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Biochar as a Soil Amendment for Avocado Production

One of the latest innovations in agriculture is the use of pyrolyzed carbon (biochar) as a soil amendment to improve soil fertility. In addition to enhancing the chemical and physical properties of soils, biochar offers a means for diverting carbon into soils to sequester carbon dioxide that would otherwise be released to the atmosphere. While similar to charcoal that is used for fuel and for cooking, the term "biochar" in used distinguish this material has been produced in a manner that makes it safe for use in agriculture. Biochar produced for agriculture can be produced from a wide variety of feedstocks, such as straw or agricultural wastes, or from woody materials such as limbs and wood from pruning operations; whereas, other types of char made from sewage sludge and municipal wastes are generally not suitable for incorporation into agricultural soil. There is now intensive research being carried out to examine the changes in soil chemical, physical, and biological properties that occur after incorporation of biochar into different types of soils, and the variation in plants responses across different soil types. In soils having low organic matter, biochar can significantly improve the cation exchange capacity (CEC), water holding capacity, lower the soil bulk density, and stimulate microbial activity. There is also evidence for increased nitrogen use efficiency, suppression of root disease, and increases in population sizes of plant beneficial microorganisms. However, there are still many questions remaining about how biochar can best be used for improving orchard soils. For example, biochar may adsorb and lower the availability of phosphorus to plants and decrease the efficacy of some pesticides, thus requiring some changes in management practices. There are no published experiments yet on how biochar affects avocado tree growth and yields, but positive results obtained with other crops suggest that it may be worthwhile to investigate how biochar might be used in avocado orchard soils. This article provides a brief overview of how biochar is produced, the current base of knowledge on its potential benefits and hazards, and considerations for how biochar might be used in avocado orchard soils.

Introduction

The idea of using charcoal, or biochar, as a soil amendment for agriculture dates back to thousands of years ago and was first described in ~3000 year old Chinese texts where it was referred to as fire manure. The technology for using biochar in agriculture was also independently developed by indigenous pre-Columbian Indians in the Amazon basin more than 2000 years ago to produce the so called Indian Black Earth soils that today are regarded as among the most fertile soils in S. America (Steiner et al., 2007). Until the 1990's, these soils were primarily of historical interest and were studied as a curiosity in that these black earth soils had the unique property of being able to maintain stable organic carbon under tropical conditions where organic matter usually never accumulates above trace amounts. The absence of soil organic matter is attributed to the warm temperatures and high moisture that result in extremely fast degradation rates of plant litter. For this reason, anthropologists had speculated prior to the discovery of terra preta, that the Amazon Basin could never have sustained agriculture at a level that would be permit development of a large population. The recent discovery of areas of forest that were formerly large fields where terra preta was deliberately generated changed this view, such that it is now believed the Amazon was able to support a large human population during pre-Columbian time. Introduction of European diseases that decimated the native people led to loss of knowledge on terra preta production technology and decline of agriculture as the region reverted to tropical forest. Today most areas containing terra preta soils are protected as they mainly occur on archeological sites that date back several thousand years.

With the advent of concern over carbon dioxide production and climate change, the possibility that soils might be used to store large amounts of stable carbon has since received considerable attention (Woolf et al., 2010). The fact that the highly fertile terra preta soils still contain high levels of stable carbon after more than 2000 years after their original application to soil has proved to be particularly provocative in stimulating research on whether biochar might provide a means to partially mitigate greenhouse gas production from fossil fuels. Quantities that are being considered for use in agricultural soils range from 1 to 50 tons per acre, which is estimated to be enough to offset 1.8 gigatons of CO_2 annually or 130 gigatons over the course of a century. This compares to the 5.6 gigatons of CO_2 that are currently being released annually from burning of fossil fuels. The main constraints that limit the extent to which biochar may be used for removing carbon from the atmosphere into the soil are mainly economic, dealing with the relative value of straw and agricultural waste for biofuel production, and the cost of the infrastructure for producing, transporting, and incorporating these materials into soils at large scales. Other benefits related to greenhouse gas production include reductions in methane emissions from rice paddies and nitrous oxide emissions from agricultural fields, as well as increased primary productivity of ecosystems that will lock up more carbon in aboveground biomass and below ground soil organic matter. Current research on this topic is being coordinated at the international level by the International Biochar Initiative, which is a public forum and information clearing house for private citizens, policy makers, and scientists across the world who are interested in the use of biochar as a method to reduce carbon emissions to the atmosphere, while simultaneously improving soil fertility and crop yields (http://www.biochar-international.org).

With respect to agriculture and crop yields, a recent meta analysis of 23 studies that have evaluated the effects of biochar on crop yields suggest that amendment of soils with biochar leads to an overall 10% increase in crop yields when evaluated across all crops and soils where biochar was used (Jeffrey et al., 2011). The benefits of biochar appear to include increases in soil fertility and soil water holding capacity. Early literature examining the use of biochar in organic matter, nutrient depleted tropical soils show much greater differences in yield, with several fold increases in yields. However, those studies examine extreme conditions in which the control soils were extremely depleted. In soils where fertility has been maintained by fertilizer and organic matter additions, the expected responses are much lower, and in some cases yields may even be decreased following biochar additions. In the meta analysis, the highest yield increases of 39% were realized in acidic, coarse–textured soils where biochar provides a liming effect by increasing the soil pH, and by increasing the soil water holding capacity. Detrimental effects were observed only in soils amended with biochar made from biosolids, whereas poultry litter char gave the highest yields. There are no published studies in the literature in which the use of biochar has been evaluated for avocado. Nonetheless, there is considerable interest in the possible benefits of using biochar in avocado and citrus orchards, not only for increasing crop yields, but also for improving the fertility of orchard soils and for improving soil biological functions that contribute to nutrient and water use efficiency, plant stress tolerance, and disease resistance.

Biochar Effects on Soil Fertility

The effects of biochar on soil fertility appear to be based mainly on the increase in soil cation exchange capacity and stabilization of organic carbon in soils containing pyrolyzed carbon. When organic matter is pyrolyzed, the resulting product consist mainly of high molecular weight polycyclic aromatic hydrocarbons. These compounds have carboxyl groups attached to the aromatic rings of the PAHs, which have a pH dependent positive charge. At neutral to alkaline pH, these carboxyl groups confer cation exchange capacity that allows the soil to adsorb and retain water soluble cations such as potassium, ammonium, calcium, and other base cations (Liang et al., 2006). The char particles also interact with decomposing organic carbon in plant litter to form aggregates with clay and soil organic matter that is stabilized and more resistant to degradation in the presence of the char. Char binds positively charged metal ions and may increase the bioavailability of iron and zinc to plants. Char also appears to inhibit the biological transformation of ammonia to nitrate and thus increases overall nitrogen retention and decreases nitrogen losses associated with nitrate leaching and denitrification.

Other beneficial, indirect effects of biochar on soil fertility include a decrease in bulk density, a lime effect in which the soil pH is increased, and increased soil water holding capacity. Due to the stimulation of mycorrhizal fungi growth in char amended soils, there is also improvement in soil aggregate formation and soil structure, leading to improved aeration and root growth. These indirect effects of the char on soil physical properties will reduce the soil resistance to root growth,with concomitant increases in nutrient and water adsorption that are attained with a more vigorous root system (Fig. 1).

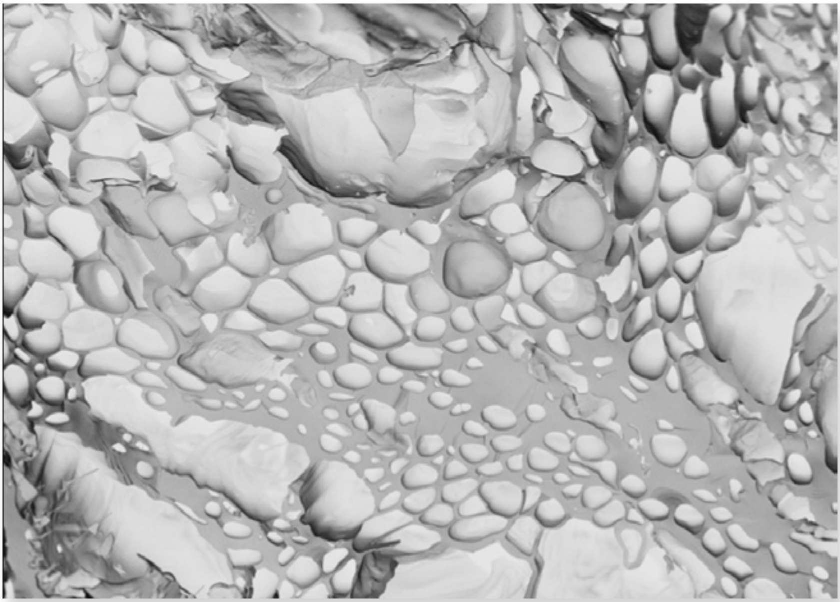

Figure 1. Magnification of biochar particle showing internal pore space that functions to increase water holding capacity, surface area, cation exchange sites, and as habitat for plant growth promoting bacteria and fungi.

The degree to which biochar affects soil fertility will depend on the baseline condition of the soil prior to its incorporation into the soil. Most research where beneficial effects have been demonstrated has been conducted in warm, tropical soils in Africa and S. America where inherent soil fertility is low due to the low soil organic matter content and acidity. In these nutrient poor soils where subsistence agriculture has further depleted the soil organic matter, incorporation of biochar into the soil can have dramatic effects on crop yields. Although much less research has been conducted on the effects of biochar additions on already fertile soils, or soils that receive high quantities of chemical fertilizers, the benefits are likely to be less dramatic than those realized in tropical soils.

Not All Biochars are Equal

Almost any organic material can be converted into biochar, with feedstocks including algae, feathers, grass, manure, palm fronds, straw, wood, nutshells, and biosolids. However, the chars that are made from all of these materials will differ in their chemical and physical properties, and in turn will have different effects on the soil physical, chemical, and biological properties after they are incorporated into the soil. Along with variations in the feedstock, the pyrolysis process can be carried out over a range of temperatures from 350 to 900 degrees Celsius, and for different lengths of time. At the commercial scale, the pyrolysis process is usually tied to biofuel production, such that about 60 to 90% of the carbon in the original feedstock is converted to biogas and biodiesel that can be used as an energy source for electricity production, or even be burned directly as biodiesel using a generator. Commercial products are subject to more careful process control and are more consistent between batches as compared to char produced locally using on farm pyrolysis equipment. Large scale operations use pyrolysis plants that deliver the feedstock into an oven where the organic material is subjected to high temperature under low oxygen conditions to produce charcoal. Smaller scale operations may use 55-gallon drums, paint cans, or even soil pits in which the organic materials are first set on fire and then covered with earth and allowed to smolder until the charring process is complete.

While the chemical and physical properties of the char will vary for different feedstocks, there are broad generalizations that can be made about the properties that can be expected when using different feedstock materials. Char products produced at low temperatures have a higher residual oxygen content or C:O ratio that is associated with a higher cation exchange capacity (CEC) than chars that are produced at high temperatures, but there is also greater potential for producing char that contains volatile oils that may be toxic to plant growth, or that contains low molecular weight polycyclic aromatic hydrocarbons (PAHs) that are of environmental concern. At higher temperatures, low molecular weight PAH are driven off into the biodiesel fraction that can be used for energy production. Actual cation exchange capacities for different char products range from as low as 3 cmol kg^{-1} to as high as 70 cmol kg^{-1}. A soil is considered to have a high CEC at values greater than 25 cmol kg^{-1}. Thus adding even a small amount of a high quality char to a sandy soil having a CEC less than 2, can significantly increase the nutrient holding capacity, leading to increased nutrient availability and decreased leaching losses. On the other hand, adding biochar to a fine clay soil with a CEC > 50 would not contribute to increased CEC. As with soil organic matter, the CEC of char is pH dependent, such that at acidic pH values below 5, the cation exchange groups are associated with hydrogen ions and will not function for adsorption of base cations such as calcium, ammonium, and potassium.

In the normal biochar production processes, the amount of biochar to biodiesel that is produced ranges from 25 to 40%, with more carbon converted to biodiesel as the pyrolysis temperatures are increased. A recent review by researchers at the University of California, Davis, documents the chemical properties of biochar materials made from different feedstocks at selected pyrolysis temperatures (Fungai et al., 2013). At very high temperatures greater than 900°C, organic carbon is converted by pyrolysis to activated carbon, which contains only carbon and hydrogen and no oxygen or carbonyl groups. Activated carbon thus has little or no cation exchange capacity, but is highly effective for adsorption of hydrophobic substances such as pesticides and other organic chemicals, hence its use for water filtration to remove organic compounds. The pyrolysis temperature and choice of feedstock will also affect the surface area of the biochar and its relative reactivity, porosity, and adsorption characteristics. At low temperatures, biochar has a relatively low surface are of less than 10 square meters per gram; whereas above 400°C, the char particles begin to open up and have an internal surface area that can be as high as several hundred square meters per gram.

There are large differences in the ash, mineral, and metal contents associated with different chars, as well as the potential for residual toxic, volatile organic compounds, and environmental hazardous PAHs. Some of the highest quality chars are made from hardwoods using pyrolysis temperatures from 500 to 800°C. A survey of the low molecular weight PAH content of commercially available biochars showed that the loading rates of PAH was relatively low for the survey materials, ranging between 1.2–19 $\mu g\ g^{-1}$ for the sum of PAH compounds that are regulated by the USEPA. At an application rate of 20–60 t biochar ha^{-1}, the concentration of PAH in the upper soil profile (~2000 metric tons of soil $ha^{-1)}$ should be well below the guidance level of 10 mg kg^{-1} for agricultural soils. From a safety perspective, biochar produced by slow pyrolysis of woody biomass possess had the lowest level of PAHs ($<10\ \mu g\ g^{-1}$).

Recently, the International Biochar Initiative has spearheaded an international effort to standardize chemical testing procedures that should be used to certify the safety of chars made using different feedstocks and processes (http://www.biochar-international.org/characterizationstandard). These include analyses of possible residual toxic chemicals and metals, salts, and chemical properties relevant to predicting its longevity in soils. For example, chars made from straw tend to have a large amount of residual labile carbon that degrades in the first year, resulting in temporarily increased methane production, and that could tie up available nitrogen in unfertilized soils. Low temperature chars made from pine may have increased levels of residual volatile compounds that are potentially phytotoxic for one or two years before the char stabilizes in the soil. Low temperature chars may also contain residual low molecular weight polycyclic aromatic hydrocarbons that are of concern as environmental pollutants. These include compounds such as pyrene, antracene, and benzo(a)pyrene that are EPA priority pollutants associated with combustion products. Thus it is important to achieve a sufficient pyrolysis temperature, generally above 400°C, at which temperature these low molecular weight PAHs have been burned off.

Due to its high surface area and surface charge, biochar can strongly bind both organic pollutants and metal ions. Organic pollutants and pesticides are bound to char surfaces through hydrophobic interactions. This can lead to decreased efficacy of herbicides and pesticides that are applied to the soil since the chemicals are mostly bound to the char and will have decreased bioavailability against the weed or pest target (Nag et al., 2011). In the study by (Nag et al., 2011), the efficacy of atrazine for weed control was reduced by approximately 3 fold, leading to higher chemical costs. Chemical adsorption to char particles can also reduce their degradation rates, leading to higher concentrations of extractable, residual pesticides in the soil. While the chemicals may not leach from the soil, there may be effects of high levels of residual pesticides on soil macrofauna such as earthworms and soil fauna that help to fragment and decompose soil organic matter. In addition to pesticides, positively charged metal ions are also strongly bound to char particles through ionic interactions. Metals including zinc, cadmium, nickel, lead, and copper become almost irreversibly bound to char, which is manifested by greatly reduced leaching of metals and lower concentrations in soil water extracts. This could potentially lower the bioavailability of essential metals such as zinc, but has also been exploited for reducing the bioavailability of heavy metals in contaminated soils that have received metals from misuse of fertilizers or through applications of heavy metal contaminated sludge or industrial wastes (Beesley et al., 2011).

There is considerable research underway that is aimed at the material science side of char production, in which freshly made char may be chemically treated with iron and manganese oxides and with organic matter containing organic acids that can artificially age the char and alter its chemical properties. Whereas freshly made char strongly binds phosphorus, metals, and pesticides, chars that have aged in the soil or fresh chars that have been chemically modified reduced adsorption properties. Biochar will continue surface modifications as it ages in soil, over time adsorbing dissolved organic carbon, and undergoing further oxidation. Much of the recent experimental work on biochar reported in the literature is for freshly generated char, and there is clearly a need for long-term studies to determine the fate and changes in chemical properties over time. One of the main considerations for the carbon sequestration objective and determining carbon credits is prediction of the longevity of biochar after it is introduced into the soil. It is generally expected that stable carbon in the form of biochar should last for hundreds to thousands of years. However, different chars will likely have different longevities, which may be predicted in part from chemical analysis of the carbon:hydrogen ratio. Along with examining the effects of these different chars on plant growth, there is parallel research that is examining how different chars affect soil microorganisms and biologically mediated processes such as denitrification, methane production, disease suppression, and plant growth promotion.

Biochar Effects on Soil Biology

The effects of biochar on soil biological processes have drawn particular attention with respect to nitrogen transformations, mycorrhizae formation, and disease suppression. The majority of studies examining char effects on nitrogen transformations show reduced rates of nitrification and concomitant reduced losses of nitrogen via denitrification. This leads to increased nitrogen use efficiency, which allows lower inputs of nitrogen fertilizers, and reduces the likelihood of runoff and contamination of groundwater supplies by nitrate. In one study conducted on an apple orchard, there was no effect of biochar on nitrate leaching 4 months after incorporation of char into the soil at a rate of 10 tons per hectare. However, in the second year, nitrate leaching was reduced by 75% in the char amended soil (Ventura et. al., 2012). Another recent study revealed more equivocal effects, with biochar additions causing shifts in microbial community structure toward a bacterial dominated community, but with no observable effects on nitrogen transformations (Jones et al., 2012). These variable results illustrate that there is still little understanding of when biochar may exert beneficial changes, and the extent to which such changes will occur in different soil types or with different biochar amendments. There is clearly a need for more research on this topic. Nonetheless, the potential ability to reduce nitrate leaching is attracting attention both in orchard operations, and also in nursery production of tree seedlings where char may be incorporated into the container media used for seedling culture.

Mycorrhizae formation can be both enhanced or decreased in soils amended with biochar, depending on the soil properties and the type of biochar that is added. Many early studies examining the effects of char additions in tropical soils showed dramatic increases in the percent of the root system that is colonized by mycorrhizal fungi, with concomitant increases in phosphorus uptake and plant yields (see review: Lehman et al., 2011). Increases in mycorrhizae formation generally were reported to be as high as 100 to 600 percent increases depending on the crop and soil. On the other hand, a recent study that was carried out to systematically evaluate the effects of different char materials in three different soil types showed that there may be both decreases and increases in mycorrhizae formation. In addition to cation exchange, biochar also has some ability to adsorb anions and is very effective in reducing phosphate leaching. In some cases, phosphorus availability was increased and led to a decrease in mycorrhizae formation in the test crop. In other cases, both phosphorus availability and mycorrhizae formation were decreased. The reasons for these highly variable effects are not yet understood, but could be related to changes in phosphorus bioavailability that provide feedback control of mycorrhizae formation, possible short term toxicity of phenolics in the pyrolysis products, or could possibly involve changes in plant signaling compounds that regulate mycorrhizae development.

There is indirect evidence that the population size and activity of plant growth promoting bacteria may also be increased in char-amended soils. The main evidence here is that plant growth is sometimes seen to be stimulated beyond a simple fertilization effect, i.e. plant growth is stimulated even in soils where the supply of fertilizer nutrients has been met by fertilization (see review: Elad et al., 2011). The effects of biochar on soil microbial communities are readily apparent using biochemical and molecular biology methods to characterize the microbial community structure. Analysis of terra preta soils show that they are approximately 50% more diverse than adjacent pristine forest soils, and that there are large shifts in the species composition. As the functions of the vast majority of soil microorganisms are still poorly understood, it is still difficult to ascertain how specific changes in the community structure will affect root growth, root health, and crop yields. Among the most important bacteria for enhancing avocado growth and stress tolerance are the plant growth promoting rhizobacteria (PGPR) that colonize plant roots. These bacteria have single or multifunctional traits that include phosphorus solubilization, plant growth hormone production (auxins), disease suppression via antibiotic production and stimulation of induced systemic resistance responses, cyanide degradation, iron solubilization, and suppression of stress ethylene (Compant et al., 2010). Inconsistencies in the effects of PGPR that are inoculated into soil can be attributed to low population densities.

A recent study on PGPR associated with avocado roots in soil from an orchard in S. California indicated that the population sizes of culturable PGPR are at the threshold size where they should be effective in reducing the inhibitory effects of salinity and drought on avocado root growth (Nadeem et al., 2012). Generally, population sizes of PGPR that suppress stress ethylene in the rhizosphere should be greater than 100,000 cells per gram of rhizosphere soil to stimulate plant root growth. In this study, populations measured for the S. California orchard ranged from 10,000 to 100,000 per gram of rhizosphere soil, suggesting that management practices such as organic matter or biochar amendments that increase the population size and activity of PGPR could be important for increasing salinity and drought tolerance.

Monitoring the effects of management practices on PGPR is still somewhat difficult since only a fraction of the soil microbial population can be enumerated using agar plate count methods, and it is difficult to quantify how many PGPR are present among the nonculturable population. Accurate determination of PGPR in soils requires enumeration using less direct methods such as quantitative PCR to quantify the population of PGPR based on copy numbers of functional genes that have been subjected to DNA sequencing. One recent study examining the changes in soil microorganisms concluded that broad level shifts observed within a year after char addition included increases in the population size of bacteria taxa that contain plant growth promoting bacterial species, but further research is needed to ascertain whether biochar amended soils actually contain greater numbers of PGPR as well as the effects of biochar on the level of PGPR activities (expression of PGPR genes) in the plant rhizosphere. Ongoing research in the author's laboratory is examining PGPR gene expression in biochar-amended soils using quantitative PCR methods.

One of the most important, but still poorly understood benefits of biochar is the reduction of plant root diseases caused by Phytophthora and other root pathogens (Fig. 2). Resistance to disease can be conferred by a mechanism referred to as induced systemic resistance (ISR), in which certain chemicals in the environment can trigger a response in plants increase the activation of plant defenses against diseases. This can be induced by a limited infection by the pathogen, but can also be stimulated by chemicals produced by PGPR. The latter is referred to as "systemic acquired resistance" and is a type of immune response in

Figure 2. Growth of healthy avocado roots in biochar-amended, phytophthora-infested soil. Biochar was produced from avocado wood trimmings and incorporated into compost for application as a surface mulch under the canopy of mature trees.

which plants have improved broad-spectrum resistance to a variety of pathogens and insects. A recent study with oak and maple tree seedlings showed that amendment of soil with 5% biochar resulted in reduced formation of lesions caused by *Phytophthora cinnamomi* (Zwart and Hyuang, 2012). Interestingly, the improved ISR was observed only in soils with 5% biochar, but was not seen in soils with higher amounts of 10 and 20% biochar, suggesting that response was elicited only at a certain concentration range. Other evidence for induced systemic resistance in biochar amended soils includes a study showing increased resistance of pepper and tomato plants to gray mold caused by *Botrytis cinerea* and powdery mildew, caused by *Leveillula taurica*, in soils amended with 1-5% biochar (Elad et al., 2010). The ISR induced by biochar also reduced the populations of broad mite (*Polyphagotarsonemus latus*) on pepper. The beneficial effects of biochar on ISR also have been shown for strawberry plants, which is more resistant to foliar fungal pathogens in biochar-amended soils (Harel et al., 2011).

Currently, there is considerable interest in using biochar as a carrier for plant growth promoting bacterial inoculants, and commercial ventures are carrying out research aimed at inoculation technology, as well as studies on the efficacy of PGPR when introduced on biochar carriers. The main advantages of using biochar as a carrier for microbial inoculants is the provision of a protected habitat in which the bacterial inoculants grow within the pore spaces of the char particles and are thus protected by predation by soil protozoa and nematodes that feed on soil bacteria. While most research is aimed at development of specific inoculants, incubating biochar with recently matured compost may also provide a means to inoculate the char with high population densities of beneficial bacteria. PGPR are often elevated in composts (de Brito et al., 1995) and when mixed with freshly produced biochar that is sterile from the pyrolysis process, will rapidly colonize and grow in the pore spaces of the char particles.

On-Farm Production and Commercial Availability of Biochar

Biochar can be produced at scales ranging from the local farm operation to large commercial production facilities. The main consideration is that the char is produced and used in a safe fashion that meets local air quality regulations during its production, and that the final product does not contain hazardous chemicals or heavy metals. Many instructional videos are available online. However, research is needed to develop a low cost and reliable process for using tree wood prunings as a feedstock for onsite production. Ideally biochar should be incorporated into the soil prior to planting, for example by tilling the biochar into soil and compost mixtures that are used to provide elevated berms that are frequently used for avocado orchards. Particle size is also a consideration, as fine powdered biochar can blow away and create a dust problem if it is left in open piles. Once the char is produced or received, it may be mixed with compost to decrease the dust problem, and thereafter can be incorporated into the soil before planting, or used in the mulch materials that are applied to the soil under the canopy of mature trees.

The cost of biochar may eventually be offset by its value as a carbon capture technology under the cap and trade agreements that are being implemented to reduce greenhouse gas emissions to the atmosphere. According to a recently published report from the Public Interest Energy Program (Weisberg et al., 2010), CO_2 offset prices will likely range from $15 to $40 per metric ton, such that biochar additions to soil would be credited at $30 to $80 a metric ton. This would provide a financial incentive to help reduce the cost associated with biochar production, and help to encourage local production in which wood waste from tree pruning would be used to produce biochar.

The International Biochar Initiative (IBI) website offers an informational agricultural extension service in which they will answer questions about how to use biochar, how to conduct a scientifically valid biochar trial, or information on the results of the most recent scientific research on this topic. They also post a document, Guide to Conducting Biochar Trials that covers the design and procedures for setting up a biochar experiment. Growers can also share their results by joining the IBI Field Trial Registry, where information can be posted for others to view and discuss your results.

Conclusions

The use of biochar in avocado orchard soils has not yet been investigated in rigorous scientific experiments. Nonetheless, the results of experiments with many different field and orchard crops suggest that this soil amendment may increase soil fertility, crop yields, water and nutrient use efficiency, and help to induce systemic resistance to root pathogens. Given these positive attributes, it is certainly important that studies should be conducted to test and optimize the use of biochar for avocado orchard soils. Biochar materials vary widely in their chemical and physical properties, and it is important to use a chemically tested product to avoid potential problems with metal and organic pollutant (PAH) contamination of the soil. It is likely that many different management practices including fertilizer recommendations, irrigation scheduling, and use of herbicides will need to be reoptimized for soils that have been amended with biochar. Particularly exciting is the possible use of biochar to control root diseases, and to promote the population and activity of plant beneficial microorganisms that can increase stress tolerance to drought, salinity, and to improve root zone aeration in heavy soils. There is a rapidly growing body of knowledge on biochar, which is now being advocated for use in all agricultural soils as a means to improve soil fertility and to offset greenhouse gas production. Growers are encouraged to experiment with biochar, but also to make sure to carefully design experiments with appropriate controls and keep good records that will allow documentation of the potential benefits and/or hazards associated with use of biochar as a soil amendment.

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