CHAPTER 1:

Introduction

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Figure 1.1. *Biochar (right) is the carbon-rich solid produced by heating biomass (left) under low-oxygen conditions. (Photo: Biomacon)*

Biomass is renewable, carbon (C)-rich organic matter derived from recently living plants and animals. *Biochar* is the C-rich solid produced by heating biomass under low-oxygen conditions to a temperature where its chemical structure transforms to a more stable form similar to that found in graphite (Figure 1.1). The conversion process spontaneously releases more energy than it consumes; this bioenergy can be used to generate electricity and as a source of heat. Like coal char (i.e., char made from coal, which is fossilized C-rich organic matter), biochar can be burned to generate energy, but this offers little or no benefit relative to burning the original biomass. Instead, biochar has greater value as an amendment to soil, to compost, and even to construction materials, where it can store C for long periods of time while providing other benefits specific to these applications [71]. By virtue of the large quantity of biomass available in agricultural and forestry residues, the generation of bioenergy during the conversion, and the enhanced stability of the C in biochar relative to the original biomass, large-scale conversion of biomass to biochar is considered an

Biochar by the Numbers

In the 17 contiguous western states, about 94 Mt or 104 MT (1 Mt = 1 million metric tonnes; 1 MT = 1 million tons) of biomass containing 42 Mt (46 MT) of C can be sustainably harvested each year from agricultural, forestry, and municipal residues [113]. Assuming a high but practical C-conversion efficiency of 49% and about 50 years to reach the maximum production rate [121], biochar containing 1,700 Mt (1,874 MT) C could be produced over the course of a century. Addition of this biochar to cropped soils in the region would increase the soil C content in the plow layer by half (i.e., by 0.75% C after accounting for some loss of biochar to oxidation). Assuming biochar C behaves similarly to native soil C, the plant-available water storage capacity in these soils would increase by nearly 4 million acre-feet [78]. Use of the heat released during biochar production to generate electricity would yield 2,500 MW of power, support 250 biomass power generation facilities distributed throughout the region, and account for 1.5% of the region's electricity production. Taken over a century, the combined impact of biochar technology in the western United States could yield a climate offset of 9.2 Gt (10.1 GT) carbon dioxide equivalent (CO_2e; 1 Gt = 1 billion metric tonnes; 1 GT = 1 billion tons). ■

important negative-emission technology that can help mitigate climate change [5, 25, 69, 79, 102, 121]. (See sidebar: *"Biochar by the Numbers" on page 3*.)

Over the last decade and a half, a number of major research efforts in the western U.S. and Pacific Northwest (PNW), and a diverse set of smaller efforts, have explored the potential for biomass conversion to biochar and bioenergy to improve forest and agricultural soil health and to draw down atmospheric C (See sidebar: *"Biochar Research in the Pacific Northwest" on page 4*). The U.S. biochar industry has been led by producers in the western U.S. since its inception [38, 48], and the PNW offers a particularly promising context for scaling up biochar production since the region has large quantities of potential feedstocks (e.g., forestry biomass, urban wood waste, crop residues) located in close proximity to large areas of diverse agricultural production with potential to support and benefit from biochar application. As of August 2020, the biochar industry in the Pacific Coastal States included eleven suppliers in Oregon, nine in Washington and 25 in California, with much of the biochar produced as a byproduct of biomass to bioenergy plants. The region is also rich in industry and academic expertise and in the engagement of both government agencies and non-governmental organizations (NGOs). Interest in scaling up is widespread as indicated by the 2019 passage of a Senate Joint Memorial in Washington State (*S-0339.1*) in support of biochar research and use, only the second such memorial in the U.S. after a similar resolution was passed in Colorado in 2017 (*SJR17-002*). In November 2020, the first C credits for biochar production in the U.S. were issued to a biochar supplier in California after a long cooperative effort involving a local sawmill and support from regional, national, and international biochar industry organizations [87].

These strengths position the western U.S., and the PNW in particular, to fully develop biochar's potential for climate change mitigation, forest health improvement and wildfire risk reduction, soil health, and ecosystem services, and rural community revitalization. While biochar production and use in the region has steadily gained momentum during the last decade, the industry has remained relatively small. Strategic investment will overcome existing barriers and magnify the value proposition, maximizing positive impacts for communities and ecological systems.

BACKGROUND

In April 2020, forty biochar practitioners and researchers representing industry, academia, NGOs, and government participated in a virtual workshop to chart a roadmap for future development of biochar technology in the PNW and beyond. Most of these individuals were from the western U.S., primarily Washington, Oregon, and California. The group met over several months to consider the exciting opportunities that conversion of biomass to biochar offers. They explored how biomass is harvested, converted to biochar, and applied, and where operational changes and funding could significantly magnify biochar's contributions.

Biochar Research in the Pacific Northwest

Starting in 2007, the Washington State Department of Ecology funded a sustained effort focused on the beneficial use of waste biomass to produce bioenergy and biochar [23, 24, 40-44, 47, 56]. Early work on biochar in Washington State was also supported by the Paul G. Allen Family Foundation as part of the *Climate Friendly Farming Project* [123]. Subsequently, USDA National Institute of Food & Agriculture funded the *Northwest Advanced Renewables Alliance* for five years. The focus of this work was on the production of jet fuel from biomass, but several reports were generated on the availability of woody biomass from forest health and fire hazard reduction treatments [7] and mill residues [10] as well as on the conversion of a residual biomass waste product (lignin) to a form of biochar that could substitute for activated C [36]. Another major effort was a three-year project funded by the Biomass Research and Development Initiative (a collaboration between the U.S. Department of Energy and the USDA) called *Waste to Wisdom*. This project, which involved 16 organizations throughout the western U.S., focused on making better use of forest residues from harvesting and thinning operations by exploring new methods of feedstock development and biomass conversion in the context of rigorous sustainability analysis [52]. In addition to these large projects, many individuals, companies, and smaller research groups in the region have explored different feedstocks, equipment configurations, and biochar applications to address a wide diversity of issues associated with conversion of biomass to biochar and lay the foundation for a vibrant biochar-based economy. ■

Examples of Biochar Technology in the Pacific Northwest

Place-based biochar production: Small (usually less than 500 tons per year [TPY] woody biomass feedstock), labor-intensive manual operations with short distance transportation of biomass, biochar used on-site.

Moderate-scale biochar production: Temporary biochar production sites, often at forest landings, using skid-mounted trailer-sized conversion systems (usually 1,000 to 100,000 TPY woody biomass feedstock) and involving some transport of biomass (less than 50 miles).

Large-scale, centralized biochar production: Permanent biomass conversion facilities (usually greater than 100,000 TPY woody biomass feedstocks) often with bioenergy production, and one-way hauling distances less than 100 miles.

Biochar integrated with municipal composting facilities: Production of biochar from woody biomass collected from solid waste and its use as a catalytic agent in composting of organic wastes.

Biochar used in agricultural soils: Biochar produced at any scale from woody biomass, manures, and crop residues and usually used as a soil amendment. Agricultural uses represent an important market due to the large volumes and potential climate mitigation and soil health benefits. ■

The main objectives of the workshop were to:

1. Explore five of the most promising contexts for biochar production and use in the Pacific Northwest, identifying current barriers and the most impactful strategies for moving each sector forward, and
2. Define strategic priorities for investors, philanthropists, policy makers and others looking to help transform biochar technology into a widespread, effective method for addressing climate change while maximizing its beneficial impacts on managed ecosystems and rural communities.

This report summarizes the collective discussions related to these two objectives and provides a prioritized list of recommendations for investors, philanthropists, policy makers and others interested in helping the region maximize benefits from biochar production and application. While most of the authors of this document are grounded in the PNW and are familiar with biochar production and application in this regional context, many of the recommendations in this report are applicable elsewhere in the U.S and even globally.

The report contains three major sections:

Section I (Chapters 1-3) summarizes the overarching workshop discussions, with a focus on Objective 2. In the remainder of Chapter 1, we describe the collective environmental and social motivation for this work. We also explain the need to capture value from biochar production systems in order to advance their development. Chapter 2 identifies the major challenges to development of the biomass-to-biochar supply chain, while Chapter 3 provides a set of recommended funding priorities for overcoming these challenges and capitalizing on current opportunities.

Section II (Chapters 4-8) contains a detailed analysis of five representative examples of biochar production and use in the PNW, summarizing the group's work on Objective 1 (see sidebar: *"Examples of Biochar Technology in the Pacific Northwest" on page 5*).

Section III provides supporting overviews on the topics of biomass supply (Chapter 9), biomass handling (Chapter 10), biochar production (Chapter 11), and air pollutant emissions and air emissions permitting for biochar production systems (Chapter 12). In these chapters, we also refer readers to more detailed references, where appropriate.

VISION AND POTENTIAL

Development of a robust biomass-to-biochar pathway offers a unique opportunity to simultaneously address four pressing societal and environmental needs: 1) Climate change mitigation; 2) Forest health improvement and wildfire risk reduction; 3) Soil health and ecosystem services; and 4) Rural community revitalization. Further development of the biomass-to-biochar supply chain to realize these benefits depends on monetizing the value of these products or services while focusing on sustainable design and implementation of biochar systems.

Climate Change Mitigation

Climate change is one of the most pressing global challenges of our era. Negative consequences are already being felt across the globe. Our own region is no exception, with drought and wildfire being two dominant and closely related impacts [80]. The events of 2015 marked a dramatic turning point that provides a preview of future climate in the PNW [76 p. 1041]. After several years of drought, record low snowpack from warmer winter temperatures resulted in water scarcity during the summer months, affecting agriculture, hydropower, and recreation, and contributing to a then-record wildfire season, which was subsequently eclipsed in dramatic fashion by the wildfires of 2020. Over the long term, warmer winters also help lay the groundwork for larger wildfires by increasing the risk of insect infestations that ultimately result in extensive tracts of dead, standing timber.

Since 2015, the economic cost associated with the wildfires in Washington, Oregon, and California alone have totaled more than $60 billion, far exceeding the $40 billion cost of wildfires in the entire U.S. for the preceding 35 years [80]. The loss of life has been equally disastrous, with 209 lives lost in the fires in Washington, Oregon, and California since 2015 compared with 184 lives lost nationally between 1980 and 2015 [80]. The effects of climate change are not felt equally by communities across the Northwest or nation, with low-income communities and those dependent on natural and cultural resources facing greater threat [76 p. 1062]. Without mitigation, these climate-related changes are expected to continue to impact the economy, health, and welfare of the region and the nation [76].

To mitigate these impacts, the scientific consensus calls for numerous strategies to reduce anthropogenic emissions and sequester or draw down atmospheric C [101, 102]. These strategies include, among others, direct air capture of carbon dioxide (CO_2), afforestation and reforestation, enhanced weathering of silicate minerals, changes in land management to increase stocks of soil organic C, and thermal conversion of biomass to bioenergy with C capture and sequestration or with co-production and storage of biochar. *Given the enormity of the task and the variety of situations, all these strategies will likely be needed*. Biochar has been recognized by the Intergovernmental Panel on Climate Change (IPCC) for its potential to contribute significantly to C sequestration [85 p. 398]. In the report *Getting to Neutral: Options for Negative Carbon Emissions in California*, biochar is one of the five classes of promising negative emissions technologies evaluated with the goal of full deployment by 2045 [8]. Importantly, biochar technology offers the potential for widespread and relatively near-term deployment.

The climate change mitigation potential of biochar technology depends on a number of factors, primarily the supply of biomass that is harvested, but also the fraction of the C in the original biomass that ends up in the biochar (i.e., the C efficiency), the alternative fate of the biomass C, the stability of the biochar after conversion, the native fertility of the soils to which biochar is applied, and whether the heat generated is used to offset fossil-C sources of energy (and if so, the carbon intensity of the existing energy supply) [25, 121].

The amount of biomass available for conversion to biochar and bioenergy is bracketed by two numbers. The larger of these is the *technical* potential, which is the amount of biomass that could be harvested sustainably regardless of the cost of doing so. The smaller number is the *economic* potential, which is the amount that can be harvested sustainably and profitably at a given market price for biomass (Figure 1.2). Due, in part, to whether and how sustainability guidelines and economic costs are considered, estimates of available biomass vary widely and are not without controversy [25]. In Figure 1.2 we show estimates for the harvest of biomass from agricultural, forestry, and municipal waste streams in 17 western U.S. states that were generated by the 2016 Billion Ton Report [113] using strict sustainability guidelines coupled with economic considerations assuming biomass market prices between $33 and $110 per bone dry[1] (BD) tonne[2] (between $30 and $100 per BD ton). Agricultural residues account for most of the available biomass (between 62% and 86%), followed by forestry residues (between 11% and 35%), and finally wood harvested from municipal solid waste (between 0% and 3.5%). The estimated total technical potential is 94 Mt (104 MT) of dry biomass (42 Mt [46 MT] of C) and is reached at market biomass prices above $80 per BD tonne ($73 per BD ton). At the current biomass market price (ca. $35 per BD tonne or $32 per BD ton, [114]), the estimated economic potential is about 20 Mt (22 MT) of dry biomass (9 Mt [10 MT] of C). Price support at $40 per BD tonne ($36 per BD ton) biomass[3] for C sequestration by biochar could

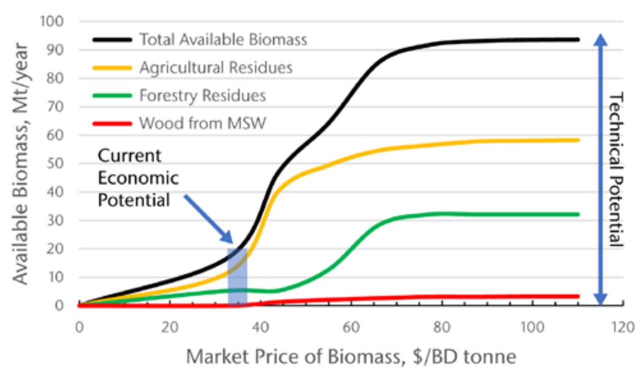

Figure 1.2. *Estimated available biomass for 2021-2030 from agricultural, forestry, and municipal sources in 17 Western States at different market prices [113]. Current biomass market price for forestry residues is about $35 per bone dry tonne [114]. Technical potential is reached at about $80 per bone dry tonne.*

1 *"Bone dry" and "oven dry" are both units used for biomass and are essentially interchangeable. Here we opt to use bone dry and abbreviate as BD.*

2 *In this report we provide values in both metric tonnes (1,000 kg; 2,204.6 lbs) and U.S. tons, as both units appear in the biochar literature.*

3 *Which is equal to $83 per tonne [$75 per ton] C, or $23 per tonne [$21 per ton] CO_2e*

Figure 1.3. *Biomass One in Medford, Oregon is a biomass power plant generating 32.5 megawatt electrical (MWe) (28.5 MWe goes to the grid). This plant consumes 200,000 tons per year of dry biomass and can recover 50,000 cubic yards of biochar annually (Photo: Karl Strahl)*

increase biomass harvest several fold. An increase in the market price of just $6.25 per BD tonne ($5.67 per BD ton) biomass to $41.25 per BD tonne ($37.41 per BD ton)[4] could double the economic potential.

Biochar production systems vary substantially [40, 128] and, as a result, their climate impacts also vary. Key considerations include the C efficiency of the biomass transformation, the emissions of greenhouse gases (GHGs) and particulates during the process, and whether the heat generated replaces fossil-C sources of energy. During biochar production, the highest C efficiencies of 30% to 55% are seen with slow pyrolysis[5]. Combustion, on the other hand, typically yields C efficiencies below 3% but releases three times as much heat that, if captured, can be used to generate electricity and for other purposes.

Biochar production technologies with higher C efficiencies, by definition, have lower emissions. These emissions, however, will vary in their content of methane (CH_4) and soot, both of which have more powerful impacts on the climate than CO_2. The main goal, then, is to eliminate emissions of CH_4 and soot during production, leaving CO_2 as the only GHG emitted. Methods to complete the conversion of CH_4 and soot to CO_2 before release to the atmosphere have been developed. These methods typically involve some form of post-pyrolysis combustion process such as funneling gases through an afterburner, re-injection of gases into the pyrolysis system, or harnessing natural convection processes to create a combustion zone above the pyrolysis zone as in flame-cap kilns and conservation burn piles.

Co-generation of electrical power and other uses of the heat released during biochar production make eminent sense from a climate-change mitigation perspective but are not always economical, particularly in areas with inexpensive hydropower, such as the PNW. Due to the capital costs involved, successful implementation usually occurs with large, centralized facilities (typically 20 MW capacity or larger) having easy access to the electrical grid and a stable supply of biomass within a 50-mile economical transportation range (Figure 1.3; see *Chapter 6: Centralized Biochar Production Facilities*). Smaller combined-heat-and-biochar systems for use with schools and light industry are practical in many instances. The climate impact of these applications depends on the fossil-C intensity of the energy supply that they replace. Supplanting electricity generated by coal will have a large beneficial impact whereas little or no benefit would be obtained by replacing solar, wind, or nuclear power.

4 *Which is equal to an increase of $13 per tonne [$12 per ton] C, or $3.50 per tonne [$3.17 per ton] CO_2e*

5 *Pyrolysis is a thermal decomposition process in the absence of oxygen that separates components of biomass into gases, liquids, oxygenated compounds, and solids. Slow pyrolysis is a form of pyrolysis characterized by heating of biomass at a slow rate (around 5-7 °C per minute). See Chapter 11: Biochar Production.*

Once biochar is made, it needs to be stored in a location where it will not release C to the atmosphere rapidly—ideally, release rates of less than 10% per century are desired. Biochar can be added to construction materials such as asphalt, where it replaces some of the fossil C, or concrete, where it replaces some of the aggregate, and in both of these instances it can improve the mechanical properties of the materials [1, 26, 29, 50, 115, 124, 126]. The most common storage location for biochar, however, is in soil, which already contains an enormous amount of C—an estimated 1,500 gigatonne (Gt; 1 billion metric tonnes) (1,650 GT; 1 billion tons) of soil organic C is stored in the top meter of soils [9, 97], compared to roughly 270 Gt (298 GT) C stored in standing forest stocks globally [33] and 885 Gt (976 GT) C currently present as CO_2 in the atmosphere [82].

Biochar's unique structure resists biological and chemical degradation. Thus, biochar persists in the soil for hundreds to thousands of years, much longer than the original feedstock [71]. The C sequestration potential is greater in temperate climates than in tropical ones, with C stability depending on biochar properties and soil characteristics as well as climate [85]. In many instances, biochar application enhances native soil C stocks through "negative priming" in which labile C forms complexes involving the biochar and mineral soil particles (See sidebar: *"Biochar's Impact on Native Soil Carbon Stocks" on page 8*). "Positive priming," where application of biochar enhances mineralization (loss) of existing soil organic C stocks, has been reported in some cases [85], but this effect seems to be temporary and, over the long term, shifts to negative priming [11, 12, 28, 54, 66, 99, 129].

Adding biochar, particularly to highly weathered soils, acidic soils, and sandy soils, can have beneficial effects on plant growth [27, 61, 64]. Highly weathered soils benefit from the increase in nutrient-retention capacity offered by the large surface area of biochar. Acidic soils benefit from the highly basic nature of many biochars, which act similarly to lime. Sandy soils benefit from significant increases in water-holding capacity (as well as nutrient-retention capacity). Biochar amendments thus offer a way of restoring degraded lands by improving their fertility. Increased productivity, in turn, provides a positive feedback loop by generating more biomass that can be converted to biochar.

Life cycle assessments (LCAs) of the climate mitigation impact of biochar technology consider biomass sourcing, transport and processing, biochar production, transport and application, fossil-fuel offsets resulting from energy produced and captured during biochar production, and the subsequent impact of biochar on plant growth and C stocks after application to soil. To quantify the net climate impact, however, a comparable set of emissions associated with the alternative fate of the biomass feedstock (e.g., natural decay, wildfire, land filling, etc.) also needs to be considered. At any point in time, subtraction of the cumulative alternative emissions from the cumulative biochar-technology emissions provides the net climate impact. When the emissions by biochar are lower than the alternative biomass pathway, the net emission are less than zero and the result is termed "C negative." In general, LCAs have indicated that biochar has a net climate impact of about -0.4 to -1.2 tonnes of CO_2 equivalents per tonne of bone dry feedstock (t CO_2e BD $tonne^{-1}$), meaning that the climate impact is beneficial (resulting in less CO_2 in the atmosphere). Increases in net emissions are possible with biochar, however, when purpose-grown feedstock is used and indirect land use change is included [25, 94, 95].

Because the impact of GHGs changes with time due to their different atmospheric residence times relative to CO_2, the climate impact will also change depending on the period being considered. A time-sensitive LCA approach fully captures this dynamic as shown in a hypothetical example for biochar and two alternative

Biochar's Impact on Native Soil Carbon Stocks

Over the past decade, a significant body of work has been devoted to the question of how biochar amendments affect the native organic C (SOC) stocks in soils. Most of this work involved laboratory incubations for a few weeks to a few years and led to a consensus that during the early stages after biochar amendment a net loss of SOC can occur, and that loss certainly occurs after addition of fresh organic matter with the biochar. Thereafter, the observed net change in SOC in the laboratory studies is either neutral or negative, meaning that, over the long run, biochar amendments either have no impact on SOC or they actively promote SOC accumulation.

For century-scale estimates of the changes in SOC, one modeling study [122] and three natural-analog studies [12, 54, 66] at abandoned charcoal production sites in Europe provide consistent estimates of the degree of SOC accumulation that can be expected. The results suggest that, over a century or more, on the order of a 30% to 60% increase in SOC occurs in sub-humid temperate-zone soils to which biochar has been applied. Field studies in similar soils in the U.S. [11] and Australia [100, 119] show rapid accumulation during the first decade followed by slower accumulation as a new equilibrium is reached. These long-term studies sow optimism regarding the ability of biochar to increase native SOC stocks but require further research to confirm. ■

biomass fates (Figure 1.4). In the top panel, total GHG emissions per unit of biomass C are shown for each of the three biomass pathways. The bottom panel shows the net GHG emissions for biochar relative to the alternative biomass pathways. In this hypothetical example, when biochar is compared to wildfire, it is always C negative. When it is compared with biomass decay, on the other hand, the emissions from biochar production exceed those of biomass decay for a short period. Eventually, cumulative emissions from biomass decay exceed those from biochar production and the net GHG emissions fall into the C-negative region. The period between biochar production and achievement of C negativity is termed the C-payback period.

The overall climate-mitigation impact is thus tied strongly to the sustainability of the harvesting practices and the ultimate fate of any products. When biochar is made from biomass waste byproducts – such as lumber mill wastes, forest management byproducts, defensible space clearing (for wildfire risk reduction), orchard and vineyard prunings, food-processing waste such as fruit and nut pits and shells, urban or suburban yard wastes, and livestock manure—the utilization for energy and biochar can be C negative (Figure 1.4). Compared to baseline disposal through on-site open burning or spreading of wood chips, production of biochar and bioenergy by modern low-emission facilities yields significant climate benefits resulting from: (a) the displacement of the need for the combustion of fossil fuels for comparable energy production, and (b) the avoidance of the disposal of the biomass wastes through either open-pile burning, or in-field decay and decomposition, either of which may release significant amounts of CH_4.

On average, using biomass to make biochar has a larger potential to mitigate climate change than combusting the same biomass for bioenergy because it sequesters C belowground, stimulates crop productivity, and reduces or avoids GHG emissions by soils [121]. This advantage for biochar is particularly true in areas such as the PNW that rely primarily on hydropower, a low-C energy source [2]. Bioenergy, however, has a greater climate change mitigation potential in some areas where coal dominates energy production and the crops do not respond to biochar amendments due to high soil-fertility levels. In the future, as the C-intensity of the energy supply decreases, the climate-mitigation potentials of both biochar and bioenergy will decrease, but that of bioenergy will decrease about 2.5 times more rapidly than biochar [121].

With respect to the global climate mitigation impact of biochar production, several detailed estimates of the biochar technical potential that invoke strong

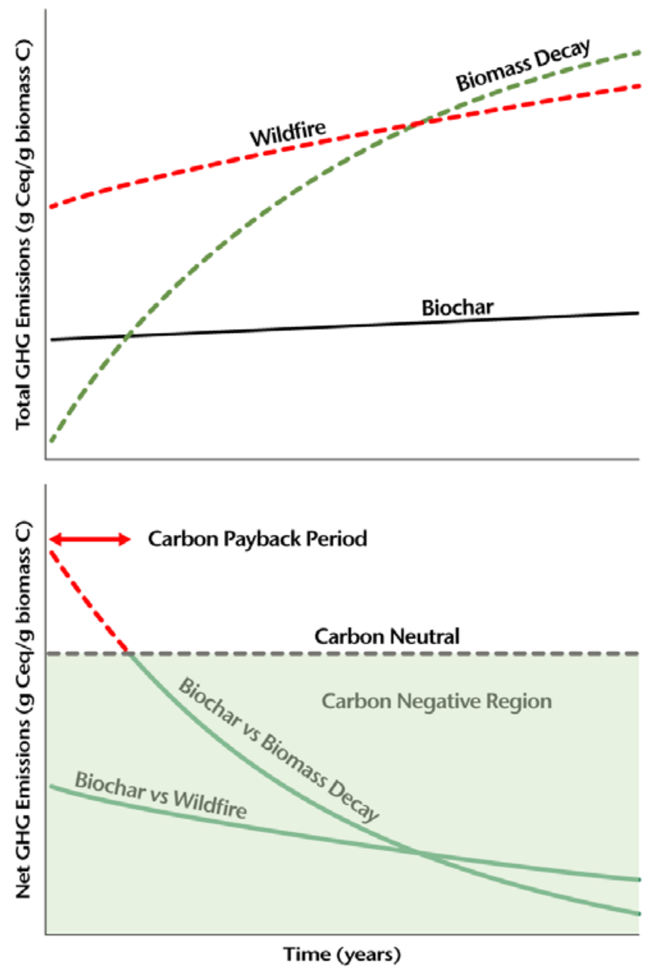

Figure 1.4. *Two stages in a hypothetical time-sensitive LCA of biochar technology. (Top) Total GHG emissions of biochar and two alternative fates of the same woody biomass feedstock (decay in place and wildfire). (Bottom) Net GHG emissions of the biochar approach relative to biomass decay and to wildfire. The C-payback period is the period during which biochar technology has higher cumulative GHG emissions than the biomass-decay option.*

sustainability criteria to determine the available biomass supply were provided by Woolf et al. [121]. The lowest of these estimates, which represented the available biomass with little change from current practices or technology, was about 3.7 Gt (4.1 GT) of CO_2e per year. The highest, which was termed the "maximum sustainable technical potential," was 6.6 Gt (7.3 GT) of CO_2e per year. These estimates covered the range of 7% to 12% of the global anthropogenic emissions in 2012 and are probably about twice as large as the corresponding economic potentials. Biochar technology thus can be a critical strategy for mitigating climate change alongside other strategies. Meanwhile, it offers the potential for many other beneficial impacts on specific sites and communities where it is used.

Wildfire Risk Reduction and Forest Health Improvement

In western U.S. forests, fire suppression and changes in forest management have resulted in heavily stocked forests that are at higher risk of damage by disease, insects, and high temperature wildfire – and of reduced ecosystem resilience in the face of climate change [55, 117 p. 22-31]. More frequent wildfires and resulting poor air quality are expected to increase respiratory illness in the coming decades [83 p. 519]. Fine particulate matter due to 2020 wildfires been linked to increases in COVID-19 cases [127]. Oregon, Washington, and California are among the top 10 states for the number of properties at high risk due to wildfires [116] and were states that experienced devastating wildfires in 2020 (Figure 1.5).

Practices aimed at reducing wildfire risk include removal of woody biomass from areas surrounding structures and thinning stands with unnaturally high density resulting from fire suppression. Haugo et al. [53] estimate that a change in forest structure is needed in approximately 40% of the forested area in Oregon and Washington with thinning or controlled (low-severity) burns as the most commonly needed treatment. Thinning forests results in large quantities of low-value forest biomass (Figure 1.6). In the 17 contiguous western states of the U.S., up to 32 million BD tonnes (35 million BD tons) of forest waste and residues could be sustainably produced each year from thinning and normal tree-harvesting operations [113; Figure 1.7].

When harvesting and thinning operations occur, the resulting forest waste and residues are typically burned in slash piles (Figure 1.8), a practice that vaporizes nutrients, generates air pollutants [18], alters soil properties [19], and forms scars on the landscape that are prone to exotic plant invasion [65]. Embers from slash pile burns can cause causes hundreds of wildfires each year across the western U.S.

While thinning and controlled burns have ecological and social value, they are expensive and difficult to implement on a large scale. The commercialization of biochar from forest residuals could lower the cost of wildfire risk-reduction treatments, making it possible to treat more acres with scarce public funding and maximize benefits to air quality and public safety.

Meanwhile, producing biochar from this low-value woody biomass instead of burning it could benefit forest ecosystems. The biochar could be used on-site to improve forest soils, increase nutrient retention, and mitigate compacted soils, erosion, and revegetation challenges created by forestry activities. It could also be exported for application to agricultural soils, reclaimed mine-land soils, or other purposes. Thus, biochar technology could significantly increase the air quality and decrease the associated health issues stemming from pile-burning in the PNW [92].

The climate impact of addressing forest-health issues with biochar production could be significant. Amonette [4] estimated available biomass, biochar production, and CO_2 drawdown potential for six forest harvest scenarios in Washington State. Depending on scenario, 5 to 8.5 million BD tonnes (5.5 to 9.4 million BD tons) of biomass was available for biochar production at centralized facilities yielding 100 to 340 Mt (110 to 375 MT) of biochar C production and 450 to 1,400 Mt (496 to 1,544 MT) CO_2e offsets over 100 years. When on-site production at the forest landing was included, these values doubled. Applying the same approach here to

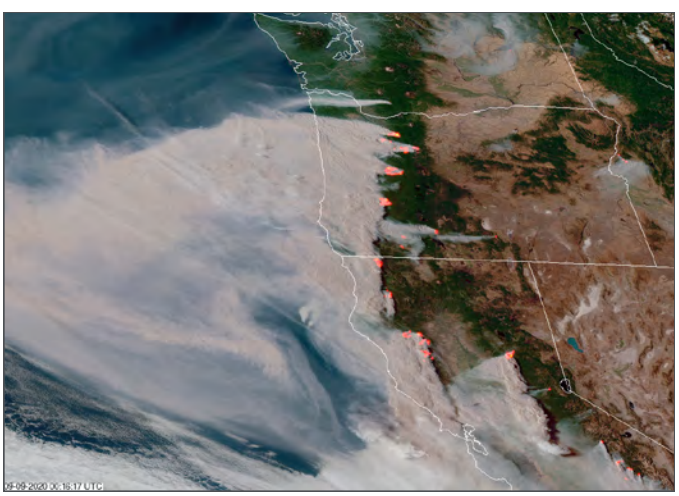

Figure 1.5. *Smoke and fires in the western U.S. visible from space on September 9, 2020. (Photo: rammb.cira.colostate.edu NOAA Satellites and Information)*

Figure 1.6. *Slash pile resulting from fuel reduction treatment near Flagstaff, Arizona. (Photo: Han-Sup Han)*

Figure 1.7. *Logs and slash piled near Flagstaff, Arizona covering four acres at a depth of approximately 20 feet. This pile was assembled but never taken off-site due to the lack of forest products manufacturing facilities nearby and was subsequently consumed in the 2019 Museum Fire. (Photo: Markit! Forestry)*

the 32 million BD tonnes (35 million BD tons) of forest biomass potentially available to centralized facilities in the 17 western states [113], suggests that 620 Mt (684 MT) biochar C and 2,400 Mt (2,646 MT) CO_2e offsets[6] could be generated over 100 years.

While this report is focused primarily on forestry residues due to the large potential for biomass contribution from states like Washington and Oregon, agricultural residues also provide a large source of feedstock for biochar systems, as much as 58 million BD tonnes (64 million BD tons) in the 17 western states. Burning of agricultural residues is less common now than it was historically, but where burning is used it can have negative air quality impacts, impacting human health. The dry organic fraction of municipal solid waste (e.g., waste wood) provides another source of feedstock (as much as 3.3 million BD tonnes [3.6 million BD tons] in the 17 western states). When used to manage municipal solid wastes, biochar production could re-capture the C value of these wastes and reduce the negative impacts of landfilling.

Soil Health and Ecosystem Services

Biochar can help avoid, reduce, and reverse land degradation—a condition that afflicts over a quarter of Earth's ice-free land [63, 85]. Due to its high porosity, extraordinary surface area, and surface-active properties, biochar has been applied to restore soil chemical, biological, and physical properties of agricultural,

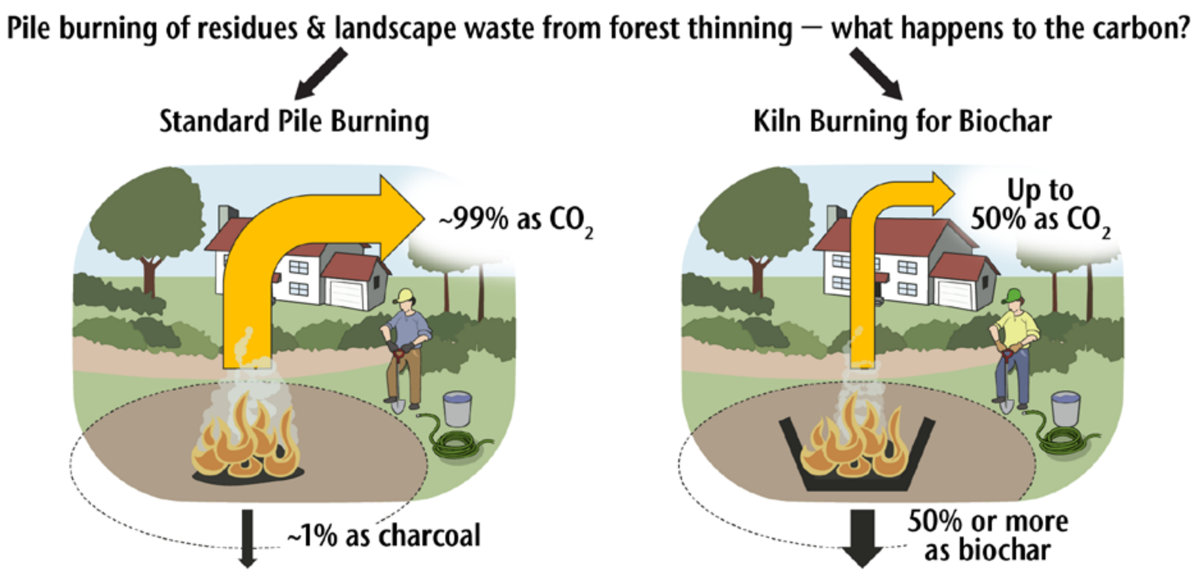

Figure 1.8. *Burning in a biochar kiln instead of a standard burn pile converts as much as half of the C in wood waste into biochar. Biochar lasts for hundreds to thousands of years in soil, benefiting forest health and sequestering C. (Figure adapted from CalFire)*

6 *The offsets for the 17 western states are higher in proportion to the biochar C generated than for Washington State because they have a 50% higher average fossil-C intensity of their energy supply.*

rangeland and forestry soils that have been degraded from overuse, mismanagement, or natural disasters [6, 84]. It has also been used for remediation of severely degraded soils associated with abandoned mine land and drilling sites.

Biochar application has been studied most extensively in agricultural soils, where improvements in soil and ecosystem health are usually seen [64, 73, 74, Figure 1.9]. In general, biochar amendments to soil increase nutrient availability [62], enhance microbial activity [35 ,49, 108], decrease nutrient losses by leaching [13, 57, 67, 105], and minimize off-site movement of pesticides [46, 51, 73]. Mechanisms responsible for these observed outcomes include decreases in bulk density, and increases in soil pH, cation-exchange capacity [67, 107], porosity, water-holding capacity [3, 30, 75, 86, 93, 125], and aggregation [15]. Over the long term, biochar amendments increase active (labile) soil organic matter [11, 12, 54, 66, 119], which helps stabilize the granular structure of the soil [110, 118] and thereby improve tilth (the physical condition of soil).

These generalizations aside, the specific effect of biochar applications on soil health depends on the characteristics of the biochar, which are impacted by feedstock and production process [59], and on the soil type, with nutrient-poor soils showing the greatest improvements [27, 32, 61]. Several studies [31, 37, 60] have also indicated potential for biochar to increase plant resistance to biotic and abiotic stresses through mechanisms shown in Figure 1.10, but this depends strongly on the biochar-soil-crop system. One can thus imagine instances, such as the application of a high pH biochar to a high pH soil, where application of biochar would lead to a decline in soil health, at least in the short run. Consequently, to ensure optimal results, application decisions need to be based on accurate characterization of the biochar and the soil with consideration given to the type of vegetation involved.

Soil health improvements, ideally, result in crop yield improvements. A wide range of impacts from decreased yield to increased yield have been reported in the literature, resulting from the wide variety in feedstocks, production and post-production methods used, and crops and soils to which resulting biochar is applied [27, 32, 61, 106]. Yield improvements from biochar tend to be more likely in nutrient-poor soils with more modest gains in nutrient-rich soils. Since the economics of biochar are marginal and are often tied to assumptions regarding duration of yield benefits, a better understanding of the dynamics at play could significantly improve ability to target applications of specific biochars to situations that offer the best potential for return on investment [27, 32, 61, 106].

Figure 1.9. *Biochar amendment can provide a host of benefits to soil. (Photo: Brennan Pecha)*

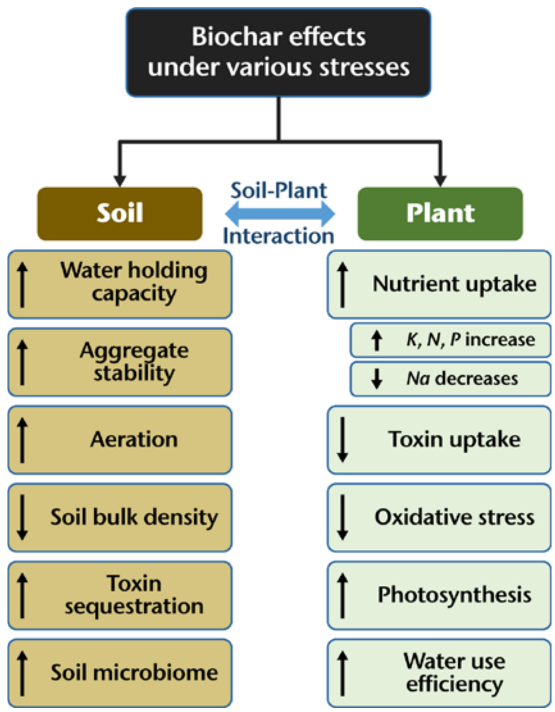

Figure 1.10. *Model of how biochar affects soil, plants, and soil-plant interactions under stressed conditions (Source: Gang 2018 [39])*

Recently, growing regional, national, and global interest in "regenerative agriculture" has sparked interest in the role that biochar (along with reduced tillage, cover cropping, amendments, and other agricultural practices) can play in revitalizing soil health and building stores of C in agricultural topsoil that has been degraded over time [14, 20, 34, 68, 103]. Biochar can contribute to current efforts to improve soil health by public and private organizations (e.g., Soil Health Institute, Soil Health Partnership, USDA, NRCS, The Nature Conservancy). And biochar can contribute to other ecosystem services in agricultural systems, such as by retaining nutrients in soil, thereby reducing nutrient pollution, and protecting waterways. As an indication of the level of interest in biochar, more than 100 innovative western U.S. farmers volunteered acreage on their farms for a U.S. Biochar Initiative (USBI) proposal to demonstrate and monitor biochar use following release of a new NRCS Conservation Practice Standard for soil carbon amendments [77, 111].

Biochar can benefit forest soils as well. Application of biochar to forest soils generally enhances soil chemical, physical, and microbial properties [72]. A recent meta-analysis found that biochar application to woody plants could result in an average 41% increase in biomass, with most pronounced results in early growth stages [109]. Though many of the relevant studies focus on deciduous forests, there are some studies of evergreen forests relevant to the region. For example, Sarauer et al. [96] found that biochar applied to forest soil in the inland Northwest increased soil C by as much as 41% and Palviainen et al. [88] showed that biochar increased the diameter of pine trees in Finland by 25% and height by 12% during the first three years after application. Keeping forests healthy and resilient improves their productivity as well as their ability to provide clean air and water, habitat for wildlife and reduced fire risk. In addition, because healthy temperate-zone forests remove about 3.4 tonnes CO_2 per hectare (1.4 tons CO_2 per acre) each year from the atmosphere (2.6 Gt [2.9 GT] CO_2 per year globally) [45, 89, 90], of which 69% to 92% is ultimately stored in forest soils [97], they are a critical tool in confronting climate change.

Revitalizing Rural Communities

More difficult to quantify, but equally important in the discussion of value provided by scaling up of biochar systems is the value of revitalizing rural communities. Rural communities across the U.S. are on balance older and poorer, with persistently slower rates of employment growth compared to urban areas [112].[7] In the Northwest, many communities that had historically relied on forest-based industries to support livelihoods have experienced dire economic circumstances in recent decades due to widespread closures of lumber and paper mills from the 1990s through the present.

In the early 1990s, the Northwest Forest Plan (NWFP) established a new forest management framework for the 24 million acres of federal forestland in Washington, Oregon, and California within the range of the Northern Spotted Owl and shifted 11 million acres of federal forestland from timber production to old-growth forest protection, dramatically accelerating a decline in timber harvests that was already underway.[8]

The dramatic drop in federal timber harvests combined with ongoing automation and industry concentration led to a wave of mill closures across the region. In 1980, for example, 405 lumber mills operated in Oregon. In the following three decades, two thirds of these mills closed. By 2007 there were only 58 mill towns in Oregon. For the region's small communities, a mill closure represents a serious economic blow to community employment and economic well-being [22]. Between 1990 and 2000, socio economic well-being indicators were more likely to drop in communities near federal forestlands in the NWFP area than in communities farther away, and the majority of communities scoring low on a socioeconomic well-being index were within five miles of a federal forest [21].

The economic fallout from the NWFP spawned numerous efforts that combined rural job creation and federal forest restoration, including Jobs in the Woods, stewardship contracting, American Recovery and Reinvestment Act, and the Coordinated Landscape Restoration Program. More recently, Good Neighbor Authority provided federal agencies with additional funding, greater authority, and the administrative flexibility to pursue the twin goals of ecological and community resilience. While these programs did not specifically include biochar development, they represent federal investment and community engagement approaches that can inform the pathway to a robust biochar industry.

Many communities in the PNW that were historically dependent on forest products continue to struggle with a lack of economic opportunity and associated social and community issues. Biochar production can provide a durable economic development engine with a manu-

7 *Rural America includes 14% of the Nation's population but accounted for only 4% of employment growth between 2013 and 2018. The rural poverty rate was 16.4% in 2017, compared with 12.9% for urban areas. In the U.S., 19% of the rural population was 65 years or older, compared with 15% in urban areas.*

8 *For example, in Oregon, in 1989, almost 5 billion board feet of timber was harvested in Oregon on federal forests. Harvests dropped to less than 200 million board feet in 2001 and averaged less than 330 million board feet per year during the most recent decade.*

facturing component that can support the economy of struggling rural communities, while reducing wildfire risk and improving forest health (See sidebar: *"Helping Rural Economies" on page 14*). Economic revitalization is particularly important in light of the economic disruption due to the Covid-19 pandemic.

Capturing Monetary Value in Biochar Systems

To realize these societal benefits, biochar production must be economically viable. This depends on monetizing the value of goods and services that are provided.

Currently, the two products that have been reliably "monetized" include the thermal energy (heat) that is produced during the pyrolysis process, and the biochar. The thermal energy can be used within a facility to reduce energy costs and can also be used to generate electrical power that can be sold. Valuation of thermal energy is relatively straightforward and depends on existing energy prices. Valuation of biochar as a soil amendment, on the other hand, is more difficult due to variable impacts and a need to identify the niches where biochar is most likely to provide economic benefits to applicators.

Meanwhile, monetizing other benefits has been a challenge to date. Monetizing the value of forest restoration and fire-hazard reduction deserves substantial attention due to the potential harm to communities and lives resulting from catastrophic fires in the West. Ultimately, it may be most likely that the other monetary benefits generated by biochar could help stretch existing public funds focused on forest restoration, enabling treatment of more acres.

Monetizing CO_2 removal from the atmosphere through C markets has significant potential to "tip the scales" toward overall economic viability of biochar production [25, 98, 104, 120]. Until recently, biochar producers in the western U.S. have not been able to take advantage of C markets and policies, even where such policies exist, such as Cap and Trade and the Low Carbon Fuel Standard (LCFS). Each potential market platform has different requirements that must be met before biochar can be recognized. Accessing these markets is an active area of work – one that could have substantial impacts if successful. One seminal success in this effort was achieved in November 2020, when C credits for biochar production were issued to a biochar supplier in California [87].

To give an idea of the potential economic impact of access to climate-related markets and policies we explore the impacts under two possible approaches.

Helping Rural Economies

Small rural towns typically have abundant supplies of agricultural or forestry residues nearby that can be used as feedstocks for biochar/bioenergy production facilities. A typical wood gasifier facility could process 300,000 BD tonnes (331,000 BD tons) of biomass annually (34 BD tonnes [37 BD tons] per hour), from which 45,000 tonnes (49,600 tons) of biochar (at 15% efficiency) and 660,000 MWh of energy could be produced. With steam generation, the facility could supply 19 MW of electricity to the local grid, enough to power 15,000 homes, and still have 57 MW of thermal energy available for other purposes such as space heating of homes, businesses, and greenhouses. A plant of this size could provide 35 jobs and support 120 people. Additional jobs would be found in biomass procurement activities such as fire-hazard reduction operations in forests. Annual expenses would total $19 million (capital $6.6 million, labor and operations $6.8 million, feedstocks $6 million). Sale of the biochar at $150 per tonne ($136 per ton) and of the electricity at a wholesale price of $30 per MWh would yield $12 million in revenue. Additional revenue from C credits, higher value biochar products, or thermal energy for space heating would be needed. For example, at a C price of $40 per tonne ($36 per ton) CO_2e, offsets from biochar-C and bioenergy could generate $7.8 million. Sale of thermal energy at $18 per MWh could generate $9 million. Development of multiple product streams could help assure profitability.

A similar analysis for a slow pyrolysis facility (31.5% biochar efficiency) shows a slight profit from biochar and electricity sales alone. Potential revenue from sales of C credits at $40 per tonne CO_2e ($14.5 million) and thermal energy ($4.6 million) adds to this profitability. ■

The first, simpler approach, is agnostic with respect to the method of production and is used for most current C credit markets. This method bases the marketable climate offset on the properties of the biochar alone and thus does not consider the amount of biomass consumed or the possible beneficial use of the energy produced. Although it accounts for the decay of biochar in the soil over time, it does not account for any ancillary impacts on soil processes or native organic matter stocks. This approach yields remarkably consistent net C values of about 2 to 2.5 tonnes CO_2e per tonne *biochar* at the time of soil application, and 1.8 to 2.3 tonnes CO_2e per tonne biochar after 100 years [17]. Under these simple and verifiable conditions, C values of $70 to $150 per tonne ($63 to $136 per ton) CO_2e could completely offset biochar production costs. Current market prices are in this range. Using a value of 2 tonnes CO_2e per tonne biochar (after 100 years) as an example, the European markets at 2020 prices would add approximately $100 per tonne ($91 per ton) of biochar value; California Cap and Trade could add $40 per tonne ($36 per ton); and the California and Oregon Low Carbon Fuel Standard could add $400 per tonne ($363 per ton) of economic value.

The second possible approach incorporates the C efficiency of the production process as well as the properties of the biochar and calculates net C value in terms of tonne CO_2e per tonne biomass C [25,104,120]. Using this LCA-based approach with biomass data from Washington State[9], estimates of net C values range from a low of about 0.14 tonnes CO_2e per tonne biomass C at 5% C efficiency to a high of more than 1.5 tonnes CO_2e per tonne biomass C when C efficiencies above 45% are attained (solid green line in Figure 1.11). Generation of electricity using process energy and consideration of impacts on soil C stocks and vegetative response increases these net C values by at least 60% (dashed green line in Figure 1.11). Although smaller than the near-constant net C value estimated on the biochar-C basis (dark grey line in Figure 1.11), these biomass-C values provide a truer representation of the C impact of biochar technology. Further, they reward high-efficiency producers, ensure maximum climate mitigation impacts from limited biomass resources, and provide a strong incentive for development of LCA-based C-market instruments.

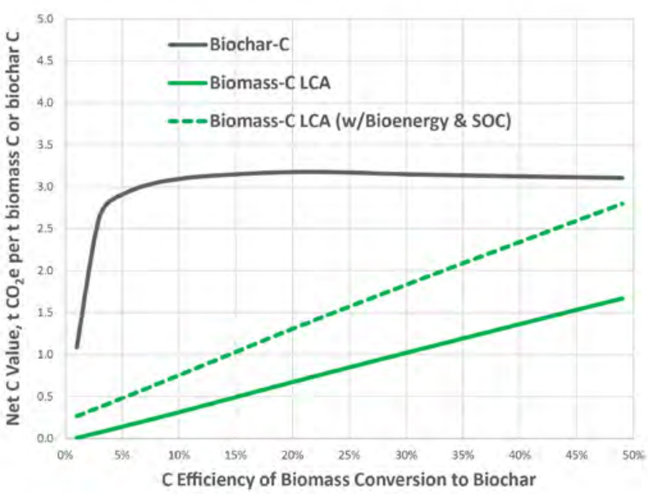

Figure 1.11. *Estimates of net C value for biochar systems in Washington State evaluated on the basis of biochar properties only (dark grey line) or with inclusion of C efficiency of biomass conversion (solid green line). The dashed green line adds the impacts of bioenergy generation and of biochar amendments on native soil organic C stocks.*

Whichever approach is taken, consistent and standard biochar characterization methods and protocols must be developed and adopted before C markets can be accessed. Existing protocols (based on biochar properties alone) can be adapted to smooth the development process and lower costs. For example, an emerging C market platform that operates in the U.S. and Germany [17] includes biochar in their trading platform and requires either a European Biochar Certificate (EBC) or International Biochar Initiative (IBI) certificate for verification. In California, a reporting protocol for biochar is presently being adapted for submission to the Climate Action Reserve. If approved, bioenergy producers could register biochar compliance offset credits under the state's Cap and Trade program. The additional economic value generated could produce millions of C offset credits and greatly accelerate the utilization of biochar throughout California and beyond [16]. Work is still needed to develop protocols based on biomass C efficiency, which have great potential to stimulate further development of a sustainable biochar industry.

While achieving the promise of biochar systems requires economic viability, it also requires a continued effort to maximize the environmental and social aspects of sustainable biochar production and use, and minimize unintended negative consequences.[9] Important considerations include safety for production personnel and equitable labor practices, transparent operations and stakeholder relationships, feedstock choices and land use before production, C efficiency, GHG emissions, energy use, and output during production, C stability and application after production, and open sharing of knowledge.

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