A Perspective on Terra Preta and Biochar

Examining the controversy about terra preta reproducing itself, and what this may mean for the theory that terra preta is ancient biochar soil

By Austin Liu - March 2020

The Modern Discovery of Terra Preta, and a Brief Modern History of Biochar

In the Amazon Basin, there exists thousands of hectares of cultivated plots consisting of unusually fertile black soil, termed Terra Preta de Indio — "dark earth of the Indians" — called Terra Preta for short. These soils are many hundreds if not thousands of years old, and have remained remarkably fertile in spite of the tropical rainfall, which accelerates the weathering of soil and the leaching of water soluble nutrients. Modern scientific interest in this material began with a Dutch scientist named Wim Sombroek, whose book Amazon Soils, published in 1966, began the modern investigation into the nature of these soils and attempts to discern their secret. It was established that these soils were artificially cultivated by an established civilization that practiced agriculture, since the soils were always found with human artifacts and near the ruins of human settlements, and often had fired-pottery fragments buried in it. It was also established through analytical examinations of the soil that these soils contained pyrogenic carbon (carbon from charred materials). These soils were seemingly permanently fertile, with double the crop yields compared to surrounding soils and holding about three times as much phosphorus and nitrogen, while consisting of about 9% carbon, whereas surrounding soils contain around 1%.

Interest in the use of charcoal as a soil amendment began to grow dramatically in the 2000s, which can be credited to various publications by Prof. Johannes Lehmann, which popularized to the scientific community the concept that the production and use of charcoal could not only supply energy, but that the charcoal could improve soil fertility while sequestering carbon to fight climate change, first proposed by Sombroek. At that time, the term *agrichar* was variously used to specify that the application of interest was the agricultural application of charcoal, but since the term "agrichar" was the trademark of Pacific Pyrolysis company, the term *biochar* was coined, and the term was officially adopted at an international scientific conference in Birmingham, England, in 2009. This is not to say that charcoal had not been studied for its agricultural applications; examples of scientific study of the use of charcoal as a soil amendment go all the way back to the 1700s [*See the book* Geotherapy *by CRC Press, Chapter 11 — “Biochar: the Field Experience”, for an account of the study of agricultural uses of charcoal in the 1700s, 1800s, 1900s, and 2000’s*], but the mixed results, the lack of mature analytical techniques for the biochemistry of soil, and the lack of a distinguishing term and concept to keep agricultural charcoal research from being lost among all the other research done on charcoal conspired to keep biochar research from getting the attention and funding it deserved.

Those of you who are new to biochar may wonder why so much research was needed. Very early on, it became clear that simply adding charcoal to the soil was not all there was to it. Just as studies on the use of charcoal as a soil amendment in the 1700s and 1800s had mixed results, early attempts to simply add charcoal to soil found that in many instances of direct application, charcoal seemed to have an initially counterproductive impact on the soil, robbing the plants of nutrients as the charcoal adsorbed nutrients out of the soil too aggressively and bound these nutrients too tightly. Scientific research focused on what the difference was between modern biochar-amended soil and terra preta, and how to reproduce the amazing fertility observed in terra preta.

Since that time, academic research on biochar has exploded, in what could appropriately be called a biochar renaissance. In 2017, the number of scientific papers published on studies of biochar exceeded the papers on compost, and the pace of research has only accelerated internationally.

A shift in thinking: Should the objective of biochar research be to reproduce terra preta?

An unspoken meta-narrative that emerges from among much of the study of biochar early on in the biochar renaissance implied that the objective of this study was to reproduce terra preta. Wim Sombroek's own challenge to soil scientists prior to his death in 2003 was to develop *terra preta nova*, "new terra preta", to address the problems of soil fertility and climate change. Even if he meant it figuratively, and did not imply this as a charge to faithfully reproduce the original terra preta, the way this challenge was framed seems to me to have colored the discussions around the topic of biochar.

Although various hypotheses abound, nobody is exactly sure of how terra preta was produced. Bold claims by various proponents of cultured "effective microbes" and enthusiasts of specific preparations of biochar to have reproduced terra preta are unwarranted and baseless. There simply is not enough evidence for us to deduce how terra preta was made, and claims by anyone who is not an anthropologist with field experience in the Amazon ought to be received with skepticism. Even knowing that terra preta contained charcoal does not give us much to infer; knowing that charcoal was involved still does not tell us what feedstocks and charring processes were used, what additional processes were involved, how it was incorporated into the soil, how long it resided in the soil until it started to show benefits, and what proportions and schedule of incorporation were used. Each of these variables has an influence on the agronomic qualities of the resulting char. There are even some who dispute that terra preta is biochar amended soil, due to the observation that terra preta seems to reproduce itself.

The objective of reproducing terra preta may be partially motivated by notions of solving a mystery and recovering lost ancient knowledge, but ultimately, in light of the body of knowledge and the practical applications and benefits of biochar that have been discovered, terra preta is irrelevant, having served its role as an inspiration. The true objective is to improve long term soil fertility and resilience, especially in the face of intensified climate change. A parallel objective is to draw down and store carbon. In as much as we achieve those ends through biochar research and policy implementation, it does not matter whether or not our efforts reproduce terra preta. The original terra preta was produced in an oxisol (a soil order of highly weathered tropical soil with oxide-rich subsoil), contains charcoal made of tropical woods, and was shaped by the soil microbiome of the Amazon. In each agricultural region, differing soil parent material, differing climate, differing crops, differing soil fauna, and differing microbiome make the goal of faithfully reproducing terra preta inappropriately narrow. Exporting terra preta in order to propagate its microbiome would not be appropriate either; besides the microbiome not necessarily being well suited to other climates, soils, and crops, transporting soil brings with it the risk of introducing invasive species.

If a particular method of application of biochar yields good results, whether or not it faithfully reproduces terra preta is irrelevant; it is not possible to ever verify that any method successfully replicated terra preta nor its production method since there are no written records documenting its production. It is enough that terra preta inspired the investigations into biochar that resulted in the discovery of the known benefits and effective agronomic applications of biochar.

Is Terra Preta Charcoal-Amended Soil?

The idea that terra preta is anthropogenic charcoal amended soil is not without controversy. Proponents of the hypothesis that terra preta is anthropogenic charcoal amended soil support this hypothesis on account of several findings: analytical methods examining the microstructure of the carbon in terra preta confirm that it is pyrogenic, and terra preta was often found to have pottery shards incorporated into it (whether incidentally or by design). Inferring from the thousands of hectares of land mass cultivated as terra preta, along with the depth of the terra preta and how thoroughly the charcoal is incorporated into the soil, the idea that terra preta formed by gradual incorporation of char from repeated massive forest fires seems implausible, especially given that it is found in the Amazon rainforest.

The strongest argument against terra preta being anthropogenic comes from the observation that terra preta regenerates. The late William Woods, one of the pioneering biochar researchers who contributed to the biochar renaissance, observed that in Brazil, terra preta has been mined and sold as fertile topsoil and potting mix for decades. The miners dig away the top 20cm of terra preta off the top of the mining area, and move on to another area, leaving the mined area to recover for 20 years. Over the course of time, the terra preta thickens as it regenerates itself from the forest litter that falls on it. By this account, it would appear that terra preta is merely a special form of forest litter compost. This also suggests that much of the observed depth of terra preta may not be originally cultivated material, but later growth due to the conversion of forest litter.

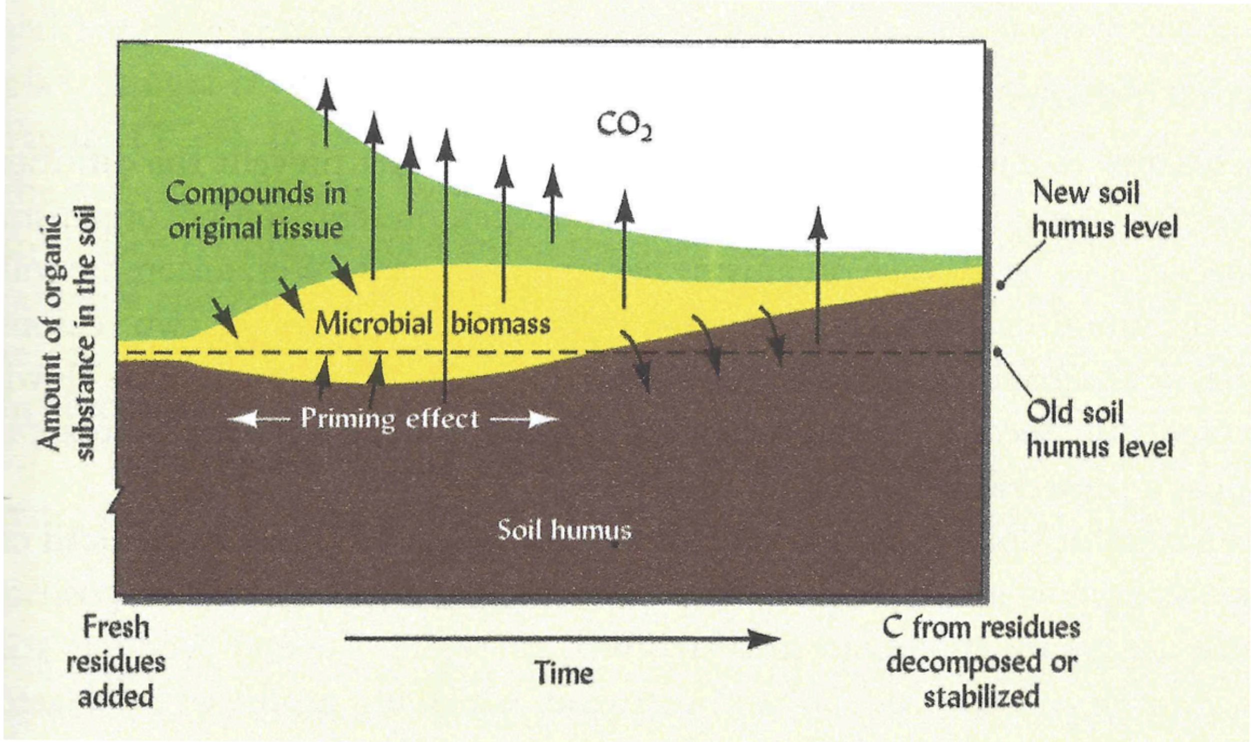
Terra preta being mined. From the 2011 BBC Documentary on terra preta titled "The Secret Of Eldorado".

The regeneration of terra preta from forest litter suggests that the microbiome of terra preta may have as much of an influence as added charcoal, imparting the character of the underlying material on organic material that decays upon it, analogous to the propagation of a sourdough starter “mother dough” into freshly added flour. However, it is important to point out that the charcoal content of terra preta cannot regenerate and cannot simply reproduce; pyrogenic carbon requires high temperatures to form its associated microstructures, and does not form in the decaying organic matter that builds up on terra preta. Furthermore, from the few videos and photos where terra preta mining can be observed, it appears that the material is not black like known examples of charcoal amended terra preta, but rather brown, suggesting that though this material is identified with terra preta, it probably does not contain charcoal, unless soil fauna have mixed deeper layers of soil with the new material (a process known as *bioturbation*), introducing charcoal into it from the underlying terra preta.

If this is so, what is going on? What is the relationship and relative contribution of charcoal and the microbiome of terra preta? And what does this mean for our theories of the origins of terra preta and our attempts to optimally use charcoal as a soil amendment? It turns out that terra preta is not the only soil that regenerates. The regeneration of terra preta appears to be an example of negative priming.

Negative Priming

Priming describes the phenomenon of the reduction of humus from soil and a multiplication of microbial biomass upon the decay of organic residues added to the soil, such as forest litter falling upon the ground in the autumn. As the microbial decomposers begin to consume the organic residue and multiply, there is a loss of humus and an increase in microbial biomass (called the *priming effect*), suggesting that the decomposition of fresh residues results in further decomposition of existing humus. As the decomposition finishes, the microbial biomass gradually reduces as the level of soil humus increases, resulting in a net increase in the amount of humus. This effect is observed in forest soils, and is termed *negative priming*.



A schematic illustration of the changes in soil carbon fractions when new forest residues are added, taken from Figure 12.5 from the Soil Organic Matter chapter of "The Nature and Properties of Soils", 15th ed. The priming effect is called out in this figure, but negative priming is not labeled. Negative priming is the subsequent increase in soil humus levels following the reduction in microbial biomass.

The regeneration of terra preta appears to be negative priming at work. The microbiome and charcoal are both involved, because the addition of charcoal appears to modify the microbiome of compost and soil. For example, the addition of biochar to compost (not the mixing of biochar with finished compost, but the addition of biochar at the beginning of the composting process) has been found to significantly abate the methane emissions of compost by favoring methanotrophs (methane eating bacteria) over methanogens (methane producing bacteria). Terra preta has even been found to foster mycorrhiza and host higher populations of free-living diazotrophs (nitrogen-fixing bacteria which are not bound to the root nodules of legumes). [*See* Geotherapy: Innovative methods of soil fertility restoration, carbon sequestration, and reversing CO2 increase*, ch. 10,* Geology into Biology*, by David Yarrow. p. 208 and p. 219.*] These are merely a couple of examples; compost and soil are home to tens of thousands of species of microbes, and biochar likely also exerts selection pressures on these microbes that result in significantly different proportions of various species, resulting in a significantly different microbiome from the surrounding soil. It would be this altered microbiome that colonizes and decomposes the new forest residue landing upon it, transforming it into regenerated terra preta populated with the same microbiome, exhibiting all of the characteristics to the parent material due to the microbiome, while lacking charcoal.

In our own field work with biochar at Gill Tract Community Farm in Albany, California, we have observed that biochar significantly alters the behavior of compost piles, resulting in compost with noticeably different characteristics. In 2018, Gill Tract Community Farm partnered with the Local Carbon Network as an early adopter of our biochar. Wary of the break-in period of suppressed plant growth incurred by adding biochar directly to soil, we decided to send the biochar through their compost piles as an exploratory application. Prior to adding biochar to their compost piles, the piles would heat up to about 130˚F, but the heat would dissipate when the piles were turned, and would not recover. After adding biochar to the compost pile, the compost would heat up to 155˚F, and would remain that hot for nearly a month. By the end of six weeks of composting, the piles would often be at temperatures over 130˚F.

Furthermore, the raised beds built using biochar compost had some notably different behavior. The raised beds at Gill Tract Community Farm at the time these photos were taken were made using an extremely compost-rich blend; each bed consisted of a blend of 20% compost made on-site, 40% purchased compost, and 40% soil. (Since then the composting program has significantly expanded, and now, hardly any purchased compost is used in the raised beds.) This mixture is packed into a frame while damp, and the frame is removed, leaving the bed unsupported, for better drainage and aeration. The raised beds made with biochar compost remained intact throughout the season, and maintained excellent aggregate stability, which appeared to be due to increased fungal activity, whereas the raised beds made with conventional compost collapsed and shrank away over the course of the season. We suspect that some of the shrinkage and collapse is due to incomplete decomposition in the compost piles without biochar.

[***Updated 11/7/2019****:* Actually, there were confounding factors pointed out to me by one of the Gill Tract interns, because some of the beds were prepared using other methods besides the packed frame method described above and the observation I made above did not account for this. For the sake of honesty and rigor, I need to qualify that the observation made above cannot be attributed to biochar without controlling for confounding factors. More rigorous experiments are needed establish whether biochar has a significant impact on this effect.

Electron Transfer Hypothesis

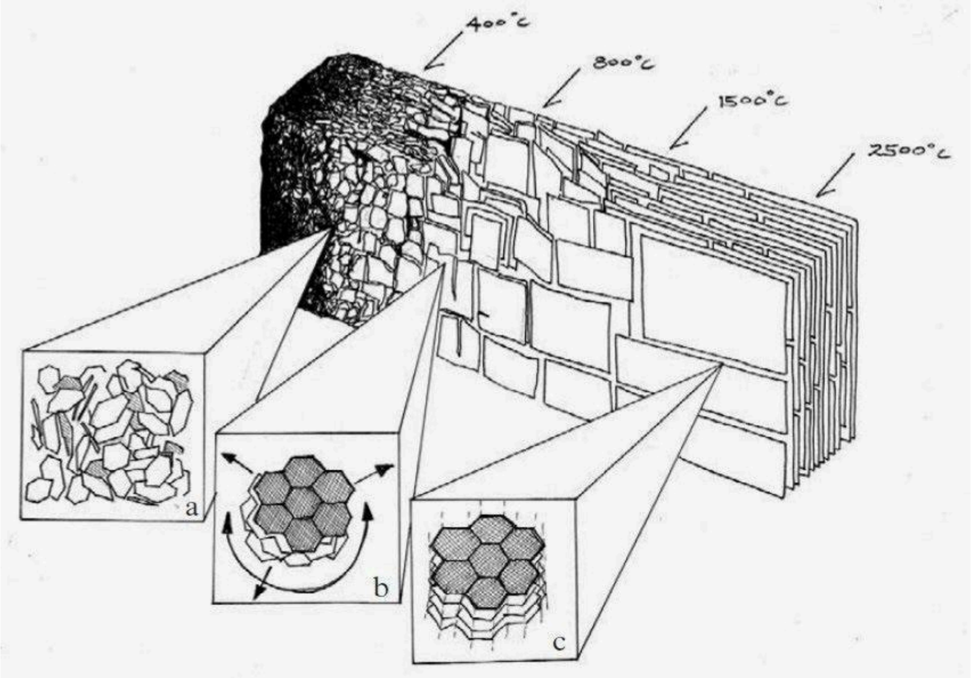
Why would biochar modify the behavior or even the composition of the microbiome of the compost and the soil? In recent years, emerging research suggests that biochar's facilitation of electron transfers among various soil microbes may play a role. For example, it was found that biochar helps abate N2O emissions from soil because of its role in transferring electrons. In 2017, it was published that biochars prepared at different temperatures were found to exhibit different mechanisms of electron transfer. In order to understand why this would have an influence on the behavior and composition of the microbiome, a bit of background explanation is needed.

The microbes in soil often carry out biochemical processes which leave them with an imbalance of electrons — in some cases, a surplus that they need to discharge, and in other cases, a deficit of electrons which they need to neutralize. These charge imbalances can build up to the point where they become bottlenecks on microbial activity. To overcome these imbalances, bacteria naturally grow microbial wires, called *pili*, to reach out and touch microbes carrying out electrically complementary activity in order to transfer electrons. The electrons obtained by these transfers are utilized in converting certain mineral nutrients into usable form. (For example, see this article on pili electron transfer in geobacter species.) Unfortunately, these microbial wires are materially expensive to grow, since they are made of protein. The number of complementary microbes that can be reached is limited by the length and the number of pili that can be grown, and the pili have fairly limited conductivity.

- This electron transfer soil service is where biochar appears to make a difference. Biochar affords bacteria two mechanisms by which they can transfer electrons more efficiently than direct electron transfer between microbes touching each other using pili: the *geobattery* mechanism, dominant in biochar produced at temperatures under 600˚C, which charges and discharges electron exchange chemical groups on its surface to exchange electrons with microbes that come in contact with these groups, and

- the *geoconductor* mechanism, a much faster and much more prolific electron transfer mechanism, found in biochar produced at temperatures over 700˚C, which directly conducts electrons between microbes in contact with the char. A macroscopic piece of biochar visible to the naked eye can host millions of bacteria and archaea on its surface, along with contact to fungal hyphae. By directly conducting electrons among them, it serves as a microbial marketplace where electrons are the currency of exchange, removing the electron transfer bottleneck for all of their relevant biochemistry.

As charcoal is heated past 600˚C, the amorphous carbon structure begins to self-organize into more stable structures. The carbon rings form small graphene-like sheets, which are electrically conductive. As the processing temperature increases, these flecks grow and dramatically increase in conductivity as the temperature exceeds 700˚C. The following illustration (used with permission) from *Biochar for Environmental Management* shows the relationship between the char processing temperature and the resulting microstructure:



At the highest temperatures and longest time exposures, the microstructure of the carbon matrix of the char converts to that of graphite.

It appears that soil microbes thrive in the presence of biochar because they exploit the electron transfer services of the biochar. A quote from the news report on this discovery:

> *"[Prof. Johannes] Lehmann and the members of his laboratory had struggled to understand why microorganisms thrived in the presence of biochar. The group removed soil phosphorus, making the environment inhospitable. They ruled out water and nutrients. They discarded the use of biochar as a food source because microorganisms cannot consume much of it. Through [Dr. Tianran] Sun's background in environmental chemistry, the scientists found that microorganisms may be drawn to electrons that the biochar can transport."*

Biochar and the Natural Selection of the Terra Preta Microbiome

In light of the electron-transfer soil service provided by biochar, I propose the following theory of terra preta's origin and apparent self-propagation from forest litter:

The original terra preta was charcoal amended soil, and was systematically cultivated because of the observed benefits. (It seems unlikely that resources and labor would have been set aside for widespread systematic production of charcoal amended soil if the charcoal required long periods of aging to offer any agronomic benefit.) The presence of charcoal modified the soil environment, favoring microbes that best exploit the soil services offered by the charcoal (such as electron transfer), resulting in a modified soil microbiome. This modified microbiome then self-propagated up into the decaying forest litter materials that accumulated on top of it, resulting in an increase in topsoil that exhibits the characteristics of the decomposed soil organic matter in the underlying charcoal-amended soil.

Co-composted Biochar

One additional confounder must be accounted for in informed speculation about the origins of terra preta: biochar is not necessarily immediately beneficial to the soil if it is directly mixed into soil as a soil amendment. In many of the early studies examining the agronomic applications of biochar, it was found that adding biochar directly to the soil was not immediately beneficial. There would be a break-in period during which biochar was found to suppress plant growth, or even repel roots and soft-bodied soil creatures like worms. This break-in period has variously been found to take as long as a couple of years in the worst instances. It is speculated that a couple mechanisms may be at work:

- Biochars that were produced at lower temperatures, which are sometimes not fully devolatilized, start out hydrophobic, due to the presence of tar — condensed from the smoke released by pyrolysis. Until the tar is broken down (primarily by fungi that can digest tar) and the char is colonized by beneficial microbes, the tars have a preservative-like biocidal effect.
- Biochars that are fully devolatilized, and especially biochars that have been exposed to reduction reactions (which we will look at in detail in later installments) have significantly higher adsorptivity, and behave like carbon filters in the soil, aggressively adsorbing and binding to nutrients, rather than loosely binding the nutrients like nutrient exchange sites in mature soil organic matter.

If this is the case, how might the indigenous Amazonians have prepared their charcoal for use in soil in the preparation of terra preta? Although we cannot know with certainty, we can speculate on what methods would have been accessible to them while yielding compelling benefits.

In the wake of various experiments and studies that reported that direct application of biochar to soil did not result in compelling benefits, various methods have been proposed to “charge” the biochar, “break it in”, and populate it with beneficial microbes for use in soil. Such methods include mixing char with fertilizer, manure, or compost, all of which have been more effective than direct application of biochar to soil. In the course of examining the scientific literature, and in our own experimentation, we have settled on co-composting biochar as the best practice for preparing biochar for use in the soil. Co-composting refers to the practice of mixing biochar with compostable materials, and letting the mixture go through the composting process. It is not to be confused with the practice of mixing biochar with finished compost The “co” in “co-composting” refers to the fact that the biochar is *with* the compost through the composting process, but does not decompose even though it influences and contributes to the process. When biochar is co-composted, the resulting biochar compost is immediately beneficial to soil. Furthermore, the addition of biochar to a compost pile reduces odor, particularly ammonia. [*A recently published paper by Lehmann’s soil science group at Cornell University found that charcoal has an incredible capacity to take up ammonia, both through adsorption and chemically binding to ammonia, thereby reducing ammonia odors and emissions.*]

At Gill Tract Community Farm, the pilot biochar deployment site for the Local Carbon Network, co-composted biochar was tested in raised beds and compared against raised beds prepared with regular compost. The results were rather unexpectedly dramatic. Every plant that received co-composted biochar exhibited incredible fertility, though no additional fertilizer was used in any of these comparisons:

Collard seedlings:

Artichoke:

The artichoke plant that got co-composted biochar continued to grow at an accelerated rate. In merely a month and a half after the photo above was taken, it had grown into this mighty behemoth:

And it yielded a ridiculous harvest of artichokes—roughly eight times as many as the plants that received conventional compost, according to the farm managers at Gill Tract Farm. This was rather unexpected, since no additional fertilizer was used.

Broccoli:

Pumpkin:

What seems to happen when biochar is co-composted is that the char adsorbs a hydrophilic porous coating of decomposition products, rich in nutrient exchange chemical sites and electron exchange sites. This coating seems to confer upon the char most of the observed benefits of char which has “aged” in the soil. Since this benefit is obtained so rapidly with co-composting, especially compared to surface oxidation by aging, it seems more plausible that this was discovered by the indigenous peoples of the Amazon. Furthermore, during the composting process, large quantities of nitrates which would otherwise be lost to off-gassing or lost through the leachate (the liquid that sweats out of compost) have been found to be captured on the biochar. These captured nitrates then serve as an abundant source of fixed nitrogen for the plants that receive the biochar, resulting in broad, deep green leaves and vigorous growth. This is the sort of compelling observed benefit that may have motivated the Amazonians to practice widespread systematic use of charcoal and compost to prepare newly cultivated land for agriculture.

Speculations on the Origins of Terra Preta

With such dramatic benefits immediately available to the crops that received co-composted biochar, here is what I suspect led to the discovery of terra preta by the ancient indigenous Amazonians.

Charcoal waste from household cooking fires were likely thrown out with household food waste and human waste. Charcoal may have even been deliberately used to control odors from manure and fecal waste. Since all of their waste consisted of biodegradable materials (with the exception of broken pottery), the mixture of char and waste essentially composted whether they intended it to or not. The observation that plants growing in and around their decomposing waste piles exhibited unusual vigor may have led to experimentation with deliberately amending agricultural soils with this composted mixture and systematically preparing compost with specially prepared charcoal for amending agricultural soils. The subsequent abandonment of farmland due to the collapse of the population from diseases introduced by contact with European explorers resulted in the Amazon forest growing back in over terra preta in depopulated areas, and the accumulation of leaf litter over the terra preta then continued to increase the soil organic matter via negative priming as the microbiome of the charcoal-amended soil propagated upwards into the forest litter, which we observe as terra preta reproducing itself.

Concluding Thoughts

Even though it is not possible to conclusively determine the method by which terra preta was produced because we have no surviving record of the process used by the ancient indigenous civilizations of the Amazon, at this point in our history, it suffices that the mystery of terra preta has inspired the scientific study of biochar, along with widespread experimentation, which has yielded so many useful applications of charcoal. With insights from soil science, we understand that terra preta is not the only soil that increases its topsoil humus/soil organic matter from plant residues (such forest litter) that accumulate upon it; this is the expected behavior of healthy soils that receive regular accumulations of plant residues. We also now understand how biochar can significantly modify the soil environment, and therefore, the conditions that favor and select for a different soil microbiome, which then propagates into organic residues that decompose upon it. With even just the agronomic benefits of co-composted biochar, produced by methods informed by these findings, we can significantly improve the fertility and resilience of our agricultural soils, and it would not matter whether or not our methods faithfully reproduced the original terra preta. What is needed now is deployment and widespread application of what we know. Whereas the ancient indigenous people of the Amazon cultivated many thousands of hectares of poor tropical oxide soils into some of the most fertile agricultural soils in the world, we in the modern developed world are destroying ours with chemical fertilizers and conventional farming practices, and those who know about biochar, though having access to mechanized farm equipment have barely matched the acreage cultivated by the ancient Amazonians. The benefit of all of our scientific insights only come from putting them to practice.