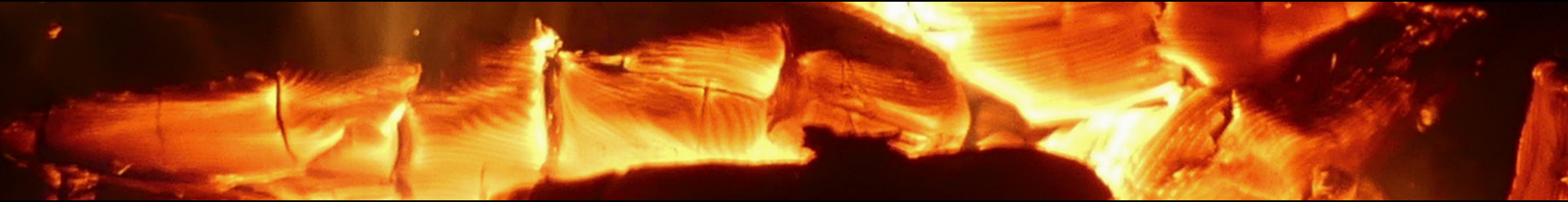
METABOLIC MATTERS

An Urban Designer’s Guide to Biochar



With Examples from Sweden and Finland

Justin Roberts

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Watercolor and marker sketch of a street in Uppsala.

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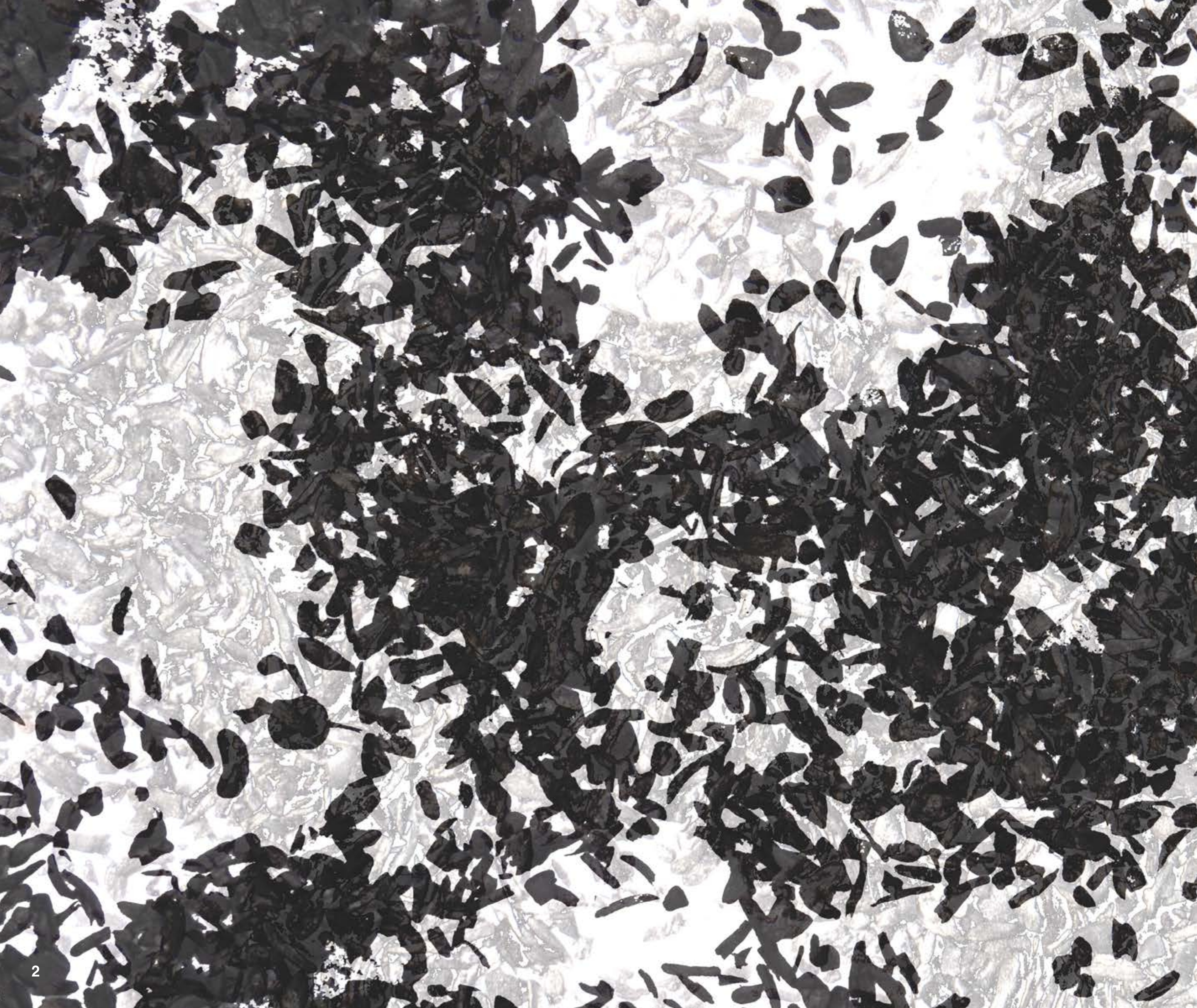
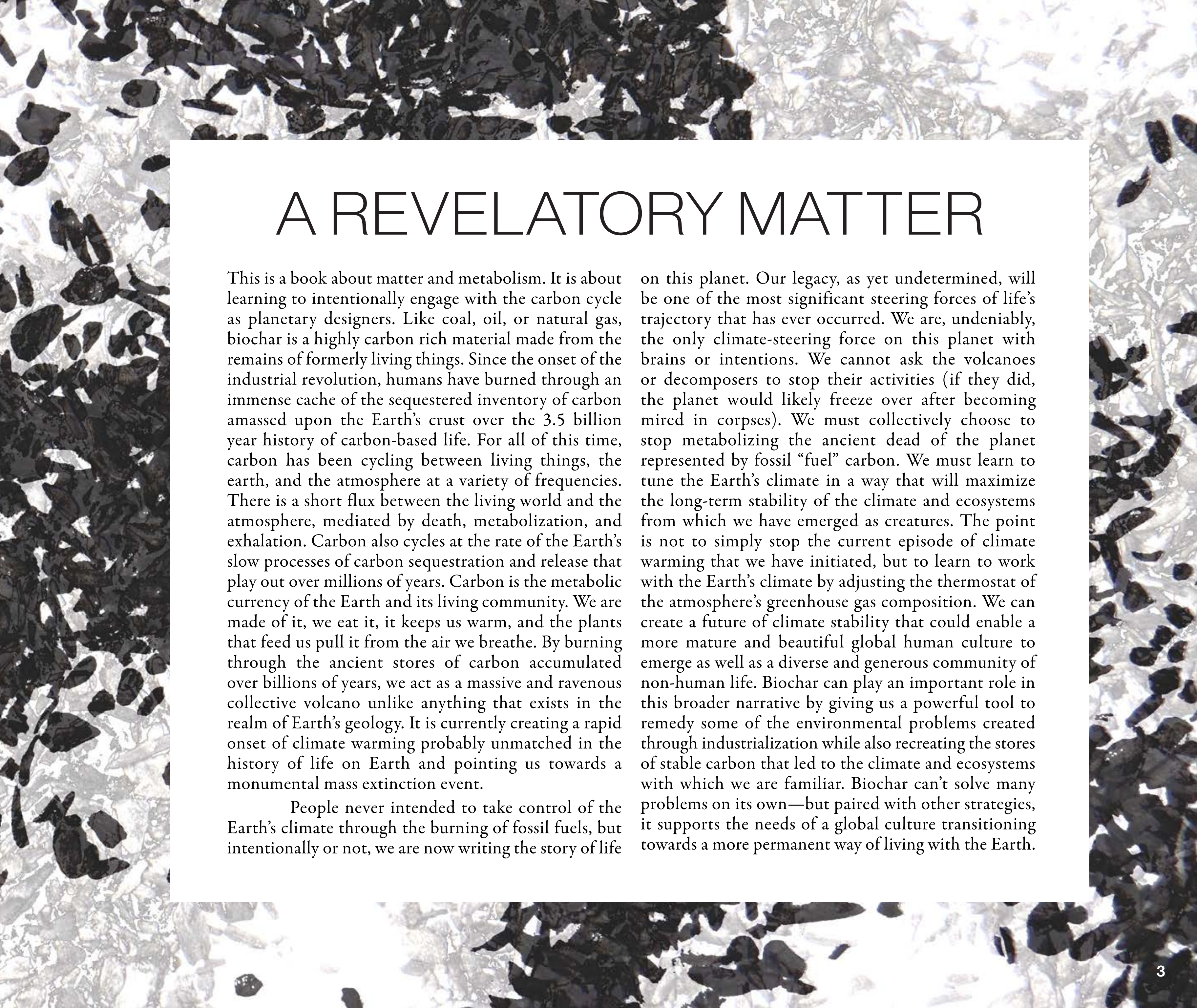




A REVELATORY MATTER

This is a book about matter and metabolism. It is about learning to intentionally engage with the carbon cycle as planetary designers. Like coal, oil, or natural gas, biochar is a highly carbon rich material made from the remains of formerly living things. Since the onset of the industrial revolution, humans have burned through an immense cache of the sequestered inventory of carbon amassed upon the Earth's crust over the 3.5 billion year history of carbon-based life. For all of this time, carbon has been cycling between living things, the earth, and the atmosphere at a variety of frequencies. There is a short flux between the living world and the atmosphere, mediated by death, metabolization, and exhalation. Carbon also cycles at the rate of the Earth's slow processes of carbon sequestration and release that play out over millions of years. Carbon is the metabolic currency of the Earth and its living community. We are made of it, we eat it, it keeps us warm, and the plants that feed us pull it from the air we breathe. By burning through the ancient stores of carbon accumulated over billions of years, we act as a massive and ravenous collective volcano unlike anything that exists in the realm of Earth's geology. It is currently creating a rapid onset of climate warming probably unmatched in the history of life on Earth and pointing us towards a monumental mass extinction event.

People never intended to take control of the Earth's climate through the burning of fossil fuels, but intentionally or not, we are now writing the story of life on this planet. Our legacy, as yet undetermined, will be one of the most significant steering forces of life's trajectory that has ever occurred. We are, undeniably, the only climate-steering force on this planet with brains or intentions. We cannot ask the volcanoes or decomposers to stop their activities (if they did, the planet would likely freeze over after becoming mired in corpses). We must collectively choose to stop metabolizing the ancient dead of the planet represented by fossil "fuel" carbon. We must learn to tune the Earth's climate in a way that will maximize the long-term stability of the climate and ecosystems from which we have emerged as creatures. The point is not to simply stop the current episode of climate warming that we have initiated, but to learn to work with the Earth's climate by adjusting the thermostat of the atmosphere's greenhouse gas composition. We can create a future of climate stability that could enable a more mature and beautiful global human culture to emerge as well as a diverse and generous community of non-human life. Biochar can play an important role in this broader narrative by giving us a powerful tool to remedy some of the environmental problems created through industrialization while also recreating the stores of stable carbon that led to the climate and ecosystems with which we are familiar. Biochar can't solve many problems on its own—but paired with other strategies, it supports the needs of a global culture transitioning towards a more permanent way of living with the Earth.

WHAT IS BIOCHAR AND WHY DOES IT MATTER?

The matter we call biochar is a carbon-rich material that can benefit the health of the soil, through its high level of porosity, surface area, and capacity to bond to chemical compounds. These features enable it to help regenerate degraded soil while also permanently sequestering carbon. It is the product of one of the Earth's most powerfully transformative metabolisms: fire. Natural fire such as forest fires can produce biochar when some of the biomass gets heated to above 250° C but is subject to minimal oxygen and thus fails to combust. This process, called pyrolysis, causes some of the formerly solid material to become gaseous and escape, while the remaining matter is what we call biochar. Biochar, then, is the carbon-rich skeleton of organic matter that has been pyrolized. While it is very similar to ordinary charcoal, the process of intentionally creating biochar through controlled pyrolysis is tuned to yield a material that is fit for a wide range of functions in the built environment, particularly in soils. The pyrolysis process can be optimized through various technologies and techniques to efficiently create biochar while also utilizing the other products of pyrolysis such as combustible gases and heat, yielding a very low-waste process.

The meaning of the term "biochar", like the material itself, is highly adept at bonding to the things around it. Efforts to define biochar continue to grapple with the diversity of organic materials, processes, purposes, and values associated with biochar production. The European Biochar Certificate (EBC), a leading voice in this effort, defines biochar as "a porous, carbonaceous material that is produced by pyrolysis of plant biomasses and is applied in such a way that the contained carbon remains stored as a long-term C sink or replaces fossil carbon in industrial manufacturing. It is not made to be burnt for energy generation".[1] This definition may evolve as animal manure and human biosolids are evaluated as potential acceptable feedstocks. This definition also fundamentally establishes the purpose of biochar as a material for embodying and sequestering carbon in the effort to cool and stabilize the Earth's climate.

The transformative power of biochar in terms of its impact on life at the individual and collective scale is rooted in its relationship with diverse metabolisms. Pyrolysis transforms what begins as the easily metabolizable carbon compounds of organic matter into a durable carbon frame that serves as a collection hub for water, air, and the nutrients or chemical compounds that empower the metabolism of microorganisms, fungi and plants.[2] It can resemble a coral reef in the soil for the rich biodiversity it can foster. Its structure and chemistry also captures carbon compounds in the soil slowing their rate of metabolization while also promoting microbial species that reduce other soil greenhouse gas emissions,[3] which are all products of bacterial metabolism. The Earth's climate is in large part controlled by the short term carbon cycle, which might be defined as the collective inhalation, subsequent metabolic transformation, and exhalation by the biosphere, of the planet's insulating atmosphere. Biochar production and use can interact with this process by enhancing the inhalation of carbon through plant growth and decreasing the exhalation of carbon dioxide and other greenhouse gases. At the same time, it offers us myriad functions for regenerating the health of the living world.

A pillbug explores biochar in Stadsparken. Lund, Sweden.

DEEP ORIGINS AND FUTURE IMPLICATIONS

Fire and the charred matter it produces has a deep history of influence on the nature of the Earth's climate and living communities. It is estimated that nearly 14% of the soil carbon on earth is found in char material, indicating that it plays an important role in the carbon cycle.[1] It isn't known what proportion of this is due to the intentional addition of char to the soil, but a growing body of research is revealing widespread deposits of so called "Anthropogenic Dark Earths" or ADEs across the world from the tropics to polar latitudes. They are all connected to human settlements and while their purpose is difficult to prove, they imply the widespread traditional use of char as a means of enhancing plant growth to support food production in parallel with the role of fire for other purposes.[2] The tropical region of Africa for example hosts char-enriched soils at the edges of current and ancient village sites, and neolithic sites across Europe show ancient settlements located next to areas of ADEs.[2] Research from 2015 based on a case in northern Germany suggests that evolution of an area of Dark Earth soil followed a similar formation pathway as Amazonian ADE, or "terra preta" as it is commonly known and has been called the "Nordic analogue" to terra preta. It is suggested to have potentially been an essential component of Viking-Slavic culture in the 9th - 10th century AD.[4]

Comparison of terra preta soil (left) and typical Amazonian soil.[3]

The most well-known example of Anthropogenic Dark Earth soil comes from the extensive terra preta soils of the Amazon region, where the soils are still sought out today as a place to practice permanent agriculture, which is otherwise impossible in the thin soils of the rainforest. Terra preta contains high levels of nutrients and organic matter, and sustains its fertility despite the leaching power of the tropical rains and vigorous plant growth of the rainforest. The secret, of course, is biochar.[5] It is thought that these soils helped sustain a highly populous network of cultures representing potentially 8-10 million inhabitants stretching back potentially thousands of years before epidemic disease unleashed by Europeans decimated the populations.[7] Up to about 10 percent of the Amazon region is estimated to contain these rich terra preta soils.[5] The implications for creating new Dark Earth soils for sustainable agriculture in tropical areas is profound given the pressure that slash and burn agriculture puts on tropical ecosystems. But the implications extend far beyond tropical agriculture. Many soils across the world are in a state of degradation from practices that enhance erosion, cause compaction, and cut off the natural symbioses between plants and living soil. Biochar is no silver bullet for these problems; but the model of terra preta, and the tool of biochar, gives us an intriguing goal to move towards. Such a proposition was essentially the vision of the late soil scientist Wim Sombroek of the Netherlands who reignited interest in terra preta soils through his doctoral research in the 1960s. He later came to advocate for the recreation of similar soils or 'terra preta nova' to enable intensive cultivation and carbon sequestration.[6] The potential to cultivate such soils represents a much needed tool for a world facing a raft of issues from a rising population and warming climate to a hastening extinction crisis. The permanent fertility and carbon sequestration of biochar soils points toward a regenerative paradigm for the way we grow plants, which is to say ourselves.

BIOCHAR IN URBAN INDUSTRIAL ECOSYSTEMS

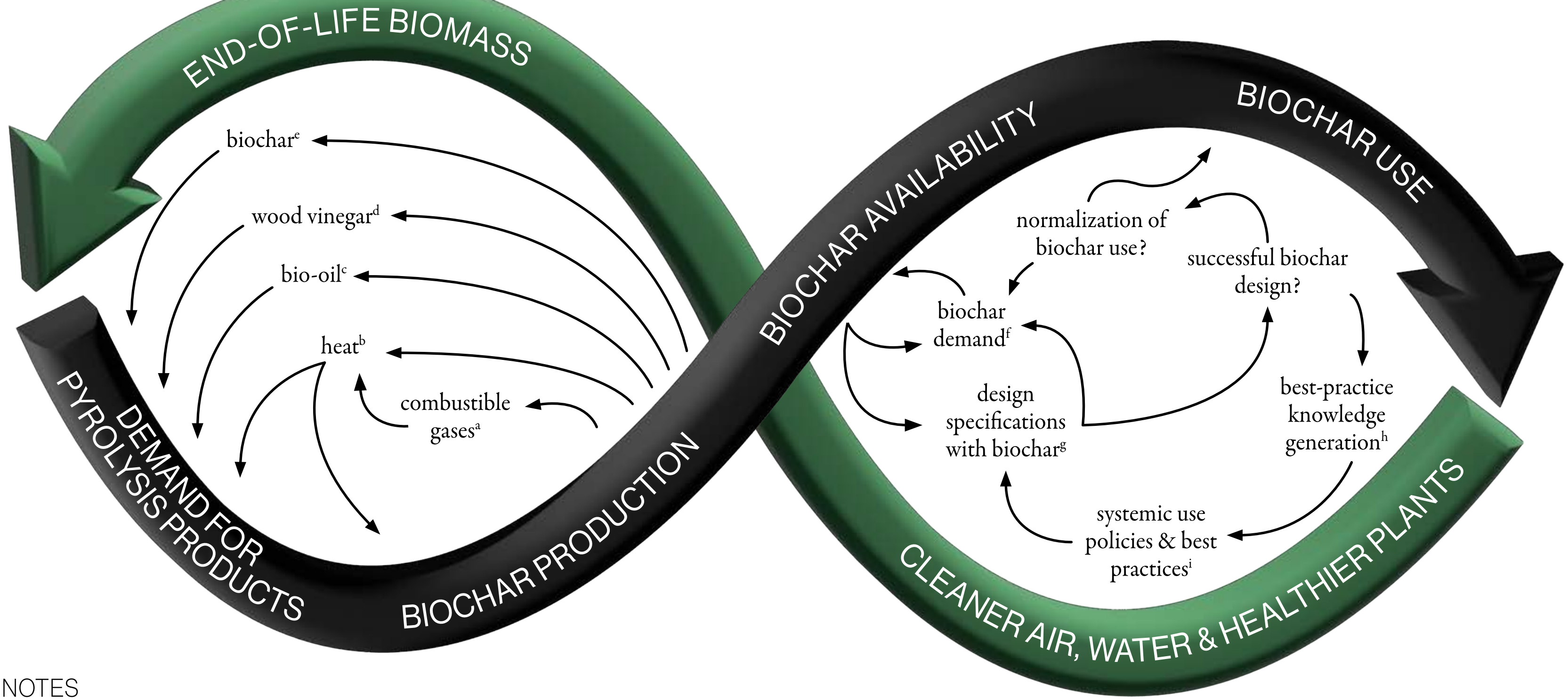
Organic Waste Becomes a Resource for Circular Systems

Biochar can be produced and used at a wide range of scales. Moderately scaled systems of production with regional networks of distribution and use represent a likely optimal synthesis of systemic benefits while avoiding the potential drawbacks of very small or large systems. Biochar can be made most simply through managing the process of fire to favor the generation of char over ash. While small scale production could be ideal for small farmers and gardeners, it probably cannot support creation of a biochar economy large enough to sequester substantial CO2. And while very large scale production can be economical, it may reduce carbon sequestration value through transportation emissions and seems less likely to spur circular economies that offer other benefits. Moderate to large scale production operations may utilize kilns that produce biochar in separate batches, which offers flexibility in terms of feedstock, production schedule and scale. Batch kilns, however, lack the efficiency of continuous operations where the heat required for pyrolysis is continuously maintained by the pyrolyzing materials themselves with no additional inputs required. At its most sophisticated, biochar can be produced using multi-million dollar systems that operate continuously, with great efficiency, and can create biochars with specific material properties based on the combination of feedstock and production conditions. The best technological strategy for production will depend on how it nests into its supporting systems of biomass production and biochar use, and what goals define the larger ecological, social, and economic environment.

IMAGES: From top left clockwise: Telge Återvinning AB raw biomass and biochar, sedum and biochar roof at the Scandinavian Green Roof Institute, pyrolysis at Carbofex.

How Do Designers and Planners Influence Biochar Systems?

As a product, biochar has the potential to be used in a wide variety of applications across a diverse set of landscapes from urban medians and green roofs to suburban yards and restoration sites. The graphic below explores the relationship between the products of biochar production, consumer demand, and the practices and policies that affect its availability and use.



NOTES

(a) Combustible gases consist mostly of carbon monoxide and hydrogen but also include carbon dioxide, methane and others. They can be combusted to power the pyrolysis process or to generate electricity.[1]v

(b) Excess heat can be used for various purposes such as heating water for district heating systems or producing electricity for sale back to the grid.

(c) Bio-oil can be used for various fuel or chemical applications or even sequestered for carbon credits.[2]

(d) Wood vinegar is a liquid that can be extracted during pyrolysis. It is essentially "liquid smoke" and has a wide array of applications for horticulture and agriculture.[2]

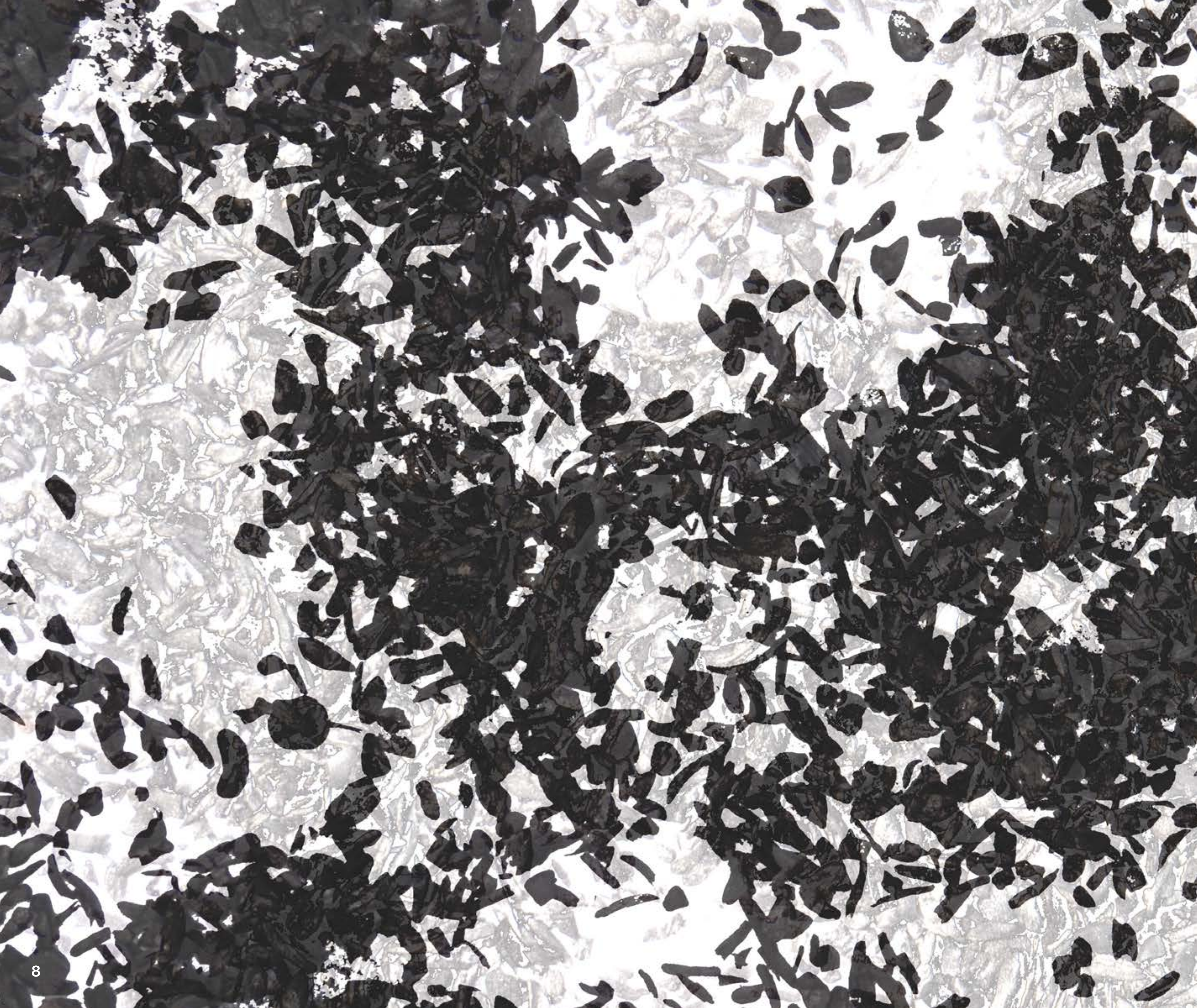
(e) For biochar, the production quantity and/or quality, and even seasonality depends on whether the pyrolysis process is geared towards biochar or other products. Biochar is often only economical when some of these other products are also considered and marketed.

(f) In the long run, biochar demand, especially when dependable, will likely create the market conditions for increased biochar supply, which could ultimately lower cost and increase demand and adoption further.

(g) Design specifications represent an opportunity for designers to help steer an increase in demand and production for biochar as well as material performance standards, encouraging a match between desired biochar function and the production parameters that define biochar properties and function used by producers.

(h) Given the emerging nature of biochar use in urban areas, projects should aim to engage in experimentation and communication of results when possible to help grow the practice more quickly.

(i) Professionals and leaders involved in the norms, policies, and practices that influence the built environment can encourage the biochar industry by enacting patterns of systemic use.



Biochar and moss. Varvsparken, Sweden.

Biochar Benefits

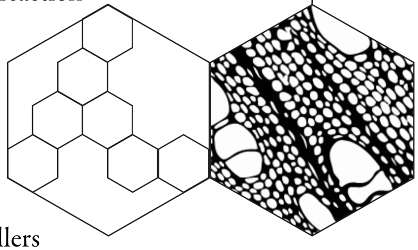
Using biochar in urban landscapes invites us to develop a more sophisticated understanding of this seemingly familiar material. Biochars exhibit a variety of functional qualities for a wide range of applications, which depend on a dizzying abundance of variables. The goal of this book, however, is to enable urban gardeners, farmers, designers, planners, and decision-makers to understand biochar enough that they can use it within the realm of the benefits it offers. We don't have time to perfectly optimize all of the variables inherent in the systems of biochar production and use if we want to take advantage of it as a shovel-ready tool to slow the pace of climate warming. Biochar is not a technology awaiting well-funded research and development efforts to become effective, scalable, and transformative; it's already there. In this guide, I attempt to synthesize enough of the existing research on biochar to give designers the necessary tools to work creatively, effectively, and experimentally with biochar. I conceive of its benefits via consideration of how it interacts with the soil and its inhabitants, the water that flows through it, as well as its potential to help us manage our atmosphere. Biochar represents life transformed into earth via pyrolysis. From that perspective, it is a form of elegant biomimicry. Biochar, typically made from plants, mimics the function of a plant's cellular structure, which is holding and transporting air and water while providing structural support, but abstracts it from the plant, and applies the same function to the soil. The pyrolysis process then contributes additional functionality at the chemical level, and transforms the molecular arrangement of the material to benefit carbon stability. Its effects on living communities from the level of our cities to the entire planet could be profound. The following section attempts to illustrate what these benefits are and how they work.

LIFE: AN AMENDMENT FOR RESILIENT SOIL COMMUNITIES

Raw Biochar

A durable carbon sponge for nutrients, toxins, air, and water

Raw biochar alters the behavior of air, water, and life in the soil depending on its size, shape, internal structure and chemistry. These properties originate from its original cellular structure and chemistry as a living material, the pyrolysis process, and any pre/post pyrolysis treatments. Resilience of soil and plant communities can be supported by designing with these properties. Biochar properties will, however, change over time in reaction to the soil environment. [1, 2]



Physical Structure

Plentiful pores and surface area can provide habitat and refuge for microbes and fungi. Biochar structure may protect these soil dwellers from drying out or being eaten by soil invertebrates.[3] Effects on the behavior of air, water, nutrients, and toxins in the soil also influence the diversity and richness of the living soil community, which can in turn transform the soil environment to be increasingly beneficial for life.[3] The physical durability of biochar is related to the feedstock as well as pyrolysis conditions. Its long life in the soil means that it contributes an essentially permanent benefit to soil fertility. [4]

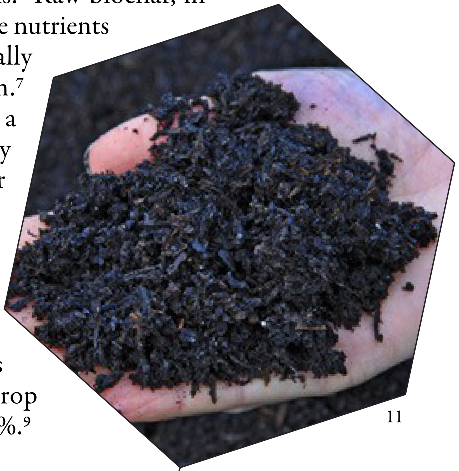
Chemical Structure

The chemistry of fresh biochar can influence the soil environment by altering its pH, interacting with biological signaling compounds[3], and shifting the soil's capacity as a nutrient reservoir by adjusting its cation exchange capacity. Fresh biochars typically have alkaline to neutral pH in relation to their ash content and a correlated liming potential.[5] They also have significant cation exchange capacity, especially biochars made at low-medium pyrolysis temperatures. This property increases over time with oxidation (though high temperature biochars can have a temporary anion exchange capacity.)[3] Additionally biochar can contain minerals and nutrients that are available to plants in varying proportions. These factors differ based on the combination of feedstock and pyrolysis conditions.[5]

Oxidized and 'Charged' Biochar

A permanent soil amendment ready to support plant growth

Biochar is typically most beneficial after it has been oxidized and "charged" with nutrients or microorganisms.[6] Raw biochar, in comparison, can temporarily make nutrients less available to plants by chemically or physically bonding to them.[7] This may have some utility as a means of favoring plants that rely on fungal symbionts to deliver nutrition.[8] Biochar that is loaded with nutrients, however, is ready to support plant growth. Co-composted biochar likely offers maximum benefits for both plant growth and toxics remediation. It has improved crop yields in some cases by up to 300%.[9]



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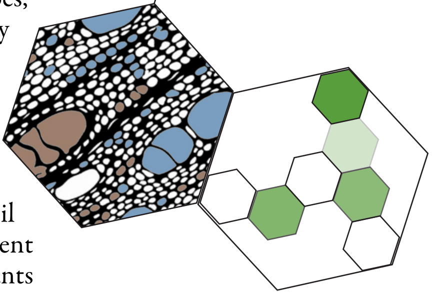


Physical Structure

As biochar surfaces gather microbes, fungi, and mineral nutrients, they become a source of slow-release nutrients for plants and the soil community. A living film of organisms and compounds comes to coat the surfaces of char over time, encouraging soil aggregate formation and nutrient retention.[10] Biological inhabitants consume any soluble pyrogenic materials that contributed initial water repellency to the char, and increase hydrophilicity by their presence. Pores may also become filled with adsorbed minerals, water, or other materials. This coating can serve to prevent further degradation of biochar in soil from oxidation and partially explain its longevity. Development of this organic coating can be expedited and optimized through co-composting.[10]

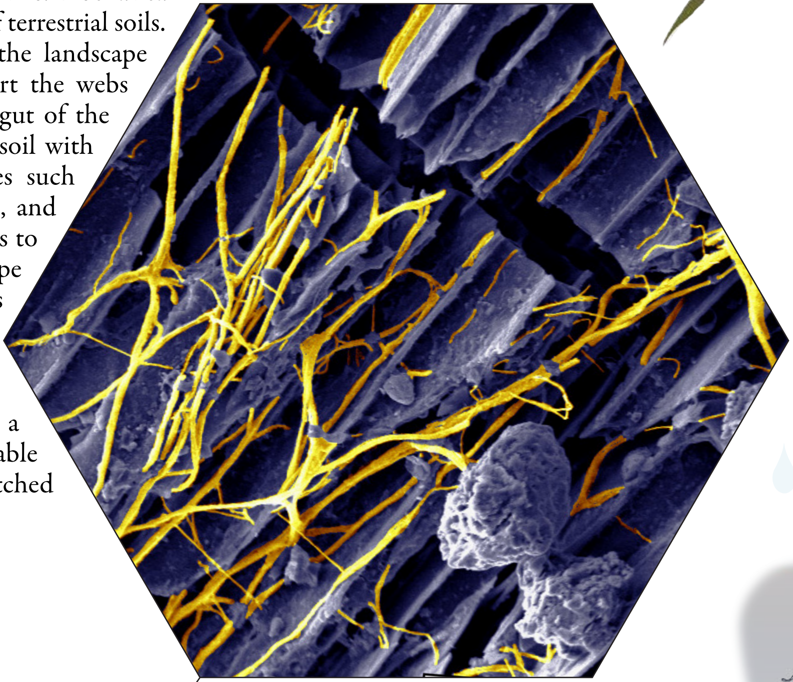
Chemical Structure

Biochar pH and liming potential may be altered during the aging process as alkaline ash in the biochar is washed away or reacts with added materials. Ionic exchange capacity will shift towards preference for cations due to oxidation.[5] The composition of the char's organic coating will greatly influence biochar chemistry.

Aged and Inhabited Biochar

A coral reef in the soil

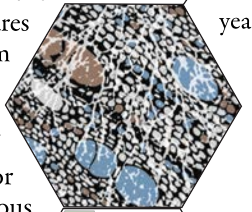
Nature is full of precedents for symbiosis between organisms of complementary structures and metabolisms, such as the coral reef, where one type of organism builds a structure that hosts a diversity of other life forms. Biochar can help us become reef builders of terrestrial soils. Biochar's greatest benefit at the landscape scale is its capacity to support the webs of soil life that represent the gut of the plant community. Amending soil with biochar, paired with practices such as composting, decompaction, and organic maintenance, invites us to envision a regenerated landscape in both urban and rural settings where the ecosystems around us can truly thrive. By helping to stabilize the climate at the same time, biochar represents a strategy for manifesting a stable future into the deep time stretched ahead of us.

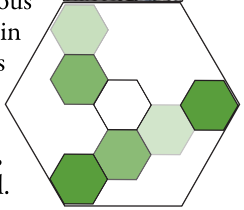


Charcoal from a forest fire magnified 800x; likely 110 years old and densely inhabited by mycorrhizal fungi.[12]

Physical Structure

Depending on the nature of the original biochar and the pressures placed on it in the soil from compaction and digestion via creatures like earthworms, the physical structure of biochar may retain its form for centuries, acting as a continuous source of mediation for fluxes in oxygen, moisture and nutrients and as a refuge for fungal mycelium and microbial life. As biochar particles degrade, they move deeper into the soil.

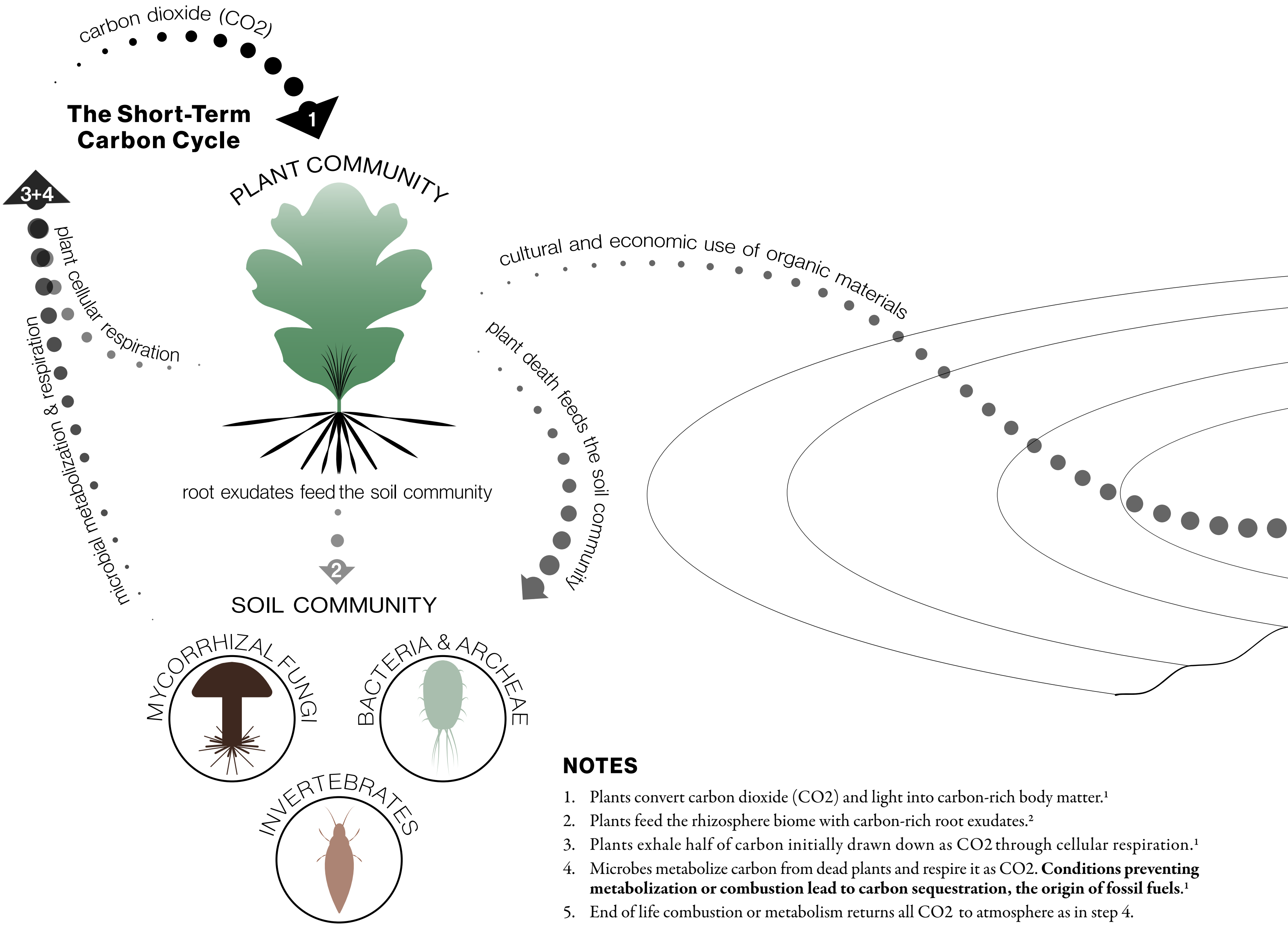




Chemical Structure

As biochar physically disintegrates, exposed surfaces oxidize and create new sites for cation exchange, and microbial colonization, meaning it will grow over time in its function as a sponge for nutrients. Eventually its tough chemical structure may be broken down by fungi, but likely not for centuries to millenia.

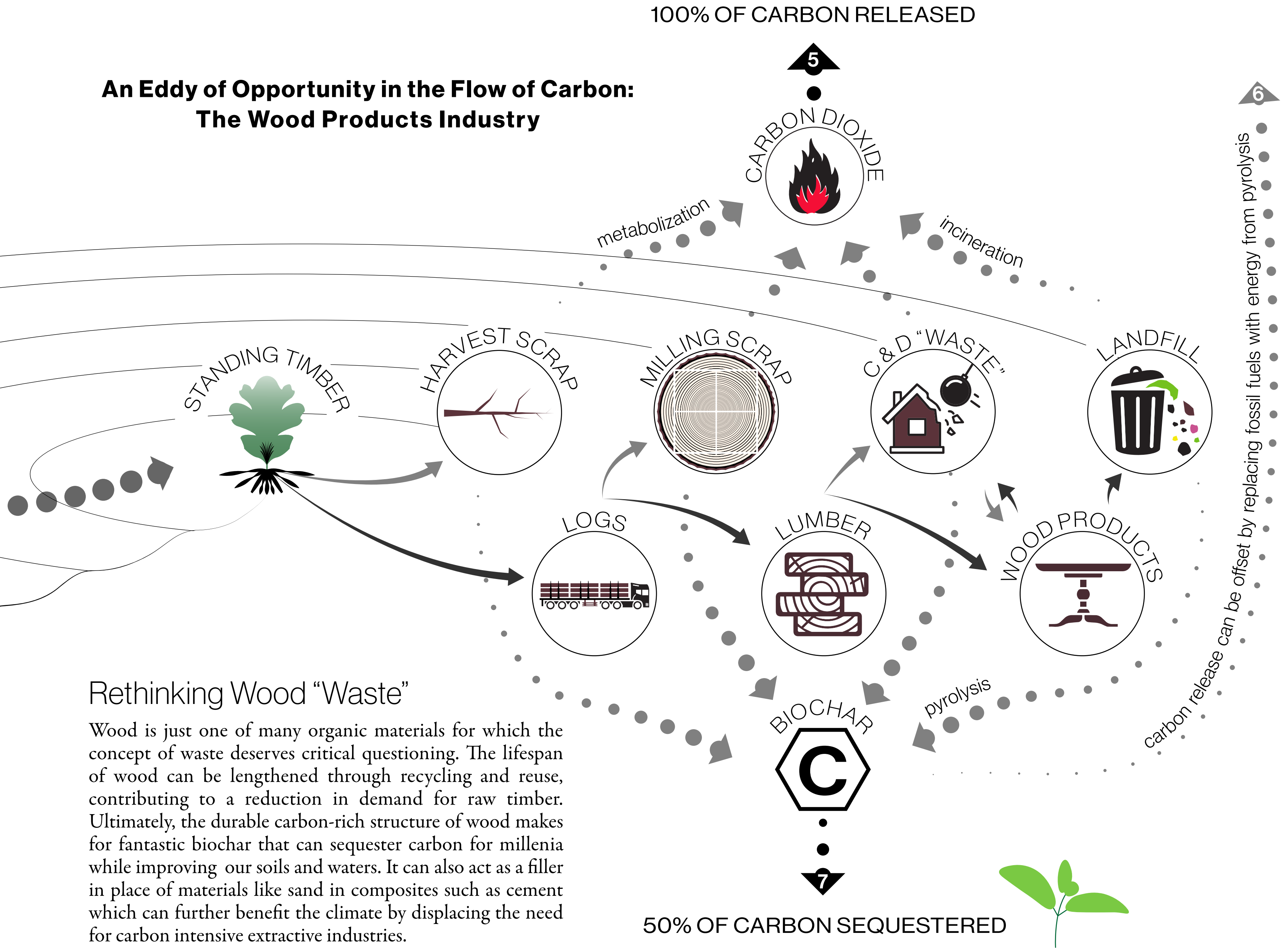
CARBON: CYCLES OF LIFE, DEATH, CULTURE AND CLIMATE



NOTES

1. Plants convert carbon dioxide (CO2) and light into carbon-rich body matter.[1]
2. Plants feed the rhizosphere biome with carbon-rich root exudates.[2]
3. Plants exhale half of carbon initially drawn down as CO2 through cellular respiration.[1]
4. Microbes metabolize carbon from dead plants and respire it as CO2. **Conditions preventing metabolization or combustion lead to carbon sequestration, the origin of fossil fuels.**[1]
5. End of life combustion or metabolism returns all CO2 to atmosphere as in step 4.
6. End of life pyrolysis returns 50% of plant carbon to atmosphere.[3]
7. End of life pyrolysis sequesters 50% of plant carbon as an essentially permanent carbon sink. [3]

An Eddy of Opportunity in the Flow of Carbon: The Wood Products Industry



Rethinking Wood "Waste"

Wood is just one of many organic materials for which the concept of waste deserves critical questioning. The lifespan of wood can be lengthened through recycling and reuse, contributing to a reduction in demand for raw timber. Ultimately, the durable carbon-rich structure of wood makes for fantastic biochar that can sequester carbon for millenia while improving our soils and waters. It can also act as a filler in place of materials like sand in composites such as cement which can further benefit the climate by displacing the need for carbon intensive extractive industries.

WATER: A FILTER AND A RESERVOIR

Living Roofs

Biochar represents a unique tool for designing living roof systems; it is lightweight and can significantly increase water retention in plant available form.[1] It also effectively retains nutrients from fertilizers or composts applied to roofs that might otherwise leach to waterways[2] and contribute to eutrophication.

Stormwater Filtration Systems

In stormwater filtration systems, biochar can improve performance compared to typical soil media, such as the more costly activated carbon, for filtration of trace organic contaminants, and nutrients such as phosphorous and nitrogen.[3] Biochar in removable filters could be subsequently utilized in other applications such as for soil amendment or use as a filler in composite materials. The stable carbon structure of biochar provides a substrate for biofiltration systems that wont lose volume over time compared to matter such as compost.

Permeable Pavement

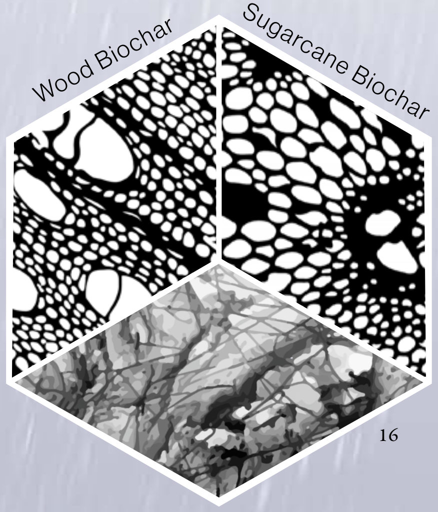
Pavement materials can incorporate biochar as a means of adding strength and durability while sequestering carbon.[10] Permeable pavements that incorporate biochar also serve as filter mechanisms for the water draining through them.[4]

Biochar and Water

The pore structure of biochar can vary tremendously based on the cellular structure of the feedstock material and the temperature and duration of pyrolysis.[6] Cellular structure will largely determine the nature of the macropores, which exist in the micron size range. These pores are just thousandths of a millimeter in diameter, but have great relevance for providing plant available water and creating habitat for the soil community which works to further regulate water movement in the soil.[11] Aerobic bacteria, which benefit from permeable pore spaces, create glue like secretions that nurture aggregates in the soil which further aid in permeability.[12] Anaerobic bacteria, which are important for denitrification of water, may benefit from isolated oxygen-deprived conditions within the internal pores of biochar.[6] Fungal hyphae are perfectly sized to utilize biochar macropores[13] and the extended mycorrhizal networks they form help to create an interconnected soil structure that benefits plant health as well as water infiltration and purification[12]. Nanopores, which are a thousand times smaller than macropores, are created through high temperatures or long durations of pyrolysis.[14] These pores, which can represent the majority of the surface area in biochar made at high temperature, act in combination with surface chemistry to enable biochar to adsorb a wide array of nutrients and pollutants, particularly organic substances.[14] This contrasts with lower temperature biochars that tend to have higher cation exchange capacity and excel at capturing inorganic nutrients and pollutants such as heavy metals.[7] Access to pores of various sizes by water is influenced by the hydrophobicity of biochar, which is partly and temporarily dependent on soluble carbon compounds or tars that can remain attached to biochars created at lower temperatures.[7] Hydrophobic tars can be removed or rearranged through steam activation,[7] biological metabolism,[8] or simply flooding with water.[9] It will happen over time in the soil as well. Hydrophobicity can also exist due to organized molecular structures created at higher pyrolysis temperatures though these degrade with biochar aging.[6]

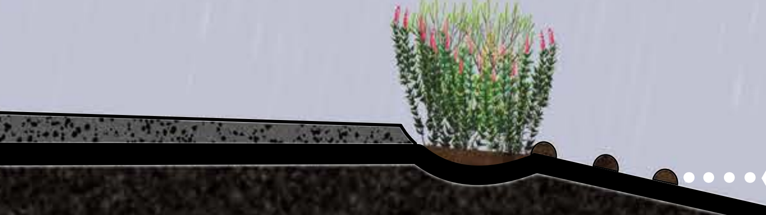
Biochar Pore Structures

If this box were a nanopore, the two page spread would represent a macropore, and a 5000 square foot house could represent the biochar particle!



Modular Filtration

Biochar can be used in cheap, portable, modular filtration systems such as flexible tubular filter socks to reduce pollution where needed.[5]



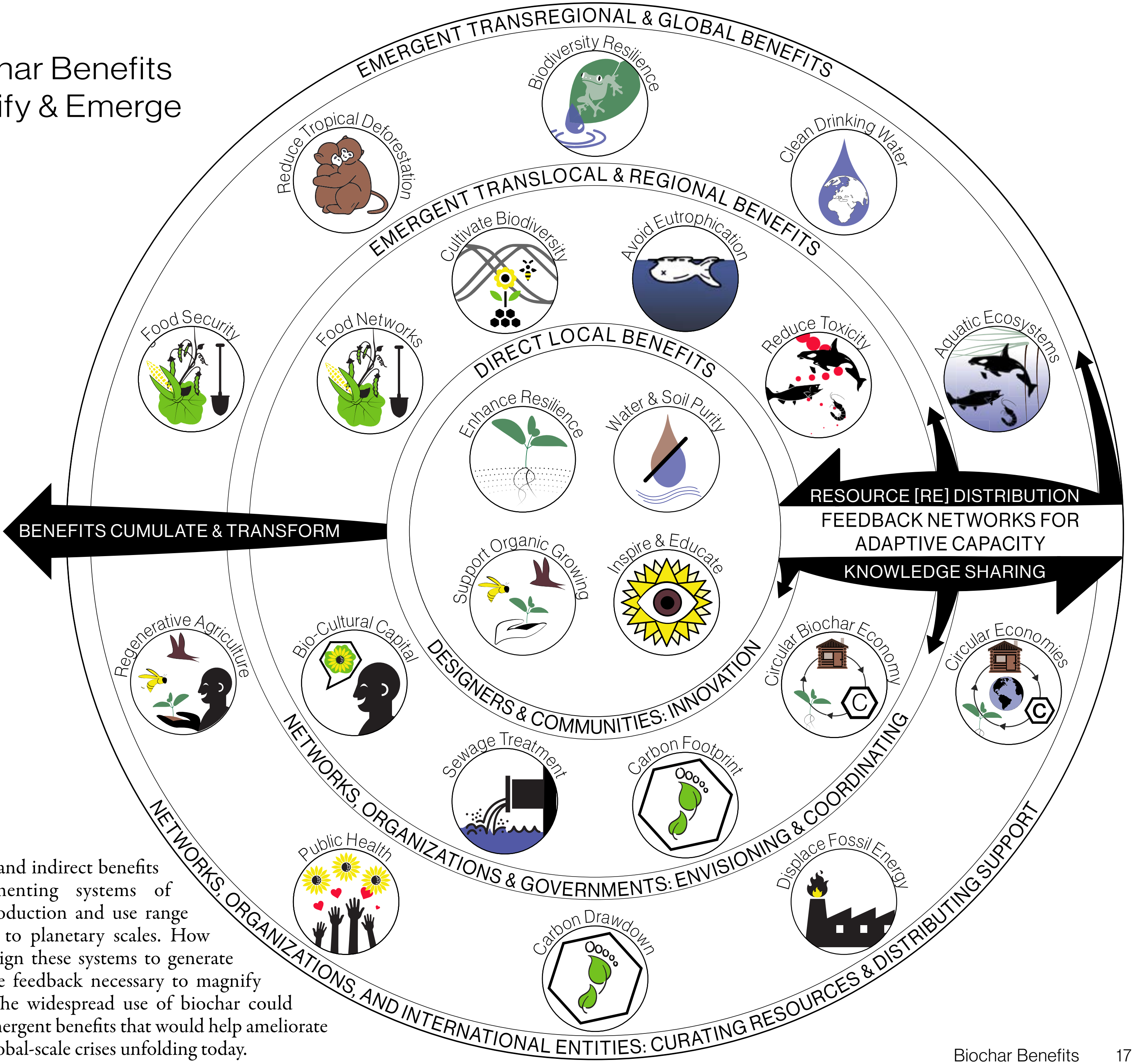
CATALYZING REGENERATIVE SYSTEMS WITH BIOCHAR

Design for Adaptive Feedback Networks and Upscaling Benefits

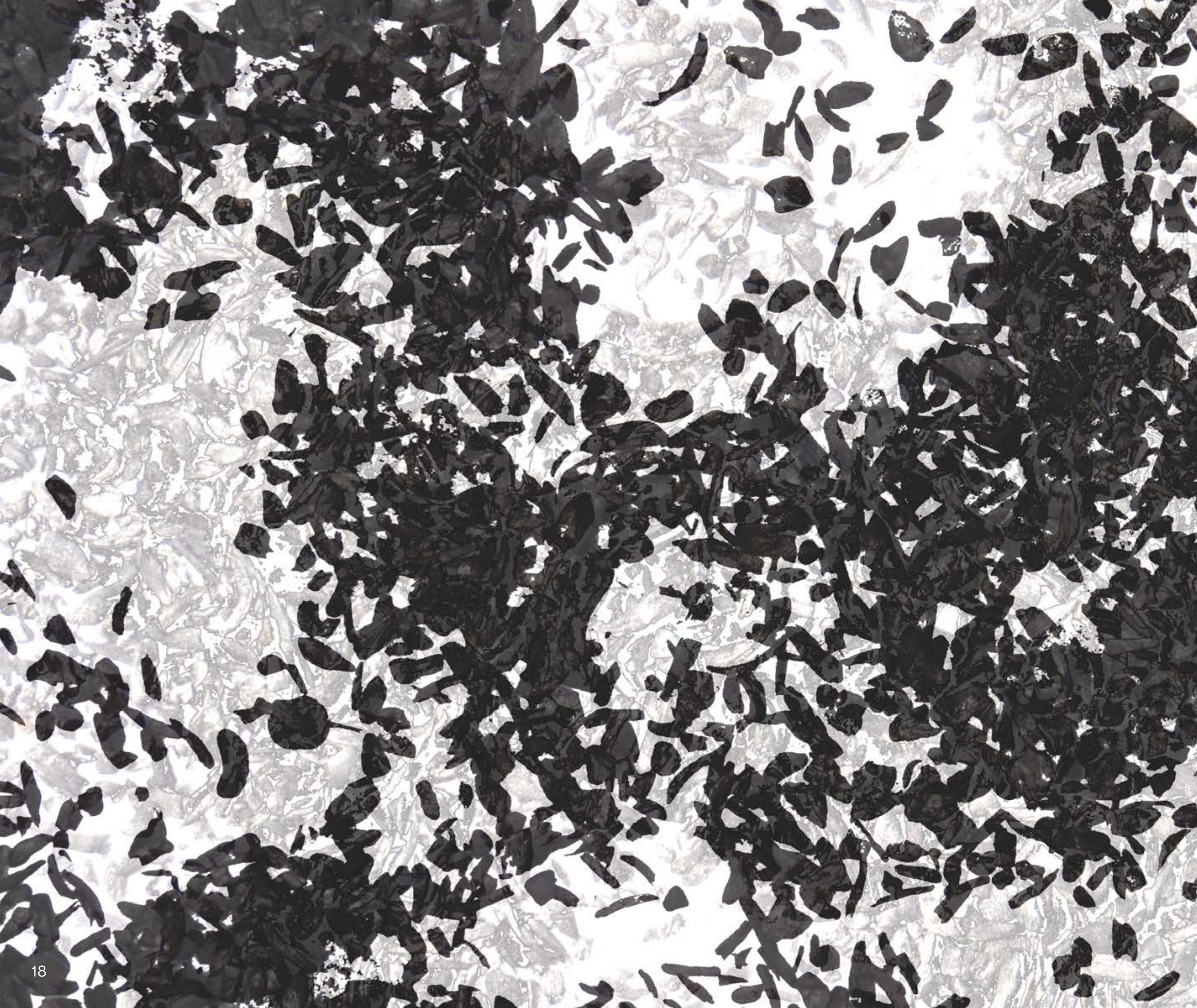
Biochar is uniquely transformative as both a material of diverse functionality across a variety of landscapes and as a generator of processes that point towards a more mature circular cycling of energy in economic ecosystems. It invites us to explore the catalytic potential of one of the earth's fundamental transformative processes: fire—here reconfigured as pyrolysis—to act as a technological metabolism capable of shaping our soils and atmosphere. Biochar is a material that carries the legacy of fire's capacity to create space. The void space created through the metabolism of pyrolysis creates room for life, air and water to take refuge in the hardened carbon frame of the char, and acts to structure the soil and reduce the flow of carbon dioxide back to the atmosphere. The diverse direct benefits of biochar production and use range from scales as wide as the global in its capacity to sequester carbon, to the hyper-local as a regenerative soil amendment, among other uses. The benefits of biochar truly blossom when it is used as a transformative element in collaboration with other materials, practices, and movements in the creation of regenerative systems. Designers involved in systems of biochar production and use have an opportunity to magnify the impact of biochar's immediate purpose by designing for its connection to broader scales and indirect benefits. Feedback infrastructures can connect biochar benefits and practices to entities at larger scales who can redistribute resources and knowledge. This potential magnification of biochar use to larger scales could encourage the manifestation of emergent global benefits. In sum, biochar offers a practical tool for managing unwanted compounds in the environment, suggests a path to regenerative low-maintenance soil and plant growing systems, and invites us to eliminate organic waste while stabilizing and re-tuning the Earth's climate. It suggests a path towards regeneration and resilience for communities from the scale of the bacteria in the garden to the humans on Earth.

Biodiverse rooftop "rock" garden. Constructed with cellular glass, sand, pumice, and biochar substrate with a range of unique plants adapted to difficult environments. Solar panel roof garden in background. Created by Peter Korn; hosted by the Scandinavian Green Roof Institute in Malmö, Sweden.

Biochar Benefits Amplify & Emerge



The direct and indirect benefits of implementing systems of biochar production and use range from local to planetary scales. How can we design these systems to generate the positive feedback necessary to magnify benefits? The widespread use of biochar could produce emergent benefits that would help ameliorate multiple global-scale crises unfolding today.



Bluegreengrey infrastructure. Vellinge, Sweden.

Examples from Sweden and Finland

Sweden is a leader in developing practices for the urban use of biochar. Its diverse functionality is being utilized in perennial and street tree plantings to encourage resilient and vigorous growth, in stormwater plantings to benefit filtration, water retention, and plant resilience and in green roofs to add lightweight substrate of high function for plant health and nutrient runoff prevention. Interest in biochar was initially fueled in Sweden largely by Björn Embrén who led the Stockholm Traffic Office and saw potential in biochar to improve tree health in Stockholm in combination with structural soils. Ultimately this championing led to development of the Stockholm Biochar Project which was funded by Bloomberg Philanthropies and enabled Stockholm to create a circular system of biochar production and use. There is now a growing array of biochar producers, designers, researchers and others working, in some cases collaboratively, to advance the potential holistic benefits of systems of biochar production and use. The Rest till Bäst project is one such network and represents a distinctly innovative and interdisciplinary collaboration. They are working to document, synthesize, and communicate examples and practices related to biochar use as well as to support overarching biochar systems. They describe their vision as "driving progress towards a climate-smart, sustainable and circular society by developing solutions to minimize the environmental and climate impact of society's organic residues while simultaneously creating sought-after beneficial products and carbon storage".[1] The following projects (excluding the last two) are part of their efforts, and the network of people involved were a crucial source of information and perspective for this guide. Both the projects themselves and the Rest till Bäst project represent powerful models to advance the state of biochar production and use around the world.

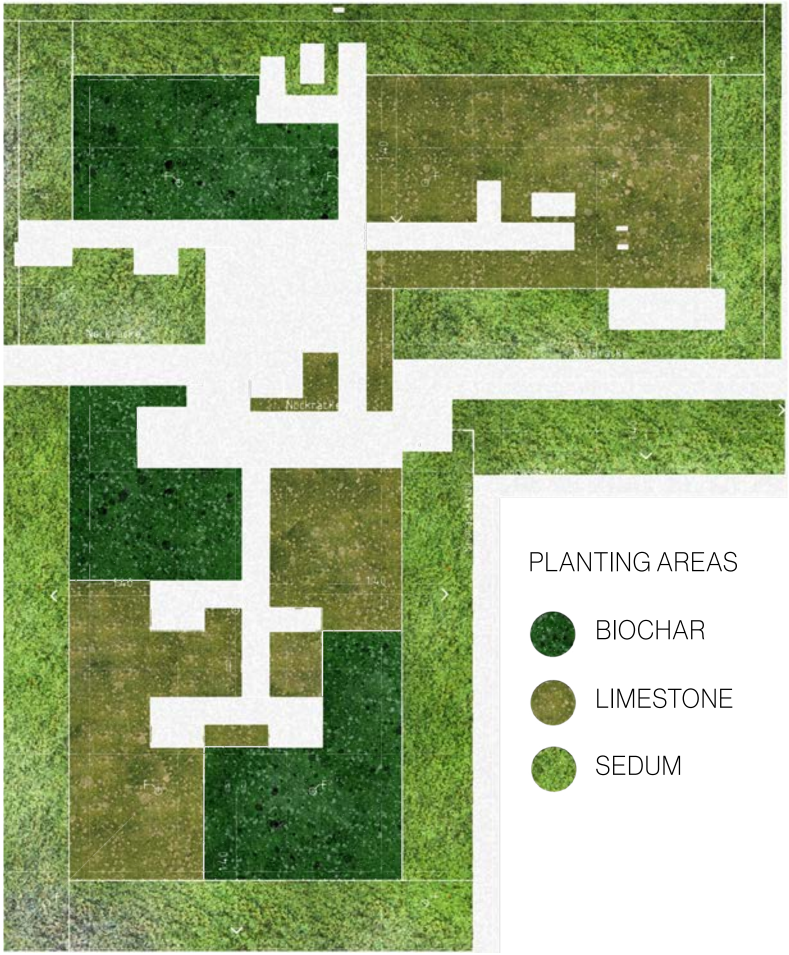
HARMONIZING SOIL AND PLANT COMMUNITIES

A Low Maintenance Limestone Steppe Roof with Biochar

Overview

This living roof, modeled after a limestone steppe biome, takes inspiration from the nearby decommissioned limestone quarry. Jonatan Malmberg, a specialist in urban vegetation systems and biochar, who designed the planting, centered the design on the creation of biotopes between 3 primary planting types. One planting type covers about half of the roof area and mostly follows the perimeter. It consists of about 10 cm of substrate and 20 species of plants, mostly from the Sedum family. The other two plantings evenly divide the remaining portion of the roof area between a meadow infused with biochar at 10% by volume and 15 cm substrate depth, and a meadow whose substrate varies between 8 and 15 cm depth within each square meter, and includes addition of limestone from the nearby quarry. The biochar serves to better enable meadow plants to thrive despite minimal soil volumes given its capacity to host beneficial soil life such as mycorrhizal fungi, as well as its ability to improve the soil's water holding capacity. Raw biochar may also alter the competitive environment in the soil to benefit slow-growing meadow species that grow in symbiosis with the mycorrhizal community over weeds that take advantage of free nutrients. Raw biochar can encourage a boom in microorganisms if it contains soluble carbon, which can cause a decrease in available nitrogen due to microbial use, and its high pH can help limit phosphorous availability. In addition, the roof is not fertilized or irrigated.[1]

Limestone steppe roof; 1st year growth.[1]



Limestone steppe planting layout.[2]

Second year of growth: a lush biochar amended area can be seen in the background with an intentionally harsh limestone steppe area in the foreground.[1]

Nearby limestone quarry.[3]

Buildings with limestone steppe roofs.[4]

Discussion

This project represents an interesting dialogue with the nearby quarry. The quarry's material bounty, limestone, is a source of both inspiration and substrate for the roof, but the use of high pH biochar with liming potential suggests a possible alternative to the use of such an extractive material. In addition to its liming potential, it is lightweight, carbon sequestering, water retentive and purifying, and potentially functional as a tool to manage weeds. To best take advantage of the potential functionality of biochar in a high demand application such as a living roof, feedstock and qualities such as density and pH should ideally be considered. Biochar used in this project was created from a feedstock of bioagropellets stemming from the waste materials of seed production. This local waste resource is positive from a sustainability point of view, though it isn't clear how the potential disintegration of pellets into many small particles of char influences the outcomes for the planting. The biochar has a high pH of 10.1 and density of 291kg/m^3, which is more dense than perlite, but significantly less than most pumice, which suggests that it does contain significant porosity. This analysis and speculation highlights the complexity of matching the functional properties of biochar to project goals given that there is commonly a lack of clear information on how a given biochar will perform in a given application. Test projects like this, however, can generate new precedent-based knowledge and help to advance best practices by giving designers a sense of what is possible despite limitations.

SUPPORTING URBAN BIODIVERSITY

A Forest Biotope Along Malmö's Urban Waterfront

Overview

The creation of an urban forest biotope in 2014 at Varvsparken or "The Shipyard Park" in Malmö's sustainability-focused Bo01 neighborhood was meant to introduce biodiversity and a wooded refuge to a park mostly composed of grassy areas and a popular playground. This was done as part of the larger BiodiverCity project which included multiple public and private partners in efforts to investigate ways to increase the city's biodiversity.[1] The design at Varvsparken is particularly notable in that it also serves as an experimental landscape for biochar function. Half of the park was planted with biochar mixed into the added soil at 10% by volume. Both sides of the park also received a top dressing of 10 cm of compost. The design included biochar because of its potential to enhance water and nutrient retention while increasing soil organic matter to mimic typical forest soils. The existing soil was gravelly and permeable fill material. It was hoped that this would lead to more successful tree establishment and growth rate in order to more quickly achieve a genuine forest environment.[2, 4]


Varvsparken in the spring.[2]


Varvsparken several years after planting. Can you guess which side of the curving path received biochar in the soil? (hint: the side with denser tree canopy; the left)[3]

Notes[2, 4]

A. A 10 cm top dressing of compost was applied across both sides of the park
B. Biochar was mixed into added topsoil at 10% by volume representing a 30-40 cm deep layer beneath the compost layer.
C. Vegetation was reported to be noticeably greener on the side of the park with biochar addition.
D. Increased growth for several species in biochar soils relative to the control group was statistically significant.
E. The Oaks (Quercus petraea) at the site weathered an extremely dry summer in 2018 much better in biochar soils than in the control as revealed by substantially less crown damage.

Varvsparken's experimental design showed enhanced plant growth and resilience for its biochar soil plantings (left side). This speculative section imagines the root networks extending deeper in the biochar soil to gather retained nutrients.

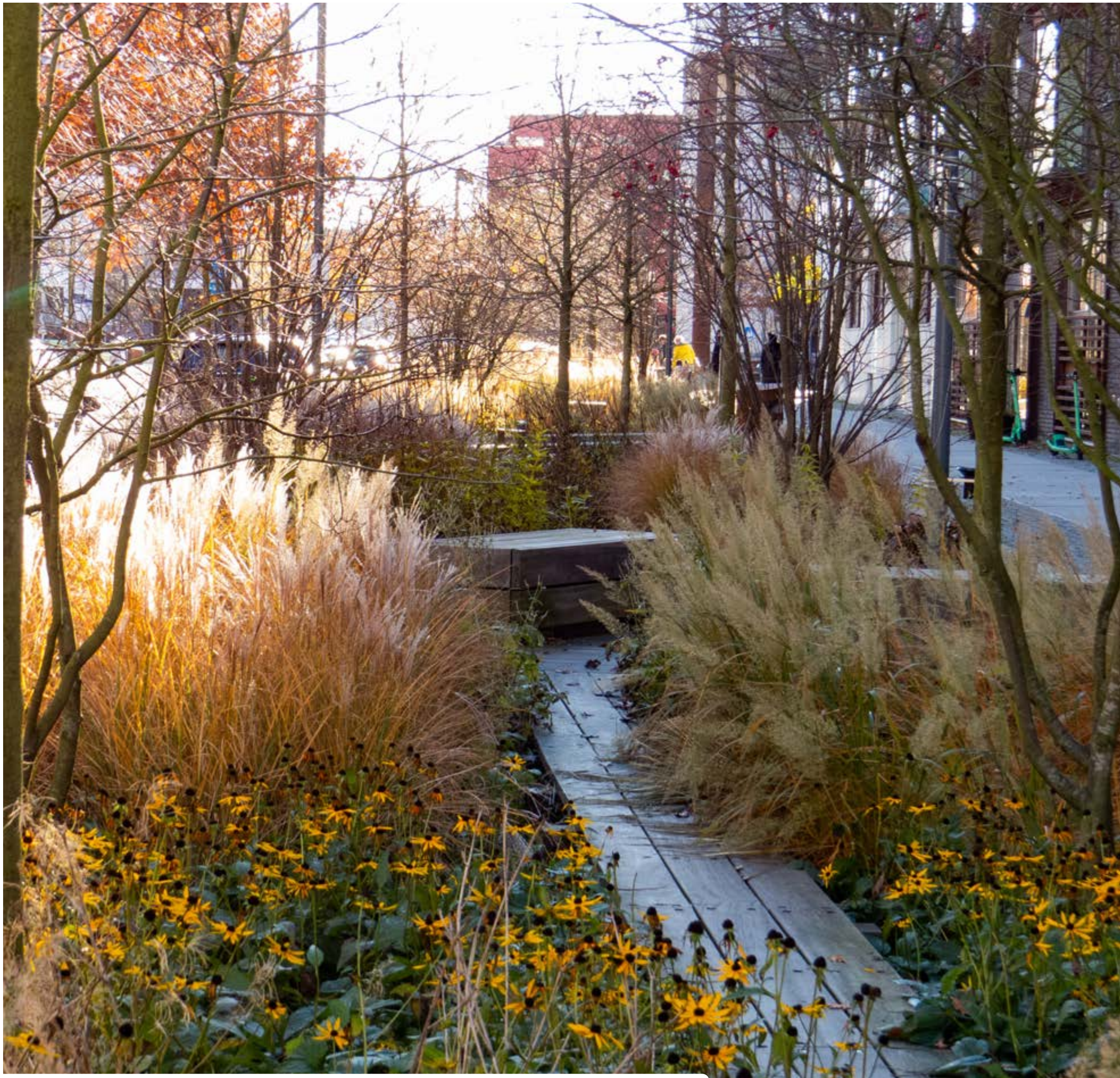
Discussion

The experimental design at Varvsparken represents a simple but important model for designers hoping to expand the role of biochar in urban landscapes and beyond. As a relatively new material that encompasses a lot of variability in its properties and performance, it is important to gather data for biochar performance in different situations. Ideally such experiments should include detailed information about the properties of the biochar itself such as surface area, particle density, particle size range upon application, and various parameters of the pyrolysis process such as the highest heating temperature, residence time, and feedstock. Details of existing soil conditions and planting strategy are important as well. Given the complexity of real life situations, it is important to realize that experimental landscapes are unlikely to precisely isolate the impact of any variable such as biochar on performance, but that the goal is to learn to use it in connection with other materials and practices to get the results we want for the living systems we are helping to create. In the case of the Varvsparken planting, little information about the nature of the biochar used exists, though particle size and woody feedstock is evident from the large pieces that now rest on the surface as the compost layer has melted away.

Biochar in Norra Djurgårdsstaden: Stockholm Royal Seaport

Overview

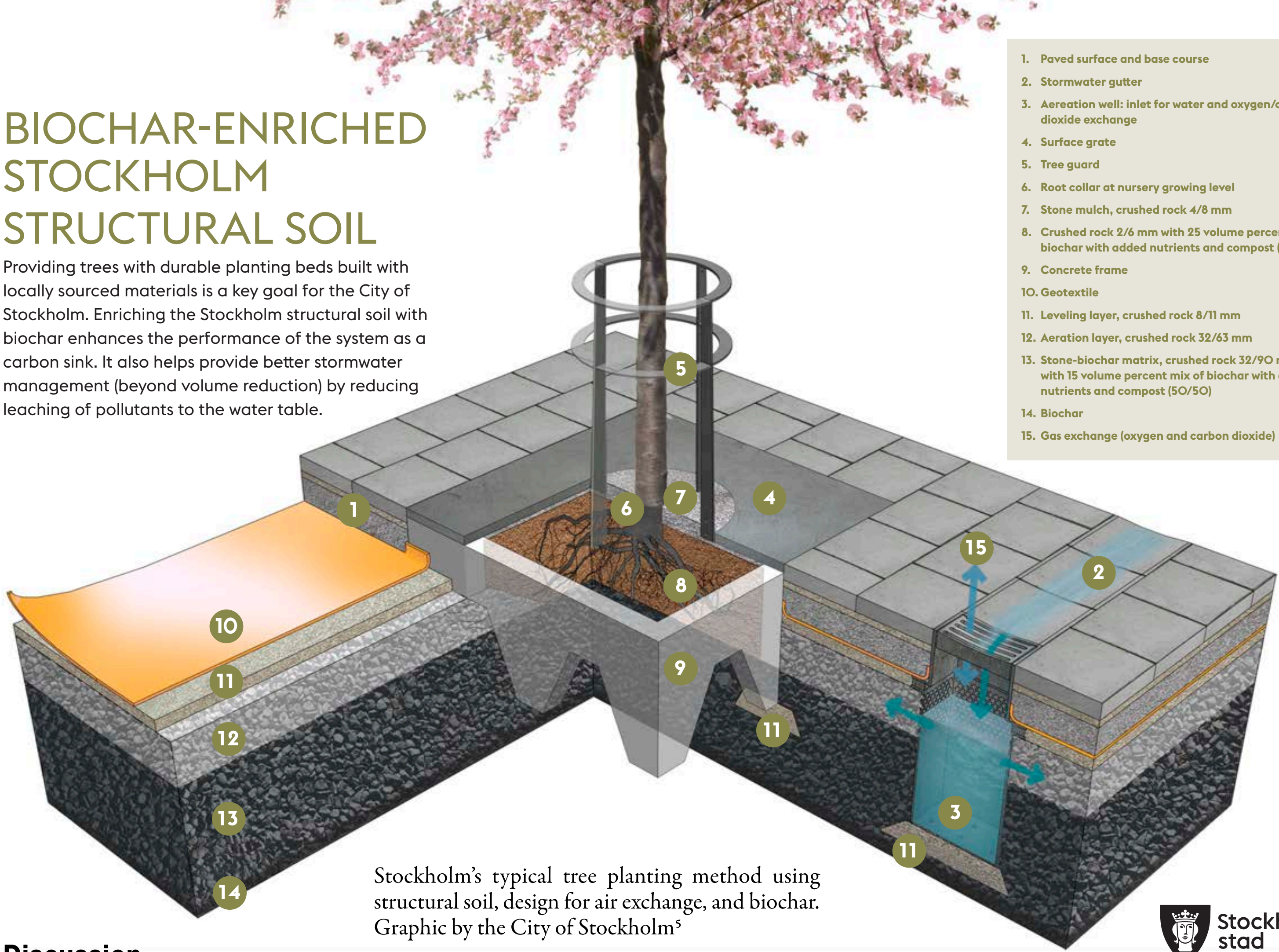
The Stockholm Royal Seaport neighborhood is a mixed-use development built upon lands formerly used for gas production and port operations. In 2009 it was designated by the city as one of its "environmental profile" areas. It is meant to serve as an incubator for sustainable development which can then be utilized throughout Stockholm's future developments.[1] It was called the most sustainable urban development project in the world in 2015 by the C40 at the Paris climate summit.[2] One of the many climate mitigation strategies used in the neighborhood is the systemic use of biochar in plantings as a means of sequestering CO2, filtering and retaining water, and ensuring the resilience of plant communities. By 2020, the use of biochar in the development had stored 1,100 tonnes of CO2 in landscape areas.[3] The use of biochar in this development fits with Stockholm's approach to planting as they have pioneered the use of biochar in urban areas. In 2014 they were one of 5 European cities to win the Bloomberg Philanthropies Mayors Challenge which provided them funding to launch the Stockholm Biochar Project, enabling the city to begin producing its own biochar from park and garden waste and to engage citizens in the process of carbon sequestration.[4]



Rain gardens along Jaktgatan in the Stockholm Royal Seaport neighborhood.[6]

BIOCHAR-ENRICHED STOCKHOLM STRUCTURAL SOIL

Providing trees with durable planting beds built with locally sourced materials is a key goal for the City of Stockholm. Enriching the Stockholm structural soil with biochar enhances the performance of the system as a carbon sink. It also helps provide better stormwater management (beyond volume reduction) by reducing leaching of pollutants to the water table.



1. Paved surface and base course
2. Stormwater gutter
3. Aeration well: inlet for water and oxygen/carbon dioxide exchange
4. Surface grate
5. Tree guard
6. Root collar at nursery growing level
7. Stone mulch, crushed rock 4/8 mm
8. Crushed rock 2/6 mm with 25 volume percent mix of biochar with added nutrients and compost (50/50)
9. Concrete frame
10. Geotextile
11. Leveling layer, crushed rock 8/11 mm
12. Aeration layer, crushed rock 32/63 mm
13. Stone-biochar matrix, crushed rock 32/90 mm with 15 volume percent mix of biochar with added nutrients and compost (50/50)
14. Biochar
15. Gas exchange (oxygen and carbon dioxide)

Stockholm's typical tree planting method using structural soil, design for air exchange, and biochar. Graphic by the City of Stockholm[5]

Stockholms stad

Discussion

Most biochar projects in Sweden, and neighboring countries for that matter, can be traced back to Stockholm. There, the use of biochar was pioneered in the early 2000s by Björn Embrén, who was in charge of the health of the city's trees in his role with the Traffic Office. Björn had an epiphany about the potential value of biochar in urban plantings based in part on his experience as a former orchid grower and aquarium keeper, where the use of charcoal or activated carbon is common.[7] Through the support of the city and an experimental approach, Björn and the team at the Traffic Office were able to develop a planting method based on structural macadam soils, design components that ensure soil air exchange, and the use of biochar and compost; the method has shown incredible results in both above and below-ground tree health. The systemic use of biochar throughout the city's plantings has multiplied the city's impact on carbon sequestration far beyond the direct impacts of the biochar they have used. The city has provided a model for other cities and greatly contributed to the market for biochar in the region by representing a steady source of demand for the material. While the initial use of biochar was motivated by the potential to improve tree health, it is now equally if not more motivated by the city's climate change mitigation goals. Stockholm's experience with biochar represents a transferable model: successful tree establishment saves money and helps pay for the expense of biochar. Systemic biochar use grows the market for the material and encourages wider adoption.

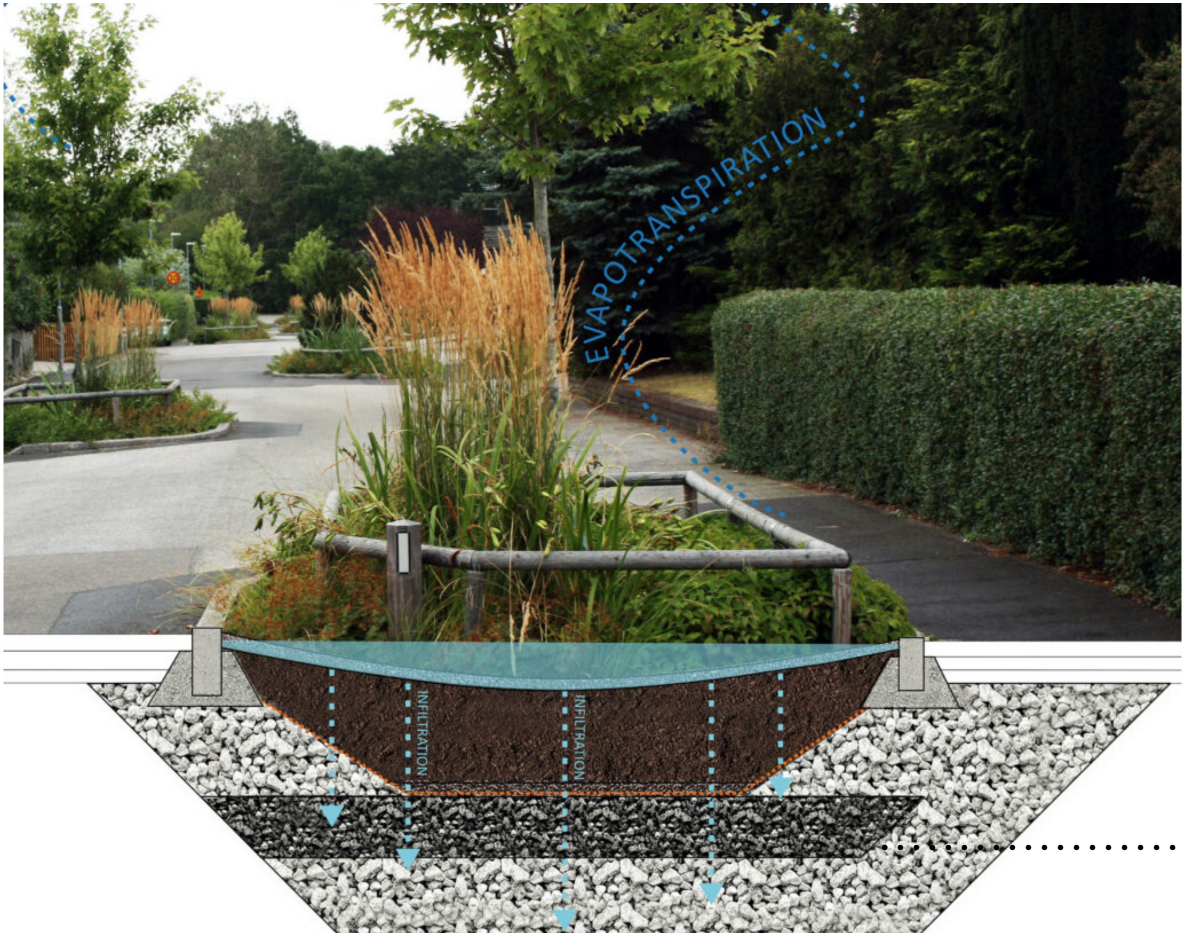
GIVING WATER THE RESPECT IT DESERVES

Vellinge's Blue Green Grey Infrastructure

Overview

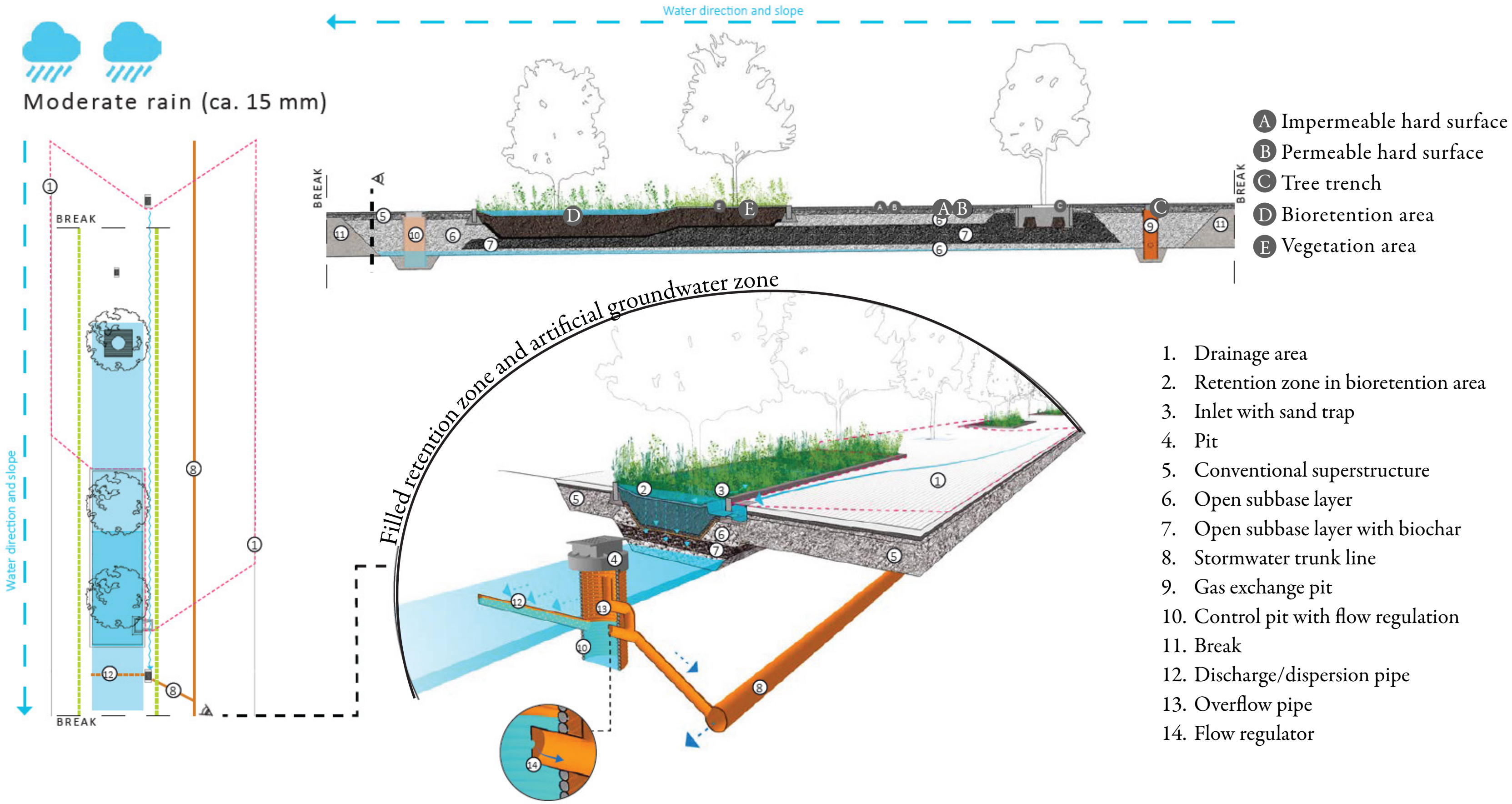
The city of Vellinge in southern Sweden enlisted Edge, a consulting and landscape architecture firm specializing in blue-green-grey (BGG) infrastructure, to redesign parts of the growing city for better stormwater management among other goals. The projects aimed to create more sustainable green spaces that would enhance biodiversity and ecosystem services while reducing the risk of flooding and creating new spaces for play and safe pedestrian movement. Edge's innovative design utilizes a load-bearing porous layer of macadam substrate that is strategically enhanced with biochar to expand water holding and filtration capacity and improve conditions for plants. The design includes gas-exchange pits which, combined with the structural soil, ensure an oxygen-rich soil environment good for above and below-ground life.[1, 4, 5, 6]

Bluegreengrey system on rundelsgatan, Vellinge.[1, 2]



Bluegreengrey system function and design.[1] Graphics by Edge.

Biochar addition to macadam substrate adds a water and nutrient retentive layer that enhances microbial habitat and root conditions for enhanced community resilience and water filtration.



A Impermeable hard surface
B Permeable hard surface
C Tree trench
D Bioretention area
E Vegetation area

1. Drainage area
2. Retention zone in bioretention area
3. Inlet with sand trap
4. Pit
5. Conventional superstructure
6. Open subbase layer
7. Open subbase layer with biochar
8. Stormwater trunk line
9. Gas exchange pit
10. Control pit with flow regulation
11. Break
12. Discharge/dispersion pipe
13. Overflow pipe
14. Flow regulator

"Illustration of flow from major rain in a BGG system. During persistent rain, stormwater runs to bioretention areas and the retention zone is filled. Infiltrated stormwater starts to fill the bottom of the open subbase layer and the flow reaches the control pit. Depending on the flow regulator setting, the water continues to the stormwater trunk line to a greater or lesser extent. Plan view (left), longitudinal cross section (above), three-dimensional view (below)." [3] Graphics by Edge; see the handbook produced by Edge for additional graphics and information.[3]

Discussion

BGG systems can significantly enhance an urban area's capacity for managing stormwater in place. Conversations with Kent Fridell and Martin Vysoký of Edge and Björn Embrén of the Stockholm Biochar Project made clear that the key to the system's success is the gas exchange enabled by the soil's structure and gas exchange or "control" pits. Biochar acts as a catalyst for this system by serving as a sustainably sourced permanent carbon structure that fosters the soil community which will in turn assist the filtration process and enable the plant community to thrive. One challenge is to avoid the loss of fine biochar particles from the system as water flushes through. Typical biochar particle size ranges from 1 to 10 mm in these systems, so it might be necessary to use larger fraction sizes, more durable feedstock, or to explore other modes of entrapment such as encouragement of the mycorrhizal fungal community.

LEVERAGING RESEARCH AND EDUCATION

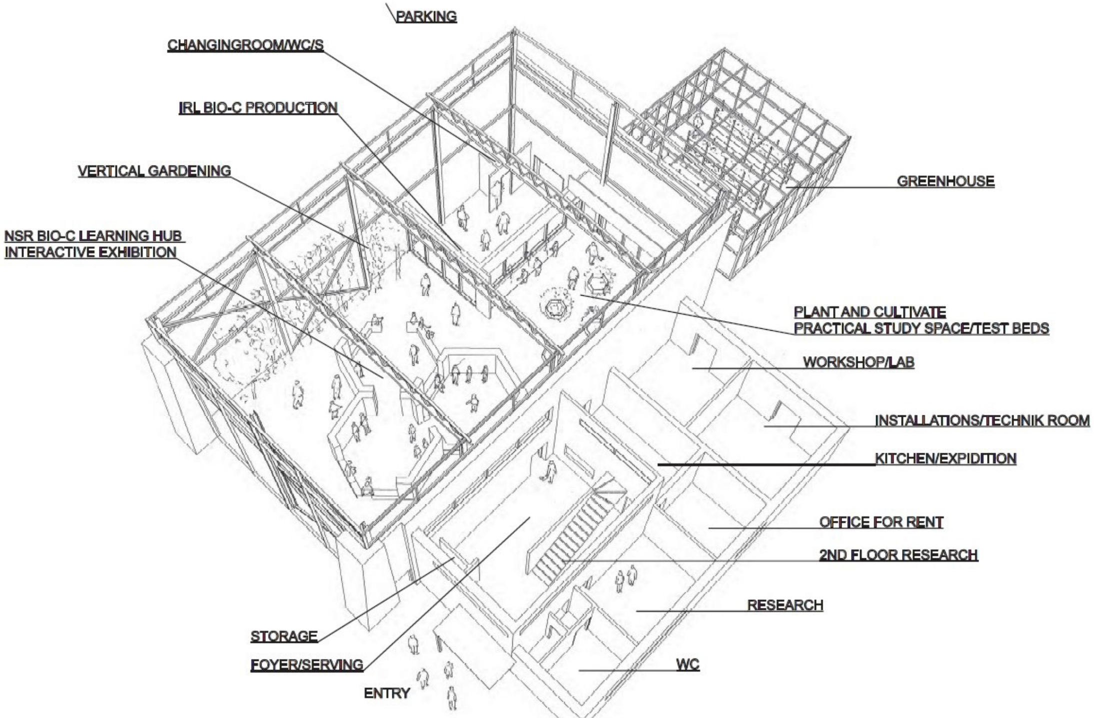
Helsingborg's Bio-C Competence Center

Overview

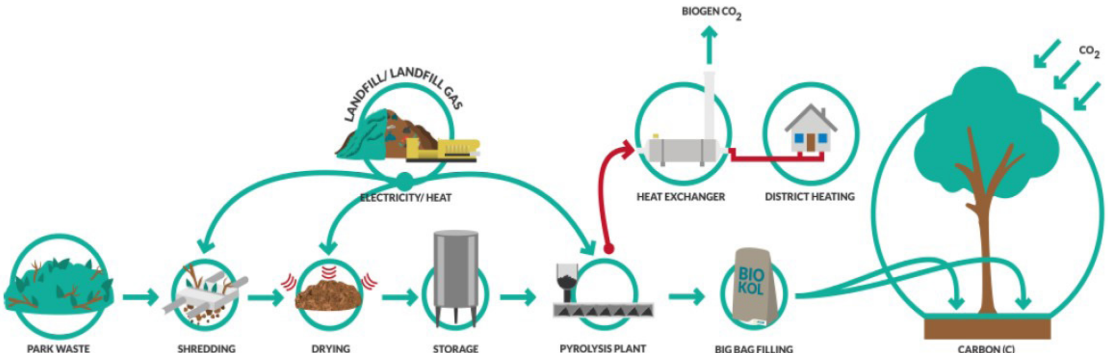
NSR, a municipally-owned waste management company located in the city of Helsingborg, is seeking to develop a new hub for knowledge generation and communication related to biochar's landscape application and climate benefits. By establishing a small scale pyrolysis facility (in addition to its large scale pyrolysis facility already under development), they hope to provide a resource for research that connects various aspects of the biochar life cycle such as feedstock and pyrolysis conditions to biochar as a multifaceted product with diverse applications. The center would additionally function as a demonstration site for biochar landscape application through experiments on site related to remediating polluted soil, green wall design, and greenhouse growing experiments. The ultimate hope is to enhance global knowledge and awareness related to biochar to magnify its effective application for diverse landscape functions and multiply its role as a carbon sink for climate stability.

Interior rendering of the Bio-C Competence Center. [1]

Competence Center renderings. [1]



Confluence of research and education functions at the Competence Center [1]



Systems diagram of the Helsingborg system for organic matter management.[2]

Discussion

This unique project offers a powerful example of multiplying the direct climate benefit that the production and use of biochar represents by creating research and education opportunities that could help scale up larger biochar systems. NSR hopes to influence biochar use in cities by managing the Center as a venue for events and conferences that will bring in politicians and other decision-makers. It will also provide researchers a purpose-made lab for developing biochar products. It demonstrates the crucial role that waste management entities can play in advancing the use of biochar and ensuring its sustainable production. NSR already has access to a variety of feedstocks, is located adjacent to economically-enabling infrastructure such as Helsingborg's district heating network hub, and manages mutually beneficial processes such as composting. This enables it to design its biochar production system as part of a wider industrial ecological network. Further development of the project hinges to a significant extent on funding from Bloomberg Philanthropies which is supporting a range of biochar projects in Europe and the U.S. This highlights a common theme for many biochar projects; whether research or production oriented, they are often motivated and funded in part by climate change mitigation efforts. Biochar production and use may represent the only truly shovel-ready and currently-scaling strategy for generating critically important negative CO2 emissions that will help stabilize atmospheric carbon levels while the energy sector attempts to become carbon neutral. The fact that biochar can sequester carbon while also performing valuable services in urban and residential landscapes, agriculture, and materials technology, and furthermore can displace extractive CO2 emitting industries makes it a unique win-win-win climate solution. Are there ways to apply this research and education focus to enhance the impact of landscape projects that use biochar?

CO-CREATING LANDSCAPES FOR EXPERIMENTATION

Carbon Lane: A Carbon Sequestration Demonstration Park

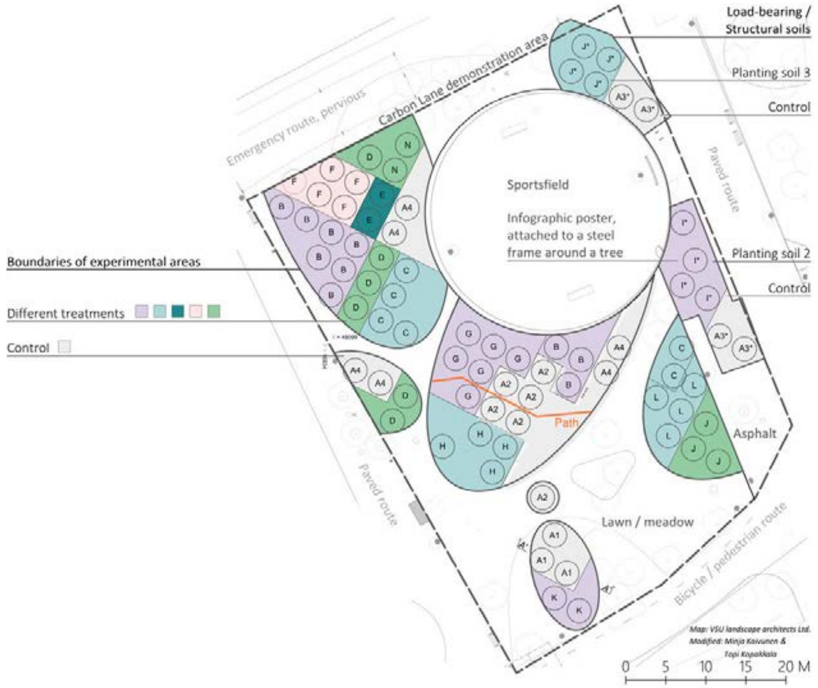
Overview

The Carbon Lane project created an opportunity for co-creation, learning, and knowledge generation among a variety of different stakeholders in the built environment who have the potential to impact carbon sequestration in urban areas. The project resulted in the design of a section of Hyväntoivonpuisto Park in the Jätkäsaari neighborhood of Helsinki Finland that would serve to sequester carbon while also functioning as an experimental research opportunity and an exploration of strategies for public engagement related to urban carbon sequestration. The primary method of sequestration was the use of a range of biochar infused soils prepared by soil producers in the region. The potential for biochar enhanced growth was also considered as a source of sequestration, though robust tracking of such advantages was recognized as a significant challenge. The conceptual design for the park was developed through a series of meetings with relevant stakeholders such as members of research institutions, private companies such as Carbofex, a Finnish biochar producer, other organizations such as environmental and biochar associations, and government entities such as the City of Helsinki. The co-creation process resulted in a wide array of conceptual designs that were generated to explore and illustrate the potential for public engagement in a park oriented around carbon sequestration and research, and also to test the design of an ideal research-oriented park against the realities of the construction process. The design was revised through a series of iterations before and during the construction process which ultimately resulted in a park that didn't align with all experimental ideals, but offers an informative window into the challenges of aligning the needs of research with construction timetables and cost limitations.[1]

Experimental "Carbon Lane" area. Hyväntoivonpuisto Park, Helsinki Finland.[2]

Treatment	Small-leaved Lime *Tilia cordata* 12 pcs	Pin cherry *Prunus pensylvanica* 18 pcs	Ash *Fraxinus excelsior* 12 pcs	Apple 'Makamik' *Malus x purpurea* 38 pcs	Lawn / meadow
1 Control * Structural soil	A	A	A*	A	A
2 Planting soil * Structural soil	J	G	I*	B	K
3 Planting soil		H		C	L
4 Planting soil				D	M
5 Planting soil				E	N
6 Planting soil				F	O
7 Planting soil					P

Ideal conceptual design. [1]

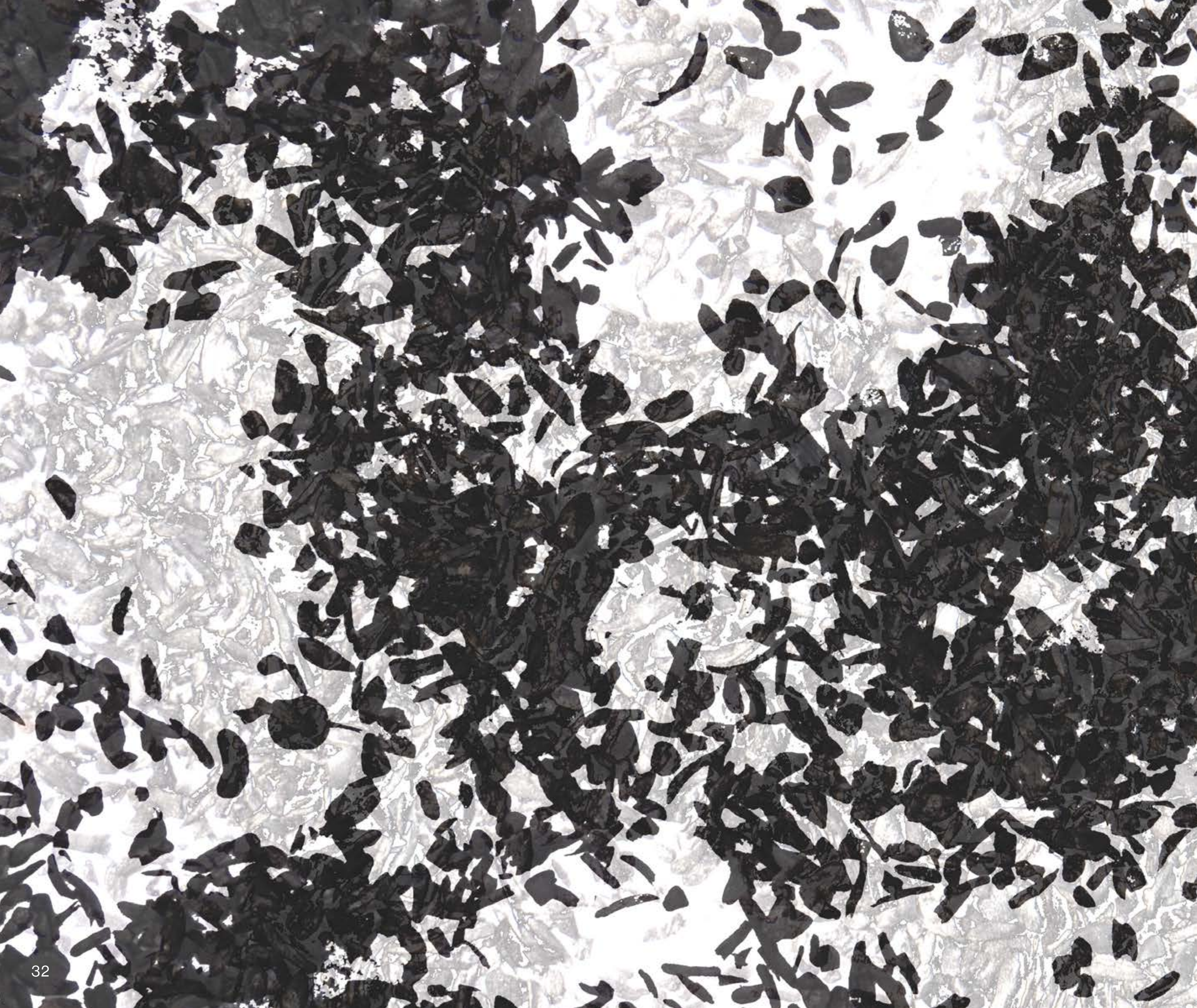


Treatment	Small-leaved Lime *Tilia cordata* 12 pcs	American mountain-ash *Sorbus americana* 21 pcs	Ash *Fraxinus excelsior* 12 pcs	Apple 'Makamik' *Malus x purpurea* 32 pcs	Media volumes approx. m³
1 Control * Structural soil	A1	A2	A3*	A4	300 88
2 Planting soil * Structural soil	K	G	I*	B	300 86
3 Planting soil * Structural soil	L	H	J*	C	290 70
4 Planting soil	M	N		D	183
5 Planting soil				E	25
6 Planting soil				F	60

Compromise design. [1]

Discussion

Carbon Lane represents a unique and valuable effort to unify an array of often disjunct professional communities and goals. It points to the complexity of aligning complex experimental setups with the realities of construction timelines in the public realm as well as the difficulty of coordinating soils that serve as experimental variables between multiple producers. The importance of clear communication and anticipation of problems between project stakeholders represent some of the lessons from the project. In this project for example, the schedule for soil delivery ultimately decided the number of experimental treatments and repetitions. Deviations in soil properties from what was expected resulted in challenges to the control of experimental variables, and insufficient communication of requirements for the documentation of the construction process may challenge follow-up research. While the project created a range of interesting conceptual designs related to citizen engagement opportunities in the park, there wasn't sufficient investment in the park to develop and realize these ideas. Mikko Jalas, one of the leaders of the project from Aalto University suggested that future designs might at least ensure that flexible space exists in such parks allowing future interpretive installations to be considered.[3]




Sedum and biochar mats produced by Veg Tech.

Suggestions for Implementation and Use

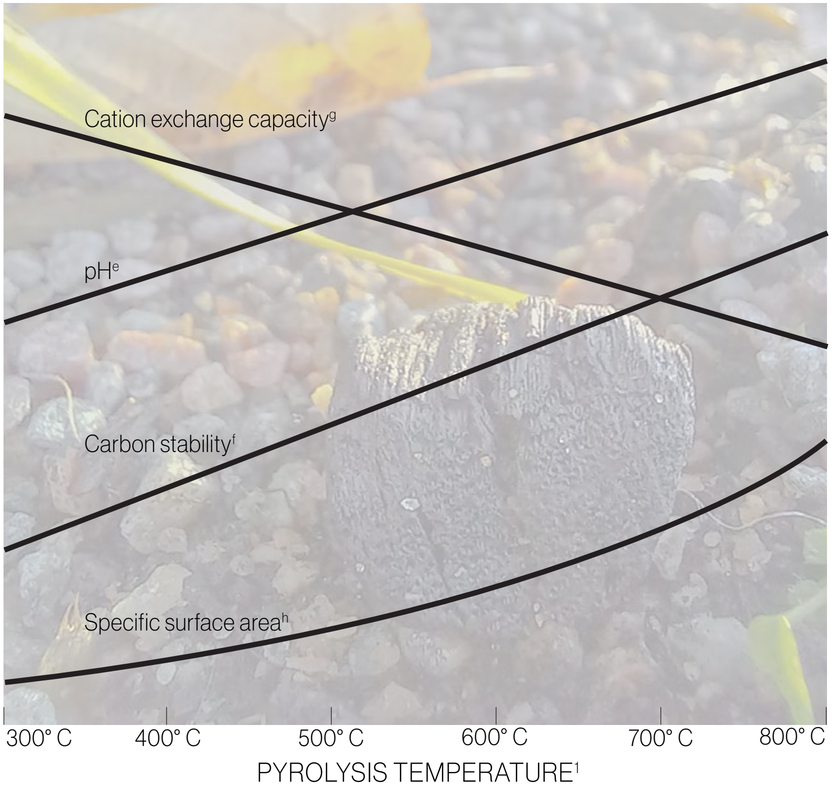
Biochar's complex material structure and variety of functions make it difficult to provide precise suggestions for biochar use from an abstract perspective. The best method for using biochar will be a function of the site conditions, design goals, properties and cost limitations of the biochar available, and the nature of maintenance that will shape the landscape over time. The following section was designed with the hope that it would give those interested in using biochar a distilled source of information relating biochar production conditions and resulting functionality. Fine-tuning biochar function, however, is a relatively small problem; the biggest hurdle for implementing more widespread use of biochar is simply its cost. Lower costs would probably follow from more reliable and high volume demand, but increasing demand is stuck on biochar's high cost. One factor that could change the economic landscape is the increasing valuation for carbon sequestration. Biochar producers can earn income through selling their biochar as a carbon credit. Individuals, project developers, municipalities or others could incorporate biochar as both a physical material and a carbon credit. Besides its climate benefit, the ability to make living systems more resilient can be thought of as a way to reduce maintenance costs through decreased need for fertilizers, irrigation, and plant (especially tree) replacement. Tree health is the factor that made biochar possible in Stockholm initially, for example. And in some high performance applications, biochar may actually represent a cheaper material than those typically used such as for activated carbon in filtration systems. Systems of biochar production and use just need a spark of support and design intention to gain some momentum. The benefits will carry them from there.

ALIGNING BIOCHARS WITH DESIGN GOALS

Choosing the Right Biochar and Strategy for Application

The unique physical and chemical properties of biochar make it a powerful tool for supporting a variety of goals in efforts to improve soil function. The suggestions that follow are meant as a starting point for design, and are organized around three major interrelated goals that biochar can support: reviving living soil communities, managing greenhouse gases, and purifying water. Chief considerations in choosing a biochar include the temperature at which it was created, post-pyrolysis treatments such as co-composting or nutrient loading, particle size, and feedstock material. The manner in which biochar is applied to the soil represents a crucial factor as well.

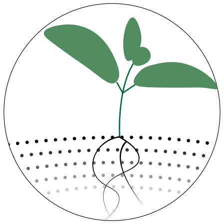
How Pyrolysis Temperature Affects Biochar Properties



NOTES

(1) Adapted from (1) Li et. al. 2019. Shows average effect of pyrolysis temperature on studied feedstocks.
(e) ~7.8-12.7; (f) Based on the oxygen to carbon ratio, a proxy for biochar's permanence. Shows a half-life range from 100 years to over 1000 years with 600° C biochar representing the 1000+ year half-life mark; (g) CEC also increases over time with physical weathering. (h) Mostly reflects nanopore formation.

Reviving Living Soil Communities



A permanent hub for nutrients in the soil. The hydrophilic pore structure and high cation exchange capacity of low to moderate temperature chars help them retain inorganic nutrients like nitrogen and phosphorous that aid plant growth. Higher temperature chars host a larger surface area though this is primarily represented by nanopores that are less accessible to plants or microbial symbionts. Using a biochar of relatively small particle size could increase accessible surface area[3] though it could also encourage biochar movement away from the planting via water or wind.[2] Post-pyrolysis treatments of biochar such as nutrient loading with fertilizer or, ideally, co-composting will speed up the rate at which biochar can serve as a nutrient hub.[4] Using char from a feedstock with a durable cellular structure such as wood may help it retain its structural form in the soil and better act as a refuge for the soil life that facilitates plant health.

A long-lasting structure for a diverse soil community. While biochar made at any temperature offers good habitat for soil life, the internal structure of low-moderate temperature chars is particularly available for microbial colonization (whereas the nanopores of high temperature chars are much smaller than bacteria and thus inaccessible).[5] Choosing a particle size large enough to host significant internal pores can create anaerobic microhabitats that support denitrifying bacteria[2] critical for some water purification goals. Co-composting would hasten the colonization process of the char[4] and enable the char to serve as refugia for compost-born microbes after they are relocated to their new home in the soil being amended.

Respiratory support for the soil. Microbes, fungi, invertebrates and roots all need to breath. Co-composted biochar, regardless of pyrolysis temperature, should contribute the greatest benefit towards a healthy and respiratory-friendly soil structure because living soil will develop good structure on its own. Chars with low bulk and particle density, large pores, moderate-large particle size, and high mechanical strength should maintain their structure best in the soil and contribute most directly to aeration. Compacted soil is likely to benefit from a combination of decompaction approaches such as mechanical decompaction, strategic choice of plants, as well as biochar and compost addition.

Managing Greenhouse Gases

A catalyst for reduced soil greenhouse gas emissions. Biochars can adsorb and immobilize organic soil compounds otherwise metabolized by plants or microbial life and respired as CO2. Nitrous oxide (N2O) emissions, which are 265 times more potent as a greenhouse gas relative to CO2 can be reduced through direct and indirect mechanisms including facilitating microbial reduction of N2O to nitrogen gas and displacement of nitrogen fertilizers. Biochars created at high temperatures do this especially well because of their enhanced ability to support the electron transfer that powers microbial metabolisms. N2O emissions from soils can be reduced by about 38% in the first year and then 10% annually, potentially for the lifetime of the biochar.[6] Biochars can also decrease soil methane emissions through measures including adsorption and pH increase, particularly in agricultural systems that rely on flooded soils such as rice paddies.[7] Trying to reduce greenhouse gas emissions from soils is a unique and complex goal but one for which biochar shows much promise. High temperature chars may be the most effective, but ultimately the details will determine the best type of char and manner of application.

A hard working carbon reservoir. One cubic yard of biochar sequesters about 2.8 metric tons of CO2 equivalent depending on and after accounting for life cycle emissions.[8] That equates to about 315 gallons of gasoline.[9] Such direct and durable carbon sequestration in a material made from waste and that supports the health of carbon sequestering soil makes biochar one of the most on-hand solutions for climate mitigation available. Furthermore, the fact that the pyrolysis process can produce energy and displace the need for fossil fuels makes biochar an obvious strategy for taking immediate steps towards climate stabilization. The carbon sequestration capacity of biochars hinge on a trade off between carbon durability and production quantity. Durability increases with pyrolysis temperature, but production quantity decreases. All biochars heated to at least 400° C should function as a durable carbon sink.[10] A similar trade-off exists for biochar and energy co-production. Pyrolysis systems geared towards energy production will produce less biochar than dedicated biochar production operations for a given feedstock quantity. As designers, the main challenge at this point is simply getting more biochar in the soil and helping to grow the market for the material.

Purifying & Choreographing Water

A filter for organic pollutants. High temperature biochars have abundant surface area composed of nanopores that intercept and adsorb organic pollutants such as phenols, dyes, pesticides, and a variety of persistent organic pollutants such as polycyclic aromatic hydrocarbons and polychlorinated biphenyls.[11, 14] The use of high temperature biochars can substantially increase the capacity for the capture and retention of pollutants and their subsequent reduction in soil bioavailability. The effect of biochar on the biodegradation of organic pollutants is complex because it entails interaction with the soil microbial community. Supporting this goal could point towards using lower temperature biochars that have more bioavailable surfaces for bacterial colonization.[14] Using co-composted biochar may also benefit remediation by enlisting beneficial microorganisms to break down targeted pollutants.

A filter for inorganic pollutants. Low-moderate temperature chars excel at capturing heavy metals suspended in water due to high cation exchange capacity and other properties.[11] Activation of char as a post-pyrolysis treatment can further enhance its capacity for heavy metal sorption.[11] Small particle size encourages water retention and can improve filtration, though it can increase particle mobility in the environment. Using a particle size of at least a medium to coarse powder allows for denitrifying conditions in water retained within internal pores.[2] While raw biochar can effectively act to capture heavy metals, it may also reduce availability of key plant nutrients in the soil. Using a nutrient-infused or co-composted char can counteract this potential challenge.

A tool for choreographing water movement. Attention should be paid to biochar particle size and post-pyrolysis treatment when trying to influence water movement in the soil. Biochar in fine powder form may act to decrease soil permeability, whereas larger particles enable water movement. Small pores in the micron range can retain plant available water while larger pores may drain more quickly, and nanopores may hold water inaccessibly.[v] Feedstock and pyrolysis temperature largely control these properties. The potential for co-composted biochar's capacity to jump start soil life could enable it to initiate soil aggregate formation that will ultimately favor soil permeability and retention.

ROLES FOR GARDENERS, DESIGNERS & DECISION-MAKERS

A Speculative Vision for Biochar in Northwest Urban Ecosystems

Biochar in the community: how urban farmers and gardeners can get involved

Kon-Tiki operation demonstration.[3]

There is no need for individuals or communities interested in working with biochar to wait for a well-developed biochar economy to emerge. Recent innovation in designs for pyrolysis kilns have yielded very simple designs that can essentially be built for free when nested in the soil or purchased for minor cost in the range of $100 - $200 dollars. These kiln models called "Kon-Tiki" use a simple design and process to manage the physics of fire to produce biochar while burning the gases released in the process through creation of a so-called "flame curtain".[1] Open-source designs can be found through the Ithaka Institute.[2] Kon-Tiki kilns can produce high quality biochar, pyrolize a range of biomass types, are simple to operate, and the process takes just a few hours to complete—perfect for grilling some food while you're at it.[1]

This represents an opportunity for the production and use of biochar to be democratized and grown from the ground up. Whether in urban community gardens, farms, or backyard gardens, the production of biochar enables urban residents to increase the fertility and resilience of their plantings while sequestering carbon in the process. It could also help avoid the risk of contaminant uptake in foods grown in potentially polluted soil and in this way could represent a tool for efforts to advance environmental justice and food sovereignty. This technique would be particularly powerful if the biochar produced was combined into composting practices as a holistic strategy for managing organic waste and regenerating soil fertility.

Expand and circulate: landscape architects can cultivate urban biochar practices

Landscape architects possess unique potential to support the role of biochar in urban areas to advance a variety of goals at scales ranging from the site to the global. The primary barrier to more widespread use of biochar besides lack of awareness about it, rests in its cost. While it is generally cheaper than materials like activated carbon, which it may replace, it is generally more expensive than materials with similar performative capacity such as pumice. For the biochar industry to grow and produce biochar more cheaply, it needs a steady return on investment. Landscape architects can empower this scaling of the industry by taking advantage of biochar's unique qualities in applications that will ultimately save businesses and cities money. The use of biochar could be justified through the costs saved with more resilient trees, cleaner stormwater, and a willingness to spend money on carbon sequestration. The best pathway towards this goal seems to be through systemic incorporation of biochar in design strategies. This helps biochar producers by creating greater reliability in their marketplace. It can also give designers leverage over the material properties of biochar by creating a collaborative relationship between producers and users where producers may be willing to tailor the pyrolysis process to enhance particular biochar properties to suit a regular buyer or industry. Such a symbiosis could grow to enable landscape architects to work with biochar producers to pyrolyze organic biomass materials generated during demolition for reuse on site or free "disposal". In this way, landscape architects can begin to grow cooperative circular economies that reduce organic waste, sequester carbon, and lead to a more resilient urban landscape.

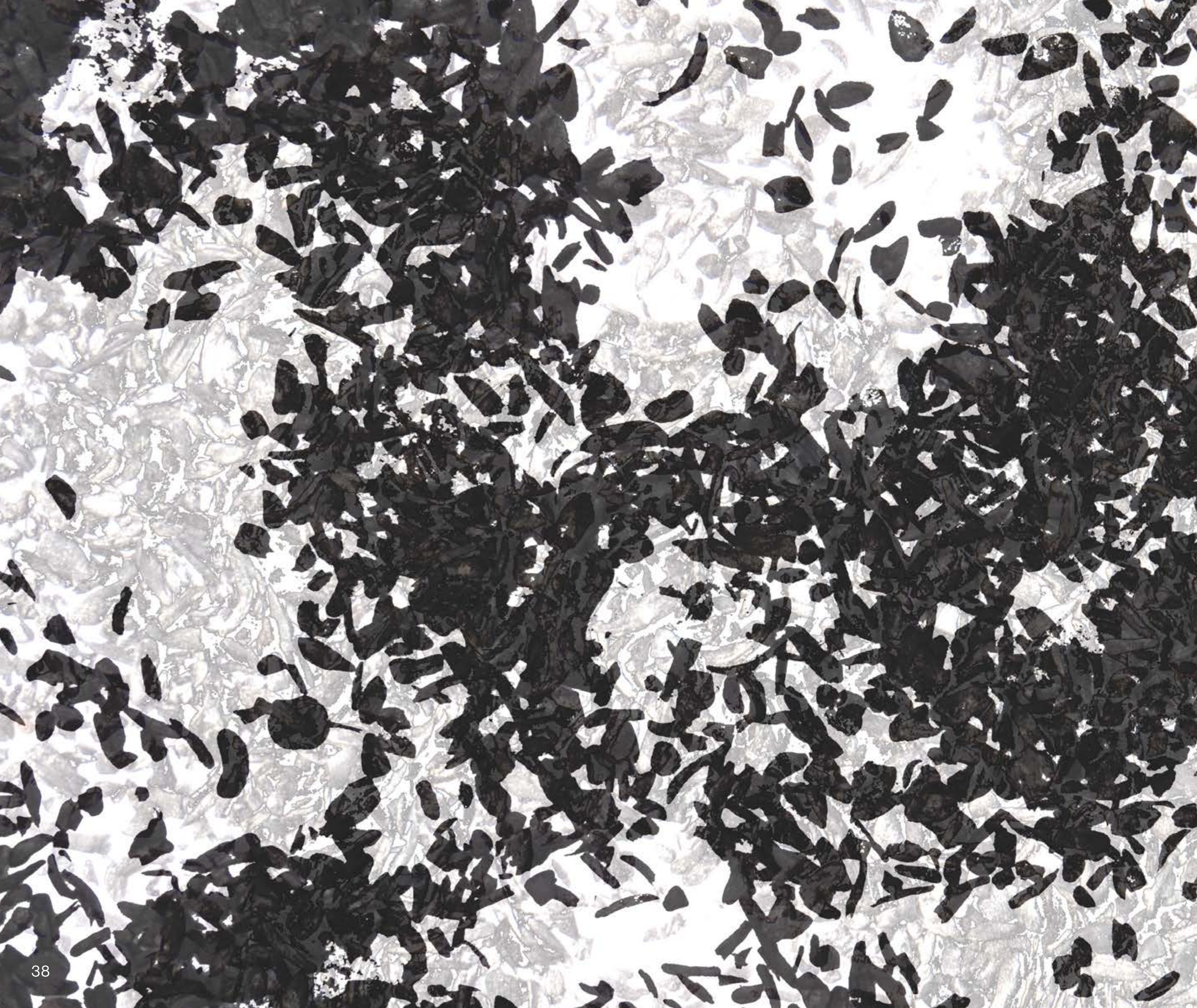
Bluegreengrey systems use biochar as a standard component.[4]

Systems design: planners and decision-makers can define a generative vision

There is an immense potential for those that shape the rules governing cities, states, or other entities to hasten the transition to more regenerative, circular, and sustainable economies. Thinking about cities as complex dynamic systems invites us to consider the most effective intervention strategies to affect positive change. Donella Meadows, a pioneering systems thinker, describes and structures these strategies as "leverage points" within a system, and highlights that the goal of the system is one of the most influential leverage points of all, while the rules of the system follow closely behind in importance.[5] Planners and decision-makers involved in the administration and leadership of cities, counties, states, or other entities have the potential to define goals that will lead us towards regenerative cultural and economic practices that have potential to influence areas and entities at larger scales.

These goals and rules need not even mention biochar specifically, but by their nature should lead us towards it. What might a city do if its goals included the elimination of waste? What if a city aimed to eliminate all polluted runoff to its waterways? How could a city become not just carbon neutral by 2050, as is the goal for Seattle, WA, but rather carbon negative? Perhaps by 2040? Biochar, of course, cannot solve any of these problems by itself, but it could represent a key strategy in addressing all three. Perhaps the goals of our cities, states and so on, do not go far enough, and fail to stimulate the powerful creativity that is a product of constraint. Like biochar in soil, cities represent incredible hubs of diverse transformative potential. For a city like Seattle, both a member of the Carbon Neutral Cities Alliance and a center of spectacular wealth, to aim only to achieve carbon neutrality by 2050, while better than nothing, is disheartening. Leaders and planners in Seattle and other wealthy cities could push for diverse and innovative strategies for carbon sequestration as well as emissions reductions. They could recognize the critical nature of the 2020s for taking diverse, replicable, creative and powerful action to stabilize the global climate. Policies and goals that support such a vision are likely to support biochar too. There is no time to waste.

Can we reset system goals and rules to find new paths into the future?



To Conclude and to Begin

What other material could claim to impart direct benefits at local, regional, and global scales while also encouraging adoption of more sustainable and regenerative ways of living on the Earth? Even widespread and substantial production and use of biochar, however, won't come close to solving the climate crisis. But it could serve as a tool in the transition to very different ways of growing the soils that become our food, and managing the flows of organic materials that often lead to waste. At a large scale, such transformations could be a game changer for climate mitigation. One effort to organize a movement to do this was initiated at the COP 21 climate meeting in Paris in 2015 by the former French Minister of Agriculture, Stéphane Le Foll. He proposed the "4 per 1000" initiative, which set a goal for all participants to increase the carbon content of their soil by .4% every year. Doing this on a global scale on agricultural lands could sequester about 1.2 billion metric tons of carbon every year, a large proportion of the annual increase in atmospheric CO2.[1] What does this have to do with urban biochar? Cities have immense transformative potential for the economies and landscapes around them. Biochar use in cities, especially if done with en eye towards communicating benefits, could help expand the use of biochar in wider markets. And the very way in which biochar benefits soils and plants suggests a very different approach than conventional agricultural practices that destroy soil carbon through tillage, toxic chemicals, and synthetic fertilizers. It is impossible to say how biochar might affect cultural and economic systems at larger scales and their interactions with the Earth's climate. But we have a duty at this point, as humans with some degree of agency, to push for a stabilization of the climate in any way we can. Perhaps biochar can help us get there, and help us grow our plants and clean our water along the way.

NOTES

WHAT IS BIOCHAR & WHY DOES IT MATTER?

1. EBC (2012) 'European Biochar Certificate - Guidelines for a Sustainable Production of Biochar.' European Biochar Foundation (EBC), Arbaz, Switzerland. (http://european-biochar.org). Version 9.5E of 1st August 2021
2. Lehmann, J., & Joseph, S. (2015). Biochar for Environmental Management: Science, Technology and Implementation. Taylor and Francis. https://doi.org/10.4324/9780203762264
3. Lehmann, J., Cowie, A., Masiello, C. A., Kammann, C., Woolf, D., Amonette, J. E., Cayuela, M. L., Camps-Arbestain, M., & Whitman, T. (2021). Biochar in climate change mitigation. Nature Geoscience, 1–10. https://doi.org/10.1038/s41561-021-00852-8

DEEP ORIGINS & FUTURE IMPLICATIONS

1. Reisser, M., Purves, R. S., Schmidt, M. W. I., & Abiven, S. (2016). Pyrogenic Carbon in Soils: A Literature-Based Inventory and a Global Estimation of Its Content in Soil Organic Carbon and Stocks. Frontiers in Earth Science, 4, 80. https://doi.org/10.3389/feart.2016.00080
2. Opare Asare, M., Afriyie, J., & Hejcman, M. (2020). Origin, distribution, and characteristics of Archaeological Dark Earth soils – A review. https://doi.org/10.5194/soil-2020-51
3. Glaser, B., Haumaier, L., Guggenberger, G., & Zech, W. (2001). The "Terra Preta" phenomenon: A model for sustainable agriculture in the humid tropics. Naturwissenschaften, 88(1), 37–41. https://doi.org/10.1007/s001140000193
4. Wiedner, K., Schneeweiß, J., Dippold, M. A., & Glaser, B. (2015). Anthropogenic Dark Earth in Northern Germany—The Nordic Analogue to terra preta de Índio in Amazonia. CATENA, 132, 114–125. https://doi.org/10.1016/j.catena.2014.10.024
5. Glaser, B., & Birk, J. J. (2012). State of the scientific knowledge on properties and genesis of Anthropogenic Dark Earths in Central Amazonia (terra preta de Índio). Geochimica et Cosmochimica Acta, 82, 39–51. https://doi.org/10.1016/j.gca.2010.11.029
6. Denevan, W. M., & Woods, W. I. (2007). Discovery and awareness of anthropogenic Amazonian Dark Earths (terra preta). Eprida, Marietta, GA. http://www.eprida.com/eacu/PDF%20Files/BDenevan.pdf (accessed December 12th, 2021)
7. Clement, C. R., Denevan, W. M., Heckenberger, M. J., Junqueira, A. B., Neves, E. G., Teixeira, W. G., & Woods, W. I. (2015). The domestication of Amazonia before European conquest. Proceedings of the Royal Society B: Biological Sciences, 282(1812), 20150813. https://doi.org/10.1098/rspb.2015.0813

BIOCHAR IN URBAN INDUSTRIAL ECOSYSTEMS

1. Biochar production and by-products. (n.d.). Biochar for Sustainable Soils. Retrieved December 12, 2021, from https://biochar.international/the-biochar-opportunity/biochar-production-and-by-products/
2. PyroTech Energy. Products. (2020, September 21). (Accessed December 12th, 2021) https://pyrotechenergy.com/products/

LIFE: AN AMENDMENT FOR RESILIENT COMMUNITIES

1. Weber, K., & Quicker, P. (2018). Properties of biochar. Fuel, 217, 240–261. https://doi.org/10.1016/j.fuel.2017.12.054
2. Beusch, C. (2021). Biochar as a Soil Ameliorant: How Biochar Properties Benefit Soil Fertility—A Review. Journal of Geoscience and Environment Protection, 09, 28–46. https://doi.org/10.4236/gep.2021.910003
3. Lehmann, J., & Joseph, S. (2015). Biochar for Environmental Management: Science, Technology and Implementation. Taylor and Francis. https://doi.org/10.4324/9780203762264
4. Leng, L., & Huang, H. (2018). An overview of the effect of pyrolysis process parameters on biochar stability. Bioresource Technology, 270, 627–642. https://doi.org/10.1016/j.biortech.2018.09.030
5. Beusch, C. (2021). Biochar as a Soil Ameliorant: How Biochar Properties Benefit Soil Fertility—A Review. Journal of Geoscience and Environment Protection, 09, 28–46. https://doi.org/10.4236/gep.2021.910003
6. (podcast) VOC235: Practical Tips, Ideas and Technologies for Homescale Biochar with Gloria Flora. Released Friday, 22nd September 2017. https://www.podchaser.com/podcasts/farm-small-farm-smart-daily-7096/episodes/voc235-practical-tips-ideas-an-21117830
7. Brtnicky, M., Datta, R., Holatko, J., Bielska, L., Gusiatin, Z. M., Kucerik, J., Hammerschmiedt, T., Danish, S., Radziemska, M., Mravcova, L., Fahad, S., Kintl, A., Sudoma, M., Ahmed, N., & Pecina, V. (2021). A critical review of the possible adverse effects of biochar in the soil environment. Science of The Total Environment, 796, 148756. https://doi.org/10.1016/j.scitotenv.2021.148756
8. Jonatan Malmberg. Personal communication.
9. Antonangelo, J. A., Sun, X., & Zhang, H. (2021). The roles of co-composted biochar (COMBI) in improving soil quality, crop productivity, and toxic metal amelioration. Journal of Environmental Management, 277, 111443. https://doi.org/10.1016/j.jenvman.2020.111443
10. Hagemann, N., Joseph, S., Schmidt, H.-P., Kammann, C. I., Harter, J., Borch, T., Young, R. B., Varga, K., Taherymoosavi, S., Elliott, K. W., McKenna, A., Albu, M., Mayrhofer, C., Obst, M., Conte, P., Dieguez-Alonso, A., Orsetti, S., Subdiaga, E., Behrens, S., & Kappler, A. (2017). Organic coating on biochar explains its nutrient retention and stimulation of soil fertility. Nature Communications, 8(1), 1089. https://doi.org/10.1038/s41467-017-01123-0
11. Hand Image: How to Make biochar enriched compost for epic veggies. (2021, March 19). Regenerative Skills. https://regenerativeskills.com/how-to-make-biochar-enriched-compost-for-epic-veggies/
12. Mycorrhizae Image: (courtesy of author) Bruckman, V., & Klinglmüller, M. (2014). Potentials to Mitigate Climate Change Using Biochar—The Austrian Perspective. IUFRO Occasional Papers, 27, 1–23.

- Cellular Structure Image: Mulabagal, V., Baah, D., Egiebor, N., & Chen, W.-Y. (2015). Biochar from Biomass-A strategy for carbon dioxide sequestration, soil amendment, power generation and CO2 utilization, Handbook of Climate Mitigation and Adaptation.

AIR: CYCLES OF LIFE, DEATH, CULTURE AND CLIMATE

1. The Carbon Cycle. (2011, June 16). [webpage]. NASA Earth Observatory. https://earthobservatory.nasa.gov/features/CarbonCycle
2. Canarini, A., Kaiser, C., Merchant, A., Richter, A., & Wanek, W. (2019). Root Exudation of Primary Metabolites: Mechanisms and Their Roles in Plant Responses to Environmental Stimuli. Frontiers in Plant Science, 10, 157. https://doi.org/10.3389/fpls.2019.00157
3. Lehmann, J., Cowie, A., Masiello, C. A., Kammann, C., Woolf, D., Amonette, J. E., Cayuela, M. L., Camps-Arbestain, M., & Whitman, T. (2021). Biochar in climate change mitigation. Nature Geoscience, 1–10.

https://doi.org/10.1038/s41561-021-00852-8

- Fire icon: Fire by Rohith M S from NounProject.com
- House Demolition by Nikita Kozin from NounProject.com
- Truck by Daniel Ensor from NounProject.com
- Lumber by Denis Devyatov from NounProject.com
- Kitchen Table by Vadym Blakyta from NounProject.com

WATER: A FILTER AND A RESERVOIR

1. Cao, C. T. N., Farrell, C., Kristiansen, P. E., & Rayner, J. P. (2014). Biochar makes green roof substrates lighter and improves water supply to plants. Ecological Engineering, 71, 368–374. https://doi.org/10.1016/j.ecoleng.2014.06.017
2. Kuoppamäki, K., & Lehvävirta, S. (2016). Mitigating nutrient leaching from green roofs with biochar. Landscape and Urban Planning, 152, 39–48. https://doi.org/10.1016/j.landurbplan.2016.04.006
3. Ulrich, B. A., Loehnert, M., & Higgins, C. P. (2017). Improved contaminant removal in vegetated stormwater biofilters amended with biochar. Environmental Science: Water Research & Technology, 3(4), 726–734. https://doi.org/10.1039/C7EW00070Gv
4. Qi, Y., Liu, Y., Qiu, D., & Li, T. (2021). Effect of biochar particles applied in bedding course of the innovative permeable pavement on enhancing nitrogen removal. Water Science and Technology, 84. https://doi.org/10.2166/wst.2021.331
5. Stormwater Filtration with the use of Biochar-filled Medium Socks. (n.d.). Black Owl Biochar. Retrieved November 22, 2021, from https://www.biocharsupreme.com/blogs/news/25967876-stormwater-filtration-with-the-use-of-biochar-filled-medium-socks
6. Mohanty, S. K., Valenca, R., Berger, A. W., Yu, I. K. M., Xiong, X., Saunders, T. M., & Tsang, D. C. W. (2018). Plenty of room for carbon on the ground: Potential applications of biochar for stormwater treatment. Science of The Total Environment, 625, 1644–1658. https://doi.org/10.1016/j.scitotenv.2018.01.037
7. Das, O., & Sarmah, A. K. (2015). The love–hate relationship of pyrolysis biochar and water: A perspective. Science of The Total Environment, 512–513, 682–685. https://doi.org/10.1016/j.scitotenv.2015.01.061
8. Enaime, G., Baçaoui, A., Yaacoubi, A., & Lübken, M. (2020). Biochar for Wastewater Treatment—Conversion Technologies and Applications. Applied Sciences, 10(10), 3492. https://doi.org/10.3390/app10103492
9. Rittl, T. F., Novotny, E. H., Balieiro, F. C., Hoffland, E., Alves, B. J. R., & Kuyper, T. W. (2015). Negative priming of native soil organic carbon mineralization by oilseed biochars of contrasting quality. European Journal of Soil Science, 66(4), 714–721. https://doi.org/10.1111/ejss.12257
10. Tagliaferro, A., Rosso, C., & Giorcelli, M. (Eds.). (2020). Biochar: Emerging applications. IOP Publishing Ltd.
11. Edeh, I. G., Mašek, O., & Buss, W. (2020). A meta-analysis on biochar's effects on soil water properties – New insights and future research challenges. Science of The Total Environment, 714, 136857. https://doi.org/10.1016/j.scitotenv.2020.136857
12. Diego Footer. (2021, September 13). How to Build Great Soil—A Soil Science Masterclass with Dr. Elaine Ingham (Part 1 of 4). https://www.youtube.com/watch?v=ErMHR6Mc4Bk
13. Jaafar, N. M., Clode, P. L., & Abbott, L. K. (2015). Soil Microbial Responses to Biochars Varying in Particle Size, Surface and Pore Properties. Pedosphere, 25(5), 770–780.
14. Gray, M., Johnson, M. G., Dragila, M. I., & Kleber, M. (2014). Water uptake in biochars: The roles of porosity and hydrophobicity. Biomass and Bioenergy, 61, 196–205. https://doi.org/10.1016/j.biombioe.2013.12.010
15. Hydro, Princeton. "Using an Ancient Technology in a New Way: Removing Nutrients in a Lake with Biochar." PRINCETON HYDRO (blog), July 17, 2020. https://princetonhydro.com/biochar/. Photo by: Colleen Lyons of the Lake Hopatcong Commission
16. Cellular Structure Image: Mulabagal, V., Baah, D., Egiebor, N., & Chen, W.-Y. (2015). Biochar from Biomass-A strategy for carbon dioxide sequestration, soil amendment, power generation and CO2 utilization, Handbook of Climate Mitigation and Adaptation.

CATALYZING REGENERATIVE SYSTEMS WITH BIOCHAR

- Biomagnification: Adapted from: Salmon by Bakunetsu Kaito from NounProject.com + Krill by Phạm Thanh Lộc from NounProject.com + Orca by #7027 from NounProject.com
- Eutrophication: adapted from: Dead Fish by Lucas Helle from NounProject.com
- Regional Biodiversity: adapted from: Flower by Template from NounProject.com + Dna Backbone by Julie Ko from NounProject.com
- Regional Food Networks: Adapted from: Corn by Slidicon from NounProject.com + Pea by Olga from NounProject.com + Shovel by Wuppdidu from NounProject.com + author creation
- Circular Economy: Author creation
- Carbon Footprint: adapted from: Eco Footprint by Fran Couto from NounProject.com
- Public Health: Hands by chiccabubble from NounProject.com + Sun Flower by bastian vieri from NounProject.com
- Biocultural Capital: Adapted from: Joke by Myles McCoy from NounProject.com + Sun Flower by bastian vieri from NounProject.com
- Circular Economy global: Author creation + Earth by Arnaldo Cabeza from NounProject.com
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- Biodiversity resilience: adapted from: Tree Frog by Lewis K-T from NounProject.com + Drop Water by Ian Rahmadi Kurniawan from NounProject.com
- Drinking Water: adapted from: Conserve Water by Mark S Waterhouse from NounProject.com

NOTES

EXAMPLES FROM SWEDEN & FINLAND

1. Biokol – Rest till Bäst. (n.d.). Retrieved December 14, 2021, from https://biokol.org/en/

HARMONIZING SOIL AND PLANT COMMUNITIES

1. Project information and images shared courtesy of the designer/horticultural engineer Jonatan Malmberg.
2. Adapted with permission from construction documents, courtesy of Jonatan Malmberg
3. Google Maps, Images, image capture: Jan 2019. User upload from Potatisen Potatisen.
4. MKB. https://www.mynewsdesk.com/se/mkb_fastighets_ab/images/holmastycket-2137756

SUPPORTING URBAN BIODIVERSITY

1. Startsida Malmö stad. (n.d.). [Text]. Retrieved December 14, 2021, from https://malmo.se/Miljo-och-klimat/Miljo--och-klimatprojekt/BiodiverCity.html
2. Fransson AM, Gustafsson M, Malmberg J, Paulsson M, 2020. Biokol Handboken för användare (The biochar manual - for users). https://biokol.org/handbok/
3. Paulsson M, 2020. Sammanfattande slutrapport för projektet Rest till Bäst (steg 2).
4. Details and insight on the project were kindly shared by lead research Ann-Mari Fransson.

DESIGNING SUSTAINABLE NEIGHBORHOODS

1. Sustainable Urban Development Programme: Stockholm Royal Seaport is leading the way to a sustainable future. https://www.norradjurgardsstaden2030.se/wp-content/uploads/2020/09/sustainable_urban_development_programme-1.pdf
2. The City of Stockholm's Environmental Work https://miljobarometern.stockholm.se/content/docs/tema/Environmental-Work-Stockholm-2017.pdf
3. Stockholm Royal Seaport Sustainability Report 2020 https://vaxer.stockholm/globalassets/omraden/-stadsutvecklingsomraden/ostermalm-norra-djurgardsstaden/royal-seaport/a-sustainable-urban-district/results-2020/sustainability-report-stockholm-royal-seaport_2020.pdf
4. Bringing biochar to your city. Lessons from the Stockholm Biochar Project. Bloomberg Philanthropies. https://nordregio.org/wp-content/uploads/2018/05/Replicating-in-Stockholm-booklet-manual.pdf
5. Image courtesy of Britt-Marie Alvem, Tree Officer, Stockholm Traffic Office.
6. Author's photos
7. Björn Embrén, personal communication.

GIVING WATER THE RESPECT IT DESERVES

1. #bluegreengrey systems at Rundelsgatan in Vellinge. (n.d.). Blue Green Grey Systems for livable streets – by edge. Retrieved December 9, 2021, from https://bluegreengrey.edges.se/project/rain-gardens-with-osl-on-rundelsgatan-in-vellinge/
2. Author's photo
3. Fridell, Kent., Sixtensson, Susanne ., et al. (2020) Livable Streets: a Handbook of Bluegreengrey Systems. Edge. Version 2.0. https://bluegreengrey.edges.se/
4. #bluegreengrey systems at Vellinge Campus. (n.d.). Blue Green Grey Systems for livable streets – by edge. Retrieved December 9, 2021, from https://bluegreengrey.edges.se/project/campus-vellinge-with-blue-green-grey-system/
5. #bluegreengrey systems in Vellinge. (n.d.). Blue Green Grey Systems for livable streets – by edge. Retrieved October 15, 2021, from https://bluegreengrey.edges.se/article/blue-green-grey-infrastructure-in-vellinge/
6. Norra Infarten: Inside the BlueGreenGrey system. (n.d.). Blue Green Grey Systems for livable streets – by edge. Retrieved December 9, 2021, from https://bluegreengrey.edges.se/article/norra-infarten-inside-the-blue-green-grey-system/

LEVERAGING RESEARCH AND EDUCATION

1. Concept Study for Bio-C Competence Center. Concept work completed by Arkitektlaget on behalf of NSR.
2. Application material for "Opportunity for Further Support for City Biochar Projects". Bloomberg Philanthropies. Provided courtesy of NSR.

CO-CREATING LANDSCAPES FOR EXPERIMENTATION

1. Tammeorg, P., Soronen, P., Riikonen, A., Salo, E., Tikka, S., Koivunen, M., Salonen, A.-R., Kopakkala, T., & Jalas, M. (2021). Co-Designing Urban Carbon Sink Parks: Case Carbon Lane in Helsinki. Frontiers in Environmental Science, 9, 346. https://doi.org/10.3389/fenvs.2021.672468
2. Author's photo
3. Mikko Jalas, personal communication

ALIGNING BIOCHARS WITH DESIGN GOALS

1. Li, S., Harris, S., Anandhi, A., & Chen, G. (2019). Predicting biochar properties and functions based on feedstock and pyrolysis temperature: A review and data syntheses. Journal of Cleaner Production, 215, 890–902. https://doi.org/10.1016/j.jclepro.2019.01.106
2. Mohanty, S. K., Valenca, R., Berger, A. W., Yu, I. K. M., Xiong, X., Saunders, T. M., & Tsang, D. C. W. (2018). Plenty of room for carbon on the ground: Potential applications of biochar for stormwater treatment. Science of The Total Environment, 625, 1644–1658. https://doi.org/10.1016/j.scitotenv.2018.01.037
3. Jaafar, N. M., Clode, P. L., & Abbott, L. K. (2015). Soil Microbial Responses to Biochars Varying in Particle Size, Surface and Pore Properties. Pedosphere, 25(5), 770–780. https://doi.org/10.1016/S1002-0160(15)30058-8
4. Hagemann, N., Joseph, S., Schmidt, H.-P., Kammann, C. I., Harter, J., Borch, T., Young, R. B., Varga, K., Taherymoosavi, S., Elliott, K. W., McKenna, A., Albu, M., Mayrhofer, C., Obst, M., Conte, P., Dieguez-Alonso, A., Orsetti, S., Subdiaga, E., Behrens, S., & Kappler, A. (2017). Organic coating on biochar explains its nutrient retention and stimulation of soil fertility. Nature Communications, 8(1), 1089. https://doi.org/10.1038/s41467-017-01123-0
5. Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. A., Hockaday, W. C., & Crowley, D. (2011). Biochar effects on soil biota – A review. Soil Biology and Biochemistry,

43(9), 1812–1836. https://doi.org/10.1016/j.soilbio.2011.04.022

6. Lehmann, J., Cowie, A., Masiello, C. A., Kammann, C., Woolf, D., Amonette, J. E., Cayuela, M. L., Camps-Arbestain, M., & Whitman, T. (2021). Biochar in climate change mitigation. Nature Geoscience, 1–10. https://doi.org/10.1038/s41561-021-00852-8
7. Jeffery, S., Verheijen, F. G. A., Kammann, C., & Abalos, D. (2016). Biochar effects on methane emissions from soils: A meta-analysis. Soil Biology and Biochemistry, 101, 251–258. https://doi.org/10.1016/j.soilbio.2016.07.021
8. Junginger-Gestrich, Hannes., Eichler, Marcel. (2021). Supplier Onboarding Manual. Guideline for biochar Producer and Wholesaler. Carbonfuture GmbH.
9. US EPA. (2015, August 10). Greenhouse Gases Equivalencies Calculator—Calculations and References. https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references
10. Leng, L., & Huang, H. (2018). An overview of the effect of pyrolysis process parameters on biochar stability. Bioresource Technology, 270, 627–642. https://doi.org/10.1016/j.biortech.2018.09.030
11. Enaime, G., Baçaoui, A., Yaacoubi, A., & Lübken, M. (2020). Biochar for Wastewater Treatment—Conversion Technologies and Applications. Applied Sciences, 10(10), 3492. https://doi.org/10.3390/app10103492
12. Edeh, I. G., Mašek, O., & Buss, W. (2020). A meta-analysis on biochar's effects on soil water properties – New insights and future research challenges. Science of The Total Environment, 714, 136857. https://doi.org/10.1016/j.scitotenv.2020.136857
13. Liu, Z., Dugan, B., Masiello, C. A., Barnes, R. T., Gallagher, M. E., & Gonnermann, H. (2016). Impacts of biochar concentration and particle size on hydraulic conductivity and DOC leaching of biochar–sand mixtures. Journal of Hydrology, 533, 461–472. https://doi.org/10.1016/j.jhydrol.2015.12.007
14. Ni, Ni, Deyang Kong, Wenzhu Wu, Jian He, Zhengjun Shan, Juying Li, Yezhi Dou, Yueqing Zhang, Yang Song, and Xin Jiang. "The Role of Biochar in Reducing the Bioavailability and Migration of Persistent Organic Pollutants in Soil–Plant Systems: A Review." Bulletin of Environmental Contamination and Toxicology 104, no. 2 (February 1, 2020): 157–65. https://doi.org/10.1007/s00128-019-02779-8.

ROLES FOR GARDENERS, DESIGNERS & DECISION MAKERS

1. Cornelissen, G., Pandit, N. R., Taylor, P., Pandit, B. H., Sparrevik, M., & Schmidt, H. P. (2016). Emissions and Char Quality of Flame-Curtain "Kon Tiki" Kilns for Farmer-Scale Charcoal/Biochar Production. PLOS ONE, 11(5), e0154617. https://doi.org/10.1371/journal.pone.0154617
2. Ithaka Institute—Kon-Tiki. (n.d.). Retrieved December 13, 2021, from https://www.ithaka-institut.org/en/kon-tiki
3. 2018 Biochar Adventure Experience. (n.d.). Biochar for Sustainable Soils. Retrieved December 13, 2021, from https://biochar.international/peru-trip/
4. Author's photo
5. Leverage Points: Places to Intervene in a System. (n.d.). The Academy for Systems Change. Retrieved December 13, 2021, from https://donellameadows.org/archives/leverage-points-places-to-intervene-in-a-system/

TO CONCLUDE AND TO BEGIN

1. Act! | 4p1000. (n.d.). Retrieved December 14, 2021, from https://4p1000.org/act

ABOUT THE AUTHOR

Justin Roberts is a landscape designer and naturalist based in Seattle Washington. Justin has a longstanding passion for growing awareness around climate change and biodiversity loss, and for connecting people to the rest of the natural world. He is an advocate for cultivating more symbiotic ways of relating to the Earth's living communities and for growing stronger bonds between human communities through caring for the Earth.

As a designer at HBB Landscape Architecture he is working to explore and develop best practices for biochar use in urban landscapes in the Pacific Northwest with a goal of expanding regional capacity, access, and interest in biochar as an innovative material. He is also keenly interested in the intersections between biochar use and assisted migration of plants, food sovereignty, and regenerative agriculture.

During his time as a masters student at the University of Washington, he completed an independent quarter abroad centered in Malmö, Sweden, funded by the Valle Scholarship & Scandinavian Exchange Program and in collaboration with the Rest till Bäst project which provided the groundwork for the material presented in this book. He also completed a capstone studio project envisioning the creation of an urban hub for regeneration of organic waste into biochar and compost while simultaneously creating more resilient ecosystems in public landscapes.

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