CHAPTER 8:

Agricultural Use

Kristin M. Trippe*, Georgine G. Yorgey*, David A. Laird, Brennan Pecha, and David Drinkard

SCOPE

Biochar has potential to reduce the environmental footprint in nearly every aspect of agricultural production. The use of biochar has been proposed to manage agricultural biomass (Stavi 2013), to process animal manure and poultry litter (Shakya & Agarwal 2017), to improve the nutritive value of feed (Man et al. 2021), and to mitigate the offsite movement of pesticides (Kahlid et al. 2020; Liu et al. 2018; Khorram et al. 2016) and soil nutrients (Gao et al. 2019; Figure 8.1). The coproducts of biochar production hold similar potential. For example, on-farm production of biochar can provide bioenergy to heat greenhouses and barns and to power farm equipment (Phillips et al. 2018). Pyroligneous acid, a coproduct of pyrolysis, has the ability to control fungal pathogens and deter pathogenic insects (Grewal et al. 2020). Although these environmental benefits are potentially substantial, their on-farm use has not been widely studied. Furthermore, the on-farm installation of biochar production facilities presents challenges that reduce the feasibility of co-production scenarios (Phillips et al. 2018).

Figure 8.1. *Agricultural biomass associated with orchard management (left) can be achieved by generating biochar that can be used onsite. In the right photo, biochar from orchard waste is applied to a commercial orchard in central Washington during tree planting to improve soil health. (Photos: Jeff Theil [left] and David Drinkard [right]).*

* *These authors contributed equally to this work.*

Table 8.1. *Biochar attributes supporting a prescriptive approach for biochar use in cropping systems.*

Biochar attributes	Type of biochar needed	Application rate/frequency
Liming/pH adjustment	High ash (>600 °C, high-ash feedstock).	As needed; calculated by pH of soil and neutralizing strength of char.
Rebuilding eroded soils	Large particle size (high coarseness) to improve infiltration.	Can be calculated from properties of soil + char and desired goal (e.g., porosity or water holding-capacity).
Reduced nutrient leaching	Large particle size (high coarseness) to improve infiltration and reduce runoff.	Annual.
Reducing disease pressure	Pre-conditioning of biochar may be needed for some applications (e.g., to reduce soilborne diseases in horticultural media) to allow time for biochar to impact microbial communities.	After germination. Variable. Frenkel et al. (2017) seems to say that lower application rates (<3% by volume) are needed for benefits relating to soilborne diseases (foliar diseases are somewhat less sensitive to higher application rates).
Residue management	On farm gasification or pyrolysis of residues, returned to the soil.	Annual trimming/harvest season.
Water retention	High temperature, oxidized for highest porosity.	As needed to achieve soil water holding capacity around roots.
Growth Stimulant	Insufficient data.	High application rate (<25% by volume) or injection with seed.

Recent recommendations regarding optimum biochar application rates for wood-origin biochars (2-5% by mass) and manure-origin biochars (1-3% by mass) (Guo 2020) translate to quite high application rates of 11 tons ac^{-1} (1%) to 57 tons ac^{-1} (5%), assuming an average bulk density. If implemented, such application rates will create an enormous demand for forest and agricultural biomass. As such, land application uses of biochar is likely to be an important driver for the scaling and development of biochar production systems.

Because land use application of biochar is widely studied, and because it has the potential to create a tremendous demand for biomass and biochar-based products, this section primarily addresses the application of biochar to agricultural soils.

NEED STATEMENT

Across all agricultural systems, a primary goal is to intensify production to supply food, fuel, and fiber to a growing global population. However, accomplishing this goal is increasingly difficult as soils become less productive, land area shrinks, and natural resources become more limited. At the same time, there is a growing public and regulatory demand for farmers to ameliorate the adverse environmental impacts of farming and to provide ecosystem services. The simultaneous and sometimes conflicting needs to improve crop yields while reducing chemical inputs, limiting greenhouse gas emissions, protecting water resources, and sequestering carbon can be achieved by improving soil health (Wheeler & Von Braun 2013).

Biochar is one important tool that has the potential to alleviate soil health deficiencies (Figure 8.2) and enhance ecosystem services by increasing soil pH (Phillips et al. 2018; Machado et al. 2018), improving tilth (Deluca & Gao 2019), increasing water holding capacity (Omondi et al. 2016; Razzaghi et al. 2020; Edeh et al. 2020) , decreasing the off-site movement of nutrients and pesticides (Kahlil et al. 2020; Liu et al. 2018; Khorram et al. 2016), and sequestering carbon (Liu et al. 2016; Bai et al. 2019; Matuštík et al. 2020). Biochars have a tremendous range in physical and chemical properties. The physiochemical properties of biochar are shaped by the nature of the feedstock, the parameters of production, and post-production treatments and processes. Therefore, biochars can be engineered to have specific attributes. Because biochars can be tuned to meet agronomic goals, prescriptive approaches that use engineered biochars to address specific soil deficiencies are possible. For example, farmers in some parts of the inland Northwest have a growing need to raise the pH of soils. Biochar that is high in ash and has a large calcium carbonate equivalence could potentially meet this need (Phillips et al. 2018). Likewise, farmers who use deficit irrigation could apply biochars to extend water holding capacity and alleviate intermittent water shortages. In order for farmers to adopt biochar-based practices, a deeper understanding of how production parameters determine biochar properties is necessary, as illustrated in Tables 8.1 and 8.2. (See end of chapter for Table 8.2).

Figure 8.2. *Outside of Spokane, Washington, wheat growth is dramatically increased in soil amended with biochar (8 tons per acre, right inset), compared to that grown in unamended soil (left inset). (Photo: Kristin Trippe)*

The impacts of biochars on soils and plants cannot be predicted from the properties of biochars alone, but also depend on how the biochar reacts with the soil, the crop, and the climate. This complexity has led to an enormous proliferation of biochar-based research publications. Despite the proliferation of the scientific literature that addresses biochar-soil, biochar-plant, and biochar-climate interactions, we are only beginning to disentangle the complexities of biochar-based amendments. As a result, few generalizable principles have emerged and biochar-based practices have not been widely adopted. In order for adoption to occur, it is paramount that farmers have the ability to predict, with reasonable accuracy, the agronomic responses to biochar applications. This ability can be achieved through the development of robust biochar-cropping systems models that are capable of predicting agronomic outcomes of biochar applications.

Robust biochar-cropping systems models are also needed to predict the environmental response to biochar application. Emerging policy initiatives that incentivize the removal of carbon from the atmosphere are currently under development. However, allocating carbon credits for soil biochar applications will require a means of estimating the long-term impact of biochar applications on net greenhouse gas emissions based on full lifecycle analysis. Direct measurement of changes in soil carbon stocks and greenhouse gas emissions at the field and farm scales is not practical, as the cost of such measurements would exceed the value of the carbon credits. Hence, computer models can be an important tool for assigning carbon credits to individual farmers based on estimates of the long-term impact of specific practices on net greenhouse gas emissions. Policy development and implementation would be strengthened by robust biochar-cropping systems models that are capable of predicting environmental outcomes of biochar applications, including estimates of carbon sequestration.

Resolving knowledge gaps and using that knowledge to build cropping systems models will substantially remove the barriers to farm-scale adoption of biochar-based practices. To accomplish this, we have developed five recommendations for implementation on the national and regional scales: *1) Establish a coordinated national scale network of long-term biochar field trials; 2) Develop a well-integrated biophysical modeling effort for application of biochar to agricultural soils; 3) Develop macroeconomic models to provide information relevant to national and sub-national policymaking; 4) Cultivate a prescriptive approach for utilization of biochar in regionally focused, cropping system specific niches; and, 5) Collaborate on regional techno-economic analyses that point towards most likely regional pathways for biochar production and use.*

RECOMMENDATIONS

Recommendation 1: Establish a coordinated national scale network of long-term biochar field trials.

We propose that the deployment of a coordinated, nationwide effort aimed at filling knowledge gaps will sufficiently lower adoption barriers by delivering decision support tools and providing prescriptive recommendations that allow farmers to improve soils and achieve agronomic goals. The coordinated effort will entail an iterative approach that uses data from long term field trials to develop, calibrate and validate agroeconomic models that can predict agronomic and environmental outcomes on local and regional scales. The outcome of the models will, in turn, inform the direction of long-term studies and prompt short-term studies to address emerging questions. The effort will be coordinated, implemented, and assessed by a network of scientists that are charged not only with conducting the research but also with consolidating and curating data in such a way that it is applicable and available to complementary investigations. Figure 8.3 outlines the structure of the proposed network. We anticipate that, through this network, a deeper and more comprehensive understanding of biochar will emerge. As such, generalizable principles that can be translated into

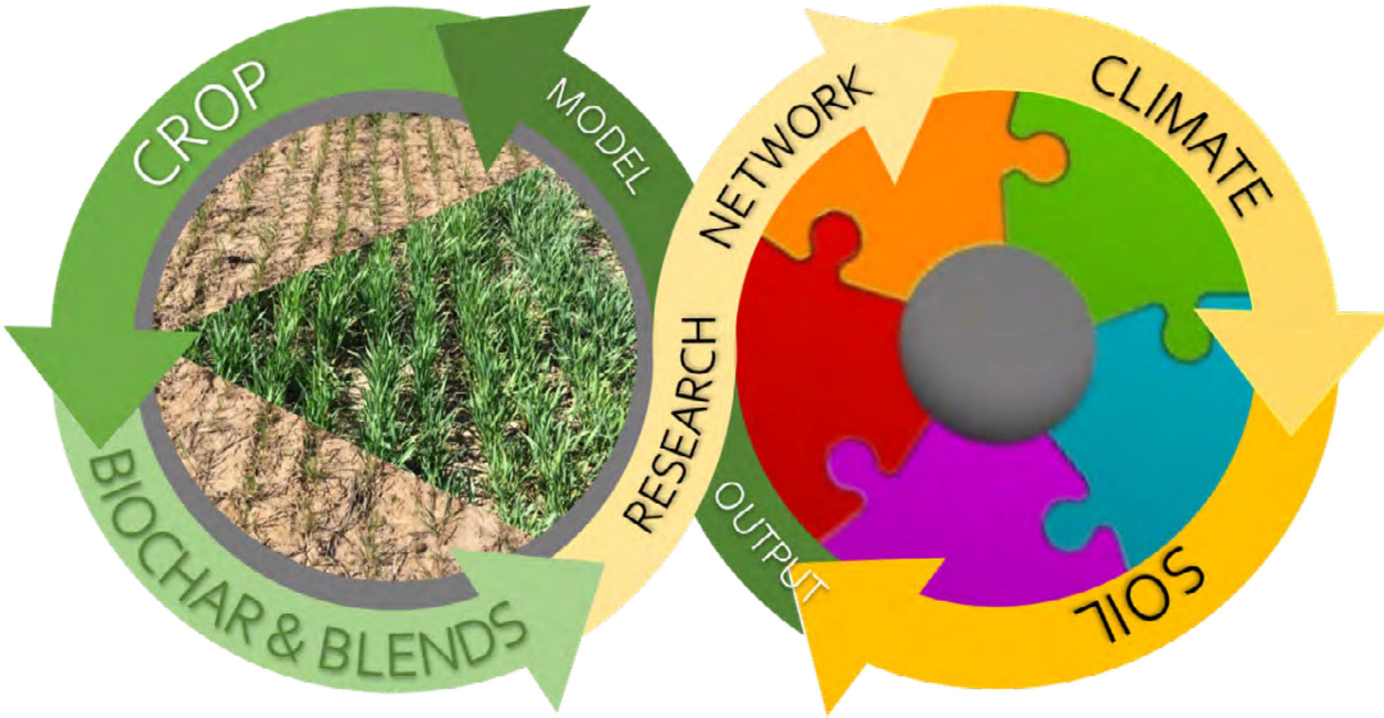

Figure 8.3. *Structure of proposed network. (Credit: Kristin Trippe)*

decision support tools, best management practices, and extension guidelines will be developed.

Research Objectives

The lack of extension recommendations regarding agronomic outcomes of biochar application at the field-scale are due to sizable knowledge gaps. Specific research questions regarding the effects of biochar on crop outcomes include: 1) the response of plant growth and crop yield to different biochar types across different climates, soil types and management systems; 2) the influence of physiochemical properties of biochar on crop nutrient use efficiency and nutrient leaching for different climates, soil types and management systems; 3) the mechanisms by which biochar improves soil health deficiencies; and, 4) the effects of biochar on system resilience in response to extreme climate events. Closing these gaps, as well as determining agronomic techniques for applying biochar (rate, timing, method) will allow researchers to develop and disseminate best management practices and extension recommendations.

While the lack of biochar adoption is due to uncertainty regarding the influence of biochar on crop outcomes, it is also due to prohibitive costs and uncertainty about return on investment. Because biochar can provision ecosystem services, policy incentives should be developed to support the implementation of the practice. The most obvious and clear case for policy incentives is based on the ability of biochar to capture and store carbon. Although several studies have examined the potential for biochar to store soil carbon, salient questions need to be addressed prior to the development of policy incentives. These questions include: 1) quantifying biochar-microbial interactions that lead to changes in carbon mineralization rates, and the effect of these changes on soil organic carbon stocks across different climates, biochar types, soil types and management systems; and 2) quantifying the effects of different biochar types on changes in soil organic carbon stocks and greenhouse gas emissions across different climates, soil types and management systems. In addition to capturing carbon, biochar also has the potential to provide other agroecosystem services, including improving water quality by reducing off-site migration of nutrients and pesticides and decreasing erosion and runoff. However, policy incentives regarding nutrient management and water quality are more difficult to measure and quantify. As such, questions that inform policy should initially be focused on quantification of carbon capture and storage.

Results obtained from strategically designed long-term field trials have the potential to provide answers regarding the agronomic and environmental outcomes of biochar application by closing the identified knowledge gaps. To accomplish this, we propose that a national network of long-term biochar field trials should be established in at least ten locations across the U.S. At these sites, which should be chosen to represent diverse soil types, cropping systems, and climates, researchers will conduct coordinated studies using a common set of biochar types, management practices, and research protocols. Each field site would yield a common minimum data set including soil physical and chemical properties, soil respiration, crop and biomass yields, and changes in soil organic carbon stocks. The field trials would be maintained for a minimum of ten years to provide long-term biochar response data. A national database of results from these field trials will be developed that can be used to robustly calibrate and validate the biochar agronomic and environmental models. In addition to these ten long term biochar research (LTBR) plots, diverse regional efforts addressing cropping system-specific questions using local management practices and feedstocks applied to economically-important crops efforts would support LTBR efforts by collecting and contributing the minimum dataset using established protocols (Figure 8.4). In return, these efforts would receive support letters, assistance with data interpretation, and the ability to store data using LTBR resources. In addition to closing knowledge gaps regarding biochar effects, the establishment of LTBR field trails coupled with regionally-specific trails will ensure that experimental results of LTBR efforts are translatable and that recommendations that emerge from the LTBR network are applicable to local cropping systems.

Figure 8.4. *Ongoing regional experiments could help ensure that experimental results from a national network are translatable to local cropping systems. The potato plants shown here are part of a Washington State University and Department of Ecology research field trial that evaluated potato production following amendment with a regionally produced biochar, co-composted biochar and compost. The darker colored, four leftmost rows illustrate the effects of fertilizer on potato biomass. (Photo: Steven Seefeldt)*

To coordinate the LTBR and the regionally-specific research efforts, a structured network of scientists must be organized to integrate efforts that generate hypotheses, establish protocols, manage data, and direct research deliverables in the form of publications and recommendations. Additionally, the network will create and coordinate efforts to archive biochar samples, create and manage data that describe biochar properties, and provide guidance to individual LTBR and related researchers on the handling and storage of soil and plant samples. Collectively, these efforts will generate iterative work that will describe mechanisms through which biochar has impact. There are several examples of existing research networks that function similarly. The framework established by the Greenhouse gas Reduction through Agricultural Carbon Enhancement network (GRACEnet) is an excellent model on which to establish a biochar-based research network. Within GRACEnet, research and geospatial data are collected with established protocols that ensure that results are comparable across GRACEnet locations. Points of contact upload data into accessible data repositories for incorporation into models and greenhouse gas inventories to produce actionable recommendations. The formation and cultivation of a similar network composed of biochar-based researchers would similarly contribute data to help develop and train models (see Recommendation 2) to better predict agronomic responses and environmental impacts.

Recommendation 2: Develop a well-integrated biophysical modeling effort for application of biochar to agricultural soils.

We propose that the development of models that can reasonably predict agronomic and environmental outcomes of biochar application will lower barriers to the adoption of biochar-based practices by providing reliable information to researchers, extension agents, crop consultants, and farmers. However, to accomplish this, models must be able to address the diversity of biochars, soils, climates, crops, and management systems. Likewise, the models must be scalable and function at the pedon, field, regional, national, and ultimately global scales. Furthermore, these models must have the ability to predict, with reasonable accuracy, crop and biomass yields, leaching of nutrients, emissions of greenhouse gases and changes in soil physical, chemical and biological properties for diverse biochar types, soil types, climates, crops, and management systems. In order to design and implement biochar-based models that accommodate diverse systems on a broad spectrum of scales that have accurate output regarding multiple parameters, several knowledge gaps must be addressed. *Specific knowledge gaps that limit the development of robust biochar-cropping systems models include: 1) biochar quality parameters; 2) priming* *effects of biochar; 3) biochar-soil-crop-climate interactions; 4) biochar impacts on autotoxicity and plant disease; 5) plant hormonal and toxin effects of biochars; 6) effects of different types of biochar; and 7) biochar management systems.*

Biochar quality parameters

Biochar models need input parameters to characterize biochar properties. The parameters need to be readily measurable properties of biochars that characterize the diversity of biochars and maximize the ability of the models to predict agronomic and environmental outcomes. For example, most biochar models assume recalcitrant and labile biochar carbon pools. To predict the fate of biochar carbon in soils, model inputs need estimates of both the size and half-lives of the labile and recalcitrant pools. These properties, however, cannot be measured directly except through long-term and expensive incubation studies. Readily measurable parameters, such as hydrogen to carbon (H/C) ratios, volatile matter, potassium permanganate ($KMnO_4$)-oxidizable carbon, and hot-water extractable carbon, need to be developed and calibrated to serve as proxies for estimating the size and half-lives of the labile and recalcitrant biochar carbon pools. Other biochar quality parameters are needed to predict the impact of biochar amendments on soil cation exchange capacity, bulk density, porosity, drainage, plant available water, nutrient cycling, and microbial activity.

Priming effect of biochar

Biochar may impact the rate of mineralization of native soil organic matter when it is added to soils through what is often referred to as a 'priming' impact. In the literature, biochar has been reported to cause positive, negative, and neutral priming of biogenic soil organic matter mineralization. Understanding both short-term and long-term priming effects of biochar in different soils under different climates and cropping systems is critical to predicting the long-term impact of biochar amendments on both soil carbon stocks and nutrient cycling. Existing biochar-cropping system models already have priming coefficients; but we need to know whether those coefficients should be positive, negative or neutral and whether they should be constant or change over time, biochar types, climates, soils, and management systems.

Biochar-soil-crop-climate interactions

Cropping system models are increasingly sophisticated in predicting crop responses to climate and management. Most such models include a limited set of soil parameters focusing primarily on the soil water and nitrogen cycling. Often soil pH, cation exchange capacity (CEC), bulk density, field capacity, and permanent wilting point are treated as constants and must be input to initiate the model. In reality, these parameters are dynamic and are influenced by climate, crop growth, and management (e.g., acidifying fertilizers, compaction caused by wheel traffic). Furthermore, biochar amendments alter these soil properties. Cropping systems models need to be revised to treat these parameters as variable and to account for biochar-soil-crop-climate interactions.

Biochar impacts on autotoxicity and plant disease

A growing body of mostly anecdotal evidence indicates that biochar amendments can reduce autotoxicity associated with decomposition of crop residues and can suppress some soil born fungal pathogens. These effects, when they occur, can have a substantial effect on crop yields, but are not currently included in cropping system models. Understanding these effects and being able to incorporate these into cropping systems models would greatly improve the accuracy of model predictions.

Hormonal and toxin effects of biochars

Biochars are known to release various organic compounds that influence plant growth and development. Which types of biochar release these compounds and whether these effects are short-term or persistent is unknown.

Effects of different types of biochar

Biochar quality varies substantially depending primarily on feedstock, peak pyrolysis temperature, and pyrolysis technology. To date most field research has been conducted using biochars produced from woody feedstocks by slow pyrolysis. The results from these studies may not be relevant for predicting crop response to biochars produced by fast pyrolysis from crop residues and herbaceous feedstocks. Field trials with diverse biochar types are needed to build robust models.

Biochar management systems

Field and laboratory research is needed to optimize biochar management options. For example, biochar can be uniformly applied in a single large surface application and incorporated by tillage; alternatively, biochar can be strategically applied on eroded hill tops or other problem soils. Biochar can be injected into problematic subsoils such as hard setting E horizons that restrict root growth or clay rich argillic horizons that restrict drainage. Various biochar-fertilizer formulations are under development that may or may not be effective for improving nutrient use efficiency in crop production. Acidified biochars can be banded with fertilizers proximal to seed placement to improve early season seedling growth and development.

Recommendation 3: Develop macroeconomic models to provide information relevant to national and sub-national policymaking.

A robust carbon negative pyrolysis-biochar-bioenergy industry will not develop without policy intervention. Without policy intervention, liquid transportation fuels produced by pyrolysis of biomass are not now, and are unlikely to be, cost competitive in the foreseeable future with liquid transportation fuels produced from petroleum. Under current policies, the environmental costs of petroleum and the environmental benefits of biochar and biofuels are both discounted. Future policies designed to address climate change will, in one way or another, put a tax on fossil fuels that penalizes the emissions of greenhouse gases and establish a carbon credit system that promotes the removal of carbon dioxide from the atmosphere. The design and development of effective policies will require macroeconomic models that can predict the impact of various policy options on the level of adoption of covered practices, energy prices, commodity prices, indirect land use effects, local and regional economies, and ultimately net greenhouse emissions. Detailed analysis concerning the types of macroeconomic models needed to facilitate policy development are beyond the scope of our discussions. However, cropping system models that predict the impact of biochar amendments on agronomic and environmental outcomes are critical tools that provide foundation for such macroeconomic models.

Recommendation 4: Cultivate a prescriptive approach for utilization of biochar in regionally focused, cropping system specific niches.

At the regional level, a prescriptive approach for utilization of biochar in regionally focused, cropping system specific niches is needed. By prescriptive, we mean an approach that is aimed at utilizing locally produced biochars as a strategy to address specific issues within regional crops and cropping systems. The approach should be informed by regional-level techno-economic analyses that point towards the most likely regional pathways for biochar production and use.

The prescriptive approach is essential because it focuses attention on those situations in which producers would be most likely to consider adoption if economics are favorable and concrete guidance can be developed. As an illustration of how this framework can be applied, Table 8.1 identifies different major impacts of biochar and describes the types of biochar and application rates that should be considered. Table 8.2 applies a prescriptive framework that marries knowledge about the potential impacts of biochars on soils with place-specific knowledge of specific agricultural niches in the Pacific Northwest where biochar may help overcome existing constraints to yield or quality in ways that may economically benefit growers. This approach focuses attention on the eventual biochar purchaser. It also emphasizes the need for ongoing biochar process/product development with the aim of producing biochars that can most effectively provide the desired attributes—though at present, it can be difficult to find biochar that is optimized for a particular use in quantities large enough to support field trials, due at least in part to the fact that current markets are not large enough to clearly support the commercial viability of such production.

Recent investigations of whether biochar could benefit blueberry production in the Pacific Northwest illustrate this approach (Sales et al. 2019). Blueberries (*Vaccinium* sp.) prefer well-drained acidic soils with high levels of organic matter. Organic amendments such as bark or sawdust are often incorporated into mineral soils before planting to increase organic matter and improve soil structure. These materials are expensive, and thus growers are interested in alternatives. Phytophthora root rot (associated with *P. cinnamomi*) can also be an issue for growers. Based on these needs, a greenhouse study explored the application of biochar alone (at 10% or 20% by volume), and biochar with bokashi (4:1 mix of biochar and bokashi produced from rice bran), to blueberry seedlings in two 12-week experiments. Bokashi was chosen because the fermentation process converts food waste to a nutrient-rich product that is low in pH and thus is likely to fit well within a blueberry system (whereas most biochars are high in pH, as is compost, another potential amendment). Plant growth was greater in soil with biochar than in unamended soil and there were also much greater levels of root colonization by mycorrhizal fungi. Biochar also appeared to improve soil aggregation but had relatively little effect on soil pH and plant nutrition and no effect on root infection by *P. cinnamomi* at the application rates used in this study. Addition of bokashi to the biochar improved plant growth and nutrition, particularly under nutrient-limited conditions. Based on these results, researchers plan to test biochar in a new field planting of highbush blueberry and to explore the best method and rate to apply it (Figure 8.5). Clarifying these factors will help the team to explore both effectiveness and cost, key to potential future adoption by growers.

Figure 8.5. *Graduate student Bryan Sales applies biochar to newly planted stands of blueberries in Aurora, Oregon. (Photo: Scott Orr)*

Generally speaking, the prescriptive approach is also informed by an awareness of the non-biochar management alternatives that producers are likely to consider, and the potential value-proposition of biochar in comparison to those other alternatives. It also responds when possible to potential regional biochar sources, in line with the concept of biochar "system-fit" (Sohi et al. 2015). As the ability to model the impacts of biochar application to cropping systems develops, this may also be used to identify additional opportunities that should receive further attention at the regional level.

Especially given the current lack of carbon policy incentives, regionally-focused approaches can be further informed by a preliminary assessment to determine particular cropping systems for which biochar can provide desired benefits at a cost that is reasonable. Several economic analyses have indicated that biochar's current economic benefits (in the absence of subsidies) exceed the cost of application only when applied to high value regional crops such as potatoes or diversified vegetables (Sessions et al. 2019; Garcia-Perez et al. 2019), whereas application to a wider range of crops (including dryland crops), becomes economically feasible only when financial policy incentives are available.

Work at the regional level will most likely take place along the discovery—application continuum (Figure 8.6). For biochar attributes that are less well understood (e.g., disease suppression), exploration of mechanisms will help develop understanding of where impacts are likely to occur. As promising prescriptive applications reach higher levels of technical readiness, field trials should emphasize demonstration and communication at scales that are relatable to farmers. Including analysis of the impacts on farm economics and profitability—across multiple years of a crop rotation and including impacts on economic risk reduction—will also help producers weigh the potential costs and benefits of biochar application. Communication of field-level results, development of use guidance, and decision support tools will all support eventual adoption.

Figure 8.6. *Stephanie Chiu and Sarah Light remove soil cores to test the response of soil water to biochar additions at a field trial site in Pendleton, Oregon. (Photo: Claire Phillips)*

We also propose that coordinating regional-level biochar field trials with the national research framework will maximize the knowledge gained from these regional trials in a number of important ways. First, by utilizing established data-collection protocols, it will ensure that data are comparable across sites. Second, it will focus attention on the collection of data most needed to advance the biochar biophysical modeling effort. Third, by connecting biochar researchers with each other and with the national network, it will raise the level of interaction and collective knowledge relating to biochar's impacts in agricultural systems, and thus the level of sophistication of individual regional efforts.

Recommendation 5: Collaborate on regional techno-economic analyses that point towards most likely regional pathways for biochar production and use.

Techno-economic analysis is critical for building a biochar-bioenergy industry. Whether focused on large centralized biorefineries or distributed on-farm pyrolysis units, building a biochar-bioenergy industry ultimately requires that pyrolysis plants be built at specific locations. For a specific pyrolysis plant to be economically viable, a local supply of feedstock, infrastructure to harvest, store, and transport the feedstock, and markets for the biochar and bioenergy co-product must exist and be accessible. Furthermore, life cycle analyses are needed to quantify energy and mass balances and net greenhouse gas emissions at the plant scale. Communication between agricultural researchers and those working on other aspects of techno-economic analysis is important to ensure that assumptions about the agricultural market size are reasonable. Cropping system models that predict the impact of biochar amendments on agronomic and environmental outcomes are also critical tools that inform techno-economic models about the potential market size for biochar co-products. Building regional biochar markets requires local on-farm research to develop solutions to local agronomic problems using locally available biochar resources.

CONCLUSION

The potential for biochar to benefit agricultural production and sustainability is substantial, but this benefit is not currently being fully realized. Further work is needed to disentangle the complexity of the interactions between the many types of biochar, soils, crops, and climate, and to develop generalizable principles. It is our feeling that a coordinated national scale network of long-term biochar field could elucidate the mechanisms of biochar's impacts in soils more efficiently than the current decentralized approach. Meanwhile, robust biochar-cropping systems models are also needed to predict the environmental response to biochar application. These models would also support developing policy initiatives to incentivize the removal of carbon through biochar, by providing a means to predict the carbon benefit of biochar application to soils.

At the regional level, a prescriptive approach for utilization of biochar should guide research efforts, in which biochar is explored as a potential solution to an identified problem for which growers are actively seeking solutions. By paying attention to the value proposition of biochar compared to other management options that are available to growers, as well as economic analysis to weigh costs and benefits, scientists have improved the likelihood of developing biochar application strategies that ultimately are meaningful to regional growers.

Table 8.2. *Examples of yield-focused, prescriptive uses for agricultural char.*

Issue addressed by biochar/ Example application in the PNW	Value proposition of biochar over other management alternatives	Potential regional sources of appropriate biochar	Technical Readiness Level	High priority research questions	Key Example References (Regional field results, when possible)
Liming from biochar can raise pH of acidic soils due to long-term use of ammonium-based fertilizers. Wheat-based dryland cropping systems (inland PNW).	Natural product. Can provide additional benefits over lime such as reduced aluminum phytotoxicity, improved soil moisture and permeability, and increased CEC. On the other hand, earlier analysis Biochar may not be cost-competitive with lime if only pH impacts are considered, but producers in many areas have not typically applied lime despite acidic conditions, so biochar may meet an unmet need.	If cost could be justified, biochar produced from poultry litter, which is high in ash and has a large calcium carbonate equivalence, could potentially meet this need, though transportation would add cost. Alternatively, to minimize cost, onsite residues could be used in areas where residue production is adequate. Combinations of biochar with other alkaline waste products (e.g., fly ash) have also been discussed and research is ongoing.	High	What is the long term neutralizing capacity of char? Can the long-term economic benefits justify the costs, and if yes, under what conditions? Approaches for reducing cost and labor for biochar production, spreading and incorporating biochar remain a challenge. Biochar from onsite residues will need to generate benefits that are competitive with alternative residue uses (e.g., baling and offsite sale of wheat straw).	Physical feasibility of biochar production and utilization at a farm-scale: A case-study in non-irrigated seed production. (Phillips et al. 2018) Alkaline biochar amendment increased soil pH, carbon, and crop yield. (Machado et al. 2018) Grass seed residue trials. Ag Energy, unpublished data.
Biochar can rebuild highly eroded "knobs" have much lower yield than surrounding areas. Eroded wheat-based dryland cropping systems (Palouse).	On-site residue use may provide an economically viable option in a cropping system with few cost-effective strategies existing (transporting other organics is cost-prohibitive).	Use of onsite residues could aid in economic viability, if costs can be kept low enough and biochar can perform well enough.	Low-Medium	Can increases in yields cover production/application costs in concentrated areas? What strategies prevent erosion from occurring again over time?	Influence of contrasting biochar types on five soils at increasing rates of application (Streubel et al. 2011).

Issue addressed by biochar/ Example application in the PNW	Value proposition of biochar over other management alternatives	Potential regional sources of appropriate biochar	Technical Readiness Level	High priority research questions	Key Example References (Regional field results, when possible)
Biochar can reduce nutrient losses from topsoil as nutrients run off fields, increasing production costs and environmental impacts. Grass seed grown on poorly drained soils/Willamette Valley. Acreage receiving repeated manure applications.	CEC adsorbs nutrients and porosity of char absorbs water - both effectively reduce nutrient leaching. Biochar is unlikely to be cost competitive with the alternative of no action. However, if changes are required to reduce nutrient losses, it may become cost competitive in some cases (e.g., requirement for reducing nutrient applications).	Use of onsite residues could aid in economic viability, if costs can be kept low enough and biochar can perform well enough.	Medium	What is the optimal application rate and schedule? What is the cost benefit calculation? Mechanisms need to be defined to inform biochar production parameters. more work is needed for specific soils and crops so that accurate results can be achieved.	Biochar impact on nutrient leaching from a Midwestern agricultural soil (Laird et al. 2010).
Biochar can reduce disease pressure from some high value crops in the PNW, with examples including nursery crops, potatoes, and small fruits. Soil-borne diseases in nursery crops and potatoes. Foliar diseases including Botrytis, Phytophthora and Powdery mildew in strawberries. Powdery mildew and late-stage diseases such as Fusarium in tomatoes (direct market production). Late-stage diseases in asparagus.	Natural, includes other benefits of biochar, may reduce pH of soil. Existing chemical strategies may be expensive and cause harm to workers. Pathogens may develop resistance to repeated fungicide applications. In addition to yield, crop quality is also often economically important, generating another avenue through which benefits can be realized. Economic benefits could also be realized by enabling maintenance or increasing the frequency of the highest value crop in the rotation.	Applications to these high value crops may be able to support higher biochar costs (and thus a wider range of biochar feedstocks and production systems) than other cropping systems—if benefits can be shown.	Low	Adding unconditioned biochar followed by infections with pathogens such as Rhizoctonia and Pythium can cause early stage diseases occasionally results in neutral or negative effects. Pre-conditioning stage should be incorporated as an important stage during biochar application in nurseries and soilless media, and possibly into soil.	Biochar as a management tool for soilborne diseases affecting early-stage nursery seedling production (Jaiswal et al. 2019). Activating biochar by manipulating the bacterial and fungal microbiome through pre-conditioning (Jaiswal et al. 2018).
Wood waste can be managed for disease control with biochar production, with reduced air quality impacts compared to open burning. Perennial tree fruit (central Washington and N central Oregon).	Air quality impacts of biochar should be lower than open burning for use with tree trimmings to be attractive.	Onsite	Med-High	What are the air quality impacts of charring trimmings compared to burning?	Apple orchards have been shown to benefit from char (Ventura et al. 2013).
Ag. residues can be turned into char rather than by using mechanical means in irrigated high residue annual cropping systems that break down quickly in the environment. Residue management for irrigated high residue annual cropping systems in the Basin.	Could result in higher persistence of residue, which may be beneficial in at least some irrigated high residue annual cropping systems.	Onsite	Med-High	How would a biochar strategy compare to other current strategies for managing residues in high residue annual cropping systems?	Charring is established as a management tool for management of residue in agro-ecosystems (Stavi 2013).
Biochar can retain water for growers who are deficit irrigating (e.g., coarse-medium texture soils). Deficit irrigated crops (e.g., wheat, N central OR) or high value crops grown without irrigation (e.g., diversified vegetables for direct markets in western WA and OR).	Provides amendment benefits in sandy/silty soils. Reduces irrigation requirements which is beneficial in situations where water access is limited for physical or regulatory reasons.	High coarse-textured char to increase retention in soil.	Low	Can biochar provide sufficient benefits in improved water holding capacity to be economically justified?	Can biochar conserve water in Oregon agricultural soils? (Phillips et al. 2020)
Biochar can be applied to soils for plants that require well-drained soils with high organic matter. Blueberries High-value irrigated crops	Wood chips/sawdust are often used to amend mineral soils prior to planting, but are expensive as they need to be replaced and don't generally result in higher yields. Biochar is more durable than wood chips and has shown benefits in greenhouse studies. Can be applied with compost utilizing the same distribution and application systems.	Application to blueberries requires a low calcium carbonate equivalence, coarse-textured char. Applications to these high value crops may be able to support higher biochar costs (and thus a wider range of biochar feedstocks and production systems) than other cropping systems—if benefits can be shown.	Medium Low	What application rates are appropriate? Can long-term benefits be demonstrated? Under what conditions) if any) can co-composted biochar or biochar + compost out-perform compost applications?	Amending sandy soil with biochar promotes plant growth and root colonization by mycorrhizal fungi in highbush blueberry (Sales et al. 2020). Integrating compost and biochar for improved air quality, crop yield, and soil health (Gang et al. 2019).

Issue addressed by biochar/ Example application in the PNW	Value proposition of biochar over other management alternatives	Potential regional sources of appropriate biochar	Technical Readiness Level	High priority research questions	Key Example References (Regional field results, when possible)
Biochar can replace vermiculite or perlite in potted/ greenhouse crops as a soil bulking agent and sometimes growth stimulant. Nursery crops (including cannabis).	More renewable than vermiculite or perlite. Marijuana wastes in at least some states are subject to additional regulations and cost regarding disposal, making onsite processing more attractive.	Applications to these high value crops may be able to support higher biochar costs (and thus a wider range of biochar feedstocks and production systems) than other cropping systems—if benefits can be shown. Production from greenhouse wastes may also be attractive in some cases due to existing disposal costs.	High	Cost benefit needs to be determined.	Substitution of peat moss with softwood biochar for soil-free marigold growth (Margenot et al. 2018). Effects of conifer wood biochar as a substrate component on ornamental performance, photosynthetic activity, and mineral composition of potted Rosa rugosa (Fascellaet et al. 2018). Influence of biochar, mycorrhizal inoculation, and fertilizer rate on growth and flowering of Pelargonium (Pelargonium zonale L.) plants (Conversa et al. 2015).

REFERENCES

Awale, R., Machado, S., Ghimire, R. & Bista, P. (2017). Soil Health. Chapter 2 in: Yorgey, G. & Kruger, C. eds. *Advances in Dryland Framing in the Inland Pacific Northwest*. Washington State University Extension Publication EM108, Pullman, WA. http://pubs.cahnrs.wsu.edu/wp-content/uploads/sites/2/2017/06/em108-ch2.pdf

Bai, X., Huang, Y., Ren, W., Coyne, M., Jacinthe, P.-A., Tao, B., Hui, D., Yang, J., & Matocha, C. (2019). Responses of soil carbon sequestration to climate-smart agriculture practices: A meta-analysis. *Global change biology* 25(8), 2591-2606. https://doi.org/10.1111/gcb.14658

Bista, P., Ghimire, R., Machado, S., & Pritchett, L. (2019). Biochar Effects on Soil Properties and Wheat Biomass vary with Fertility Management. *Agronomy* 9(10), 623. https://doi.org/10.3390/agronomy9100623

Conversa, G., Bonasia, A., Lazzizera, C., & Elia, A. (2015). Influence of biochar, mycorrhizal inoculation, and fertilizer rate on growth and flowering of Pelargonium (Pelargonium zonale L.) plants. *Frontiers in Plant Science* 6, 429. https://doi.org/10.3389/fpls.2015.00429

DeLuca T.H., & Gao, S. (2019). Use of Biochar in Organic Farming. In: Sarath Chandran, C., Thomas, S., & Unni, M. (eds) *Organic Farming*. Springer, Cham. https://doi.org/10.1007/978-3-030-04657-6_3

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

Fascella, G., Mammano, M.M., D'Angiolillo, F., & Rouphael, Y. (2018). Effects of conifer wood biochar as a substrate component on ornamental performance, photosynthetic activity, and mineral composition of potted Rosa rugosa. *The Journal of Horticultural Science and Biotechnology* 93(5), 519-528. https://doi.org/10.1080/14620316.2017.1407679

Frenkel, O., Jaiswal, A.K., Elad, Y., Lew, B., & Graber, E.R. (2017). The effect of biochar on plant diseases: What should we learn while designing biochar substrates? *Journal of Environmental Engineering and Landscape Management*, 25(2), 105-113. https://doi.org/10.3846/16486897.2017.1307202

Gang, D., Collins, D., Jobson, T., Seefeldt, S., Berim, A., Stacey, N., Khosravi, N., & Hoashi-Erhardt, W. (2019). *Integrating Compost and Biochar for Improved Air Quality, Crop Yield, and Soil Health*. Center for Sustaining Agriculture and Natural Resources, Washington State University, 98 pp. http://csanr.wsu.edu/publications/integrating-compost-and-biochar-for-improved-air-quality-crop-yield-and-soil-health/

Garcia-Perez, M., Brady, M., & Tanzil, A.H. (2019). *Biochar Production in Biomass Power Plants: Techno-Economic and Supply-Chain Analysis*. Center for Sustaining Agriculture and Natural Resources, Washington State University, 20 pp. https://csanr.wsu.edu/wp-content/uploads/sites/32/2019/08/Biochar-Production-in-Biomass-Power-Plants-.pdf.

Grewal, A., Abbey, L., & Gunupuru, L.R. (2018). Production, prospects and potential application of pyroligneous acid in agriculture. *Journal of Analytical and Applied Pyrolysis* 135, 152-159. https://doi.org/10.1016/j.jaap.2018.09.008

Gao, S., DeLuca, T.H., & Cleveland, C.C. (2019). Biochar additions alter phosphorus and nitrogen availability in agricultural ecosystems: A meta-analysis. *Science of The Total Environment* 654, 463-472. https://doi.org/10.1016/j.scitotenv.2018.11.124

Guo, M. (2020). The 3R principles for applying biochar to improve soil health. *Soil Systems* 4(1), 9. https://doi.org/10.3390/soilsystems4010009

Jaiswal, A.K., Elad, Y., Cytryn, E., Graber, E.R., & Frenkel, O. (2018). Activating biochar by manipulating the bacterial and fungal microbiome through pre-conditioning. *New Phytologist* 219(1), 363-377. https://doi.org/10.1111/nph.15042

Jaiswal, A.K., Graber, E.R., Elad, Y., & Frenkel, O. (2019). Biochar as a management tool for soilborne diseases affecting early stage nursery seedling production. *Crop Protection* 120, 34-42. https://doi.org/10.1016/j.cropro.2019.02.014

Khalid, S., Shahid, M., Murtaza, B., Bibi, I., Natasha, Naeem, M.A., & Niazi, N.K. (2020). A critical review of different factors governing the fate of pesticides in soil under biochar application. *Science of The Total Environment* 711, 134645. https://doi.org/10.1016/j.scitotenv.2019.134645

Khorram, M.S., Zhang, Q., Lin, D., Zheng, Y., Fang, H., & Yu, Y. (2016). Biochar: a review of its impact on pesticide behavior in soil environments and its potential applications. *Journal of Environmental Sciences* 44, 269-279. https://doi.org/10.1016/j.jes.2015.12.027

Laird, D., Fleming, P., Wang, B., Horton, R., & Karlen, D. (2010). Biochar impact on nutrient leaching from a Midwestern agricultural soil. *Geoderma* 158(3), 436-442. https://doi.org/10.1016/j.geoderma.2010.05.012

Liu, Y., Lonappan, L., Brar, S.K., & Yang, S. (2018) Impact of biochar amendment in agricultural soils on the sorption, desorption, and degradation of pesticides: a review. *Science of the Total Environment* 645, 60-70. https://doi.org/10.1016/j.scitotenv.2018.07.099

Liu, S., Zhang, Y., Zong, Y., Hu, Z., Wu, S., Zhou, J., Jin, Y., & Zou, J. (2016). Response of soil carbon dioxide fluxes, soil organic carbon and microbial biomass carbon to biochar amendment: a meta-analysis. *Gcb Bioenergy* 8(2), 392-406. https://doi.org/10.1111/gcbb.12265

Machado, S., Awale, R., Pritchett, L., & Rhinhart, K. (2018). Alkaline biochar amendment increased soil pH, carbon, and crop yield. *Crops & Soils Magazine* 51(6),38-39. https://doi.org/10.2134/cs2018.51.0604

Man, K.Y., Chow, K.L., Man, Y.B., Mo, W.Y., & Wong, M.H. (2021). Use of biochar as feed supplements for animal farming. *Critical Reviews in Environmental Science and Technology* 51(2), 187-217. https://doi.org/10.1080/10643389.2020.1721980

Mahler, R.L., Halvorson, A.R. & Koehler, F.E. (1985). Long-term acidification of farmland in northern Idaho and eastern Washington. *Communications in Soil Science and Plant Analysis* 16(1), 83-95. https://doi.org/10.1080/00103628509367589

Margenot, A.J., Griffin, D.E., Alves, B.S.Q., Rippner, D.A., Li, C., & Parikh, S.J. (2018). Substitution of peat moss with softwood biochar for soil-free marigold growth. *Industrial crops and Products* 112, 160-169. https://doi.org/10.1016/j.indcrop.2017.10.053

Matuštík, J., Hnátková, T. & Kočí, V. (2020). Life cycle assessment of biochar-to-soil systems: A review. *Journal of Cleaner Production* 259, 120998. https://doi.org/10.1016/j.jclepro.2020.120998

Omondi, M.O., Xia, X., Nahayo, A., Liu, X., Korai, P.K., & Pan, G. (2016). Quantification of biochar effects on soil hydrological properties using meta-analysis of literature data. *Geoderma* 274, 28-34. https://doi.org/10.1016/j.geoderma.2016.03.029

Phillips, C.L., Light, S.E., Gollany, H.T., Chiu, S., Wanzek, T., Meyer, K. & Trippe, K.M. (2020). Can biochar conserve water in Oregon agricultural soils? *Soil and Tillage Research* 198, 104525. https://doi.org/10.1016/j.still.2019.104525

Phillips, C.L., Trippe, K., Reardon, C., Mellbye, B., Griffith, S.M., Banowetz, G.M., & Gady, D. (2018). Physical feasibility of biochar production and utilization at a farm-scale: A case-study in non-irrigated seed production. *Biomass and Bioenergy* 108, 244-251. https://doi.org/10.1016/j.biombioe.2017.10.042

Razzaghi, F., Obour, P.B., & Arthur, E. (2020). Does biochar improve soil water retention? A systematic review and meta-analysis. *Geoderma* 361, 114055. https://doi.org/10.1016/j.geoderma.2019.114055

Rogovska, N., Laird, D.A., Leandro, L., & Aller, D. (2017). Biochar effect on severity of soybean root disease caused by Fusarium virguliforme. *Plant and Soil* 413,111-126. https://doi.org/10.1007/s11104-016-3086-8

Sales, B.K., Bryla, D.R., Trippe, K.M, Weiland, J.E., Scagel, C.F., Strik, B.C., & Sullivan, D.M. (2020). Amending Sandy Soil with Biochar Promotes Plant Growth and Root Colonization by Mycorrhizal Fungi in Highbush Blueberry. *HortScience* 55(3), 353-361. https://doi.org/10.21273/hortsci14542-19

Sessions, J., Smith, D., Trippe, K.M., Fried, J.S., Bailey, J.D., Petitmermet, J.H., Holamon, W., Phillips, C.L., & Campbell, J.D. (2019). Can biochar link forest restoration with commercial agriculture? *Biomass and BioEnergy* 123, 175-185. https://doi.org/10.1016/j.biombioe.2019.02.015

Shakya, A., & Agarwal, T. (2017). Poultry litter biochar: an approach towards poultry litter management–a review. *Int J Curr Microbiol App Sci* 6(10), 2657-2668. https://doi.org/10.20546/ijcmas.2017.610.314

Sohi, S.P., McDonagh, J., Novak, J.M., Wu, W., & Miu, L.-M. (2015). Biochar systems and system fit. *In* Lehman, J. & Joseph, S. (Eds.), *Biochar for Environmental Management: Science, Technology and Implementation*. Routledge, New York, pp. 737-761.

Stavi, I. (2013). Biochar use in forestry and tree-based agro-ecosystems for increasing climate change mitigation and adaptation. *International Journal of Sustainable Development & World Ecology* 20(2,) 166-181. https://doi.org/10.1080/13504509.2013.773466

Streubel, J.D., Collins, H., Garcia-Perez, M., Tarara, J.M., Granatstein, D.M., & Kruger, C.E. (2011). Influence of contrasting biochar types on five soils at increasing rates of application. *Soil Science Society of America Journal*. 75(4), 1402-1413. https://doi.org/10.2136/sssaj2010.0325

Ventura, M., Sorrenti, G., Panzacchi, P., George, E., & Tonon, G. (2013). Biochar reduces short-term nitrate leaching from a horizon in an apple orchard. *Journal of Environmental Quality* 42(1), 76-82. https://doi.org/10.2134/jeq2012.0250

Wheeler, T. & Von Braun, J. (2013). Climate change impacts on global food security. *Science* 341(6145), 508-513. https://doi.org/10.1126/science.1239402

This page intentionally blank.