

# Technical Potential for CO<sub>2</sub> Drawdown using Biochar in Washington State

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# Abstract

This is the final report in a series that describes development and application of a high-resolution scalable method to estimate the technical potential for atmospheric carbon (C) drawdown by biochar in Washington State using crop residues, forestry residues and waste wood as primary feedstocks. The method includes spatial integration of soil productivity and crop information at 1-hectare (ha) resolution, estimates of changes in soil organic C levels resulting from feedstock harvesting and biochar application, estimates of increases in productivity stemming from biochar application to cropland, sigmoidal growth of biochar production capacity, and tracking of biochar production and soil storage capacities over time.

Ten biomass-feedstock and biochar-process scenarios were developed, including one each for agricultural crop residues and for waste wood harvested from municipal solid waste (MSW) and processed at a central facility, and eight full scenarios for the combination of crop residues and MSW waste wood with forestry residues from four levels of timber harvest and two processing locations (either a central facility or both a central facility and in the field). Individual results for each county were generated.

The combined results for Washington State show that over 100 years, the agricultural crop-residue scenario could generate 36 million metric tons (megatonnes; Mt) of biochar C, a total immediate offset of 44 Mt of C-equivalent (Ceq, which equals 162 Mt of CO<sub>2</sub>-equivalent; CO<sub>2</sub>eq) and, after accounting for climate-system responses, an ultimate drawdown of 10 ppbv of atmospheric CO<sub>2</sub>eq. The MSW scenario could generate 6.6 Mt of biochar C, a total immediate offset of 8.5 Mt of Ceq (which equals 31 Mt of CO<sub>2</sub>eq) and an ultimate drawdown of 1.8 ppbv of atmospheric CO<sub>2</sub>eq. For the eight full scenarios, each which includes results for crop-residue, MSW, and forestry residue feedstock streams, substantially higher values were obtained: 144-381 Mt of biochar-C production, 174-430 Mt of Ceq offsets (636-1580 Mt CO<sub>2</sub>eq), and an ultimate drawdown of 38-93 ppbv of atmospheric CO<sub>2</sub>eq. At the maximum biomass-utilization rate, which is achieved after five decades, biochar production could offset between 8% and 19% of the greenhouse-gas emissions in Washington State (taken at 2018 levels). If the same sustainably procured biomass were instead combusted for renewable energy, these offset and drawdown values decrease by 58% to 62%, primarily due to the low C-intensity of the primary energy supply in Washington State, but also due to the inability of bioenergy to provide the unique benefits associated with soil incorporation of biochar.

# Introduction

As outlined by Amonette et al. (2016a,b), production of biochar from waste wood in Washington State using modified biomass boilers has the potential to yield many benefits, including improved biomass productivity, decreased irrigation costs, and, perhaps most importantly, drawdown of atmospheric CO<sub>2</sub>. Although Amonette et al. (2016a,b) used the results of an earlier global model (Woelf et al., 2010) to estimate that on the order of 500-600 Mt atmospheric CO<sub>2</sub> could be offset in Washington State over the course of a century (before accounting for releases of C currently in the oceanic and terrestrial pools), they recommended further analysis be made to refine and solidify this estimate.

Amonette (2018) took the first step along this path, by developing and demonstrating a high-resolution scalable method for estimating the net 100-year CO<sub>2</sub> drawdown technical potential of biochar for Spokane County with the aim to apply the method to the entire state in subsequent work. His method took into account local, site-specific factors such as (1) the availability and distribution of waste-wood biomass, (2) the locations of existing biomass boilers, (3) the soil types and land-use categories receiving biochar amendments, and (4) the expected primary productivity responses to biochar amendments (a positive-feedback loop). Global climate system responses to drawdown, such as net losses of non-pyrogenic soil organic C (npSOC, which is distinguished from the pyrogenic organic C present in biochar) and the ex-solution of oceanic CO<sub>2</sub>, were also considered.

The second report of the series (Amonette, 2019) strengthened this approach in several ways. First, land capability classes and cropping systems were explicitly related at a 1-ha spatial resolution for use in estimating primary productivity responses to biochar amendments. Second, soil priming effects (i.e., the change in npSOC levels expected from additions of biochar) were updated to reflect recent literature suggesting a small enhancement of npSOC by biochar amendments to agronomic soils. This effect was treated separately from the decreases in forest-npSOC levels expected when forestry residues were harvested to make biochar. Third, explicit time-dependent tracking of both biochar production levels and biochar soil storage capacities was incorporated. This was to account for the exports of biochar from counties that have exceeded their storage capacities to counties for which storage capacities in excess of their own biochar production capacity exist. This tracking provided the first assessment of the relative levels of production and consumption over time among the 26 counties included in the study and set the stage for a future economic assessment that includes transportation costs as a factor.

The present work builds on the previous results by adding a new feedstock scenario to account for the contributions from agricultural crop residues (chiefly straw from cereal production) and two forestry feedstock scenarios that account for biomass from thinning operations associated with potential wildfire hazard-reduction efforts. It significantly improves the estimates of soil priming effects by incorporating first-order kinetic models to account for the rate of npSOC increase over time, the loss of biochar to oxidation, and a saturation level of npSOC per unit of biochar added. These priming effects are then scaled according to the initial npSOC stocks, which account for various site-specific factors such as temperature, rainfall, mineralogy, etc. that

affect equilibrium npSOC levels. Thus, for the same level of biochar amendment, a smaller increase in npSOC would be predicted for a low-npSOC soil in the hot and dry regions of the state than for a high-npSOC soil in the cooler and wetter regions.

Finally, the present work applies the method to all 39 counties in Washington State, individually and collectively, thereby providing a more detailed and scientifically defensible estimate of the statewide potential of biochar technology to draw down atmospheric CO<sub>2</sub> over a century than that provided earlier by Amonette et al. (2016a,b).

## **Methods**

### **BGRAM Algorithm**

The algorithm used to perform the assessment is a modification of the Biochar Global Response Assessment Model (BGRAM) implemented in spreadsheet form by Woolf et al. (2010). This algorithm considers biomass composition, pyrolysis and combustion process parameters, energy production, C intensity of energy being offset, rate of technology adoption, biochar properties, biomass growth response, biomass and biochar transport, biochar decomposition rates, and greenhouse gas emissions at every stage of the cycle from biomass harvest to 100 years after biochar has been added to the soil. The original version was developed for a global analysis based primarily on the use of agricultural biomass residues, and required modest revisions to be able to work with smaller national, regional, and local datasets. Extensive details about the original BGRAM algorithm can be found in the online supplemental information file associated with the Woolf et al. (2010) publication.

The BGRAM algorithm performs calculations for a specific input scenario, which basically consists of estimates of the amount and composition of sustainably available biomass for each feedstock being considered, coupled with information about whether the biomass is processed in the field by a mobile unit or at a central location, whether pyrolysis (for biochar) or combustion (for bioenergy) processes are to be used, and the travel distances required to get the biomass to the processor and the biochar to the land where it is to be applied. For this study, four primary feedstock streams were used: agricultural crop residues (straw from cereal crops), residual forest biomass from timber-harvesting operations, wood reclaimed from municipal solid waste (MSW; dimensional lumber, engineered wood, pallets and crates, natural wood, and other non-treated wood), and green waste also reclaimed from the MSW stream. In addition, a fifth secondary feedstock stream, based on the additional drawdown stemming from biomass response to biochar amendment (i.e., enhanced yield), was considered in each scenario.

### **Enhanced yield**

The estimation of enhanced yield involves allocating the yield response among 56 different possible combinations of land capability class (eight levels) and crop group (seven levels). As described in detail in the Soil and Crop Yield Inputs section, geographic information system (GIS) software was used to determine the fractional areal extent of each crop group for each land capability class based on a 1-ha grid. The total biomass yield in the county for each crop group was then distributed among the eight land-capability classes according to fractional areal extent.

The response of these biomass yields to biochar amendment was then estimated as the fraction of the maximum response rate (0.022 Mg C/ha for cereals, and 0.066 Mg C/ha for all other crops; Woolf et al., 2010) that varied with the land-capability class. For example, crops growing in soil having a land-capability class of 1 (i.e., prime farmland) received only 10% additional yield response to the addition of biochar, whereas crops growing where the land-capability class was 8 (e.g., badlands, sandy beaches, mine tailings, etc.), received 100% of the maximum response rate. The fractional yield responses for land-capability classes of 1 through 8 were somewhat arbitrarily assigned to be 10, 20, 30, 40, 60, 80, 90 and 100%, respectively, of the maximum response rate. Obviously, there is room for further improvement in the estimate of enhanced yields including: (1) use of actual biomass yield data for different land-capability classes (rather than assuming the same pre-biochar yield across all land-capability classes, which is the only option currently available); (2) incorporation of actual yield response rates for given crop, soil, and biochar combinations; and (3) use of the National Commodity Crop Productivity Index approach (NRCS-USDA, 2012) or similar models such as CropSyst (Stöckle et al., 2019) rather than the rather broad-stroke approach represented by land-capability classes to assess soil fertility. Future versions of BGRAM will hopefully incorporate some or all of these improvements, as relevant datasets and models become available.

## **Tracking of biochar production and storage capacity**

Another improvement to BGRAM involves time-dependent tracking of biochar production and soil storage capacity for each county. This allows estimation of the point at which the agricultural soil in the county becomes “saturated” with biochar (currently assumed to be incorporation of 50 t biochar C/ha to a 15-cm depth). At that point, the county then must export biochar to other counties in the state with available storage capacity. As will be shown in the results, assembling and analyzing the data collected across the state allows a better grasp of the biochar export/import economy and helps provide input to future techno-economic studies of the probable development path of the biochar industry in Washington State.

## **Impact on soil organic C stocks**

The most important change to BGRAM in the present work was to develop a mechanistically based algorithm to estimate the losses (positive priming) in npSOC stemming from harvesting of biomass for production of biochar as well as the gains (negative priming) in npSOC, stimulated by amendments of biochar to agronomic soils. These changes replaced the relatively simple approach taken in Amonette (2019) for estimating the priming effects of biochar technology.

### **Analysis of prior studies**

Over the past decade, a significant body of work has been devoted to the question of how biochar amendments affect npSOC stocks (for example, see reviews by Whitman et al., 2015; Wang et al., 2016; and Ding et al., 2018). Most of the studies conducted were relatively short-term (weeks to a few years) incubations and helped form a general consensus that during the early stages after biochar amendment some positive priming of npSOC can occur, and certainly positive priming of fresh organic matter additions occurs. Thereafter, priming of npSOC generally is either neutral or negative, meaning that, in the long run, biochar amendments either have no impact on npSOC stocks or they actively promote npSOC formation/accumulation. From the standpoint of the present work, we are interested in developing a way to estimate the degree of priming for 100

years after biochar amendment and, aside from the insights just discussed, the results of short-term incubations add relatively little value to that effort.

Fortunately, one modeling study and three natural-analog studies of npSOC changes in soils at abandoned charcoal-production sites provide consistent estimates of the degree of negative priming that can be expected over the course of a century in temperate-zone soils. Woolf and Lehmann (2012) modeled two 100-year scenarios involving the removal of 50% of crop biomass (maize) from soils in Iowa, Kenya, and Colombia after establishment of npSOC “equilibrium” in each soil. In the first scenario, the biomass was removed and diverted to other unspecified uses. In the second scenario, the biomass was converted to biochar by slow pyrolysis and added back to the soil on an annual basis. Their model showed significant decreases (21-28%) in npSOC stocks relative to the initial equilibrium when biomass was removed from the cropping system. In contrast, conversion of this biomass to biochar followed by soil amendment was estimated to yield net increases of 35-60% in npSOC stocks (relative to equilibrium) after 100 years.

Borchard et al. (2014), Hernandez-Soriano et al. (2016), and Kerré et al. (2016) characterized the npSOC and biochar stocks in soils at former charcoal-production sites in Germany and Belgium. The use of earth-mound kilns to produce the charcoal (i.e., biochar) resulted in its inadvertent addition to soils in relatively discrete locations. Sampling and characterization of pairs of biochar-amended and nearby unamended soils at each site allowed estimates of the net impact of biochar on npSOC stocks over the course of at least 60-150 years since charcoal production had ceased. Calculations based on the results of Borchard et al. (2014) showed a 117% increase in npSOC in a base-rich forest soil (pH 4.8-5.3) and a 380% increase in an extremely acidic forest soil (pH 3.8-4.1) 60 years after charcoal production ceased. Work by Hernandez-Soriano et al. (2016) and Kerré et al. (2016) focused on carbon isotopic data to determine the fraction of maize-derived OC in each soil pair after at least 12-17 years of cultivation. In their sites, charcoal production had ceased roughly 150 years beforehand. Hernandez-Soriano et al. (2016) measured a 42% increase in maize-derived OC in the biochar-treated plots relative to the unamended plots, whereas Kerré et al. (2016) measured increases of 60-70% for this comparison. Kerré et al. (2016) also measured differences in npSOC and found significant results only when the dichromate oxidation method was used. Their results ranged from no effect to as much as a 40% increase in npSOC with biochar amendment.

The long-term modeling and natural-analog results provide a strong argument for negative priming by biochar on a century time scale. Recent reports by Blanco-Canqui et al. (2019) and Zomer et al. (2017) suggest that the increase in npSOC in cropland soils following changes in practice (biochar amendment or other farming practices) would largely manifest themselves over a period of a few decades. Calculations based on data from Blanco-Canqui et al. (2019) show an increase of 7.7% (1.27%/yr) of the npSOC stocks in the top 30 cm of soil 6.1 years after amendment with 7.25 t biochar C/ha. When compared to the control treatment with no biochar amendment, which lost npSOC over the 6 years, the net increase in npSOC was 9.3% (1.52%/yr). Zomer et al. (2017) modeled global increases in npSOC with major changes in farming practices and management, based on the assumptions of Sommer and Bossio (2014). Calculations based on the Zomer et al. (2017) results predict 4.1% to 8.5% increases (0.68%/yr to 1.39%/yr) in npSOC globally over the same period for the medium- and high-rate scenarios.

To estimate the impact of biochar on npSOC accumulation in soils, one needs to know, at a minimum, how much biochar C was added, the concentrations of npSOC before and after biochar addition, and the time elapsed between biochar addition and each sampling of the soil.



Knowledge of biochar and soil pH, and the sampling depths and bulk density when each soil sample is taken improve the quality of the estimate. Besides the work of Blanco-Canqui et al. (2019) only a few studies have provided these types of data. Slavich et al. (2013) and Weng et al. (2017) studied the same pasture site after amendment with a green waste biochar at 7.6 t C/ha. The initial soil pH was 4.7 and that of the biochar was 7.8. They found the npSOC stock in the top 15 cm to increase by 16% after 3 years and 47% after 9.5 years. Dong et al. (2018) added 15, 29, or 44 t C/ha of a high pH (10.6) biochar to a pH 8.0 soil with relatively low initial npSOC stocks. When compared to a control treatment that did not receive biochar, positive priming was observed in direct proportion to the amount of biochar added. Nevertheless, increases in npSOC were observed relative to the initial level present in the soil. Evidently, the biochar increased soil pH and this interfered with the rate of accumulation of npSOC. After 5 years, the relative increases in npSOC stock were 60%, 41%, and 22% for the 15, 29, and 44 t C/ha treatments. The control treatment increased npSOC by 82%. These results clearly show the importance of matching biochars to soils—for best results a high-pH biochar should not be added to an alkaline soil.

### **Development of algorithm**

In the present work, a simple algorithm to estimate the impact of biochar on npSOC was developed using the data from the four recent biochar studies cited in the previous paragraph, while staying cognizant of (and consistent with) the results of the longer-term modeling and natural analog studies. First, the recent npSOC response data were normalized by putting them in terms of percent increase per tonne of biochar C added per ha. A first-order kinetic model [ $B = A_0(1 - \exp(-kt))$ ] was fit to the data that yielded a maximum npSOC increase ( $A_0$ ) of about 37% (28% in the first 100 years) and a rate constant,  $k$ , of 0.0134 % / t biochar-C ha<sup>-1</sup> yr<sup>-1</sup>. This model was matched with an existing two-pool biochar decay model already in BGRAM to account for the loss of biochar by oxidation over time. A third first-order model was used to simulate biochar-saturation effects. That is, as shown by the Dong et al. (2018) data, increasing levels of biochar yield smaller increases in npSOC per unit of biochar C added. This decay model was constrained so that the maximum increase in npSOC in a given soil would be 100%, which is consistent with observed maximum C levels in Terra Preta soils of the Amazon region that received biochar amendments by indigenous peoples before the European conquest (Trujillo et al. 2020) and in the more recent natural-analog studies (Hernandez-Soriano et al., 2016). The saturation model assumed a “decay” constant of 0.693 / t biochar C ha<sup>-1</sup> and achieved saturation when about 10 t biochar C ha<sup>-1</sup> had been added.

Implementation of this algorithm in BGRAM assumed the biochar-stimulated increases in npSOC stocks scaled with the initial levels of npSOC in the soil. That is, soils with already naturally low levels of npSOC would not be expected to respond (in absolute terms) to the same degree as soils with higher initial npSOC levels. The relative increase would be the same, but the total amounts of C involved would differ from one soil to the next. The rationale is that natural npSOC levels integrate the various impacts of temperature, moisture, pH, mineralogy, texture, etc. to establish equilibria that otherwise would be extremely difficult to model. Fixed inputs for each county were the average values for the concentration of SOC and bulk density, assuming a given soil depth (23 cm in the database available), and the total area of arable land in the county available for biochar amendment. These values allow calculation of initial npSOC stocks in t C, increases to which were then added to the C-sequestration outputs of BGRAM for each county.

These improvements were consolidated in version 1.94 of BGRAM, which was used to process all scenarios for the 39 counties.

## Soil and Crop Yield Inputs

As described in the previous section, the enhanced-yield secondary feedstock stream in BGRAM required input data for initial crop yields distributed among land capability classes. A significant GIS-assisted effort was required to obtain these data. The approach involved creation of two perfectly aligned raster datasets at 1-ha spatial resolution, one for crop type and the other for land capability class, and then interrogating them in a spreadsheet to assign the dominant crop type/land capability classification to each ha of cropped land in the county. These were then summed to yield the number of ha in each category and normalized by crop to yield the fraction of each crop type grown in a particular land capability class.

The land capability classification data were obtained from published soil-survey data available online from the U.S. Department of Agriculture, Natural Resources Conservation Service (<https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx>). The soil survey areas covering each county (several may be involved) were downloaded, and the tabular soil property database loaded into Microsoft Access <sup>TM</sup>. A simple query for the land capability classification data was run, and the resulting table downloaded to Microsoft Excel <sup>TM</sup> and saved as a comma-separated-value (csv) file. The spatial soil dataset was loaded as a vector layer into QGIS (v 2.18.18), a free, open-source desktop GIS software package (<https://qgis.org/en/site/>), followed by the tabular land capability classification csv dataset and the two layers joined on the basis of map unit symbol. This layer was trimmed to fit within the county boundary and set to display the non-irrigated land capability class variable. This vector file was then converted to a raster format at a 100 m x 100 m spatial resolution and to a rectangular extent that exceeded the dimensions of the county.

Some soil survey data either were not publicly available (e.g., some urban areas, federal reservations, and tribal lands) or had no agricultural lands (e.g., National Parks), and, consequently, these were not included in the present analysis.

For crop type, a raster file containing crop type information at 30 m x 30 m resolution was downloaded from the U.S. Department of Agriculture, National Agricultural Statistics Service (<https://nassgeodata.gmu.edu/CropScape/>), loaded into the QGIS county project, converted to a 100 m x 100 m (i.e., 1-ha) resolution raster, and trimmed to roughly the same rectangular extent as the land capability classification raster.

The two (or more, depending on the number of soil survey areas involved) 1-ha resolution rasters with approximately the same areal extents were then aligned, a process that ensures direct comparability between raster points and the exact same number of data points in each raster. The positions and values of these raster data points (i.e.,  $x$ ,  $y$ , and  $z$ ) were extracted into a csv file for each raster. These csv files were then loaded into a Microsoft Excel <sup>TM</sup> spreadsheet and the integer values of  $z$ , which ranged between 1 and 8 for the land capability classification data and between 1 and 254 for the crop-type data were sorted to yield the number of pixels (i.e., ha) for each crop type-land capability class combination. The crop types were then combined into seven broad categories (cereals, orchard crops, hay, oilseed, pasture, pulse, and vegetable/berry crops). The result was a 7 x 8 matrix of crop category and land capability class. The values for each crop

category were normalized to give the distribution (in percentages) of a given crop category across the range of land capability classes (i.e., for a given crop category, the percentages for the eight land capability classes sum to 100). Finally, the matrices for each soil survey in the county were combined (with weighting of each survey on the basis of the number of cropped ha) to obtain the matrix used as input to BGRAM.

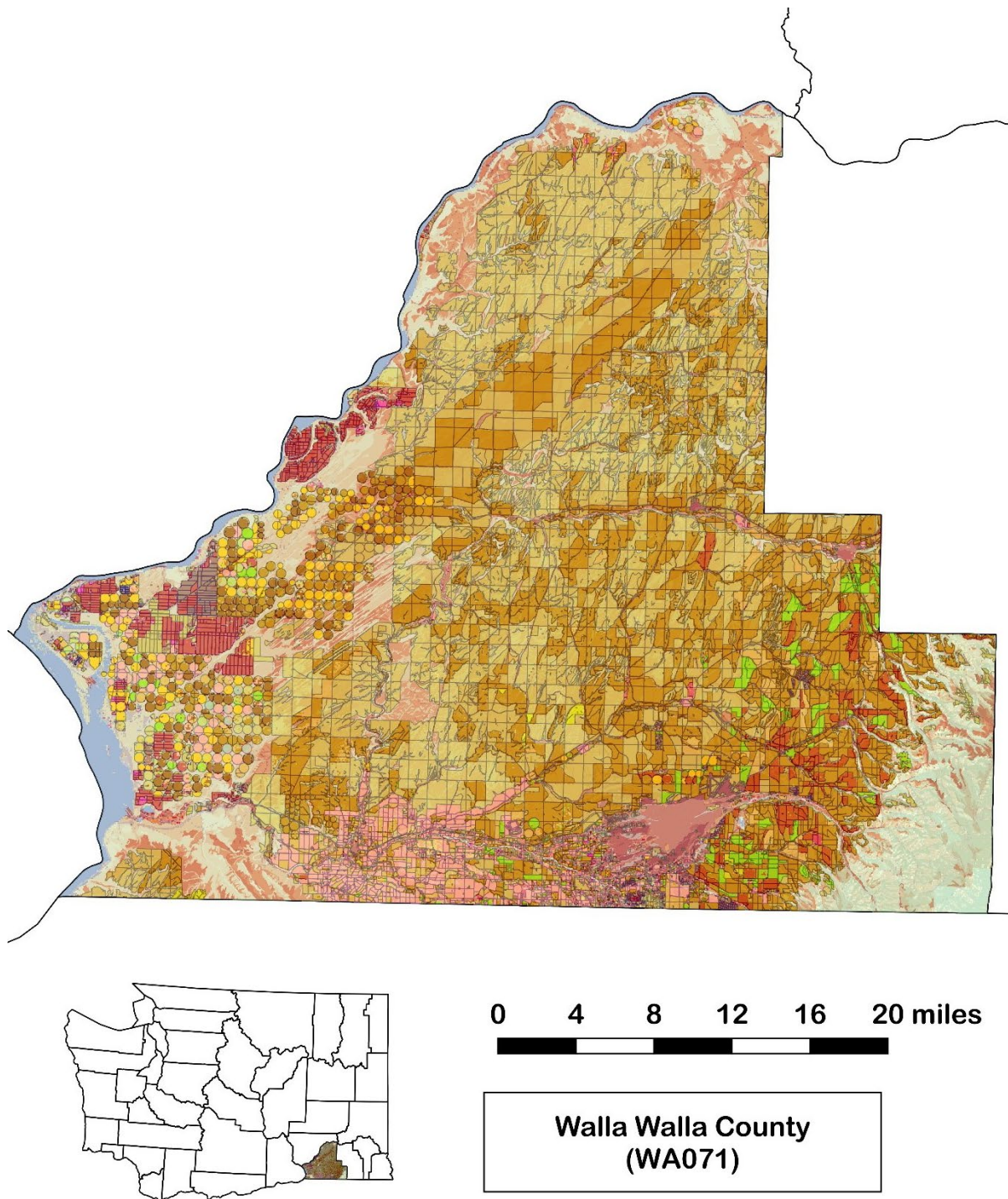
The area of land cropped to each crop in the county (and by summation, the total area of cropped land in the county) was obtained from the 2018 version of the Washington State Department of Agriculture database (in the form of a Microsoft Excel <sup>TM</sup> pivot table), available online (<https://agr.wa.gov/departments/land-and-water/natural-resources/agricultural-land-use>). These contain essentially the same data as in the US Department of Agriculture raster dataset. To determine the total crop production for each crop type, crop yields were taken directly from the US Department of Agriculture, National Agricultural Statistics Service Quick Stats database ([https://www.nass.usda.gov/Quick\\_Stats/](https://www.nass.usda.gov/Quick_Stats/)), or estimated on the basis of total statewide production and area harvested. These data were converted to county levels of production based on the areas from the pivot table. Finally, the data for the many crops were consolidated into the seven broad categories used previously to create the matrix with the land capability classification data.

For images provided in Appendix (an example of which is provided in Figure 1), both the crop-type raster from the US Department of Agriculture and a similar agricultural land use vector data set available from the Washington State Department of Agriculture (<https://agr.wa.gov/departments/land-and-water/natural-resources/agricultural-land-use>) were loaded as layers because together they provided a more visually definitive graphic. The land capability classification data were also set as a visible layer.

## **Biomass Supply Inputs**

### **Agricultural crop residues**

Residues for cereal crops were modeled as a feedstock stream in BGRAM. These crops include wheat, corn grain, barley, buckwheat, hemp, quinoa, rye, sunflower seed, triticale, oats, and any crop grown for commercial seed production (grasses, vegetables, legumes). Total residue production values for each county were obtained from the cereal-crop yield data (see Soil and Crop Yield Inputs section) by multiplying the grain yield by a straw:grain factor (Lal, 2005) of either 1.5 (most cereals) or 1 (oats, field corn). To obtain the harvested biomass for use in biochar production, these values were adjusted by an availability factor to account for the fraction of residue removed or lost during subsequent distribution. A residue availability factor of 66% was chosen, which is considerably higher than that used in the original version of BGRAM (8%) and the values recommended in the literature (generally below 35%, Woolf et al., 2010; Lal, 2005). The higher residue removal rate is justified by the new ability in BGRAM to estimate the beneficial long-term impact of biochar on formation of npSOC (i.e., negative priming), results for which show a net gain in npSOC for most agronomic soils amended with biochar when residue removal rates to make the biochar *exceed* 25-40%.



**Figure 1: Map of Walla Walla County, Washington showing cropped agricultural lands (clearly delineated rectangular and circular polygons in a variety of colors), non-irrigated land capability classes (reddish, non-delineated zones), non-agricultural land (other non-delineated zones), and water (blue areas). Inset shows location of Walla Walla County in Washington State.**



## **Municipal solid waste**

Two woody biomass feedstock streams recovered from MSW were modeled in BGRAM: green waste and reclaimed waste wood. Estimated quantities for these in each county were developed from a survey conducted in 2015-2016 and reported on the basis of 2014 tonnage rates by the Washington State Department of Ecology (Ecology, 2016). Among the categories of MSW surveyed, quantities for “Yard & Garden Waste—Prunings” were considered to be green waste, whereas the sum of quantities for “Dimensional lumber, Engineered wood, Pallets & Crates, Other untreated wood, and natural wood” was used as the value for reclaimed waste wood in BGRAM. In addition to statewide totals, the survey results are reported on the basis of six waste generation areas representing different geographic regions of the state. To obtain county-level estimates, the values in each waste generation area were apportioned among the counties in that area on the basis of population and adjusted for changes in population between 2014 and 2019. Official estimates of county population available from the Washington State Office of Financial Management (OFM, 2019) were used for these calculations.

## **Timber harvest residues**

Estimates of harvestable woody biomass were generated for each county using the DNR biomass calculator (<http://wabiomass.cfr.washington.edu/default.aspx>; Pérez-García et al. 2013). As provided by the calculator, this biomass consists of the trimmings from tree stems harvested for lumber. Because the focus of this study is on the technical potential and a goal was to estimate the highest possible potential, only one set of economic conditions was specified: low biomass harvest costs and high (\$100 per bone-dry ton) biomass price paid at facility. All existing and potential biomass processing facilities within four hours driving time of the harvest location were selected for consideration of economic viability. Several biomass harvest models were selected for each of two five-year periods ranging from 2020 to 2030. These models generally fell into conservative, average, and aggressive estimates of available biomass.

The output from the calculator grouped the biomass into three categories: scattered, roadside, and market. Scattered biomass was left at various locations on the harvest site where the trees were cut and trimmed. Roadside and market biomass was gathered and brought to a roadside “landing” at the harvest site for possible loading and transport to a central facility. Market biomass was actually loaded and transported, whereas roadside biomass was not transported. Of these three categories, roadside and market biomass were considered available for processing into biochar. Roadside biomass could be processed using a mobile pyrolysis platform brought to the landing. Market biomass could be processed at a central pyrolysis facility identified by the biomass calculator. As the estimates of available harvestable biomass did not differ greatly among the two time periods, mean data from the two periods were calculated for use in the input scenarios.

Of the total amount of residues produced from timber-harvest operations in Washington State, roadside biomass accounts for 36%, and market biomass for 32%. Thus, residue removal rates for harvested timber lands are 68%, which is comparable to the 66% assumed for agricultural cropped lands. In the current version of BGRAM, however, the biochar produced with this residual biomass is assumed to be applied only to agricultural croplands.

## Results and Discussion

Calculations were performed using input generated at both the individual county level and the state level (using an averaged set of input parameters to represent the entire state). The state-level calculations provide a more realistic assessment than the simple sum of the county-level results because they implicitly allow export and import of biochar across county lines to achieve a greater degree of soil incorporation than is possible when all biochar remains in the county in which it was produced. Although they tend to underestimate the total impact of biochar technology by 21-26%, the county-level calculations nevertheless provide key insights into local biomass supply and biochar production levels, as well as biochar storage capacities.

The presentation of results and discussion here will focus generally on the overall summation of results grouped by scenario. Results for individual counties are tabulated by scenario in Appendix A. Summaries of County-Level Technical Assessment Results by Scenario. Results for each county separately are available in Appendix B. Individual County Technical Assessment Results.

### Biomass Supply

The biomass inputs (reported as green weights) for the ten scenarios considered ranged from a total of 354 Mt for the MSW (Facility) scenario to 25,400 Mt for the Aggressive (Facility + Field) scenario, a factor of 72 (Table 1). The vast majority of the available biomass in Washington State comes from timber-harvesting residues, which account for 73% to 91% of the total in the eight full scenarios that include all three sources of biomass (i.e., crop residues, MSW, and timber-harvesting residues).

On average, the proportion of the biomass coming from MSW is small, ranging from 1.3% to 3.6% of the total for the eight full scenarios. For individual counties, however, the MSW proportion ranges more widely (see Appendix A. Summaries of County-Level Technical Assessment Results by Scenario). For example, the MSW proportion for the full scenarios in King County ranges from 9% to 30%, whereas the range for Grays Harbor County is 0.14% to 0.49%, reflecting the large differences in the types of biomass available in urban population centers and heavily timbered rural counties.

The amount of biomass from crop residues is about 6 times larger than that from MSW and, after accounting for the 66% residue availability factor, it represents 8% to 23% of the total biomass for the eight full scenarios. As with MSW, the proportion of biomass from crop residues varies significantly across counties—from nil in several heavily timbered west-side counties to above 97% in several rural eastern counties where no timber is harvested (Appendix A. Summaries of County-Level Technical Assessment Results by Scenario).

### Biochar Production and Storage Capacity

As logic would dictate, the cumulative 100-year biochar-C gross production levels follow the same trends as the biomass input levels (Table 2). Production levels range from 6.6 Mt C for the MSW Only (Facility) scenario to 381 Mt C for the Aggressive (Facility + Field) scenario, roughly a factor of 52. The net number of years of agricultural soil storage capacity for the ten

scenarios follows the reverse trend (Table 2), and includes an estimate of biochar C oxidation (i.e., is calculated on the basis of *net* biochar production = gross production - oxidation) that effectively maximizes the storage capacity. If MSW is the only source of biomass, nearly two millennia of storage capacity is available (Table 2). With progressively higher biochar production levels, however, the years of available storage capacity drop quickly—to 106 years for the Conservative (Facility) scenario and as little as 62 years for the Aggressive (Facility + Field) scenario. The physical storage capacity estimates assume a maximum of 50 t biochar C in the top 15 cm of each ha of cropped agricultural soil. Larger physical storage capacities could be envisioned with deeper incorporation of biochar and spreading on range and forested lands.

**Table 1: Annual biomass inputs by harvest scenario for Washington State**

Harvest scenario	Processing location		Biomass inputs				
	Facility	Field	Harvested crop residues	Harvested forestry residues	MSW recovered wood	MSW green waste	Total biomass processed
			----- thousands of green tonnes -----				
Feedstock-Specific Scenarios							
Crop Residues	X	X	2020	n/a	n/a	n/a	2020
MSW	X		n/a	n/a	311	43	354
Full Scenarios with Facility Processing							
Conservative	X		2020	6,360	311	43	8,730
Average	X		2020	9,190	311	43	11,600
Aggressive	X		2020	11,100	311	43	13,400
Average w/Thin	X		2020	9,780	311	43	12,200
Full Scenarios with Facility and Field Processing							
Conservative	X	X	2020	13,500	311	43	15,900
Average	X	X	2020	19,200	311	43	21,600
Aggressive	X	X	2020	23,000	311	43	25,400
Average w/Thin	X	X	2020	20,800	311	43	23,100

At the county level, the results differ substantially within a given scenario as well as across scenarios. To offer an idea of the major trends in the county-level results, the cumulative 100-year biochar-C gross production levels for the three endmember scenarios [i.e., Crop Residues, MSW, and Full:Aggressive (Facility + Field)] with the counties ranked from highest to lowest are plotted in Figures 2, 3, and 4. For the Crop Residues scenario, (Figure 2) the rural counties in the central and southeastern portion of the state dominate. For the MSW Only (Facility) scenario (Figure 3), the highly urbanized counties dominate, with King County alone accounting for about 1.5 Mt C, 23% of the total for Washington State. For the maximum level of biochar production

given by the Full:Aggressive (Facility + Field) scenario (Figure 4), largely rural counties with ample timber-harvest activity, led by Grays Harbor and Lewis Counties, dominate.

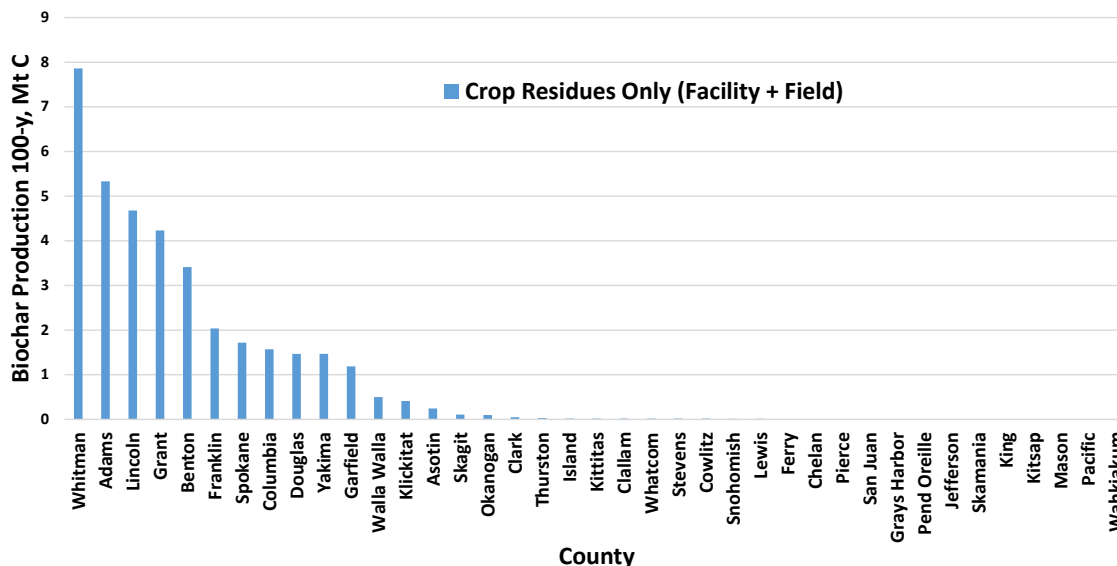
Producing biochar, however, is only half of the solution. A place to store it is needed, and currently the most favorable storage option is to incorporate biochar into agricultural soils, where it is safe from inadvertent combustion and has numerous benefits with respect to agricultural production (as suggested by the enhanced-yield feedstock stream in BGRAM). It is in this regard that the dominant agricultural counties make essential contributions to the overall use of biochar technology in Washington State. A plot of the biochar-C storage capacities of all 39 counties, ranked in the same order as for the maximum biochar-C production levels shown in Figure 4, shows that the counties with small woody-biomass biochar production capacities generally have large biochar-C storage capacities (Figure 5). In fact, the counties having the largest biochar-C production, such as Grays Harbor and Lewis, will generally exceed their intra-county storage

**Table 2: Cumulative 100-year biochar gross production and net years of storage capacity in agricultural soils summed by harvest scenario for Washington State.**

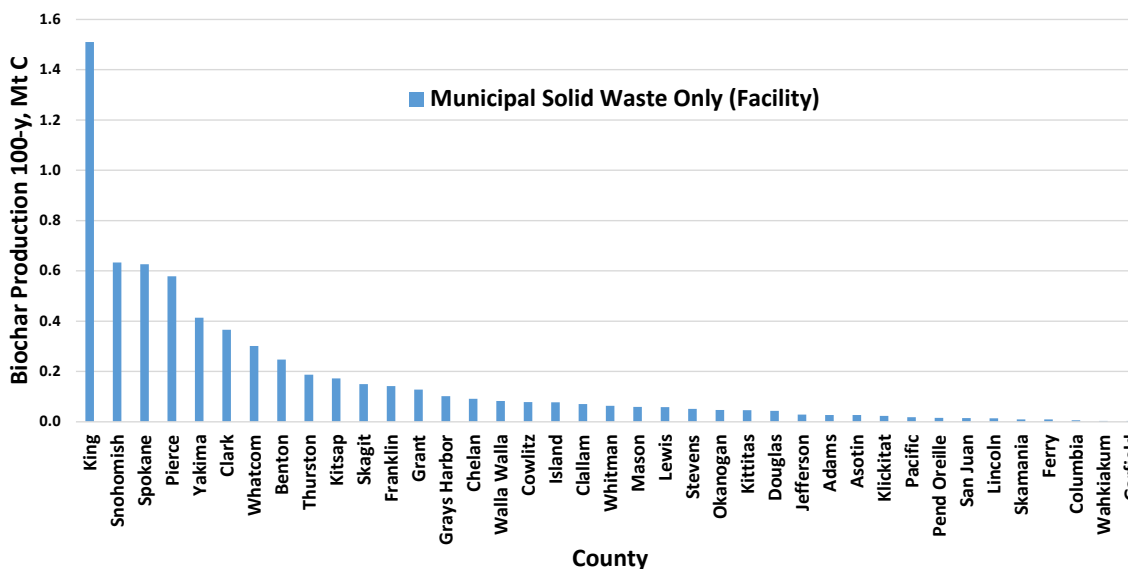
Harvest scenario	Processing location		Biochar <sup>a</sup>	
	Facility	Field	Gross production (100-yr)	Net storage capacity in agricultural soils
			Mt C	Years
Feedstock-Specific Scenarios				
Crop Residues	X	X	36 (37)	329 (325)
MSW	X		6.6 (6.5)	1697 (1775)
Full Scenarios with Facility Processing				
Conservative	X		144 (134)	106 (121)
Average	X		187 (174)	98 (103)
Aggressive	X		214 (200)	90 (94)
Average + Thin	X		195 (182)	95 (100)
Full Scenarios with Facility and Field Processing				
Conservative	X	X	249 (233)	82 (85)
Average	X	X	329 (311)	68 (70)
Aggressive	X	X	381 (363)	62 (64)
Average + Thin	X	X	350 (333)	65 (67)
<sup>a</sup> First value in each cell is calculated using the state-average input parameters. Second value (in parentheses) is the sum of individual county-level calculations and does not consider exports or imports of biochar among counties to alleviate soil-storage capacity limitations				



capacity within the first two decades of production (Appendix A. Summaries of County-Level Technical Assessment Results by Scenario) and will become biochar exporters for the remainder of the century. Large-scale adoption of biochar technology, therefore, will require a substantial effort to transport not only biomass to processing facilities, but also biochar to storage sites that may be 100-200 miles distant. Although the climate impact of this transportation effort is relatively small compared to the overall benefit, the economic impact will likely be very large. Further techno-economic study of the problem is needed to refine the overall C drawdown potential of biochar technology in Washington State and to identify the locations where it is most likely to be economically viable.



**Figure 2: Cumulative 100-year biochar production from crop residues in Washington State ranked by county**



**Figure 3: Cumulative 100-year biochar production from MSW in Washington State ranked by county**

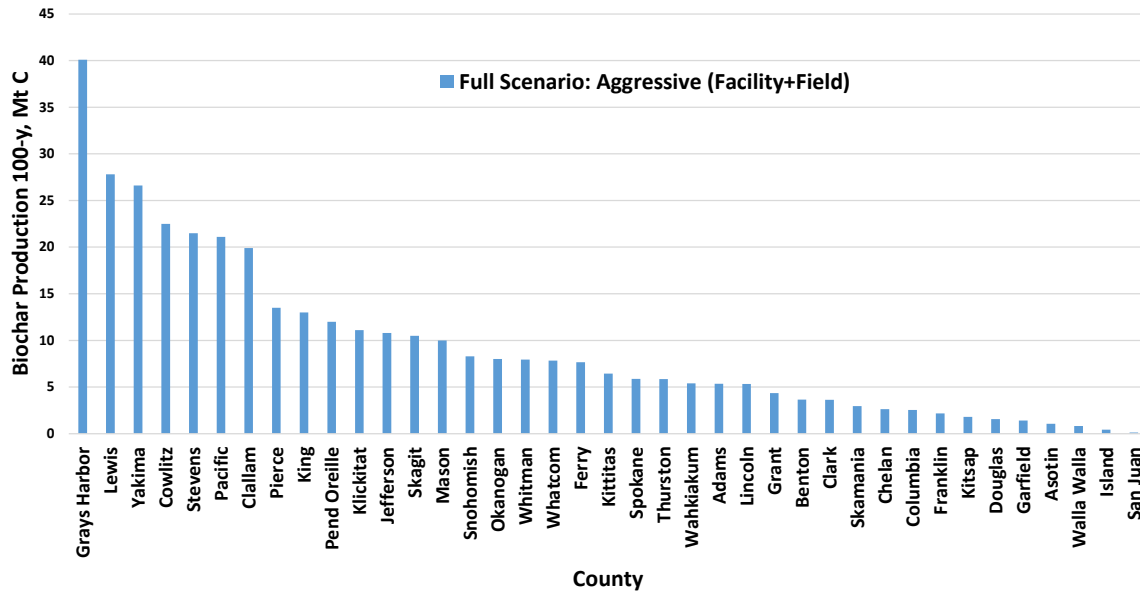


Figure 4: Maximum cumulative 100-year biochar production for all feedstocks in Washington State ranked by county

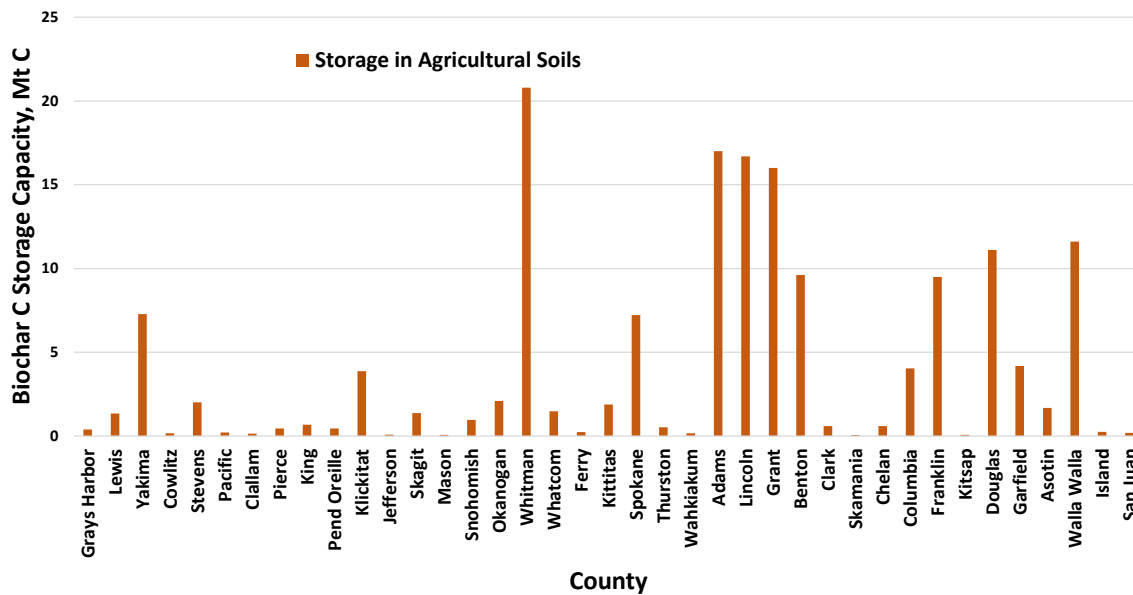
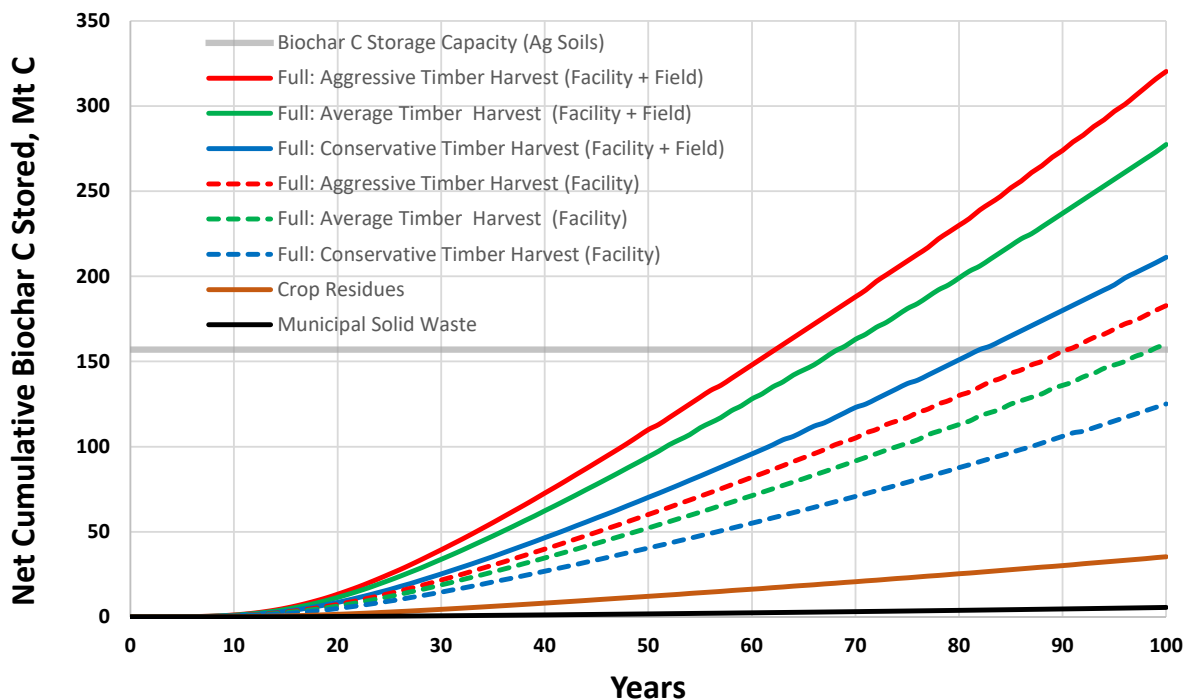


Figure 5: The initial biochar storage capacity in agricultural soils for each county in Washington State ranked by maximum cumulative 100-year biochar production for all feedstocks

Another, somewhat more tractable issue, relates to the overall state-wide biochar-C storage capacity. A timeline comparison of the net cumulative biochar-C stored, which is the difference between the gross biochar produced and that which is oxidized once in soil, shows that five of the eight scenarios plotted fully saturate the available storage capacity during the first 100 years (Figure 6), and as shown in Table 2 above, a sixth scenario would reach saturation within 106 years. Although not plotted in Figure 6, the full scenarios that included thinning operations would both saturate the available storage capacity during the first 100 years (Table 2).



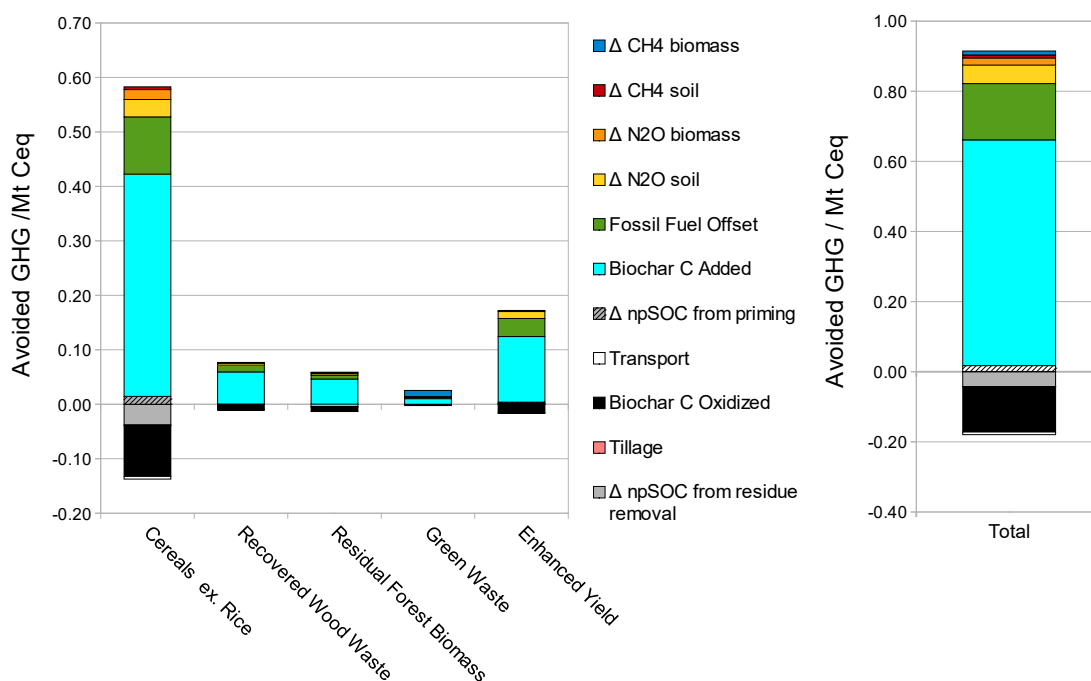
**Figure 6: Cumulative net biochar C stored in Washington State during the first 100 years of production for each of eight scenarios calculated using state-wide averaged input data. The horizontal gray line shows the initial biochar storage capacity in agricultural soils for the state. State-wide soil-storage capacity is saturated when the scenario curves intersect the horizontal line**

This seemingly dire limitation to the overall C-drawdown potential of biochar, however, can be addressed in part by developing additional locations for storage. Examples include incorporation to greater depths in agricultural soils (to some extent this will happen organically, as biochar particles weather and move further into soil profiles over time). A simple doubling of the initial depth of incorporation to 30 cm will double the storage capacity. Application of biochar to the ground surface in range and forested lands offers another potential way of significantly increasing the storage capacity, albeit not as efficient or beneficial as addition to agricultural lands would be. The pH of any surface-applied biochar likely will need to be near neutral to avoid positive priming (enhanced oxidation) of forest and range surface litter (Wardle et al., 2008), and additional limitations may be encountered.

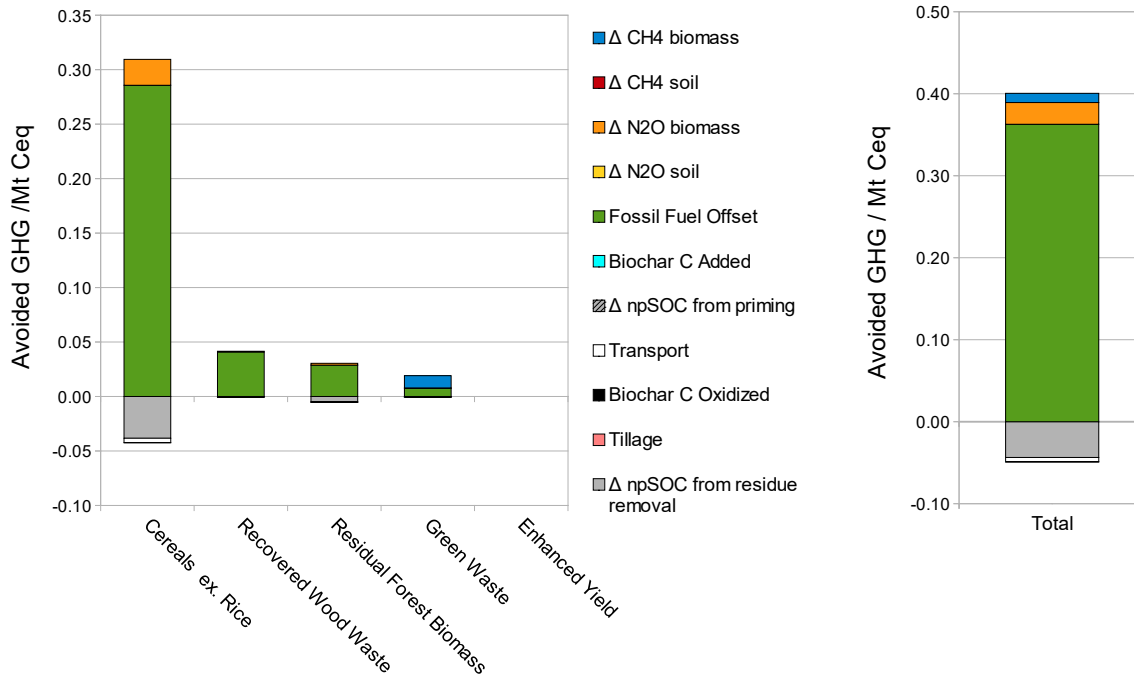
Other potential solutions involve storage of biochar in places other than soil. Mixing biochar with waste materials designated for land filling might have environmental benefits such as decreased leaching of hazardous metals and organic compounds, and lower emissions of methane, while at the same time providing a fire-protective environment that would preserve the biochar C-storage function. Using biochar to substitute for aggregate in concrete or for asphalt in paving material (Zhao et al. 2014; Gupta and Kua 2017; Akhtar and Sarmah 2018; Zeidabadi et al. 2018; Cuthbertson et al. 2019; Draper 2020; van Zyl 2020) also show great potential. These concepts need research to identify which are technically and economically viable solutions to the biochar storage problem. Fortunately, the current results suggest that we will have several decades at least to develop alternative storage options.

## Climate Offsets

To assess the climate impact of a given scenario, BGRAM calculates a variety of offsets for each feedstock stream, which are summed for the individual feedstock stream (Figure 7, left panel), and then over all feedstock streams to obtain a total offset (Figure 7, right panel). In addition to results for biochar, which assume slow pyrolysis, BGRAM also calculates results for complete combustion of the same biomass to generate bioenergy (Figure 8). These two sets of results bracket the range of offsets possible by different methods for making biochar, such as slow pyrolysis, fast pyrolysis, gasification, etc., with slow pyrolysis being the most C-efficient process for making biochar and combustion being the extreme case in which no biochar is produced. They also highlight the different contributions to the climate offset, with biochar-C added being most important for biochar and fossil-fuel emissions offset being the most important for bioenergy.



**Figure 7: Contributions of feedstocks and offset mechanisms to the total offset for biochar (slow pyrolysis) under the Conservative (Facility) scenario for Walla Walla County**



**Figure 8: Contributions of feedstocks and offset mechanisms to the total offset for bioenergy (i.e., complete combustion) under the Conservative (Facility) scenario for Walla Walla County**

The total 100-year offsets for biochar and bioenergy in the ten scenarios are listed in Table 3. The results can be interpreted in two ways: the *immediate* offset (Mt Ceq), which accounts for the initial C drawdown, and the *ultimate* offset (ppbv CO<sub>2</sub>eq), which is expressed here in terms of atmospheric CO<sub>2</sub> levels and adds the long-term buffering response of the earth's climate system to the initial C drawdown. As discussed by Amonette (2018) [based on the work of Cao and Caldeira (2010)], when expressed in the same units as the immediate offset, the ultimate offset is smaller by a factor of 2.17 to account for release of CO<sub>2</sub> from other labile reservoirs in the earth's climate system, primarily the oceans. Put simply, to lower the ultimate (equilibrium) concentration of CO<sub>2</sub> in the atmosphere by 1 ppmv, 2.17 ppmv of CO<sub>2</sub> need to be removed.

The 100-year climate offsets generally follow the expected trend established by the size of the biomass inputs (Table 3). Thus, addition of biochar and bioenergy production in the field (i.e., Facility + Field scenarios) increases the climate offsets by 70% to 80% over those obtained when only centralized facilities (Facility scenarios) are used for processing. For biochar, the immediate offset ranges from 8.5 Mt Ceq for the MSW Only (Facility) scenario to 430 Mt Ceq for the Aggressive (Facility + Field) scenario. The ultimate offset ranges from 1.8 ppbv CO<sub>2</sub>eq to 93 ppbv CO<sub>2</sub>eq for the scenarios analyzed. Implementation of forest-thinning operations to reduce wildfire risk is predicted to increase the available biomass by 5-7% (Table 1) and the net offset for biochar by a similar percentage (Table 3).

**Table 3: Total 100-year offsets for production of biochar and bioenergy summed by harvest scenario, and the ratios of the bioenergy offsets to the biochar offsets for Washington State.**

Harvest scenario	Processing location		Total 100-year offsets <sup>a</sup>				
	Facility	Field	Biochar	Bioenergy	Biochar	Bioenergy	Bioenergy / Biochar
			Mt C <sub>eq</sub> (immediate)		ppbv CO <sub>2(eq)</sub> (ultimate)		
Feedstock-Specific Scenarios							
Crop Residues	X	X	44 (45)	18 (18)	10 (10)	3.9 (4.0)	0.41 (0.37)
MSW	X		8.5 (10)	4.5 (4.5)	1.8 (2.2)	1.0 (1.0)	0.53 (0.52)
Full Scenarios with Facility Processing							
Conservative	X		174 (144)	66 (53)	38 (31)	14 (11)	0.38 (0.38)
Average	X		223 (180)	85 (67)	48 (39)	18 (15)	0.38 (0.38)
Aggressive	X		253 (203)	98 (77)	55 (44)	21 (17)	0.39 (0.38)
Average+Thin	X		232 (188)	89 (71)	50 (41)	19 (15)	0.38 (0.38)
Full Scenarios with Facility and Field Processing							
Conservative	X	X	291 (232)	115 (88)	63 (50)	25 (19)	0.39 (0.39)
Average	X	X	376 (299)	154 (117)	81 (65)	33 (25)	0.41 (0.39)
Aggressive	X	X	430 (343)	179 (137)	93 (74)	39 (30)	0.42 (0.39)
Average+Thin	X	X	398 (319)	164 (127)	86 (69)	35 (28)	0.41 (0.39)
<sup>a</sup> First value in each cell is calculated using the state-average input parameters. Second value (in parentheses) is the sum of individual county-level calculations and does not consider exports or imports of biochar among counties to alleviate soil-storage capacity limitations							

The annual climate offset at maximum biochar production rate for each scenario can be estimated by dividing the Total 100-year offsets in Table 3 by a factor of 81.26, which accounts for the average biochar production rate during the century. For the eight full scenarios, the maximum annual biochar climate offsets range from 2.1 to 5.2 Mt C<sub>eq</sub>. Comparison of these values with the 27.2 Mt C<sub>eq</sub> [99.6 Mt CO<sub>2(eq)</sub>] estimated for total annual GHG emissions for Washington State in 2018 (WA-ECY 2021) shows that biochar production has the potential to offset between 8 and 19% of the state's emissions depending on the biomass scenario selected.

Recognizing that the current levels of atmospheric CO<sub>2</sub> are on the order of 415 ppmv (NOAA-ESRL-GMD, 2021) as compared to pre-industrial levels of 270 ppmv and a recommended target level of 350 ppmv to avoid significant climate disruption (Hansen et al. 2008), it is clear that the maximum potential contribution of biochar produced from biomass in Washington State, while large, addresses only 0.14% of the needed global drawdown (assuming no further increase in atmospheric concentrations). Fortunately, this is roughly in proportion to the fraction of the earth's unglaciated land surface occupied by Washington State (0.13%) and further supports the

concept that global adoption of biochar technology can make a significant contribution to the drawdown effort. The magnitude of the drawdown effort required to address climate change is truly significant and requires a comparably sized contribution from every region of the planet.

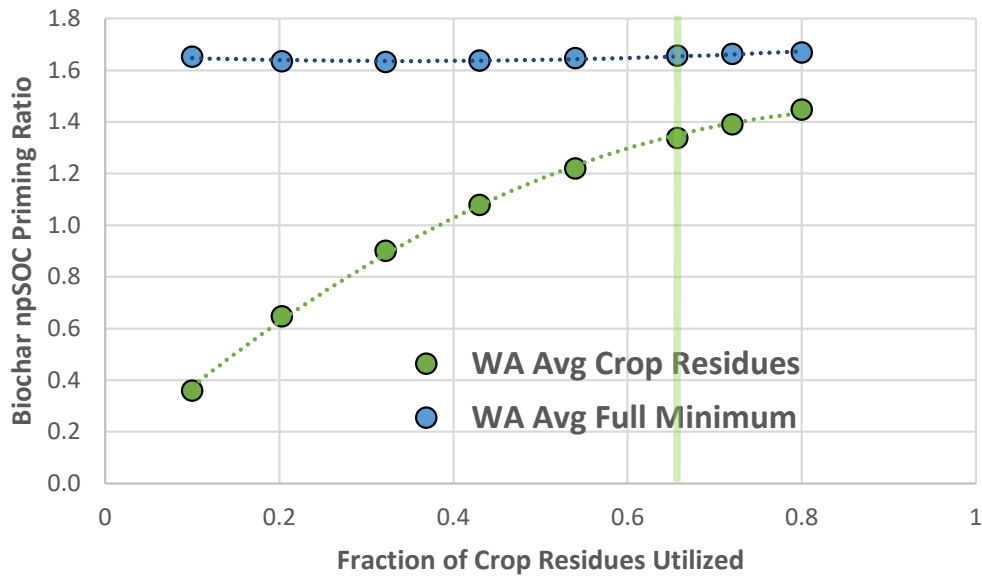
## Impact on non-Pyrogenic Soil Organic C

In BGRAM, the predicted impact of biochar on stocks of npSOC depends on two opposing factors: (1) the gain in C due to negative priming of npSOC formation by biochar incorporated into soil, and (2) the loss in C due to harvesting of biomass residues (that would otherwise contribute to npSOC formation) for use as feedstocks in biochar production. The ratio of these two factors (i.e., the absolute value of the quotient of the priming gain and the harvest loss) provides an easy way to compare different scenarios and counties, with ratio values greater than 1 indicating a net increase in npSOC and smaller than 1 indicating a net decrease. In the present work, this ratio is termed the npSOC priming ratio.

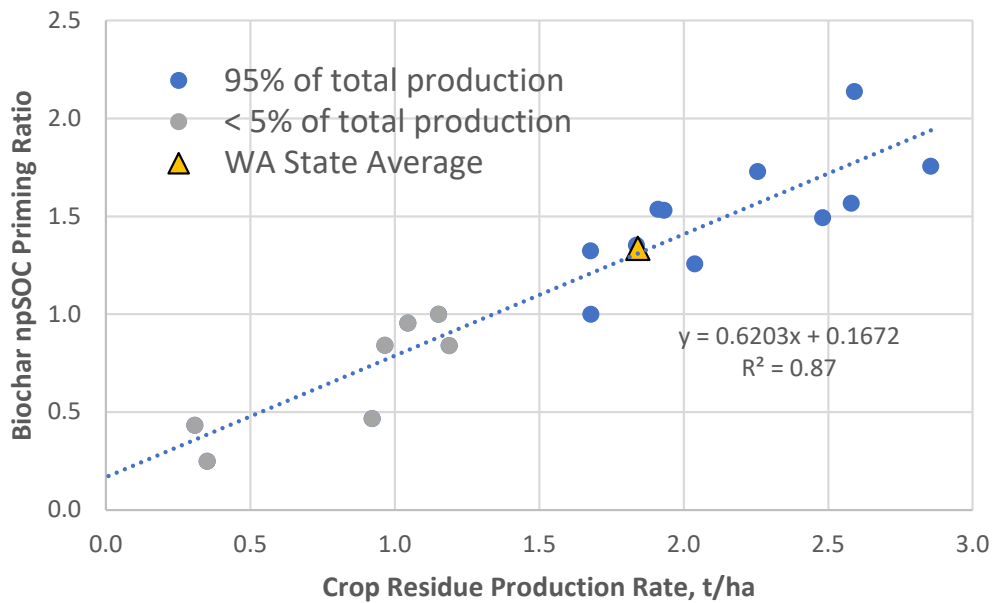
A third factor is the quantity of pre-existing npSOC stocks relative to the biochar and residues involved. That is, a small amount of biochar or residue harvest relative to npSOC stock would have a small impact. As the relative amount of biochar produced and residue harvested increase, the npSOC priming ratio would be expected to increase until a new equilibrium is established at a maximum biochar production rate. Indeed, this seems to be the case, and is most easily seen in results for the Crop Residues scenario, which involves relatively small quantities of biochar and residues relative to the npSOC stocks involved (Figure 9). In this scenario, when more than 38% of crop residues produced are harvested, a net gain in npSOC is seen (i.e., the npSOC priming ratio is greater than 1). When the total available biomass is 4.3 times larger, as in the Conservative Full Scenario with Facility Processing (i.e., the Full Minimum scenario in Figure 9), a higher npSOC priming ratio of about 1.65 is estimated indicating a significant net gain in npSOC regardless of the fraction of crop residues harvested. Both scenarios plotted in Figure 9 are state-averaged input data.

A more detailed view of the impact of total biomass quantity on npSOC priming ratio is provided in Figure 10, where the npSOC priming ratio for each county with at least 20% of its arable land used for cereal production is plotted as a function of the crop residue production rate (t/ha) in the Crop Residues scenario assuming a 66% availability fraction. A linear increase in npSOC priming ratio is seen as production rate increases. Counties having production rates above 1.5 t/ha account for 95% of all cereal production in Washington State and have priming ratios greater than 1 indicating a net increase in npSOC from biochar production and amendment.

As suggested by the npSOC priming ratio results, the total impact of biochar technology on npSOC stocks in Washington State is positive. Current npSOC stocks, estimated at 115 Mt in the top 23 cm of agronomic soils, are predicted to increase by 13 Mt (11%) for the Crop Residues scenario and to nearly triple (i.e., by 224 Mt (195%)) for the Full Aggressive Facility + Field scenario. To validate these predictions, additional field research into the long-term impact of biochar amendments on npSOC stocks should be a high priority.



**Figure 9: Calculated relationship between npSOC priming ratio and the fraction of crop residues utilized to make the biochar for two Washington State scenarios. Vertical green line indicates fraction of crop residue utilization assumed for all other calculations in this study. Priming ratios greater than 1 indicate a net increase in npSOC from biochar production and amendment**



**Figure 10: Calculated relationship in the Crop Residues scenario between npSOC priming ratio for counties in Washington State and the crop residue production rate per hectare assuming 66% of crop residues are utilized to make biochar. Counties shown have at least 20% of their arable land devoted to cereal crop production. Priming ratios greater than 1 indicate a net increase in npSOC from biochar production and amendment**



## Bioenergy

In general, the climate offsets from bioenergy in Washington State are about 40% of those estimated for biochar (Table 3). This is largely due to the low C intensity of the primary energy supply (10.16 kg C / GJ, U.S. Energy Information Agency, 2019) stemming from the large contributions of hydro- and wind-power to the electrical grid, but also to the degree of enhanced yield obtained when biochar is applied to soils (see Woelf et al., 2010 for further discussion). In most scenarios, bioenergy also forgoes the increases in npSOC content stimulated by biochar amendments while still paying the penalty for removal of residual biomass from soils. For the MSW scenario, however, no penalty for removal of residual biomass from soils is applied and, as a result, the relative offset for bioenergy increases to 52%. Given the relatively small contribution of MSW biomass to the full scenarios, however, the general observation that biochar is 2.5 times more effective than bioenergy as a climate mitigation option in Washington State still applies.

Implementation of forest-thinning operations to reduce wildfire risk is predicted to increase the available biomass by 5-7% (Table 2) and the net offset for bioenergy by the same percentage (Table 3). In contrast to biochar, the impact of bioenergy on npSOC stocks, however, does not seem beneficial and further underscores the need for long-term field research to confirm the extent of the decline in npSOC stocks associated with residue removals.

## Conclusions

This assessment of the C-drawdown potential of biochar technology when implemented in Washington State over the course of 100 years shows that a wide range in drawdown potential exists, depending primarily on the size of the woody biomass supply.

- Use of recovered woody biomass from MSW yields a total immediate greenhouse gas offset of 8.5 Mt Ceq.
- Use of cereal crop residues yields a total immediate greenhouse gas offset of 44 Mt Ceq.
- Addition of timber-harvest residual biomass to the MSW and crop-residue biomass results in 174 to 430 Mt Ceq depending on the harvest scenario and process facility location.
- Addition of field processing of biomass to that done in centralized facilities roughly doubles the available biomass and increases the C drawdown potential by 70% to 80%.
- When equilibrium with the climate system reservoirs is considered, an ultimate greenhouse gas offset can be calculated in terms of decreases in atmospheric CO<sub>2</sub> levels. This metric yields a drawdown potential range from 1.8 to 93 ppbv CO<sub>2</sub>eq. The highest drawdown level corresponds to 0.14% of what is needed to stabilize the earth's climate system from today's levels of CO<sub>2</sub>.
- With residue harvesting rates of 66% (crop residues) to 68% (forestry residues), biochar technology increases npSOC stocks when the crop residue production rate is greater than 1.5 t/ha.

- Use of the same biomass to generate bioenergy instead of biochar yields about 40% of the climate drawdown potential obtained with biochar.
- The biochar-C storage capacity is lowest for counties that generate large amounts of woody biomass, and consequently, after a few decades they will need to export their biochar to agricultural counties, located primarily in the south east quadrant of the state.
- Under current storage potential assumptions, the biochar-C soil-storage capacity will be saturated in 62 to 106 years for the full scenarios that include crop residues, MSW, and timber-harvest biomass residues. This limit, however, can be pushed to higher levels with the development of additional storage reservoirs (e.g., forest and rangeland soils) and technologies (e.g., incorporation into construction materials).
- At the maximum biomass-utilization rate, which is achieved after five decades, biochar production could offset between 8% and 19% of the greenhouse-gas emissions in Washington State (taken at 2018 levels).
- The biochar-C storage capacity is lowest for counties that generate large amounts of woody biomass, and consequently, after a few decades they will need to export their biochar to agricultural counties, located primarily in the south east quadrant of the state.

## References

- Akhtar, A., & Sarmah, A.K. 2018. Novel biochar-concrete composites: Manufacturing, characterization and evaluation of the mechanical properties. *Science of the Total Environment*, 616-617, 408-416. <https://dx.doi.org/10.1016/j.scitotenv.2017.10.319>
- Amonette, J.E., Garcia-Pérez, M., Sjoding, D., Fuchs, M.R. 2016a. Biochar from biomass and its potential agronomic and environmental use in Washington: A promising alternative to drawdown carbon from the atmosphere and develop a new industry. *PNNL-25239*. [http://www.pnnl.gov/main/publications/external/technical\\_reports/PNNL-25239.pdf](http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-25239.pdf)
- Amonette, J.E., Garcia-Pérez, M., Sjoding, D., Fuchs, M.R. 2016b. Biochar from biomass and its potential agronomic and environmental use in Washington: A promising alternative to drawdown carbon from the atmosphere and develop a new industry. Invited Keynote Presentation by James E. Amonette at Biochar 2016, Corvallis, OR on 23 August 2016. [http://biochar-us.org/sites/default/files/presentations/Amonette\\_USBI\\_Aug2016\\_finfinfin.pdf](http://biochar-us.org/sites/default/files/presentations/Amonette_USBI_Aug2016_finfinfin.pdf)
- Amonette, J.E. 2018. Assessing local technical potentials for CO<sub>2</sub> drawdown using biochar from forestry residues and waste wood in Washington State. p. 271-293 (Chpt. 14) in *Advancing Organics Management in Washington State: The Waste to Fuels Technology Partnership 2015-2017 Biennium*. Washington State Department of Ecology Publication Number 18-07-010. <https://fortress.wa.gov/ecy/publications/documents/1807010.pdf>
- Amonette, J.E. 2019. *Assessment of the Local Technical Potential for CO<sub>2</sub> Drawdown using Biochar from Forestry Residues and Waste Wood in 26 Counties of Washington State*. Report for The Waste to Fuels Technology partnership 2017-2019 biennium: Advancing organics management in Washington State. Center for Sustaining Agriculture & Natural Resources, Washington State University, Pullman, WA. 174 pp. <https://csanr.wsu.edu/publications/assessment-of-the-local-technical-potential-for-co2-drawdown-using-biochar-from-forestry-residues-and-waste-wood-in-26-counties-of-washington-state/>
- Blanco-Canqui, H., Laird, D.A., Heaton, E.A., Rathke, S., & Acharya, B.S. 2019. Soil carbon increased by twice the amount of biochar carbon applied after 6 years: Field evidence of negative priming. *Global Change Biology Bioenergy*, 12, 240-251. <https://dx.doi.org/10.1111/gcbb.12665>
- Borchard, N., Ladd, B., Eschemann, S., Hegenberg, D., Mösel, B.M., & Amelung, W. 2014. Black carbon and soil properties at historical charcoal production sites in Germany. *Geoderma*, 232–234, 236–242. <https://dx.doi.org/10.1016/j.geoderma.2014.05.007>
- Cao, L., Caldeira, K. 2010. Atmospheric carbon dioxide removal: long-term consequences and commitment. *Environ. Res. Lett.* **5**, 024011. <https://iopscience.iop.org/article/10.1088/1748-9326/5/2/024011/pdf>
- Cuthbertson, D., Berardi, U., Briens, C., Berruti, F. 2019. Biochar from residual biomass as a concrete filler for improved thermal and acoustic properties. *Biomass and Bioenergy*, 120, 77-83. <https://dx.doi.org/10.1016/j.biombioe.2018.11.007>

- Ding, F., Van Zwieten, L., Zhang, W-D., Weng, Z-H., Shi, S-W., Wang, J-K., Meng, J. 2018. A meta-analysis and critical evaluation of influencing factors on soil carbon priming following biochar amendment. *Journal of Soils and Sediments*, 18, 1507-1517. <https://dx.doi.org/10.1007/s11368-017-1899-6>
- Dong, X-L., Singh, B.P., Li, G-T., Lin, Q-M., Zhao, X-R. 2018. Biochar application constrained native soil organic carbon accumulation from wheat residue inputs in a long-term wheat-maize cropping system. *Agriculture, Ecosystems and Environment*, 252:200-207. <https://dx.doi.org/10.1016/j.agee.2017.08.026>
- Draper, K. 2020. *Opportunities for drawdown: How biochar can help the construction industry pivot from emitting carbon to banking it*. Presentation given at Scaling Biochar Forum (<https://www.scalingbiochar.com/>), October 13, 2020. <https://youtu.be/trcTMpNjgY0> accessed 27 Feb 2021.
- Ecology. 2016. 2015-2016 Washington statewide waste characterization study. Washington State Department of Ecology *Publication Number 16-07-032*. <https://fortress.wa.gov/ecy/publications/documents/1607032.pdf>
- Gupta, S., Kua, H.W. 2017. Factors determining the potential of biochar as a carbon capturing and sequestering construction material: Critical review. *Journal of Materials in Civil Engineering*, 29, 04017086. [https://dx.doi.org/10.1061/\(ASCE\)MT.1943-5533.0001924](https://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0001924)
- Hansen, J., Sato, M., Kharecha, P., Beerling, D., Berner, R., Masson-Delmotte, V., Pagani, M., Raymo, M., Royer, D.L., Zachos, J.C. 2008. Target atmospheric CO<sub>2</sub>: Where should humanity aim? *Open Atmos. Sci. J.* 2, 217-231. <https://dx.doi.org/10.2174/1874282300802010217>
- Hernandez-Soriano, M.C., Kerré, B., Goos, P., Hardy, B., Dufey, J. & Smolders, E. 2016. Long-term effect of biochar on the stabilization of recent carbon: soils with historical inputs of charcoal. *Global Change Biology Bioenergy*, 8, 371–381. <https://dx.doi.org/10.1111/gcbb.12250>
- Kerré, B., Bravo, C.T., Leifeld, J., Cornelissen, G., & Smolders, E. 2016. Historical soil amendment with charcoal increases sequestration of non-charcoal carbon: a comparison among methods of black carbon quantification. *European Journal of Soil Science* 67, 324-331. <https://dx.doi.org/10.1111/ejss.12338>
- Lal, R. 2005. World crop residues production and implications of its use as a biofuel. *Environment International* 31:575-584. <https://dx.doi.org/10.1016/j.envint.2004.09.005>
- NRCS-USDA. 2012. User guide for the National Commodity Crop Productivity Index (NCCPI) Version. 2.0. Natural Resources Conservation Service, United States Department of Agriculture. Available online at [https://www.nrcs.usda.gov/Internet/FSE\\_DOCUMENTS/nrcs142p2\\_050734.pdf](https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_050734.pdf)
- NOAA-ESRL-GMD. 2021. Trends in atmospheric carbon dioxide. Global monthly mean CO<sub>2</sub>. U.S. Department of Commerce, National Oceanic & Atmospheric Administration, Earth System Research Laboratory, Global Monitoring Division. Available online at: <https://www.esrl.noaa.gov/gmd/ccgg/trends/global.html>. Accessed 29 April 2021.

- OFM, 2019. April 1 official population estimates. Available online at: [https://www.ofm.wa.gov/sites/default/files/public/dataresearch/pop/april1/ofm\\_april\\_population\\_change\\_and\\_rank.xlsx](https://www.ofm.wa.gov/sites/default/files/public/dataresearch/pop/april1/ofm_april_population_change_and_rank.xlsx). Accessed 21 December 2019.
- Pérez-Garcia, J., Oneil, E., Hansen, T., Mason, T., McCarter, J., Rogers, L., Cooke, A., Connick, J., McLaughlin, M. 2013. Washington forest biomass supply assessment. Available online at <http://wabiomass.cfr.washington.edu/docs/WashingtonForestBiomassSupplyAssessment.pdf>. Accessed 15 May 2017.
- Slavich, P.G., Sinclair, K., Morris, S.G., Kimber, S.W.L., Downie, A., Van Zwieten, L. 2013. Contrasting effects of manure and green waste biochars on the properties of an acidic ferralsol and productivity of a subtropical pasture. *Plant and Soil* 366:213-227. <https://dx.doi.org/10.1007/s11104-012-1412-3>
- Sommer, R., Bossio, D. 2014. Dynamics and climate change mitigation potential of soil organic carbon sequestration. *Journal of Environmental Management* 144:83-87. <http://dx.doi.org/10.1016/j.jenvman.2014.05.017>
- Stöckle, C.O., Pickering, N., Nelson, R. 2019. *Using CropSyst to Evaluate Biochar as a Soil Amendment for Crops*. A report for the Waste to Fuels Technology Partnership: 2017-2019 Biennium. <https://csanr.wsu.edu/publications/using-cropsyst-to-evaluate-biochar-as-a-soil-amendment-for-crops/>
- Trujillo, L., Luizão, F.J., Lehmann, J., Liang, B-Q., Ribeiro, G. 2020. Respiração do solo e dinâmica da liteira fina em Terra Preta de Índio e solos adjacentes, na Amazônia Central. *Revista Brasileira de Ciencias da Amazonia* 9:7-20. <https://cpb-us-e1.wpmucdn.com/blogs.cornell.edu/dist/8/7329/files/2021/02/RevBrasCiAmazonia-9-7-20-2020-Trujillo.pdf>
- U.S. Energy Information Agency. 2019. *Energy-Related Carbon Dioxide Emissions at the State Level, 2000-2016*. Available online at: <https://www.eia.gov/environment/emissions/state/analysis/excel/table8.xlsx> Accessed 23 June 2019.
- van Zyl, A. 2020. *Use of biochar in asphalt: an enormous carbon sequestration opportunity*. Presentation given at Scaling Biochar Forum (<https://www.scalingbiochar.com/>), October 14, 2020. <https://youtu.be/sAddAfqCn-4> accessed 27 Feb 2021.
- WA-ECY. 2021. *Washington State Greenhouse Gas Emissions Inventory: 1990-2018*. Available online at: <https://apps.ecology.wa.gov/publications/SummaryPages/2002020.html> accessed 24 September 2021.
- Wang, J-Y., Xiong, Z-Q., Kuzyakov, Y. 2016. Biochar stability in soil: meta-analysis of decomposition and priming effects. *Global Change Biology Bioenergy* 8, 512-523. <https://dx.doi.org/10.1111/gcbb.12266>
- Wardle, D.A., Nilsson, M., Zackrisson, O. 2008. Fire-derived charcoal causes loss of forest humus. *Science* 320, 629. <https://dx.doi.org/10.1126/science.1154960>
- Weng, Z.H., Van Zwieten, L., Singh, B.P., Tavakkoli, E., Joseph, S., Macdonald, L.M., Rose, T.J., Rose, M.T., Kimber, S.W., Morris, S., & Cozzolino, D. 2017. Biochar built soil

- carbon over a decade by stabilizing rhizodeposits. *Nature Climate Change*, 7(5), 371-376. <https://dx.doi.org/10.1038/NCLIMATE3276>
- Whitman, T., Singh, B.P., Zimmerman, A.R. 2015. Priming effects in biochar-amended soils: implications of biochar-soil organic matter interactions for carbon storage. In J. Lehmann & S. Joseph (Eds.), *Biochar for Environmental Management: Science, Technology and Implementation*. (pp. 455-487). Taylor and Francis, London, UK.
- Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J., Joseph, S. 2010. Sustainable biochar to mitigate global climate change. *Nature Comms* **1**, 56. <http://www.nature.com/articles/ncomms1053>
- Woolf, D., Lehmann, J. 2012. Modelling the long-term response to positive and negative priming of soil organic carbon by black carbon. *Biogeochem.* **111**, 83-95. <https://dx.doi.org/10.1007/s10533-012-9764-6>
- Zeidabadi, Z.A., Bakhtiari, S., Abbaslou, H., Ghanizadeh, A.R. 2018. Synthesis, characterization and evaluation of biochar from agricultural waste biomass for use in building materials. *Construction and Building Materials*, 181, 301-308. <https://dx.doi.org/10.1016/j.conbuildmat.2018.05.271>
- Zhao, S., Huang, B-S., Shu, X., Ye, P. 2014. Laboratory investigation of biochar-modified asphalt mixture. *Transportation Research Record: Journal of the Transportation Research Board*, 2445, 56-63. <https://dx.doi.org/10.3141/2445-07>
- Zomer, R.J., Bossio, D.A., Sommer, R., Verchot, L.V. 2017. Global sequestration potential of increased organic carbon in cropland soils. *Scientific Reports* 7:15554. <https://dx.doi.org/10.1038/s41598-017-15794-8>

# Appendices

*Appendices to this report are available by request by emailing [csanr@wsu.edu](mailto:csanr@wsu.edu). A summary of the information contained in each appendix is provided below.*

## **Appendix A. Summaries of County-Level Technical Assessment Results by Scenario**

contains county-level results for each of Washington's 39 counties, including tables showing annual biomass processed, 100-year greenhouse gas offests, and biochar production and storage data for the following scenarios (as described in the report).

- Feedstock-Specific Agricultural Crop Residues (Facility + Field) scenario
- Feedstock-Specific MSW (Facility) scenario
- Conservative Full (Facility) scenario
- Average Full (Facility) scenario
- Aggressive Full (Facility) scenario
- Average + Thin Full (Facility) scenario
- Conservative Full (Facility + Field) scenario
- Average Full (Facility + Field) scenario
- Aggressive Full (Facility + Field) scenario
- Average + Thin Full (Facility + Field) scenario

**Appendix B. Individual County Technical Assessment Results** contains individual county technical assessments results for each of Washington's 39 counties:

A map showing cropped agricultural lands, non-irrigated land capability classes, non-agricultural land, and water.

### BGRAM Input Data

- Annual biomass inputs by harvest scenario under all scenarios and the extent of cropped land.
- Annual production of crops and the fractions produced on the eight land capability classes.

### BGRAM Results

- Total 100-year offsets for production of biochar and bioenergy summed by harvest scenario, and the ratios of the bioenergy offsets to the biochar offsets, under all scenarios.
- Cumulative 100-year biochar gross production, final production rate, and the storage capacity (Mg C and years) in agricultural soils under all scenarios.
- Contributions of feedstocks and offset mechanisms to the total offsets for biochar (slow pyrolysis) and bioenergy (complete combustion) under the Crop Residues Only scenario.
- Contributions of feedstocks and offset mechanisms to the total offsets for biochar (slow pyrolysis) and bioenergy (complete combustion) under the MSW Only (Facility) scenario.
- Contributions of feedstocks and offset mechanisms to the total offsets for biochar (slow pyrolysis) and bioenergy (complete combustion) for the eight full scenarios.