Chapter 7

How Biochar Helps the Soil

Hugh McLauglin, PhD PE
Director of Biocarbon Research, Alterna Biocarbon Inc.

IN THIS CHAPTER YOU WILL LEARN:

- The constituents of biochar and how they act.
- How biochar mitigates physical deficiencies in the soil.
- How biochar helps the soil do more with less.
- How biochar restores the soil to its natural biological role.

"Biochar helps conserve plant nutrients by storing them within its matrix and making the nutrients available when crops need them."

INTRODUCTION

We know that biochar can help the soil. Biochar-amended soils have had documented beneficial effects on crop yields. However, it is not fully understood *how* biochar delivers those benefits.

Better understanding of how biochar works is essential. Optimizing the use of biochar will help feed soaring populations saddled with depleted or poor soil.

Ongoing research will clarify this important, complex subject. In the meantime, this chapter attempts to offer some coherent and plausible explanations.

BIOCHAR – A TEAM PLAYER

Biochar is a permanent soil amendment, but does not act alone. There are few direct biochar-crop interactions.

Biochar in effect acts as part of a team, working in combination with the local soil and its amendments, the individual crop or grouping of crops, and the local climate. As a soil-amending teammate, biochar improves how the soil functions as the host medium for a growing crop, even as both are subjected to the buffeting variability of growing seasons and climate.

THE ONGOING DIALOGUE ON BIOCHAR

Additional Reading

Those interested in exploring the breadth of the current dialogue on biochar are invited to download the following reports, all of which can be accessed and downloaded at http://biocharinfo.com:

- "Biochar Application to Soils–A Critical Scientific Review of Effects on Soil Properties, Processes and Functions." Report of the EU Joint Research Centre, Institute for Environment and Sustainability.
- "Biochar, climate change and soil: a review to guide future research." *CSIRO Land and Water Science Report*, May 2009.
- "Biochar as a soil amendment: A review of the environmental implications." Dominic Wolf (unpublished).

These reports are balanced and comprehensive, and leave the reader with an awareness of both the extent and limitations of the research to date.

Short research summaries on specific themes, as well as biochar fact sheets, white papers, technical bulletins, and practical guides, are available from the International Biochar Initiative (IBI) at:

http://www.biochar-international.org/publications/IBI.

An extensive list of scientific literature and hundreds of reports, updated monthly, can be found on the IBI website at:

http://www.biochar-international.org/biblio.

THE CONSTITUENTS OF BIOCHAR

To better understand the general action of biochar in soil, it is helpful to examine biochar as a small number of constituents, each of which has predictable roles in the soil.

As shown in Figure 7.1, one useful approach is to view the biochar as being made up of two portions: the "mobile" portion that will dissolve (leach) into the soil water and the "resident" portion that will remain as a stable part of the non-leachable soil matrix.

Each portion contains both **organic** and **inorganic** fractions—and each has a different destiny. In general, the mobile portion will have its greatest impact over the first one or two growing seasons, and the resident portion will remain in the soil, with sustained impact, for a very long time (decades, centuries, even millennia).

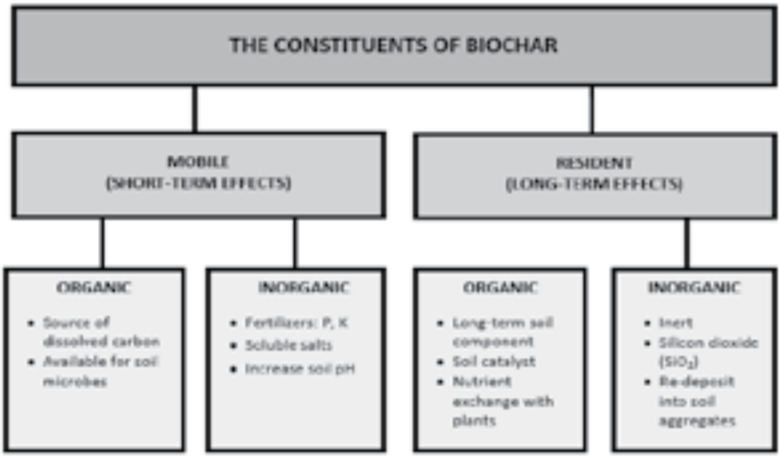

Fig. 7.1 The Constituents of Biochar

MOBILE PORTIONS

The mobile portion of biochar—the portion that can move in water or be rapidly decomposed by microbes—contains both organic and inorganic parts.

Mobile Organic Portion

The function of the mobile organic portion is fairly straightforward: it will be a source of dissolved organic carbon and will also be available organic matter for soil microbes (as later discussed in greater detail). In this regard, the biochar acts like many other sources of degradable soil carbon, such as compost and naturally deposited detritus. Over a short time frame, on the order of years, the leachable and biodegradable organic portions of the biochar are metabolized by the microbes in the soil, or washed away into streams or ground water.

Concerns have been raised about possible toxicity in soil due to mobile organics from biochar. Indeed, biochars can introduce toxic constituents, but almost invariably the toxic constituents were present in the original biomass before its conversion to biochar. For example, treated lumber can be the source of heavy metals that remain in the biochar. The actual process of **pyrolysis**—which converts biomass to biochar—has not been shown to generate significant quantities of toxic products such as **PAHs (polycyclic aromatic hydrocarbons)**. If fire produced significant toxic constituents from biomass, then every forest fire would leave behind a legacy of toxicity. Instead, renewed growth typically follows. Biochar is also well known to **adsorb** these toxic compounds when they are present in soil, in a sense "locking them up."

Mobile Inorganic Portions

The inorganic portion of biochar is transformed into ash after the biochar is burned or heated at high temperature to oxidize and remove the organic portion (which includes the carbon atoms of the char). Measurements have shown that most biochar ash is soluble in water. This is to be expected, since the ash originated as dissolved minerals in the soil water, which were then transported into the growing plants that later formed the biomass from which the biochar was created.

The mobile inorganic portion of biochar may include fertilizers, such as phosphorus and potassium, and other components that have a liming effect on the soil (that is, raise its **pH**). Generally, these inorganic constituents have the potential to improve soil fertility and crop yield in places where the specific nutrients are limiting and higher pH levels in the soil are desirable. Increasing soil pH can diminish some soluble metal toxicities (such as aluminum), when such toxicities are present. On the other hand, in alkaline soils, additional liming may not help and can actually make fertility conditions worse.

The mobile inorganic portion also contains compounds that act like salt, including sodium chloride and other neutral ion pairs. These compounds may be benign or can introduce excess dissolved salts (**total dissolved solids or TDS**), resulting in saline soil conditions. Such excess dissolved salts do not help the plants and can, in fact, inhibit or prevent seed germination and healthy crop growth. In general, salts wash out of the soil with precipitation and normally do not build up to levels that cause concern. Problems result when excessive salts are added, such as by excessive irrigation with brackish water, or where the climate provides insufficient precipitation to flush away the accumulating salts. For this reason, applications of biochars that contain salts need to be coordinated with and balanced against the local irrigation practices and precipitation patterns.

RESIDENT PORTIONS

The resident portion of biochar—the portion that stays put within the soil matrix—also contains both organic and inorganic parts.

Resident Inorganic Portion

Some plants convert dissolved minerals into stable insoluble forms, such as silica (silicon dioxide). This non-leachable component of biochar ash is a minor constituent of the biochar, and is typically inert or slowly dissolved and re-deposited into soil aggregates over time. In some plants, carbon can be locked up in these silica structures, and they have been proposed as making a significant contribution to long-term carbon sequestration. (See "Next Generation Carbon Bio-Sequestration Solutions" at http://www.plantstone.com.au/AboutPlantstone.html.)

Resident Organic Portion

The most fascinating and unique fraction of biochar is the organic portion that becomes a permanent soil component. This portion, which can also be described as "recalcitrant" or "resident," is insoluble (non-leachable). It is not consumed by growing plants, but appears to be degraded by both non-biological and biological processes over a very long time scale—stretching literally into millennia.

In light of this longevity, it is reasonable to label biochar as a "soil catalyst." The bulk of biochar remains substantially unchanged, yet enables improvements in the overall environment that the soil provides for the plants and microbes that live in it. This notion is key to many of the attributes of biochar discussed next.

BIOCHAR MITIGATES SOIL'S PHYSICAL DEFICIENCIES

One of the significant and predictable impacts of biochar is on soil drainage. Some soils, typically those containing elevated portions of clays and which are poorly aggregated, are too tight and do not drain effectively. Ineffective drainage results in extended periods of inadequate soil aeration. Other soils, especially those dominated by sandy matrices, may drain too efficiently. Overly efficient drainage can shorten the benefit of periodic wetting. In both cases, the addition of biochar compensates for the native soil deficiency in the following ways:

- Clayey and poorly aggregated soils become less compacted and provide better aeration.
- Sandy soils acquire additional bulk moisture storage capacity.

In seeking to improve bulk moisture dynamics, the initial soil texture will dictate how biochar should be introduced. To improve aeration in clay soils, the biochar must be mixed throughout the root zone; plowing or tilling is likely required.

For sandy soils, biochar can also be introduced by working it into the root zone, or by top-dressing and surface incorporation. Through the latter approach, surface water will eventually transport the biochar downward, deeper into the soil matrix; however, the biochar must be protected from erosion by wind and water until it has had time to migrate deep enough.

One way to protect the biochar after incorporating it into the surface of sandy soil is to mulch on top of it, although in some cases only deeper incorporation will protect from water erosion.

Regardless of soil texture, biochar can be applied in bands in situations where turning the soil is undesirable (for example in reduced tillage or no-till agriculture), or to avoid disturbing root integrity in perennial crops.

Using biochar to correct soil drainage properties can be a one-time fix that usually requires a significant volume of biochar to achieve the desired result. Other biochar contributions to soil dynamics can be achieved through a series of smaller, incremental applications.

BIOCHAR HELPS THE SOIL DO MORE WITH LESS

One of the major challenges in agriculture is to make the nutrients in the soil available to the plant when the plant can benefit from them. Fertilizers can often only be applied early in the growing season, before the crop canopy closes and field operations are no longer feasible. Unfortunately, between the time the fertilizer is applied and the crop takes it up, fertilizer can be leached out of the soil by excess rainfall, consumed by weeds, or metabolized by microbial activity in the soil.

Biochar helps conserve plant nutrients by storing them within its matrix and making the nutrients available when the crops need them. This happens because of a property in biochar, certain clays, and soil organic matter known as **cation exchange capacity** (CEC). CEC is a measure of a biochar's capacity to retain positive ions, such as ammonium and potassium **cations**, in an exchangeable form that is available to plants.

CEC not only helps conserve the fertilizers added to the crop during the growing season, but also improves the soil's ability to capture and retain nutrients from other sources available at other times. For example, at the end of the growing season crop residues are often left in fields to decompose. When this organic matter decomposes, biochar captures some of the nutrients released, saving those nutrients for the next growing season. Moreover, biochar's inherent capacity for storing nutrients, as measured by CEC, has been shown to actually increase as the biochar interacts with the soil matrix over long time periods.

Biochar also modifies and improves the soil's performance by retaining moisture and making it available during periods of low precipitation and hot, dry soil conditions. This is possible because many biochars have very large internal surface areas—typically over 100 square meters per gram in biochars that have good **adsorption capacity**. This internal surface area adsorbs moisture when water availability within the soil is high and releases it back into the soil when water availability is depressed.

Thus, during annual cycles when rainfall is sparse—and in drought conditions—biochar can improve retention of soil moisture. In many areas of non-irrigated agriculture, crops are planted during the rainy season, followed by a growing season that ends due to lack of moisture. In this situation, the biochar helps the soil conserve precious moisture reserves, in effect extending the growing season.

In sum, biochar helps save precious water where irrigation is used and provides critical support where it is not, improving crop performance during periods of drought.

BIOCHAR RESTORES THE SOIL TO ITS NATURAL BIOLOGICAL ROLE

Healthy, natural soil involves more than simply metering nutrients to plants. A healthy soil-plant nutrient exchange involves a pivotal intermediary: innumerable soil microbes, which synergistically participate in cycling those nutrients. One example of this remarkable partnership is **mycorrhiza**[7] (from the Greek words for "fungus" and "root"), the symbiotic association between beneficial fungi and plant roots. A more detailed description of how it works follows in the box labeled "Amazing Mycorrrhiza."

This exchange effectively improves the plant's ability to absorb minerals, allowing nutrients such as phosphorus and zinc to be passed from the soil into the fungus, and then into the plant roots.

This soil-microbe-plant troika has developed over billions of years and is essentially a life-or-death proposition for plants. Of the 17 necessary elements for plant growth, 13 are derived from mineral matter in the soil. Only the remaining four—carbon, oxygen, hydrogen and nitrogen—are obtained from the atmosphere. And nitrogen acquisition, in the absence of commercially produced fertilizers, requires the assistance of microbes.

Since 95% of all plant families are mycorrhizal, this exchange phenomenon is the norm rather than the exception for natural plant growth. Simply put, plants make their own food (see the text box labeled "Plants Make Their Own Food")—although now we know they do it with the help of microbes.

If plants are fed nitrogen and other nutrients from synthetic fertilizers, mycorrhizal exchange is inhibited. After all, the exchange does draw energy from plants in the form of excreted sugar, which plants can use for other survival needs if alternate nutrient sources are available that do not demand investment in mycorrhizal exchange.

HOW DOES BIOCHAR FIT IN?

Biochar makes a significant contribution to mycorrhiza by promoting soil microbe populations. Specifically, biochar:

- Detoxifies soil water by adsorbing compounds that inhibit microbe growth.
- Provides a protective habitat for microbes (see Figure 7.2).
- Improves soil moisture management, as discussed above.

[7] The term "myccorrhiza" refers to both this symbiotic relationship and a participating fungus. In the latter sense, the plural is "mycorrhizae."

AMAZING MYCORRHIZA: HOW DOES THE PARTNERSHIP WORK?

Soil microbes and fungi live in intimate contact with soil particles and moisture, aided in this by their large surface area to cell volume ratio. A fungus has a large mass of filaments called mycelia (singular, mycelium), which are much smaller than plant root hairs. These filaments give the fungus extensive surface area and, with it, a high capacity for absorbing water and mineral nutrients. (Biochar has the same property.) However, for the fungus and other soil microorganisms to thrive, they need energy in the form of carbohydrates.

Plants photosynthesize sugars (such as glucose and sucrose) from carbon dioxide, water and sunlight. To carry on this activity, plants need minerals from the soil for myriad enzymatic processes and to form chlorophyll (which is similar to hemoglobin in animals except with the iron replaced by magnesium). However, while all plants can extract some minerals from the soil through their root hairs, they benefit from increased mineral nutrients that support their areal growth and fertility.

So, here's the deal: The mycorrhizae (fungi) make soil nutrients available and extend their filaments into plant roots, thereby providing nutrients for uptake by the plants. The plants in return send sugar from the leaves down to the roots where it is excreted to feed the fungi.

But the deal goes deeper: deep roots of trees and grasses bring minerals up from lower in the earth and deposit them to the topsoil in the form of leaf and other plant litter. Fungi break this dead material down into simpler components (they extend their filaments into dead material also) and extract energy from it, as well as building it into the organic structures of their bodies. When the fungi and other soil organisms die and decompose, they provide organic nutrients to the plants.

In the natural world, leaf litter, decaying animals, and plants provide a moist and aerated protective mat, resulting in a perfect environment for the soil microorganisms and fungi. In human agriculture, mulching and composting can replicate this environment to grow strong, disease resistant, and nutritious plants.

—*Paul Taylor (Ed.)*

MORE GOOD NEWS ABOUT MICROBES

- **Phosphorus Uptake.** Plant roots on their own may be incapable of taking up demineralized phosphate ions—for example, in alkaline soils. However, the mycelia of mycorrhizal fungi provide access to this phosphorus, and transmit it to the plants they colonize.
- **Getting Nitrogen.** The Haber-Bosch process, invented in the early 1900s, paved the way for commercially produced nitrogen fertilizers. But before then, virtually all farmer-applied nitrogen fertilizers were recycled animal manures. And before there were farmers—or even animals—plants obtained their nitrogen via nitrogen fixation, by forming nodules with certain bacteria.

PLANTS MAKE THEIR OWN FOOD

As Arthur W. Galston discussed in *Life Processes in Plants* (Scientific American Library, 1994):

We have not always understood that plants synthesized their own food. The ancients believed that plants derived their food from the soil, and that the root system was a kind of diffuse mouth sucking nutrition from the earth's breast. This notion was proved wrong early in the seventeenth century, when a Dutch physician named Jan Baptista van Helmont planted a 5-lb willow sapling in a container of dried soil weighing exactly 200 lb. For five years, he added nothing to the container except rainwater. When he harvested the tree, he found its weight to be 169 lb, while the dried soil now weighed 199 lb 14 oz, a small loss he attributed to experimental error…

Van Helmont also concluded … that plants derived no materials at all from the soil other than water. He did not appreciate that the approximately two ounces lost by the soil included mineral elements that were in fact essential to the well-being and growth of his tree [page 18]. …

If the plant is fed any form of fixed nitrogen, especially ammonia or amino acids, both nodulation and nitrogen fixation are strongly inhibited. This makes good sense, since both processes are "expensive" from an energy point of view. Plants obviously prefer to take the easy road to obtaining their fixed nitrogen by adsorbing ready-made compounds if they are available, but they can switch to a more independent, energy-intensive mode when required [page 202].

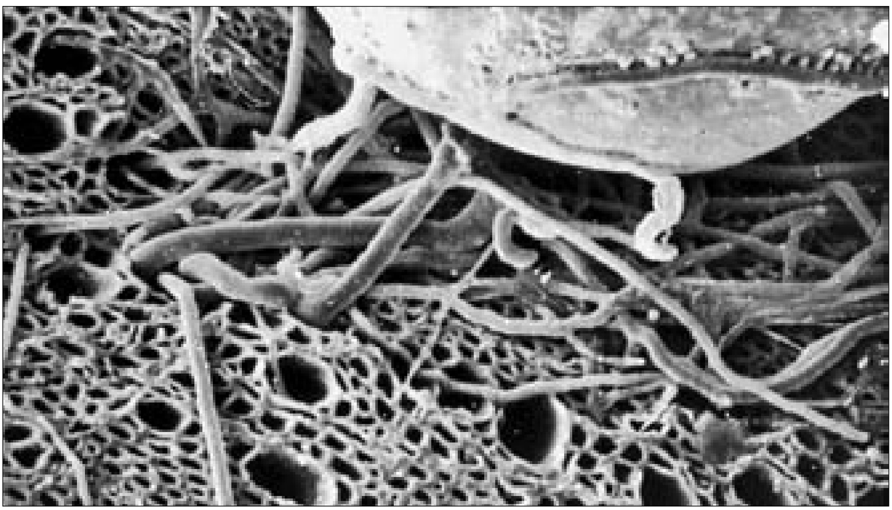

Fig. 7.2 Mycorrhiza Fungal Hyphae Growing into Biochar Pores

Source: Ogawa (1994)

BIOCHAR WAS SOIL'S FIRST AMENDMENT

"Biochar" is merely the current name for natural or manufactured pyrolyzed biomass; nature has in fact deposited "biochar" in the soil via groundcover fires for billions of years. The soil-microbe-plant interaction has developed over time via natural selection, with the successful combinations prospering and the failures fading away.

Today, there are many ways to promote crop productivity. In modern industrial agriculture, fertilization is the dominant approach. Although such fertilization can replace depleted nutrients, it is a temporary solution and does not contribute to overall, long-term soil quality.

Biochar does. Given the significant soil benefits described in this chapter, biochar—an original soil amendment created and validated by nature—offers immeasurable potential in the modern world for helping to grow food sustainably, especially when used to address deficiencies in local agriculture.

CONCLUSION

Using biochar will not cause plants to grow in a new way. Rather, it helps the soil provide conditions more conducive to plant growth.

KEY POINTS FROM THIS CHAPTER

- Biochar's constituents have a predictable role in the soil that enables conclusions about the benefits of biochar in specific growing situations.
- Biochar works in combination with other soil components and soil microbes to permanently improve the overall soil dynamics and plant nutrition, which in turn improves plant growth and yield.
- Biochar is made up of two portions. One portion is mobile, and includes biodegradable and leachable constituents. The other portion is resident: it is non-leachable and decomposes extremely slowly.
- The resident organic portion of biochar has unique internal structure and properties that give biochar its compelling benefits. This portion will remain in the soil, with beneficial amending impact, for a very long time—decades, centuries, and even millennia. Although conventional fertilizers may provide short-term benefits, they do not contribute to overall, long-term soil quality.
- Biochar is a natural material that has been deposited into soil by groundcover fires for billions of years. In its modern application, however, biochar can be manufactured and applied to improve soil fertility.
- Biochar thus offers substantial potential to the modern world for growing food sustainably, especially where soils are poor.