although incorporating large trees is a suggested action to increase biomass (Strategy 1), a meadow type landscape may be more desirable for the site conditions and use. The designer should not incorporate large trees just for carbon sequestration but rather balance the strategies and actions with the needs of the site and intended use. In a meadow landscape, a designer can still increase biomass by including both fast and slow growing plants (Action 1.3) and including deep-rooted plants (Action 1.4). Similarly, if the site design allows for a woodland type landscape, then including warm season grasses (Action 3.4) may not be appropriate. The strategies and actions are formulated to be as flexible and useful as possible to the many situations and time constraints that designers routinely face.

Strategy 1: Increase Biomass

Figure 3.1 Larger trees with deeper roots sequester more carbon in biomass

Biomass generally refers to the dry weight of plant matter. Plants construct themselves out of elements from the environment, including a large proportion of carbon. The rate and amount of carbon that trees sequester in biomass depends on size at maturity, longevity, and growth rate (Figure 3.1). If you were to choose trees based on which individual trees sequestered the most carbon over their life span, you would want to choose trees that are large-sized, long-lived, and fast growing (Nowak 2002). However, in order to maximize carbon storage of the plant community and ecosystem on the site, planting only large, fast-growing trees is not the best strategy. It is more important to create a whole complex system with layers (see strategy 5*)* than include many large trees and plants into an area. Trees and plants that fill in understory layers in a tree-dominant landscape will add more biomass and nurture more diverse soil ecology than a landscape with only large tree species. For this reason, it is important to balance choosing large plants and trees with including a diversity of plants and trees (see strategies 2 and 3).

These actions build off both the dominance hypothesis and the niche-complementary hypothesis that explain how plant traits affect ecosystem properties. Including larger or longer-lived trees in a landscape change the dominant species that affect the processes of the whole system, while including both fast and slow-growing plants fill complementary niches in the system that help it become more resilient.

Actions:

1.1 **Include larger trees and plants, if given appropriate space**
Trees and plants that reach a large size at maturity will consist of more biomass that contains carbon (Mcpherson 1999). Larger plants also shed more litter, which adds more carbon to the soil (Conti and Díaz 2013). However, do not plant trees that are too large for the space and will need extra pruning. Balance planting larger trees with planting a diverse understory of smaller trees and plants.

1.2 **Include species that are longer-lived and low-maintenance**
Longer-lived species will store carbon in the biomass for a longer period of time. Include species that will need less pruning and removing of biomass over their life span.

1.3 **Include both fast and slow-growing trees and plants**
Although fast-growing trees sequester carbon faster, they are often more prone to maintenance issues or do not live as long. For example, fast-growing trees tend to lose a lot of branches in storms because they've invested fewer resources in structural strength. Slower-growing trees and plants tend to have denser wood, living for longer and requiring less maintenance. Including a mix of both helps the landscape system sequester

carbon faster and longer (Reed and Stibolt 2018).

1.4 **Include deep-rooted trees and plants**
Trees and plants with deeper root systems will sequester more carbon in belowground biomass, as well as deposit more carbon into the deep soil.

1.5 **Increase the amount of woody plants**
Woody plant material has a high carbon-to-nitrogen ratio, the litter of which feeds fungi more than bacteria in the soil. Having a healthy proportion of fungi to bacteria in the soil is beneficial for soil carbon sequestration (need to find citation). Woody plants also sequester more carbon in biomass because wood is denser than herbaceous plant biomass (McPherson 1999; Conti and Díaz 2013).

1.6 **Include deciduous trees in the plant palette**
Deciduous trees generally sequester more carbon than similar-sized evergreen trees (Mcpherson 1999). However, diversity is also important, so it is useful to include deciduous trees in the plant palette along with evergreen trees when it serves other design needs.

1.7 **Increase vertical layering of plant types**
Layering plants of different heights and forms allows the system to take advantage of light, water, and nutrients through filling spatial niches. This can pack more biomass into a system than including large trees and plants alone, and supports self-organization of species into a resilient system.

Strategy 2: Increase Biodiversity

Figure 3.2 Biodiversity

Different types of diversity matter more than others, but some are simpler to achieve. Functional diversity is a key measure of diversity for increasing carbon sequestration. Although this project provides a user-friendly way to increase functional diversity, it can be difficult to know if important functional roles or niches in a system will be filled by a particular plant palette. Designing for functional diversity also takes more time to compose a plant palette with a range of many types of plants. Increasing biodiversity is likely also increase functional diversity (Milcu et a. 2014), and provides another benchmark to assist in creating functional diversity in a landscape. Biodiversity also has important co-benefits of supporting habitat for other species. All the species in an ecosystem contribute to its complexity and cycling of resources such as carbon. Increasing biodiversity is important so that a carbon-sequestering landscape has multiple co-benefits to support other ecosystem services and habitat for many species (Figure 3.2).

A

ctions:

2.1 Include a diversity of plant species

Evidence from ecological studies supports the importance of species diversity. Across many types of natural ecosystems in China, species diverse diversity is associated with increased soil carbon sequestration, due to increased productivity and belowground biomass (Chen et al. 2018). Species diversity in grasslands across the US led to increased soil carbon sequestration through increased carbon inputs from roots and increased soil microbial diversity and activity (Weisser et al. 2017, Yang et al. 2019). Species diversity increases carbon sequestration in part because it tends to bring a diversity of functional traits that fill different niches in the system. However, species diversity in a system does not always correlate to functional diversity. For example, a diversity of succulent plant species can have very similar above and belowground sizes and shapes; this system will not be as efficient as a more functionally diverse system with the same number of species.

2.2 Increase phylogenetic diversity of the plant community

Phylogeny is the evolutionary history of an organism. Plants that are less related to each other, or phylogenetically diverse, have evolved different strategies to adapt to their environment and thus tend to be more functionally diverse. There is some evidence that phylogenetic diversity may be a more accurate proxy for functional diversity than species diversity, although more research is needed on this subject. Phylogenetic diversity may be better at predicting characteristics of soil ecosystems than species diversity (Milcu et al. 2013). Another study found that a system with a diversity of plant families may be more likely to have roots that occupy different spatial niches in the soil than a diversity of plant species (Kesanakurti et al. 2011). I have two suggestions for increasing the phylogenetic diversity of the plant palette: 1) use on online tool such as phylomatics to assess the relatedness of the plants, and 2) include a diversity of plant families. Studying botany to understand the evolution of plants can also inform choosing plants for phylogenetic diversity (Beck 2012).

2.3 Choose native plants

Non-native plants and cultivars are often used in landscape design due to their predictable habit and performance, especially with the pressures of urban environments. Although non-native plants can sometimes provide nectar to pollinators or create beneficial habitat structure, native plants are generally better for the purpose of creating habitat for a diversity of other native species. Supporting species diversity in a landscape is important to support the functioning of the whole system, and the functioning of the whole system is important for carbon sequestration. In general, native insects are adapted to use native plants. They have over time adapted to “disarm” the chemical defensive compounds in particular plant species, and are not adapted to eat other plants with different defensive compounds (Tallamy 2009). Also, non-native ornamental plants support 29 times fewer species of ianimals than do native ornamentals (Tallamy 2009).

It may not seem as urgent to avoid non-native plants in a landscape that is not bordering a natural area. However, water, wind, animals and people can transport seeds long distances into natural areas where invasive species can establish spread undetected until they are almost impossible to suppress. Furthermore, there is growing evidence that climate change is increasing invasions of introduced species to the detriment of native ecosystems (Gervais et al. 2020).

Native plant cultivars may or may not be as beneficial ecologically as the straight species. One issue is that cross-pollination between cultivated relatives of a wild plant and the wild plant can lead to the loss of the wild plant species or variety (Tangren 2019). Another issue is that breeding plants for specific aesthetic traits may affect its provisioning for pollinators and other species. Double-blooming native cultivars can be sterile and can prohibit pollinators from accessing the pollen or nectar (Wheeler 2017). Cultivars to selected to have altered leaf color can significantly reduce insect herbivory (Baisden et al. 2018). Many horticultural plants selected for abundant, colorful fruits actually provide such low nutritional value that birds eating them suffer from malnourishment.

Designers should take great care that plants do not become invasive because climate change is affecting how plant species survive in different areas. It is beyond the scope of this project to discuss assisted migration or how to choose plants adapted to a changing climate. However, native plants are so critical to support other native species that it may be best to continue using local native plants until there is evidence they will no longer perform well, and to consider near-native species for climate change rather than introduce species from far away.

2.4 Choose genetically local plant sources

Genetic diversity is generally accepted as necessary for a plant population to have long-term resilience against changing environmental conditions, pests, and disease (Beck 2012). Native plant cultivars have reduced genetic diversity and are often clones of a single individual to emphasize dependable traits. Populations with diverse genetics have subtle variations that help individuals better adapt to their environment. To increase the resilience and functioning of the plant communities in a project, designers should choose locally provenanced native plants to the extent possible, and use providers that periodically return to genetically diverse natural populations to wild-collect seeds for grow out. Genetically local plants help preserve the diversity and long-term viability of the species and will be better adapted to the location (Beck 2012).

Strategy 3: Increase Plant Functional Diversity

Figure 3.3 Plants with various functional traits layered together

Increasing the functional diversity of plants in a community increases the potential carbon sequestration (Figure 3.3). When a wider range of plant traits are represented, the plant community fills more niches and supports more diversity of life in the soil (Conti and Díaz 2013; Milcu et al. 2014; Lange et al. 2015). A diversity of functional traits may drive biodiversity-ecosystem functioning relationships more so than taxonomic richness because traits better capture the complementarity of plant functions (Milcu et al. 2014). Functional trait composition was found to explain effects on community biomass more than species richness (Weisser et al. 2017). A variety of trait values such as leaf nitrogen concentration were correlated with increased carbon storage (Conti and Díaz 2013). A study of grassland restoration over 22 years found that both plant species diversity and specific combinations of plant functional traits can maximize belowground carbon storage on degraded agricultural lands (Yang et al. 2019).

Functional diversity facilitates the self-organization of complementary types of organisms into interconnected communities, leading to increased system efficiency and resilience (Figure 3.3). More functional diversity leads to more complex interactions such as nonlinear feedbacks that can buffer a system against potential shocks (Gunderson 2000; Levin et al. 2013). A more resilient ecosystem is better at protecting stores of carbon in biomass and soil over a longer period of time, preventing it from being released back to the atmosphere.

Actions:

3.1 **Include a range of plant sizes: height and spread**
Plant communities with plants at a range of heights more efficiently utilize available sunlight to photosynthesize and space to grow. Traits that are strongly correlated with carbon sequestration, but are difficult to measure, such as leaf nitrogen concentration and specific leaf area, are also correlated with a diversity of heights (Milcu et al. 2014). Including plants that have different horizontal spreads also can occupy different niches and help the community utilize resources efficiently.

3.2 **Include a range of plant forms and habits**
Combining plants with different habits or form, such as upright, trailing, spreading, pyramidal, arching, pendulous, or vase-shaped, will fill more vertical and horizontal spatial niches in the plant community, contributing to the whole ecosystem using resources more efficiently and sequestering more carbon.

3.3 **Include a diversity of root depths and architectural type**
Root traits have been found to have strong linkages to soil carbon sequestration. Deeper roots deposit carbon deeper in the soil, while shallow roots are important to feed microbes in the top soil. Plants with roots that occupy many spatial niches in the soil have more room to grow and create more biomass, and transfer more carbon to soil microbial communities that facilitate long-term carbon storage. A diversity of root architectural types, such as tap roots, fibrous roots, and bulbous roots, also contribute to filling more spatial niches in the soil. The fibrous roots of grasses are particularly important to include, as

fibrous roots are more finely distributed in the soil, encountering more soil particles and entrapping them into aggregates that protect carbon. (Rillig et al. 2015; Demenois et al. 2018; De Deyn et al. 2008).

3.4 Include both warm and cool season grasses

Warm season and cool season grasses have optimum growing times at different times of year, contributing to the plant community utilizing sunlight and resources throughout the year. Warm season grasses also have a unique process of doing photosynthesis, called C4 photosynthesis. Cool season grasses and most temperate plants utilize C3 type photosynthesis. C4 or warm season plants are more efficient at processing carbon dioxide and nitrogen from the atmosphere and nitrogen in the soil (OSU 2020).

3.5 Include nitrogen-fixing plants, especially with warm season grasses

Plants such as legumes that are “nitrogen-fixers” have symbiotic bacteria living in root nodules that mine nitrogen from the soil and make it biologically available to plants. Plant mixes that include legumes have potential to sequester more carbon than including a diversity of plants without legumes (De Deyn et al. 2011). A study on grassland restoration found that the presence of both legumes and C4 grasses together were correlated with higher carbon storage (Yang et al. 2019).

Strategy 4: Design with Plant Life History Strategies

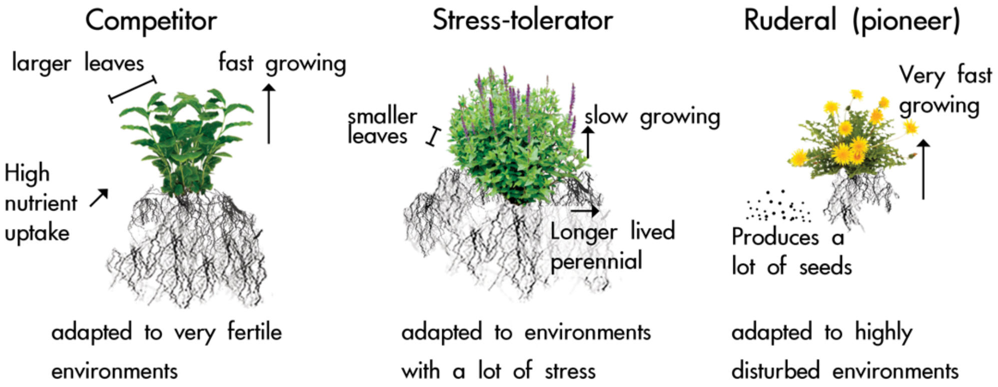


Figure 3.4 Plant life history strategies (Grime 1977)

Designing with plant life histories is another way to increase diversity of plant functional traits as well as performance traits. Grime's system of classifying plants into **competitor plants**, **stress-tolerator plants**, and **ruderal plants** (see chapter 2) can inform choosing plants that are better adapted to the site and function together as a community, supporting increased carbon sequestration (Figure 3.4).

Actions:

4.1 Match plant life history strategies to the site.

If the site is naturally very fertile, with lots of available nutrients, moisture, and sunlight, then competitor type plants may be best. Plants face a lot of competition in fertile sites since the growing conditions are ideal. Competitor plants will thrive and be able to outcompete undesirable ruderal plants. If the site is characterized by high stress, then a palette of mostly stress-tolerator plants may be best. A site by a windy beach or in deep shade will need plants adapted to conditions that lack moisture or ample sunlight, respectively (Dunnett 2004; Rainer and West 2015).

4.2 Mix plant life history strategies when appropriate

Most sites experience a combination of stress, disturbance, and fertility. Including ruderal type plants in a mix will help the community get established and survive disturbances. Stress-tolerant plants are long-lived and tolerate slowly changing conditions, such as increased heat and drought in climate change. Competitive plants can resist weed pressures and help maintain diversity as long as they are not too abundant or too competitive. A mix of plant life history strategies will take better advantage of micro-climates in the landscape (Dunnett 2004; Rainer and West 2015). Combining plants with productive or resource acquisitive strategies with plants with more conservative strategies supports carbon sequestration (Deyn et al. 2008).

4.3 Include both annual and perennial plants, but a larger proportion of perennial plants

Perennial plants are better for carbon sequestration because they tend to have woodier biomass, have more extensive root systems, and have stronger associations with mycorrhizal fungi. Annual plants, however, are useful to help establish a site and fill in gaps. It is important not to plan for annual plants to be replanted because annual planting disturbs the soil. A better strategy is to seed annual plants or allow them to self-seed around the plant community.

4.4 Avoid including plants that will be too competitive or aggressive

The mix of plants should include plants that will not spread so much that they crowd out other plants and reduce the diversity of the plant community. Evaluate whether the plants in the mix have complementary levels of aggressiveness. This especially important because aggressive plants may escape the site and become invasive in the larger landscape.

Strategy 5: Layer and Cluster Plants

Figure 3.5 Layering plants

To create a carbon sequestering landscape, choosing a diversity of plants that fill complementary niches is generally more important than exactly where those plants go in the design. However, layering and grouping plants can pack in more biomass create nested ecosystems that form rich interconnections and self-organize (Figure 3.5).

Actions:

5.1. Grouping small plant communities

The whole site may be thought of as one "plant community" or ecosystem, but smaller communities can exist throughout the site. Achieve complexity by designing sub-communities of plants that will self-organize to support each other. Group plants together that will all thrive in a similar microclimate condition, such as in the protected nook of rocks or under the shade of trees. Create more functional diversity within these sub-plant-communities by including different types of plants such as grasses, nitrogen-fixing plants, and deep-rooted plants.

5.2. Clustering or massing similar types of plants

Creating consistency and repetition through massing and clustering plants supports interconnection and resilience in the system, while adding visual coherence. Individual plants from the same species are more likely to share resources with each other through the mycorrhizal network (Gorzalek et al. 2015). Plan for plants of the same species to be spaced apart, but close enough that their roots can connect through the mycorrhizal network. Exactly how close depends on the plant, but a guideline can be within the distance of one to two canopy widths. Designing clusters of trees scattered in the landscape, instead of randomly placed, also helps to create microclimates and opportunities for the small plant communities in action 1. A co-benefit is that masses of flowering plants are better for pollinator habitat.

5.3. Vertical layering

Vertical layering can mean incorporating a canopy layer, shrub layer, and ground layer in a woodland. Designing a grassland provides the opportunity for finer-scale layering. Rainer and West, in their book *Planting for a Post-Wild World* (2015), suggest a method of layering plants in a grassland to achieve diversity while creating visual coherence. The method consists of four types of layers. The ground cover layer consist of low, shade-tolerant plants that spread and cover the ground. The filler layer consists of rapidly spreading plants that fill gaps. The seasonal theme layer are mid-height plants that are supportive throughout the year, but become visually dominant for a season for flowering or other display. The top layer is the structural layer consisting of large plants that have distinct forms and are long-lived.

5.4. Layering through time

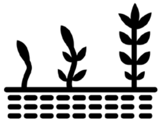
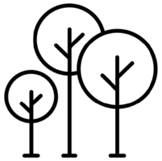
Plan out how a planting can have plants throughout the year that are growing and flowering at different times (Dunnett 2004). This is a common approach, as in English herbaceous borders, to achieve visual interest as well as pollinator habitat throughout the year, but it also enhances carbon sequestration by increasing functional diversity.

Illustration of Design Strategies

The five strategies (indicated by yellow numbers) are used to illustrate the differences in potential carbon sequestration between two landscape conditions. The first section illustration (Figure 3.6 on page 68) shows a landscape that is often seen in parks: a monoculture of lawn with scattered trees. The amount of tree cover may be similar to a natural woodland, but ecologically it is functionally different. This landscape has limited carbon storage because the lack of diversity results in empty niches above- and below-ground. Additionally, the high maintenance regime of lawn mowing releases carbon emissions.

The second section illustration (Figure 3.7) shows how application of the five strategies can support increased system efficiency and resiliency. Adding a diversity of trees and plants fills above and belowground niches, leading to more potential carbon sequestration.

DESIGN TOOLKIT

	Strategies		Description	Actions
1	Increase Biomass		Increasing the size and longevity of plants can increase the potential carbon sequestration in biomass. Layering plants can increase the potential biomass of the whole system.	**1.1** Include larger trees and plants, if given appropriate space **1.2** Include species that are longer-lived and low-maintenance **1.3** Include both fast and slow-growing trees and plants **1.4** Include deep-rooted trees and plants **1.5** Increase the amount of woody plants **1.6** Include deciduous trees in the plant palette **1.7** Increase vertical layering of plant types
2	Increase Biodiversity		Maximizing biodiversity provides another avenue to achieve functional diversity of plants and has important co-benefits to provide habitat	**2.1** Include a diversity of plant species **2.2** Increase phylogenetic diversity of the plant community **2.3** Choose native plants **2.4** Choose genetically local plant sources
3	Increase Plant Functional Diversity		Combining plants with a diversity of functional traits can create a system where more spatial and functional niches are filled, leading to increased productivity and carbon sequestration potential.	**3.1** Include a range of plant sizes: height and spread **3.2** Include a range of plant forms and habits **3.3** Include a diversity of root depths and architectural type **3.4** Include both warm and cool season grasses **3.5** Include nitrogen-fixing plants, especially with warm season grasses
4	Design with Plant Life History Strategies		Planting the right type of plant for the site or combining plant types can increase the efficiency and resilience of the landscape.	**4.1** Match plant life history strategies to the site. **4.2** Mix plant life history strategies when appropriate **4.3** Include both annual and perennial plants, but a larger proportion of perennial plants **4.4** Avoid including plants that will be too competitive or aggressive
5	Layer and Cluster Plants		Layering and grouping plants can pack in more biomass create nested ecosystems that form rich interconnections and self-organize.	**5.1** Grouping small plant communities **5.2** Clustering or massing similar types of plants **5.3** Vertical layering **5.4** Layering through time

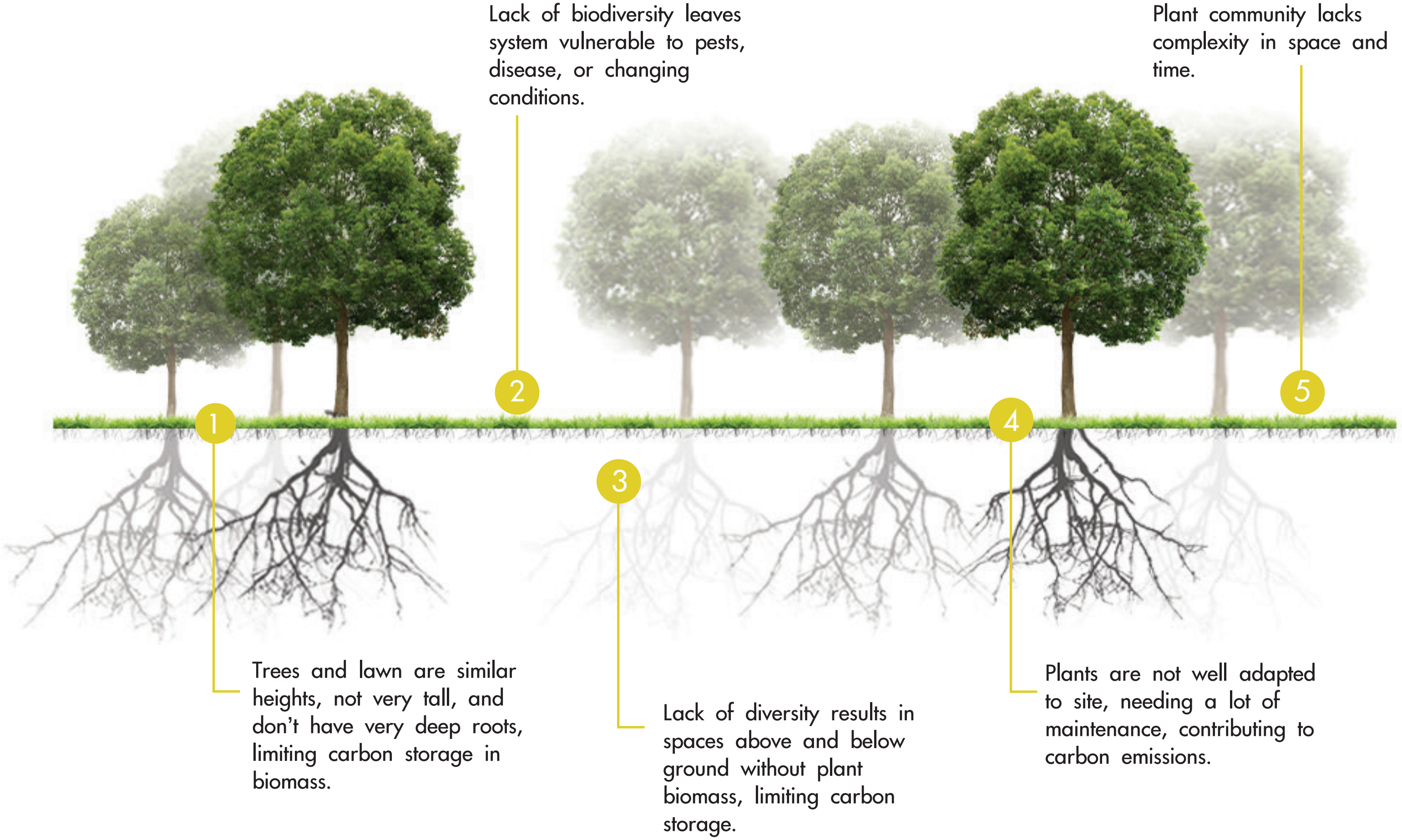
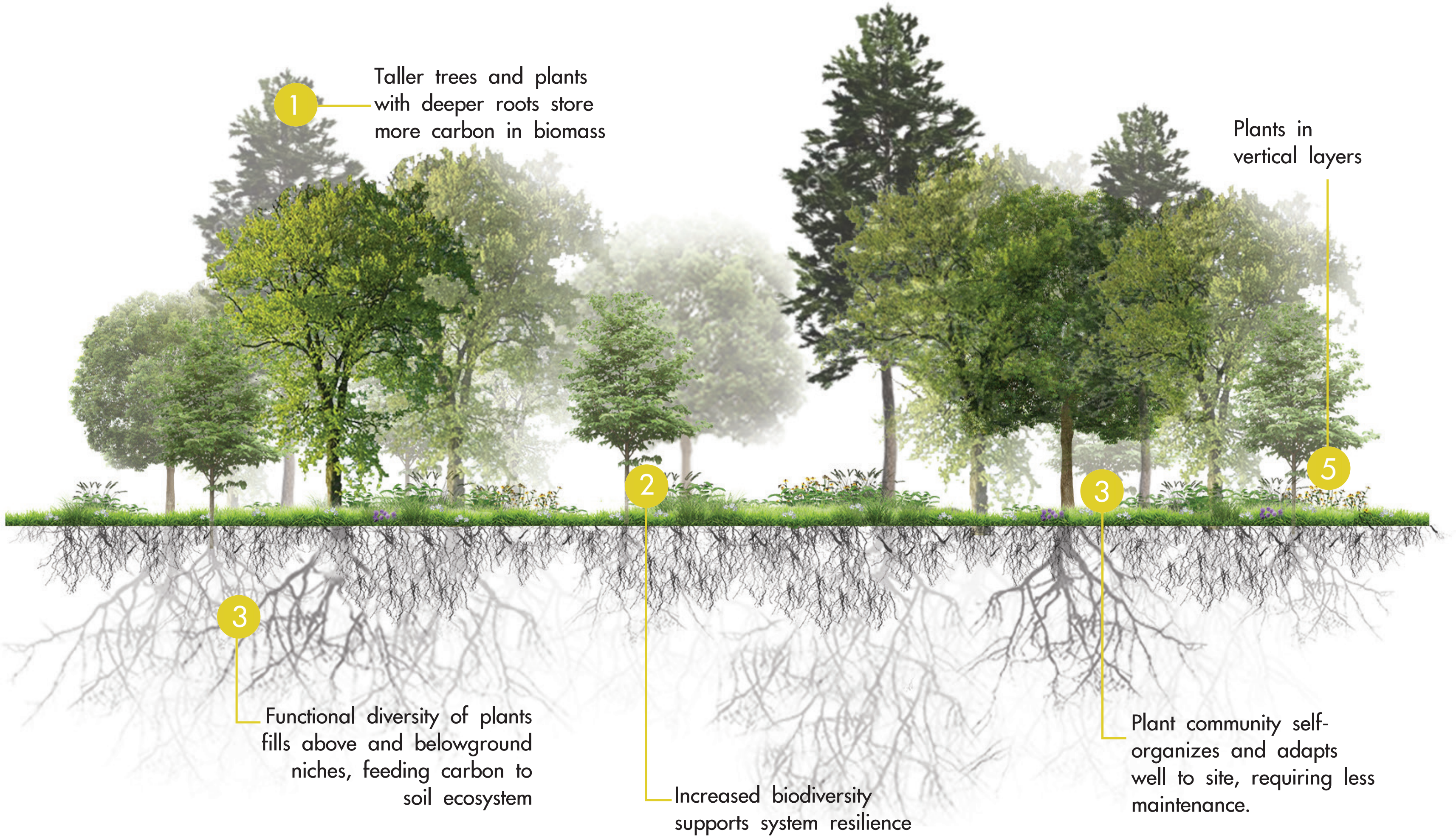


Figure 3.6 Typical Park Landscape



Taller trees and plants with deeper roots store more carbon in biomass

Plants in vertical layers

Functional diversity of plants fills above and belowground niches, feeding carbon to soil ecosystem

Increased biodiversity supports system resilience

Plant community self-organizes and adapts well to site, requiring less maintenance.

Figure 3.7 Carbon Sequestering Woodland Landscape

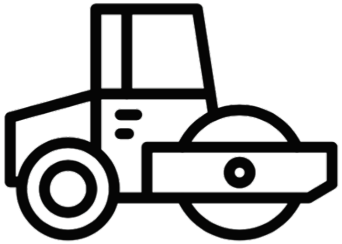
Chapter 4 Strategies for Installation

Installation is a critical time to start a landscape on a trajectory towards functional diversity, self-organization, and resilience. Complex adaptive systems are particularly sensitive to initial conditions, which may affect the structure and functioning of the system for the long-term. The four strategies for installation are formulated to protect and nurture soil health and carbon sequestration capacity and reduce emissions from transporting materials.

1. Protect Existing Soil from Compaction
2. Soil Amendments
3. Prevent Soil Erosion with Plant Cover
4. Reduce Emissions from Materials

Protecting soil health from compaction and erosion is key to plant community health and fundamental to an efficient and resilient landscape. Adding soil amendments such as bio-char or mycorrhizal propagules can help establish native soil microbial communities and can boost carbon sequestration. However, the key is to prime the soil ecosystem to engage plant-soil feedback loops that continue to build productivity and resilience, not to just keep adding the maximum amount of carbon. To ensure the design is net climate positive, designers should pay attention to emissions from construction and plant materials.

Strategy 1: Protect Existing Soil From Compaction



Good soil structure is critical for movement of water, air, and nutrients through the soil to support plants and the soil ecosystem. Good soil structure consists of different sizes of aggregates, or clumps of soil particles. These particles sequester carbon as well as creating larger pockets, or pore spaces, for air and water to flow through the soil. These pore spaces are also essential for roots and fungal hyphae to grow throughout the soil. Soil compaction causes these aggregates to break apart and the pore spaces to get much smaller, restricting movement of roots, water, and air. When compacted soil inhibits growth of plant roots and fungal hyphae, it can significantly impact plant health and performance and microbial activity essential to carbon cycling. It is important when installing a designed landscape, to prevent compaction of soil and to restore soil that is already compacted.

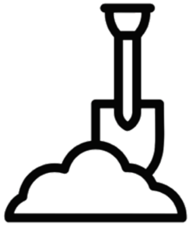
Actions:

1.1 **Restrict machinery and traffic to specific areas of site**
Heavy machinery used to move soil or materials significantly compacts the soil. Before any construction, plan or layout paths for machinery or delineate protected areas where machinery or foot traffic should not go. Ideally areas to be planted should have the soil protected. Laying out boards for machines to roll over can help prevent some compaction. Extra caution should be taken around established trees.

1.2 **Minimize stockpiling of soil**
The soil in the bottom of a large stockpile gets compacted. Stockpile soil in as short as possible piles, and spread over a larger area instead of a taller pile. A structure can be built to keep the soil in lifts. Keep the soil stockpiled for as short of a time as possible. When moving soil around in general, try to move larger lifts that keep the same spatial arrangement of soil particles to protect soil life such as fungal hyphae.

1.3 **Deeply till compacted soil before planting**
If an existing soil is very compacted, it needs to be mechanically de-compacted to prepare the site for planting. Evaluate how deep the compaction goes, and if needed, remove the top layer of soil in lifts. Then use machinery to till the sub-soil and replace top soil. Amending soil with compost will also help compaction (see strategy 2). However, this should only be done if soil is very compacted.

Strategy 2: Soil Amendments



Soil amendments can help with plant establishment, address soil deficiencies or imbalances, and add extra carbon to the soil. It is important to be informed and mindful with soil amendments, and not to apply the same treatment to every soil and site. Appropriate use of soil amendments can support soil ecological health that is critical to carbon sequestration, while misuse can undermine carbon sequestration.

Actions:

2.1 **Test the soil before adding soil amendments**
It is important to only add extra nutrients or organic matter if the soil has low levels. If too much fertilizer is applied for the situation, then plants won't take it up and it is likely to run off into and harm the aquatic ecosystems. If the soil is too fertile, it may favor competitor plants instead of desired plants. Too much fertilizer can cause spikes in populations of microbes, which is not beneficial for a resilient soil ecosystem. It is also important to conserve use of minerals that have to be mined and transported

2.2 **Amend top soil with compost and biochar**
If soil already has high levels of organic matter (more than 15%), it may be best not to add more to avoid disturbing the soil ecosystem and its physical structure. Otherwise, use compost to add nutrients and carbon to the soil instead of synthetic fertilizers. Ideally, use locally produced compost, derived from wood as well as food waste. Wood compost feeds fungi, while reducing food waste helps reduce emissions. Biochar is structured carbon similar to charcoal, produced by pyrolysis, or burning in the absence of oxygen. Biochar amendment adds carbon content while helping create structure for microbes to inhabit in the soil. Blending

compost with biochar adds nutrients while adding more carbon to the soil than just compost alone (Sánchez-Monedero et al. 2019). The carbon in biochar can stay in the soil long-term and contribute to mitigating climate change through enhanced soil carbon sequestration (Tisserant and Cherubini 2019).

2.3 Add extra carbon to fill or constructed soils

One study found that constructed soils amended with compost to have higher carbon content than natural soils kept 70% of the carbon after three years and then carbon content increased from plant inputs (Rees et al. 2019). Adding compost to soil horizons below the topsoil needs to be done carefully so soil structure is maintained and anaerobic conditions are not created. Biochar may be a better choice to add to deeper soil horizons when adding fill or constructed soil due to its stronger structure. Adding compost or biochar to deep soil should only be done when fill or constructed soil is necessary for other reasons. Otherwise, it is better not to disturb native soil.

2.4 Inoculate with mycorrhizal fungi

Mycorrhizal inoculation is the amending of soil with mycorrhizal fungi propagules, which consist of spores, hyphae, and vegetated root fragments. These can be obtained from commercial mixes or cultured from the root systems of local plants ("trap cultures"). Mycorrhizal inoculation can help establish robust vegetation more rapidly and help increase species richness in restoration (Neuenkamp 2019; Farrell 2020). Although propagules for mycorrhizal inoculation are commercially available, landscape architects should consider trap cultures. Locally adapted fungi are more likely to benefit plant growth than commercially available inocula, even when diverse. A diversity of mycorrhizal fungal species can better support plant growth across different environments (Koziol et al. 2018; Bermudez 2020). Reintroducing the native microbiome of plants can help restore plant community diversity (Koziol et al. 2020), which, as has been previously established, is important for carbon sequestration.

Strategy 3: Prevent Soil Erosion with Plant Cover

When soil is left bare and unprotected by plants, its structure and ecosystem can be damaged. Rainfall and wind can compact and erode the soil. Sunlight bakes the ecosystem, harming some organisms, and increasing metabolism of bacteria which releases carbon. Covering the soil quickly with plants is generally best because plants help create good soil structure and continually add carbon to the soil, feeding the soil ecosystem. Mulch can have a higher environmental cost than plant material and should be used judiciously as a ground cover.

Actions:

3.1 Plant cover crops until desired plantings grow in

Cover crops are plants that spread to cover the soil quickly to protect it from erosion. Cover crops also add nutrients and help build up organic matter and improve soil structure. Nitrogen-fixing clover is often used to add nitrogen to the soil. Be careful not to plant cover crops that can become invasive (Dunnett 2004; Rainer and West 2015).

3.2 Spread seeds in gaps between plants from containers

Wildflowers or annual plants can cover the soil until perennial plants from containers grow in (Dunnett 2004; Rainer and West 2015).

3.3 Include spreading or groundcover plants in design

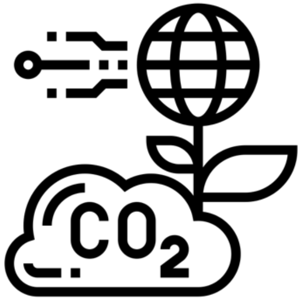
Add extra groundcover plants in between and under plants that will take years to reach full size.

3.4 Use mulches only when necessary

"Mulch" can refer to a variety of materials spread on landscapes including woodchips, leaves, and rocks. Rock mulches may be appropriate if local material is available and the landscape is particularly arid. Otherwise, avoid rock mulch. Organic mulch can be very useful to cover the soil until plants grow in, although it is better to just establish plant cover quickly. Organic mulch ideally should not be used as a permanent cover for the landscape. Organic mulch such as wood chips decompose quickly on the surface of the soil, releasing as much as 80% of their carbon back to the atmosphere (McPherson 2014). Wood chips also need to be replaced every couple years to keep down undesirable plants.

3.5 **Use diversity of organic mulch material**
When organic mulch is necessary, vary the size, shape and type of materials used. Include leaves and other types organic material along with wood chips to assist with microbial activity to bring the carbon down into the soil. Layering types of mulch or organic material, referred to as sheet mulch, can be beneficial to start gardens on small sites. Be careful that leaf mulch does not carry seeds or propagules of invasive plants.

Strategy 4: Reduce Emissions from Materials



Transportation of materials to the site typically occurs by diesel truck, which releases carbon emissions that can cancel out the benefit to the climate of carbon sequestration in the landscape (Figure 4.1). To help the project and landscape to be climate positive, be intentional about choosing materials. In general the more the ground is covered by plants instead of hardscape, the lower the emissions from materials. However, discussing emissions from hardscape and non-plant construction materials is out of the scope of this project. These actions are suggestions to reduce emissions from constructing the "landscape" that is vegetated, not covered by hardscape.

Actions:

4.1 Source plants from nurseries that propagate and grow the plants to size

It is common in the nursery trade for plants to be propagated at one nursery, then bought by another nursery to be grown to size. Sometimes plants are shipped around multiple times before the final trip to the site.

4.2 Use local plants and materials

Source materials as locally as possible to avoid emissions from transportation of materials long distances.

4.3 Order smaller plant pot sizes or using seeding

Ordering larger plant sizes adds to the emissions of the project through adding weight and taking up space in the truck. Smaller sizes of plants may avoid an extra trip in the truck. Smaller plants also often have better success establishing than larger plants (Reed and Stibolt 2018). Seeding plants is even better in terms of transport emissions.

4.4 Avoid importing soil

Balance cut and fill so that it is not necessary to import fill soil. Never import top soil because the site has "poor soil". Either amend the soil with compost or other amendments, or use a constricted plant palette that will thrive in that soil.

Figure 4.1 Truck delivering plants

INSTALLATION TOOLKIT

Strategies	Description	Actions
1 Protect Existing Soil from Compaction	Compaction reduces pore space available for plant roots and soil organisms to grow and flourish.	**1.1** Restrict machinery and traffic to specific areas of site **1.2** Minimize stockpiling of soil **1.3** Deeply till compacted soil before planting
2 Soil Amendments	Establishing a new landscape is an opportunity to add extra carbon into the soil, much of which is likely to remain as long as plant cover is established and retained.	**2.1** Test the soil before adding soil amendments **2.2** Amend top soil with compost and biochar **2.3** Add extra carbon to fill or constructed soils **2.4** Inoculate with mycorrhizal fungi
3 Prevent Soil Erosion with Plant Cover	Plant cover is the best way to protect soil from erosion and adds carbon and nutrients to the soil, jumpstarting or reviving soil ecology and microbial processes.	**3.1** Plant cover crops until desired plantings grow in **3.2** Spread seeds in gaps between plants from containers **3.3** Include spreading or groundcover plants in design **3.4** Use mulches only when necessary **3.5** Use diversity of organic mulch material
4 Reduce Emissions from Materials	Emissions from trucking materials can cancel out the climate benefit of a carbon sequestering landscape.	**4.1** Source plants from nurseries that propagate and grow the plants to size **4.2** Use local plants and materials **4.3** Order smaller plant pot sizes or seed plants **4.4** Avoid importing soil

Chapter 5 Strategies for Management

The five strategies integrate the three principles into recommendations for maintaining a complex adaptive landscape over time, with healthy soil ecology and minimal emissions. The concept of adaptive management frames the approach to maintaining diversity and complexity.

1. Allow Landscape to Change
2. Apply Coarse-Scale Management
3. Protect Soil Life
4. Reduce Maintenance-Related Emissions
5. Improve Lifecycle Management of trees

Introduction

Adaptive Management accepts the reality that landscapes are dynamic, complex systems that will never stay the same as they were when installed or restored. Human management should adjust to the changing system instead of insisting on maintaining a static state (Gunderson 2000, Dunnett 2004). It's impossible to predict the changes that will happen, so policies and management plans must be created in a way that can be updated or revised (Gunderson 2000). It is important to understand that when you impact a complex system, the effect may not show right away because it is likely to respond nonlinearly (*see chapter 2*). A cyclical process of planning, where a management process or experiment is planned, then the outcome of that informs revision of the process, is a solution to adapting plans for changing landscapes (Pulliam and Johnson 2002). Monitoring and data collection is important to understand landscape has performed or changed over time.

Management should allow the plant community to self-organize while guiding its development towards desirable plant composition and diversity, enhancing its resilience. A self-organizing landscape system will maintain its essential structure and functioning throughout disturbances and changes in management. Smaller shifting of species composition helps the community adapt to microclimates and creates **heterogeneity** (Dunnett 2004, Levin 2013). Maintaining functional diversity and redundancy will increase system resiliency by making sure components that perform different essential functions will remain in place (Levin 2013). Protecting soil life, especially mycorrhizal fungal networks, supports system connectivity that serve as avenues for negative feedbacks that buffer the system against shocks (Gunderson 2000, Chapin 2011).

Climate Positive Design becomes especially important for management of carbon sequestering landscapes. Resources used for maintenance throughout the life span of the landscape should be minimized to ensure that the carbon sequestration of the landscape is having a net benefit to mitigate climate change. The practice of mulching trees at the end of their life and spreading the wood chips on landscapes can result in the release of a majority of the carbon from the trees. Climate Positive Design is important in urban areas, where the functioning of landscapes depends on their maintenance by humans, which is subject to social, ecological, and political changes (Cadenasso and Pickett 2008). Landscape designs that are more resilient to disturbances and changes in maintenance will continue to have more ecological functioning throughout the highly dynamic social environment of urban spaces. Looking at the whole landscape system, including maintenance inputs and emissions as well as carbon sequestration, is critical in urban areas.

Management of landscapes should be adaptive, maintain soil ecological health, and prevent maintenance-related carbon emissions. Adaptive management can help a landscape sequester carbon by ensuring that it maintains high diversity and functionality throughout its life.

Strategy 1: Allow landscape to change

Change is a fundamental part of natural plant communities and can be phenological, cyclical, or successional. **Succession** is longer-term change in community structure. Phenological change is seasonal change in vegetation over a year. Cyclical change is change in structure between years. Allowing these different types of landscape change is important to supporting a self-organizing, diverse ecosystem in the landscape (Dunnett 2004).

Actions:

1.1 Allow plant species composition to shift over time

Plant communities allowed to shift around will be more resilient because individual plants can move around, spreading and self-seeding, to find their own niches or microclimates that are optimal for their survival. The mix of plants planted at the beginning can be planned as best as possible for a complementary mix of species that will maintain diversity, not have one species dominate, but it is difficult to predict how the species will react. Allowing the species mix to self-organize over time will allow the mix of species to achieve a complementary mix for functional diversity (Dunnett 2004; Rainer and West 2015). The designer should decide on guidelines for an acceptable amount of change and a plan for how to maintain a range of possible outcomes.

1.2 Guiding succession

Guiding successional change can result in a more complex, productive, and resilient landscape. This can be planned such that the planting can start with early successional species and a later planting can include later successional species. It can also mean accepting more woody vegetation when they appear and changing management practices to maintain tidiness and diversity of the new landscape structure (Dunnett 2004; Rainer and West 2015). In some cases, an early successional landscape, such as a grassland may be more desired than a woody landscape. In this case, working with succession doesn't need to mean the addition of woody species, but can mean a guided trend towards more perennial, deep-rooted species.

1.3 Maintain functional diversity of plants

A functional diversity of plants uses resources more efficiently and maintains functioning in the face of disturbances. A diversity of plants is more pleasing aesthetically and can reduce maintenance (Dunnett 2004). Plant mixes should be designed with plants that the plants will be sociable and not one plant will come to dominate, but even with a well-designed mix, the plants may shift around such that one species may come to dominate. Allow the plants to shift around only to the extent that the diversity of the community is not compromised.

Strategy 2: Apply coarse-scale management

Maintenance of formal or lush landscapes is resource-intensive, involving substantial mowing, pruning, fertilizing, or watering. It is important that maintenance of designed landscapes conserves resources and minimizes carbon emissions, or the landscape may become a net source of carbon emissions (Climate Positive Design). Focusing on coarse-scale management techniques, not maintenance of individual plants, allows the plant community to self-organize, which may lead to increased resource use efficiency and reduced maintenance inputs. Managing the whole plant community as a unit instead of individual plants can nudge it towards desirable trajectories of change (Dunnett 2004; Rainer and West 2015).

Actions:

2.1 **Apply management to a group of plants or the whole community instead of individual plants**

Coarse-scale management actions such as thinning, mowing, or burning can help maintain community structure without the resource intensity of maintenance such as weeding, pruning, or chemical use (Rainer and West 2015).

2.2 **Apply management infrequently such as monthly or seasonally**

Management practices such as mowing or pruning will be more sustainable on a larger scale if practiced infrequently such as monthly or seasonally. If maintenance is happening weekly, it is a sign that the plant community is not an established, self-organizing system.

2.3 **Apply the intermediate disturbance hypothesis**

The intermediate disturbance hypothesis states that the most biodiversity in a plant community occurs at intermediate levels of disturbance. This is because at low levels of disturbance, very competitive species may dominate that are adapted to environments with low levels of disturbance (Grime 1977). At higher levels of disturbance, not many species can survive (Pulliam and Johnson 2002). To understand the best disturbance regime, or pattern of maintenance, look at the historical patterns for that area or type of ecosystem. Was it adapted to frequent flooding? Or burning by native people? How often or how intense was the historic type of disturbance? Often a novel disturbance regime will need to be designed. It is important that new techniques be tested and monitored, and adjusted depending on success. This idea is used often in ecological restoration, but should be considered for designed ecosystems as well. The purpose is to create and maintain a system with the highest functional diversity and functioning, and this will lead to higher carbon sequestration.

2.4 Adjust plant community over time

Use disturbances to favor some species over others, working towards a community that self-maintains diversity (Dunnett 2004; Rainer and West 2015). Thinning or selective removal of plants infrequently can help to maintain a diverse community composition of plants, without frequent hand weeding or chemical control. It is important to maintain full coverage of desirable plants to prevent unwanted weeds. However, be open to some “weeds” as long as they do not harm mycorrhizal fungi and are not aesthetically off-putting to remain in the mix. Monitor weedy species for invasiveness and control early to prevent spread beyond the site.

Strategy 3: Protect soil life

Soil ecological health is a critical factor in maintenance since many maintenance activities such as chemical use harm soil organisms. For carbon to be stored long-term in the soil, there needs to be a healthy ecosystem of microbes and other life in the soil (Kallenbach et al. 2016; Frey et al. 2019). Microbes such as mycorrhizal fungi distribute carbon throughout the soil and assist in the formation of soil aggregates that protect the carbon from release back to the atmosphere. An abundance and diversity of microbes, especially mycorrhizal fungi, help form complex layers of ecosystems within larger systems, creating cross-scale interconnections and relationships that support resilience (Simard et al. 2012). Soil microbes are very vulnerable to disturbances, which can reduce the functioning of the soil ecosystem that sequesters carbon. Extreme disturbances can alter the ecosystem, such as a high severity fire or excessive tilling, breaking down protected carbon stores and releasing the carbon to the atmosphere. Designing a landscape that is complex with functional diversity, and adaptive, meaning allowed to self-organize, can reduce the amount of maintenance needed that might be harmful to soil organisms.

Actions:

3.1 **Use compost and compost tea instead of synthetic fertilizers**

A well-designed plant community will be adapted to its environment and not need much supplemental nutrients. However, if the system does need some assistance, boost fertility by adding compost of compost tea. Compost or compost tea are rich with organic matter and microorganisms that help populate and restore balance to the soil microbial community. A functioning soil microbial community will mine the soil and bed rock for nutrients and make them available to plants. Also when nutrients are "stored" in the bodies of soil microbes and cycling in the soil ecosystem, they will be more reliably available to plants over time. Compost and compost tea are better because synthetic fertilizers can cause immediate blooms of microbial growth that put the microbial ecosystem out of balance. Nitrous oxide, a potent greenhouse gas, released from use of synthetic fertilizers is a significant reason lawns can be net emitters of carbon (Gu et al. 2015).

3.2 Eliminate use of pesticides, herbicides, fungicides, except in extreme circumstances where there is no alternative.

Virtually all pesticides, herbicides, fungicides cause mass death of microbes in the soil, and can even harm larger organisms like earthworms (van Bruggen et al. 2019). Because of the critical role of microbes in soil carbon sequestration, application of these chemicals undermines carbon sequestration. These chemicals can also several harm pollinators that are essential to ecosystem functioning. Aim to manage pests and weeds by creating a diverse, self-organizing system that is not vulnerable to attack.

3.3 Keep soil covered with plants to prevent erosion and compaction

After establishment, the ground surface of a carbon sequestering landscape should ideally be completely covered with plants. Bare soil is vulnerable to losing nutrients from erosion and losing soil structure from compaction. Many landscape designers use mulch to cover the soil, but there are issues with wood chip mulch (*see strategy 5*). Plant coverage is best because the plants feed carbon into the soil ecosystem.

3.4 Avoid unnecessary digging and tilling

Fungal hyphae are critical support networks that facilitate long-term storage of carbon and shuffle resources between trees and plants in the landscape. Hyphae are very fragile and easily severed by digging and tilling the soil. They will grow back, but take more or less time to reestablish depending on the species. Plan maintenance practices such as infrequent mowing that nudge the community towards the desired plant composition instead of digging up unwanted weeds. Re-seed annual plants instead of replanting to fill in gaps.

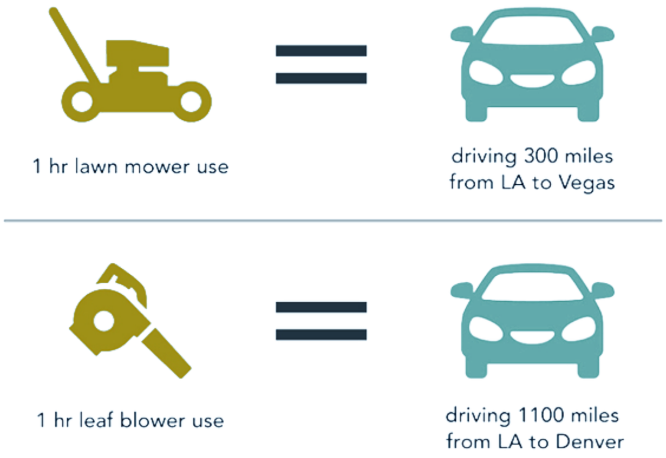


Figure 5.1 High emissions cost of gas-powered tools (image source: CA Air Resources Board)

Strategy 4: Reduce maintenance-related emissions

To ensure that the whole landscape system is net climate positive, designers should specify management and tools that contribute minimum greenhouse gas emissions. Designers and the public may mistakenly believe that a landscape that looks green and lush, with grass and trees is of net benefit to the environment. However, some urban landscapes are actually contributing to climate change due to high maintenance emissions (Figure 5.1).

Actions:

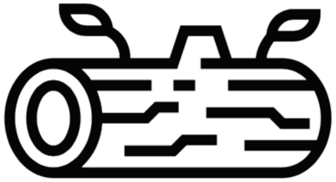
4.1 **Eliminate, reduce size of lawn, or replace with diverse and low-mow grass mix**
Lawns sequester carbon, but the frequent mowing with a gas-powered mower and fertilizer use means that they are often

net emitters of carbon (Gu et al. 2015). To ensure the landscape is net climate positive, include a minimal area of lawn or replace with an alternative plant community. A mix of a few species of grasses with some low forbs can still be mowed to keep a tidy appearance, but look decent a bit longer, allowing more infrequent mowing or use of an electric trimmer.

4.2 Reduce use of machines for maintenance or shift to electric

Gas-powered maintenance machines such as lawn mowers and leaf blowers are generally inefficient and produce a significant amount of emissions. Using a leaf blower for one hour generates the same emissions as driving a 2017 Toyota Camry 1100 miles from LA to Denver (Figure 5.1) (CA Air Resources Board). Avoid these emissions by designing a low-maintenance self-organizing landscape, use human-powered tools such as rakes and clippers, or switch to electric-powered machines.

Strategy 5: Improve lifecycle management of trees



Improving the lifecycle management of trees is critical to management of landscapes to be net carbon sequestering. An urban tree sequesters carbon in its biomass as it grows, but when it dies and/or needs to be cut down, the standard practice is to chip the wood into mulch, which gets spread on landscapes or taken to the landfill. Use of wood chip mulch is encouraged as part of a sustainable landscape. Mulch is indeed better for controlling undesirable plants than using chemicals, and is better than leaving soil bare. However, decomposition of wood chip mulch can release a significant amount of the carbon back to the atmosphere. The amount varies with characteristics of the wood and environmental conditions, but a survey of literature by Mcpherson and Kendall (2014) assumed that 80% of the carbon from wood chip mulch is released back to the atmosphere.

Why might wood chips release so much carbon, when downed wood in a forest is a significant long-term carbon pool (Magnussen et al. 2016; Harmon et al. 1986)? The size of logs in forests is negatively correlated with their rate of decomposition–meaning the larger the piece of wood, the more slowly it decomposes (Harmon et al. 1986). Perhaps the small size of wood chips is related to how quickly they decompose. Because logs decompose more slowly, a more slow and steady drip of carbon is cycled into the soil by microbes and other organisms (Magnussen et al. 2016; Harmon et al. 1986). When wood chips decompose so quickly, there is not as much time for soil organisms to incorporate the carbon deeper into the soil.

Urban street trees can emit more carbon than they sequester, mostly due the release of the carbon from cut down wood through combustion or decomposition of wood chips (Mcpherson and Kendall 2014).

Urban forests or trees in a landscape architecture project cannot be conceived of as having a climate benefit through carbon sequestration unless their biomass carbon is largely prevented from release at the end of their life.

Actions:

5.1. **Keep logs and pruned woody material on site as woody debris**
Logs decompose slowly, giving a diversity soil organisms time to assimilate the carbon and cycle it down into long-term storage (Magnussen et al. 2016; Harmon et al. 1986). The diversity of organisms that can inhabit a log in the landscape supports habitat for many species (Magnussen et al. 2016). Smaller pruned branches can be left in piles for habitat, provided the site is not in a high fire-risk area.

5.2. **Use wood from removed trees for building or furniture**
Using the wood in buildings or furniture increases the amount of time the carbon is kept out of the atmosphere, although generally does not permanently store the

carbon (Dirrenberger et al. 2014). Not all urban tree species would be suitable for this, but it is an option to keep in mind. Facilitating the carbon from trees getting into the soil is the best way to ensure the carbon is stored permanently.

5.3. Turn removed wood into bio-char to add carbon to soil

The carbon in bio-char may stay stored permanently in the soil (Tisserant and Cherubini 2019). Processing wood from cut down trees into bio-char has much higher potential for permanent carbon storage than application of wood chip mulch.

5.4. Hugelkulture

Hugelkulture is a permaculture practice of burying logs in large mounds that serve as a reservoir of carbon, water, and nutrients to nourish the plants on the mounds. The mounds can be started in a pit and built up high to 5 or 6 feet tall. Layers of organic materials are applied on top of the logs and then it is planted with a diversity of plants. Although the carbon storage potential of Hugelkulture mounds has not been studied, wood buried in forests decomposes very slowly and can be preserved over centuries (Moroni et al. 2015). Burying wood in mounds, similar to Hugelkulture, could be a novel technique for landscape architects to manage disposal of pruned park trees for carbon sequestration.

MANAGEMENT TOOLKIT

Strategies		Description	Actions
1	Allow Landscape to Change	Allowing the landscape to shift over time allows plants to move and find microclimate niches they are more suited to, improving efficiency and resilience.	**1.1** Allow plant species composition to shift over time **1.2** Guided succession **1.3** Maintain functional diversity of plants
2	Apply Coarse-Scale Management	Use infrequent and coarse-scale actions to manage the whole plant community instead of intensive maintenance of individual plants.	**2.1** Apply management to a group of plants or the whole community instead of individual plants **2.2** Apply management infrequently such as monthly or seasonally **2.3** Apply the intermediate disturbance hypothesis **2.4** Adjust plant community over time
3	Protect Soil Life	Soil organisms are vulnerable to impacts from chemical inputs such as pesticides, herbicides, and fertilizers. These chemicals can cause mass death of soil microbes, undermining healthy soil functioning as well as carbon sequestration.	**3.1** Use compost and compost tea instead of synthetic fertilizers **3.2** Eliminate use of pesticides, herbicides, fungicides, except in extreme circumstances where there is no alternative. **3.3** Keep soil covered with plants to prevent erosion and compaction **3.4** Avoid unnecessary digging and tilling
4	Reduce Maintenance-Related Emissions	Landscape maintenance machines are especially inefficient and produce significant carbon emissions.	**4.1** Eliminate, reduce size of lawn, or replace with diverse and low-mow grass mix **4.2** Keep pruned materials on site **4.3** Reduce use of machines for maintenance or shift to electric
5	Improve Lifecycle Management of Trees	Decomposition of wood chip mulch releases as much as 80% of the carbon, and little cycles down into permanent soil carbon storage. Alternatives should be found for the recycling of carbon from removed wood.	**5.1** Keep logs and pruned woody material on site as woody debris **5.2** Use wood from removed trees for building or furniture **5.3** Turn removed wood into bio-char to add carbon to soil **5.4** Hugelkulture (burying logs in mounds of sheet mulch)

Chapter 6 Final Thoughts

In this chapter I review key points I want designers to take away from this work, discuss the approach I have taken with this project, and explore possibilities for further developments. This work could be applied to existing programs, such as SITES as well as be useful as a stand-alone guide for design, installation, and management of landscapes.

Importance of Framework

The framework I developed helps fill a gap in knowledge for the field of Landscape Architecture. Projects such as i-Tree or the Pathfinder app have set a precedent that may lead designers to believe that carbon sequestration can be reduced to numbers plugged into a calculator. These tools are very useful for visualizing the potential climate impact of landscape architecture projects but should not take the place of more rigorous investigation into the complex and dynamic reality of carbon sequestration in landscapes. This work provides an alternative but complementary solution: designers can choose plants based on their potential to work together as a carbon-sequestering designed ecosystem.

The recommended strategies and actions are formulated to create a complex adaptive landscape, increasing the potential carbon input by photosynthesis and protecting carbon long-term in the soil. The strategies integrate the three key principles into user-friendly recommendations. This project is unique not only in its focus on soil but also because it draws from scientific literature that connects specific plant traits to soil microbial processes and soil carbon sequestration; it translates them into an easy to implement framework for design. I created a flexible palette of options that designers can apply to many situations, especially with tight time constraints. This flexibility increases the project's relevance to the field because the framework has the capacity to adapt to changing knowledge in the future. This project could be the beginning for many more landscape architects to collaborate with scientists to further this work and the field's potential to sequester carbon in landscapes.

Key takeaways: complex adaptive systems and soil carbon

The principles of complex adaptive systems and soil ecological health provide a frame to guide application of scientific concepts in carbon sequestration to design practice. Designing only for biomass carbon sequestration is not enough. Designers need to incorporate soil carbon dynamics into the design process to fully address the potential of landscape carbon sequestration. Soil carbon sequestration is not a linear process where you can simply put in more carbon of a particular type and know that it will get stored in the system. There needs to be diversity of plants and microbes interacting as a self-organizing system, allowing the macroscopic process of carbon sequestration to emerge. I want to encourage people to move away from reductionist thinking about which components in a system sequester the most carbon. We need to design complex adaptive systems with a functional diversity of plants that work together to pack the most carbon into biomass AND soil. Designing for functional diversity can have a significant impact on supporting soil ecological health and the co-benefits of increasing soil ecological health. Increasing carbon-rich organic matter in the soil supports plant productivity, plant health and resistance to disease, increased water holding capacity, and increased pollution filtration. Designing for carbon sequestration supports other design goals through this co-benefit of increased ecological health.

Monitoring and application to existing programs

Although I am arguing that it is not possible to measure carbon flows from specific plants for the purposes of design, measurement and monitoring carbon in landscapes can help designers better understand the impact of their decisions on carbon sequestration. If landscape architecture wants to stay relevant as a climate change solution, it should take the lead, collaborating with scientists to develop more user-friendly methods of measuring soil carbon in landscapes. It is, however, important that monitoring analyze the whole landscape system, taking into account the complex interactions between plants and soil microbes that lead to carbon sequestration in soil. This project drew on many helpful studies that examined how particular variables, such as soil type, plant type, or organic matter inputs, affected soil carbon sequestration. However, very few of these studies specifically examined urban areas, which have particular challenges such as pollution or compacted soil. More research is needed to understand how different variables in designed urban landscapes affect carbon sequestration.

Although I advocate for a holistic approach that incorporates the complexity of natural solutions, and my framework works as a stand-alone project, strategies and actions from this work could be applied to existing landscape architecture programs to enhance their efforts at addressing climate change. The Landscape Architecture Foundation's case study series could account for emissions associated with projects and include more information about whether the project has a diversity of plants and has increased soil health. At the least, the series should be more circumspect about listing carbon sequestration benefits of tree planting without further investigation of the net climate benefit of the project. The Sustainable SITES Initiative could utilize some of the strategies developed here for credits in its certification program, such as increased functional diversity of plants and improved life cycle management of trees. These particular strategies have potential for a significant impact and are under-recognized in the field.

The Climate Positive Design Challenge and its Pathfinder app developed by Pamela Conrad at CMG landscape architecture has increased awareness worldwide of carbon sequestration and the emissions impact of landscape projects. The principle of net climate positive design, is necessary to analyze whether or not projects have a net benefit to the climate. My work has been inspired by Pamela Conrad's work and I aimed to complement her project by filling in important gaps. My work could contribute to and strengthen CMG's resource in multiple ways. Although it is not feasible to input data about the specific amount of carbon that plants send into the soil, there are some things from this project that could be used as parameters to enrich the Pathfinder app (a carbon calculator). For example, phylogenetic diversity could serve as a proxy for functional diversity and would be more feasible to compute from inputting plant species. A carbon sequestration benefit "credit" could be assigned to having increased diversity, although it may not be feasible to calculate the amount of increased carbon sequestered. For the app to incorporate soil carbon sequestration, more research is needed to gather data about how plant communities in particular regions or environments influence soil carbon sequestration. Some of the strategies from my project could be added climate positive design toolkit, including increasing functional diversity, increasing amount of deep-rooted plants, and burying wood in hugelkulture.

Carbon sequestration as a co-benefit

Designers should integrate and balance carbon sequestration among other design goals as a co-benefit in landscape architecture projects. It is short-sighted to think that people can dedicate large areas of land only for carbon sequestration, especially in urban areas. It is more feasible and more beneficial to the communities of people and species that inhabit landscapes, to design multi-functional and multi-purpose landscapes that include carbon sequestration as a co-benefit. Landscapes should be for people and be for the species and ecosystems that make up the biological component of the landscape. Other uses or goals for a landscape, such as growing food or filtering stormwater, are completely compatible with this approach to designing for carbon sequestration. It is also dangerous to advocate for large projects which have a singular goal of carbon sequestration because it could have negative impacts on habitat or human uses, such as growing food or providing accessible green space. For these reasons, this project does not advocate for "maximizing" the carbon sequestration in a particular landscape, which could impact other design purposes to create a functional place for people and species. Integrating carbon sequestration as a co-benefit in landscape architecture projects could be an effective avenue to increase the number of projects that design for carbon sequestration.

Climate Action Plans and Urban Areas

The research and framework presented in this project could be useful in formulating climate action plans that include carbon sequestration. Not many climate action plans include carbon sequestration because of the lack of guiding resources and because other issues, such as reducing emissions from transportation, may be more urgent to address. Integrating landscape design for carbon sequestration into climate action plans could be beneficial for several reasons. Many of the changes needed to address climate change can be perceived by the public as negative: taking away conveniences and luxuries that they have grown accustomed to, such as driving cars or eating meat. Additionally, recognizing the destructive power of climate change can bring despair (eco-grief) and telling people the only way to address climate change is through compromising on valued lifestyle practices isn't effective. Restoring and designing landscapes for carbon sequestration can help motivate people to take action and help with eco-grief through the personally healing effects of gardening and through the sense of correcting the damage to the planet.

Larger-scale planning for natural climate solutions is needed; it is difficult to calculate the amount of carbon sequestered by people landscaping many small sites. Nevertheless, implementing carbon sequestration in urban areas is important. Landscape projects for carbon sequestration can incorporate educational components about the process of carbon sequestration and why larger areas of land need to be protected. It is easier for people to manage smaller areas of land close to where they live for the increased diversity and complexity important for carbon sequestration.

Assisting nature's ability to restore itself

Although natural systems evolved to be excellent at sequestering carbon, much of the environment on this planet has been changed by modern consumer civilization. Soils worldwide are degraded, and invasive species are a ubiquitous threat to biodiversity. Urban areas are especially impacted and have diverged sharply from the historical landscape. Although I advocate for the use of genetically local native plants, I recognize it is not feasible in many cases to return to the historical landscape. To sequester significant amounts of carbon from the atmosphere, designers and land managers should work with the natural ecological processes of landscapes, guiding them towards increased diversity and complexity.

Letting nature "take over" is not the right approach and is likely to lead to an overrun of invasive plants. Neither is hyper-control, involving high levels of resource-intensive maintenance or creating too simple of a system. Designing for increased carbon sequestration should be a sort of middle road that creates a novel ecosystem and gets it off to a good start, but lets it shift around, and applies the right amount of management (disturbance) to help it maintain diversity. Humans should restore complex natural systems not only for carbon sequestration but also for other key life-support services, such as suppression of disease and water filtration. I advocate for restoring nature, but more than that, for restoring nature's ability to restore itself and to continue the life-support services of natural systems, especially the service of climate regulation.

Most of all, I want designers to ask more questions. Instead of simply planting trees and saying we are benefitting the climate, we have to ask these questions: Are we nurturing and protecting the soil with a diversity of plants? Are we maintaining the landscape with gas-powered machines that release emissions? Are we making sure that when those trees die, the carbon is not released to the atmosphere? The answers to those questions matter and influence whether or not those trees truly are benefiting the climate. This work is an important beginning step for the field to incorporate more science-based principles into design. The more landscape architects integrate landscape design for carbon sequestration into their everyday work, the more they can be advocates for and collaborate with scientists and planners to create larger-scale change.

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