FINAL REPORT

Use of Biochar from the Pyrolysis of Waste Organic Material as a Soil Amendment

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Use of Biochar from the Pyrolysis of Waste Organic Material as a Soil Amendment

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This report is available on the Department of Ecology's website at www.ecy.wa.gov/beyondwaste/organics. Some of the figures and photos are in color and can be seen in color in the on-line file. The reader may be interested in the other project reports supported by Organic Waste to Resources and Waste to Fuel Technology funding sponsored by Ecology. These are also available on the "organics" link. The Washington State University Extension Energy Program will make this report accessible in its broader library of bioenergy information at www.pacificbiomass.org.

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Beyond Waste Objectives

Turning organic wastes into resources, such as compost, bioenergy, biofuels, recovery of stable carbon and nutrients and other products promotes economic vitality in growing industries, and protects the environment. This creates robust markets and sustainable jobs in all sectors of the economy, and facilitates closed-loop materials management where by-products from one process become feedstocks for another with no waste generated.

Executive Summary.

Biochar is a charcoal-like material produced by the thermochemical pyrolysis of biomass materials. It is being considered as a potentially significant means of storing carbon for long periods to mitigate greenhouse gases. Much of the interest comes from studies of Amazonian soils that appear to have been amended with biochar which led to significant improvements in soil quality and large increases in crop yields. These changes have persisted for hundreds, if not thousands, of years. What is not known is how long it takes for biochar to integrate with the soil and thus express its benefits.

However, biochar does represent a stable form of carbon in soils and thus provides an intriguing potential carbon storage strategy. In this study, biochars from several different feedstocks were evaluated for their characteristics and their fate in five different Washington State soils. Herbaceous feedstock sources such as switchgrass and digester fiber (from anaerobically digested dairy manure) had C contents of 60 and 67% respectively, as well as significantly higher N contents then the other biochars. Woody feedstock biochars had C contents above 75% with C:N ratios ranging from 176-588. Activated charcoal had a C and N content of 87% and 0.47%, respectively. Biochars tested in this project raised soil pH, but did not lead to consistent plant growth improvements. Soil nitrate levels were reduced with increasing biochar rate, perhaps due to ammonium adsorption by the biochar. All biochars on all soil types did increase soil C; the largest carbon impact was on the Quincy sand, the soil with the lowest organic matter content. Biochar C was stable in soil, and mean residence times are estimated to be in the hundreds of years. Also, the biochar did not accelerate loss of indigenous organic matter through the ‘priming effect.’

A bench-scale pyrolysis reactor was built at Washington State University (WSU) to provide biochar from different underutilized biomass feedstocks in the state, and at different process temperatures using slow pyrolysis. In order to consider agricultural use of biochar without unintended environmental consequences, a literature review was conducted on the presence of dioxins and polyaromatic hydrocarbons (PAH) in biochar and bio-oil. No evidence was found. Samples of biochar and bio-oil were then qualitatively and quantitatively analyzed for these compounds. Only phenanthrene, a PAH, was found above the limits of detection, but at levels much lower than those considered an environmental hazard by the Dept. of Ecology. These tests involved biochars made from four different feedstocks and at four different temperatures. While the results cannot be extended to all other feedstocks and temperatures, they do indicate a very low likelihood of environmental contamination by biochar.

Currently, there is no commercial pyrolysis facility in Washington State (May 2009). An economic analysis was done to determine the cost of production of biochar, using biomass from forest thinning done for wildfire risk reduction as a case study. Using fast pyrolysis, a stationary facility with the material hauled to a central site had the lowest breakeven cost of about $87 per

metric ton of biochar. The few businesses with biochar have mentioned possible pricing of $200 per ton. These businesses are typically co-located with a feedstock, at a location where waste heat can be utilized, and eligible for various renewable energy credits. Thus, pyrolysis appears to be economically feasible at larger scale, and smaller scale systems could be viable when using existing collected wastes, which dramatically decreases transportation costs. Construction debris, storm debris, and right-of-way clearing biomass could all represent opportunities for pyrolysis, along with co-location at forest products industry sites and municipal solid waste facilities. The development of bio-oil refineries to produce transportation fuels and other high value products will improve the economic viability of pyrolysis. Recent studies demonstrated that at least 40 mass % of bio-oil can be converted into green gasoline and green diesel at prices close to $2 per gallon, and that pyrolytic sugars in bio-oil can be separated and fermented to ethanol, improving the refining process and the potential value. The deployment of bio-oil refining capacity is critical for the success of this industry. If the U.S. develops a mandatory carbon cap and associated markets, and if biochar is approved for carbon storage payments, then the economics could be dramatically altered. At a price of $31 per metric ton CO_2, all the facilities modeled in this study would be profitable.

If pyrolysis of biomass expands due to changing energy prices and policies, the economic optimization of biochar and bio-oil developed in this study will be a valuable tool (but will not guarantee profitability if prices are too low). Slow pyrolysis and lower temperatures generally favor biochar production, while fast pyrolysis and higher temperatures produce mostly bio-oil with a small amount of biochar. Temperature also affects product quality, and quality affects product value. In one section of this study, we assume energy content is the basis for value of biochar and bio-oil. For slow pyrolysis the optimal estimated yield and price for biochar are 26% and $0.077/kg, and for bio-oil optimal yield and price are 38% and $0.192/kg. Maximum revenue for slow pyrolysis is $0.09296/kg of forest-based feedstock (assuming both products are used solely for their energy value). The implied price ratio (bio-oil:biochar) for slow pyrolysis is 2.4686. If the market prices were fixed and constant across the process temperature range, this price ratio would lead to an economically optimal temperature of 360°C for slow pyrolysis, favoring biochar production.

For fast pyrolysis, economically optimal biochar yield (based on energy content) is 19.8%, with bio-oil yield at 54%. Biochar price is $0.076/kg, and bio-oil price $0.19/kg. Maximum revenue is $0.11848/kg. So, based on energy content, the fast pyrolysis provides higher revenues by $0.0255/kg; an increase of 27%. It is possible that the economic value of the biochar for its energy content would exceed its value for carbon storage. This might then reduce the impetus to make biochar, as it is likely more efficient to use the original feedstock directly for energy rather than the pyrolysis process. In contrast, if biochar has a higher value than that of its energy content, this would induce lower pyrolysis temperatures and resulting biochar yields would be higher than those listed above.

Pyrolysis can address two challenges – the need for renewable energy, in particular, liquid fuels; and alternatives to burning as a disposal method for waste biomass. The controlled thermochemical conversion of pyrolysis can wring valuable products from biomass that would otherwise only contribute air pollutants. Further research into the potential soil and crop productivity benefits of biochar are needed in order to make its use economically feasible for land managers and to provide a value stream back to the pyrolysis business to also make it economically viable. While agriculture and forestry represent the potential to store large amounts of biochar, specialty uses such as buffer strips, water treatment, and compost amendment need to be explored as they could be more economically attractive in the near term despite a smaller overall potential market.

Next Steps

To build on the initial results from this study and the growing interest in biochar and pyrolysis, several steps should be considered.

1. Develop a pyrolysis unit in-state that can provide quantities of biochar needed for field level research (e.g., 10-20 tons/year). A slow pyrolysis system may be preferable because it will produce a greater percentage of biochar from biomass, and the system should also allow capture of bio-oil to help continue that line of research. Field research to date has been hampered by lack of appropriate quantities of biochar.
2. Expand research on crop response to biochar amendments of Washington soils. Where responses are seen, conduct research on the mechanisms responsible so that predictions of biochar efficacy can be made.
3. Research the biochar “aging” process. We do not currently understand whether biochar needs to integrate with the soil matrix over time in order to express any benefits. Development of a method to artificially age biochar in soil would be an important step.
4. Evaluate biochar as an additive to other organic amendments (e.g., compost) and a potential carrier for microbial inoculants and nutrients.
5. Test novel uses of biochar to recover nutrients from water (e.g., livestock lagoons, drainage canals) and recycle them back to land.

Key findings

Chapter 2.

- Biochar yield decreases (at a decreasing rate) with increasing slow pyrolysis temperature.

Chapter 3.

- The thermodynamics of the pyrolysis process do not support formation of dioxins and PAHs, as confirmed by a literature search, qualitative analysis, and quantitative analysis.

- The only compound found above the limit of detection was phenanthrene, and its environmental hazard was far below standards set by Ecology. All dioxin levels were similar to background levels found in Washington State soils.

Chapter 4.

- Biochar carbon concentration and pH increase with increasing pyrolysis temperature, while N and S concentration generally remain unchanged.
- Woody feedstocks lead to higher biochar C concentration than herbaceous feedstocks, but they are of lower pH and liming value.
- Biochar added to soil did not lead to significant changes in CEC, but did lead to some increase in soil water holding capacity for the Quincy sand.
- All biochars on all soil types did increase soil C with increasing rates, and the C appears stable. The biochar did not accelerate loss of indigenous organic matter through the 'priming effect.'
- Biochar led to a decreasing amount of soil nitrate production and a general decrease in available N concentration with increasing biochar rate. The N added with biochar does not become plant available.
- Biochar addition to soil did not increase wheat plant growth in a greenhouse trial.
- Biochar did interact with two herbicides tested, and this would need to be considered by farm managers.

Chapter 5.

- Higher temperatures (up to a point) lead to more bio-oil and less biochar, as does fast pyrolysis versus slow pyrolysis.
- The relative prices of bio-oil and biochar influence the economic trade-off between production of bio-oil and biochar. If producers can receive high prices for bio-oil but low prices for biochar, they can increase sales revenue by choosing a temperature and heating rate that yields more bio-oil at the expense of biochar (i.e., high temperature, fast pyrolysis). In contrast, if biochar prices are high and bio-oil prices are low, there is an incentive to choose a lower final temperature and slow pyrolysis that will provide more biochar and less bio-oil.
- As temperature increases, the yield of biochar decreases but bio-oil increases up to a point, then declines. Above about 525^{o}C, bio-oil production declines in the case of fast pyrolysis; thus this represents an economic threshold to stay below. For slow pyrolysis, the upper bound economically valid temperature is about 549^{o}C.
- Choosing the final process temperature can be economically important. However, even if the optimal combination of biochar and bio-oil is produced, it may not provide an economically profitable enterprise. Profitability depends on whether or not the revenues from the sale of biochar and bio-oil outweigh the cost of producing the two products.

Chapter 6.

- Forest thinning represents a major potential feedstock source for pyrolysis in Washington in terms of quantity of under-utilized biomass.

- Based solely on energy content, biochar is worth about $114/metric ton and bio-oil about $1.06/gallon.
- Among the four types of facilities studied, only the large-scale, stationary facility has positive returns over total production cost ($4/ton dry feedstock) for biochar and bio-oil production at prices based on energy content.
- The break-even selling price for biochar from a stationary facility is $87/metric ton without transportation to the end user.
- The break-even selling price for bio-oil from a stationary facility is $1.03/gallon without transportation to the end user.
- If bio-oil can be sold for $1.15/gallon, then the break-even price for biochar from a stationary facility drops to $7/metric ton.
- Labor costs are the major factor in driving up costs for a smaller mobile pyrolysis unit.
- For a stationary facility to be profitable under the assumed prices and costs, feedstock cost should not be higher than $22/ton.
- Another key factor for profitability is the steady supply of feedstock. Siting pyrolysis with existing collected feedstocks, uses for waste heat, and other synergies is important for its economic viability.

Chapter 7.

- Biochar represents an offset of about 2.93 MT CO_2 per MT biochar applied to the soil. (MT = metric ton = 1000 kg or 2200 lb)
- Biochar production via pyrolysis still provides a large C sequestration potential even after emissions from process energy are subtracted.
- Biochar can substitute for agricultural lime for raising soil pH, but is much more expensive.
- With carbon offsets, biochar production can become profitable when trading prices per metric ton CO_2 are $16.44, $3.39, and $1.04 for the smaller mobile, transportable, and relocatable facilities, respectively. A stationary facility is profitable without a carbon credit.

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Chapter 1. INTRODUCTION.

“Biochar”, a by-product of biomass pyrolysis for energy, is being promoted for its potential large-scale and low-cost carbon sequestration in soil. Much of the knowledge regarding biochar derives from studies of Terra Preta soils in the Amazonian basin (Lehmann *et al*., 2004), where biochar-like materials appear to have substantially altered soil physical and chemical properties and led to long-lasting carbon storage and improved crop production. How this material might impact agricultural soils in Washington State is unknown, especially given the diversity of soils and agroclimatic conditions. A recent study of the impact of fire by Native Americans on Illinois soils showed dramatic effects, with the largest being maintenance of grass versus forest vegetation (Krug and Hollinger, 2003). They found that fire converted plant biomass to stable carbon in the form of charcoal, with 20-25% of grass biomass, and 40-50% of tree biomass, respectively, found as charcoal after a fire. Despite volatile N loss from fire, repeated burning led to soil N accumulation that was a necessary companion to increasing soil carbon.

Biochar is a loosely defined term, and its performance in soil will likely depend on the feedstocks used, the process temperature, the rates applied, and the crops grown. Based on the research to date, it is not clear that adding biochar to soil leads to the equivalent of the Terra Preta soils. The production processes used by the Amazonians are not well-defined, and other bioactive constituents may have been added to the soil along with the biochar. It is possible there is a time period over which freshly added biochar becomes more integrated into the soil, and therefore results from tests with fresh biochar addition might be considerably different from soils with a long history of biochar. Some biochar enthusiasts propose that the real benefits come when biochar is integrated with compost and other biologically active materials, creating a synergistic effect. Given the timeframe and resources for this project, it was not possible to go beyond the initial characterization that we have done to explore these more complex possibilities. Given the promising results from our initial studies, future research in these areas is certainly warranted.

The process in which thermal bonds are cracked (lysis) under the action of heat (pyro) is called “pyrolysis”. Biochar is a typical by-product of biomass pyrolysis. It is a carbonaceous material formed when biomass constitutive polymers (cellulose, hemicelluloses and lignin) are subjected to the action of heat in low oxygen environments. In these conditions thermal scission of bonds and poly-condensation reactions occur. While thermal scission (cracking) reactions lead to the formation of bio-oils and gases, the polycondensation reactions are responsible for the formation of biochar. Biomass pyrolysis is being explored in the state as a potential technology for converting dry biomass wastes into renewable energy and other products. Validation of biochar as a beneficial soil amendment and carbon sink in our state would add important economic value to the pyrolysis process and spur more adoption and waste utilization. This project conducted the first rigorous study of biochar use in agricultural soils for Washington State.

1.1. Beyond Waste.

The goal of this project, funded by the Washington State Dept. of Ecology “Beyond Waste” initiative, is to move “beyond waste” by converting representative organic waste materials available in Washington State into biochar and to evaluate the potential benefits of this material as a soil amendment. Washington State has an annual production of 16.9 million tons of underutilized waste biomass, according to the State biomass inventory (http://www.ecy.wa.gov/biblio/0507047.html). Most of the biomass generated by the state is woody biomass. The huge amount of underutilized softwood woody biomass and bark generated by the forest and paper industries represents a clear opportunity to spur rural economic activity. The state also generates 130,000 tons of dry grass seed straw. Field burning of grass seed straw is allowed by the State of Washington when it is reasonably necessary to carry out agricultural activities. Pyrolysis offers the possibility of reducing the emissions from agricultural burning and utilizing these wastes to produce valuable products.

Pyrolysis as a biomass conversion technology is particularly well-suited to low moisture organic wastes, such as forest residuals (8.2 million tons/yr), straw and other field residue (2.3 million tons/yr), dry manure solids (1.8 million tons/yr), fruit pits, seed waste, and even the paper fraction of municipal solid waste (2.4 million tons/yr). Thus, if biochar proves a valuable by-product, it could induce more use of pyrolysis conversion that would be applicable to over half the underutilized wastes identified in the state biomass inventory.

The research conducted in this project helps provide missing information on applicability and performance of biochar made from Washington waste feedstocks on Washington agricultural soils. Informal recommendations by others have proposed soil application rates of biochar as high as 50 MT/ha, and if biochar is 70% carbon with 90% of the C stable, that would equal 31.5 MT/ha C sequestration. For each 1 million hectares (2.47 million acres) of agricultural land thus treated, this would sequester 31.5 million MT of C in the state. Our project tested lower rates, up to 39 MT/ha (20 tons/ac).

There is no commercial pyrolysis system operating in the state at this time, suggesting that economic and/or technical barriers exist. Sourcing enough biochar for application to commercial farm fields is nearly impossible, due to lack of supply. The pyrolysis process can involve a trade-off between biochar and other possible products, such as bio-oil or heat. Process optimization will depend on the relative values of the various products, and this study is a first step in understanding the value of biochar. Pyrolysis is currently a capital-intensive venture, and a better understanding of the economics of the system, including biochar, is needed.

1.2. Project outline.

The project research consisted of several interrelated parts: a biochar production component, an assessment of environmental risk, studies of the biochar chemical characteristics and its influence on soil chemistry and biology; greenhouse studies of plant response to biochar amendments; exploratory research on biochar as an odor and nutrient trap in livestock manure management; and an assessment of the economic feasibility of biochar production and its value in carbon sequestration. Field studies with biochar could not be carried out both because of lack of biochar availability in large quantities and because of the short duration of the grant period. However, further research has already been launched as a result of this initial project that includes field studies of crop response to biochar.

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Chapter 2. PRODUCTION OF BIO-CHAR.

2.1. Introduction.

Biochar is not a readily available commercial product, or one defined by clear constituent or performance specifications. In order to test whether biochar is a useful soil amendment for carbon sequestration and other benefits, the project team decided to build a bench-top pyrolysis reactor to supply the biochar for research purposes. This chapter describes the construction of bench-scale pyrolysis units at Washington State University (WSU) and the production of biochar in these units. The system was designed and built at WSU in the Dept. of Biosystems Engineering (BSE) in order to provide the biochar and bio-oil needed for research purposes from various in-state wastes, and to utilize several process temperatures to determine their effect on the biochar characteristics. No low-temperature (slow) pyrolysis systems were operating in the region, and no commercial systems in the country had excess biochar to provide for this study. Therefore, one key project objective was to establish this capability in the state of Washington, at WSU.

2.2. Construction of a batch pyrolysis reactor at WSU.

In order to carry out the project tasks, it was necessary to build a new pyrolysis reactor. The mechanical construction and assembly of the batch pyrolysis reactor used for the production of project biochar was completed by the BSE Engineering Technician (Mr. Wayne Dewitt) on May 27, 2008. The system was operational between June 1 and August 15, 2008, to produce part of the biochar needed for the project. Figures 2.1 and 2.2 show a schematic and a photo of the batch pyrolysis reactor designed and built at Washington State University.

This system was able to pyrolyze 200 g of biomass (wood pellets, switchgrass, digested fiber or softwood bark) per run. The batch reactor vessel was a 585 mm long and 100 mm diameter horizontal metal tube (Figure 2.1). The reactor was heated to temperatures between 250 and 600^{o}C and kept at that temperature for 30 minutes using a Lindberg/Blue M (Model HTF55322A) furnace. The pyrolysis vapors were evacuated from the reactor using 1 L/min of nitrogen as a carrier gas. Four ice-cooled traps connected in series were used as condensers to collect bio-oils. After each run, the charcoal was left behind in the reactor under nitrogen until it reached ambient temperature to avoid oxidation with air. The mass of the initial biomass and biochar obtained were determined and the yield of biochar calculated.

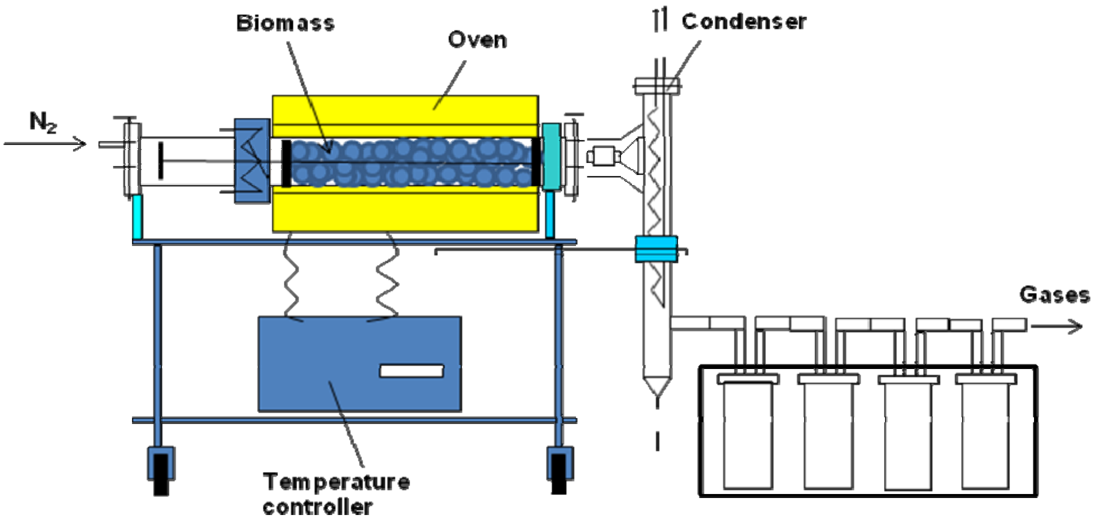

Figure 2.1. Schematic of the Batch Pyrolysis reactor designed and built at WSU.

Figure 2.2. Photo of the Batch Pyrolysis Reactor built at WSU.

2.3. Feedstock used.

Four different feedstocks were used in this project: (1) softwood bark, (2) wood pellets, (3) anaerobic digester dairy manure fiber, and (4) switchgrass. All feedstocks represent potential biomass resources in Washington State that could be diverted to pyrolysis conversion for renewable energy, waste-to-resource utilization, and biochar production.

The softwood bark [Douglas fir (*Pseudotsuga menziesii*) bark] used in this study was generously provided by Mr. Jeff Gage from Swanson Bark & Wood Products (240 Tennant Way, Longview, WA). The wood pellets were produced by Bear Mountain Forest Products (Cascade Locks, OR, 97014) (web-site: www.bmfp.com), using Douglas fir feedstock originating from forests along the Washington-Oregon border. The switchgrass (*Panicum virgatum*) and the digester fiber were supplied by Dr. Hal Collins (USDA-ARS, Prosser, WA).

2.4. Yield of biochar.

Biochars from the four biomass feedstocks were produced at four different pyrolysis temperatures (350, 425, 500 and 600°C) in the system shown in Figures 2.1 and 2.2. Although three temperatures were originally planned for testing, it was decided to cover a wider range of temperatures and additional pyrolysis at 600°C was done. At least 200 g of each feedstock was pyrolysed per run resulting in at least 75 g of biochar per run. In total more than 4 kg of biochar were produced for use in the lab analyses. The yield of biochar obtained from each of the feedstocks studied at different temperatures is shown in Figure 2.3. The biochar produced was sent to Dr. Collins per the project schedule.

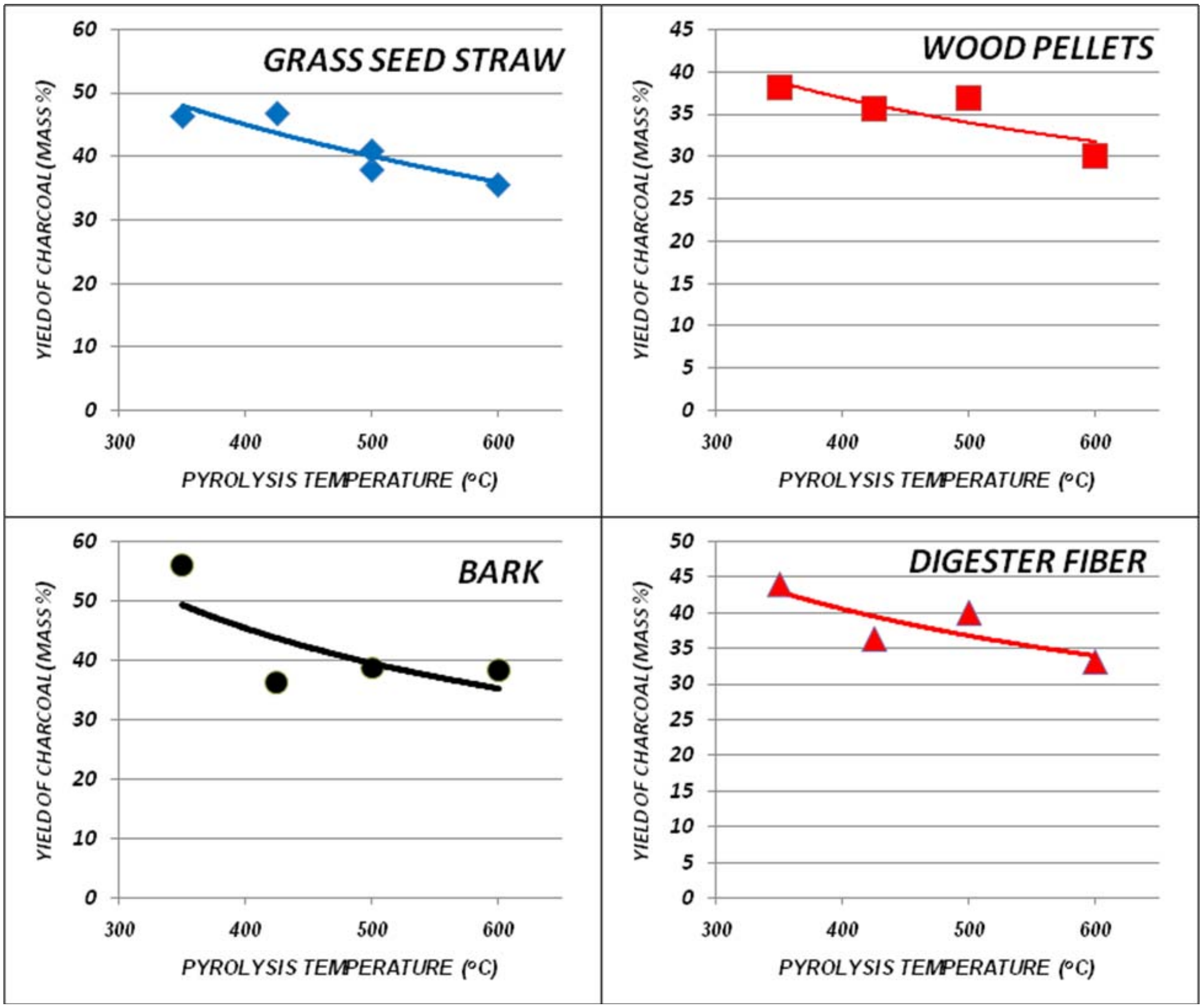

Figure 2.3. Yield of charcoal for each of the biomasses studied in the batch reactor (temperature range: 350-600 °C).

2.5. Construction of an auger pyrolysis reactor at WSU.

The project originally intended to produce larger amounts of biochar for greenhouse studies (3 kg) using the auger pyrolysis reactor available at the University of Georgia (UGA). Professor K.C. Das, one of our collaborators, had kindly offered the use of his installation free of charge. After our August 2008 visit to UGA, it was evident that we could not solve all the problems encountered in that system during short visits of only 10 days. It was therefore more cost effective to upgrade the WSU batch pyrolysis reactor to a continuous system similar to the one in operation at UGA. The WSU Agriculture Research Center provided the extra funding needed to upgrade our system. Having an operational continuous reactor at WSU allowed for increased production of biochar and bio-oil at WSU. Figures 2.4 and 2.5 show a schematic and a photo of the continuous system designed and built at WSU by the BSE Engineering Machinist.

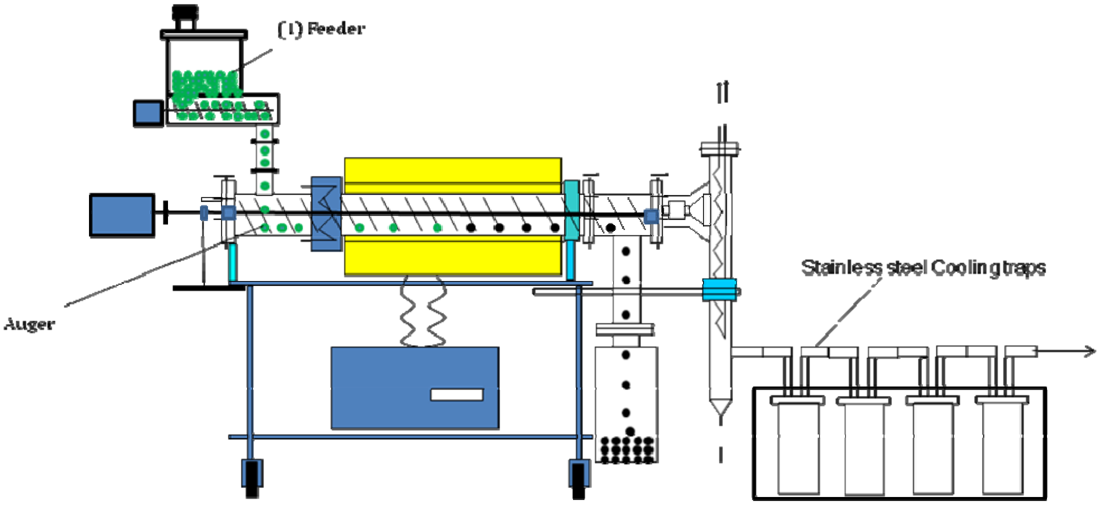

Figure 2.4. Schematic of the upgraded auger pyrolysis reactor built at WSU.

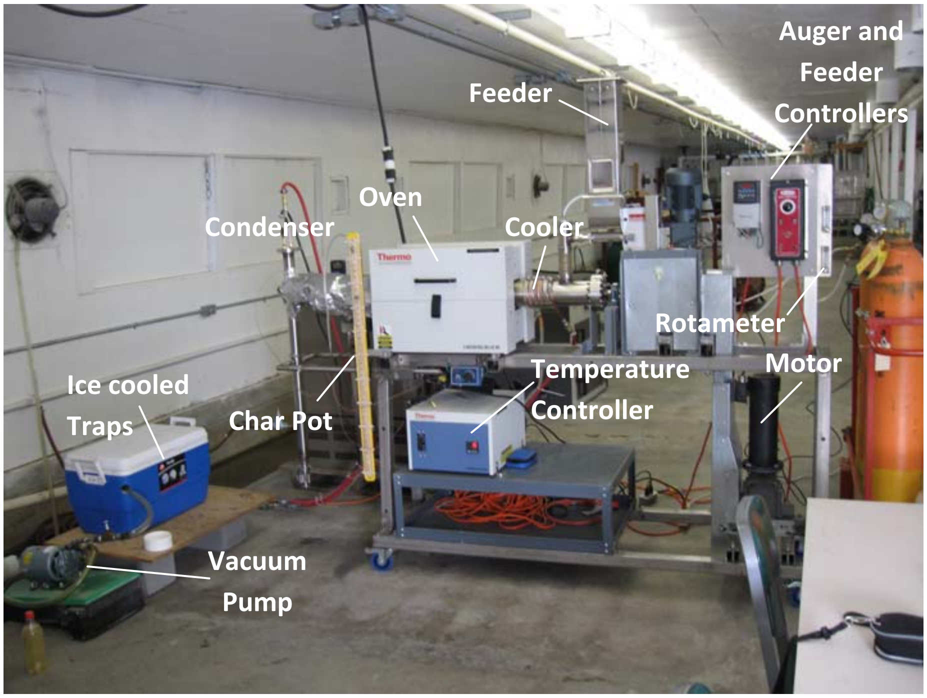

Figure 2.5. Photo of the upgraded auger pyrolysis reactor operational at WSU.

Briefly, the auger pyrolysis reactor consists of an indirectly heated continuous flow reactor fabricated at WSU. This system has been operated at a throughput capacity between 1 to 2 kg of dry biomass per hour. The biomass is fed by a Volumetric Single Screw Stirring Feeder (DSR28, Brabender Technology). The reactor consists of a 100 mm diameter stainless-steel tube placed in a Lindberg/Blue M (Model HTF55322A) furnace with an auger driven by a 1 hp motor (maximum speed: 1725 rpm, 10.9 A). A cooler was installed between the hopper and the furnace to prevent heating the biomass in the hopper. The residence time of the biomass inside the reactor can be controlled by changing the speed of the auger through a manual controller. The biochar was collected in a stainless-steel container located downstream of the auger. A vertical condenser followed by a series of ice-cooled traps was used to condense the pyrolysis vapors. The pressure inside the reactor was maintained a few millimeters of water below atmospheric pressure using a vacuum pump with a valve to control the pressure inside the reactor. The flow of nitrogen to the reactor was controlled and measured using two rotameters (one measuring the flow of nitrogen to the hopper and the other to the auger reactor). Although the reactor can be operated continuously, the capacity of the current biochar pot limits the number of hours that the system can be operated. In total 300 g of biochar can be produced per run (around 1 hour).

Another 1.5 kg of biochar were produced with this continuous system for greenhouse trials. Also, 200 g of switchgrass (naturally enriched in ^{13}C) biochar was produced that was used by Dr. Collins group to investigate the stability of biochars in soils.

The availability of the continuous pyrolysis system at WSU was critical for obtaining two grants for almost $300,000 from the Western Sun Grant Program (see 8.2).

2.6. Conclusions.

A batch pyrolysis reactor was designed, built, and further upgraded to an auger pyrolysis reactor at the Biological Systems Engineering Department at Washington State University. The batch pyrolysis reactor was employed to produce biochars from four in-state biomass feedstocks (pine pellets, softwood bark, switchgrass and digester fiber) at four different temperatures (350, 425, 500 and 600^{o}C). The resulting biochars were provided to Dr. Collins for chemical and biological characterization. Larger amounts of biochar for greenhouse studies (1.5 kg) and 200 g of switchgrass biochar were produced in the auger pyrolysis system at 500^{o}C and sent to Dr. Collins for further studies.

Chapter 3. ASSESSING THE ENVIRONMENTAL IMPACT OF BIOCHAR APPLICATION TO SOILS.

3.1. Introduction.

WSU and Ecology both recognize the need to understand whether there is potential for toxic emissions to the environment from pyrolysis and biochar use. Therefore, project personnel conducted a literature review on this topic to identify if there were published studies on the potential development of hazardous toxic elements in the biochar as a result of biomass pyrolysis reactions and the potential impact of these products on the environment. The review focused on the likelihood that the reactions leading to the formation of dioxins, chlorinated furans and poly-aromatic hydrocarbons could occur during biomass pyrolysis in the range of temperatures between 350 and 600^{o}C. Qualitative and quantitative laboratory analyses on bio-oil and biochar samples were carried out to verify the absence of PAHs and dioxins in the biochar. The results from the literature review and the laboratory analyses are described below.

3.2. Literature review.

Ms. Judy Metcalf and Dr. Garcia-Perez conducted the literature review focusing on the potential development of hazardous or toxic elements in the biochar and bio-oils as the result of biomass pyrolysis reactions. The final report is available to the general public at the WSU Energy Program website (http://pacificbiomass.org/Library.aspx#Gasification).

Several sections were added to the review that describe biomass composition, fast pyrolysis technologies and thermo-chemical reactions in order to create a self-contained document that offers a more complete overview of the complex phenomena associated with the formation of these undesirable compounds.

The review starts with a brief introduction describing some basic elements of biomass composition and existing pyrolysis technologies, and goes on to focus on known pathways for the formation of polyaromatic hydrocarbons (PAHs) and dioxins, their toxicity, and ways to control their production during pyrolysis. The possible relationships between the composition of the biomass, the reaction conditions and the presence of PAHs and dioxins in bio-oils and biochars are discussed.

It was not possible to find any experimental evidence suggesting the presence of dioxins or chlorinated furans in slow or fast pyrolysis bio-oil and biochar. The main two mechanisms proposed to explain the formation of dioxins during incineration of municipal solid wastes are pyrosynthesis (or precursor mechanism), and de novo synthesis. Both mechanisms occur simultaneously and/or independently and result in the formation of compounds with unique finger prints:

(1) The pyrosynthesis (also known as precursor mechanism) supposes that the dioxins are formed by the polycondensation of precursors (e.g. polychlorophenols, polychlorobenzenes, PCBs) which are formed at temperatures around 1000^{o}C. This mechanism occurs in the gas phase when the precursors are quenched to temperatures between 300 and 600°C.
(2) The de novo synthesis involves the presence of carbon as the solid phase. O_2 is also essential for the de novo formation. This mechanism occurs at temperatures between 200 and 400°C.

The lack of oxygen inside pyrolysis reactors, the very low content of chlorine in the biomass and the fact that the precursors of dioxin formation should be generated at temperatures as high as 1200^{o}C could explain why it was not possible to find any reference on the presence of dioxins and chlorinated furans in biochar.

Likewise, the literature does not report any evidence of leachable polyaromatic hydrocarbons (PAHs) in the biochar produced from biomass fast pyrolysis. Very low content of PAHs (less than 10 ppm) have been reported for fast pyrolysis oils. These concentrations are one order of magnitude lower than that for slow pyrolysis oils (exceeding 100 ppm) and several orders of magnitude below those obtained for gasification tars (over 80 mass %). The PAHs identified in fast pyrolysis oils (concentration below 10 ppm) are highly branched in nature. These branched compounds are known to have lower environmental and toxicological impacts compared with the tars obtained at higher temperatures (through gasification or combustion), which tend to have more condensed structures and contain less oxygen. Conversely to biomass combustion processes where the PAHs are released to the atmosphere, the small amounts of PAHs found in bio-oils will not find their way to the environment, since these compounds will be converted to gasoline or will result in coke during bio-oil hydrotreatment in petroleum refineries.

3.3. Qualitative analyses.

The qualitative analyses of dioxins and PAHs in biochar were carried out using CH_2Cl_2 to extract the compounds strongly sorbed on the biochar surface. All the tests were carried out using 1 gram of biochar per 30 g of CH_2Cl_2 overnight. The biochar was removed by filtration and the resulting liquids were analyzed by an Agilent 6890 Gas Chromatograph coupled with an Inert XL mass spectrometer. Then 1 microliter of the liquid was injected and the inlet temperature was maintained at 250^{o}C. A split ratio of 10:1 and a solvent delay of 5 minutes were used. The vapors were separated by means of a 30 m x 0.25 μm (film thickness) non-polar column coated with 5 % phenyl methyl-polysiloxane. One ml/min of helium was used as carrier gas. The chromatography column was heated from 40 to 280^{o}C at a heating rate of 3^{o}C / min and held at the final temperature for 10 minutes. Typical conditions used in the mass spectrometer are the following: line transfer temperature 150^{o}C, ion source 230^{o}C, electron energy 70 eV (see Figure 3.1). The chromatograms obtained (see Appendix A) confirm that concentrations of leachable PAHs and dioxins in the CH_2Cl_2 solution are bellow 10 ppm (sensitivity of our GC/MS).

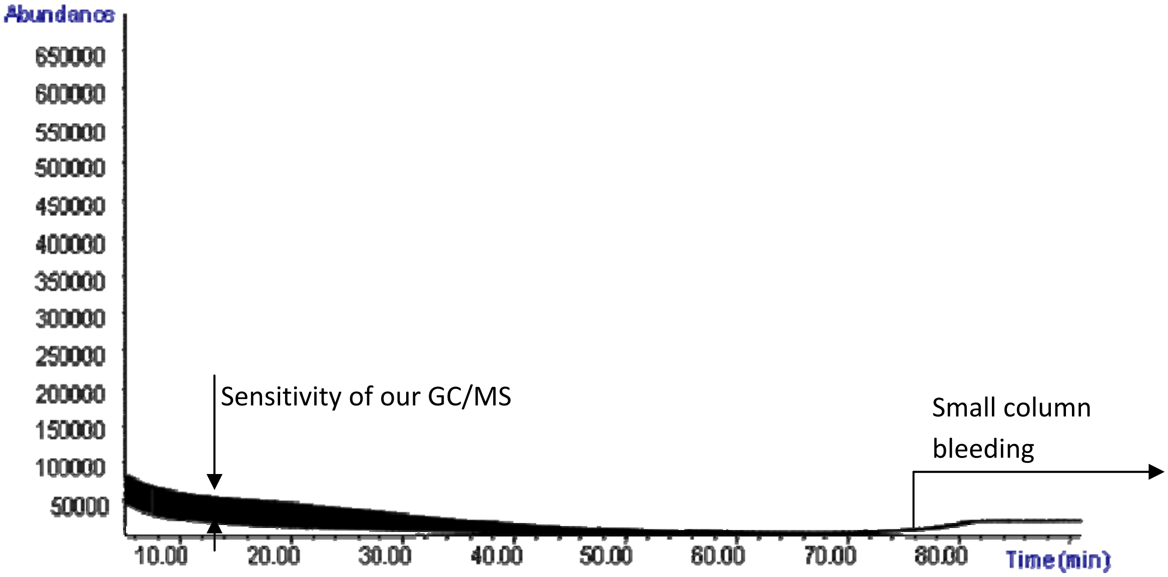

Figure 3.1. Total Ion Chromatogram of CH_2Cl_2 solutions resulting from the extraction of bark derived biochars produced in this project (pyrolysis temperature 500^{o}C).

A limited bleeding of the column was observed at residences times over 70 min. For all practical purposes, our preliminary qualitative results show that the biochar produced in the WSU pyrolysis reactor from softwood bark, switchgrass, digested fiber and pine pellets at temperatures between 350 and 600^{o}C do not contain leachable PAHs and dioxins detectable by GC/MS.

3.4. Quantitative Analyses.

Biochar and bio-oil samples were sent to a certified analytical laboratory (Summit Environmental Lab, Cuyahoga Falls, OH) to confirm the results obtained in our qualitative analyses. The analyses for dioxins and PAHs were carried out following the methods 8290 and 8270, respectively.

Dioxins and Furans

Six biochar samples were analyzed for dioxins and furans (Method 8290). The samples were coded as: **Sample 1** (biochar from softwood bark, 500^{o}C), **Sample 2** (biochar from wood pellets, 500^{o}C), **Sample 3** (biochar from digested fiber, 500^{o}C), **Sample 4** (biochar from switchgrass, 500^{o}C), **Sample 5** (Water soluble fraction of bio-oil from softwood bark, 500^{o}C), **Sample 6** (Oily phase of bio-oil from softwood bark, 500^{o}C).

The results shown in Table 3.1 confirmed our qualitative analyses. The content of dioxins and furans in the biochars produced in this study were extremely low. Although the aqueous phase from softwood bark contained measurable contents of OCDD, these small concentrations cannot be considered as environmental hazards because the aqueous phase will not be applied to soils.

This phase will be further processed to produce transportation fuels.

Summit Environmental laboratory was able to detect the presence of 1,2,3,4,6,7,8-HpCDD and OCDD in several of the biochars produced, but in all cases the concentration was below the calibration limits. We decided to evaluate the toxicity and carcinogenic risk for the mixtures of dioxins and furans following the procedure recommended by the Washington State Dept. of Ecology (Ecology) considering that the actual concentration of these two dioxins/furans was equal to the calibration limit reported by the lab. This is a very conservative approach but allowed us to obtain an estimate of the health risks posed by dioxins and chlorinated furans.

Table 3.1. Content of dioxins and furans (Method 8290)

Parameter	Range of Calibration Limit (ng/kg)	Sample (ng/kg)					
		1	**2**	**3**	**4**	**5**	**6**
2,3,7,8-TCDF	0.47-1.1	ND	ND	ND	ND	ND	ND
1,2,3,7,8-PeCDF	0.59-1.5	ND	ND	ND	ND	ND	ND
2,3,4,7,8-PeCDF	0.47-1.2	ND	ND	ND	ND	ND	ND
1,2,3,4,7,8-HxCDF	0.27-0.64	ND	ND	ND	ND	ND	ND
1,2,3,6,7,8-HxCDF	0.24-0.51	ND	ND	ND	ND	ND	ND
2,3,4,6,7,8-HxCDF	0.25-0.59	ND	ND	ND	ND	ND	ND
1,2,3,7,8,9-HxCDF	0.27-0.62	ND	ND	ND	ND	ND	ND
1,2,3,4,6,7,8-HpCDF	0.33-0.72	ND	ND	ND	ND	ND	ND
1,2,3,4,7,8,9-HpCDF	0.42-0.9	ND	ND	ND	ND	ND	ND
OCDF	0.81-1.5	ND	ND	ND	ND	ND	ND
2,3,7,8-TCDD	0.52-1.2	ND	ND	ND	ND	ND	ND
1,2,3,7,8-PeCDD	0.47-1.8	ND	ND	ND	ND	ND	ND
1,2,3,4,7,8-HxCDD	0.41-1.0	ND	ND	ND	ND	ND	ND
1,2,3,6,7,8-HxCDD	0.57-1.4	ND	ND	ND	ND	ND	ND
1,2,3,7,8,9-HxCDD	0.46-1.1	ND	ND	ND	ND	ND	ND
1,2,3,4,6,7,8-HpCDD	0.54-50.0	ND	ND	ND	6.79J (SSCL-50.0)	6.21J (SSCL-30.3)	6.49J (SSCL-33.2)
OCDD	1.4-99.9	ND	15.38J (SSCL-65.6)	14.53 J (SSCL-94.5)	21.64J (SSCL-99.9)	**61.61** **(SSCL-60.6)**	30.8J (SSCL-66.4)
Total TCDF	2.4-4.0	ND	ND	ND	ND	ND	ND
Total TCDD	2.4-4.0	ND	ND	ND	ND	ND	ND
Total PeCDF	3.0-5.0	ND	ND	ND	ND	ND	ND
Total PeCDD	3.0-5.0	ND	ND	ND	ND	ND	ND
Total HxCDF	3.0- 5.0	ND	ND	ND	ND	ND	ND

J means: Conc. < Calibration Range; ND not detected, SSCL-Sample Specific Calibration Limit.

The Toxicity Equivalent Factor (TEF) methodology proposed by EPA and recommended by Ecology was used to evaluate the toxicity and assess the risks associated with exposure to dioxin and furan mixtures. Ecology suggests that when establishing and determining compliance with cleanup levels and remediation, mixtures of CDDs and CDFs shall be considered as a single substance. For mixtures of dioxins/furans the reference chemical is **2,3,7,8-tetrachlorodibenzo-p-dioxin (2,3,7,8-TCDD).** It is the most toxic and best studied of the 210 CDDs and CDFs. The values of TEF are 0.0001 for the OCDD and 0.01 and for the 1,2,3,4,6,7,8-HpCDD. In our calculations we assumed the calibration limit for OCDD is 99.9 ng/kg and the calibration limit for 1,2,3,4,6,7,8-HpCDD is 50 ng/kg. The Total Toxicity Equivalent Concentration (TTEC) for these biochars equals **0.51 ng/kg**. These concentrations are in the range of the background levels found in Washington soils [residential urban areas (0.13-19 ng/kg), forest land (0.033-5.2 ng/kg), open areas (0.040-4.6 ng/kg) and agricultural lands (0.0078-1.2 ng/kg] (Rogowski and Yake, 2005; Rogowski et al., 1999).

According to the data available at the Cleanup Level and Risk Calculation (CLARC) website (https://fortress.wa.gov/ecy/clarc/CLARCHome.aspx), the 2,3,7,8-tetrachlorodibenzo-p-dioxin (2,3,7,8-TCDD) equivalents permissible for unrestricted soil use (method B) is 1.1E-5 mg/kg (**11 ng/kg**). It is **2.9 ng/kg** for protection of ground water and **2 ng/kg** for protection of wildlife. We thus conclude that the TTEC for the biochars studied here are several times lower than the required cleanup levels. If we take into account that the biochar will be added to soils in a range of 1-10 mass %, then TTEC levels will be even smaller: (**0.0051-0.051 ng/kg**). We conclude that the small content of furans and dioxins that could be present in the biochars produced in this project will not represent a hazard when this material is used as a soil amendment. It clearly meets the cleanup standards for dioxins /furans established by the state of Washington.

Polyaromatic Hydrocarbons

Ten charcoal samples were analyzed for PAHs. The samples were coded as: **Sample 7** (biochar from softwood bark, 350^{o}C), **Sample 8** (biochar from softwood bark, 425^{o}C), **Sample 9** (biochar from softwood bark, 500^{o}C), **Sample 10** (biochar from softwood bark, 600^{o}C), **Sample 11** (biochar from wood pellets, 350^{o}C), **Sample 12** (biochar from wood pellets, 600^{o}C), **Sample 13** (biochar from switchgrass, 350^{o}C), **Sample 14** (biochar from switchgrass, 600^{o}C), **Sample 15** (biochar from digested fiber, 350^{o}C), **Sample 16** (biochar from digested fiber, 600^{o}C).The results obtained are shown in Table 3.2.

The only PAH detected was phenanthrene (between 0.5 and 4.3 ppm). The toxicity and risk assessment of this compound was carried out using the toxicity equivalent factor (TEF). When establishing and determining compliance with cleanup levels and remediation levels for mixtures of carcinogenic polyaromatic hydrocarbons under the Model Toxics Control Act Cleanup Regulation (WAC 173-340-708 (8)(e)), Ecology advises the mixture to be considered as a single hazardous substance. This means that a target cancer risk level of one in one million (10^{-6}) is used when calculating cleanup levels under Method B. For mixtures of cPAHs the reference is **benzo(a)pyrene**. Benzo(a)pyrene was chosen as the reference chemical because its toxicity is well characterized. The TEF for each cPAH is an estimate of the relative toxicity of the cPAH compound compared to benzo(a)pyrene. Although phenanthrene is not listed as a PAH required for testing by the state of Washington (WAC 173-340-708 (e)), we decided to include phenanthrene in our assessment because Ecology suggests taking into account a compound if the data indicate this compound is in the material studied (Table 708-3-MTCA Rule adopted 2007).

Table 3.2. Content of leachable PAHs (Method 8270)

Parameter	Reported Limit (mg/kg)	Sample (mg/kg)									
		7	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Acenaphthylene	0.21	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Acenaphthene	0.21	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Anthracene	0.21	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Benzo(a)anthracene	0.15-0.16	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Benzo(a)pyrene	0.052	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Benzo(b)fluoranthene	0.21	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Benzo(ghi)perylene	0.21	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Benzo(k)fluoranthene	0.21	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Chrysene	0.21	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Dibenzo(a,h)anthracene	0.052	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Fluorene	0.21	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Fluoranthene	0.21	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Indo(1,2,3-cd)pyrene	0.15-0.16	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Naphthalene	0.21	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Phenanthrene	0.21	**4.3**	**0.8**	**3.3**	**1.5**	**0.6**	**0.5**	**3.0**	**3.6**	**3.4**	**1.7**
Pyrene	0.21	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2-Methylnaphthalene	0.21	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1-Methylnaphthalene	0.21	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2-Chloronaphthalene	0.21	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Carbazole	0.21	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Phenanthrene, 3,6dimethyl	TIC	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Retene	TIC	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Perylene	TIC	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
C3-Phenanthrenes/Anthracenes	0.21	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
C4-Phenanthrenes/Anthracenes	0.21	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
C1-Fluororanthene/Pyrene	0.21	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

It was not possible to find the cancer potency-equivalent factor for phenanthrene at the Ecology web site. The value used for our analyses (TEF = 0.001) was obtained from the following publication: Chalbot, M-C., I. Vei, S. Lykoudis, I.G. Kavouras. 2006. Particulate polycyclic aromatic hydrocarbons and n-alkanes in recycled paper processing operations. *Journal of Hazardous Materials* A137:742-751. The mathematical expression to determine the total toxicity equivalent concentration is provided below:

$$\text{Total Toxicity Equivalent Concentration (TTEC)} = \sum C_n \bullet TEF_n$$

Considering the concentration of phenanthrene in biochar to be as high as 4.3 ppm, the Total Toxicity Equivalent Concentration (TTEC) is 0.0043 ppm.

According to the data available at the CLARC website, the level of benzo(a)pyrene equivalents permissible for unrestricted soil use (method B) is **0.14 mg/kg** (ppm). Levels of **2.33 mg/kg** are required for protection of groundwater and **12 mg/kg** for protection of wildfire. We conclude that the TTEC for the levels of phenanthrene measured in biochar (**0.0043 ppm**) is 32 times lower than the required cleanup levels for benzo(a)pyrene. If we take into account that the biochar will be added to soils in a range of 1-10 mass %, then TTEC levels will be 10 to 100 times smaller: (**0.000043-0.00043 ppm**). Using biochar as a soil amendment does not represent a hazard. It clearly meets the cleanup standards for cPAHs established by the state of Washington.

3.5. Conclusions.

The literature review conducted by our team supports the view that available data indicate no human health or environmental hazard from biochar, with the caveat that the literature on the subject is not expansive. The results of this project, together with the literature review conducted, suggest that under the pyrolysis conditions studied, it is possible to produce biochars with concentrations of PAHs and dioxins/furans several times lower than current clean up levels required under the Model Toxics Control Act, Chapter 70.105D RCW. The concentrations of dioxins measured are very close to those reported for background levels in Washington soils (Rogowski and Yake, 2005). Since our conclusions are based on a limited number of samples (5 samples for dioxins/ furans and 10 samples for PAHs), it is advisable not to generalize these results to other feedstocks and pyrolysis technologies. Additional studies of biochar produced with other technologies and feedstocks are needed to confirm our findings. Although we do not have any evidence suggesting the existence of other families of pollutants in biomass derived charcoals, extending our studies to other groups of compounds (e.g., heavy metals) is recommended to ensure that the use of biochar as a soil amendment will not create human health concerns or harm the environment. We recommend that all pyrolysis and biochar studies including commercial scale production activities include assessment of human health risk from toxic organic compounds created during pyrolysis and metals concentrated in pyrolytic reduction of the biomass.

References

Rogowski, D.L. and W. Yake. 2005. Typical dioxin concentrations in agriculture soils of Washington State and potential sources. *Environ. Sci. Technol*. 39:5170-5176.

Rogowski, D.L., S. Golding, D. Bowhay, and S. Singleton. 1999. Final Report: Screening Survey for Metals and Dioxins in Fertilizer Products and Soils in Washington State. Wash. St. Dept. Ecology Publ. 99-309, Olympia, WA. 177 pp. http://www.ecy.wa.gov/pubs/99309.pdf

Yake, W. 1999. A study of dioxins in Washington’s agriculture soils. Focus No. 99-1380, Wash. St. Dept. Ecology, Olympia, WA. 3 pp. http://www.ecy.wa.gov/pubs/991380.pdf

Chapter 4. BIOCHAR CHARACTERIZATION, AND SOIL AND PLANT EFFECTS.

4.1. Introduction.

Biochar is not a precisely defined material, compared to a commercial fertilizer such as ammonium sulfate. It is similar to materials called "compost" in that the term covers products that share a similar production process, but process conditions and feedstocks can be quite different, resulting in different characteristics of the end material and different impacts on plant growth. We conducted some initial characterization of biochars, looking at the effect of pyrolysis temperature and feedstock on the char itself and on properties of biochar-amended soils. In particular, stability of the carbon in biochar needs to be established in order to be able to claim a carbon credit for storing C. Also, it is important to measure whether the biochar changes any soil properties (e.g., pH) that could affect plant growth, and ultimately to conduct growth studies with plants to see what the net effect is of biochar amendment. All these tasks were completed during the project. Given the project duration, we could not measure the effect of biochar amendment over time. It is not clear whether any potential benefits of biochar can be expected immediately after soil amendment, or whether it takes a number of years for the biochar to integrate with the soil matrix (physically, chemically, and biologically) in order to express its impacts. Therefore, the results reported below represent the effect of biochar amendment upon initial addition to soil.

4.2. Characterization of Feedstocks and Biochars.

Bio-chars from 4 feedstocks from the state of Washington (wood pellets [*Pseudotsuga menziesii*], softwood bark [*Pseudotsuga menziesii*], switchgrass [*Panicum virgatum*] straw, anaerobic digester fiber) were produced at four different pyrolysis temperatures (350, 425, 500 and 600 ^{o}C) using the WSU pyrolyzer (see Chapter 2). In addition, a softwood bark biochar (from the same lot as used in Pullman) and a peanut-hull biochar made in the University of Georgia-Athens pyrolyzer were included in some tests. Biochars produced at 500 ^{o}C were evaluated using a variety of characterization parameters. Chars were evaluated for pH, cation exchange capacity, water retention, soil nutrient availability (N, P, K, S, micronutrients), soil biological activity, and C sequestration potentials based on 225 day laboratory incubations. A smaller set of analyses was conducted on biochars developed under the remaining temperatures.

Table 4.1 provides the C, N and S concentrations of the feedstocks prior to pyrolysis. The C content ranged from 432 to 480 g kg^{-1} with the digested fiber having the highest C concentration and the switchgrass residue the lowest. Nitrogen (N) and sulfur (S) concentrations were significantly higher for herbaceous feedstocks [switchgrass (SG), digested fiber (DF)] than the woody feedstocks.

Table 4.1. Feedstock C, N, and S concentrations.

Feedstock	C	N	S	C:N	C:S
	------------- g kg^{-1}	---------------			
Switchgrass	432 (8)[†]	23.5 (0.3)	1.2 (0.2)	18	360
Digested fiber	480 (2)	20.0 (0.2)	3.3 (0.2)	24	145
Softwood bark	470 (2)	3.3 (0.1)	0.3 (0.1)	142	1567
Wood Pellets	477 (9)	1.2 (0.1)	0.3 (0.1)	398	1590

[†] Std. error of mean in parentheses.

Char yield among the feedstocks is presented in Chapter 2, Figure 2.3, with a decline in biochar yield as pyrolysis temperature increased from 350 to 600 ^{o}C. Herbaceous feedstocks (SG and DF) lost 41 – 50% of total C in contrast to the woody feedstocks (SB and WP) that lost 40 – 45% of the total C during pyrolysis (Table 4.2). As the char yield decreased, for each 100 ^{o}C rise in pyrolysis temperature the C concentration of each char increased an average of 41 g C kg^{-1} among feedstocks (Figure 4.1). As pyrolysis temperature increased from 350 to 600 ^{o}C, feedstocks lost 60 - 70% of their total N content (Table 4.2).

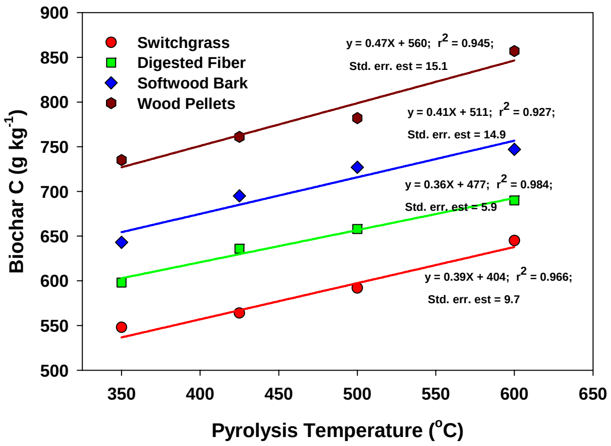

Figure 4.1. Relationship between pyrolysis temperature and the C concentration of the resulting biochar.

Table 4.3 lists C, N and S concentrations of each biochar following pyrolysis. A commercially available activated charcoal was included as a comparison to biochars. Herbaceous feedstocks, SG and DF pyrolyzed at 500 ^{o}C had C concentrations of 60 and 66% respectively, as well as significantly higher N concentrations similar to feedstock concentrations prior to pyrolysis (Table 4.1). The woody feedstocks: bark-UGA, softwood bark (SB) and wood pellets (WP) had C concentrations above 70% with C:N ratios ranging from 200-600. Activated charcoal had a C and N concentrations of 87% and 0.47%, respectively. Typically, activated charcoal is derived from hardwoods.

Table 4.2. Change in C and N concentrations following pyrolysis.

Source	Production Temperature	Biochar Carbon †Char Yield	Char C Conc.	Char C Content	Loss of C from Original Feedstock	
	^{o}C	g kg^{-1}	g g^{-1}	------- g kg^{-1} -------		%
Switchgrass	350	460	0.548	252.1	179.9	41.6
	425	460	0.554	254.8	177.2	41.0
	500	400	0.592	236.8	195.2	45.2
	600	350	0.645	225.8	206.3	47.7
Digested fiber	350	420	0.598	251.2	229.8	47.8
	425	370	0.636	235.3	245.7	51.1
	500	380	0.658	250.0	231.0	48.0
	600	320	0.690	220.8	260.2	54.1
Softwood bark	350	570	0.643	366.5	103.5	22.0
	425	380	0.695	264.1	205.9	43.8
	500	390	0.727	283.5	186.5	39.7
	600	390	0.717	279.6	190.4	40.5
Wood Pellets	350	370	0.735	272.0	205.1	43.0
	425	360	0.761	274.0	203.0	42.6
	500	360	0.782	281.5	195.5	41.0
	600	300	0.857	257.1	219.9	46.1

	Production Temperature	Biochar Nitrogen †Char Yield	Char N Conc.	Char N Content	Loss of N from Original Feedstock	
	^{o}C	g kg^{-1}	g g^{-1}	------- g kg^{-1} -------		%
Switchgrass	350	460	0.0183	8.4	15.1	64.2
	425	460	0.0204	9.4	14.1	60.1
	500	400	0.0199	8.0	15.5	66.1
	600	350	0.0206	7.2	16.3	69.3
Digested fiber	350	420	0.0223	9.4	10.6	53.2
	425	370	0.0230	8.5	11.5	57.5
	500	380	0.0223	8.5	11.5	57.6
	600	320	0.0217	6.9	13.1	65.3
Softwood bark	350	570	0.0033	1.9	1.4	43.0
	425	380	0.0035	1.3	2.0	59.8
	500	390	0.0035	1.4	1.9	58.8
	600	390	0.0036	1.4	1.9	57.1
Wood Pellets	350	370	0.0012	0.4	0.8	64.2
	425	360	0.0011	0.4	0.8	67.3
	500	360	0.0013	0.5	0.7	62.2
	600	300	0.0015	0.5	0.7	61.5

† Char yield from Chapter 2, Figure 2.3.

Nitrogen concentrations of the chars were > 2% for the herbaceous feedstocks and declined to <0.4% for the woody sources. The bark-UGA char and softwood bark char originated from the same feedstock but were processed in different pyrolysis reactors. Their characteristics are somewhat similar (Table 4.2).

Table 4.3. Selected characteristics of the six biochars used in the laboratory analyses. Activated charcoal included as a standard analysis and comparison to biochars.

		[‡]Biochar Characteristics					
Source	Production Temperature	C	N	S	C:N	C:S	pH
	°C	------------- g kg^{-1} -------------					
Switchgrass	350	548 (1)[†] a	18.3 (0.2) a	1.3 (0.11) a	30	422	8.5 a
	425	554 (2) b	20.4 (0.2) b	1.4 (0.10) a	27	396	9.1 b
	500	592 (13) c	19.9 (0.7) ab	1.5 (0.26) a	30	395	9.4 c
	600	645 (26) d	20.6 (0.3) b	1.6 (0.40) a	31	403	9.4 c
Digested fiber	350	598 (2) a	22.3 (0.2) a	3.3 (0.21) a	27	181	8.3 a
	425	636 (3) b	23.0 (0.3) b	3.3 (0.16) a	28	193	9.1 b
	500	658 (10) c	22.3 (0.2) a	3.1 (0.22) a	30	212	9.3 c
	600	690 (5) d	21.7 (0.1) c	3.6 (0.04) b	32	192	9.3 c
Softwood bark	350	643 (1) a	3.3 (0.1) a	0.3 (0.08) a	195	2143	6.0 a
	425	695 (2) b	3.5 (0.3) a	0.3 (0.04) a	200	2317	7.2 b
	500	727 (17) c	3.5 (0.2) a	0.3 (0.20) a	208	2423	7.6 c
	600	717 (5) c	3.6 (0.1) a	0.3 (0.04) a	200	2390	8.4 d
Wood Pellets	350	735 (2) a	1.2 (0.2) a	0.8 (0.40) a	571	2000	6.0 a
	425	761 (4) b	1.1 (0.1) a	0.3 (0.04) a	692	2537	6.7 b
	500	782 (18) c	1.3 (0.2) a	0.7 (0.36) a	602	1117	7.2 c
	600	857 (2) d	1.5 (0.8) a	0.2 (0.04) a	571	4285	7.4 c
Peanut hull	500	706 (12)	17.4 (0.9)	0.6 (0.1)	41	1178	9.6*
Bark-UGA	500	745 (4)	3.4 (0.3)	0.3 (0.1)	219	2483	7.6*
Act. Charcoal		873 (3)	4.7 (0.6)	7.6 (0.4)	186	115	9.1*

[†]Std. error of mean in parentheses. UGA- the bark was made using a pyrolyzer unit located at the University of Georgia, Athens. Statistical comparisons were not made among biochars. Values for a biochar within a column followed by the same letter are not significantly different at p = 0.05.
*Std. error of mean is 0.1 for

Acid hydrolysis is a method used to determine the concentration of recalcitrant C. Acid hydrolysis of the biochar removes labile forms of C such as sugars, cellulose, fats and oils that may remain after pyrolysis. The herbaceous biochar materials (SG and DF) lost 6-8% of their total C and < 0.2% N after acid hydrolysis, where the woody feedstocks (SB and WP) remained largely unchanged. We believe that the C loss originates from condensates of the bio-oil coating the biochar following pyrolysis. It is unclear why we did not observe the loss with the woody feedstocks. The acid-resistant fraction has been shown to have a mean residence time (MRT) of 100’s to 1000’s of years.

Table 4.4. Selected characteristics of the six biochars used in laboratory analyses following 6 N HCl acid hydrolysis. Activated charcoal included as a standard for comparison to biochars.

	Production	[‡]Biochar Characteristics					
Source	Temperature	C	N	S	C:N	C:S	pH
	°C	------------- g kg^{-1} -------------					
Switchgrass	350	589 (2)[†] a	19.0 (0.4) a	0.9 (0.02) a	31	654	nd[‡]
	425	602 (8) b	21.2 (0.2) b	0.8 (0.10) a	28	752	nd
	500	641 (12) c	17.9 (0.3) ab	1.4 (0.47) ab	36	458	nd
	600	685 (10) d	20.0 (0.3) b	1.6 (0.40) b	34	428	nd
Digested fiber	350	650 (5) a	22.6 (0.2) a	2.9 (0.17) a	29	224	nd
	425	672 (4) b	23.3 (0.5) b	2.4 (0.17) a	29	280	nd
	500	709 (17) c	23.4 (0.4) a	3.2 (0.72) a	30	222	nd
	600	710 (7) c	21.7 (0.1) c	3.3 (0.12) a	33	215	nd
Softwood bark	350	656 (5) a	3.0 (0.1) a	0.4 (0.18) a	219	1640	nd
	425	690 (2) b	3.4 (0.2) a	0.4 (0.14) a	203	1725	nd
	500	737 (17) c	3.5 (0.3) a	0.3 (0.57) a	211	2457	nd
	600	712 (28) bc	3.5 (0.2) a	0.5 (0.07) a	203	1424	nd
Wood Pellets	350	723 (7) a	1.1 (0.1) a	0.7 (0.16) a	657	1033	nd
	425	755 (5) b	1.3 (0.1) a	0.4 (0.01) a	581	1888	nd
	500	785 (15) c	1.5 (0.1) a	0.9 (0.53) a	523	872	nd
	600	827 (4) d	2.1 (0.1) a	0.5 (0.09) a	394	1654	nd
Peanut hull	500	711 (3)	17.9 (0.3)	0.2 (0.11)	40	3555	nd
Bark-UGA	500	758 (2)	4.1 (0.3)	0.1 (0.01)	185	7580	nd
Act. Charcoal	---	867 (14)	5.8 (0.5)	7.6 (0.4)	150	115	nd

[†] Std. error of mean in parentheses.. [‡] Acid hydrolysis is a method used to determine the concentration of recalcitrant C (Collins et al., 2000) and causes significant changes to the natural pH of materials, so pH was not determined (nd) after acid hydrolysis. UGA- the bark was made using a pyrolyzer unit located at the University of Georgia, Athens. Statistical comparisons were not made among biochars. Values for a biochar within a column followed by the same letter are not significantly different at $p = 0.05$.

As pyrolysis temperature increased from 350 to 600 °C, pH showed a curvilinear increase from 8.3-9.4 for the herbaceous feedstocks and 6.0- 8.4 for the woody feedstocks (Table 4.2, Figure 4.2).

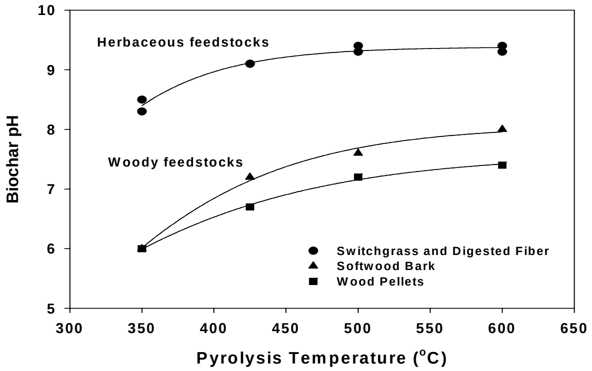

Figure 4.2. Influence of pyrolysis temperature on the pH of a variety of biochars.

4.3. Influence of Biochars on Soil Characteristics.

The biochars were added to five different soils from Washington State representing the diversity of agroclimatic regions and important crops in each region. The following soils were chosen:

Quincy sand (mixed, mesic Xeric Torripsamment). Young alluvial soil, low nutrient and water holding capacity, found in central Washington. Crops grown under irrigation. Common crops: potatoes, corn, wheat, alfalfa, apples.

Naff silt loam (fine-silty, mixed, mesic Ultic Argixeroll). Soil formed from loess deposits under grassland in eastern Washington. Dryland farming, annual cropping. Common crops: wheat, barley, peas, lentils.

Palouse silt loam (fine-silty, mixed, mesic Pachic Ultic Haploxeroll). Soil formed from loess deposits under grassland in eastern Washington. Dryland farming, annual cropping. Common crops: wheat, barley, peas, lentils.

Thatuna silt loam (fine-silty, mixed, mesic Boralfic Argixeroll). Soil formed from loess deposits under grassland in eastern Washington. Dryland farming, annual cropping. Common crops: wheat, barley, peas, lentils.

Hale silt loam (coarse-loamy over sandy or sandy-skeletal, mixed, mesic Aquic Haplorthod). Soil formed from loess and volcanic ash over glacial outwash in western Washington. Rainfed cropping, some summer irrigation, seasonal waterlogging. Common crops: hay, corn silage, and other forages for dairy cows.

Table 4.5 provides some selected characteristics of the soils used in the analyses. They represent a range in soil organic matter (C), pH, and CEC, all of which could be influenced by biochar amendment.

Table 4.5. Selected characteristics of the five soil types used in the laboratory analyses.

Soil	Soil Characteristics							
Series	Texture	C	N	S	C:N	C:S	pH	CEC
		--------- $g\ kg^{-1}$	---------					$cmol\ kg^{-1}$
Quincy	Sand	4.3 (0.5)[†]	0.5 (0.1)	0.2 (0.03)	8.6	22	7.1	3.3
Naff	Silt loam	18.0 (1.0)	1.5 (0.1)	0.2 (0.02)	12.0	90	4.5	15.4
Palouse	Silt loam	23.2 (0.5)	2.0 (0.1)	0.4 (0.11)	11.6	58	4.6	16.0
Thatuna	Silt loam	26.9 (0.5)	2.4 (0.1)	0.4 (0.11)	11.2	67	4.6	16.1
Hale	Silt loam	39.9 (0.9)	3.4 (0.1)	0.6 (0.10)	11.7	67	4.6	16.6

[†] Std. error of mean in parentheses. Statistical comparisons were not made between soils.

Soils were amended with three rates of biochar (0.4% by mass, or 5 short tons/acre or 9.8 metric tons (Mg) per hectare; 0.75% by mass, or 10 short tons/acre or 19.5 metric tons/ha; 1.5% by mass, or 20 short tons/acre or 39.0 metric tons/ha). Tables 4.6-4.10 show concentrations of C, N, and S recovered after amendment and the influence of char on soil pH, CEC, and water holding capacity with increasing additions of biochar to the five soils. Soil pH was found to increase 1 unit for the highest amendment rate (1.5%) of biochar addition for the herbaceous feedstocks and

0.5-1.0 units for the woody sources. Figure 4.3 shows the sigmoidal nature of pH change with the addition of biochar. The pH of the Quincy sand showed a rise to a maximum for each of the biochars added. The increase in soil pH reached a maximum at an application rate of 19.5 Mg biochar ha^{-1}. This response differed for the silt loam soils which showed a similar plateau with 9.8 and 19.5 Mg biochar ha^{-1}but showed an additional exponential increase in pH to 39 Mg biochar ha^{-1}. The difference is likely do to the greater buffering capacity of fine textured soils.

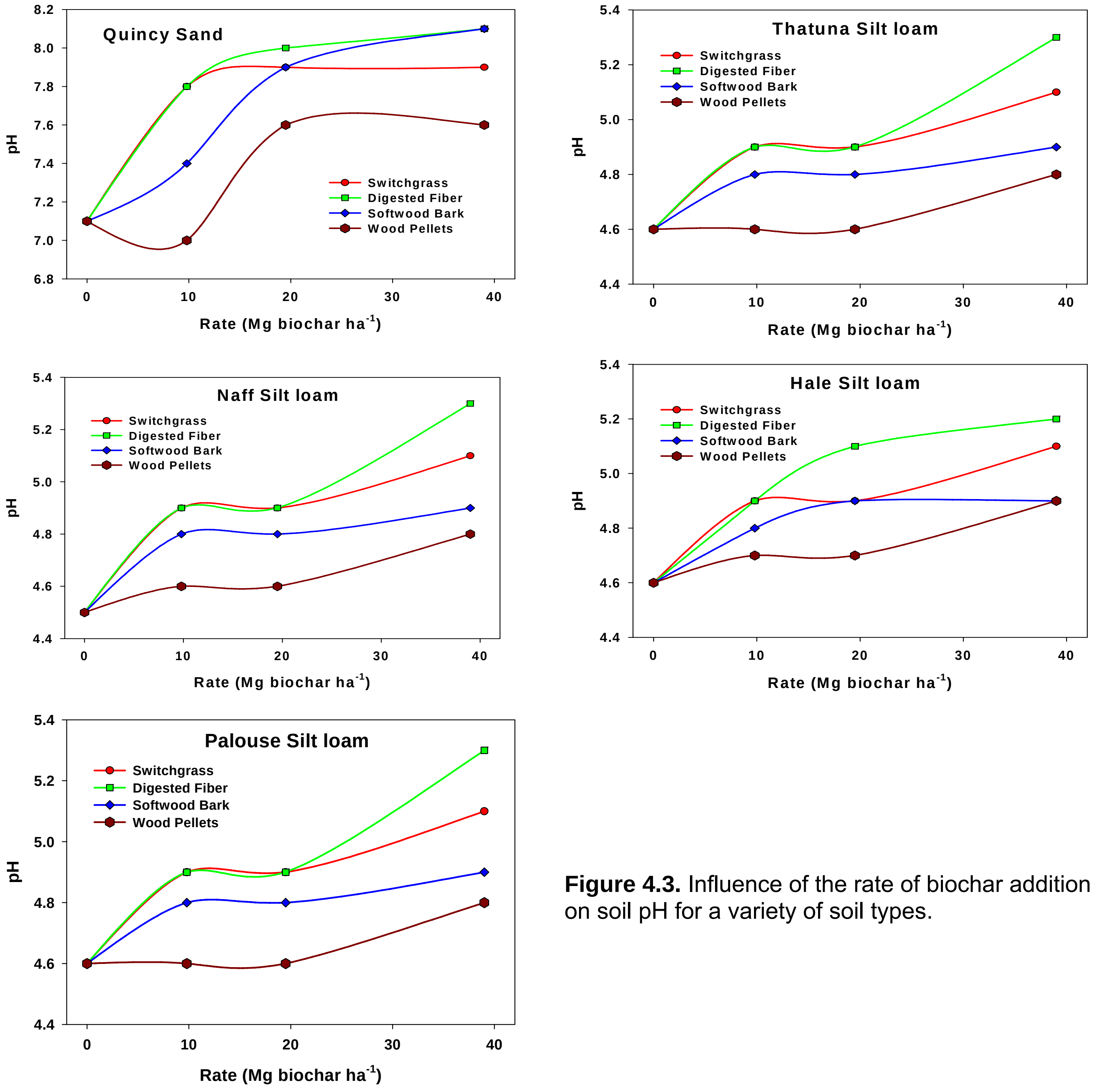

Figure 4.3. Influence of the rate of biochar addition on soil pH for a variety of soil types.

Biochar did not lead to significant increases in soil cation exchange capacity, but did impact water holding capacity in two instances (Tables 4.6- 4.10).

The increase in soil C and N after biochar additions followed the pattern of Hale<Thatuna<Palouse<Naff< Quincy. This pattern was the result of high background soil C for the silt loams versus low soil C for the sand. On the Quincy sand, biochar from woody feedstock tended to raise the soil C more than the herbaceous feedstock char at the higher amendment rates, with a three-fold increase in total C at the 20 ton/ac rate.

Figure 4.4 illustrates the relationship between the amount of C added as biochar and the amount of additional C measured in the soil after amendment. The straight line relationship indicates that virtually all of the added biochar is accounted for in total C analyses. We found a similar response for soils containing biochar following acid hydrolysis (Figure 4.5). This stable C pool comprised between 60 - 90% of the total soil C depending on soil type (Tables 4.11 – 4.15). The size of this pool indicates the recalcitrance and persistence of biochar in soil.

4.4. Effect of Biochar on C-Mineralization, C-Storage and C-Turnover.

Mineralization of SOM plays a fundamental role in soil fertility through the release of nutrients and subsequent influence on net primary productivity. The measurement of CO_2 evolution from soil has been widely used to determine the effect of environmental variables on the oxidation of SOM. The C-mineralization coefficient, i.e. the percentage of total organic C evolved as CO_2, has been used to compare soils under varying management (Collins et al., 1992; Paul *et al*., 1998; Collins *et al*., 1999; Paul *et al.,* 2007). Long-term incubations (>200 day) of soil with measurements of the CO_2 evolved have been widely used to differentiate functional C pools in soil (Motavalli *et al*., 1994; Paul *et al*., 1998). This method constitutes a biological fractionation of organic matter, whereby the most labile fractions (C_a) are the most rapidly depleted by the soil microorganisms and subsequent soil C (C_s) are more slowly mineralized. By analyzing the CO_2 release rates, a variety of mathematical models can be fit to derive estimates for functional C pool sizes and their turnover rates. The most commonly used models are based on the assumption of first-order kinetics, i.e., where the rate of C mineralization is proportional to the amount of C in the organic matter pool. When integrated over time this produces an exponential decay curve. Simulation models that have been used to analyze incubation data often include two or more first-order components (Paul *et al*., 1994; Paul *et al*., 1998; Collins *et al*., 2000; Cochran *et al*., 2007).

Figures 4.6 - 4.11 represent the long-term C-mineralization incubations (up to 300 d) and illustrate the stability of the biochar material. Mineralization among the rates of biochar addition within a soil type was significantly greater in the initial days of the incubation and can be partly explained by the presence of labile C in the biochars. The increase in CO_2 evolved was 1-10 mg CO_2-C kg^{-1} d^{-1} soil depending on the source of the char.

To verify that there was not enhanced degradation of native soil organic matter (SOM), we conducted an additional study evaluating the isotopic concentration of $\delta^{13}C$ in the CO_2 evolved from soils amended with the switchgrass biochar. Atmospheric CO_2 contains both radioactive (^{14}C) and stable (^{13}C) isotopes suitable for tracer studies. ^{13}C is incorporated into plants by photosynthesis and eventually into soils through decomposition processes. The isotope concentration of a plant is retained essentially unchanged in the SOM (Boutton 1996; Follet *et al.*, 1997; Follet and Pruessner, 2001). Switchgrass is a C_4 plant with a ^{13}C signal of $-12^{o}/_{oo}$ and when incorporated into a C_3 dominated soil environment (-25‰ common for soils of the Pacific Northwest) allows for accurate assessments of the change in C dynamics (Garten and Wullschleger, 2000). We identified that the 1-10 mg kg^{-1} d^{-1} flush of CO_2 was derived from the switchgrass biochar and not the native SOM (Figure 4.12). We hypothesize that the increased CO_2 evolved during incubation from any char originates from a fraction of the gaseous condensates (bio-oil) left behind during pyrolysis and not native SOM. The highest rate of biochar addition (39.0 Mg ha^{-1}) of the digested fiber and bark consistently maintained a significantly higher rate of CO_2 evolution than the control soil across all soil types.

We estimated the size and turnover rates of each pool by curve fitting the CO_2 evolved per unit time (C_t) using a three-component first-order model:

$$C_t = C_a e^{-kat} + C_s e^{-kst} + C_r e^{-krt}$$

where; C_a, k_a=Active pool; C_s, k_s=Slow pool; C_r, k_r=Resistant pool.

Three parameters, C_a , k_a , and k_s were estimated using the non-linear regression model (NonLIN) of Systat (Systat, Inc., Evanston, IL). The slow pool C_s pool was defined as; $C_s = C_t - C_a - C_r$. Mean residence time (MRT) was the reciprocal (k^{-1}) of the decomposition rate constant in first order rate reaction. The MRT derived from laboratory incubation at 25 °C was scaled to the mean annual temperature (MAT, Table 1) by assuming a Q_{10} of 2 ($2^{(25-t)/10}$; where t=MAT). Acid hydrolysis determined the size of the resistant C pool (C_r).

Tables 4.11 - 4.15 provide the C pool sizes and C-mineralization kinetics of each soil for the active and slow C pools amended with 0, 9.8, 19.5 and 39 Mg ha^{-1} each biochar and further illustrate the stability of the biochar material. C-mineralization after biochar additions followed the pattern of Thatuna>Palouse> Hale>Naff> Quincy. This pattern was the result of greater initial soil C in silt loams versus low soil C for the sand. The rate of biochar addition had only minor effects on total C mineralized. The proportion of the total C mineralized in un-amended soils ranged from 8.4 to 9.1% for the Naff, Palouse and Thatuna soils and 5.9 and 4.6 for the Quincy and Hale soils, respectively. That the Hale soil had the highest soil C and the lowest proportion of C mineralized is likely a function of the higher clay content of this soil type protecting soil organic matter from oxidation and microbial degradation. When the soils were amended with biochar the percentage of total C mineralized decreased as the amount of biochar additions increased. The reduction in C-mineralization results from the dilution of soil organic C with C that is largely biologically inert. C mineralization as a proportion of total soil C declined an average of 25% from addition of 39.0 Mg ha^{-1} among soil types.

The proportion of soil organic C in the active pool (C_a) of the un-amended soils ranged from 0.2 to 1.4% with the silt loam soils maintaining higher concentrations of labile C. The size of the C_a pool followed the pattern of Thatuna> Hale>Palouse>Naff> Quincy. The size of the C_a pool declined nearly 40% among all soil types as the rate of biochar addition increased, once again related to the dilution effect of the stable biochar C. Laboratory MRT's of the active pool among all sites ranged from 11-30 d in the un-amended soils and tended to decrease for all soils as application rates increased except for the Quincy sand and Naff silt loam which showed > 50% increase in MRT for all biochars as application rate increased. The increase would not be unexpected for the Quincy soil given the low C status of this soil type.

The proportion of total C in the slow pool (C_s) ranged from 26 to 50% in the un-amended soils following the pattern Quincy>Naff=Thatuna>Palouse=Hale (Tables 4.11 – 4.15). The size of the C_s pool declined 78, 48, 46, 32, and 28% for the Quincy, Naff, Palouse, Thatuna and Hale soils, respectively as the rate of biochar addition increased to 39.0 Mg ha^{-1}. These reductions resulted from the dilution of the soil organic C with the un-reactive biochar C comprising the majority of the resistant C pool (C_r) after amendment. The field MRT of the C_s pool was 8.7, 5.2, 3.6, 5.8, and 7.1 years for Quincy, Naff, Palouse, Thatuna and Hale soils, respectively. We suspect that the incubation period for the silt loam soils was too short to get an accurate accounting of the turnover time of C in the C_s pool. We base this on the high rates of CO_2-C (>10 mg kg^{-1} d^{-1}) evolved at 200 d from the silt loam soils compared to the Quincy sand soil (<2 mg kg^{-1} d^{-1}). The incubations for silt loam soils should be extended to 400-500 days.

The proportion of total C in the acid-resistant C (C_r) pool comprised 50% of the total soil organic C in the un-amended Quincy sand to 90% after addition of 39.0 Mg biochar ha^{-1}. There were only minor differences due to the type of biochar added. In Appendix B, Tables B1.1 and B1.2 provide a comparison of predicted and measured C_r pool concentrations after addition of biochar among soils. For the Quincy sand the mass of C in the C_r pool increased 1.2, 2.5 and 5-fold after addition of 9.8, 19.5 and 39.0 Mg biochar ha^{-1}, respectively. For the silt loam soils, the C_r pool also increased, but with smaller relative changes than the sand due to their higher initial C_r levels. Origin of the biochar made little difference. This difference from the Quincy sand can be attributed to soil texture (silt and clay content). The MRT of the resistant non-acid hydrolyzable C pool has been shown to range from 1000 to 2500 years for surface silt loam soils of the Midwest (Paul *et al*., 2001).

4.5. Effect of Biochar on N-Mineralization and N-Storage.

Figures 4.13 - 4.18 present the N mineralized over a 49 d incubation. N-mineralization among biochars and soil types showed a consistent decrease in nitrate production with increasing rates of biochar. This reduction may be related to biochar's NH_4^+ sorption capacity, potentially reducing the NH_4^+ availability to nitryfing microorganisms in the soil and thus depressing nitrate production. These data suggest that the N contained in the biochar is locked into the carbon matrix and not available to microorganisms or plants. In a few instances N-mineralized early in the incubation was higher than the un-amended control across for soils amended with the SG, DF and SB biochars. We suspect that this may originate from some of the condensates during pyrolysis as was suggested for the higher rates of C-mineralized early in laboratory incubations. Future research projects are needed to verify the mechanism(s) influencing ammonification and nitrification in biochar amended soils.

4.6. Effects of Biochar on Wheat Growth.

A greenhouse study was conducted with the softwood bark and wood pellet biochars amended to the five soils: Quincy, Naff, Palouse, Thatuna and Hale, using wheat as the test crop (vegetative growth only). There was not enough digested fiber or switchgrass biochar to conduct the greenhouse studies. Results are presented in Table 4.16. Photographs of the greenhouse study can be seen in Appendix B, Figure B2.2. There were no significant differences in total wheat plant biomass (root plus shoot) due to biochar rate for any of the biochars among soil types. However, although not statistically significant there were several interesting trends that warrant further investigation. Among the soils, increasing biochar additions tended to reduce both root and shoot growth except for the 19.5 Mg biochar ha^{-1} rate which showed increases (not statistically significant) for both root and shoot growth. At this time we have no explanation for this observation.

4.7. Other Effects of Biochar Additions.

The project work plan called for an initial investigation of the potential for biochar to interact with livestock manure handled in lagoon systems, particularly ammonia and phosphorus. That study has not yet been completed. A graduate student is using this for his M.S. thesis project and will continue to work on phosphorus adsorption and biochar.

Another potential impact of biochar in soil is its impact on the efficacy of agricultural chemicals, especially herbicides. Activated charcoal has long been used in research to deactivate certain types of herbicides known to have residual effects in soil that could influence future experiments. Dr. R. Boydston (USDA-ARS, Prosser, WA) and colleagues conducted an exploratory study of herbicide retention by biochar at four different rates, in comparison with soil only and activated charcoal. Two herbicides susceptible to binding by activated charcoal were used – atrazine and metribuzin (Table 4.17). The activated charcoal bound the majority of both herbicides, while soil alone did little. Biochar at the same rate as activated charcoal had a binding percentage similar to soil only. The binding did increase with increasing biochar rate, but never reached the level of activated charcoal, even when used at 100 times the rate of the activated charcoal. However, the high rate (5 tons/ac) is well within the range that biochar proponents are proposing for field application rates. Based on this study, biochar can clearly bind certain herbicides and this fact will need to be considered in management decisions. The binding had little effect on herbicide efficacy in a related experiment by Dr. R. Boydston (USDA-ARS, Prosser, WA).

4.8. Summary.

A large amount of data was generated on the characterization of biochar and its effect on soil and plant growth. Several observations can be made at this point. Feedstock will influence biochar characteristics. With the biochars studied here, biochars from herbaceous feedstocks (switchgrass, digester fiber, peanut hulls) had lower carbon content, higher nitrogen content, and higher pH than the woody feedstock biochars. The former also lost more carbon during the initial incubation, suggesting they contain more labile carbon compounds that are easily decomposed by soil organisms. The higher pH of the herbaceous biochars gave them a greater liming impact per ton of biochar added to soil. The effects of biochar were different across soils, with the low organic matter Quincy soil experiencing the greatest increase in soil C with biochar amendment. All biochars on all soil types did increase soil C with increasing rates, and the C appears stable. Carbon storage in soil is one of the primary motivations for evaluating biochar. Based on the incubation studies, calculations were made of the three different carbon pools (active, slow, resistant) for each of the five soils. For the purposes of carbon credits, the resistant pool represents the potential for long-term storage. Mean residence times were calculated for each soil for the active and slow pools and estimated for the resistant pools. The carbon left after acid hydrolysis is essentially the resistant carbon, and can be used for determining carbon credits for biochar application by subtracting the non-amended resistant fraction from the resistant fraction after biochar amendment. The nitrogen added with biochar amendment does not appear to be available, and increasing biochar rate led to reduction in soil nitrate, perhaps due to ammonium adsorption by the biochar. If this ammonium is available for plant roots, then this effect could lead to improved nitrogen conservation in soils, possible improved plant growth due to a blend of ammonium and nitrate ions, and less off-site movement of nitrate. Plant growth data are still being analyzed, but no large boost in wheat growth in a greenhouse trial was noted due to biochar amendment. Biochar did interact with two herbicides (atrazine and metribuzin) and thus herbicide management would need to be evaluated if a field had received or was going to receive a biochar amendment, as the biochar could deactivate the herbicide. A field trial was established in April 2009 at WSU Prosser using a fast pyrolysis biochar and corn as the test plant. Results from this trial will complement the initial findings from the laboratory and greenhouse studies done in this project.

NOTE: Two sets of analyses (effect of biochar amendment on soil moisture, nutrient content of biochar) were not completed during the project period. These samples are being analyzed without charge by two other laboratories as their schedule allows. Also, tests on the adsorption/desorption of phosphorus in dairy effluent with biochar have not yet been completed. Data from these three analyses will be provided to Ecology by January 31, 2010.

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Table 4.6. Concentrations of soil C and N, pH , CEC and water holding capacity after additions of biochars (500 °C) to the Quincy sand soil.

Soil		Biochar	Soil + Biochar								
Series	Biochar	†Rate	C	N	S	C:N	C:S	pH	CEC	Water Holding (%)	
		Mg ha^{-1}	------- g kg^{-1} soil------						cmol kg^{-1}	0 MPa§	0.1 MPa
Quincy	Switchgrass	0	4.3 (0.5)‡ a	0.5 (0.05) a	0.2 (0.03) a	9	22	7.1 a	3.3	26.0 (0.3) a	4.0 (0.1) a
		9.8	2.6 (0.1) b	0.2 (0.03) b	0.2 (0.08) a	13	13	7.8 b	Nd	29.3 (0.9) b	4.1 (0.1) ab
		19.5	4.6 (0.3) ac	0.2 (0.01) b	0.2 (0.04) a	23	23	7.9 b	Nd	29.8 (0.5) b	4.3 (0.1) bc
		39.0	8.9 (0.3) d	0.3 (0.04) c	0.1 (0.01) b	30	89	7.9 b	Nd	31.3 (1.0) c	4.5 (0.2) c
	Digested Fiber	0	4.3 (0.5) a	0.5 (0.05) a	0.2 (0.03) a	9	22	7.1a	3.3	26.0 (0.3) a	4.0 (0.1) a
		9.8	2.5 (0.6) b	0.2 (0.05) b	0.1 (0.04) b	13	25	7.8 b	4.2	27.5 (0.9) b	4.5 (0.2) b
		19.5	4.9 (0.3) ac	0.2 (0.01) b	0.2 (0.04) a	25	25	8.0 c	4.2	29.4 (0.5) c	4.5 (0.2) b
		39.0	9.9 (0.7) d	0.4 (0.04) c	0.2 (0.02) a	25	50	8.1 c	4.4	32.5 (1.0) d	4.4 (0.3) b
	Softwood Bark	0	4.3 (0.5) a	0.5 (0.05) a	0.2 (0.03) a	9	22	7.1a	3.3	26.0 (0.3) a	4.0 (0.1) a
		9.8	3.3 (0.3) b	0.1 (0.02) b	0.1 (0.05) b	33	33	7.4 b	4.3	26.1 (1.2) a	3.9 (0.2) a
		19.5	5.7 (0.7) ac	0.1 (0.02) b	0.1 (0.04) b	57	57	7.9 c	4.4	27.8 (0.3) b	4.0 (0.2) a
		39.0	9.4 (0.4) d	0.2 (0.06) c	0.1 (0.12) b	47	94	8.1 c	4.4	29.0 (0.8) c	4.0 (0.1) a
	Wood Pellets	0	4.3 (0.5) a	0.5 (0.05) a	0.2 (0.03) a	9	22	7.1a	3.3	26.0 (0.3) a	4.0 (0.1) a
		9.8	4.5 (0.7) ab	0.1 (0.03) b	0.2 (0.08) a	45	47	7.0 a	4.1	26.1 (0.9) a	4.1 (0.1) ab
		19.5	5.6 (0.7) b	0.1 (0.02) b	0.2 (0.11) a	56	16	7.6 b	4.2	26.3 (0.6) a	4.2 (0.1) b
		39.0	11.2 (1.4) c	0.1 (0.01) b	0.1 (0.06) a	112	35	7.6 b	4.2	26.0 (1.5) a	4.0 (0.1) a

†Rate of biochar application. Mg/ha=megagrams per hectare=metric tons per hectare. 1 metric ton per hectare = 890 lb/acre or 0.445 short tons per acre. A short ton = 2000 lb. Nd –not determined at the time of this report. ‡Std. error of mean in parentheses. Statistical comparisons were not made among biochars. Values for a biochar within a column followed by the same letter are not significantly different at p = 0.05. §MPa = 0.1 bar.

Table 4.7. Concentrations of soil C and N, pH, CEC and water holding capacity after additions of biochars (500°C) to the Naff silt loam soil type.

Soil		Biochar	Soil + Biochar								
Series	Biochar	[†]Rate	C	N	S	C:N	C:S	pH	CEC	Water Holding (%)	
		Mg ha^{-1}	-------- g kg^{-1}-------						cmol kg^{-1}	0 MPa[§]	0.1 MPa
Naff	Switchgrass	0	18.0 (1.0) [‡] a	1.5 (0.05) a	0.2 (0.02) a	12	90	4.5 a	15.4	50.3 (3.1) a	Nd
		9.8	19.9 (0.4) b	1.6 (0.03) b	0.2 (0.01) a	12	100	4.7 b	Nd	52.7 (1.6) a	Nd
		19.5	22.6 (0.9) c	1.7 (0.04) c	0.2 (0.02) a	13	113	4.9 c	Nd	49.4 (1.4) a	Nd
		39.0	27.8 (0.6) d	1.8 (0.04) d	0.2 (0.01) a	15	139	5.0 c	Nd	49.6 (1.3) a	Nd
	Digested Fiber	0	18.0 (1.0) a	1.5 (0.05) a	0.2 (0.02) a	12	90	4.5 a	15.4	50.3 (3.1) a	Nd
		9.8	20.7 (1.0) b	1.6 (0.05) b	0.2 (0.03) a	13	104	4.7 b	16.1	52.7 (2.0) a	Nd
		19.5	22.9 (0.6) c	1.7 (0.02) c	0.2 (0.04) a	14	115	4.8 b	16.6	51.2 (1.9) a	Nd
		39.0	26.6 (0.4) d	1.8 (0.03) d	0.2 (0.04) a	15	133	5.3 c	16.8	53.5 (2.3) a	Nd
	Softwood bark	0	18.0 (1.0) a	1.5 (0.05) a	0.2 (0.02) a	12	90	4.5 a	15.4	50.3 (3.1) a	Nd
		9.8	21.4 (0.3) b	1.5 (0.01) a	0.2 (0.03) a	14	107	4.8 b	17.1	54.1 (5.1) a	Nd
		19.5	23.0 (0.7) c	1.5 (0.03) a	0.2 (0.01) a	15	115	4.8 b	17.2	52.3 (5.9) a	Nd
		39.0	30.2 (0.7) d	1.5 (0.03) a	0.2 (0.01) a	20	151	4.9 c	18.6	50.9 (2.3) a	Nd
	Wood Pellets	0	18.0 (1.0) a	1.5 (0.05) a	0.2 (0.02) a	12	90	4.5 a	15.4	50.3 (3.1) a	Nd
		9.8	20.8 (0.9) b	1.4 (0.04) a	0.2 (0.01) a	15	104	4.6 b	15.5	51.1 (0.7) a	Nd
		19.5	24.3 (1.8) c	1.5 (0.03) a	0.3 (0.05) b	16	81	4.6 b	15.8	50.6 (2.3) a	Nd
		39.0	34.2 (1.1) d	1.4 (0.06) a	0.3 (0.04) b	24	114	4.8 c	16.1	57.2 (2.4) a	Nd

[†]Rate of biochar application. Mg/ha=megagrams per hectare=metric tons per hectare. 1 metric ton per hectare = 890 lb/acre or 0.445 short tons per acre. A short ton = 2000 lb. Nd –not determined at the time of this report. [‡]Std. error of mean in parentheses. Statistical comparisons were not made among biochars. Values for a biochar within a column followed by the same letter are not significantly different at p = 0.05. [§]MPa = 0.1 bar.

Table 4.8. Concentrations of soil C and N, pH, CEC and water holding capacity after additions of biochars (500°C) to the Palouse silt loam soil type.

Soil		Biochar	Soil + Biochar								
Series	Biochar	[†]Rate	C	N	S	C:N	C:S	pH	CEC	Water Holding (%)	
		Mg ha^{-1}	-------- g kg^{-1}-------						cmol kg^{-1}	0 MPa[§]	0.1 MPa
Palouse	Switchgrass	0	23.2 (0.5)[‡] a	2.0 (0.04) a	0.4 (0.11) a	12	58	4.6 a	16.0	53.9 (3.4) a	Nd
		9.8	26.0 (0.3) b	2.0 (0.01) a	0.3 (0.04) a	13	87	4.7 a	Nd	53.3 (2.2) a	Nd
		19.5	28.3 (0.7) c	2.1 (0.04) b	0.4 (0.13) a	13	71	4.9 b	Nd	55.2 (3.9) a	Nd
		39.0	32.0 (0.6) d	2.2 (0.01) c	0.3 (0.04) a	15	107	5.1 c	Nd	55.5 (2.7) a	Nd
	Digested Fiber	0	23.2 (0.5) a	2.0 (0.04) a	0.4 (0.11) a	12	58	4.6 a	16.0	53.9 (3.4) a	Nd
		9.8	25.6 (0.3) b	2.0 (0.04) a	0.5 (0.13) a	13	51	4.9 b	16.0	51.8 (1.4) a	Nd
		19.5	29.4 (0.7) c	2.2 (0.04) b	0.4 (0.05) a	13	74	4.9 b	16.3	57.9 (4.6) a	Nd
		39.0	38.1 (0.6) d	2.6 (0.04) c	0.4 (0.03) a	15	95	5.3 c	16.6	52.6 (4.3) a	Nd
	Softwood bark	0	23.2 (0.5) a	2.0 (0.04) a	0.4 (0.11) a	12	58	4.6 a	16.0	53.9 (3.4) a	Nd
		9.8	27.2 (1.0) b	2.2 (0.05) a	0.3 (0.05) a	12	91	4.8 a	16.1	55.5 (2.3) a	Nd
		19.5	28.2 (0.7) c	2.3 (0.07) a	0.3 (0.03) a	12	94	4.8 a	16.2	61.4 (1.5) b	Nd
		39.0	36.5 (0.8) d	2.2 (0.01) a	0.4 (0.12) a	17	91	4.9 b	17.6	60.3 (0.7) b	Nd
	Wood Pellets	0	23.2 (0.5) a	2.0 (0.04) a	0.4 (0.11) a	12	58	4.6 a	16.0	53.9 (3.4) a	Nd
		9.8	26.3 (0.6) b	1.9 (0.02) a	0.3 (0.04) a	14	88	4.6 a	15.8	58.5 (4.0) a	Nd
		19.5	34.9 (1.3) c	2.2 (0.04) a	0.3 (0.07) a	16	116	4.6 a	17.5	56.2 (2.2) a	Nd
		39.0	38.7 (1.0) d	2.3 (0.11) a	0.3 (0.05) a	17	129	4.8 b	18.7	53.3 (3.3) a	Nd

[†]Rate of biochar application. Mg/ha=megagrams per hectare=metric tons per hectare. 1 metric ton per hectare = 890 lb/acre or 0.445 short tons per acre. A short ton = 2000 lb. Nd –not determined at the time of this report. [‡]Std. error of mean in parentheses. Statistical comparisons were not made among biochars. Values for a biochar within a column followed by the same letter are not significantly different at p = 0.05. [§]MPa = 0.1 bar.

Table 4.9. Concentrations of soil C and N, pH and CEC after additions of biochars (500°C) to the Thatuna silt loam soil type.

Soil	Biochar		Soil + Biochar								
Series	Biochar	[†]Rate	C	N	S	C:N	C:S	pH	CEC	Water Holding (%)	
		Mg ha^{-1}	-------- g kg^{-1}-------						cmol kg^{-1}	0 MPa[§]	0.1 MPa
Thatuna	Switchgrass	0	26.9 (0.5) [‡] a	2.4 (0.04) a	0.4 (0.11) a	11	67	4.4 a	16.1	57.2 (1.6) a	Nd
		9.8	28.3 (0.4) b	2.2 (0.03) b	0.3 (0.05) a	13	94	4.5 a	Nd	55.3 (2.0) a	Nd
		19.5	31.0 (0.5) c	2.2 (0.06) b	0.3 (0.07) a	14	103	4.9 b	Nd	59.9 (1.7) a	Nd
		39.0	37.6 (1.5) d	2.4 (0.02) a	0.4 (0.15) a	16	94	5.1 c	Nd	57.7 (2.4) a	Nd
	Digested Fiber	0	26.9 (0.5) a	2.4 (0.04) a	0.4 (0.11) a	11	67	4.4 a	16.1	57.2 (1.6) a	18.4 (0.3) a
		9.8	29.6 (0.3) b	2.3 (0.05) b	0.3 (0.03) a	13	99	4.6 b	16.1	56.7 (1.0) a	18.5 (0.2) a
		19.5	30.4 (0.3) c	2.3 (0.03) b	0.3 (0.04) a	13	101	4.9 c	17.2	56.8 (2.2) a	18.3 (0.4) a
		39.0	37.2 (0.3) d	2.5 (0.04) a	0.3 (0.04) a	15	124	5.0 c	16.0	56.5 (2.1) a	18.6 (0.1) a
	Softwood bark	0	26.9 (0.5) a	2.4 (0.04) a	0.4 (0.11) a	11	67	4.4 a	16.1	57.2 (1.6) a	Nd
		9.8	28.3 (1.1) b	2.1 (0.03) b	0.3 (0.04) a	12	94	4.6 a	16.1	53.9 (1.5) a	Nd
		19.5	31.9 (1.6) c	2.1 (0.01) b	0.3 (0.03) a	12	106	4.8 b	17.8	52.7 (3.4) a	Nd
		39.0	34.9 (2.8) c	2.1 (0.07) b	0.3 (0.03) a	17	116	4.9 b	18.0	58.7 (1.6) a	Nd
	Wood Pellets	0	26.9 (0.5) a	2.4 (0.04) a	0.4 (0.11) a	11	67	4.4 a	16.1	57.2 (1.6) a	Nd
		9.8	27.8 (1.3) a	2.1 (0.02) b	0.3 (0.03) a	14	93	4.5 a	15.1	52.9 (2.1) b	Nd
		19.5	30.3 (0.7) b	2.1 (0.07) b	0.3 (0.04) a	16	101	4.6 b	16.4	50.7 (1.9) b	Nd
		39.0	35.9 (2.3) c	2.1 (0.04) b	0.3 (0.04) a	17	120	4.6 b	17.3	56.8 (1.4) a	Nd

[†]Rate of biochar application. Mg/ha=megagrams per hectare=metric tons per hectare. 1 metric ton per hectare = 890 lb/acre or 0.445 short tons per acre. A short ton = 2000 lb. Nd –not determined at the time of this report. [‡]Std. error of mean in parentheses. Statistical comparisons were not made among biochars. Values for a biochar within a column followed by the same letter are not significantly different at $p = 0.05$. [§]MPa = 0.1 bar.

Table 4.10. Concentrations of soil C and N, pH, CEC and water holding capacity after additions of biochars (500°C) to the Hale silt loam soil type.

Soil		Biochar	Soil + Biochar								
Series	Biochar	†Rate	C	N	S	C:N	C:S	pH	CEC	Water Holding (%)	
		Mg ha^{-1}	-------- g kg^{-1}-------						cmol kg^{-1}	0 MPa§	0.1 MPa
Hale	Switchgrass	0	39.9 (0.9) ‡ a	3.4 (0.09) a	0.6 (0.10) a	12	67	4.7 a	16.6	52.9 (1.5) a	23.8 (0.9) a
		9.8	43.7 (1.7) b	3.4 (0.13) a	0.6 (0.05) a	13	73	4.7 a	Nd	57.3 (3.1) a	25.0 (0.3) ab
		19.5	44.1 (1.5) b	3.4 (0.11) a	0.6 (0.07) a	13	74	4.9 b	Nd	58.0 (4.1) a	25.0 (0.1) ab
		39.0	49.2 (1.3) c	3.6 (0.11) a	0.6 (0.15) a	14	82	5.0 b	Nd	58.6 (3.0) a	25.4 (0.4) b
	Digested Fiber	0	39.9 (0.9) a	3.4 (0.09) a	0.6 (0.10) a	12	67	4.7 a	16.6	52.9 (1.5) a	23.8 (0.9) a
		9.8	42.6 (1.4) b	3.4 (0.09) a	0.6 (0.03) a	13	71	4.8 a	15.6	55.3 (2.2) a	25.3 (0.5) b
		19.5	44.7 (1.9) b	3.5 (0.09) a	0.7 (0.04) a	13	64	4.9 b	16.6	61.4 (3.1) a	25.4 (0.4) b
		39.0	48.9 (2.3) c	3.6 (0.14) a	0.7 (0.04) a	14	71	5.1 c	16.5	58.8 (2.0) a	25.3 (0.3) b
	Softwood bark	0	39.9 (0.9) a	3.4 (0.09) a	0.6 (0.10) a	12	67	4.7 a	16.6	52.9 (1.5) a	23.8 (0.9) a
		9.8	42.5 (0.5) b	3.4 (0.07) a	0.6 (0.04) a	13	71	4.8 a	15.5	52.6 (4.4) a	24.8 (0.2) a
		19.5	44.5 (1.5) c	3.2 (0.09) a	0.6 (0.03) a	14	74	4.8 a	17.0	55.3 (1.3) a	22.6 (0.3) a
		39.0	49.5 (1.0) d	3.2 (0.13) a	0.6 (0.03) a	15	83	4.9 b	16.7	56.9 (5.5) a	23.1 (0.1) a
	Wood Pellets	0	39.9 (0.9) a	3.4 (0.09) a	0.6 (0.10) a	12	67	4.7 a	16.6	52.9 (1.5) a	23.8 (0.9) a
		9.8	43.3 (0.5) b	3.4 (0.12) a	0.6 (0.03) a	13	72	4.7 a	15.7	39.4 (1.9) b	24.8 (0.4) a
		19.5	45.7 (1.3) c	3.2 (0.14) a	0.6 (0.04) a	14	76	4.7 a	17.2	42.4 (2.3) b	24.7 (0.6) a
		39.0	50.3 (2.3) d	3.3 (0.06) a	0.6 (0.04) a	15	84	4.9 b	15.8	39.2 (5.8) b	24.7 (0.2) a

†Rate of biochar application. Mg/ha=megagrams per hectare=metric tons per hectare. 1 metric ton per hectare = 890 lb/acre or 0.445 short tons per acre. A short ton = 2000 lb. Nd –not determined at the time of this report. ‡Std. error of mean in parentheses. Statistical comparisons were not made among biochars. Values for a biochar within a column followed by the same letter are not significantly different at p = 0.05. §MPa = 0.1 bar.

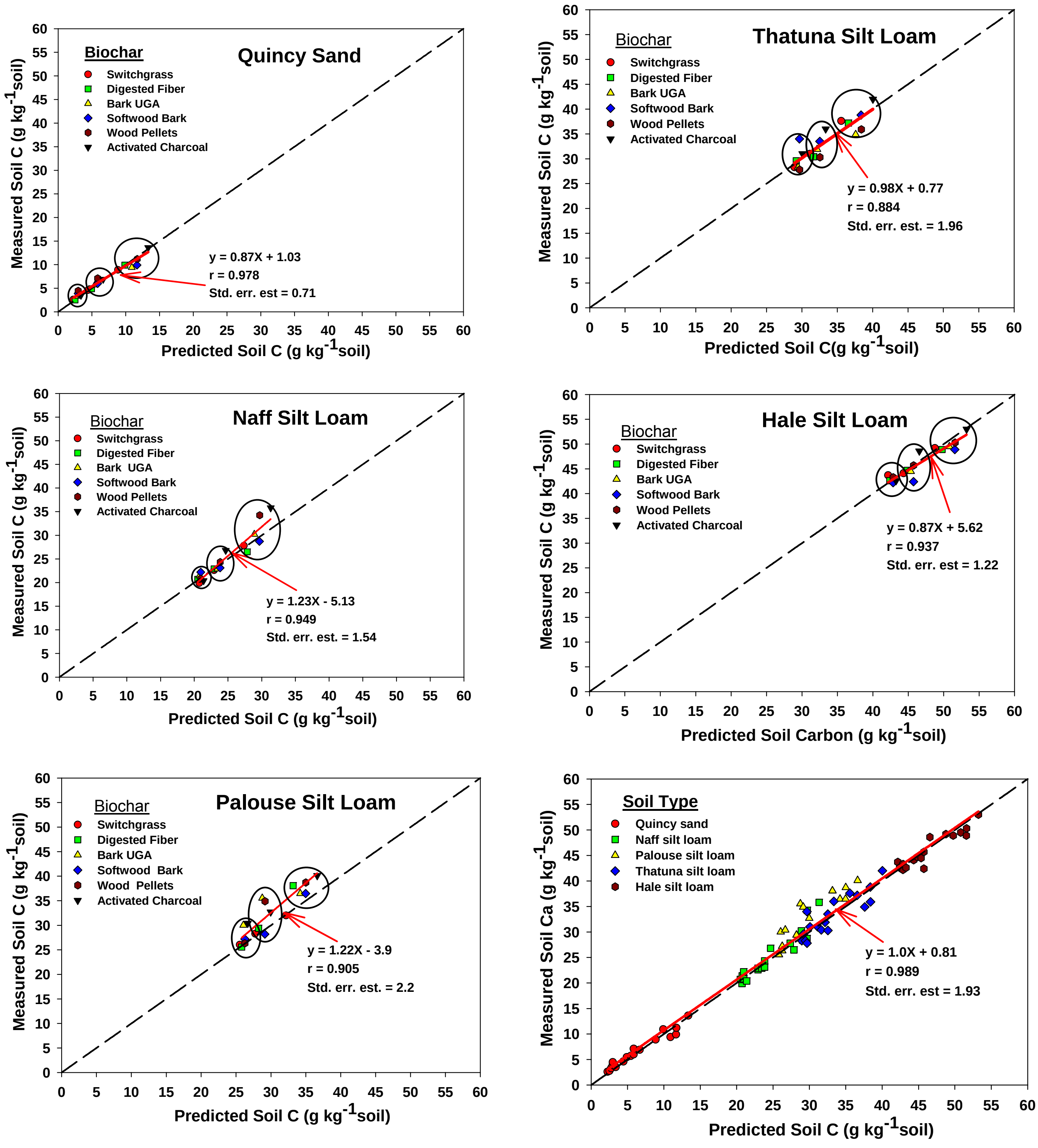


Figure 4.4. Comparison between the amount of C added in the biochar amendments and the amount of additional C measured in the soil after amendment. The consecutive circles indicate the biochar rate additions of 9.8, 19.5 and 39.0 Mg ha^{-1}, respectively.

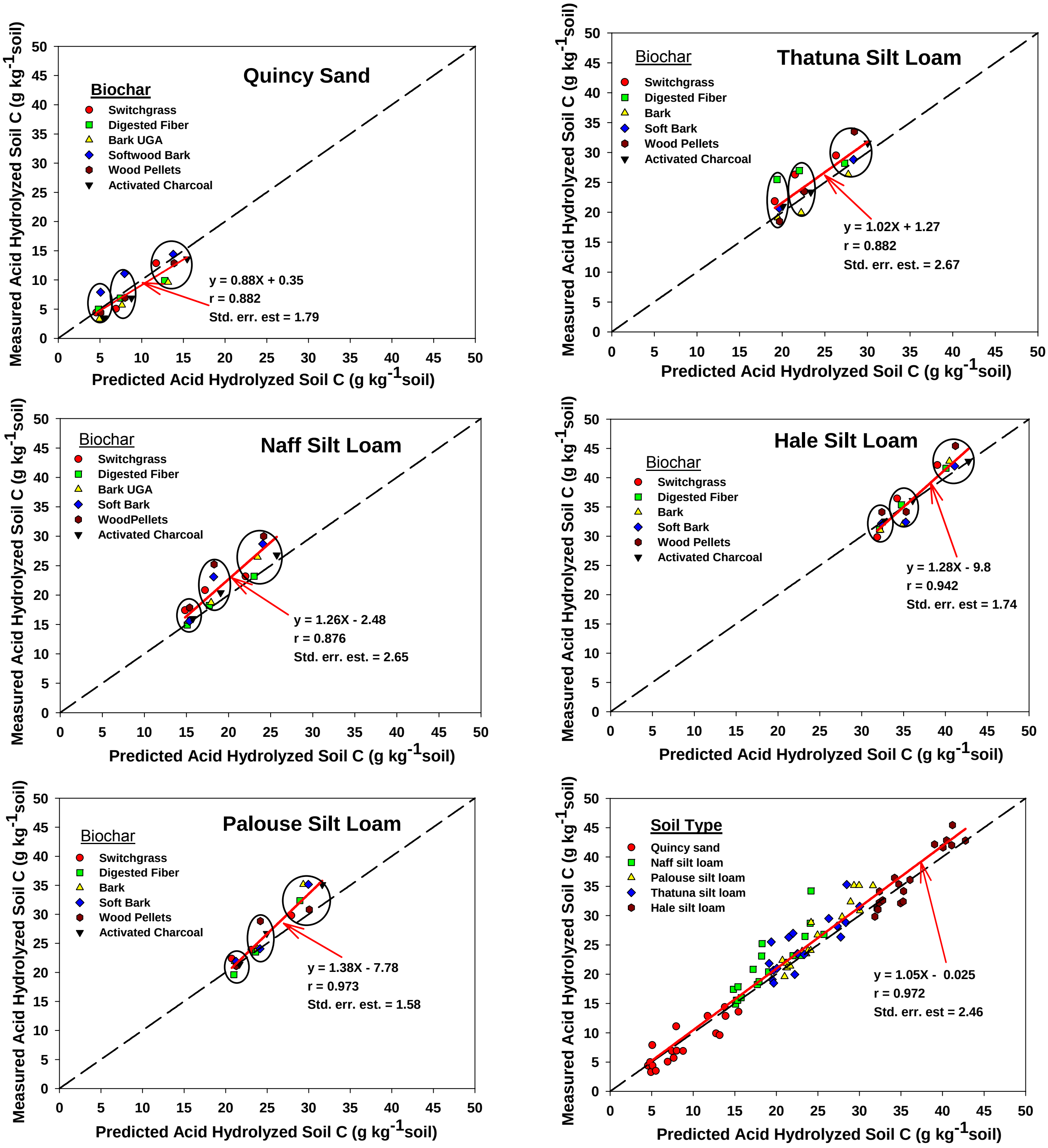
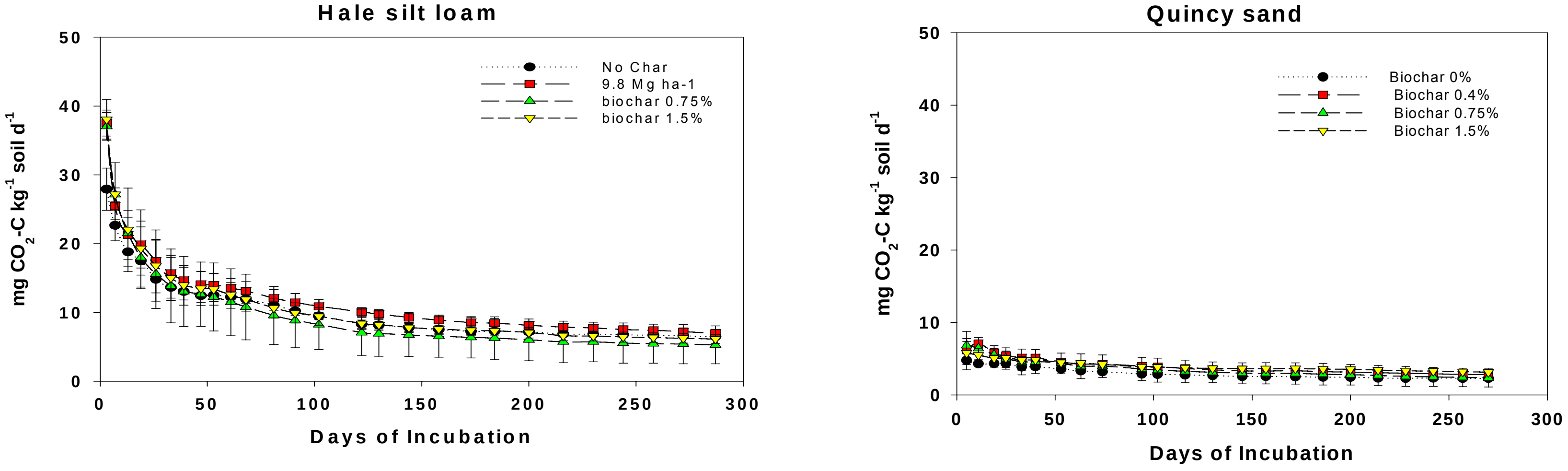


Figure 4.5. Comparison between the amount of C added in the biochar amendments and the amount of additional C measured in the soil after acid hydrolysis. The consecutive circles indicate the biochar rate additions of 9.8, 19.5 and 39.0 Mg ha^{-1}, respectively.

CARBON MINERALIZATION

PEANUT HULL BIOCHAR



ACTIVATED CHARCOAL

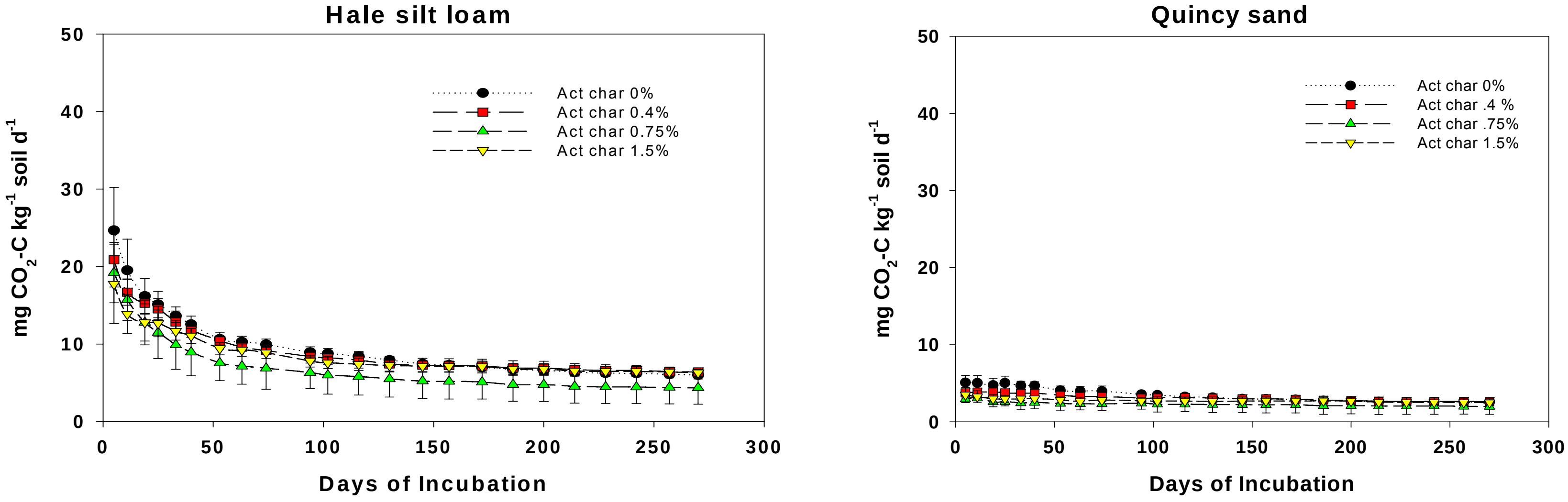


Figure 4.6. Soil C-mineralization rates for the Quincy sand and Hale silt loam soils incubated with peanut hull biocharand activated carbon amendment.

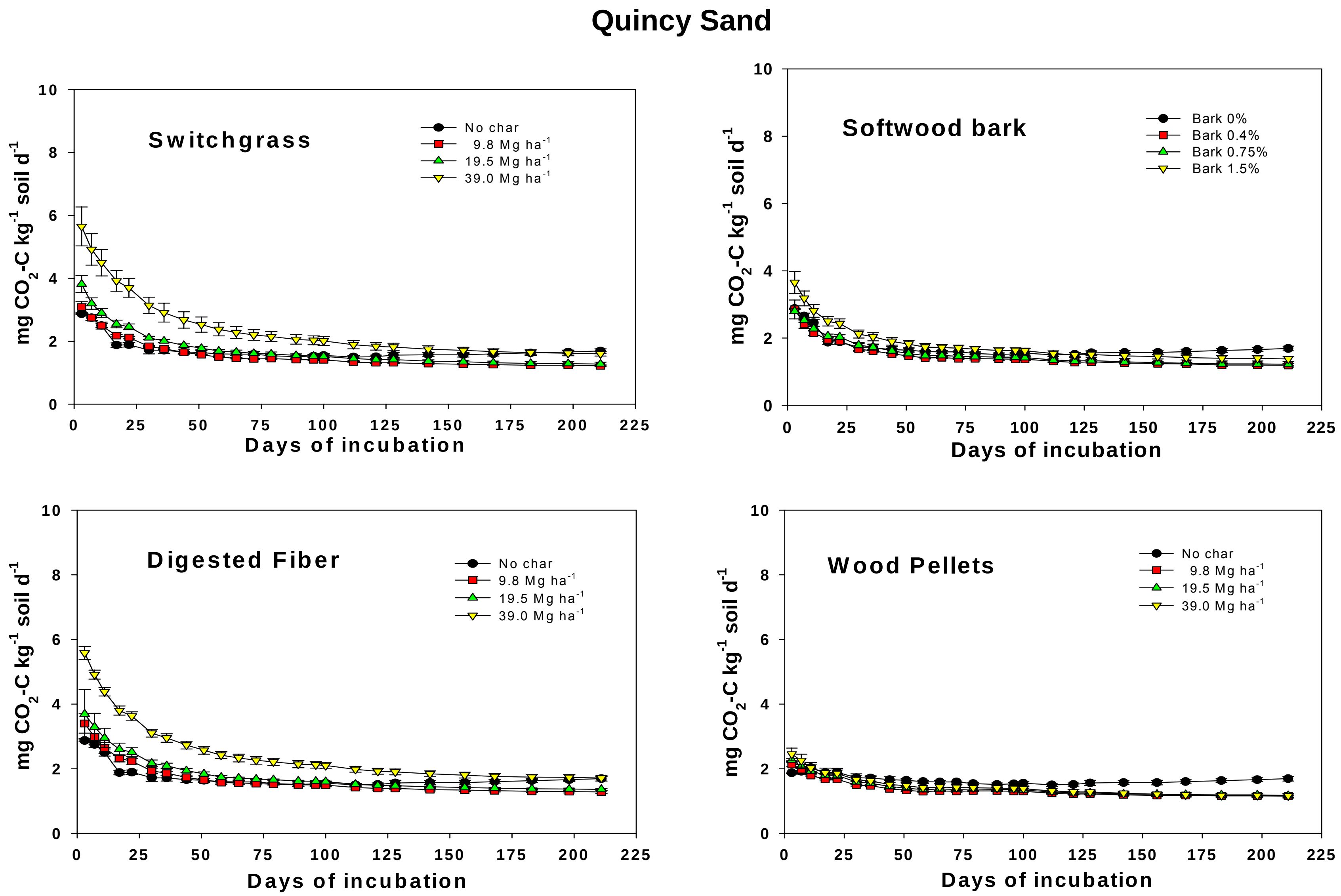


Figure 4.7. Soil C-mineralization rates for the Quincy sand incubated with biochar amendments. The biochars were made at a pyrolysis temperature of 500°C.

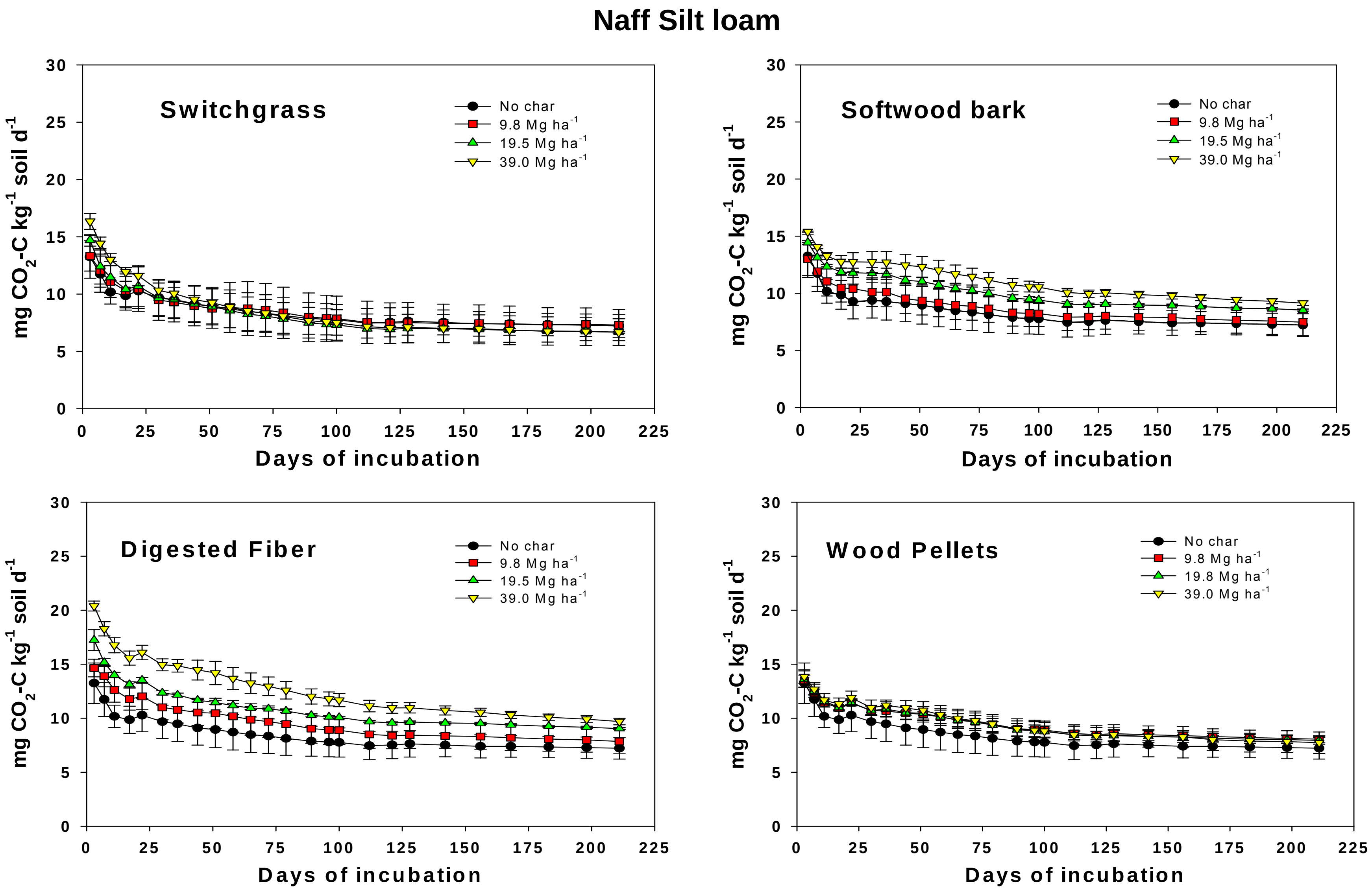


Figure 4.8. Soil C-mineralization rates for the Naff silt loam incubated with biochar amendments. The biochars were made at a pyrolysis temperature of 500°C.

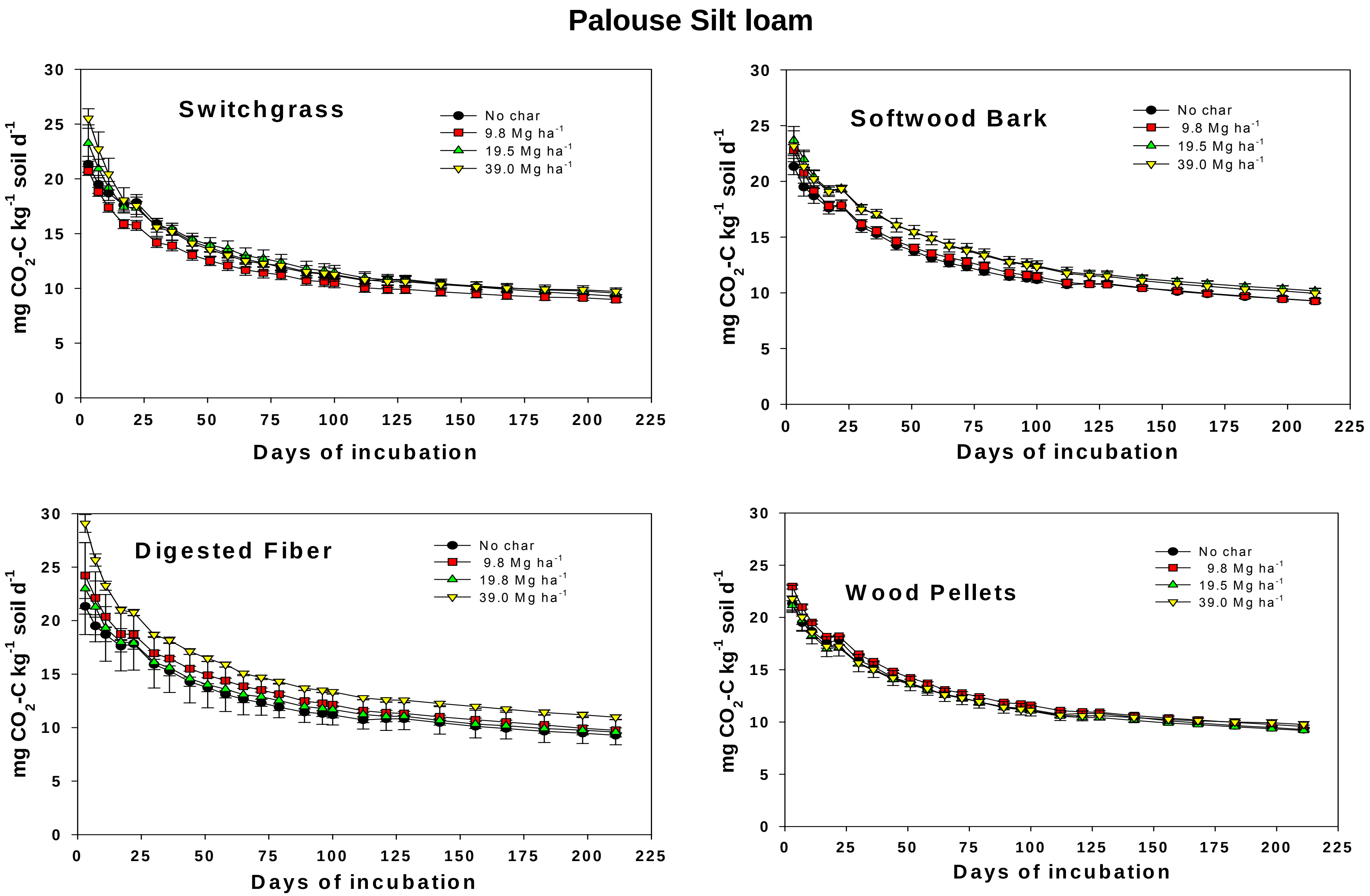


Figure 4.9. Soil C-mineralization rates for the Palouse silt loam incubated with biochar amendments. The biochars were made at a pyrolysis temperature of 500°C.

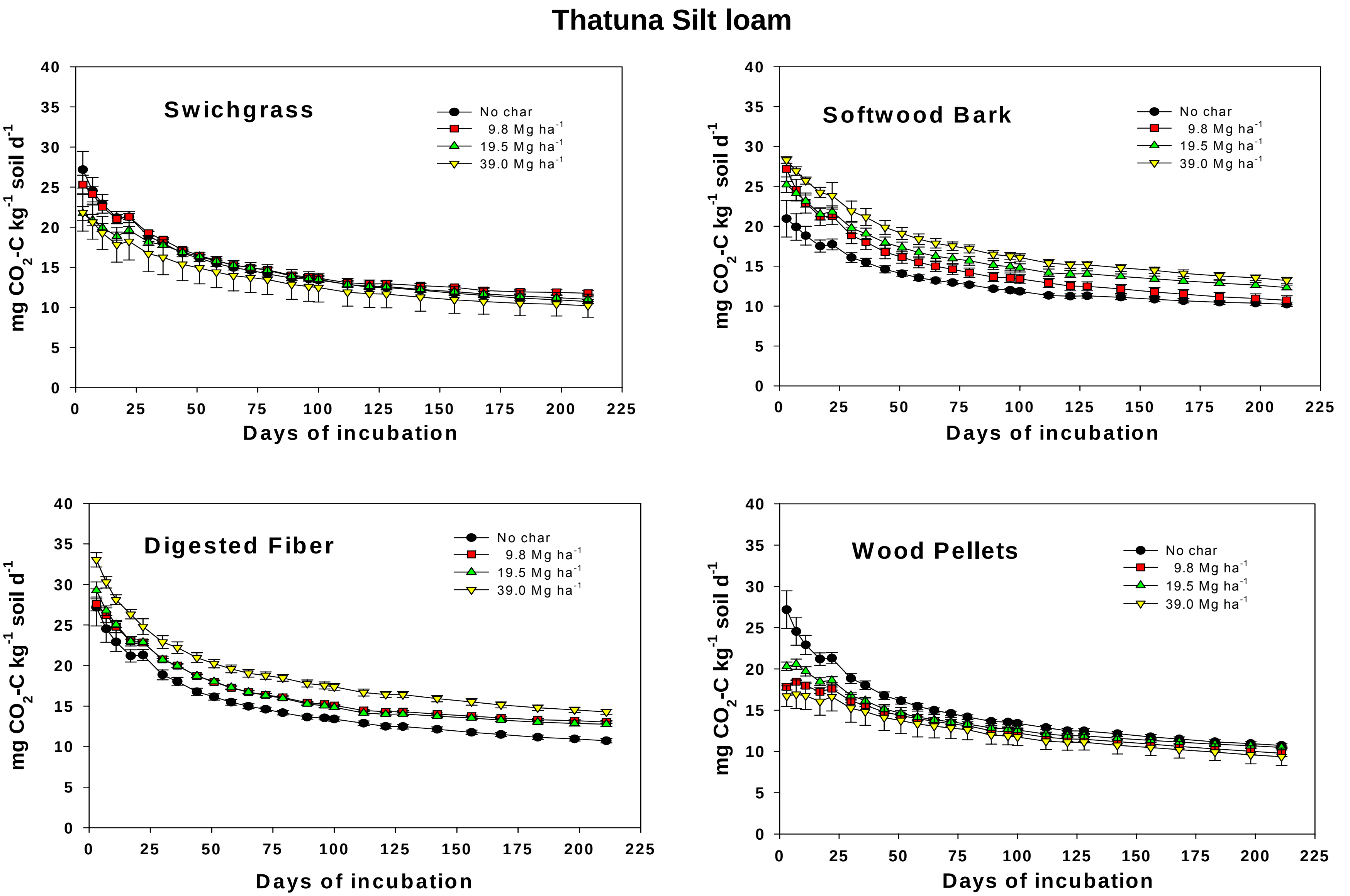


Figure 4.10. Soil C-mineralization rates for the Thatuna silt loam incubated with biochar amendments. The biochars were made at a pyrolysis temperature of 500°C.

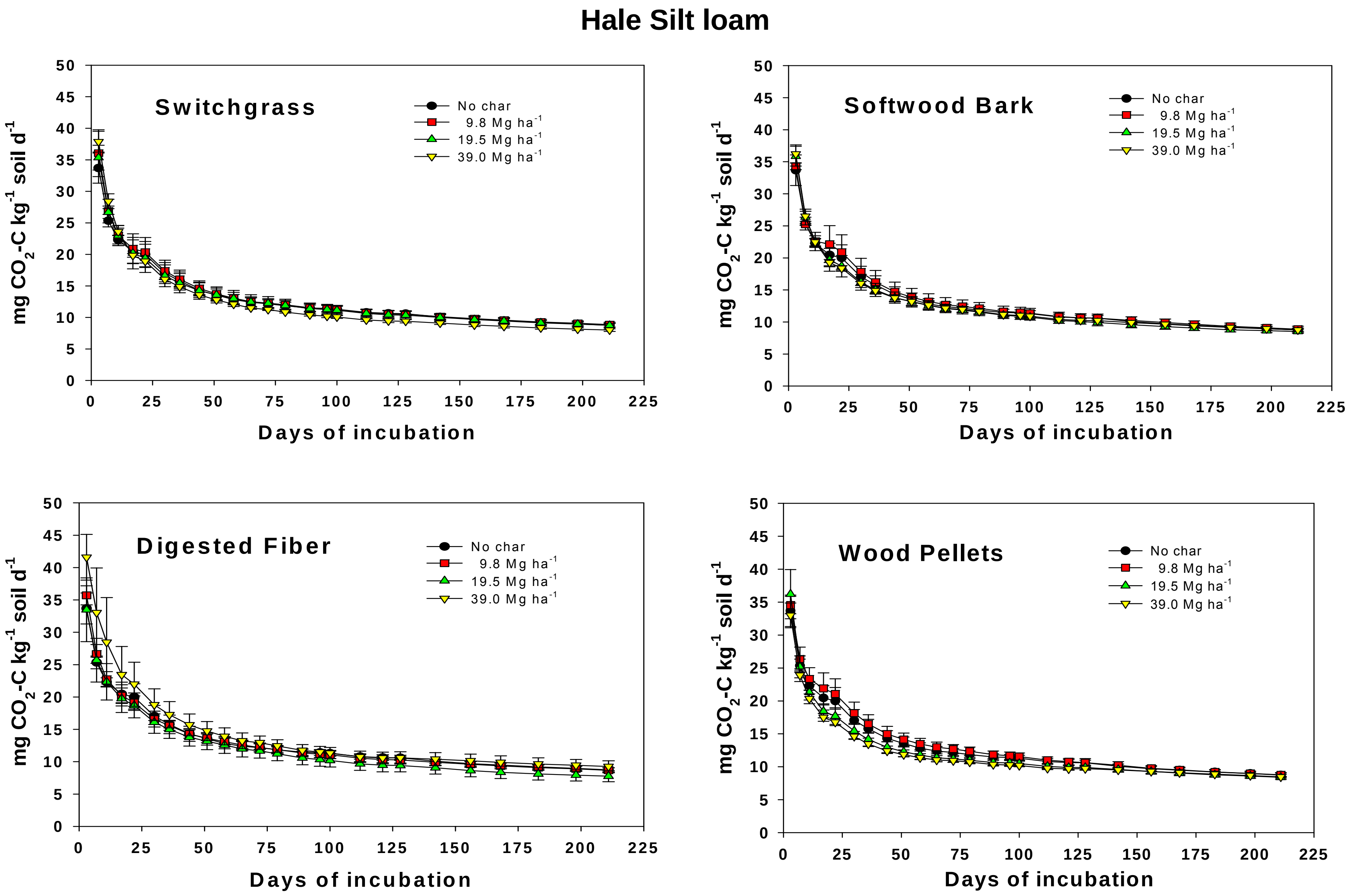


Figure 4.11. Soil C-mineralization rates for the Hale silt loam incubated with biochar amendments. The biochars were made at a pyrolysis temperature of 500°C.

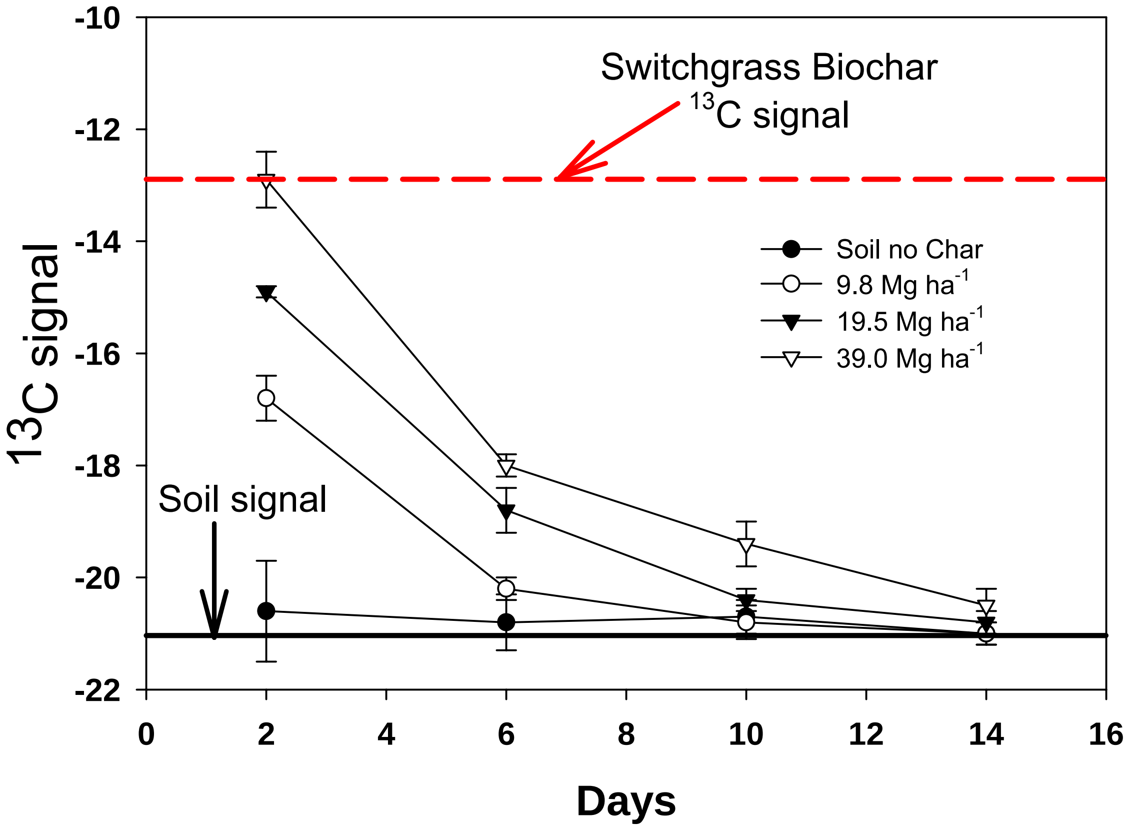


Figure 4.12. δ ^{13}C signals from soil, switchgrass biochar and soil biochar mixes. The dashed line represents the δ ^{13}C signal from the biochar and the solid line the background δ ^{13}C of the soil. The symbols represent the different rates of biochar additions. The signal within 14 days returns to the soil background indicating the majority of the initial flush of CO_2 originated from the biochar and not the native soil organic matter.

Table 4.11. Pool sizes and C-mineralization kinetics of soil for the active and slow C pools for the Quincy sand soil amended with 0, 9.8, 19.5 and 39 Mg ha^{-1} biochar.

		C-Mineralization		Active Pool			Slow Pool			Resistant Pool	
Cultivar	Rate	Cum. CO_2-C	C-min /SOC	C_a	Lab MRT	†Field MRT	C_s	Lab MRT	†Field MRT	C_r	C_r /SOC
	Mg ha^{-1}	mg kg^{-1}	(%)	mg kg^{-1}	------ d ------		mg kg^{-1}	------ y ------		mg kg^{-1}	%
Switchgrass	0	252 (15) a	5.9	19	11	28	2161	3.5	8.7	2120 (100) a	49.3
	9.8	258 (6) a	5.6	38	21	52	1952	3.7	9.1	4473 (120) b	69.6
	19.5	270 (13) a	4.0	50	21	52	1755	3.0	7.5	5989 (80) c	79.3
	39.0	337 (15) b	3.1	86	23	57	1344	2.8	7.0	12303 (560) d	89.1
Digested Fiber	0	252 (15) a	5.9	19	11	28	2161	3.5	8.7	2120 (100) a	49.3
	9.8	270 (10) ab	5.8	40	19	47	1946	3.4	8.6	4897 (400) b	70.8
	19.5	286 (6) b	4.1	49	22	54	1749	2.9	7.1	7169 (250) c	80.5
	39.0	361 (19) c	3.0	72	20	51	1343	2.8	7.0	11328 (960) d	90.0
Softwood Bark	0	252 (15) a	5.9	19	11	28	2161	3.5	8.7	2120 (100) a	49.3
	9.8	251 (11) a	4.8	28	17	43	2114	4.1	10.2	3300 (290) b	69.7
	19.5	258 (6) a	3.3	33	22	55	2072	3.9	9.8	5130 (370) c	78.4
	39.0	292 (17) b	2.4	43	20	49	1987	3.2	8.0	9610 (200) d	86.6
Wood Pellets	0	252 (15) a	5.9	19	11	28	2161	3.5	8.7	2120 (100) a	49.3
	9.8	242 (6) a	3.8	18	20	49	2143	4.4	11.0	4390 (870) b	70.3
	19.5	248 (11) a	2.9	23	23	56	2120	4.3	10.7	6940 (830) c	78.9
	39.0	245 (14) a	1.8	27	23	58	2078	4.1	10.2	12870 (2080) d	86.8

†MRT-Mean residence times converted to field rates using a Q_{10} of 2; $(2^{(25-t)/10})$; where t is mean annual temperature = 11.9°C. §Values followed by the same letter within a column by treatment are not significantly different at P=0.05. Values between treatments followed by “*” within a depth increment are significantly different at P=0.05.

Table 4.12. Pool sizes and C-mineralization kinetics of soil for the active and slow C pools for the Naff silt loam soil amended with 0, 9.8, 19.5 and 39 Mg ha^{-1} biochar.

		C-Mineralization		Active Pool			Slow Pool			Resistant Pool	
Cultivar	Rate	Cum. CO_2-C	C-min /SOC	C_a	Lab MRT	†Field MRT	C_s	Lab MRT	†Field MRT	C_r	C_r /SOC
	Mg ha^{-1}	mg kg^{-1}	(%)	mg kg^{-1}	------ d ------		mg kg^{-1}	------ y ------		mg kg^{-1}	%
Switchgrass	0	1645 (31) a	9.1	39	6	20	6424	1.7	5.2	11547 (600) a	64.1
	9.8	1690 (162) a	8.5	65	14	42	6208	1.8	5.6	16500 (1050) b	75.8
	19.5	1548 (84) a	6.8	118	19	59	5970	1.9	5.8	20820 (1580) c	82.5
	39.0	1407 (14) b	5.1	167	21	64	5546	1.7	5.3	22330 (1850) c	79.6
Digested Fiber	0	1645 (31) a	9.1	39	6	20	6424	1.7	5.2	11547 (600) a	64.1
	9.8	1658 (108) a	8.0	79	18	55	6190	1.6	4.9	14900 (1450) b	70.8
	19.5	1908 (21) b	8.3	54	9	28	6027	1.3	4.0	17500 (640) c	75.0
	39.0	2047 (64) c	7.7	47	7	21	5651	1.1	3.5	23190 (3960) d	83.4
Softwood Bark	0	1645 (31) a	9.1	39	6	20	6424	1.7	5.2	11547 (600) a	64.1
	9.8	1717 (63) ab	8.0	52	15	46	6373	1.8	5.5	15550 (940) b	71.0
	19.5	1800 (19) b	7.8	32	9	28	6356	1.5	4.6	18220 (650) c	75.9
	39.0	1927 (41) c	6.4	18	4	12	6295	1.3	4.0	26430 (2050) d	82.9
Wood Pellets	0	1645 (31) a	9.1	39	6	20	6424	1.7	5.2	11547 (600) a	64.1
	9.8	1700 (70) a	8.2	32	10	31	6412	1.6	5.0	17850 (1510) b	77.4
	19.5	1678 (73) a	6.9	52	17	54	6374	1.6	5.1	23730 (130) c	85.4
	39.0	1742 (108) a	5.1	95	33	102	6293	1.6	5.1	30040 (3090) d	83.4

†MRT-Mean residence times converted to field rates using a Q_{10} of 2; ($2^{(25-t)/10}$); where t is mean annual temperature = 8.7 °C. [§]Values followed by the same letter within a column by treatment are not significantly different at P=0.05. Values between treatments followed by “*” within a depth increment are significantly different at P=0.05.

Table 4.13. Pool sizes and C-mineralization kinetics of soil for the active and slow C pools for the Palouse silt loam soil amended with 0, 9.8, 19.5 and 39 Mg ha^{-1} biochar.

		C-Mineralization		Active Pool			Slow Pool			Resistant Pool	
Cultivar	Rate	Cum. CO_2-C	C-min /SOC	C_a	Lab MRT	†Field MRT	C_s	Lab MRT	†Field MRT	C_r	C_r /SOC
	Mg ha^{-1}	mg kg^{-1}	(%)	mg kg^{-1}	------ d ------		mg kg^{-1}	------ y ------		mg kg^{-1}	%
Switchgrass	0	1958 (32) ab	8.5	203	26	81	6111	1.2	3.6	16846 (100) a	72.7
	9.8	1895 (55) a	7.3	159	19	58	5965	1.2	3.8	22370 (5850) a	81.0
	19.5	2017 (70) ab	7.1	152	16	51	5787	1.0	3.2	23900 (4080) a	81.5
	39.0	2051 (67) b	6.4	178	14	44	5386	1.0	3.0	27770 (5380) a	84.7
Digested Fiber	0	1958 (32) a	8.5	203	26	81	6111	1.2	3.6	16846 (100) a	72.7
	9.8	2057 (47) b	8.1	176	19	60	5944	1.0	3.1	19600 (1940) ab	76.5
	19.5	2020 (253) ab	6.9	160	18	57	5772	1.0	3.2	23500 (2270) b	79.4
	39.0	2314 (49) c	6.1	140	11	35	5409	0.8	2.3	29960 (1620) c	80.8
Softwood Bark	0	1958 (32) a	8.5	203	26	81	6111	1.2	3.6	16846 (100) a	72.7
	9.8	1957 (51) a	6.5	200	23	70	6076	1.1	3.5	21880 (2150) b	74.0
	19.5	2143 (45) b	6.0	182	23	72	6057	1.0	3.1	23290 (1380) b	71.2
	39.0	2102 (97) ab	5.8	196	27	84	5968	1.0	3.1	29360 (2290) c	81.9
Wood Pellets	0	1958 (32) ab	8.5	203	26	81	6111	1.2	3.6	16846 (100) a	72.7
	9.8	2020 (30) bc	7.7	201	23	71	6094	1.1	3.5	21090 (1060) b	78.0
	19.5	1940 (32) a	5.6	195	25	77	6082	1.2	3.7	28840 (2000) c	80.6
	39.0	2062 (57) c	5.3	172	21	65	6067	1.1	3.6	30820 (2120) c	81.3

†MRT-Mean residence times converted to field rates using a Q_{10} of 2; ($2^{(25-t)/10}$); where t is mean annual temperature = 8.7 °C. §Values followed by the same letter within a column by treatment are not significantly different at P=0.05. Values between treatments followed by "*" within a depth increment are significantly different at P=0.05.

Table 4.14. Pool sizes and C-mineralization kinetics of soil for the active and slow C pools for the Thatuna silt loam soil amended with 0, 9.8, 19.5 and 39 Mg ha^{-1} biochar.

		C-Mineralization		Active Pool			Slow Pool			Resistant Pool	
		Cum.	C-min		Lab	†Field		Lab	†Field		C_r
Cultivar	Rate	CO_2-C	/SOC	C_a	MRT	MRT	C_s	MRT	MRT	C_r	/SOC
	Mg ha^{-1}	mg kg^{-1}	(%)	mg kg^{-1}	------ d ------		mg kg^{-1}	------ y ------		mg kg^{-1}	%
Switchgrass	0	2264 (57) a	8.4	388	30	93	10049	1.9	5.8	16423 (210) a	61.1
	9.8	2482 (67) b	8.8	333	31	96	9914	1.7	5.4	21830 (2060) b	70.8
	19.5	2317 (67) a	7.5	370	50	155	9692	1.8	5.6	26300 (2020) c	76.3
	39.0	2332 (32) a	6.2	314	37	116	9373	1.9	5.7	29460 (2340) c	75.6
Digested	0	2264 (57) a	8.4	388	30	93	10049	1.9	5.8	16423 (210) a	61.1
Fiber	9.8	2749 (37) b	9.3	293	27	83	9950	1.5	4.7	19390 (830) b	75.6
	19.5	2682 (65) b	8.8	296	24	73	9759	1.5	4.7	26970 (1700) c	78.4
	39.0	3013 (70) c	8.1	253	19	59	9419	1.3	4.0	28200 (230) c	74.8
Softwood	0	2264 (57) a	8.4	388	30	93	10049	1.9	5.8	16423 (210) a	61.1
Bark	9.8	2156 (120) a	7.6	386	29	90	10013	1.9	5.7	19460 (790) b	66.7
	19.5	2590 (71) b	8.1	266	25	78	10096	1.6	5.0	19950 (2080) b	65.3
	39.0	2787 (85) c	8.0	297	28	88	9990	1.4	4.5	26340 (1780) c	74.1
Wood	0	2264 (57) a	8.4	388	30	93	10049	1.9	5.8	16423 (210) a	61.1
Pellets	9.8	2064 (81) b	7.4	402	61	189	10016	2.2	6.8	18480 (1390) a	65.1
	19.5	2214 (32) a	7.3	294	4	11	10106	2.0	6.2	23460 (1550) b	72.7
	39.0	2054 (206) ab	5.7	423	71	220	9939	2.3	7.3	33350 (1990) c	79.7

†MRT-Mean residence times converted to field rates using a Q_{10} of 2; ($2^{(25-t)/10}$); where t is mean annual temperature = 8.7 °C. [§]Values followed by the same letter within a column by treatment are not significantly different at P=0.05. Values between treatments followed by "*" within a depth increment are significantly different at P=0.05.

Table 4.15. Pool sizes and C-mineralization kinetics of soil for the active and slow C pools for the Hale silt loam soil amended with 0, 9.8, 19.5 and 39 Mg ha^{-1} biochar.

		C-Mineralization		Active Pool			Slow Pool			Resistant Pool	
Cultivar	Rate	Cum. CO_2-C	C-min /SOC	C_a	Lab MRT	[†] Field MRT	C_s	Lab MRT	[†] Field MRT	C_r	C_r /SOC
	Mg ha^{-1}	mg kg^{-1}	(%)	mg kg^{-1}	------ d ------		mg kg^{-1}	------ y ------		mg kg^{-1}	%
Switchgrass	0	1844 (64) a	4.6	418	19	59	10282	2.3	7.1	29180 (990) a	73.2
	9.8	1866 (79) a	4.2	430	17	54	10080	2.2	6.8	30360 (110) a	72.2
	19.5	1844 (66) a	4.2	399	16	50	9926	2.2	6.7	34210 (1160) b	77.1
	39.0	1686 (45) b	3.5	449	15	47	9501	2.3	7.1	41050 (1770) c	82.0
Digested Fiber	0	1844 (64) a	4.6	418	19	59	10282	2.3	7.1	29180 (990) a	73.2
	9.8	1830 (81) a	4.3	399	16	49	10107	2.2	6.9	31170 (770) a	74.2
	19.5	1743 (66) a	3.9	462	20	62	9856	2.3	7.0	34190 (1340) b	76.8
	39.0	1863 (106) a	3.7	550	17	54	9385	2.0	6.1	41620 (1200) c	81.7
Softwood Bark	0	1844 (64) a	4.6	418	19	59	10282	2.3	7.1	29180 (990) a	73.2
	9.8	1873 (94) a	4.4	467	22	67	10195	2.3	7.0	31040 (1060) ab	74.1
	19.5	1795 (57) a	4.0	397	15	47	10228	2.3	7.3	32110 (670) b	74.4
	39.0	1845 (53) a	3.7	363	13	41	10187	2.3	7.0	41940 (1050) c	81.8
Wood Pellets	0	1844 (64) a	4.6	418	19	59	10282	2.3	7.1	29180 (990) a	73.2
	9.8	1854 (70) a	4.3	486	22	68	10195	2.2	7.0	34120 (3050) ab	76.9
	19.5	1774 (30) a	3.9	343	12	37	10320	2.4	7.4	35520 (2620) b	77.2
	39.0	1783 (81) a	3.5	314	12	38	10311	2.4	7.6	44870 (1360) c	83.3

†MRT-Mean residence times converted to field rates using a Q_{10} of 2; ($2^{(25-t)/10}$); where t is mean annual temperature = 9.6 °C. [§] Values followed by the same letter within a column by treatment are not significantly different at P=0.05. Values between treatments followed by "*" within a depth increment are significantly different at P=0.05.

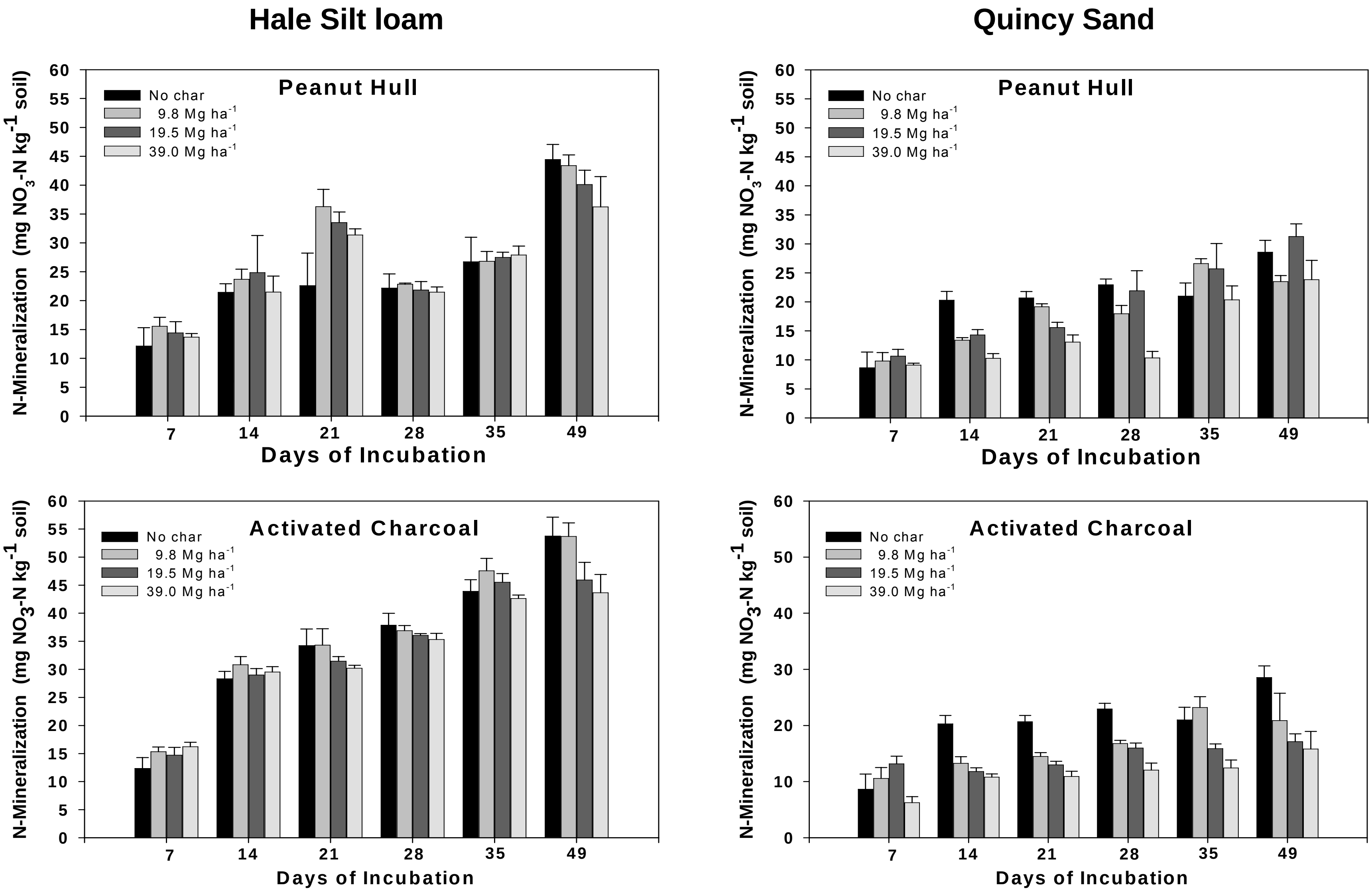


Figure 4.13. Soil N-mineralization rates for the Hale silt loam and Quincy sand incubated with peanut hull biochar and activated charcoal amendments. The biochar was made at the pyrolysis temperature of 500°C.

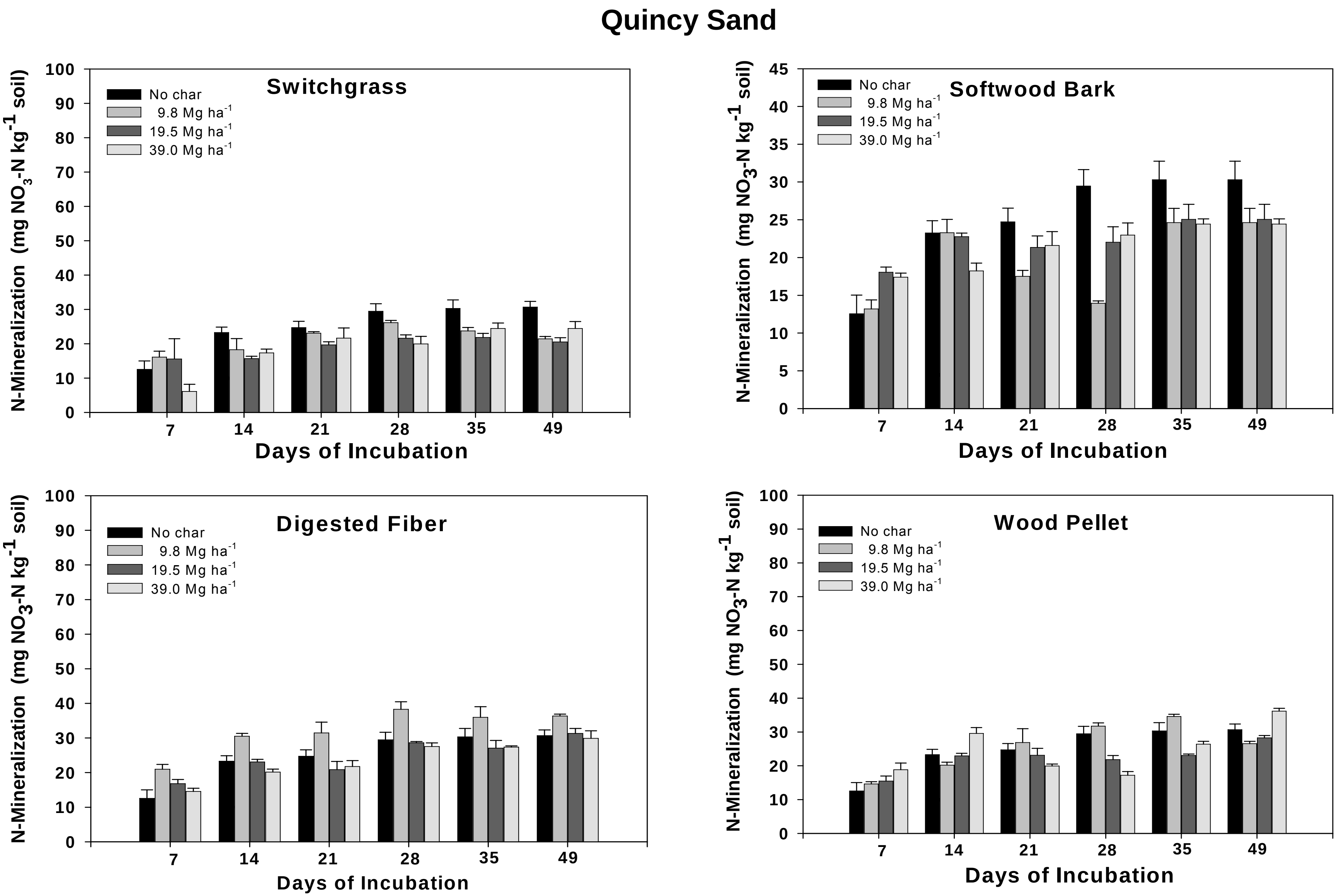


Figure 4.14. Soil N-mineralization rates for the Quincy sand incubated with biochar amendments. The biochars were made at the pyrolysis temperature of 500°C.

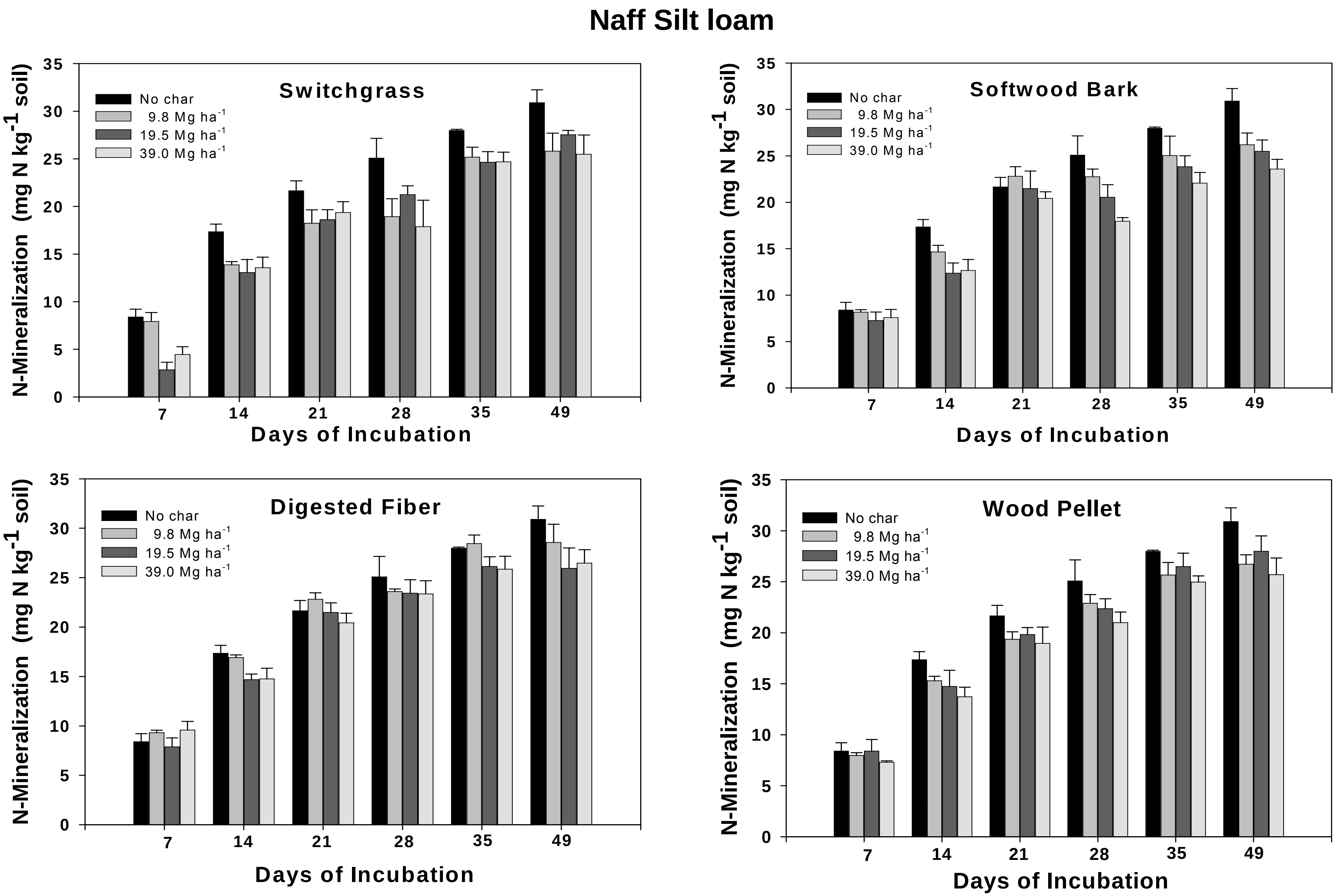


Figure 4.15. Soil N-mineralization rates for the Naff silt loam incubated with biochar amendments. The biochars were made at the pyrolysis temperature of 500°C.

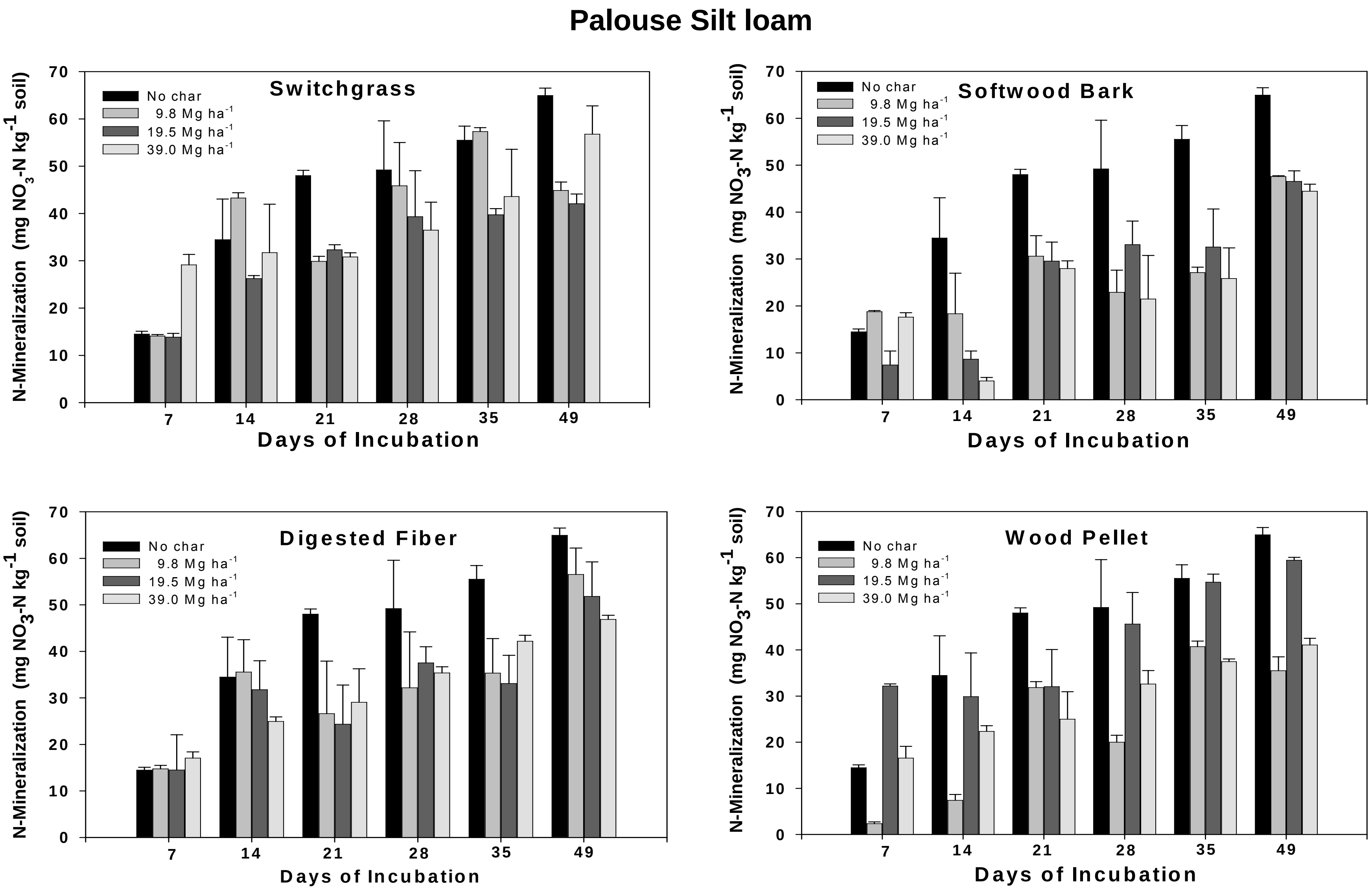


Figure 4.16. Soil N-mineralization rates for the Palouse silt loam incubated with biochar amendments. The biochars were made at the pyrolysis temperature of 500°C.

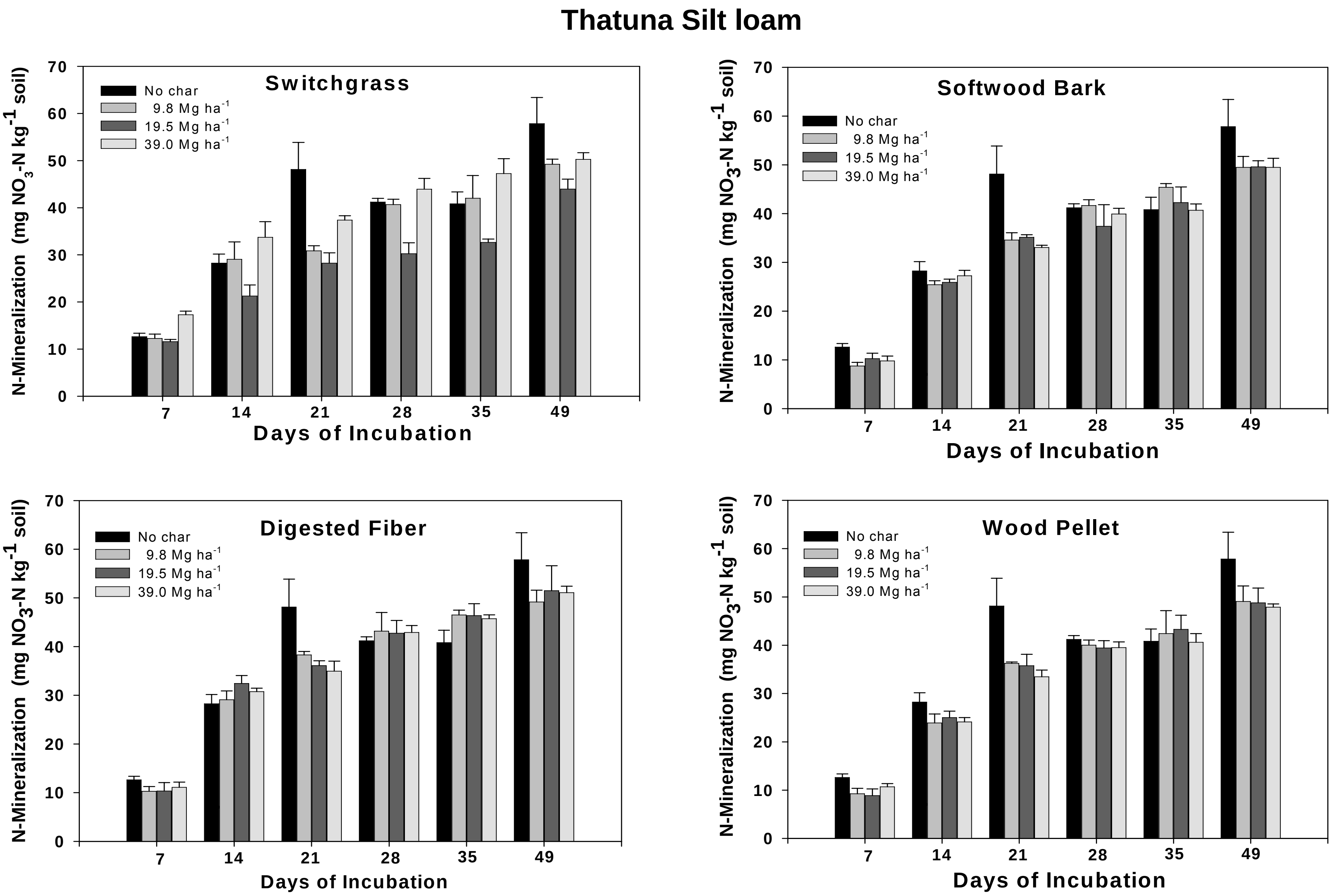


Figure 4.17. Soil N-mineralization rates for the Thatuna silt loam incubated with biochar amendments. The biochars were made at the pyrolysis temperature of 500°C.

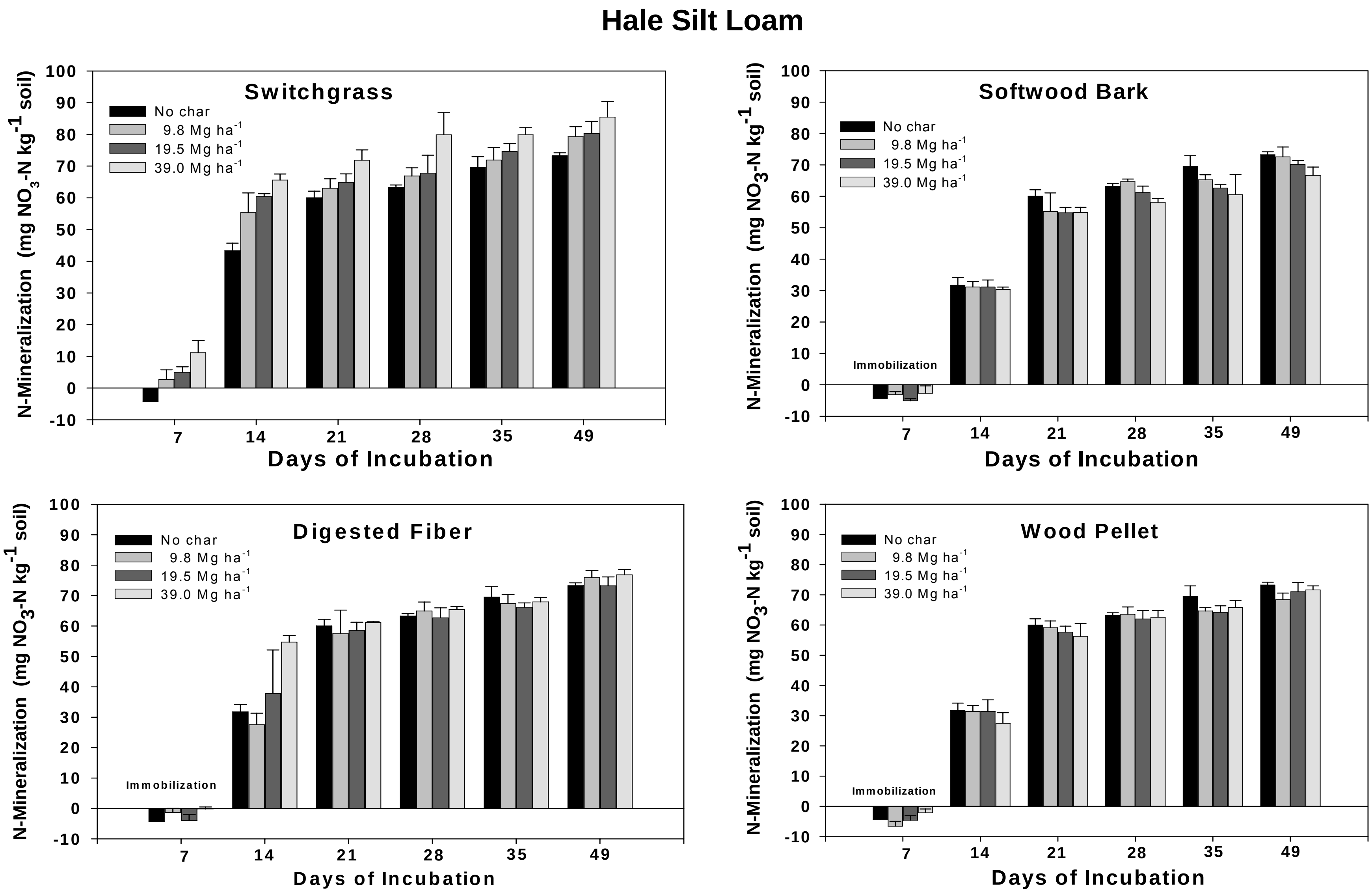


Figure 4.18. Soil N-mineralization rates for the Hale silt loam incubated with biochar amendments. The biochars were made at a pyrolysis temperature of 500°C.

Table 4.16. Wheat roots, shoots and root:shoot ratio after growth in soils amended with the softwood bark and wood pellets biochars.

Soil Series	Plant Characters					
	Biochar	†Rate	Root	Shoot	Total	R:S
		Mg ha^{-1}		--------- g ---------		
Quincy	Softwood bark	0	12.3 (3.6) a	10.3 (3.1) a	22.6 (5.0) a	1.19
		9.8	11.3 (3.6) a	10.3 (3.1) a	21.6 (5.9) a	1.10
		19.5	10.5 (3.8) a	12.2 (2.9) a	22.7 (5.9) a	0.86
		39.0	8.6 (3.5) a	9.1 (1.6) a	17.7 (5.0) a	0.95
	Wood pellets	0	18.5 (7.3) a	8.3 (1.8) a	26.8 (9.6) a	2.22
		9.8	14.0 (9.7) a	9.7 (2.5) ab	23.7 (11.7) a	1.44
		19.5	12.1 (5.5) a	12.4 (1.9) b	24.5 (7.1) a	1.00
		39.0	11.2 (3.1) a	8.2 (2.2) a	19.4 (4.5) a	1.37
Naff	Softwood bark	0	7.3 (1.5) a	5.1 (1.0) a	12.4 (1.8) a	1.43
		9.8	12.9 (3.8) b	4.9 (1.3) a	17.8 (4.9) a	2.63
		19.5	13.9 (4.4) b	5.9 (1.0) a	19.8 (4.8) a	2.36
		39.0	12.6 (5.7) ab	3.8 (1.5) a	16.4 (6.2) a	3.32
	Wood pellets	0	7.3 (1.5) a	5.1 (1.0) a	12.4 (1.8) a	1.43
		9.8	5.0 (1.6) ab	4.7 (1.1) a	9.8 (2.3) a	1.06
		19.5	6.1 (1.0) ab	7.0 (0.7) b	13.1 (1.6) a	0.87
		39.0	4.6 (1.0) b	4.0 (1.6) a	8.6 (2.4) a	1.15
Palouse	Softwood bark	0	8.7 (2.1) a	6.8 (1.3) a	15.5 (3.0) a	1.28
		9.8	8.4 (2.9) a	7.0 (1.2) a	15.3 (3.2) a	1.20
		19.5	11.8 (3.4) a	12.3 (1.7) b	24.1 (4.5) b	0.96
		39.0	8.6 (2.2) a	8.7 (2.2) ab	17.4 (4.2) ab	0.99
	Wood pellets	0	11.7 (2.5) a	4.8 (1.0) a	16.6 (3.2) a	2.44
		9.8	10.0 (2.3) a	4.3 (1.0) a	14.3 (2.8) a	2.33
		19.5	13.2 (3.0) a	7.0 (1.9) a	20.2 (4.8) a	1.88
		39.0	9.3 (2.0) a	4.0 (1.2) a	13.4 (2.8) a	2.33
Thatuna	Softwood bark	0	14.8 (2.4) a	4.8 (1.4) a	19.6 (4.6) a	3.10
		9.8	19.4 (6.4) a	5.7 (1.3) a	24.1 (7.8) a	3.40
		19.5	24.5 (8.6) a	7.9 (2.9) a	32.4 (11.3) a	3.10
		39.0	15.6 (4.9) a	4.7 (1.2) a	20.3 (5.3) a	3.32
	Wood pellets	0	10.9 (2.4) ab	4.8 (1.4) a	15.7 (3.5) ab	2.27
		9.8	10.2 (2.9) ab	5.1 (1.2) a	15.3 (3.8) ab	2.00
		19.5	14.6 (4.4) a	7.6 (1.1) b	22.1 (5.1) a	1.92
		39.0	6.7 (1.8) b	4.6 (1.0) a	11.3 (2.5) b	1.46
Hale	Softwood bark	0	10.1 (3.9) a	7.3 (2.7) a	17.4 (5.4) a	1.38
		9.8	11.4 (2.6) a	9.1 (1.5) a	20.5 (3.5) a	1.25
		19.5	12.9 (3.0) a	11.6 (2.6) a	24.5 (5.2) a	1.11
		39.0	10.3 (2.8) a	9.1 (2.6) a	19.4 (5.1) a	1.13
	Wood pellets	0	10.1 (3.9) a	7.3 (2.7) a	17.4 (5.4) a	1.38
		9.8	9.3 (1.6) a	6.3 (2.1) a	15.6 (3.0) a	1.48
		19.5	11.3 (4.7) a	7.5 (1.5) a	18.9 (5.8) a	1.51
		39.0	9.7 (2.2) a	5.2 (1.4) a	14.9 (2.2) a	1.86

‡Std. error of mean in parentheses. Statistical comparisons were not made among biochars because the wheat was not grown at the same time. Values for a biochar within a column followed by the same letter are not significantly different at p = 0.05.

Table 4.17. Effect of biochar and activated charcoal amendment on binding of herbicides in soil.

Treatment	Biochar added	Herbicide Atrazine	Metribuzin
	(lb/ac)	------ % Bound ------	
Soil only		3.72	4.43
Act. charcoal	200	87.25	60.71
Biochar	200	3.72	3.99
Biochar	2000	10.42	7.92
Biochar	10000	30.71	17.76
Biochar	20000	56.39	32.08

Boydston, R., et al. 2009. Unpublished data.

BIOCHAR ECONOMICS

Chapter 5 focuses on the tradeoffs in the joint production of biochar and bio-oil. The pyrolysis process converts the feedstock into three main products – biochar, bio-oil and gas. The gas is generally used as an energy source for sustaining the pyrolysis process. Biochar and bio-oil are the primary marketable products. This chapter estimates graphically the relationship (called a production transformation curve) between the production of biochar and bio-oil as a function of pyrolysis temperature, pyrolysis type, and feedstock type. The analysis facilitates the selection of the optimal pyrolysis temperature for a given set of relative biochar and bio-oil market prices.

Chapter 6 extends Chapter 5, and examines the economic feasibility of biochar and bio-oil production at commercial scale using wood from forest thinning. The analysis is based on an enterprise budget accounting approach. An enterprise budget presents estimates of revenues (income), costs, and profits associated with the production of a particular product. The results suggest that market prices of biochar (and/or bio-oil) must be quite high for smaller-scale enterprises to be economically sustainable.

Chapter 7 focuses on the potential economic value of biochar application on farms for carbon sequestration, assuming a carbon trading mechanism for biochar C sequestration is established.

Note: As used in the next three chapters, ‘tons’ refers to metric tons [~2204.62 lb or 1000 kg, also called 1 megagram (Mg)]. A U.S. ton is 2000 lb, sometimes called a short ton.

Chapter 5. ECONOMIC TRADEOFF BETWEEN BIOCHAR AND BIO-OIL PRODUCTION VIA PYROLYSIS.

This chapter examines some of these economic tradeoffs in the production of biochar and bio-oil. The pyrolysis process can be performed with different final temperatures, and with different heating rates. Varying these and other factors can change the relative quantity and quality of biochar and bio-oil produced for a given feedstock. These changes in quantity and quality of both products affect the potential revenue from their production and sale. We estimate quadratic production functions for biochar and bio-oil as the basis of our economic analysis. The results are then used to calculate a relationship (called a product transformation curve, which plots the largest yields of bio-oil and biochar that can be produced for a given amount of feedstock; movement along the curve corresponds to changes in temperatures) that can be used to infer optimal pyrolysis temperature settings for a given ratio of biochar and bio-oil prices. In a pyrolysis process, feedstock biomass is consumed to produce three outputs: biochar, bio-oil, and gases. The gases are produced from the feedstock, but then immediately consumed to sustain the heating process. We assume here that all of the gas produced via pyrolysis is subsequently consumed as an energy source for the pyrolysis process itself. Data available from published studies provided us with the percentage of biochar, bio-oil, and gas, by mass, produced under a given temperature for a given amount of feedstock.

5.1. Non-technical chapter summary.

High final heating temperatures provide more bio-oil and less biochar from a given amount of feedstock, and low final heating temperatures provide more biochar and less bio-oil. Similarly, fast pyrolysis, characterized by fast heating rates, provides more bio-oil and less biochar than slow pyrolysis (with slow heating rates). Furthermore, for a given feedstock type, the quality of both bio-oil and biochar depends in part on temperature. If producers can receive high prices for bio-oil but receive low prices for biochar, then they can increase sales revenue if they produce bio-oil at the expense of biochar by choosing a temperature and a heating rate that best suits these market price conditions. This chapter provides a framework for choosing the optimal final temperature and heating rate (fast or slow) for a given market setting, and provides some examples for use.

In section 5.2 we provide a conceptual model for maximizing revenue with two products, bio-oil and biochar. Using this model we develop a decision rule that provides the optimal temperature for a given set of biochar and bio-oil market prices. We also consider the case in which market prices for a given quantity of bio-oil and biochar depend on the quality of these products.

In order to use the model, the production relationships between temperature and both bio-char and bio-oil must be estimated. That is, an estimate is required of how much bio-oil and biochar are produced for a given final pyrolysis temperature. Data collected from a number of published studies were used in conjunction with primary data generated through this project. Standard statistical regression methods were used to estimate these production relationships.[1]

The estimated production relationships show that as final pyrolysis temperature increases, the amount of biochar produced declines. In contrast, as final temperature increases, the amount of bio-oil increases to a point (about 525-550^{o}C), and then begins to decline. These relationships are shown in Figure 5.3. Used together, these two production relationships provide a formula for choosing the revenue maximizing temperature for a pair of bio-oil and bio-char prices. This relationship between prices and optimal final heating temperature is illustrated in Figure 5.5 for both fast and slow pyrolysis.

The price of biochar could vary significantly depending on the market. For example, if a market supports the production of biochar at a break-even price of $600 per ton (based on an initial enterprise budget), this translates to $0.60 per kg. If we assume $1.00 per gallon of bio-oil, this translates to $0.22 per kg of bio-oil. The result is a price ratio of bio-oil to biochar of 0.37, suggesting heavy emphasis on low temperature slow pyrolysis (at or around a minimum acceptable final temperature of 350°C). In contrast, if biochar is of relatively little value, say $50 per ton, then the price ratio is 4.4, suggesting that fast pyrolysis at higher temperatures (about 522°C) is optimal. Biochar yield declines from about 40% of the original dry feedstock mass at 350^{o}C to 26% at 540^{o}C for slow pyrolysis. For fast pyrolysis, it declines from 32% to 18% for the same temperature range.

Temperature not only affects the quantity of biochar and bio-oil produced from a given quantity of feedstock, but the quality of these products changes depending on temperature as well. Generally speaking, the quality of both products is low for temperatures lower than about 350°C, and generally increases up to some point (depending on end use) as temperature increases. If market prices are different in response --- higher for higher quality products and lower for lower quality products --- then this will affect the optimal heating temperature as well. We provide an example of optimal heating temperature based on the assumption that bio-oil and biochar will both be used, and valued, for their energy content. For the price response function, we estimate the linear relationship between pyrolysis temperature and the energy content of the two products. In this example, the optimal temperature is relatively high for both fast and slow pyrolysis, in part because of the revenue gains from quality improvements. For slow pyrolysis, the revenue maximizing temperature is 536°C. The optimal estimated yield and price for biochar are 26% and $0.077/kg, and for bio-oil optimal yield and price are 38% and $0.192/kg. Maximum revenue for slow pyrolysis is $0.09296/kg ($92.96/metric ton) of dry forest-based feedstock. For

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[1] The data and data source references are available as an Excel spreadsheet at www.ecy.wa.gov/beyondwaste/organics.

fast pyrolysis the estimated optimal temperature is 522^{o}C. Biochar yield is 19.8%, and bio-oil yield is 54%. Biochar price is $0.076/kg, and bio-oil price is $0.19/kg. Maximum revenue is $0.11848/kg ($118/metric ton). So, based on energy content, fast pyrolysis provides higher revenues by $0.0255/kg; higher by 27%.

The basic take-home message of this chapter is that increasing pyrolysis temperatures tends to lead to more and better bio-oil and less biochar --- up to a point. Lower final temperature and slow pyrolysis provide more biochar and less bio-oil (of perhaps lower quality), and therefore provide higher revenues when biochar prices are high and bio-oil prices are low. In contrast, if bio-oil prices are high and biochar prices are low, then fast pyrolysis at high temperature will lead to higher revenues. In either case, there is an optimal temperature to be found. The remainder of this chapter and Appendix C provide the technical details that support the above synopsis.

This chapter primarily provides tools for optimizing pyrolysis temperature and type subject to economic conditions including price conditions and feedstock characteristics. There are three potential levels of using the information in this chapter. First, the specific graphical results and cases can be used for developing an informal (“back of the envelope”) understanding of the economic relationships between temperature pyrolysis type, and feedstock. A second level is to use the actual equations estimated and presented in this chapter and Appendix C to provide an estimated optimal temperature for the conditions under which producers find themselves. And finally, the general mathematical and statistical methods can be used along with a producer’s own process data to refine the results and improve revenues for their specific enterprise.

5.2. Economic foundations.

Although the quality of the biochar and bio-oil will change according to the final pyrolysis temperature, as well as the heating rate, data in published studies generally do not include quality characteristics. However, a few studies include data on the heating value of biochar and bio-oil as a function of temperature. So we perform two types of analyses: we first provide an analysis in which quality characteristics are not accounted for, and then extend the analysis to allow for prices to change according to changing product quality (called endogenous prices), which in turn depends on temperature.

Given that temperature is a primary variable of choice in the pyrolysis process, we focus on choosing the optimal temperature for a given set of prices, conditional on the type of process (fast or slow pyrolysis) and the type of feedstock being used.[2] Below we develop a two product

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[2] For a given temperature, the bio-oil and biochar yields as a percentage of biomass will tend to be independent of the scale of production. This characteristic allows the production relationships estimated in this

objective, to maximize the sum of the revenues from the two outputs (bio-oil and biochar) minus the input costs, by choosing temperature:

$$\max_{T} V = P_c C(T,\mathbf{Z}) + P_L L(T,\mathbf{Z}) - K \quad , \qquad (1)$$

where V is net value of production, T is final temperature, P_C and P_L are biochar price and bio-oil price respectively, $\mathbf{Z}$ is a vector (a set) of other factors affecting yield, $C(\cdot)$ and $L(\cdot)$ are production functions relating T and $\mathbf{Z}$ to biochar yield (C) and bio-oil yield (L) respectively, and K is a fixed cost of production per unit of feedstock (feedstock cost), which may include market purchase of supplemental energy to sustain the pyrolysis process.[3]

As temperature increases, biochar quantity decreases, but bio-oil increases up to a point, then declines. Thus, an increase in temperature increases bio-oil revenues at the expense of biochar revenues. To maximize revenue, temperature should be increased to the point at which the increase in revenue from bio-oil no longer outweighs the revenue losses from biochar with an increase in temperature. In other words, the temperature that maximizes V in equation (1) is that which equates the marginal revenue gains from bio-oil to the revenue losses from biochar.[4]

This condition is shown graphically in Figure 5.1. The curved line is the *product transformation curve* (PTC). Any point on this line represents the output of biochar (on the vertical axis) and bio-oil (on the horizontal axis) that will be produced from pyrolysis at a given temperature for a given feedstock quantity and type. An increase in temperature will lead to a movement along this line down and to the right, providing more bio-oil and less biochar. The straight line from axis to axis in Figure 5.1 is an *isorevenue line*. This is the set of combinations of biochar and bio-oil that provides a given total revenue for a given pair of biochar and bio-oil prices.[5] A combination that provides the highest possible revenue for a unit of feedstock is provided by the specific combination where the product transformation curve is tangent with the isorevenue line. In Figure 5.1, C_1^* and L_1^* is the optimal combination of yields for the price ratio shown. The dotted (partial) isorevenue line implies a higher bio-oil price relative to biochar price, and is associated with a higher optimal bio-oil yield (L_2^*) and lower biochar yield C_2^*.

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chapter to be applicable to larger pyrolysis units. Although it does not mean that the pyrolysis process is scale independent in terms of optimal total production output and profitability, it does imply that the optimal pyrolysis temperature is independent of scale.

[3] The analysis in Chapter 6 allows for some of the bio-oil and/or biochar to be used to help sustain the pyrolysis process. We do not assume this here, but the opportunity cost of bio-oil or biochar from a previous period of pyrolysis production is equal to the value it could accrue for an alternative use, which might be its sale for a market price.

[4] The mathematical treatment of this condition is provided in Appendix **C.**

[5] If revenue is $R = P_C C + P_L L$, rearranging this with C alone on the left hand side provides the line $C = \frac{R}{P_C} - \frac{P_L}{P_C} L$. This is the straight line from axis to axis in Fig. 5.1, with intercept R/P_c and slope of $-P_L/P_C$.

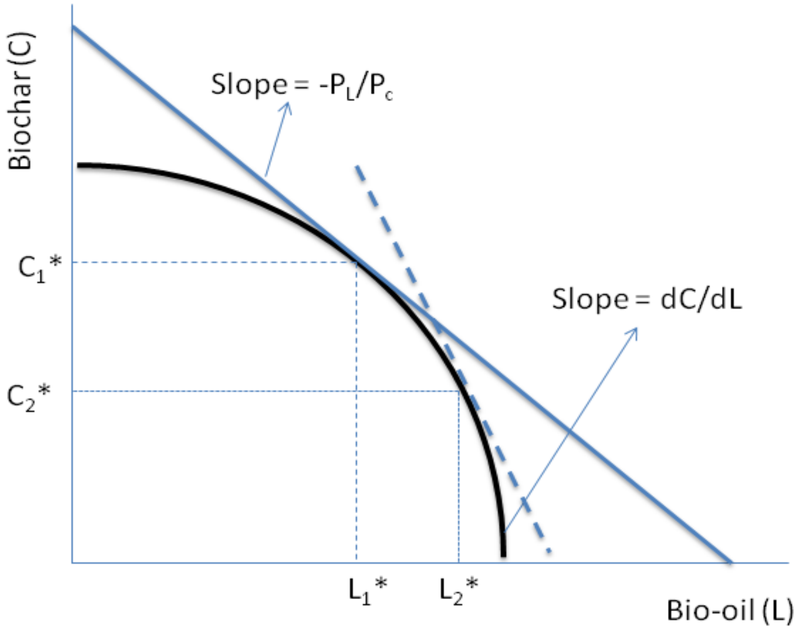

Figure 5.1. Optimal combination of biochar (C_1*) and bio-oil (L_1*) yield for prices P_L and P_C. Higher oil price P_L relative to char price Pc (dotted isorevenue line) leads to higher optimal yields of bio-oil relative to biochar.

In the discussion above, bio-oil and biochar prices do not depend on temperature. This is economically equivalent to assuming that the quality does not vary in terms of economic value over the feasible temperature range, or at least, that market prices would not vary according to quality. This may be a misleading assumption in some cases. For example if energy content is the basis for economic value, both bio-oil and biochar increase in energy value as pyrolysis temperature increases over the relevant temperature range. In general, if the price increases with temperature, there is an additional revenue gain from each incremental temperature increase. This means that for otherwise similar circumstances, the incremental price increase will tend to push the optimal temperature higher than if prices were fixed and constant.[6] In the production setting under consideration here, the combination of *C* and *L* are chosen indirectly by choosing the temperature at which pyrolysis is performed, and the pair of production relationships *C(T)* and *L(T)* imply a product transformation curve between *C* and *L*. At this point, specific equations representing the relationships between process factors (temperature, feedstock, heating rate, etc.)

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[6] The mathematical treatment of this problem is provided in Appendix C.

and the two products (biochar and bio-oil), are necessary to proceed. Regression analysis is applied to the data we collected from published research on pyrolysis.

5.3. Econometric model and yield function estimation.

A large literature exists for estimating production functions for application to economic problems. This literature provides a wide range of production relationships and estimation methods, ranging from restrictive to highly flexible functions to represent (global or local) production relationships, and restrictive to highly flexible estimation methods.[7] After exploratory analysis, given the limited published data on biochar and bio-oil, and to provide a practical foundation for interpretation, this analysis relies on a relatively simple quadratic production relationship between the input (temperature) and the outputs (biochar and bio-oil).[8]

The regression model used can be represented in general as:

$$C(T_i) = \boldsymbol{\alpha}_0' \boldsymbol{Z}_i + \alpha_1 T_i + \alpha_2 T_i^2 + \varepsilon_i \qquad \text{(2a)}$$

$$L(T_i) = \boldsymbol{\beta}_0' \boldsymbol{Z}_i + \beta_1 T_i + \beta_2 T_i^2 + \nu_i \qquad \text{(2b)}$$

where *i* is an observation index, $[\boldsymbol{\alpha}_0 \quad \alpha_1 \quad \alpha_2]$ and $[\boldsymbol{\beta}_0 \quad \beta_1 \quad \beta_2]$ are parameters to be estimated (bold represents a vector containing several parameters); $C(T_i)$, and $L(T_i)$ are biochar and bio-oil yield for observation *i*, respectively; T_i, and $\boldsymbol{Z}_i$ are factors that affect yield; and ε_i and ν_i are random disturbance terms. Using T_i and the square of T_i as regressors allows for temperature to have a nonlinear effect on yields, which is important for solving for the optimal pyrolysis temperatures. The derivation of the optimal temperature and the product transformation curve is given in Appendix C.

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[7] Beattie and Taylor (1993) and Chambers (1988) provide general theoretical foundations. Among many seminal papers, Christensen *et al.* (1973) is an example of foundations and estimation of flexible production frontiers. More recently, some studies look at the productivity and utilization of scarce natural resources such as: fisheries [e.g., Felthoven *et al.* (2009) used a transformation production function; Lazkano (2008), short-run translog cost function; Hutchinson (2008), Generalized Leontief production function]; forest resources [e.g., Holmes *et al.* (2008), natural disturbance (forest fires, invasive species) production functions; Kohlin and Amacher (2005), forest collection production functions of different household labor categories]. There are also studies that examine issues related to agriculture such as: technical efficiency of enterprises or farmers [e.g., Ajibefun (2008) and Nyemeck Binam *et al.* (2005), stochastic frontier production function]; and risks in production of using pest control and GM crop technologies [e.g., Shankar *et al.* (2008), 'flexible risk' production function models; Christiaans *et al.* (2007), micro-data based agricultural production functions].

[8] This simplicity economizes on degrees of freedom in estimation, and allows for ease of interpretation within the sampling range (and economically meaningful range) of the available data, and provides a second-order approximation to more flexible forms for the relationship between temperature and yields. One issue arises because the dependent variables in these regressions are percentages, and do not range outside of the [0,100] interval. This in principle can cause complications for Ordinary Least Squares (OLS) if there are numerous observations near or on the range limit. This is generally not the case with the data used here, so we ignore this issue.

The data for this analysis are taken from published studies that are based on fast pyrolysis and/or slow pyrolysis, and numerous different types of feedstocks. The variables in the matrix ***Z*** include factors other than temperature that affect product yield per unit of feedstock mass, such as feedstock type and heating rate (fast or slow). In the regression results presented below, we include as explanatory variables in ***Z*** an indicator variable to distinguish between fast (*fast=1)* and slow (*fast=0*), as well as indicator variables for four different feedstock categories: *agricultural crop residues, other agricultural feedstocks, forest products,* and *other feedstocks.*[9] If we allow for price response to temperature differences as in equations (3) and (4), $P_C(T)$ and $P_L(T)$ must be specified. Our data do not allow direct estimation of these functions. However, assuming linear price response functions as an approximation, they can be characterized as

$$P_C(T) = \delta_0 + \delta_1 T \tag{3a}$$

$$P_L(T) = \gamma_0 + \gamma_1 T, \tag{3b}$$

If prices increase with temperature in the relevant temperature range, then all coefficients will be positive. The consequence is that there is an additional incremental benefit from increasing temperature: not only do you have an incremental increase in bio-oil yield, but prices tend to increase with temperature, so that the optimal temperature will tend to be higher than when price is independent of temperature. The optimal temperature given these price functions is derived in Appendix C.

5.4. Data.

Data on biochar and bio-oil yields from different feedstocks were collected from various studies on pyrolysis and are classified as follows: [10]

- *Agricultural field residue* — includes tobacco stalk, rice straw, cotton stalk, corn stover, and wheat straw;
- *Agricultural feedstock (other)* — includes hazelnut shell, sugarcane bagasse, coconut shell, sorghum bagasse, sunflower hulls, flax shives, corn cob, and olive waste (from oil production);
- *Forest products* — includes pine chips/wood/bark, pine sawdust, beech, poplar-aspen cellulose, maple bark, softwood bark, poplar sawdust, spruce sawdust, birch wood;
- *Other feedstock* — bamboo, tea factory waste, newsprint, fine paper, pulp mill waste, peat moss.

Biochar and bio-oil are joint products of a pyrolysis process, categorized into two types: fast pyrolysis and slow pyrolysis. The main difference in the two technologies in terms of revenue is

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[9] These categories include several different specific feedstock types, but are aggregated to larger categories in order to economize on degrees of freedom in estimation.

[10] Data are obtained from studies listed in Appendix C, Table C1.

how fast the materials are heated (i.e., the rate of increase in temperature per minute up to the final process temperature). Faster heating rates in fast pyrolysis favor reactions leading to the formation of higher yields of oil and lower yields of biochar.

Slow pyrolysis, on the other hand, results in higher yields of biochar compared to fast pyrolysis, and in the formation of two liquid phases – a much lower amount of oil relative to the fast pyrolysis process, and an aqueous phase (water plus a variety of organo-oxygen compounds of low molecular weight). Different rates of temperature increase, final pyrolysis temperatures, and feedstock type alter the quality characteristics of bio-oil and biochar. This in turn will affect their economic value for different uses. The temperatures in our dataset correspond to the final heating temperature. Although our data differentiate between *fast* and *slow* pyrolysis applications, information is not available to control for differences in heating rates and other characteristics within these two categories. Further, data are not sufficiently available to allow modeling bio-oil and biochar quality differences. We therefore use a simple binary categorical distinction between fast and slow pyrolysis in the regression estimation.

Note that the above discussion relates to outputs and revenues specifically. There are also likely to be cost differences between fast and slow pyrolysis as well. In particular, fast pyrolysis requires the use of small (usually <2 mm), pre-processed feedstock particles (Bridgewater *et al.*, 1999, p. 1481), whereas slow pyrolysis does not require such preprocessing to be effective. Therefore, the variable K in equation (1) may be different for slow and fast pyrolysis, and the higher revenues for fast pyrolysis may not imply higher net revenues (revenues minus costs). These costs are considered in the enterprise budgets in the following chapter.

Table 5.1 provides summary statistics for the data used in the analysis. For a kilogram (kg, or 2.2 lb) of feedstock, pyrolysis yields 26.37 percent (0.2637 kg) biochar and 43.56 percent (0.4356 kg) bio-oil. The remainder of the biomass is converted to gas, which is immediately consumed to sustain the pyrolysis process. Seventy-one percent of our sample data from the published studies we used were generated using fast pyrolysis, and the majority of the sample data (53%) are based on various (woody) forest product feedstocks. A fundamental choice variable in the pyrolysis process is temperature. Temperatures in our sample data range from 250° to 1000° Celsius.

Table 5.1. Summary statistics of variables used in estimation and analysis (n=206).

Variable	Mean	Std. Dev.	Min	Max
Biochar, % of feedstock mass	26.37	13.50	3	77
Bio-oil, % of feedstock mass	43.56	16.51	3.2	81.9
Indicator for fast pyrolysis	0.71	0.46	0	1
Pyrolysis temperature, Celsius	553.76	155.97	250	1000
Feedstock: Agricultural field residue indicator	0.18	0.38	0	1
Feedstock: Agricultural – other	0.23	0.42	0	1
Feedstock: Forest products	0.53	0.50	0	1
Feedstock: Other	0.06	0.24	0	1

Figure 5.2 is a series of descriptive scatter plots showing the relationship between bio-oil yield and biochar yield, by feedstock and pyrolysis type. The estimated regressions performed below are designed to be able to, among other things, define a relationship between biochar and bio-oil yields as a function of temperature, and holding constant other factors such as feedstock type. These quadratic fits are imprecise because they do not control for feedstock type.

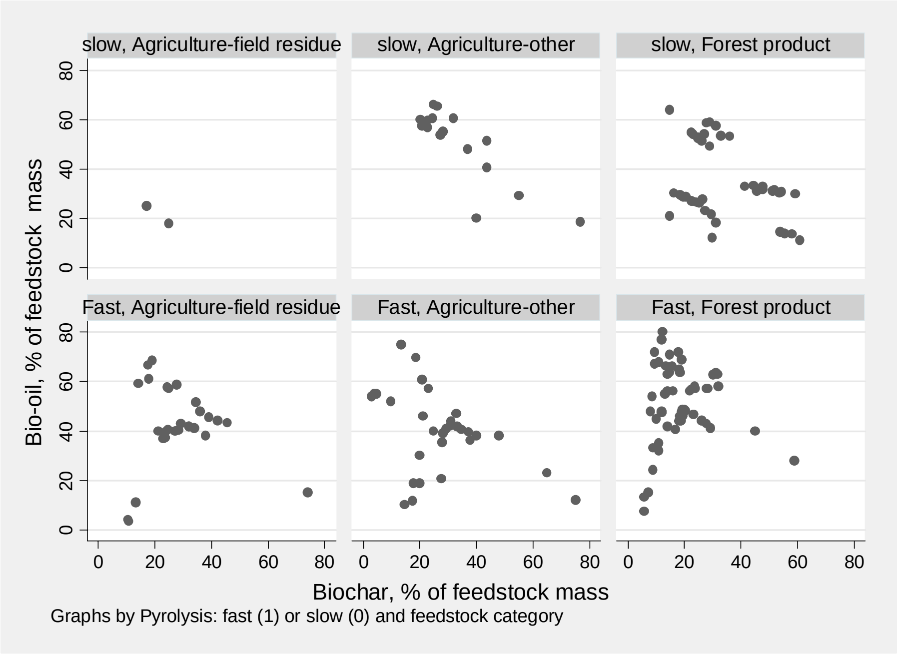

Figure 5.2. Scatter plots of biochar versus bio-oil yield, by feedstock category and pyrolysis type. This visual representation of the data from various studies roughly illustrates the trade-off in the production of bio-oil and biochar from various feedstock categories.

5.5. Results and discussion.

In this section we summarize the regression results, generate estimates of product transformation curves and optimal temperature for a given set of prices, and discuss revenue optimization.

Tables 5.2 and 5.3 provide the regression results for biochar yield and bio-oil yield, estimated for slow and fast pyrolysis separately. Indicator variables are included for feedstock categories, although no observations exist for *other feedstocks* under slow pyrolysis. The coefficients on the other indicator variables represent the intercepts of the regression lines for each feedstock type. A constant was omitted from each regression to avoid perfect collinearity. The difference in these parameter estimates then represents the difference in yield among feedstocks for any given temperature. For example, in the first (left hand) regression in Table 5.2 slow pyrolysis, the feedstocks included in the *Ag[ricultural field] residue* category tend to provide approximately 0.04 percent less biochar than the feedstocks included in the *Forest Products* category (103.43-103.39 = 0.04).[11] The R-square measures in Tables 5.2 and 5.3 show that the regression explains approximately ninety percent of the variation in each regression.[12]

These regressions provide a foundation for understanding the revenue tradeoffs implicit in the choice of temperatures, feedstock types, and pyrolysis types. They also provide the information necessary to develop product transformation curves and construct the relationship between output prices and optimal temperature settings. For example, the estimates for the temperature (*Temp(C)*) parameters in the slow pyrolysis biochar and bio-oil regressions provide the values $\alpha_1 = -0.2253$ and $\beta_1 = 0.1371$, respectively, in equations 2a, 2b, and appendix equations A3a, A3b, A4, A7 and A8. The parameters associated with temperature squared (*Temp sq.*) are $\alpha_2 = 1.5E-04 = 0.00015$ (Table 5.2) and $\beta_2 = -1.2E-04 = -0.00012$ (Table 5.3).

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[11] There are only two observations that correspond to slow pyrolysis applied to agricultural field residues. Most of the explanatory power relating to agricultural field residues comes from the 35 observations of fast pyrolysis applied to field residues.

[12] Estimation is carried out equation by equation using Ordinary Least Squares, and White's Heteroskedastic-consistent standard errors are reported.

Table 5.2. Regression results. Dependent variable: Biochar as a percent feedstock mass.

Dependent variable →	Biochar, % feedstock mass, slow pyrolysis				Biochar, % feedstock mass, fast pyrolysis			
Indep. variable	Est.	Std. Err.	95% conf. int.		Est.	Std. Err.	95% conf. int.	
Temp (C) sq.[1]	1.5E-04	5.8E-05	3.5E-05	2.7E-04	9.4E-05	2.5E-05	4.5E-05	1.4E-04
Temp (C)	-0.2253	0.0623	-0.3501	-0.1005	-0.1655	0.0322	-0.2291	-0.1019
Forest prod.[2]	103.43	15.60	72.17	134.70	80.67	9.97	60.96	100.37
Ag residue	103.39	15.12	73.09	133.69	91.27	10.12	71.26	111.29
Other Ag	106.14	16.39	73.29	138.99	89.67	9.97	69.96	109.38
Other[3]					88.63	10.40	68.07	109.19
R^2	0.93				0.89			
N	60				146			

[1] The estimates for the temperature (*Temp(C)*) parameters in the biochar regressions correspond to α_1 in equations 2a and 2b, and appendix equations A3a, A3b, A4, A7 and A8. The parameters associated with temperature squared (*Temp sq.*) correspond to α_2.

[2] Coefficients associated with feedstock types (the four last rows of coefficients) represent the intercept for slow pyrolysis applied to each respective feedstock type. The constant is omitted to avoid perfect multicollinearity.

[3] No observations are available for slow pyrolysis applied to *Other Feedstock*.

Table 5.3. Regression results. Dependent variable: Bio-oil as a percent feedstock mass.

Dependent variable →	Bio-oil, % feedstock mass, slow pyrolysis				Bio-oil, % feedstock mass, fast pyrolysis			
Indep. variable	Est.	Std. Err.	95% conf. int.		Est.	Std. Err.	95% conf. int.	
Temp (C) sq.[1]	-1.2E-04	8.3E-05	-2.9E-04	4.2E-05	-2.1E-04	3.4E-05	-2.8E-04	-1.4E-04
Temp (C)	0.1371	0.0894	-0.0421	0.3163	0.2205	0.0444	0.1328	0.3083
Forest prod.[2]	0.556	22.396	-44.327	45.438	-3.420	13.753	-30.610	23.770
Ag residue	-4.871	21.702	-48.363	38.621	-11.090	13.969	-38.707	16.528
Other Ag	14.552	23.533	-32.609	61.714	-9.531	13.757	-36.730	17.667
Other[3]					-7.446	14.351	-35.819	20.927
R^2	0.88				0.94			
N	60				146			

[1] The estimates for the temperature (*Temp(C)*) parameters in the bio-oil regressions correspond to β_1 in equations 2a and 2b, and appendix equations A3a, A3b, A4, A7 and A8. The parameters associated with temperature squared (*Temp sq.*) correspond to β_2.

[2] Coefficients associated with feedstock types (the four last rows of coefficients) represent the intercept for slow pyrolysis applied to each respective feedstock type. The constant is omitted to avoid perfect multicollinearity.

[3] No observations are available for slow pyrolysis applied to *Other Feedstock*.

Figure 5.3 plots the yields of biochar and bio-oil from woody forest products as a function of temperature, for slow and fast pyrolysis, respectively. The two graphs have common scales for clear comparison. First consider the differences between the fast and slow pyrolysis functions. Together, the graphs show that for any given temperature, slow pyrolysis is estimated to provide more biochar and less bio-oil for a given amount of feedstock than fast pyrolysis does. This implies that the relative economic efficacy of slow and fast pyrolysis will depend, in part, on the relative prices of the two outputs.

Second, the graphs show that for our temperature range, bio-oil yield increases with temperature for low temperatures, but then begins to decline. For slow pyrolysis, the temperature that provides maximum bio-oil is about T=549.31°C (at the vertical dotted line in the first panel of Figure 5.3). For fast pyrolysis, the temperature that provides maximum bio-oil is 524.92°C. In contrast, biochar yields decline over the entire range. Given the specific shapes of these two functions, the economic region of temperature must be lower than that which provides the maximum bio-oil yield, i.e., the area to the left of the vertical dotted lines.

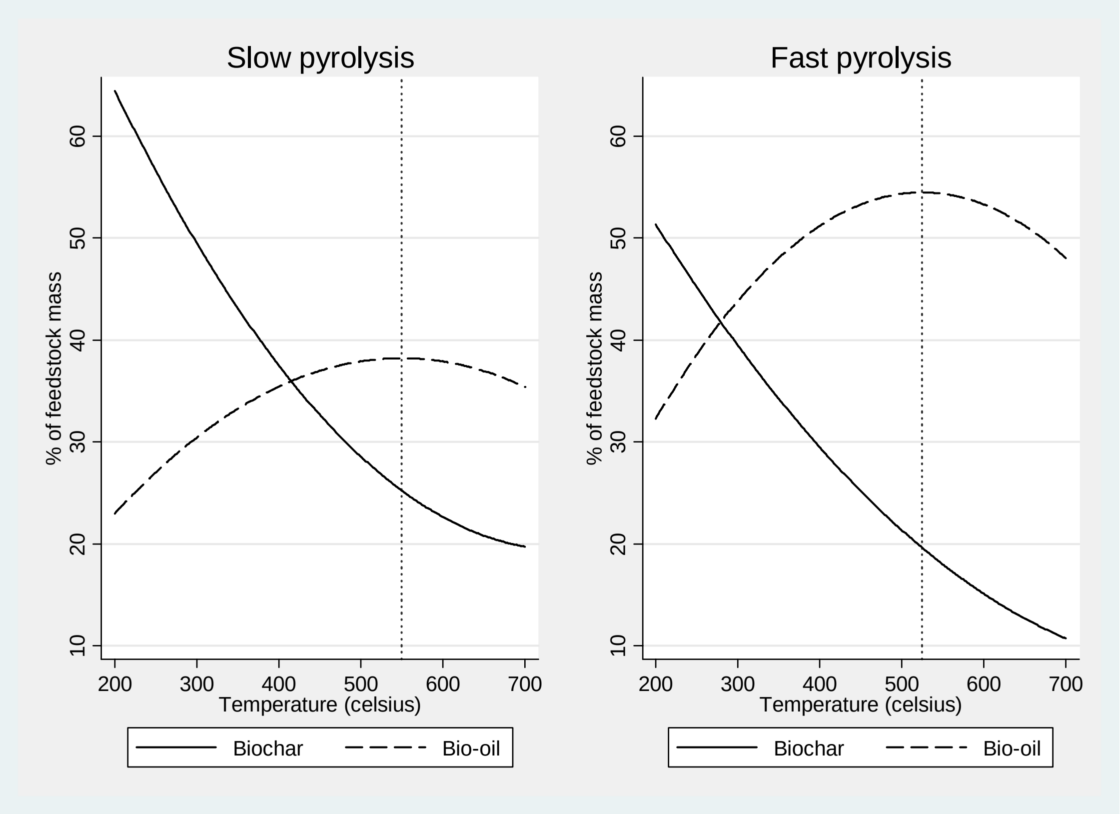

Figure 5.3. Biochar and bio-oil yields under slow and fast pyrolysis.

At low temperatures, there is a tradeoff; biochar yield declines but bio-oil increases as temperature increases. The optimal temperature depends on the relative prices of the two outputs. At higher temperatures, both yields decline, so in this region, a further increase in temperature necessarily reduces revenue (and reducing temperature necessarily increases revenue), thus making production at and above the temperature where bio-oil yields begin to decline uneconomical regardless of relative prices. Figure 5.4 shows the estimated product transformation curves (PTC) under slow and fast pyrolysis. These two curves cross, such that slow pyrolysis PTC is above that for fast pyrolysis on the left, but below on the right. This is of some interest because it implies that slow pyrolysis may tend to provide higher revenues per unit of feedstock than fast pyrolysis under some price conditions, and vice versa.[13] As Figure 5.1 shows, revenue maximization for a given quantity of feedstock entails choosing the combination of biochar and bio-oil (indirectly through pyrolysis temperature) subject to the prices of these two outputs.

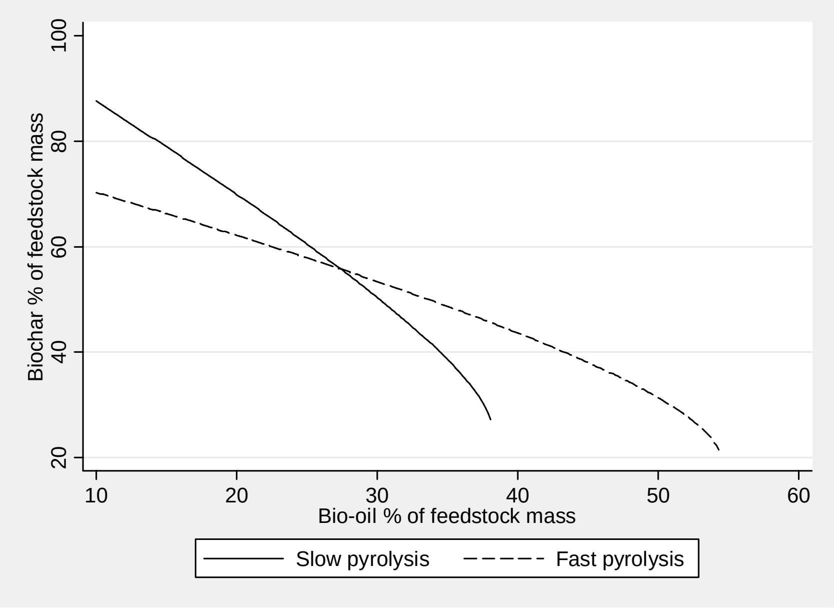

Figure 5.4 Product transformation curves under slow and fast pyrolysis.

5.6. Optimal temperature for fixed prices.

Figure 5.5 shows the optimal temperature for a given price ratio under fast and slow pyrolysis. These curves are derived by substituting the appropriate regression coefficients from the fast and

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[13] Costs are not accounted for here. Even if the product transformation curve for fast pyrolysis lies above that of slow pyrolysis at the optimal temperature, the production costs can still affect profitability.

slow pyrolysis regressions, respectively, into appendix equation (A4). Because the units of measure for the two outputs are the same, the units of measure should be equivalent for each price when interpreting the results. For concreteness, we examine specific cases below based on price per kilogram (kg) for each output. At relatively low bio-oil prices, the optimal temperature under fast pyrolysis is higher than for slow pyrolysis, but the opposite is true for higher ratios of bio-oil and biochar. Notice that the upper bounds on these curves (to the right on the graph) approach the economic maxima of temperature discussed earlier.

The minimum temperature in our data sample is 250°C. However, the valuable characteristics of both biochar and bio-oil deteriorate below about 350°C. This (latter) temperature is optimal under slow pyrolysis for a price ratio of $P_L/P_C = 2.40$. For fast pyrolysis, the price ratio implying an optimal temperature of 350°C is 1.36. Anything below this price ratio would call for more emphasis on biochar. On the other end of the economic spectrum, profits necessarily decline (regardless of prices) at about 549.3°C (slow) and 524.9°C (fast), so this will be an upper bound economically valid temperature, and would apply if, for example, the price of biochar is very small so that the price ratio P_L/P_C becomes very large.

It is useful to consider a set of feasible or possible prices and their outcomes as an example. Because the data on biochar and bio-oil yield (and therefore the estimated parameters and the analysis developed above) are based on percent of feedstock mass, the units of measure for biochar and bio-oil, as well as the prices for each, must be in the same unit of measure. This analysis below uses kilograms as units, and dollars per kilogram as the price unit. The range of

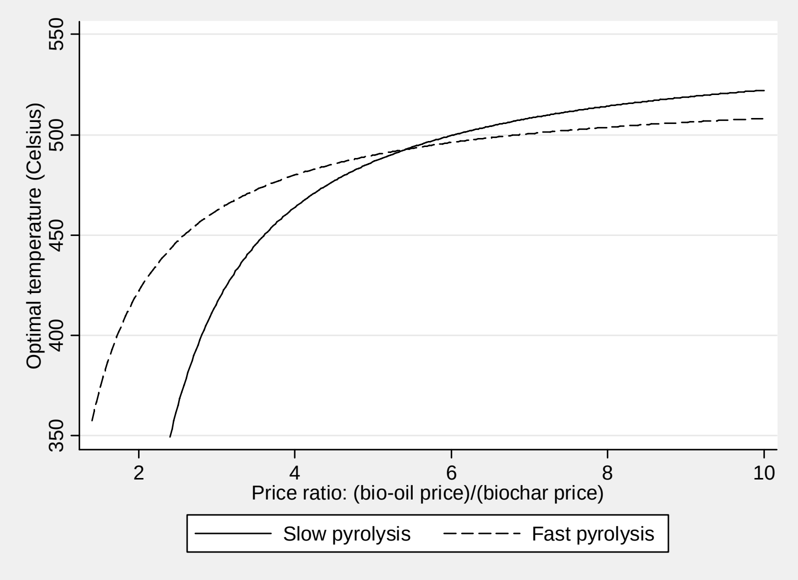

Figure 5.5. Estimated optimal temperature for bio-oil and biochar price ratios.

estimates for bio-oil is from about \$0.60 to about \$1.06 per gallon (Zeman, 2007). If we assume \$1.00 per gallon of bio-oil, this translates to \$0.22 per kg of bio-oil. The price of biochar could vary significantly depending on the market. Suppose a market supports biochar production at a break-even price of \$600 per ton, this translates to \$0.60 per kg. The result is a price ratio of $P_L/P_C = 0.37$, suggesting heavy emphasis on low temperature, slow pyrolysis. In contrast, if biochar is of relatively little value, say \$50 per ton, then the price ratio is 4.4, suggesting that fast pyrolysis at higher temperatures (about 522°C) is optimal.

5.7. Optimal temperature for endogenous prices.

When price is a function of quality, which in turn is a function of temperature, the price ratio itself is determined in part by the chosen temperature. Therefore, there is no fixed price ratio determining the optimal temperature. Instead, optimal temperature and price are simultaneously determined. A specific set of price parameters is developed here and used to solve for the optimal temperature. The data for this relationship between bio-oil quality (and therefore price) and temperature are very limited. The following analysis relies on linear extrapolation of the price-temperature relationship, putting some of the calculated results outside the range of the original data. This example begins with the assumption that both biochar and bio-oil will be used as an energy source, with price related to energy content of the product. Further, we assume that bio-oil is a substitute in use for fossil crude oil, and biochar is a substitute for coal. The energy content of biochar tends to be higher than coal, and the energy content of bio-oil tends to be lower than that of fossil crude oil. However, as an approximation, we assume that the *price per unit of energy* of bio-oil is equal to that of fossil oil, and that the price per unit energy of biochar is equal to that of coal.[14]

Let the high heating calorific value of crude oil and bio-oil be 45.7 MJ/kg and 18 MJ/kg, respectively. If the price of crude oil is \$52/barrel, the price is also equivalent to \$0.398/kg or \$0.008709/MJ. Figure 10 in Garcia-Perez *et al.* (2008) provides an estimated regression that relates fast pyrolysis temperature to high heating value (dry) based on temperatures between 350°C and 575°C. Substituting these numbers into equation (3b), we approximate the energy content function for bio-oil to be

$Calories\left(MJ/kg\right) = 17.85 + 0.007\bar{5}\,\mathrm{T}^{\circ}\mathrm{C}$, so that price in dollars per kilogram is

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[14] This equal price reflects a market outcome driven by the assumed (perfect) substitutability of the two related goods (e.g. biochar and coal). If production cost of one of them is higher than the other — that is, if the market supply curves differ, then the quantities produced of the two goods will differ. If the two goods are not perfect substitutes in consumption, then prices will tend to differ also. In particular, if one has some disadvantages in terms of refinement (an intermediate demand), then it will tend to fetch a lower price per MJ.

$$\begin{aligned} P_L(\$/kg) &= 0.008709 \times \left(17.85 + 0.007\bar{5}\,\mathrm{T}^{\circ}\mathrm{C}\right) \\ &= 0.15545514 + 0.0000658\,\mathrm{T}^{\circ}\mathrm{C}. \end{aligned} \tag{4}$$

This provides a price of $0.188 per kilogram of bio-oil at T=500.

A price of $68.10/metric ton of coal provides a price of $0.068/kg or $0.002528/MJ from coal [i.e., ($0.068/kg) /(26.9 MJ/kg)]. Substituting these numbers into equation (3a) provides an estimated relationship between calorific content of biochar as a function of pyrolysis temperature of

$Calories(MJ/kg) = 16.2 + 0.02678571\,\mathrm{T}^{\circ}\mathrm{C}$, so the price of biochar would be

$$\begin{aligned} P_C(\$/kg) &= 0.002528 \times \left(16.2 + 0.02678571\,\mathrm{T}^{\circ}\mathrm{C}\right) \\ &= 0.0409536 + 0.00006771\,\mathrm{T}^{\circ}\mathrm{C}. \end{aligned} \tag{5}$$

This provides a price of $0.0748 per kilogram of biochar at T=500.

Using equations (4) and (5) and estimated counterparts of equations (2a) and (2b) for slow pyrolysis applied to forest feedstocks to specify the revenue function (appendix equation A5) provides revenue as a function of temperature. This revenue function is shown in Figure 5.6. Using appendix equation (A6) allows the calculation of an optimal temperature of 536.4°C.

Making use of the yield functions and price functions, for slow pyrolysis the optimal estimated yield and price for biochar is 26.037% and $0.077/kg, and for bio-oil optimal yield and price are 38.19% and $0.192/kg. Maximum revenue for slow pyrolysis is $0.09296/kg of forest-based feedstock. The implied price ratio for slow pyrolysis is 2.4686. If the market prices were fixed and constant across the temperature range as in the previous section, a price ratio of 2.4686 would lead to optimal temperatures of 360.14°C for slow pyrolysis, which is much lower than for the case of endogenous prices.

For fast pyrolysis, the estimated optimal temperature is 521.9°C. Biochar yield is 19.8%, and bio-oil yield is 54.46%. Biochar price is $0.076/kg, and bio-oil price $0.19/kg. Maximum revenue is $0.11848/kg. So, based on energy content, the fast pyrolysis provides higher revenues by $0.0255, an increase of 27.4%. Thus, if energy content provides the highest value for both products, fast pyrolysis provides higher revenues.

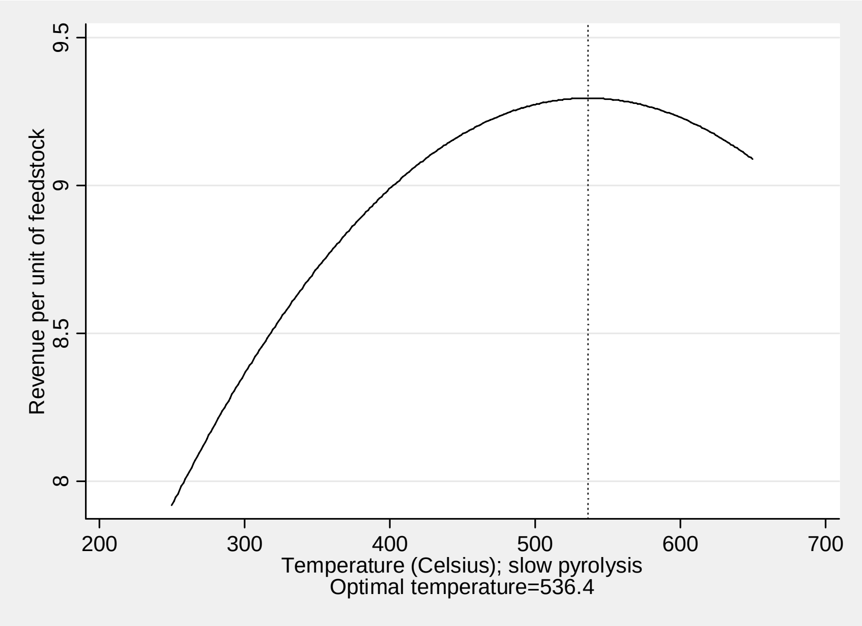

Figure 5.6. Revenue function for slow pyrolysis with endogenous prices. Vertical dotted line shows optimal temperature of 536.4^{o}C.

5.8. Summary.

This chapter provides a model and estimates for maximizing the sum of revenues from the joint production of bio-oil and biochar. The primary control variables in this process are the type of pyrolysis used (either fast or slow), and the final pyrolysis temperature, but feedstock type is important as well. We provide a method for choosing the revenue maximizing pyrolysis temperature in two cases: first, when market prices are fixed and do not vary with temperature, and second, when output quality and therefore price changes as pyrolysis temperature is altered. The dataset is limited, and relies on several different types of feedstocks to estimate the yield parameters, using a relatively restrictive functional form. Further, the price response functions in the final example above are limited to only one, albeit fundamental, use of biochar and bio-oil, so these results are relatively narrow in scope. Nonetheless, the results are generally plausible and provide a foundation for refinement.

Maximizing revenues by choosing process temperature can be economically important. However, even if the optimal combination of bio-oil and bio-char is produced, it may not provide an economically viable (profitable) enterprise. This ultimately depends on whether the revenues from production outweigh the costs. The data used in this analysis of the tradeoffs between biochar and bio-oil production do not allow a cost analysis. For this, we turn to an enterprise budget approach in the next chapter.

Chapter 6. ECONOMIC FEASIBILITY OF BIOCHAR PRODUCTION.

An enterprise budget is developed in this chapter to estimate the various costs of biochar production at different scales of operation, and with technology of varied portability. Enterprise budgets present estimates of revenues (income), costs, and profits associated with the production of a particular product. A comparison of these costs to potential revenues from biochar and co-products allows an assessment of the economic viability of biochar production. As a first step of the feasibility analysis, we examine the availability of different types of biomass feedstocks in Washington State that can be utilized as input to biochar production. These potential biomass feedstocks include forest residues, grain straw and animal waste.[1] This section is followed by a brief review of studies that have assessed the cost of biochar production using certain feedstocks. The last section presents the enterprise budgets for the production of biochar and bio-oil via pyrolysis of softwood from forest thinning.

6.1. Overview of biomass feedstock availability in Washington.

A 2005 study of biomass feedstocks (Frear, 2008) identified, categorized, and mapped 45 different types of biomass in Washington State at the county level. The categories are municipal solid waste, forest residues, field residues, animal waste, and food packing/processing waste. The study found that Washington has a comparatively large annual production of under-utilized cellulosic biomass (~17 million dry tons/yr). Furthermore, lignocellulosic waste (e.g., forestry, field straws and yard waste) is the predominant type of biomass available in the State. Frear (2008) explained that some of the inventoried feedstocks, such as mill residues, were already quite effectively utilized in industrial energy production. There were other inventoried biomass sources that have substantial quantities available, such as animal waste used as fertilizer, but considered under-utilized as a direct energy source.

Yoder *et al*. (2008) described lignocellulosic biomass availability in Washington, particularly municipal solid waste, forest residues, field residues and dedicated energy crops (such as switchgrass and hybrid poplar). Sixty-six percent of the available lignocellulosic biomass in Washington comes from forest residues. Figure 6.1 summarizes the inventory of these four types of biomass, in addition to animal waste. County-level estimates for lignocellulosic feedstocks described below are high end estimates.

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[1] The economic analyses in this chapter, however, focuses on forest thinnings as feedstock.

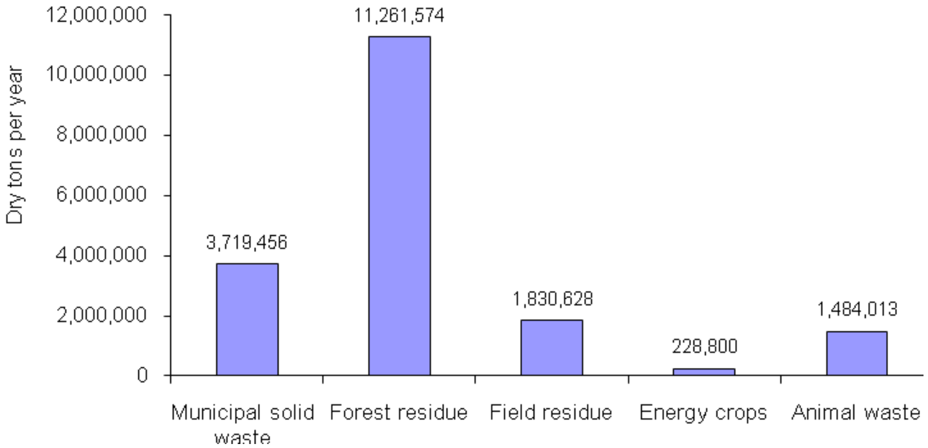

Figure 6.1. Washington's potential biomass by group (Yoder *et al.*, 2008; Frear, 2008).

6.1.1. Field crop residues

This category includes wheat straw, barley straw, grass seed straw, corn stover and other field crop residues. Figure 6.2 shows the amounts of field residues that can be collected by county per year in dry tons. The top three wheat producing counties in Washington —Whitman, Lincoln, and Adams— account for 45 percent of the state's total field residues. Sixty-one percent of the total field residue is from wheat straw, which can be used for compost, animal bedding, animal feed and building material (e.g., strawboard panels) (Fouts, 1997; Stewart and Trombly, 2002; Frear, 2008; Stevens, 2008). Wheat straw and other crop residues are also being explored as feedstock for biofuel production (Kerstetter and Lyons, 2001; Lal, 2005; Greer, 2005; Geranios, 2008).

A key question is how much of the biomass can be collected. The amount of potential harvestable crop residue depends critically on how much needs to be left for soil conservation. The assumed sustainable collection rate is 25 percent for wheat straw, barley straw and corn stover. For grass seed straw, the amount of sustainable residue is 2.2 tons residue per acre planted (Frear, 2008; Yoder *et al*., 2008). However, care must be taken when utilizing these factors because they are constant rates applied to all fields. They do not take into account the different yield potentials of the fields across the state, which are subject to the climate, soil disturbance, moisture and vegetation that vary from region to region. Therefore, in practice, the sustainable collection rate could be less than 25 percent. Also, some agricultural experts and some studies caution against removing any crop residues from the fields in order to preserve soil quality and minimize erosion (Lal, 2005; Geranios, 2008). Concern may be lessened, however, if biochar produced from field residues is subsequently returned to the soil.

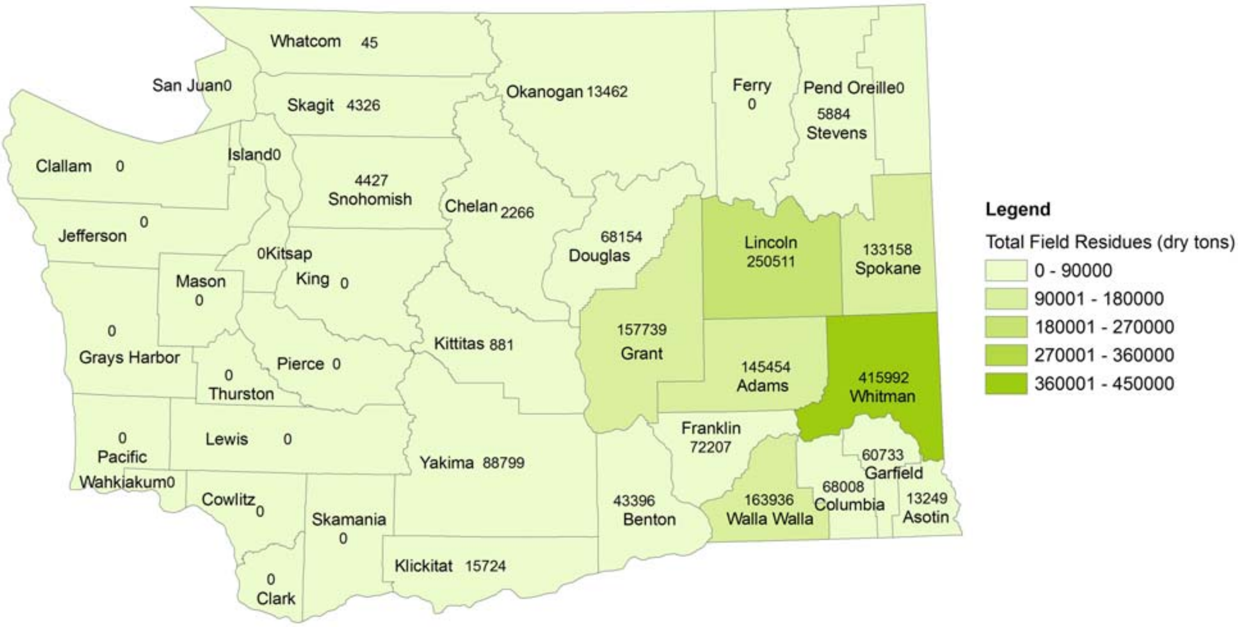

Figure 6.2. Total field residues by county, dry tons/year (Frear, 2008).

6.1.2. Forest residues

Table 6.1 presents the supply estimates of forest residues in Washington from three data sources. The Western Governors Association (WGA, 2008) estimates 1,855,034 tons of total forest residues per year. However, this is lower compared to the estimates from Skog *et al*. (2008) and Frear (2008) which are 8,540,515 tons/year and 11,261,574 tons/year, respectively. The disparity is attributed to a conservative estimate of available mill residue in WGA (2008) while the other two data sources include all mill waste. Compared to Frear (2008), Skog *et al*. (2008) reports a lower estimate of total forest residues since it excludes logging residues and has a lower estimate of forest thinning.

Forest residues are from logging, tree thinning, mills, and land clearing. Six counties in Western Washington —Cowlitz, Grays Harbor, Clallam, Lewis, Pierce and Snohomish— account for about 46 percent of the total forest residues in the State per year. Of the total forest residues, 47% comes from mills, 32% from forest thinning, 17% from logging and 4% from land clearing (Frear, 2008). Thinnings available in each county are shown in Figure 6.3. The counties of Okanogan and Ferry have the most thinnings in Washington State.

Table 6.1. Forest residue supply estimates.

Data Source	Type	Dry Tons	Cost($/dry ton)
WGA, 2008	High Case, Total, N/D	1,855,034	30
Skog *et al.*, 2008	Thinning	2,720,865	40
Skog *et al.*, 2008	Other Removals	10,319	30
Skog *et al.*, 2008	Urban Wood Residue	530,980	N/A
Skog *et al.*, 2008	Mill Residue	5,278,351	N/A
Total		8,540,515	
Frear, 2008	Logging Residue	1,901,072	42-122
Frear, 2008	Forest Thinning	3,663,554	42-122
Frear, 2008	Mill Waste	5,278,353	20-60
Frear, 2008	Land Clearing	418,595	N/A
Total		11,261,574	

Note: All estimates are preliminary and subject to revision.
N/A: Not Available; *N/D*: Not Disaggregated by Type

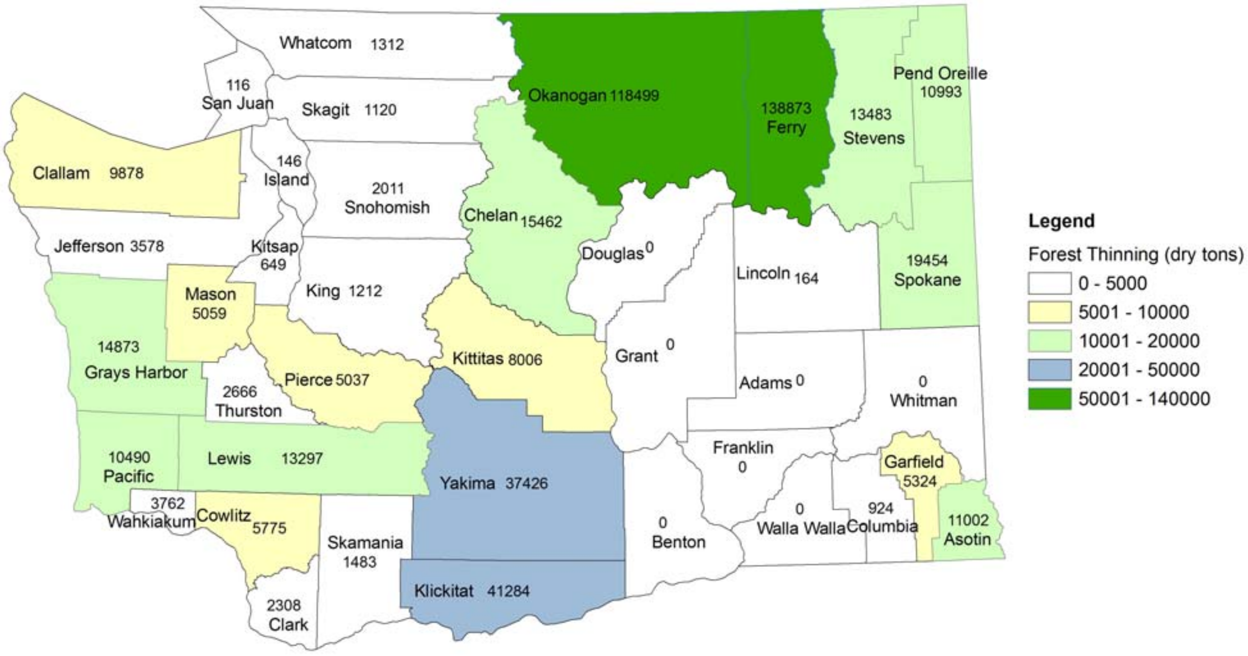

Figure 6.3. Forest thinnings by county, dry tons/year (Frear, 2008).

The challenges of utilizing these feedstocks include their location, which may lead to high collection and hauling costs, and existing competing uses. For example, the utilization rate of mill residues in existing markets is about 95 percent. A question then arises about the impacts of introducing new uses of forest residues on the existing markets. On the other hand, forest thinning treatments (especially in overstocked forests) have social and private economic benefits since they can help restore the health of forests and reduce the risk of catastrophic wildfires (Polagye *et al*., 2007). A cost-benefit study by Mason *et al*. (2006) estimated that forest thinning had positive net benefits of at least $1,400 per acre for high-risk forests and about $600 per acre for moderate-risk forests. As mentioned earlier, the largest quantities of thinnings available are found in Okanogan and Ferry counties. The feasibility of producing biochar (and bio-oil) from forest thinning in the Okanogan National Forest is examined in section 6.3 of this chapter.

6.1.3. Animal waste

Animal waste is also a potential feedstock for biochar production.[2] Several studies have evaluated its agronomic potential. For example, Gaskin *et al*. (2008) examined the properties of biochar produced from poultry litter, as well as peanut hulls and pine chips via low temperature pyrolysis. Their results showed that, in general, poultry litter biochar contained more nutrients, including nitrogen, phosphorus and potassium; but lower C content relative to biochar from peanut hulls or pine chips. A project in Australia (Van Zwieten, 2005) tested the benefits of a range of biochars (from poultry litter, cattle feedlot wastes, greenwaste, papermill waste) and found that poultry litter and greenwaste biochar had significant benefits to soil fertility and yields of corn and faba bean. Chan *et al*. (2008) conducted a pot trial of poultry litter biochar as a soil amendment by assessing its impacts on the yield of radish, and they observed increases in yields.

The total animal waste presented in Figure 6.4 includes amounts of dairy, cattle, and poultry manure that are deemed in Frear (2008) to be collectible. The collectible amounts as percentage of total waste produced are 28% for cattle manure, 85% for dairy manure and 80% for poultry manure. Currently, animal waste is commonly used as a source of fertilizer and soil amendment. Farms in seven counties — Skagit, Pierce, Whatcom, Snohomish, Lewis, Yakima and Thurston — generate more than 100,000 tons of animal waste per year per county, which in aggregate accounts for nearly 80 percent of the total animal waste (Figure 6.4). Most of the dairy waste comes from dairy farms in Whatcom and Yakima counties, each with more than 110,000 tons per year or a combined 51 percent of the total dairy waste per year. Whatcom, Grant and Yakima counties comprise the top three producers of cattle waste. Poultry farms in Lewis and Thurston counties produce the most amount of poultry litter. At the state level, poultry litter accounts for 52 percent of the total animal waste per year.

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[2] Some amount of bio-oil is also produced during the process but it is of low quality. Direct recovery of energy content in pyrolytic vapors (i.e., burning the bio-oil in the process) is a desirable approach for using bio-oil.

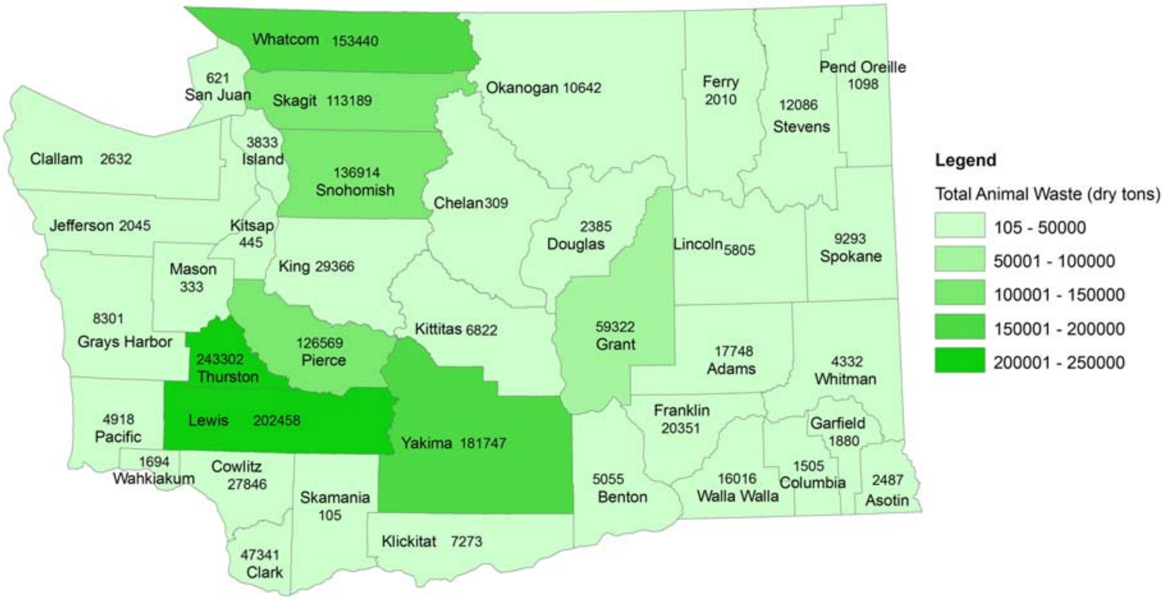

Figure 6.4. Total animal waste (dairy, poultry and cattle) by county, dry tons/year (Frear, 2008).

6.2. Feasibility of biochar production – Related studies.

There are a number of studies about the agricultural and environmental benefits of biochar, but only a few assess the economic viability of biochar production. The results vary, depending in part on the type of feedstock and the type of processing facility used.

Lima *et al.* (2008) estimated the production cost of granular activated carbon from broiler litter. The study assumed the following: daily supply of 20 tons of litter; farm gate value of broiler litter at $5.50 per ton; transportation to the processing facility, which was 10 miles away, at a cost of $27.50 per ton; and operation of the processing facility on a continuous basis (24 hours per day and 330 days per year). The unit cost to manufacture the broiler litter-based activated carbon was estimated at $0.65 per pound.[3] Biochar is a precursor to manufacturing activated carbon. Activated carbon is not used as a soil amendment; rather, it is applied in cleansing processes such as drinking water filtration and air purification (Sohi *et al.*, 2009). If biochar is the main product rather than activated carbon, however, the production cost will be lower than

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[3] This is based on an annual production of activated char from broiler litter, 2,438,383 lbs; and an annual production cost of $1,599,000.

$0.65 per pound because there will be no "activation" step in the production process and the yields of char will be higher (I. Lima, personal communication).[4]

McCarl *et al.* (2009) provided an economic assessment of fast and slow pyrolysis processes using maize stover. The feedstock was hauled to a large-scale, stationary pyrolysis facility with a capacity of 70,080 tons of feedstock per year. The study examined the fixed and variable costs of plant operation, end use values of biochar and bio-oil,[5] and value of greenhouse gas (GHG) offset for carbon markets based on life-cycle carbon emissions from biochar and bio-oil. Based on the estimated returns and costs of production, results showed net losses of approximately $45 per ton if a fast pyrolysis process was utilized, and $70 per ton if via slow pyrolysis. Hence both were considered unprofitable under the market conditions assumed in the study. Slow pyrolysis became profitable if the price of biochar exceeded $246 per ton, while fast pyrolysis required a price of biochar greater than $1,047 per ton to become profitable.

The returns and costs of production affect the estimation of break-even (BE) prices. McCarl *et al.* (2009) found that the BE price of biochar was lower for slow pyrolysis than for fast pyrolysis, because slow pyrolysis has much higher yields of biochar compared to fast pyrolysis (about 8 times higher). Hence, if biochar price is increased for the higher yields of slow pyrolysis, revenues will increase faster than with the relatively low biochar yields of fast pyrolysis.

Polagye *et al.* (2007) examined the economic feasibility of producing bio-oil from forest thinnings via fast pyrolysis under four types of facilities — mobile, transportable, stationary and relocatable.[6] Other products of pyrolysis — char and gas — were used for process heating. The value of char as an energy source was not estimated. However, the study provides a useful and detailed account of the characteristics of the facilities and their corresponding process flow structures, showing various operations from the collection and delivery of feedstock to the production of biofuels. Revenue from bio-oil sale was assumed to be $0.77/gallon.[7] For a mobile facility, the net losses per gallon of bio-oil produced (total revenue minus total cost, excluding cost of long-haul transportation from forest edge to end use) were estimated at $1.93/gallon; $0.55/gallon for a transportable facility; $0.19/gallon for a relocatable facility; and $0.08/gallon for a stationary facility (Polagye, 2009). These costs reflect the energy efficiency

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[4] The contribution of the "activation step" to the overall cost is not given in the study so an estimate of any savings from producing biochar (i.e., excluding the activation step) cannot be derived from the published results.

[5] In the study, the end uses of biochar and bio-oil are as soil amendment and electricity generation, respectively.

[6] The rated capacity of each facility is as follows: 10 tons per day – mobile; 100 tons per day – transportable; 1,653 tons per day – base case for stationary unit since the capacity depends on area thinned; and 500 tons per day – relocatable.

[7] The study assumes that bio-oil price is equal to the price of #6 residual fuel oil (Los Angeles receiving terminal) in 2004.

and bio-oil mass yield of each facility, where the mobile facility has the lowest values. None of the production facilities appeared to be a viable prospect based on this study.

Radlein and Bouchard (2009) assessed the economics of the fast pyrolysis process by Dynamotive Energy Systems Corp., focusing on wheat straw as feedstock. The study assumed a plant with capacity of 200 dry tons per day, and the base prices of bio-oil and biochar at $0.62/gallon and $150.39/ton, respectively. The net income was about US$230,473 (in year 1).[8] If the revenue from the sale of biochar is treated as a credit in pyrolysis production, the bio-oil price has to be $0.59/gallon to break-even. This figure is lower than their assumed base price for bio-oil. If the sale of bio-oil is considered a credit, on the other hand, the estimated break-even price of biochar is $195/ton, which is about 23% higher than the base price. Nonetheless, looking at the general picture, the study finds the pyrolysis production profitable.

Lima *et al*. (2008) and Polagye *et al*. (2007) did not specifically examine the economics of biochar production. In contrast, Radlein and Bouchard (2009) and McCarl *et al.* (2009), examined the production of both biochar and bio-oil. Both also assumed crop residues as feedstock source in their studies. The total production cost, however, is higher in McCarl *et al.* because the study includes the capital and operating costs of a pre-treatment plant and a power generation plant, in addition to the pyrolysis plant. Radlein and Bouchard focused only on the cost of a pyrolysis plant.

McCarl *et al.* (2009) examined biochar application to agricultural fields, and accounted for both conventional market and carbon market values of biochar and bio-oil. Also, McCarl *et al*. (2009) and Lima *et al*. (2008) both considered a large, stationary processing facility. These four studies provide a useful framework for estimating the costs of biochar production using potential biomass feedstocks in Washington. For our case study, however, we will mainly utilize the assumptions and data from Polagye *et al.* (2007).

6.3. Estimated costs and returns for producing biochar and bio-oil in Washington State.

This section develops the feasibility analysis of biochar and bio-oil production through pyrolysis. A brief description of the pyrolysis process and its co-products is provided. The section also outlines the assumptions of our case study, particularly concerning the feedstock used in the pyrolysis process (i.e., forest thinnings) and four types of processing facilities — mobile, transportable, relocatable and stationary. These assumptions are mainly based on Polagye *et al.* (2007). Supporting data are obtained from Polagye (2009) and published statistical reports. Lastly, enterprise budgets of the four facilities are provided for their respective biochar and bio-

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[8] Available revenue-cost data for the plant are only for Year 1. The plant's economic life is 15 years.

oil production. The budgets present estimates of revenues, costs and returns of production, which are used to calculate the break-even prices of bio-oil and biochar.

6.3.1. Joint products from pyrolysis

The pyrolysis process converts a viable feedstock into three main products: gas, biochar and bio-oil. The relative quantity of the three outputs produced from a given quantity of feedstock depends mainly on the temperature of the pyrolysis process. Gas is recovered and reused to heat the pyrolysis unit, while biochar and bio-oil have potential for commercial and agricultural use. For instance, bio-oil can be used as a source of energy for heating and electrical generation on-site. Alternatively, it is considered as a substitute for No. 2 heating oil and No. 6 residual fuel oil, typically used as fuel in industrial boilers and kilns (Zeman, 2007; Dynamotive Energy Systems, 2009a). A more promising alternative to refine the bio-oils to produce transportation fuels was not taken into account in this study because of the lack of technical and economic information on bio-oil refineries. Biochar can potentially be used as a source of energy in the pyrolysis process or as a soil additive.[9]

6.3.2. Case study on forest thinning

The slow pyrolysis unit built at WSU for the current biochar project (by Dr. Garcia-Perez and his team) utilizes an auger reactor with a feedstock capacity of 1-2 kg/hour. In the laboratory experiments using this unit, biochar was produced from softwood bark, wood pellets, digested fiber and grass seed straw. However, using the laboratory reactor as a basis for economic analysis of small-scale to large-scale commercial production of biochar and bio-oil is difficult due to likely differences in economies of scale. Polagye *et al.* (2007) and Polagye (2009) have documented data available about the production costs of the two pyrolysis products we are interested in; but they focus on *fast pyrolysis*. For the purpose of illustrating the production costs of biochar and bio-oil from different scales of operation, we utilize the data from these studies.[10]

For our case study, we focus on forest thinnings and use the estimated production costs under four types of facilities from the Polagye studies. Forest thinning falls in the same category of forest residue biomass as softwood bark and wood pellets (from Douglas fir) that are used in the

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[9] Other potential uses include water purification, gas cleaning and for charcoal in home cooking (McCarl *et al.*, 2009).

[10] The main reasons for using the Polagye studies are because: the primary author provided well documented data where the bio-oil and biochar yields as well as inputs of production can be easily altered; and removal of forest thinnings is a forest management practice that promotes forest health and minimizes the risk of forest wildfires. Furthermore, using forest thinnings as feedstock is a less critical issue compared to using crop residues like wheat straw due to concerns about soil quality when the residues are removed from the field. Returning biochar to the agricultural fields may alleviate these concerns but there are no conclusive findings yet on the impacts of biochar on crop responses and on fertilizer use. More details will be discussed in Chapter 7.

current biochar project. The yields of pyrolysis products from the Polagye studies, in weight percentage of dry biomass, are: volatiles, 59.9%; reaction water, 10.8%; char, 15.4%; ash, 0.8%; and light gas, 13.1%. Bio-oil yield is comprised of volatiles, reaction water and feedstock water. All biochar is burned for process heat.

Table 6.2 shows the yields of biochar and bio-oil produced by each type of facility. All four facilities have the same biochar yield and they differ only in the net yields of bio-oil. The difference is due to some amounts of bio-oil that are used in a diesel engine for process electricity (in mobile and transportable facilities) and burned in the suspension combustor for process heat (in all facilities). The net yield of bio-oil is lower when no biochar is used for process heat because more pyrolysis bio-oil will be used to make up for the loss in the energy contribution of biochar.

Table 6.2. Yields of biochar and bio-oil from fast pyrolysis.

Facility	Char Yield (metric tons)	Bio-oil Yield (gallons)					
		If all biochar is burned for process heat			If no biochar is burned for process heat		
		Total yield	Supp-lemental bio-oil	Net Yield	Total yield	Supp-lemental bio-oil	Net Yield
Mobile	84,392	98,631,476	27,085,502	71,545,973	98,631,476	44,793,443	53,838,033
Transportable	84,392	98,631,476	16,585,977	82,045,498	98,631,476	23,273,703	75,357,773
Stationary	84,392	98,631,476	6,108,426	92,523,049	98,631,476	23,816,367	74,815,109
Relocatable	84,392	98,631,476	6,108,426	92,523,049	98,631,476	23,816,367	74,815,109

Source: Polagye (2009). Notes: The reactor exit temperature is 850 K or 576.85 degrees Celsius. Supplemental bio-oil refers to amounts of bio-oil burned in diesel engine generator for process electricity (mobile and transportable facilities), and burned in suspension combustor for process heat (all facilities).

Furthermore, we assume that biochar is marketable and sold as a source of energy or soil amendment. Hence, we zeroed out the contribution of biochar combustion to process heat. This departs from the assumption in the Polagye studies with regard to biochar use. However, we employ other assumptions from Polagye regarding the type and source of feedstock and characteristics of different production facilities, as described below:

Feedstock and source

The Okanogan National Forest on the east slope of the Cascade Mountains in Washington has nearly 800,000 acres at risk to wildfire. The annual acreage thinned is assumed at 80,000 acres per year for 10 years, corresponding to 1,096,000 wet tons of forest thinnings per year. The cost of cutting and transporting the thinnings to the logging deck is assumed to be $20 per wet ton thinned[11]. Each deck covers an area of 20 acres and is located 2 km away from other decks. The thinnings are then loaded into container trucks and transported to the production facility, except the mobile facility since it is assumed to be located at the logging deck. The different production facilities are further discussed below. It is also assumed that the thinnings are chipped and debarked at the production facility before conversion to biochar and bio-oil. Debarking is done due to the high ash content of bark that can adversely affect the composition of the bio-oil yield.[12]

Production facilities

The suitable location for a production facility will depend not only on the fixed and variable costs of production, but also costs of forest transportation (delivering feedstock from the logging deck to the transfer point or facility) and costs of long-haul transportation (delivery of product to end-users). For example, production by a small-scale facility at the logging deck will incur lower forest transportation costs compared to production at a larger but more distant facility; however, the outputs at the logging deck will also be relatively lower. The trade-off issues in transportation and production are studied by considering four types of facilities — mobile, transportable, relocatable and stationary. Transportation options are illustrated in Appendix C Figure C1, and the associated assumptions are summarized in Appendix C Table C2 (Polagye *et al*., 2007; Polagye, 2009).

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[11] Currently, the U.S. Forest Service oversees forest thinning on federal land. For example, the Wenatchee-Okanogan National Forest office awards at least 6 or more thinning contracts annually. They also have recently implemented the biomass utilization stewardship project, which is a trial project. They contracted a Post Falls, ID company to remove the slash left behind after thinning and fuel treatment projects on the Tonasket Ranger District. The slash is chipped onsite and delivered to a power plant in Kettle Falls, WA. The contract value is about $130,000-$140,000. In addition to the above projects, there are also Eastern Washington Woody Biomass Removal Contracts awarded in late April 2009. Activities include slash removal from landings, noncommercial thinning and fuels reduction treatments, commercial thinning with removal of primarily non-sawtimber products, and gathering and removal of existing slash from within stands. Awards were made to twelve contractors, and the maximum value of awarded contracts is $416,000 each award (B. Flatten, Wenatchee-Okanogan National Forests, 2009, personal communication). For more details, see: https://www.fbo.gov/index?s=opportunity&mode=form&id=82f5af726f3dcafd2cfc2b15b48bf0cd&tab=core&_cview=1.

[12] Bark is assumed to remain in the forest (at or around the logging deck) for the case of the mobile or transportable facility. The bark may be dispersed on-site which can potentially provide nutrient benefits to the forest. For facilities located outside the forest, i.e., relocatable/stationary, it is assumed that the bark will be disposed. However, the disposal mechanism and the cost involved in the dispersion or disposal of bark are not included in the Polagye study.

Mobile unit: The facility has a capacity of 10 dry tons per day (DTPD) and is located at the logging deck. It is assumed that the system is mounted on a semi-trailer truck. Given that thinning a large forest requires multiple logging decks, a mobile unit remains at a logging deck until all available thinnings there are processed, then it will move to another logging deck (i.e., 23 moves per year). Daily production requires a three-shift operation, with an average of 1.7 personnel on-site during each shift.[13] Power is supplied by a diesel generator since the mobile unit is located in a remote area and has no access to grid electricity. The facility's lifetime is assumed to be no more than 15 years due to the heavy wear and tear from moving to several decks in a given year. The number of units necessary to process the annual thinning yield is 196.[14]

Transportable unit: It has a capacity of 100 DTPD and is located at a more central location in the forest. It is assumed that the system is transported by three semi-trailer containers and assembled on-site. The facility is assumed to move three times per year. Similar to the mobile unit, a diesel generator is also used for power supply and the facility's lifetime is no more than 15 years. Daily operations require three shifts with two personnel during each shift. However, additional cost is incurred by transporting the feedstock from the logging deck to the location of the facility (see appendix C figure C1). Twenty one units are necessary to process the annual thinning yield.[15]

Relocatable unit: The facility has a capacity of 500 DTPD and is located outside the forest area. Daily operations are done in three shifts and six operators are needed per shift.[16] It has access to grid electricity. The system's design allows it to be readily broken down and assembled in another site at the conclusion of the thinning operation. This gives it an advantage over the stationary unit since its flexibility alleviates operating difficulties that may be caused by disruptions in the long-term feedstock supply. However, additional costs are incurred for the set-

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[13] There are three shifts of operation, but during one shift a logging crew will be on-site: $(2+2+1)/3 \approx 1.7$.

[14] Number of required mobile units = $\frac{\text{Annual tonnage thinnings}}{\text{Annual consumption of a single unit}} = \frac{1{,}096{,}000{,}000\,\text{wet kg}}{5{,}618{,}943\ \text{wet kg}} = 195.1$.

This number is rounded to 196 physical units that are required; however, one unit would operate 10% of the time and sit idle the other 90%. As a result, fixed operating costs and annualized capital cost will be incurred per year but the variable operating costs will only be incurred 10%.

Using the above calculation, if Ferry County is the feedstock source where the available thinnings per year is 138,873 dry tons (see figure 6.3) or 277,746 wet tons (assuming feedstock has 50% moisture content), the number of mobile units required to process the available thinning is 50. If Yakima County is the feedstock source, 14 mobile units are required to process the 37,426 dry tons (or 74,852 wet tons) of available thinnings. King, Whatcom and Skagit counties have small amounts of forest thinnings (less than or equal to 2,809.47 dry tons per year) and would require 1 mobile unit.

[15] Number of required transportable units = $\frac{1{,}096{,}000{,}000\,\text{wet kg}}{54{,}518{,}750\,\text{wet kg}} = 20.1$, rounded to 21 physical units. The same assumption on availability and costs incurred as in the footnote above.

[16] Two operators per shift at 100 tons per day. Given a rated capacity of 500 DTPD, the required number of operators = $2*(500/100)^{0.6781} \approx 6.0$.

up and breakdown of the relocatable unit on top of the cost of transporting the feedstock from the logging deck to the relocatable facility. The estimated lifetime of the facility is 20 years. Four physical units are required to process the assumed annual thinning yield.[17]

<u>Stationary unit:</u> The capacity depends on the area thinned, but Polagye *et al.* (2009) assumed this at 1,816 DTPD for the case of 80,000 acres thinned per year. Only one unit is required to process the annual thinning yield. It is built outside the forest area and has access to grid electricity, similar to the relocatable facility. There are three shifts of operation per day requiring an average of 14.3 operators per shift.[18] Additional cost is incurred for transporting the feedstock to the facility due to its distant location from the forest edge. There is also an issue about the lack of flexibility of the stationary unit with the availability of feedstock. When feedstock supply in a given area is exhausted, the facility cannot be easily moved to another site thereby the feasibility of a stationary unit comes into question in the face of feedstock supply disruption. It is assumed that the lifetime of the facility is tied to the thinning duration (10 years).

The technical availability of each facility is assumed to be 85% to allow for scheduled maintenance and/or unexpected outages (or 20.4 hours per day on average). There are 335 working days per year for mobile and transportable systems, and 355 for relocatable and stationary facilities. Other details about each facility are given in Table 6.3.

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[17] Number of required relocatable units = $\frac{1{,}096{,}000{,}000 \text{wet kg}}{295{,}710{,}938 \text{wet kg}} = 3.7$, rounded to 4 physical units. The same assumption on availability and costs incurred as in the footnotes above.

[18] Two operators per shift at 100 tons per day. Given a rated capacity of 1,816 DTPD, the required number of operators = $2*(1816/100)^{0.6781} \approx 14.3$.

Table 6.3. Characteristics of production facilities.

	Mobile	Transportable	Relocatable	Stationary
General				
Footprint	Semi-trailer	Multiple semi-trailer containers (e.g., 3)	Standard industrial site	Standard industrial site
Rated capacity	10 DTPD	100 DTPD	500 DTPD	Variable[a]
Location	Logging deck	In forest	Outside forest	Outside forest
Feedstock transportation[b]	N/A	45 km*	60 km	60 km
Facility				
Lifetime	15 years	15 years	20 years	Variable[c]
Construction period	None	None	1 year	Variable[d]
Salvage value (% of total plant cost)	0%	0%	0%	20%
Facility operation				
Working hours per day[e]	24	24	24	24
Working days per year[f]	335	335	355	355
Technical availability[g]	85%	85%	85%	85%

Source: Polagye, *et al.* (2007), Polagye (2009).

*From Polagye (2009). All remaining numbers in Table 6.3 are from Polagye, *et al.* (2007)

[a] Depends on area thinned. For the case study, this is 1,816 DTPD based on 80,000 acres thinned per year.

[b] Transportation from logging deck to production facility.

[c] Same as thinning duration = 10 years.

[d] Depends on scale: ≤ 500 DTPD = 1 year; ≤ 1,000 DTPD = 2 years; ≤ 1,500 DTPD = 3 years; > 1,500 DTPD = 4 years.

[e] Three-shift operation, 2 operators per shift; hourly salary including benefits = $30/hr.

[f] Mobile and transportable: 365 days minus 10 holidays and 20 days of extreme weather. Stationary and relocatable: 365 days minus 10 holidays.

[g] A system will not always be available for operation due to scheduled downtime for maintenance and/or unexpected outages.

6.3.3. Enterprise budgets for production of biochar and bio-oil

The enterprise budgets presented here represent the estimates of revenues, total costs and returns incurred by different types of facilities: mobile, transportable, relocatable and stationary, in producing biochar and bio-oil. *Revenue* is obtained by the sale of outputs. *Total cost* is the sum of two general cost components: *fixed costs*, which do not vary with the level of output; and *variable costs*, which vary with output within a production period. *Return* or profit is equal to total revenue minus total cost.

Table 6.3. Characteristics of production facilities (continued).

	Mobile	Transportable	Relocatable	Stationary
Mobility economics				
Mobility capital	Semi-trailer: $60K	Containers: $200K	N/A	10% of total plant cost
Feedstock storage	N/A	0.19 ha[h]	0.98 ha[h]	N/A[h]
Setup/breakdown time	4 hours (2 hr each)	4 days (2 days each)	2 months	N/A
Setup/breakdown charge (% of total plant cost)	0%	1%	10%	N/A
Mileage charge	$1 per km	$3 per km	$100 per km	N/A
Moves per year[i]	23[j]	3	1 per thinning duration	N/A
Site separation (km)	2	50	750	N/A
Transport speed (km/hr)	40	40	80	N/A
Capacity factor[k]	77%	75%	81%	83%

Source: Polagye, *et al.* (2007).

[h] Concrete pad for on-site storage of feedstock (transportable: 14 days storage; stationary and relocatable: 28 days). Pad cost estimated at $100K at 1.2 ha (3 acres), scale factor = 0.5. Cost for this pad is included in the capital cost for stationary production.

[i] Base case of 80,000 acres per year.

[j] 300 hours to process feedstock from a single site plus transportation time = 22.5 sites/year within operational window.

[k] Defined as the fraction of a time a system operates at its rated capacity, taking into account the number of non-working days, time of transporting equipment from site to site, time of breaking down and setting up equipment, technical availability and working hours per day.

The various inputs for production are based on Polagye *et al*. (2007) and Polagye (2009). Since the costs of inputs in these studies are in 2004 US dollars, we adjusted the input costs to 2008 US dollars or used published 2008 data. Skog *et al.* (2008) provides supply estimates of forest biomass resources in Washington (and other Western states), including forest thinning. The roadside costs[19] of forest thinning assumed in the study range from $10/dry ton to $200/dry ton. The lower end of the range is chosen as the price of feedstock in the enterprise budgets (Table 6.4).[20] The prices of energy and labor are taken from published statistical reports for 2008. Other input costs are adjusted by using the implicit price deflators (IDP) for these two years (BEA, 2009)[21]:

$$Cost_{2008} = Cost_{2004} \times \left(\frac{IDP_{2008}}{IDP_{2004}} \right).$$

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[19] Roadside cost is the cost to harvest and move wood to roadside.

[20] If the price of forest thinning is in the higher range, it is likely that a potential producer of biochar and bio-oil may not find production viable because the feedstock is too expensive.

[21] Implicit GDP deflators in 2004 and 2008 are 109.454 and 122.415, respectively.

Table 6.4. Prices of selected inputs.*

Selected Inputs	Unit	2004 data from Polagye studies**	Used for the Case Study (2008 figures)		
		$/unit	$/unit	Note	Source
Feedstock cost	Wet ton	20.00	20.00	Or $10/dry ton***	/a
Diesel fuel	Gal	2.50	3.80	Diesel (On-Highway) - All Types	/b
Oil	Gal	2.00	3.30	Gasoline - All Grades	/b
Grid electricity	kWh	0.06	0.07	Ave. retail price - Industrial	/c
Labor	Hour	30.00	30.00	WA Department of Labor and Industries	/d

* Complete details on input costs by type of facility are given in appendix tables C3-C6.

**Polagye *et al.* (2007) and Polagye (2009).

*** Thinning is assumed to have a 50% moisture content. 1 wet ton of thinning = 0.5 dry ton of thinning (Polagye, 2005). *Price/wet ton* is converted to *price/dry ton* based on the relative weight of thinning.

Sources of 2008 data: /a Skog *et al.* (2008); /b EIA (2009a) - Annual Retail Gasoline and Diesel Prices, Cents per gallon including taxes (http://tonto.eia.doe.gov/dnav/pet/pet_pri_gnd_dcus_nus_a.htm); /c EIA (2009b) Average Retail Price of Electricity to Ultimate Customers: Total by End-Use Sector, Cents per kWh (http://www.eia.doe.gov/cneaf/electricity/epm/table5_3.html); /d Washington State Department of Labor and Industries (2008) - The 2008 prevailing wage in Washington State for a general laborer is $30.36 per hour, rounded to $30 per hour. See http://www.lni.wa.gov/PrevailingWage/jwages/20082/Labo.asp.

Joint costs and returns

A summary of cost and returns incurred by the joint production of biochar and bio-oil under each type of facility is given in Table 6.5. *Variable cost* refers to the operating cost and includes the cost of feedstock, hourly labor and power. Power cost pertains to the cost of fuel and maintenance of diesel engine generators used by mobile and transportable facilities, and to purchased electricity for stationary and relocatable facilities. Other variable costs include maintenance, overhead, ash disposal, mobility expenses (transfer of unit from one site to another), and loading, unloading and chipping of the feedstock. *Fixed costs* are annualized capital costs of the loader, chipper, debarker and fast pyrolysis unit. Variable costs and fixed costs, combined, equal *total cost. Total revenue* is the sum of revenues (price *times* quantity produced) of biochar and bio-oil.

The price of biochar is approximated by the relative energy content of biochar and coal. A wood based biochar has an energy content of 12,000-12,500 BTU/lb (Dynamotive, 2007a). It is close to the energy content of the Central Appalachian coal (12,500 BTU/lb) with a price of $116.38 per metric ton as of 2008 (EIA, 2009c). If we use the average energy content of biochar (12,250 BTU/lb), the combustion value of biochar is assumed at $114.05/metric ton or 98% that of Central Appalachian coal.

Table 6.5. Summary of joint annual costs and returns for bio-oil and biochar production, by type of facility, US$ per ton of feedstock[1].

	Mobile	Transportable	Relocatable	Stationary
Biochar				
Yield (tons)	84,392	84,392	84,392	84,392
Price ($/ton)	114.05	114.05	114.05	114.05
Bio-oil				
Yield (gallon)	53,838,033	75,357,773	74,815,109	74,815,109
Price ($/gallon)	1.06	1.06	1.06	1.06
Revenue ($ per ton of feedstock)	121.70	163.33	162.28	162.28
Pre-treatment capital cost, total[2] ($ per ton of feedstock)	39.82	16.44	8.41	6.41
Grinding capital cost	*1.13*	*0.37*	*0.13*	*0.09*
Total Production cost excluding long-haul transportation ($ per ton of feedstock)[3]				
Total Cost (TC)	372	215	178	158
Returns over TC	-251	-52	-16	4
Variable Cost (VC)	266	155	137	124
Returns over VC	-144	8	25	38
Total Production cost including long-haul transportation ($ per ton of feedstock)[4]				
Total Cost (TC)	424	231	174	194
Returns over TC	-302	-68	-32	-12

1 Feedstock (forest thinning) = 548,000 dry tons

2 Pre-treatment capital cost includes the capital costs of fuel handling, grinding, drying and burner.

3 This represents the cost of the joint production of biochar and bio-oil, incurred by the producer. Production cost and returns are rounded to the nearest whole number.

4 This assumes that the producer will shoulder 100% of the cost of long-haul transportation of bio-oil from forest edge to the end-user. Production cost and returns are rounded to the nearest whole number.

As mentioned earlier, bio-oil is considered a substitute for No. 2 heating oil or No. 6 residual fuel oil but it is closer to the No. 6 fuel oil based on their fuel properties (see appendix C table C7). The spot price of No. 6 fuel oil in 2008 was about $2.11/gallon. The calorific values of No. 6 fuel oil and wood based bio-oil are 42.5 MJ/kg and 16 MJ/kg[22], respectively; and the respective densities (at 15°C) are 0.986 kg/liter and 1.2 kg/liter (Czernik and Bridgewater, 2004; Dynamotive, 2007b). Based on the relative calorific properties, the price of bio-oil should be $1.06 per gallon.[23]

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[22] The calorific value (or high heating value – HHV) of wood based bio-oil ranges between 16 and 19 MJ/kg. The minimum value (16 MJ/kg) is used in the case study.

[23] To estimate the price of bio-oil based on its relative energy content with respect to No. 6 Residual Fuel Oil, the following conversion factor is used: $\frac{\$2.11}{gallon} \div \left(\frac{42.5\ MJ\ kg^{-1}}{17.5\ MJ\ kg^{-1}}\right)\left(\frac{0.986\ kg\ liter^{-1}}{1.2\ kg\ liter^{-1}}\right) \approx \frac{\$1.06}{gallon}$. (Source: Conversion factor from M. Garcia-Perez, personal communication).

Assuming an expected yield of 84,392 tons of biochar for $114.05 per ton and a price of $1.06/gallon for bio-oil and corresponding yield per facility, only the stationary facility is found to be profitable. On the other hand, the total net losses *per ton of feedstock* are about: $251 for a mobile facility; $52, transportable; and $16, relocatable. These figures exclude the long-haul transportation cost of bio-oil to end-users. If, however, the producer would entirely pay for the long-haul transportation expenses[24], the net losses per ton of feedstock become larger by a margin of $51 for a mobile facility and $16 for transportable, relocatable and stationary facilities. With long haul transportation cost, none of the facilities is profitable under current market conditions.

Although technically feasible, we know of no firms that are refining bio-oil commercially for the production of bio-gasoline, ethanol and phenols. If bio-oil refinement processes develop sufficiently to produce refined energy products, the competitive price for bio-oil may be higher in order to reflect the value of more highly-valued refined fuels. Bio-oil contains approximately 60% to 70% of the calorific value of fossil crude oil by volume. If we assume that the price received for bio-oil is approximately equal to fossil crude in terms of calorific value, and if crude costs $100/barrel ($2.38/gallon), bio-oil would be priced (in a competitive market) at approximately $1.43/gallon. This is higher than the $1.06/gallon used in the analysis above. If this higher price for bio-oil is applied to our enterprise budget, the returns over total costs (including bio-oil long-haul transportation costs) for the stationary, relocatable, transportable, and mobile units, respectively are $39, $19, $-17, and $-266 per ton of feedstock. It should be reiterated that these technologies have not been commercialized. This example simply approximates the energy value of bio-oil relative to gasoline if conditions were economically conducive to refining bio-oil.

A study by the Pacific Northwest National Laboratory (Jones *et al.*, 2009) analyzed the feasibility of producing bio-oil via fast pyrolysis and refining it into transportation fuels (gasoline and diesel). The study assumed a plant with a capacity of 2,000 dry tons per day of hybrid poplar wood chips, with production capacity of 76 million gallons of gasoline and diesel per year. This size is close to the capacity of the stationary facility in our case study. Jones *et al.* (2009) found that, with a stand-alone plant, the minimum selling price of gasoline and diesel was $2.04/gallon (2007 basis) to get a 10% return on investment. However, if the plant was co-located with a refinery, the cost of capital investment went down and the minimum selling price of transportation fuel was $1.74/gallon. The price of gasoline in 2007 ranged between $2.81/gallon and $2.91/gallon, while the price of diesel was $2.87/gallon to $2.94/gallon during the same year. If the future market supports the estimated fuel prices of the PNNL study, then bio-oil refining may be competitive with fossil crude oil refining.

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[24] Alternatively, the end-user could pay for all or share a portion of the long-haul transportation cost.

Cost allocation of joint products

A *joint cost allocation* was also done to further examine the profitability of each of the joint products by treating the revenue from one of the products as a credit (e.g., bio-oil revenue) and subtracting this revenue from the total cost of production[25]. What remains is an estimate of the production cost attributed to the other product (e.g., biochar).[26]

If bio-oil revenue is the credit, the estimated cost attributed to biochar production is equal to: $147 million for a mobile facility; $38 million, transportable facility; $18 million, relocatable facility; and $7 million, stationary facility. We solve for the profitability of biochar by calculating the break-even (BE) price of biochar: $\text{BE Price}_{\text{Biochar}} = \dfrac{\text{Total Cost} - \text{Price}_{\text{Bio-oil}}\ \text{Quantity}_{\text{Bio-oil}}}{\text{Quantity}_{\text{Biochar}}}$. At the break-even price, the costs equal revenue at a given production level. There is no loss or profit at this point, and all opportunity costs have been paid. Table 6.6 shows the estimated break-even selling prices of biochar. The first break-even price is the price required to cover variable costs (VC). Results show that the base price of biochar ($114.05/ton) is less than the VC break-even price of the mobile facility. This implies that it would not be economically viable to produce biochar this way, even in the short run, because the added costs of production are greater than the added returns.

Table 6.6. Break-even selling prices of biochar ($/metric ton), by type of facility.

	Mobile	Transportable	Relocatable	Stationary
Break-even price to cover variable cost	1,048	60	-48*	-134*
Break-even price to cover total cost excluding long-haul transportation cost	1,742	450	218	87
Break-even price to cover total cost including long-haul transportation cost**	2,077	554	322	191

Notes: Figures are rounded to the nearest whole number and are calculated given the base yield of biochar in Table 6.5 for each facility. The base price of biochar is $114.05/metric ton.

* A negative break-even price means that the bio-oil credit is substantially higher than the variable costs of production.

**This assumes that the long-haul transportation expenses are entirely shouldered by the producer.

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[25] Total cost *excludes* long-haul transportation expenses.

[26] There are other joint cost allocation methods, such as: (a) Physical Measure or Quantities Method, where joint costs are allocated to the joint products based on their relative physical measure (e.g., weight, volume, etc.); and (b) Sales Value at Split-off Method, where joint costs are allocated based on their relative sales value. For more details, see: www.csus.edu/indiv/m/mackeyjt/accy121/powerpoint/11ch16.ppt.

The second break-even price is what the producer needs to receive in order to recover the total costs of production, including cash costs, depreciation and opportunity costs for investments in machinery and buildings. As shown in Table 6.6, for the stationary facility, the price of biochar needs to be approximately \$87/ton in order to break even with respect to total production costs, given the base yield of biochar. The third break-even price refers to the price that should be received by the producer to cover the total production costs *plus* the long-haul transportation cost. For the stationary facility, it is estimated at \$191/ton. If the base price is greater than the break-even price, this means that in addition to covering all costs, a profit is earned such as in the case of the stationary facility. However, the other facilities did not earn a profit under the assumed parameters, because their total production costs are higher than the estimated economic value of biochar. The production of biochar is not economically feasible in the mobile, transportable and relocatable facilities since the estimated break-even prices are more expensive than the estimated market price of biochar (\$114.05/ton).

Now we treat biochar revenue as a credit toward the production of bio-oil using the allocation method described earlier. The cost that can be ascribed to the production of bio-oil is approximately: \$194 million for a mobile facility; \$108 million for a transportable facility; \$88 million for a relocatable facility; and \$77 million for a stationary facility. In order to assess whether it would be profitable to sell bio-oil, a break-even price is also measured:

$$\text{BE Price}_{\text{Bio-oil}} = \frac{\text{Total Cost} - \text{Price}_{\text{Biochar}}\ \text{Quantity}_{\text{Biochar}}}{\text{Quantity}_{\text{Bio-oil}}}.$$

Table 6.7 shows the estimated break-even selling prices of bio-oil. The break-even price to cover total variable costs (VC) is: \$2.52/gallon for a mobile facility; \$1.00/gallon, transportable facility; \$0.88/gallon, relocatable facility; and \$0.78/gallon, stationary facility. It is lowest in the stationary facility, where the VC break-even price is less than the assumed base price of bio-oil by a margin of \$0.28/gallon.

The break-even prices to cover total production costs range from \$1.03/gallon to \$3.61/gallon if long-haul transportation costs are excluded; and from \$1.15/gallon to \$4.14/gallon including long-haul transportation costs. The break-even prices of the mobile, transportable, and relocatable facilities are higher than the assumed current price of bio-oil, which is \$1.06/gallon. This implies that the smaller-scale facilities are not economically feasible to produce bio-oil at current market conditions. The market situation could improve if high value products were developed from bio-oil or if the bio-oil were refined to produce transportation fuels.

Table 6.7. Break-even selling prices of bio-oil ($/gallon), by type of facility.

	Mobile	Transportable	Relocatable	Stationary
Break-even price to cover variable cost	2.52	1.00	0.88	0.78
Break-even price to cover total cost excluding long-haul transportation cost	3.61	1.44	1.18	1.03
Break-even price to cover total cost including long-haul transportation cost*	4.14	1.55	1.29	1.15

Notes: Figures are rounded to the nearest hundredth and are calculated given the base yield of biochar in Table 6.5 for each facility. The base price of bio-oil is $1.06/gallon.

*This assumes that the producer shoulders all long-haul transportation expenses.

Figure 6.5 is based on the break-even prices needed to cover the total production cost excluding long-haul transportation cost. It provides a view of the break-even combinations of bio-oil and biochar prices. For example, if the producer can sell bio-oil at $1.15/gallon, the break-even price of biochar to cover total cost (excluding long-haul transportation) should be about: $7/ton when production is done in a stationary facility; $138/ton in a relocatable facility; $369/ton in a transportable facility; and $1,684/ton in a mobile facility. These prices are lower compared to the break-even prices of biochar when the assumed base price of bio-oil ($1.06/gallon) is utilized (Table 6.6).

Production costs in this case study do not include the land use or rent charges that will be incurred by establishing stationary and relocatable facilities. The costs also exclude any expenses associated with storing and transporting bio-char to end-users. More in-depth work is also needed to take into account any productivity losses or nutrient replacement costs from removing the forest thinnings; and any productivity increase if biochar is returned to the forest area where biomass originated or delivered to farmers for use as soil amendment in agricultural fields.

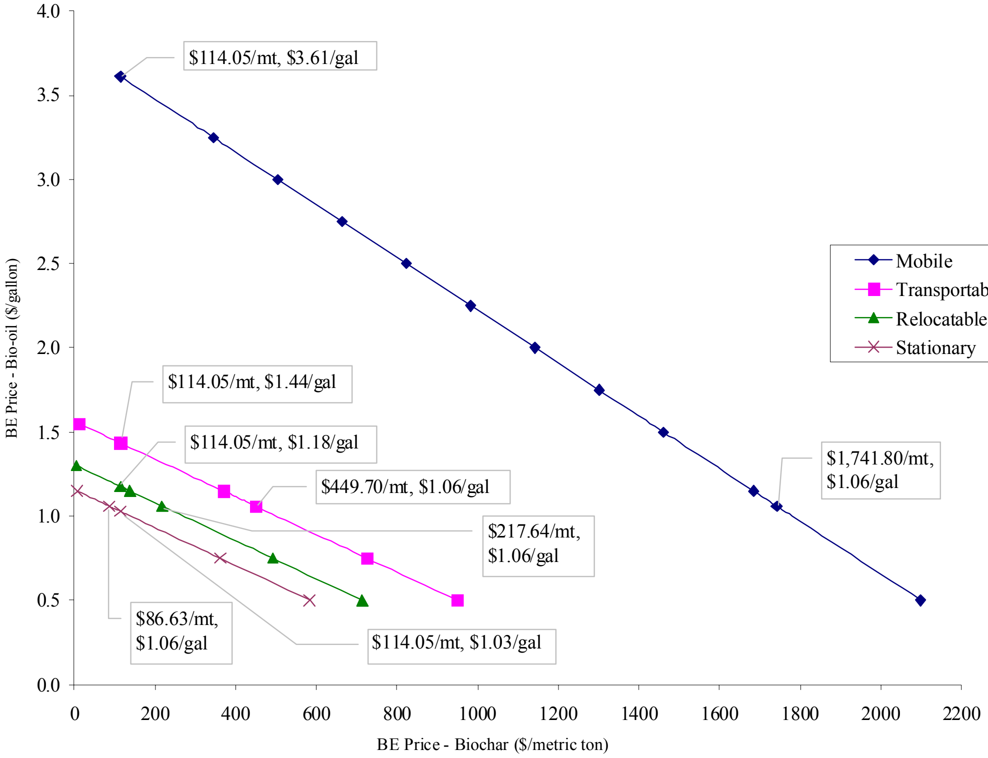

Figure 6.5. Break-even (BE) prices of biochar and bio-oil, various combinations.

Note: For example, under the mobile facility (farthest line to the right) and given the base price of biochar equal to $114.05/metric ton, the producer will break even if the price of bio-oil is $3.61 per gallon. If, however, the price of bio-oil is $1.06 per gallon, the producer will need to sell biochar at a price of $1,741.80/metric ton in order to break-even.

6.3.4. Simulated feasibility scenarios

The analyses presented so far show that only the stationary facility is economically feasible under the assumed parameters and current market conditions. Table 6.8 shows the various cost items as percentage of total cost (including in-forest transportation).[27] Substantial shares in the total production cost are attributed to feedstock handling, labor, capital cost and transportation cost. Feedstock handling and transportation costs increase with the distance of the facility from the feedstock source. Labor cost and capital cost are highest in the mobile facility.[28]

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[27] In-forest transportation refers to the transport of feedstock from logging deck to the facility.

[28] Recall from Section 6.3.2 of this study that 196 mobile units are needed to process the annual thinning yield. Furthermore, there are three shifts of operation on site, requiring an average of 1.7 workers per shift (i.e., [2+2+1]/3 ≈ 1.7) per mobile unit.

In this section, we discuss the scenarios under which a pyrolysis facility will be profitable. The three key variables that should be noted are the: proximity of the facility to the feedstock source leading to cost savings; cost of feedstock; and cost of transporting the feedstock to the facility.

Table 6.8. Cost item as a percentage of the total production cost, by facility.

Item	Mobile (10 DTPD)	Transportable (100 DTPD)	Relocatable (500 DTPD)	Stationary (1816 DTPD)
Operating or Variable Costs				
Feedstock handling	14.28%	23.44%	28.28%	31.70%
Biofuel production:				
Fixed Operating Cost	10.33%	9.13%	7.35%	4.28%
Variable Operating Cost	43.80%	20.49%	15.73%	13.59%
Power	*1.92%*	*3.17%*	*8.08%*	*9.11%*
Labor	*41.87%*	*8.97%*	*5.94%*	*4.33%*
Other	*0.005%*	*8.35%*	*1.71%*	*0.14%*
Total Variable Cost	68.42%	53.05%	51.36%	49.56%
Fixed Costs (Annualized capital cost)				
Other capital cost	0.53%	0.91%	1.15%	1.41%
Biooil and biochar production capital cost	27.65%	24.43%	18.75%	16.62%
Total Fixed Cost	28.18%	25.33%	19.90%	18.03%
In forest transportation				
Capital cost (truck)	0.50%	2.54%	3.09%	3.48%
Operating cost	2.90%	19.07%	25.65%	28.92%
Total Forest Transportation Cost	3.40%	21.62%	28.74%	32.40%
Total Variable Cost –incl. forest transportation	**71.32%**	**72.12%**	**77.01%**	**78.49%**
Total Cost – incl. forest transportation	**100.00%**	**100.00%**	**100.00%**	**100.00%**

DTPD means "dry tons per day"; refers to the capacity of the facility.
Note: See Appendix C Table C8 for more details.

***Location of pyrolysis facility on the feedstock site*.** Following Dynamotive's organization as a model (see Section 6.3.5 below), we can approximate the facility's cost-saving characteristics if we remove the operating and capital costs associated with: feedstock harvest (assuming the feedstock is a waste product provided to the facility at no charge), feedstock handling (deck loading and facility unloading) and delivery of feedstock from log deck to the processing facility. For a transportable, relocatable or stationary facility located on the feedstock source, the result is that the returns over variable cost and total cost are positive. The mobile facility, on the other hand, remains not economically feasible even with the above cost savings. In part, this is due to the small capacity of the mobile facility (10 tons per day) relative to the other facilities.[29] The extent to which firms can reduce capital and operating costs along the lines of the examples provided above will reduce the break-even prices examined in our analysis. Thus, for operations that can capitalize on such cost savings, the cost estimates developed here will tend to be high.

***Feedstock cost*.** At the assumed price of $20 per ton of feedstock (thinnings), the feedstock cost ranges from approximately 11% to 25% of the total production cost. The stationary facility is found to be economically profitable at this price but it will not be profitable if the price of thinning is more than $22.11 per ton. *Holding other variables constant*, the relocatable facility becomes profitable if the price of feedstock lies between $0 and $13 per ton (Figure 6.6). Removal of forest thinnings, especially in overstocked forests, lessens the risk of wildfires and maintains the health of forests. Prevention of wildfires leads to social and private economic benefits. It is possible that the price of thinnings may be negotiated with the forest management agency so that the price will be lower than we assumed in our study. The transportable and mobile facilities, in contrast, are not profitable even if the feedstock is free.

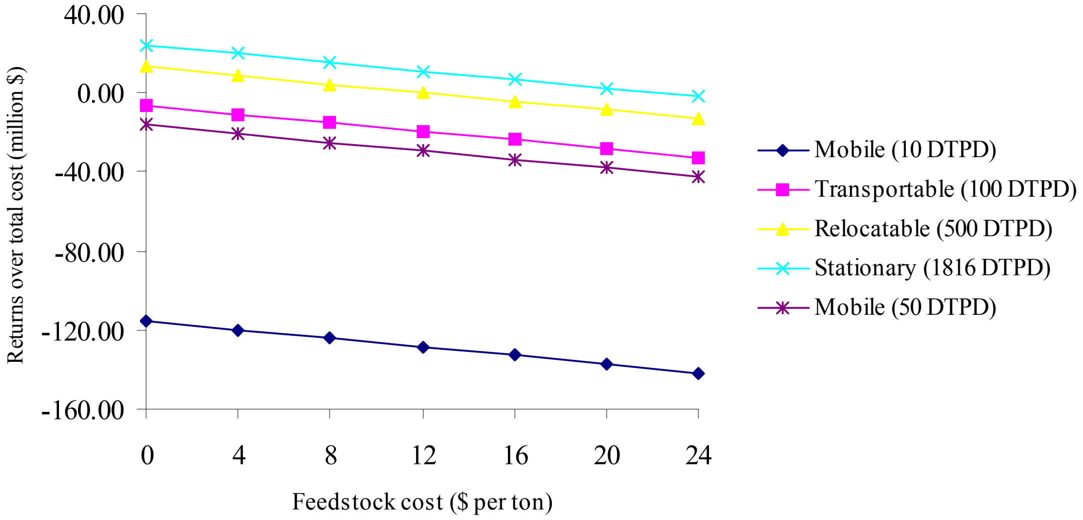

Figure 6.6. Feedstock cost and returns over total cost.

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[29] Same result is found even if the capacity of a mobile facility is increased from 10 tons per day to 50 tons per day.

Transportation cost. Moving the facility closer to the location of the feedstock source reduces the transportation cost. The transportable facility is not feasible even if the transportation cost is zero. For a relocatable facility to be feasible, the transportation cost has to be reduced by at least 32 percent, *while holding other variables constant* (Figure 6.7). Building a relatively large facility inside the forest area will likely be infeasible because of the large area that would have to be cleared. If transportation cost savings will be used as a feasibility indicator, it might be more appropriate to set up a relocatable facility in another site or source of feedstock. For example, the Dynamotive facility in Ontario built a bio-oil cogeneration facility on the site of Erie Flooring and Wood Products. Hence, the site of a plant that processes wood products (e.g., pulp and paper mill) and generates sufficient wood residues as feedstock may be a potential location that is feasible for this type of facility. Recall that a relocatable facility has a capacity of 500 tons per day. It can also be considered a small-scale stationary facility if it is co-located with a mid-size plant, such as a pulp and paper mill. In Washington, there are 18 pulp and/or paper mills (CPBIS, 2007). Skog *et al.*(2008) estimated a total of 5.3 million dry tons of mill residues generated annually in the State. Hence, on average, a mill is estimated to produce about 826 dry tons of residue per day, which can be handled by a relocatable/small-scale stationary facility.[30]

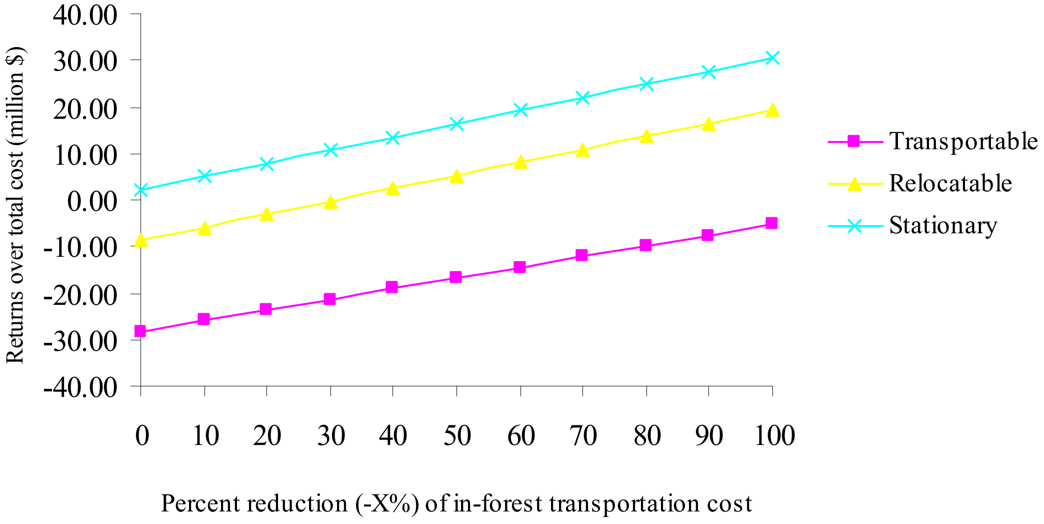

Figure 6.7. Transportation cost and returns over total cost.

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[30] Calculated as follows: (5,278,351 dry tons of mill residues ÷ 18 plants) ÷ 355 days ≈ 826 tons of mill residue per plant per day. It is assumed that the plant operates 355 days a year (365 days minus 10 holidays). It should be noted, however, that the utilization rate of mill residues in existing markets is about 95 percent according to Frear (2008). Skog *et al.* (2008) finds that most of the mill residues are currently used as fuel byproducts and fiber input for pulp or panels; and that un-used residues account for only 0.4% of the total mill residues.

Mobile and transportable facilities

Results show that neither the mobile nor the transportable facility is viable given the scenarios where the feedstock cost and transportation cost are zero. If the capacity of a mobile facility were increased from 10 to 50 dry tons per day, we find that it is still not viable although the net losses are much lower compared to that of the smaller facility (Figure 6.6).

For a mobile facility, cost savings in both feedstock and transportation are not enough to make it economical. These low or negligible costs would have to be accompanied by a reduction in the cost of other variables in order to be viable; such as, lower capital costs due to the development of a more efficient, lower cost technology, or a larger relative advantage for dealing with biochar transportation and marketing. A transportable facility, on the other hand, will be viable given a combination of reductions in feedstock cost and transportation cost. For instance, if the price of feedstock is $12 per ton, the transportation cost needs to be reduced by about 85 percent. If the feedstock is free, a reduction in transportation cost by at least 28 percent is needed. If the transportation cost is zero, the feedstock cost should not be more than $15.23 per ton in order to earn a profit.

Summary of results

The above analyses can be summarized as follows:

1. The mobile facility is not economically feasible under the assumptions used here mainly because the capital cost and labor cost are substantially higher.
2. The transportable facility, with a capacity of 100 tons per day, can be established on the site of the feedstock that can provide a minimum of 33,500 tons of feedstock per year. However, the facility will be viable if there are reductions in both the transportation cost and feedstock cost.
3. The relocatable facility in this case study is assumed to be 60 km away from the logging deck (see also Appendix C Table C2 and Figure C1). At this distance, the facility will be viable if the feedstock cost is not more than $12 per ton, holding other variables constant. If we consider the transportation cost, holding other things equal, it has to be reduced by about 32 percent in order to be profitable, which may mean setting up the facility about 40.8 km from the logging deck.
4. The stationary facility is found to be economically feasible. The feedstock cost should not be higher than $22.11 per ton, otherwise the facility will not be profitable. The size of the facility is too big to be co-located with a mid-size feedstock source such as a pulp and paper mill. To maximize its capacity, nearly 2,000 tons per day of feedstock need to be available in a single location. Otherwise, the facility will have to obtain biomass from other sources.

6.3.5. Comparisons to existing commercial pyrolysis enterprises

Dynamotive Energy Systems Corporation, an energy solutions provider headquartered in Vancouver, B.C., Canada, has built a pyrolysis plant in Ontario and has recently executed a contract with Arkansas to develop a bio-oil plant. It also has projects commissioned in Australia and Brazil. What are the factors that make them thrive when other studies show unfavorable economics for the pyrolysis of biomass? Dynamotive's pyrolysis process produces gas, char and bio-oil but bio-oil is the main saleable product, being marketed as a fuel source for electricity generation or a potential substitute for conventional heating oil.

Factors that support the company's viability are its location at the feedstock source and financial incentives from the government and other partners or sponsors. Dynamotive's stationary pyrolysis facility located at the feedstock source ensures a steady supply of feedstock and transportation savings. There are also savings on feedstock handling since their partner company (the feedstock source) takes care of this process. Note that in our case study, mobile facilities have the lowest in-forest transportation cost (involving log deck loading and facility unloading) because it is operating at the feedstock source, i.e., about 76 percent lower than the in-forest transportation costs of the other facilities.

There are often numerous unique vertical and horizontal coordination opportunities that the general model presented in this chapter does not incorporate. For example, Dynamotive's West Lorne, Ontario bio-oil cogeneration facility is a pyrolysis plant located on the site of Erie Flooring and Wood Products, which can produce about 100 tons of sawdust and wood chips per day. Erie supplies the biomass (surplus sawdust); and the West Lorne facility converts the biomass into bio-oil, gas and char. Bio-oil is used to fuel a turbine that produces heat and 2.5 MW electricity for the pyrolysis plant and flooring mill, and provides steam to dry the flooring mill's wood. Any remaining electricity is sold into the provincial grid under contract. The 2.5 MW generator can provide 300 to 1,300 kW of electricity to the distribution system (Hamilton, 2006; Dynamotive, 2005).

In Dynamotive's Arkansas operation, a long-term contract (10 years) has been executed for the supply of feedstock (sawdust) for a planned 200 TPD Bio-oil plant to be developed in southern Arkansas. The contract was entered with Springhill Land and Timber, a leading producer of timber in the southeast which has a cooperative working relationship with over 25 hardwood sawmills in a four state area (Dynamotive, 2009b).

Financial incentives from the government are also a factor. Ontario's *Renewable Energy Standard Offer Program* (SOP) is designed for operators of small renewable energy generating facilities. Under the program, they will participate in Ontario's electricity supply system by supplying power through their local electricity distributors. They are also paid a stable price for the power they provide. In 2007, Dynamotive signed a contract with the Ontario Power Authority to supply renewable power under the province's SOP. The terms of the contract specify that Dynamotive will deliver electricity to the grid from its 2.5 MW cogeneration facility at West Lorne. Dynamotive will sell renewable power to the grid at 11.08 cents (Canadian) per kilowatt hour for up to 20 years (Dynamotive, 2007c; Ontario Power Authority, 2009). This program guarantees a market for Dynamotive.

In Arkansas, the state expanded its comprehensive Alternative Fuels Program by increasing funding for feedstock processors from $2 million to $3 million annually. Under this program, alternative fuel distributors will receive $300,000 in grant funding; and production incentives under this program remain financially attractive — $2 million in grant funding may be used for capital investment and/or operations costs. Dynamotive has a subsidiary in the U.S. and will apply to this program (Dynamotive, 2009a).

Partners and sponsors can also provide financial support for pilot/demonstration projects. Financing was crucial to develop Dynamotive's technology, demonstrate how it works and confirm bio-oil's potential as a substitute for conventional oil. The European Commission-Joule Program and the Department of Trade and Industry (in the United Kingdom) provided support to Dynamotive's subsidiary in Europe. Dynamotive also received support from the British Columbia (BC) Advanced Systems Institute, a private company which invests in local technology companies (Dynamotive, 2001). The company has received and continues to receive financial support for research and development from the Federal Government of Canada through the Technology Partnerships Canada (TPC), National Resources Canada (NRCan) and National Research Council of Canada (Dynamotive, 2009b).

6.3.6. Potential biochar transportation savings for soil amendment

The analysis above assumes that biochar will be used as an energy source, and the price (or value) received by the biochar processor is the same across all facility types.[31] As such, biochar transportation costs are not explicitly considered in the above analysis. In fact, depending on the final use of biochar, these transportation costs may be important for the scale of biochar and bio-oil production. In particular, Chapter 7 below examines the use of biochar as a soil amendment. Even if carbon offset credits are available as discussed below, biochar application to land for any of myriad uses is likely to be subject to diminishing returns to application. The result is that biochar transportation costs are likely to be higher for stationary processing facilities than for more mobile processing facilities. Indeed, it seems very plausible that a mobile unit could travel to a biomass site, utilize the biomass through pyrolysis, reapply the biochar on site, and then

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[31] Furthermore, we assume free disposal of ash from the use of biochar for energy.

transport only the energy-dense bio-oil offsite. In contrast, a stationary unit (in conjunction with the users of biochar) would have to incur more biochar transportation costs than would be incurred under a mobile unit in this setting.

If we apply this scenario to our analysis above, the differences in the break-even prices for biochar under the different production facility types are relatively modest because in this enterprise budget, biochar production is assumed to be only 15.4% biochar per unit of feedstock. If unit costs of transporting biochar are assumed to be the same as feedstock transportation costs, and if we assume that biochar will be backhauled to the original feedstock source, this will add 15.4% to feedstock transportation costs. These costs are highest for the stationary processing units and become lower as mobility increases, with zero additional costs for the mobile unit given that the biochar will be produced on the feedstock source site. Adding this additional transportation cost increases the break-even price of biochar by 27% for the stationary processing units (including long-haul costs of bio-oil), by 16% for the relocatable unit, by 7% for the transportable unit, and by 0% for the mobile unit.

Suppose that biochar were to play a more central economic role due to a higher relative biochar price. For example, if slow pyrolysis at low final temperatures were used, then biochar production would be larger, perhaps around 25-30% based on results in Chapter 5.[32] Given this scenario, the stationary units would be less cost-effective compared to if the biochar were used for local energy without biochar hauling costs. However, it appears from our analyses here that mobile units would likely remain less cost-effective than stationary units unless feedstock and biochar transportation costs were substantially higher than we assume here.

6.3.7. Difference from other studies

Table 6.9 summarizes the estimates of the break-even prices of bio-oil and biochar from different studies. Differences concerning the estimated profitability of biochar and bio-oil production arise due to a number of factors, such as assumptions on the feedstock source, base prices of bio-oil and biochar, capacity of the pyrolysis plant, and variable and fixed inputs to production.

Polagye *et al.* (2007) did not account for biochar as a separate, potential commercial product. Also the study equated the price of bio-oil to the price of No. 6 residual fuel oil. In our case study, on the other hand, we treated bio-oil and bio-char as two saleable products from pyrolysis and we estimated the bio-oil price based on the relative energy content of bio-oil and No. 6 residual fuel oil. Looking at the break-even prices of bio-oil, estimates are lower in Polagye *et al.* because all of the biochar was used to supply process heat. This translates to more net yield of bio-oil since less supplemental bio-oil for process electricity will be needed.

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[32] For endogenous prices, the estimated optimal biochar production is 26% of feedstock biomass.

Similarly, the estimates of break-even price from Radlein and Bouchard (2009) are lower compared to the estimates in our case study. This is attributed to the difference in scales of the plant and feedstock sources, leading to different processing requirements and production costs.

McCarl *et al*. (2009) used maize stover as feedstock and evaluated the feasibility of biochar/bio-oil production in a stationary facility via slow or fast pyrolysis. Our case study focuses on fast pyrolysis and we estimated the breakeven price for biochar from a stationary facility at about $87/ton. This figure is lower than the estimate in the McCarl study for fast pyrolysis, which is $1,047/ton. In part, the difference is due to differences in how the value of biochar is estimated. Their calculation is based on the productivity gains in maize after applying biochar in the soil plus savings in fertilizer inputs minus cost of biochar application to soil, which amounts to a biochar value of $47.36/ton. We estimated the value of biochar at $114.05/ton based on its energy content relative to that of Central Appalachian coal. It should be noted that this value will differ if we consider another type of feedstock since it has a different energy content. For instance, the energy content of Central Appalachian coal is 12,500 BTU/lb. Wood-based biochar (as in our case study) has 12,000-12,500 BTU/lb which is 98% that of Central Appalachian coal.

Table 6.9. Comparison of estimates from different studies.

	Assumed base price					Estimated break-even price	
Study	Bio-oil	Biochar ($/ton)	Type of pyrolysis	Feed-stock	Plant capacity	Bio-oil	Biochar ($/ton)
Polagye et al. (2007)*	$0.77/gallon	N/A	Fast	Forest thinning	Mobile: 10 DTPD	$2.70/gallon	N/A
					Transportable: 100 DTPD	$1.32/gallon	N/A
					Relocatable: 500 DTPD	$0.96/gallon	N/A
					Stationary: 1,816 DTPD	$0.85/gallon	N/A
Radlein & Bouchard (2009)	$0.62/gallon	$150.39	Fast	Wheat straw	200 DTPD	$0.59/gallon	$195
McCarl et al. (2009)	$0.097/kWh to $0.122/kWh*	$43.36	Fast	Maize residue	192 DTPD**	$0.304/kWh*	$1,047
			Slow	Maize residue	192 DTPD**	$0.115/kWh*	$246
Our case study	$1.06/gallon	$114.05	Fast	Forest thinning	Mobile: 10 DTPD	$3.61/gallon	$1,742
					Transportable: 100 DTPD	$1. 44/gallon	$450
					Relocatable: 500 DTPD	$1.18/gallon	$218
					Stationary: 1,816 DTPD	$1.03/gallon	$87

*Price based on cost of electricity production using a dual engine fueled by diesel and bio-oil. **Approximate value. Original figure is 70,080 dry tons of feedstock per year, divided by (1 year/365 days) ≈ 192 dry tons per day.

Maize stover-based biochar (as in the McCarl study) is assumed to have an energy content of 4,900 BTU/lb or 39.2% that of Central Appalachian coal. Furthermore, the break-even prices depend on the returns and costs of production.

Other differences between our study and others are as follows:

(1) The McCarl study assumed a stationary facility with a capacity of 70,080 tons of feedstock per year, while our case study is based on a stationary facility with a capacity of 644,680 tons of feedstock/year. The scales are different and so are the associated fixed and variable costs of operation.

(2) Hauling costs are also different. The McCarl study indicated that their assumptions on these costs cannot be used for forest residues because transportation logistics involving crop residues and forest residues are different.

(3) When calculating the net returns of production (total revenue minus total cost), their study included the:

- value of electricity generation: bio-oil and gas are used in plant operation and electricity generation. It is assumed that the energy generated is for sale; and
- value of GHG offsets.

We do not include these two items in our enterprise budgets. However, in the next chapter, we will examine the value of biochar for carbon sequestration so we will be able to incorporate potential carbon credits in the budgets.

The next chapter focuses on another potential future source of revenue in the form of returns from carbon sequestration possibilities.

Chapter 7. ECONOMIC VALUE OF BIOCHAR IN CROP PRODUCTION AND CARBON SEQUESTRATION.

The previous two chapters examined the economic tradeoff between biochar and bio-oil production and the economic feasibility of producing these outputs given different scales of processing facilities. This chapter extends the economic analysis to the assessment of potential earnings by farmers if they use biochar as a soil amendment, and the potential value of biochar for income from sequestering carbon. The first two sections provide a brief review of studies that examined the impacts of biochar application in the soil to crop productivity and to carbon (C) sequestration. The third section will present estimates of the costs and returns in crop production, for the case of wheat, with and without the application of biochar.

7.1. Impacts of biochar on crop productivity — Related studies.

A number of studies have investigated the response of crops to biochar application. Albeit not an exhaustive list of all available studies on the subject, Table 7.1 presents examples of these studies showing the impacts of biochar on crop response in terms of yield or plant biomass. Observed impacts vary depending on interactions between the types of biochar used, crop studied, soil type, local conditions, among others. However, while biochar is not intended as a substitute for fertilizers, some studies have observed increased crop productivity from using biochar alone (Baum and Weitner, 2006; Chan *et al.*, 2008). Other studies found a more positive crop response when biochar is applied together with fertilizers (Steiner *et al.*, 2007).

Table 7.1. Summary of studies on biochar used as a soil amendment.

<table>
<tr><th>Author(s)</th><th>Location</th><th>Soil type</th><th>Type of biochar</th><th>Biochar application rate</th><th>Crop</th></tr>
<tr><td>Kishimoto and Sugiura (1985)[a,b]</td><td>Japan</td><td>Volcanic ash soil, loam</td><td>Unknown wood</td><td>0, 0.2, 2.0 and 6.1 t/acre</td><td>Soybean</td></tr>
<tr><td colspan="6">Crop response: At 0.2 t/acre, increased yield by 51%. At 2 t/acre and 6.1/acre, reduced yield by 37% and 71%, respectively. Reductions were attributed to micronutrient deficiency induced by an increase in pH.</td></tr>
<tr><td>Mikan and Abrams (1995)[b]</td><td>United States (Pennsylvania)</td><td>Forest area on relic charcoal hearths</td><td>Wood for charcoal production</td><td>Unknown</td><td>Vegetation in hearth and non-hearth areas compared after 110 years</td></tr>
<tr><td colspan="6">Crop response: Tree density and basal area were reduced by 40%.</td></tr>
<tr><td>Young *et al*. (1996)</td><td>United States (Appalachian mountains)</td><td>Forest area on relic charcoal hearths</td><td>Wood for charcoal production</td><td>Unknown</td><td>Trees</td></tr>
<tr><td colspan="6">Crop response: Lower overstory tree cover and density on relic charcoal hearths than on adjacent, non-hearth areas. The richness and diversity of overstory and understory tree cover as well as ground vegetation were consistently lower on hearths.</td></tr>
<tr><td>Glaser *et al*. (2002)</td><td>Brazil</td><td>Xanthic Ferralsol</td><td>Secondary forest wood</td><td>0, 27.2 and 54.7 t/acre</td><td>Rice, Cowpea</td></tr>
<tr><td colspan="6">Crop response: At application rate of 27.2 t/acre, biomass increased by: 20%, rice; 50%, cowpea compared to control treatment where no biochar was applied. At application rate of 54.7 t/acre, biomass of cowpea increased by 100%.</td></tr>
<tr><td>Steiner (2006)[c]</td><td>Brazil</td><td>Xanthic Ferralsol</td><td>Wood</td><td>4.5 t/acre</td><td>Banana</td></tr>
<tr><td colspan="6">Crop response: Reduced soil acidity and increased K uptake</td></tr>
<tr><td>Yamamoto *et al*. (2006) [c]</td><td>Indonesia</td><td>Acid soil</td><td>Bark</td><td>6.1 t/acre</td><td>Maize</td></tr>
<tr><td colspan="6">Crop response: Higher yields with biochar and fertilizer, than fertilizer alone</td></tr>
<tr><td>Steiner *et al*. (2007)</td><td>Brazil</td><td>Xanthic Ferralsol</td><td>Secondary forest wood</td><td>4.5 t/acre</td><td>Rice, Sorghum</td></tr>
<tr><td colspan="6">Crop response: Charcoal plus mineral fertilizer improved yield by a factor of 1.5-2 and improved stover by a factor of 1.3-1.4. Using charcoal plus compost and/or fertilizer, yields are consistently greater (i.e., 4 to 12 times greater) compared to using fertilizer alone.</td></tr>
<tr><td>Van Zwieten (2007)</td><td>Australia</td><td>Semi-tropical soil</td><td></td><td>4 t/acre</td><td>Wheat, soybeans</td></tr>
<tr><td colspan="6">Crop response: Wheat: biomass tripled Soybeans: biomass more than doubled. Percentage increase in biomass is the same when nitrogen fertilizer is applied together with biochar. Biochar raised soil pH at about 1/3 the rate of lime.</td></tr>
</table>

Notes: [a] Adapted from Glaser *et al*. (2002); [b] Adapted from Chan and Xu (2009); [c] Adapted from Blackwell *et al*. (2009)

Table 7.1. Summary of studies on biochar used as a soil amendment (continued).

Author(s)	Location	Soil type	Type of biochar	Biochar application rate	Crop
Van Zwieten *et al*. (2007) [b]	Australia	Ferrosol	Paper mill sludge	4 t/acre	Wheat
Crop response: 30-40% increase in wheat height in acidic soil but not in alkaline soil					
Collins (2008)	Washington	Quincy sand, Hale silt loam	Peanut hull (PH), fir bark (SB)	0, 5, 10 and 20 t/acre	Wheat
Crop response: Quincy: Root-shoot ratio of wheat decreased in all application rates of biochar. Hale: Using PH, decline in root-shoot ratio of wheat at 10 t/acre of biochar compared to nil; no change at 5 t/acre and 20 t/acre. Hale: Using SB, root-shoot ratio of wheat increased in all treatments. 0.5 to 1 unit increase in soil pH due to biochar addition					
Chan *et al*. (2008)	Australia	Alfisol	Poultry litter	0, 4, 10.1 and 20.2 t/acre	Radish
Crop response: With biochar, without N fertilizer: yield increased from 42% at 4 t/acre of biochar to 96% at 20.2 t/acre of biochar, relative to the yield from unamended control.					
Van Zwieten *et al*. (2008)[c]	Australia	Ferrosol	Poultry litter (PL), Paper mill waste(PM)	Maize: 0.2-20.2 t/acre PL. Beans: 4 t/acre PL and PM versus 1.2 t/acre lime	Maize, Faba beans
Crop response: Maize: 51% yield increase at 4 t/acre; and 109% yield increase at 20.2 t/acre compared to nil. Beans: Yields are highest with biochar plus fertilizer, compared to biochar alone. PL biochar outperformed lime amendment.					

Notes: [a] Adapted from Glaser *et al*. (2002); [b] Adapted from Chan and Xu (2009); [c] Adapted from Blackwell *et al*. (2009)

Some studies have found negative crop response when grown in biochar-amended soil. For example, Kishimoto and Sugiura (1985) reported reductions in soybean yields with higher application rates of biochar. Collins (2008) found a decline in the root-shoot ratio of wheat in Quincy sand soil amended with peanut hull biochar and softwood bark biochar compared to unamended soil.[1] An increase in the root-shoot ratio of wheat, however, is found in Hale silt loam soil amended with softwood bark biochar. Lehmann *et al*. (2006) mentioned a greenhouse study in Columbia where biochar application led to low N availability to crops. Leguminous crops were found to compensate for this due to biological N_2 fixation induced by biochar application. On other hand, non-legume crops were found to require additional N fertilizers due to low N availability. These studies are controlled, small-scale experiments. Therefore, it is still premature to draw any quantitative conclusions from current biochar research, particularly in projecting the impacts of biochar on long-term crop productivity. Furthermore, biochar will not behave like conventional fertilizer so any reductions of chemical fertilizer requirement as a result

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[1] The root/shoot ratio is the ratio of below-ground level biomass and above-ground level biomass.

of biochar addition are still in question.[2] Nonetheless, evidence from available studies suggests that applying biochar to the soil can be beneficial.

Improvement in the soil pH is another observed impact of biochar addition, which implies a liming value of biochar. Collins (2008) found nearly a unit increase in soil pH with biochar derived from herbaceous feedstocks (switchgrass, digested fiber) and 0.5 to 1 unit increase in the soil pH with biochar derived from woody sources (softwood bark, wood pellets) (Table 7.2). Van Zwieten *et al.* (2007) also reported an increase in the soil pH and 30 to 40 percent increase in the height of wheat when biochar was applied to an acidic soil. Biochar may be considered a potential substitute for agricultural lime, especially in agricultural regions that have acidic soils. However, a unit change in the soil pH would require 0.54 ton to 3.91 tons per acre (0.6 short tons to 4.3 short tons per acre). of agricultural lime, depending on the soil type (CPHA, 2002) For example, a sand soil type requires 0.54 ton/acre of lime to increase the soil pH by a unit as compared to about 17 tons of biochar per acre[3] needed to achieve the same desired change in soil pH (Collins, 2008). This means that it may not be economically feasible for farmers to use biochar in crop production solely for pH adjustment since it would entail a relatively higher cost compared to agricultural lime. On the other hand, other potential benefits from adding biochar to the soil such as avoided emissions of lime and the capacity of biochar to sequester carbon (to be discussed in the next section), should be considered. It is possible that the economic returns from using biochar may be higher than using lime after accounting for any environmental benefits or other non-pH related plant growth benefits. If a carbon market exists for biochar C sequestration in agricultural cropland, it may provide an economic incentive for farmers to use it in order to generate additional income as on offset for carbon markets.

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[2] In Collins (2008), total nitrogen in the soil is found to increase (although at small amounts) after addition of biochar. This does not, however, imply that a lesser amount of N fertilizer may be needed when biochar is added to the soil. N in biochar is not available to plants. It is fused in the C matrix (H. Collins, personal communication).

[3] This refers to Quincy sand soil type. The biochar requirement to raise the pH by a unit depends on the type of char used, e.g., switchgrass, digested fiber, bark, etc. Assuming an average pH increase across the chars of 0.058 pH unit/ton of biochar, it would require about ~17.24 tons of biochar to increase the soil pH by 1 unit.

Table 7.2. Selected characteristics of six biochars (slow pyrolysis at 500°C) used in the laboratory analyses.

Source of biochar	Biochar Characteristics					
	C	N	S	C:N	C:S	pH
	--------- % ---------					
Switchgrass	60.5	2.06	0.20	30	350	9.4
Digested fiber	66.7	2.23	0.30	30	228	9.3
Peanut hull	70.6	1.74	0.04	41	1203	9.6
Bark (UGA)	74.5	0.34	0.03	220	2833	7.6
Softwood bark	77.8	0.44	0.06	176	1482	8.4
Wood Pellets	80.0	0.14	0.04	588	1855	7.4
Activated Charcoal	87.3	0.47	0.80	186	114	9.1

Source: Collins (2008).

Note: Activated charcoal is included as a standard analysis and comparison to biochars.

7.2. Biochar carbon sequestration — Related studies, policy and program.

The main products of pyrolysis can influence the global carbon (C) cycle in two ways. First, all three pyrolysis products: liquid (bio-oil), biochar, and gas products may be used as an energy source that can displace fossil energy use. Second, if biochar is produced from a biomass feedstock that removes carbon dioxide (CO_2) from the air via photosynthesis and which would otherwise have decomposed (carbon capture), and if the carbon-rich and stable biochar is incorporated to the soil (carbon storage), the char-amended land becomes a carbon sink.

7.2.1. Related studies

Lehmann *et al.* (2006) estimated an annual sequestration of 0.2 Pg C (200 million metric tons) through slash-and-char (instead of slash-and burn) and biochar application to the soil. Furthermore, the study reported that low-temperature pyrolysis of biomass combined with the capture of gas and liquid products for bioenergy production and soil application of biochar, could sequester the equivalent of about 10% of the annual US fossil-fuel emissions.

Laird (2008) proposed a national system of distributed fast pyrolyzers for converting biomass into bio-oil, gas and char. Similar to Lehmann *et al.* (2006), he assumed that bio-oil and gas are used as energy sources that can displace fossil fuel use, while char was applied to agricultural soils. Assuming the United States can produce 1.1 billion metric tons of biomass per year from harvestable forest and crop lands, the implementation of Laird’s (2008) proposal could displace 25% of the nation’s fossil fuel oil consumption per year. The study also estimated the aggregate carbon credit for fossil fuel displacement and biochar C sequestration to be 10% of the average annual US CO_2-C emissions.

The carbon content of biochar varies depending on the feedstock. Collins (2008) showed biochar carbon content ranging from 61% to 80%, the highest being from wood pellets (Table 7.2). Woody feedstocks (bark, wood pellets) tended to have a higher carbon content compared to herbaceous feedstocks (switchgrass, digested fiber). Based on these figures, we can approximate that 0.61 to 0.80 ton of carbon (or 2.2 to 2.93 tons of CO_2)[4] is sequestered for every ton of biochar applied to the soil.

7.2.2. Kyoto Protocol, trading system and national programs

Incentives for greenhouse gas mitigation such as carbon market credits or offsets may tip the scale in favor of biochar as a soil amendment rather than as a renewable energy source. At the international level, the Kyoto Protocol under the United Nations Framework on Climate Change (UNFCCC) only allows C sequestrations from afforestation and reforestation in the trading program established under the Clean Development Mechanism (CDM) (UNFCCC-CDM, 2009). Carbon sequestration in agricultural crops and soils is not currently eligible under CDM (Lehmann *et al.,* 2006; FAO, 2009).

In the United States, the Chicago Climate Exchange (CCX), North America's only greenhouse gas (GHG) emissions registry, reduction and trading system, has developed standardized rules for soil carbon management offsets in the agricultural sector. Eligible projects are conservation tillage[5] and grass planting[6], which have to be enrolled with a CCX-registered Offset Aggregator. Projects are also verified by a CCX-approved party (CCX, 2008). Recent policy discussions at the national level suggest increased momentum toward a binding national carbon market as well. There are a number of registered aggregators of carbon offsets in the United States, and they include the:

AgraGate Climate Credits Corporation – created in 2003 to expand the Iowa Farm Bureau Federation Carbon Credit Aggregation Program. AgraGate reports a registration of more than 1 million acres of land, aggregated from farmers, ranchers and private forest owners in 16 states. The purchasers of carbon credits include power plants, manufacturing companies and state and local governments (AgraGate, 2007).

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[4] To convert from carbon to carbon dioxide, multiply by 44/12 (~3.67) (Blasing *et al*., 2004).

[5] For the purposes of the CCX, conservation tillage is defined as continuous *no till* or *strip-till* (conservation tillage). The requirements are as follows: (a) a minimum five-year contractual commitment to continuous no-till or strip-till on enrolled acres; (b) tillage practice must leave at least two-thirds of the soil surface undisturbed and at least two-thirds of the residue remaining on the field surface; (c) contracts are issued for conservation tillage at a rate between 0.2 and 0.6 metric tons CO_2 per acre per year; (d) projects must be enrolled with a CCX-registered Offset Aggregator; and (e) projects are subject to independent verification.

[6] Offsets will be issued to land managers who commit to maintain increases in soil carbon stocks realized as a result of permanent grass cover plantings that were undertaken on or after January 1, 1999. The grass cover must be maintained through2010 on the acres specified upon project registration.

National Farmers Union Carbon Credit Program –North Dakota Farmers Union began the program in 2006 and enrollments are open to other states (NDFU, 2008). Total earnings for 2006 and 2007 practices amounted to $5.9 million and more than 2,300 farmers and ranchers received payments for carbon offsets achieved by no-till cropping practices and conversion of cropland to long-term grass stands (Good Fruit Grower, 2008).

National Carbon Offset Coalition (NCOC) – founded by the Montana Resource Conservation and Development groups in 2001. The organization serves as a carbon credit aggregator and partners with the Department of Energy research laboratories, tribal organizations, private sector and the universities and governments in Idaho, Montana, South Dakota, Washington and Wyoming (NCOC, 2008).

In general, these groups provide a venue for agricultural producers and landowners to earn income by storing carbon in the soil through conservation tillage, grassland conversion, sustainable management of native rangelands and afforestation.

Interested farmers in the Pacific Northwest can also register their carbon footprint reductions with the Pacific Northwest Direct Seed Association (PNDSA). The association was formed in 2000 and it is the first group in North America to register a list of direct seed (no-till) acres available for a Carbon Offset Trade. Farmers gain credits for CO_2 reductions by direct seeding of their fields. Currently, PNDSA is under a 10-year contract with a Louisiana-based energy company (Entergy Corporation). Pooled carbon credits are sold to Entergy which uses the credits to offset the CO_2 emissions from the company's power plants (PNDSA, 2009).

Neither the Chicago Climate Exchange nor the offset aggregators include C sequestration from the practice of adding biochar to cropland. Current adoption of biochar looks bleak without greenhouse gas mitigation incentives, but the future is potentially more promising. The International Biochar Initiative (IBI) is leading the effort to raise the profile of biochar as a climate mitigation and adaptation technology within the United Nations Framework on Climate Change (UNFCCC). The Kyoto Protocol will end in 2012. In light of this, new international responses to address climate change will be negotiated at the UNFCCC Conference on December 2009 in Copenhagen. Supporting documents have been submitted to the UNFCCC, which are aimed at including agricultural mitigation technologies and practices, such as biochar production and application to soils (IBI, 2009). Hence, it is possible that biochar C sequestration will become eligible in UNFCCC emissions trading mechanisms post-Kyoto Protocol. Furthermore, if biochar C sequestration becomes one of the eligible projects of the CCX Agricultural Soil Carbon Offsets, it may persuade farmers, who are usually reluctant to apply unproven products in their fields, to consider the technology. The presence of an established carbon trading mechanism for biochar will place farmers in a better position to evaluate whether or not the value being offered is incentive enough to incur additional costs and risks in their crop production.

In 2008, prices of traded CO_2 offsets on the Chicago Climate Exchange were volatile, ranging from US$1 to US$7.40 per metric ton CO_2 (CCX, 2008). During the same year, the market prices of CO_2 offsets in the European Climate Exchange varied between US$17 and US$31 per metric ton CO_2 (ECX, 2008).[7]

In the following section, we estimate the value of biochar both as an input in crop production and as an instrument in C sequestration. We assume that a carbon market exists for avoided emissions and C sequestration due to use of biochar as soil amendment. Also, for the value of potential CO_2 offset, we use a low-high range of US$1 per metric ton and US$31 per metric ton for sensitivity analysis.

7.3. Estimated costs and returns for using biochar as a soil amendment.

In this section, our goal is to derive the value of biochar as a soil amendment, in conjunction with the pyrolysis process studied in the Chapter 5. The calculation is done in three stages. First, we assess the avoided emissions with the application of biochar to agricultural soils as a substitute for lime and the amount of carbon sequestered. The result will be taken as CO_2 offsets that can be sold to existing trading systems. Second, we adjust the break-even prices of biochar and bio-oil from different scales of the pyrolysis process by incorporating the additional income from selling the CO_2 offsets. Third, we calculate the profit of crop production given two scenarios — without biochar but with lime application to the soil, and with biochar application as replacement for lime.

7.3.1. Benefits of biochar as soil amendment

Avoided emissions. Agricultural lime is commonly applied to soils to ameliorate a decline in soil pH. The recommended rates of lime application in western Washington range from 1 to 5 short tons per acre (Craig Cogger, personal communication). Less lime is needed, if at all, in Washington east of the Cascades because the native soil pH is high. Soil pH decline in the annual crop region of eastern Washington is generally not enough to warrant liming. If lime is needed, application rates range from 1-3 short tons per acre, but application is likely to take place on only about 10 percent of crop acreage (Richard Koenig, Craig Cogger, Joan Davenport, personal communication). However, decades-long use of ammonium-based nitrogen fertilizers can reduce pH to a level where crop response to liming occurs in wheat and other crops. Mahler *et al.* (1985) found that pH of soils in eastern Washington and northern Idaho had significantly declined. In 1960, less than 15% of the soils in all eastern Washington counties had a pH below

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[7] “Offsets” here refer to Certified Emission Reduction Futures contracts.

6. By 1980, 15-45% of the soils in Stevens, Pend Oreille, Spokane, Columbia and Garfield counties had a soil pH less than 6, and more than 65 percent in Whitman County.

West and McBride (2005) estimated the net CO_2 emission from application of agricultural lime in the United States at about 0.059 metric ton C (or 0.22 metric ton CO_2) per ton of limestone.[8] This is the amount of emissions that can potentially be avoided by replacing lime with biochar. Using the CO_2 offset price range of US$1 to US$31 per metric ton CO_2, the value of avoided emissions amounts to US$0.22-US$6.82 per metric ton of lime.

Biochar carbon sequestration. Biochar from herbaceous and woody feedstock sources are found to have a carbon content of 60.5%-66.7% and 74.5%-80%, respectively. We can assume from these figures that for every ton of biochar applied to the soil, 0.61 to 0.80 ton of carbon (equivalent to 2.2-2.93 tons of CO_2) can be sequestered (Collins, 2008). Using the highest carbon content of the wood-based biochar (i.e., 80%) and the CO_2 offset price range, the approximate value of biochar C sequestration is US$2.93-US$90.83 per metric ton biochar.

***Omitted factors*.** The dynamics of the relationship between fertilizers and biochar are not included in the analysis. Studies show mixed results about crop response to biochar with regard to the availability of nutrients for the plant. Some studies, such as Chan and Xu (2009) and Lehmann *et al.* (2006), state that biochar may have an indirect effect of increasing the efficiency of fertilizer use. However, there are also field experiments where biochar addition led to low N availability to crops, and therefore may contribute to additional N fertilization (Lehmann *et al.* 2006). Collins (2008) found that the N in biochar is not available to plants because it is fused in the C matrix. More research is needed to study the effects of biochar on nutrient dynamics in the soil. On the other hand, findings about the positive effects on soil pH by adding biochar to the soil are consistent (e.g., Collins, 2008; Van Zwieten, 2007; Rondon *et al.*, 2007).

7.3.2. Adjusted break-even prices of bio-oil and biochar

Table 7.3 shows the revenues, costs and returns from fast pyrolysis of forest thinning, expressed per dry ton of feedstock by dividing the figures by 548,000 dry tons. Break-even prices of bio-oil and biochar that account for the carbon value of biochar as a soil amendment are also given in the table. The break-even (BE) prices are calculated by subtracting the revenue of a co-product and the income from carbon offsets from the total cost of production. Equations (1) and (2) are employed to solve for the profitability of biochar and bio-oil, respectively:

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[8] The approximation of net CO_2 emission following agricultural lime application to soils is based on the: agricultural lime dissolution, transport, subsequent precipitation and dissolution in the ocean, and evolution of these processes over time.

$$\text{BE Price}_{\text{Biochar}} = \frac{\text{Total Cost} - \text{Price}_{\text{Bio-oil}}\ \text{Quantity}_{\text{Bio-oil}} - \text{Price}_{\text{CO}_2\text{ offset}}\ \text{Quantity}_{\text{CO}_2\text{ offset}}}{\text{Quantity}_{\text{Biochar}}} \quad (1)$$

$$\text{BE Price}_{\text{Bio-oil}} = \frac{\text{Total Cost} - \text{Price}_{\text{Biochar}}\ \text{Quantity}_{\text{Biochar}} - \text{Price}_{\text{CO}_2\text{ offset}}\ \text{Quantity}_{\text{CO}_2\text{ offset}}}{\text{Quantity}_{\text{Bio-oil}}} \quad (2)$$

The assumptions and calculation of income from carbon offsets are presented in appendix C. Results show that only the stationary facility is economically profitable when the carbon market price is US$1 per metric ton CO_2. Under this scenario, the break-even prices of biochar that will cover total cost under the mobile, transportable and relocatable facilities remain high. However, in comparison to the case where the environmental benefits of biochar are excluded, the adjusted break-even prices are lower by 5.7% to 45.5%.

On the other hand, when the prevailing market price of CO_2 offset is US$31 per metric ton, we estimate that all of the facilities are economically feasible, and the largest profit is realized by the stationary facility. The trading prices of CO_2 that would make the four types of pyrolysis facilities break even are: US$ 16.45 per metric ton CO_2 for the mobile facility; US$3.39 metric ton CO_2, transportable facility; and US$1.05 per metric ton CO_2, relocatable facility. Any price higher than these would yield a positive return for each respective facility. This implies that given one of the aforementioned prices, a certain type of pyrolysis facility can be feasible in the US if the carbon-market value of biochar of these respective magnitudes or higher can be accrued.

Table 7.3. Annual costs and returns of pyrolysis production and income from CO_2 offset by type of facility (US$ per dry ton of feedstock), and break-even (BE) prices of bio-oil and biochar given low and high range of CO_2 offset market prices.

Revenue, Production Cost, BE prices	Mobile		Transportable		Relocatable		Stationary	
	US$1/mt CO_2	US$31/mt CO_2	US$1/mt CO_2	US$31/mt CO_2	US$1/mt CO_2	US$31/mt CO_2	US$1/mt CO_2	US$31/mt CO_2
Biochar sale	17.56		17.56		17.56		17.56	
Bio oil sale	104.14		145.77		144.72		144.72	
GHG offset value	15.24	472.46	15.24	472.46	15.24	472.46	15.24	472.46
Variable cost (VC)	265.56		155.07		137.25		124.10	
Returns over VC[1]	-128.62	328.60	23.50	480.72	40.27	497.49	53.42	510.64
Total cost (TC)	372.38		215.02		178.23		158.06	
Returns over TC[2]	-235.44	221.78	-36.45	421.77	-0.71	456.51	19.46	476.68
BE price over VC – adjusted:								
Char ($/metric ton)	949.23	(-)	(-)	(-)	(-)	(-)	(-)	(-)
% change from original BE price of biochar over VC	-9.44%							
Oil ($/gallon)	2.37	(-)	0.89	(-)	0.77	(-)	0.67	(-)
% change from original BE price of biochar over VC	-6.15%		-11.08%		-12.73%		-14.31%	
BE price over TC – adjusted:								
Char ($/metric ton)	1,642.83	(-)	350.74	(-)	118.67	(-)	(-)	(-)
% change from original BE price of biochar over TC	-5.68%		-22.01%		-45.47%			
Oil ($/gallon)	3.46	(-)	1.33	(-)	1.07	(-)	0.92	(-)
% change from original BE price of biochar over TC	-4.30%		-7.72%		-9.49%		-10.85%	

[1] Returns over VC = Biochar sale + Bio-oil sale + CO_2 offset value – Variable Cost

[2] Returns over TC = Biochar sale + Bio-oil sale + CO_2 offset value – Total Cost

(-) Break-even prices are negative since the bio-oil or biochar credit and income from CO_2 offset are substantially higher compared to the cost of production. These indicate that a facility will earn a profit even when biochar is provided to end-users for free.

Note: The assumed base price of biochar = $114.05 per metric ton; base price of bio-oil = $1.06 per gallon.

7.3.3. Costs and returns of crop production

In the previous section, we show that including the value of carbon offsets (US$1 per metric ton CO_2) due to biochar application will lower the production cost of fast pyrolysis of forest thinnings and the break-even price of biochar as much as nearly 45 percent, as compared to no carbon-based returns. At this carbon market price, the producer of a relocatable facility needs to sell biochar for US$118.67 per metric ton and receive the value of the embodied carbon in order to break-even. The transportable and mobile facilities need to sell biochar for $350.74 and $1,642.83 per metric ton, respectively. In this section, we will examine the potential economic returns to farmers if they utilize biochar as a substitute for agricultural lime under three price scenarios: (a) when the market price of biochar is US$350.74 per metric ton (median break-even price of biochar in table 7.3); (b) based on the energy content of a wood-based biochar, US$114.05 per metric ton[9]; and (c) $87 per metric ton (break-even price of biochar produced in a stationary facility in Chapter 6, table 6.6).

Wheat, a key economic crop in Washington, belongs to a group of crops that can tolerate slightly acid (i.e., 6.0-6.5) soil pH (CPHA, 2002). In general, wheat tends to favor soil pH between 6 and 7 (Beegle and Lingenfelter, 2005). For this case study, we focus on changes in winter wheat yield given changes in the soil pH. The crop yield is estimated through the following equation adopted from Mahler (1986):

$$\text{Winter Wheat Yield} = -2{,}960.56 + 1{,}530\ \mathit{SOILPH} \qquad (3)$$

where *winter wheat yield* is in kilograms per hectare, and *SOILPH* refers to the value of the soil pH of Palouse silt loam. Assuming the base soil pH of 4.5 for this soil type from Collins (2008), increasing the soil pH to 6 would require 2.59 metric tons of limestone per acre (CPHA, 2002) or 30.62 metric tons of biochar per acre (H. Collins, unpublished data).[10]

Using equation (3) with soil pH of 4.5, wheat yield is estimated at about 3,924.44 kg per hectare or 58.36 bushels per acre.[11] On the other hand, with a soil pH of 6, the estimated wheat yield is

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[9] This value represents the opportunity cost of the foregone use of biochar as energy source. A wood-based biochar has an average energy content of 12,500-12,500 BTU/lb (Dynamotive, 2007). The energy content of the Central Appalachian coal is 12,500 BTU/lb and its price is US$116.38 per metric ton as of 2008 (EIA, 2009). Using the energy content as basis, the combustion value of biochar is 98% that of Central Appalachian coal or US$114.05/metric ton.

[10] Note that the impact of char on soil pH depends on the soil type and the type of char. For the Palouse silt loam soil type, an average pH increase across the chars is ~0.049 pH unit/ ton of biochar per acre. Based on this, it would require about 30.62 tons/acre to increase the soil pH from 4.5 to 6 (i.e., increase by 1.5 units).

[11] Conversion: 1 bushel per acre x 0.06725 = 1 metric ton (or 1,000 kg) per hectare. Source: Prairie Grains Magazine June 2003—Grain Math Weights, Measures, and Conversion Factors (http://www.smallgrains.org/springwh/June03/weights/weights.htm).

about 6,219.44 kg per hectare or 92.5 bushels per acre. Profits from winter wheat production, with and without the application of biochar, are calculated as follows:

Without biochar or agricultural lime:

$$\text{Profit}_1 = \text{PW*Q} - \text{Total Cost}; \qquad (1)$$

Without biochar, with agricultural lime:

$$\text{Profit}_2 = \text{P}_\text{W}\text{*Q} - \text{Total Cost} - \text{P}_\text{L}\text{*AGLIME}; \qquad (2)$$

With biochar, without agricultural lime:

$$\text{Profit}_3 = \text{P}_\text{W}\text{*Q} - \text{Total Cost} - \text{P}_\text{Bi}\text{*BCHAR} + \text{COFFSET} \qquad (3)$$

where P_W refers to the Fall 2008 contract price of winter wheat, which is US$7.50 per bushel (Union Elevator, 2008).[12] Q is the estimated yield of winter wheat given a soil pH of 4.5 in equation (1) and given a soil pH of 6 in equations (2) and (3). P_L is the price of lime at US$51.53 per metric ton[13] for a 100-lb bag in 2008 (J.A. Jack and Sons, personal communication, 2009); *AGLIME* refers to the application rate of agricultural lime (2.59 metric tons per acre); P_B means the biochar price; *BCHAR* represents the application rate of biochar (30.62 metric tons per acre); and *COFFSET* is the value of carbon offset from biochar C sequestration from replacing lime with biochar. *Total Cost* denotes the sum of fixed cost and variable cost of winter wheat crop production based on the Eastern Whitman County 2008 Enterprise Budget (Painter, 2008), exclusive of lime or biochar cost.

Table 7.4 shows the estimated profits with and without the incorporation of biochar to the soil. A farmer will still gain a profit with the addition of agricultural lime. On the other hand, the farmer will incur losses if the price of biochar is high, e.g., at $351/ton or $114/ton, which means that the income from offsets is not enough to support the adoption of biochar in agricultural production. If, however, the price of biochar goes down to $87/ton, a profit is gained and it is higher than the case where agricultural lime is used instead. This case implies that when the price of biochar is low enough, the income derived from carbon offsets can outweigh the cost of biochar.

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[12] August 2008 price from Union Elevator (FOB Lind) posted on July 15, 2008.

[13] Originally given as US$46.75 per short ton, then converted to price per metric ton.

Table 7.4. Comparison of profits from winter wheat production* (US$ per acre), with and without biochar application.

Scenario	Revenue	Total Cost[a]	Cost of Ag Lime**	Cost of Biochar**	CO_2 Offset Value[b]	Profit
Without biochar or ag lime application	$438	$415	—	—	—	$23
With ag lime application	$694	$415	$133	—	—	$146
With biochar application, *when the price of biochar (P_B) is…*						
P_{B1} = $350.74/metric ton	$694	$415	—	$10,740	$2,799	-$7,662
P_{B2} = $114.05/metric ton	$694	$415	—	$3,492	$2,799	-$414
P_{B3} = $87/metric ton	$694	$415	—	$2,664	$2,799	$414

[a] From 2008 Enterprise Budget for Eastern Whitman County, Conventional Tillage (Painter, 2008). To illustrate the estimation of a farmer's profits with and without ag lime or biochar application, we chose Eastern Whitman County as example based on Mahler *et al.* (1985). The study found that the pH of soils in eastern Washington had significantly declined. By 1980, more than 65 percent in Whitman County had a soil pH less than 6.

[b] CO_2 Offset Value = 90.29 metric tons CO_2 offset per acre from avoided emissions of lime and biochar C sequestration *times* US$31 per metric ton CO_2 (see appendix C table C9).

Notes: Figures for the revenue, cost and profit are rounded to the nearest whole number. *The assumed base soil pH is 4.5. Biochar or agricultural lime application is intended to raise the assumed soil pH to 6. ** The cost does not include the cost of applying lime or biochar to agricultural land (machinery and labor cost). Including this would further drive up the estimated losses or decrease any profit earned. The farmer will break even (profit = 0) if the price of biochar is approximately $100.52 per ton. The farmer's estimated profit with biochar application will be equal to the profit with ag lime application ($146/acre) if the price of biochar is about $95.75 per ton.

7.3.4. Implications

Biochar can be further processed into an activated carbon to be utilized in cleansing processes like water and air filtration (Lima *et al.*, 2008). Biochar can also be burned to produce energy (Polagye *et al.*, 2007). A wood-based biochar has a higher energy content than field residues (12,250 BTU/lb on average or 98% of the combustion value of Appalachian coal). For example, maize stover has a combustion value of 4,900 BTU/lb (McCarl *et al.*, 2009). The question is, would it be more feasible to use biochar as a soil amendment than use it for energy production or other alternative uses? The choice will ultimately depend on which has a higher opportunity cost, i.e., which alternative would be more costly if foregone. The energy content of wood-based biochar suggests that it may be more economically attractive as an energy source (i.e., as a substitute for coal). Lehmann *et al.* (2006) concluded that energy is released more efficiently when wood is directly burned to generate energy. However, the process loses the added benefits of applying biochar to soils, such as gains in agricultural productivity, increases in soil pH, and payments for C sequestration. More substantial increases in crop production need to be documented across a range of crops and soils that can add value to the farm at a level beyond the current value of biochar for C sequestration. Under the current economic situation, growers are unlikely to adopt biochar use without greater payback, and biochar production is unlikely to expand unless unique situations such as that of Dynamotive can be found to dramatically reduce the cost of production, or if higher value products can be developed from bio-oils. Recent studies funded by the US Dept. of Energy suggest that 40 mass % of the bio-oils can be converted to green gasoline and green diesel (Jones et al., 2009). Another study funded by the Washington State Department of Ecology (Garcia-Perez et al., 2009) found that the pyrolytic sugars present in bio-oils can be easily converted into ethanol. Thus, the phenols can be extracted and converted into gasoline while the pyrolytic sugars could be converted to ethanol. The deployment of these bio-oil refining techniques could increase the value of bio-oils and enhance economic viability of biochar production. At this time, however, even if growers found biochar beneficial, they could face difficulty in sourcing quantities large enough for farm application.

The quantitative economic analysis presented in this report is limited to the analyses of production and larger-scale application of biochar for market returns. It is clear that biochar has potential as a soil amendment for a very wide variety of uses, and its value as such would likely increase as social and regulatory interest in carbon sequestration increases, because of the longevity of carbon in the soil. Our quantitative analyses focus on using biochar as: (a) an energy source, thereby offsetting the use of fossil fuels for energy; and (b) soil amendment and its potential carbon sequestration benefits for agricultural uses. We find that pyrolysis production and biochar soil application can be economically feasible given the following scenarios:

- if the technology, strategic location of pyrolysis facility and incentives from public and private sectors are present such that a combination of these elements dramatically reduce the cost of production;
- if there exists a carbon market that recognizes the avoided emissions and carbon sequestration due to the application of biochar to (agricultural) soils. This is a necessary condition if we are to promote biochar as a technology for a carbon sequestration;
- if there is a carbon market, the offset price should be high enough so that a pyrolysis producer can earn a profit; and
- if the market price of biochar is low enough so that a farmer will earn a profit after applying biochar to the crop field.

7.3.5 Potential uses of biochar

Many niche opportunities (of varying scale) for biochar use are possible, ranging from soil amendment and compost use outside of agriculture, including for urban gardens, lawns, parks, ball fields, street landscape strip, grass swales, highway rights of way, and more. Some of these uses might entail biochar rates per area much higher than those proposed for agriculture, but with less potential area of application. Individuals not involved in commercial agriculture are considering how they can make biochar themselves with homemade stoves or kilns and on-site waste feedstocks. In most cases, these individuals are not motivated by a positive economic return, and would make and use biochar for the environmental benefit it would accrue. The extent of potential biochar production and use through such a channel is unknown in size and was not within the scope of this analysis, but it could be considerable. Biochar could be blended with compost, which is widely used in non-agricultural settings. Under current conditions, it would likely be a more expensive component than the compost and thus would require a change in pricing. However, if the biochar improved specific properties of the compost, or if a carbon credit for the biochar was high enough and could be captured by the compost producer, this might be an economically viable strategy.

Biochar could be suitable as a precursor to generate activated carbon, commonly utilized in industrial filtration process (Azargohar and Dalai 2006). Several studies have examined biochar for use in municipal wastewater treatment (e.g. Bansode et al. 2003, Ng et al. 2003), and for other water filtering systems (Kearns 2008). Biochar can also be potentially used as an energy source, such as combustion fuel to power the pyrolysis process or as a gasifier feedstock (Boateng 2007) and for water heating and cooking (Johannes 2008, IBI 2009). There may be other potential uses, including contaminated site cleanup, soils herbicide/pesticide management, and contaminant mitigation, human health exposure reduction, and of course carbon sequestration. There may be some additional demand for biochar in some of these niche markets as a “green” product subject to certification and marketing as such.

The extent of development of these markets, of course, depends on many factors that relate to the cost of biochar production relative to existing alternatives, as well as the relative effectiveness of biochar from pyrolysis for intended uses. One issue that often arises, however, is that niche markets for co-products of high value products such as biofuels can be locally or more globally flooded, leading to substantial price decreases for these co-products (markets for glycerine from biodiesel production is one example).

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Chapter 8. OUTREACH, OUTCOMES, CONCLUSIONS.

8.1. Outreach.

Project personnel have been involved in a variety of outreach activities over the short life of the project. Demand for information on biochar began near the start of the project prior to any research results. People inquiring about biochar were made aware of the project and the anticipated results. Project staff contacted the leaders of the SeaChar initiative in Seattle and provided them with the project progress reports and suggestions on small-scale charcoal stove design.

Hal Collins gave a presentation entitled *"Biochar As A Pyrolysis Byproduct"* at the Harvesting Clean Energy Conference in Portland, OR, on January 29, 2008. He spoke as part of the special workshop on *"The Promise of Biochar"* at Harvesting Clean Energy Conference in Billings, Montana in January 2009 and made a presentation on his project findings at the Pacific Northwest Biochar Initiative regional group meeting in Corvallis, OR, in April, 2009. Dr. Garcia-Perez made a presentation on existing technologies to produce biochar at the Pacific Northwest Biochar Initiative workshop in Richland, WA, on May 21, 2009. Dr. Collins presented a poster at the meeting on his studies and hosted the group at his biochar field plots at Prosser the next day. He has had inquiries from two commercial companies involved in pyrolysis or gasification that are interested in the project biochar findings for consideration as part of a business model. The Ecology news release about the Beyond Waste research projects led to an interview of Hal Collins and a subsequent article in *Geotimes* (July 2008, pp. 38-39) **www.geotimes.org?july08/article.html?1d=trends.html** "Charcoal: Out of the Grill and into the Ground" by Cassandra Willyard**.** The article describes the incubation studies, and the use of biochar derived from low temperature pyrolysis as a soil amendment to improve soil quality (e.g., lower leaching losses of nutrients, water holding capacity, C-sequestration). The target audience is crop producers, consultants and other scientists.

Dr. Collins submitted an abstract "Use of Biochar from the Pyrolysis of Waste Organic Material as a Soil Amendment" for the 2009 North American Biochar Conference that was accepted. He will present a paper on some of the project results and will also participate in the biochar session at the American Society of Agronomy annual meeting in November 2009. Dr. Collins is a member of the national biochar effort being supported by USDA-ARS and he has installed a field trial at WSU Prosser using a parallel design with five other locations across the country. Biochar was supplied to all sites by Dynamotive (fast pyrolysis).

David Granatstein discussed the project with attendees at the ACEEE (energy efficiency in agriculture) conference in Des Moines, IA in February 2008. He worked with a WSU media person on an article about the project for the WSU College of Engineering news. David also attended the PNW biochar meeting in Richland, WA, where he joined a committee to develop uniform protocols for biochar testing in the region and to collect and analyze data from biochar trials, particularly small trials by individuals.

Chad Kruger worked with Ecology to design the Beyond Waste workshop in June 2009 to discuss the findings from the various research projects, including the biochar project, and to consider next steps. Nearly 100 people attended. Chad gave two introductory talks. David Granatstein introduced the biochar project during the poster session, and Hal Collins and Suzette Galinato presented their posters.

Chad Kruger co-chaired the State of Washington's Agricultural Sector Carbon Market Workgroup in 2008. Recommendations from the workgroup in Section VI, "Development of Potential Offsets Related to Agricultural Carbon Management" provide a framework for the potential inclusion of biochar as an amendment which could be eligible for carbon offset credits in a cap and trade system. The report is available at: (http://www.ecy.wa.gov/climatechange/2008FAdocs/Ag_Offset_Recc_Pkg_FINAL.pdf)

The literature review of pyrolysis was put into a report entitled "The Formation of Polyaromatic Hydrocarbons and Dioxins during Pyrolysis: A Review of the Literature with Descriptions of Biomass Composition, Fast Pyrolysis Technologies and Thermochemical Reactions." This report is available to the general public at the WSU Energy Program Pacific Region Biomass Energy Partnership website (http://pacificbiomass.org/Library.aspx#Gasification).

8.2. Outcomes.

The project has led to a number of additional research activities on biochar, positioning team members as national leaders in this new field of inquiry. Dr. Collins is a member of the USDA-ARS national biochar effort. He has established a field trial at WSU Prosser to test biochar, using larger quantities of biochar procured by USDA from Dynamotive in Canada. Dr. Collins also has a graduate student working on the use of biochar with animal manure, and they have submitted a proposal to USDA Western SARE for funding this work. He is also a co-operator with Dr. Jim Amonette (PNNL) on a USDOE/USDA bioenergy proposal that is currently being developed after the pre-proposal was accepted. A biochar proposal has been submitted to the NSF BREAD program with collaboration among WSU and USDA-ARS researchers.

The continuous pyrolysis system at WSU built with project funds was critical for obtaining two grants from the federal Sun Grant Initiative (U.S. Dept. of Transportation) for almost $300,000 over the next two years. The projects funded by the Western Sun Grant Program are:

- Englund, K., M. Garcia-Perez, and M.-P. Laborie. *A Forest Residue-Based Pyrolysis Biorefinery*. Sept. 2009-Mar. 2011. $179, 547.
- Garcia-Perez M. and S. Chen. *New Concept to Obtain High Yields of Pyrolytic Sugars for Ethanol Production.* Sept. 2009-Aug. 2011. $120,000.

In addition, a joint project with Australia was funded (Li, C-Z., Garcia-Perez, M. High quality transportation bio-fuels from Australian and American biomasses via pyrolysis and bio-oil refinery. International Science Linkages, Australian Government $237,772 USD. January 2009-January 2011), and a proposal is pending with the National Science Foundation (Garcia-Perez M, Ha S, Pedrow P. Hydrocarbons from Biomass via Selective Pyrolysis and Bio-oil Hydrotreatment. NSF $2 million USD).

8.3. Conclusions.

The biochar project has provided a number of important steps towards understanding the potential for biochar to store carbon in soil for long periods of time in an environmentally sound manner. It is not clear from our results whether biochar can deliver plant growth improvements that will help justify the high cost that farmers would incur in its use in agricultural soils. A binding U.S. carbon cap and trade program may lead to higher carbon prices in coming years. If so, this will help improve the economics of biochar use as estimated in parts of this study. Biochar production appears most feasible when co-located with an existing underutilized waste stream at a facility that can also benefit from waste heat.

This is the case with the Dynamotive facility in Ontario, Canada., and their cost of production appears to be about $107 per dry ton of feedstock without transportation cost, based on the budget developed here (and $54 per dry ton without transport or feedstock cost). However, they use a fast pyrolysis process which does not produce a large portion of biochar from the feedstock. So agricultural use of biochar on any scale will require several changes to occur: documented crop benefits; a U.S. carbon market with prices higher than in recent years; and large quantities of biochar available at an affordable price and without high shipping charges.

The deployment of bio-oil refineries to convert bio-oil into transportation fuels (green gasoline, green diesel and ethanol) could significantly improve the economic viability of pyrolysis technology. These changes could all occur over the next several years. Just increasing the value of bio-oil from $1.06/gallon to $1.15/gallon reduces the break-even cost for biochar to $7/ton, making it affordable for widespread agricultural use.

In the meantime, more will be learned about biochar from the collective experience ranging from individuals making biochar for their own gardens to the USDA researchers involved with uniform field trials. If biomass pyrolysis expands due to changes in energy prices and policies, then biochar could be a by-product that does not have to carry the entire process economically. However, it is likely that such a process would be fast pyrolysis, which would not produce large quantities of biochar. The optimization study included in this report would then provide an excellent tool for pyrolysis operators to use in adjusting their process to maximize economic returns based on the relative prices of bio-energy and biochar.

This project just began the investigation of the agronomic benefit of adding biochar to Washington soils. Clearly biochar additions influenced some soil properties and not others. Much more research is needed to document how crop plants will respond to biochar amendment in different soil types, and what mechanisms are at work in temperate zone soils. Also, the effect of time on integrating biochar into the soil matrix, and therefore changing its effect, needs to be understood for effective management and for useful research. In the meantime, smaller scale use of biochar might be more likely for specialty situations (e.g., riparian buffers, water treatment), or as part of improved organic waste management (e.g., pyrolyzing woody construction debris) where biochar sales do not have to drive the economics and it can be applied to soil simply for carbon storage purposes.

APPENDICES

Appendix A. Results from qualitative analysis of biochar for dioxins and PAHs.

Figures A1-A16. Total ion chromatographs for all the liquids resulting from the CH_2Cl_2 extraction of produced charcoals.

Appendix B. Biochar characterization and effect on soil and plant growth.

Table B1 – B2. Predicted and measured total C and resistant C pools.

Figure B1. Photos of wood pellets used in laboratory and greenhouse studies.

Figure B2. Photographs of greenhouse trials. Planted variety was Eden spring wheat.

Appendix C. Biochar economic analysis.

Table C1. Sources of pyrolysis data.

Table C2. Assumptions about transportation.

Table C3. Annual costs and returns of biochar and bio-oil production, Mobile Facility.

Table C4. Annual costs and returns of biochar and bio-oil production, Transportable Facility.

Table C5. Annual costs and returns of biochar and bio-oil production, Relocatable Facility.

Table C6. Annual costs and returns of biochar and bio-oil production, Stationary Facility.

Table C7. Fuel properties of wood based bio-oil, No. 2 heating oil and No. 6 heavy or residual fuel oil.

Table C8. Cost item as a percentage of the total production cost, by production facility.

Table C9. Value of CO_2 offset from biochar carbon sequestration.

Figure C1. Transportation options.

Appendix A: Total ion chromatographs for all the liquids resulting from the CH_2Cl_2 extraction of produced charcoals. These are the outputs from the GC/MS qualitative analyses conducted by Dr. Garcia-Perez for the presence of dioxins and PAHs.

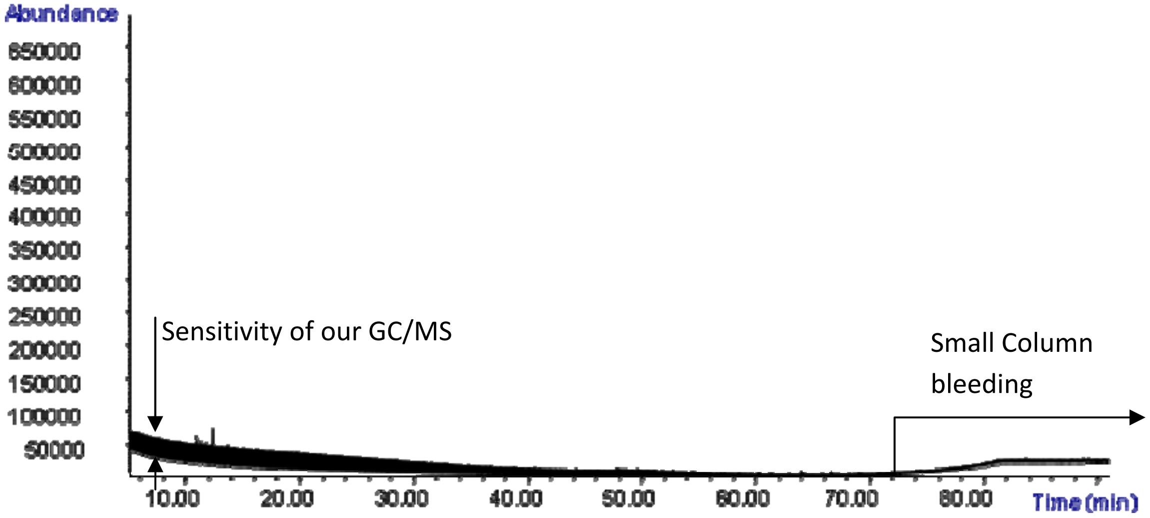


Figure A1. Bark derived biochar (pyrolysis temperature 350 °C)

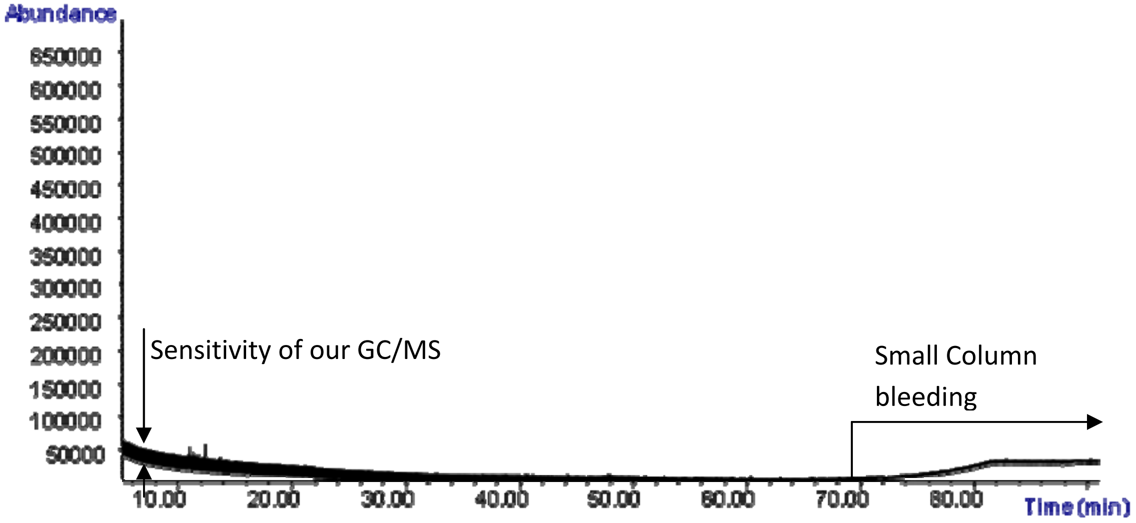


Figure A2. Bark derived biochar (pyrolysis temperature 425 °C).

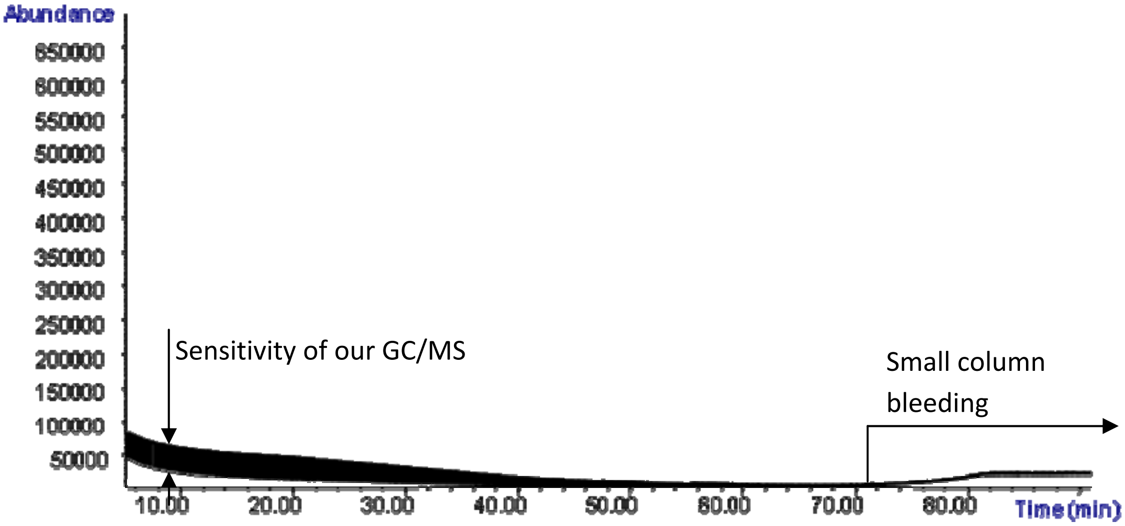


Figure A3. Bark derived biochar (pyrolysis temperature 500 °C).

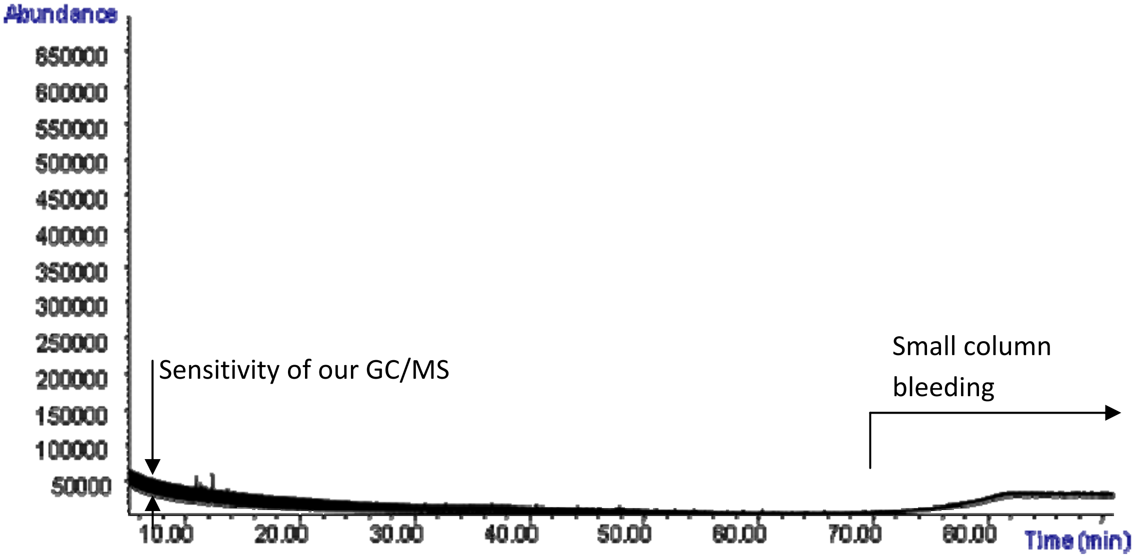


Figure A4. Bark derived biiochar (pyrolysis temperature 600 °C).

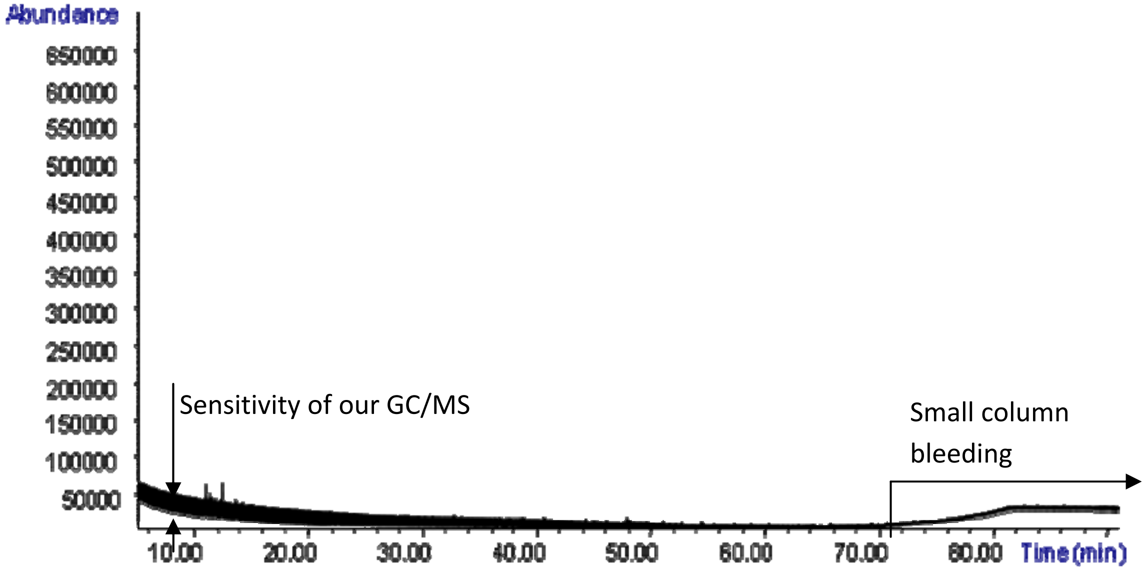


Figure A5. Fiber derived biochar (pyrolysis temperature 350 °C).

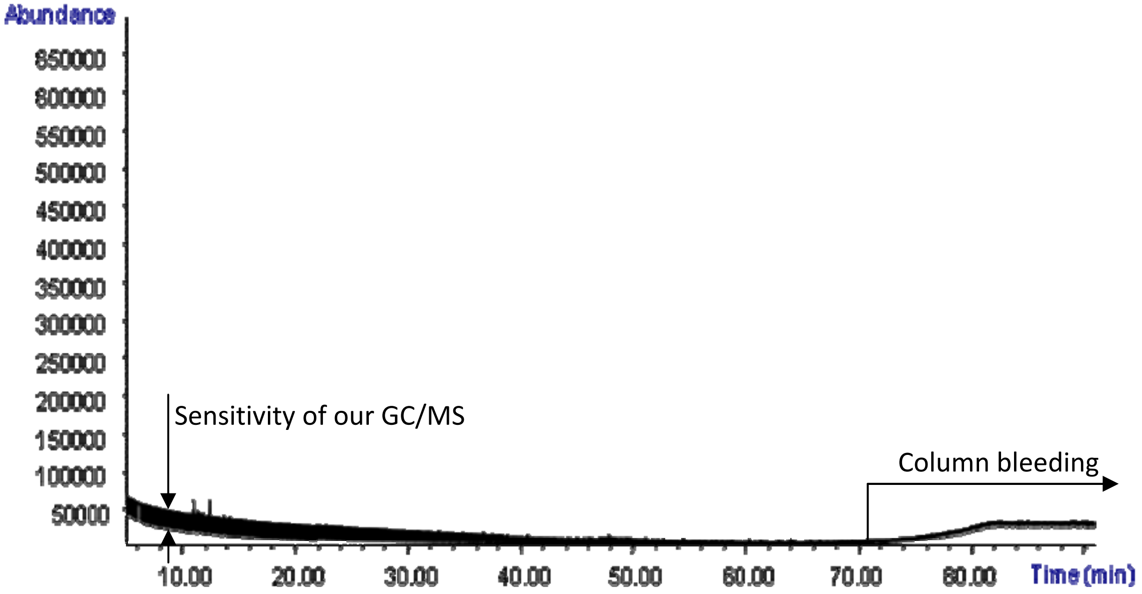


Figure A6. Fiber derived biochar (pyrolysis temperature 425 °C).

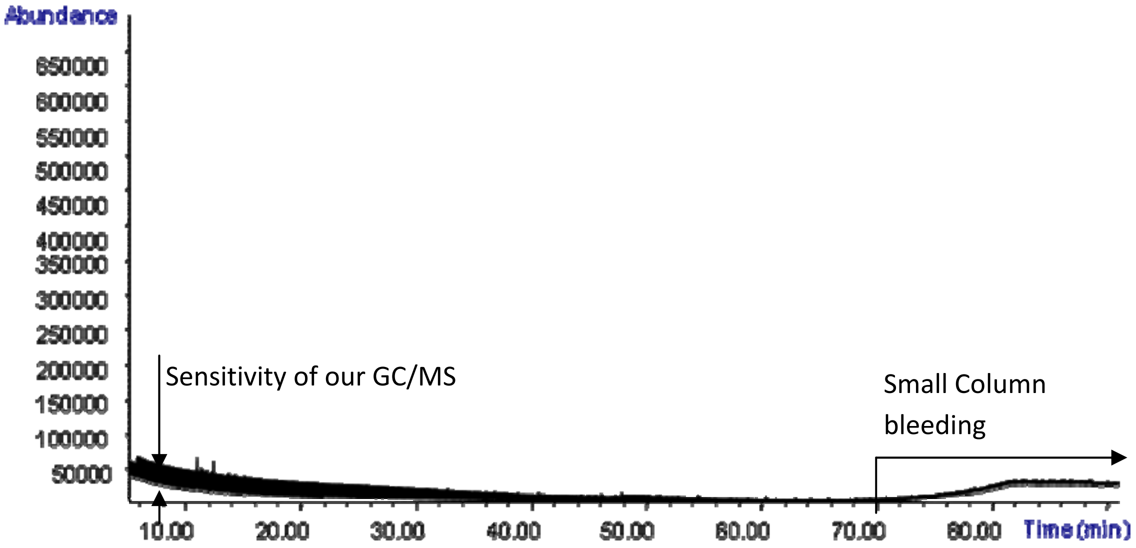


Figure A7. Fiber derived biochar (pyrolysis temperature 500 ^{o}C).

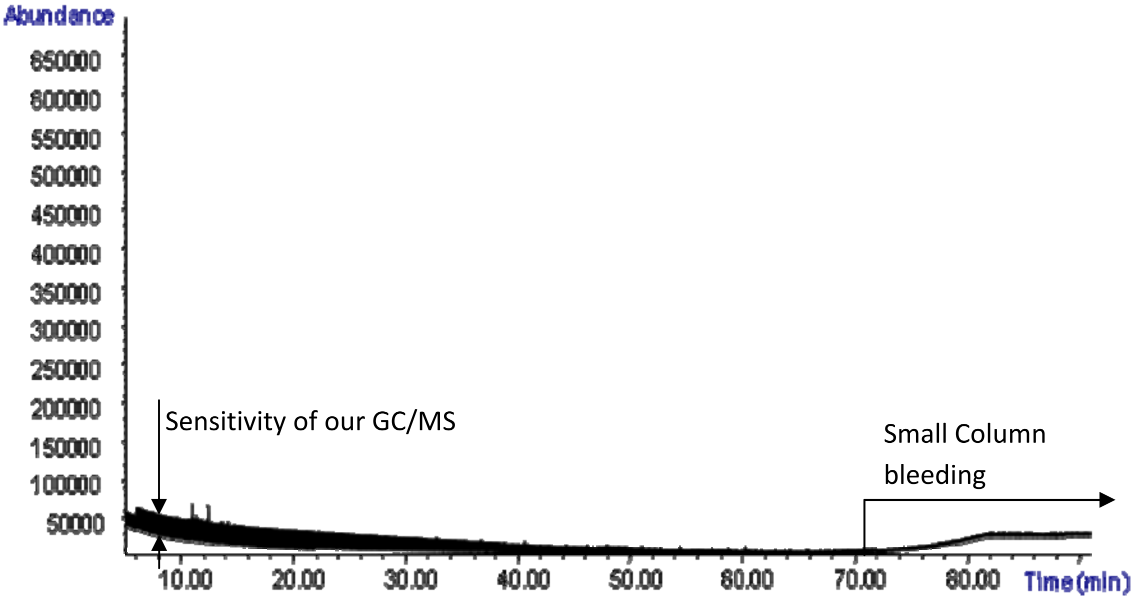


Figure A8. Fiber derived biochar (pyrolysis temperature 600 ^{o}C).

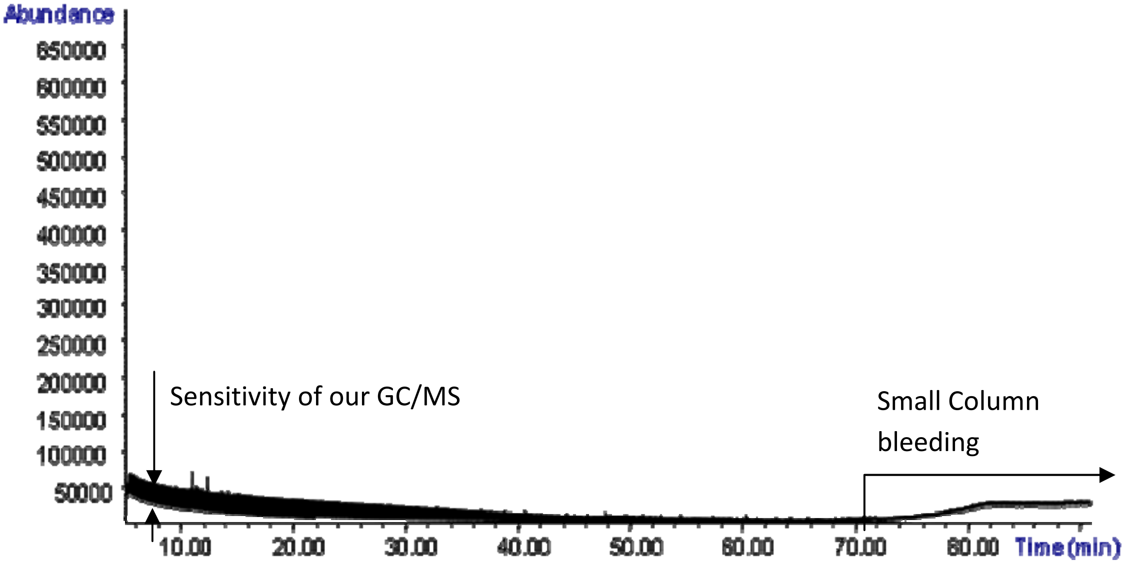


Figure A9. Grass derived biochar (pyrolysis temperature 350 ^oC).

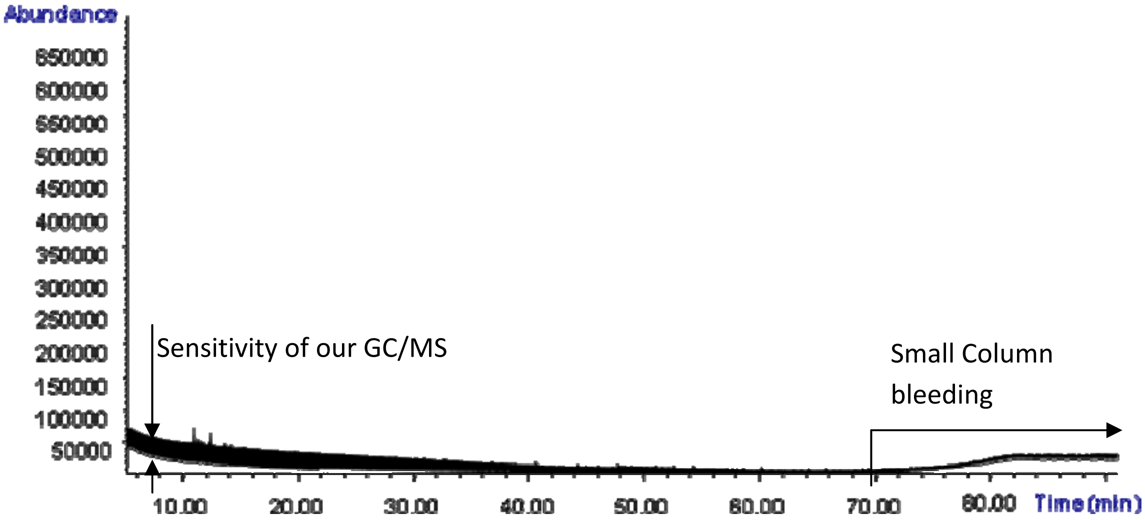


Figure A10. Grass derived biochar (pyrolysis temperature 425 ^oC).

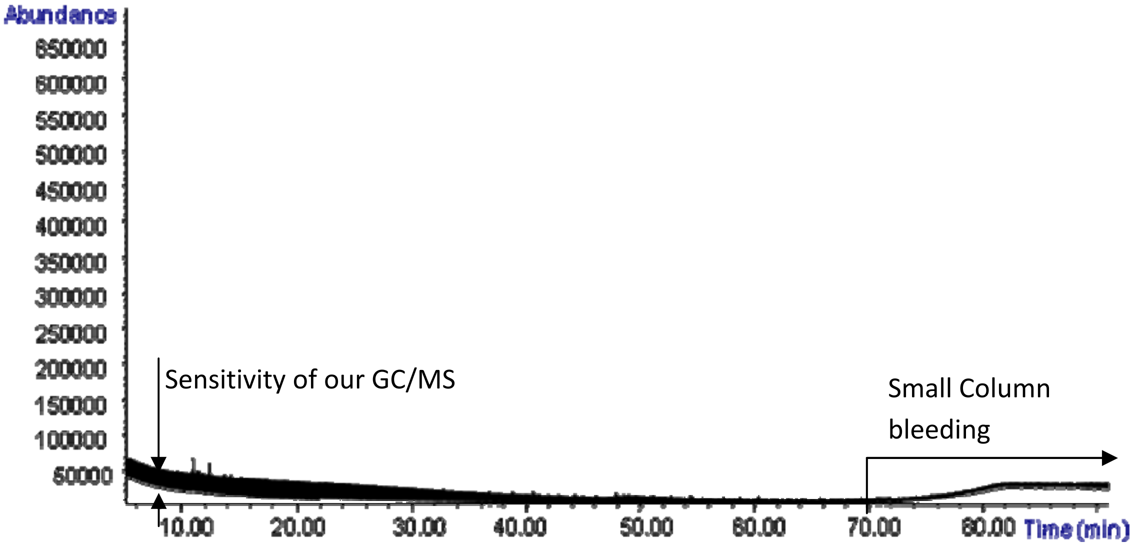


Figure A11. Grass derived biochar (pyrolysis temperature 500 ^{o}C).

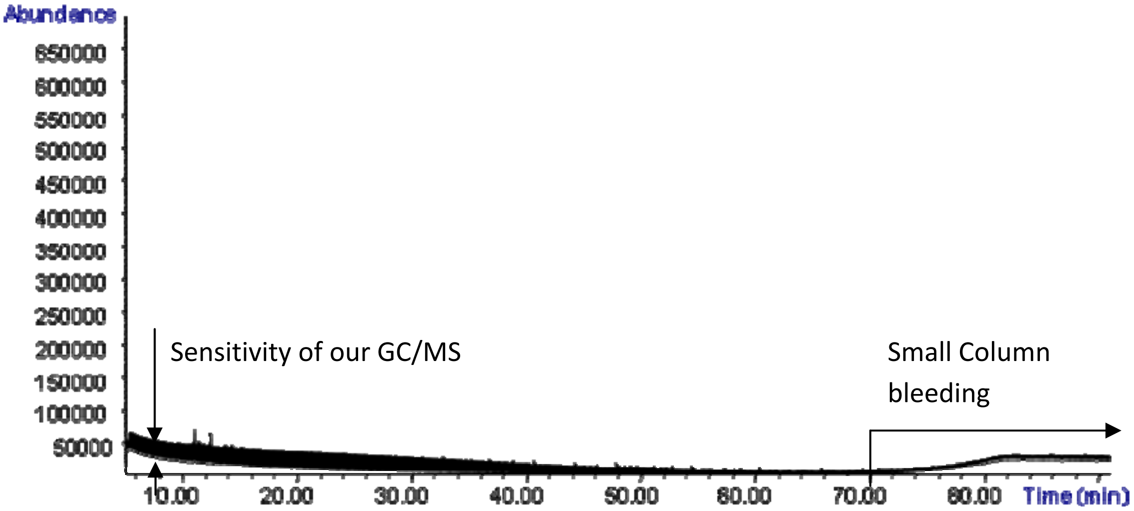


Figure A12. Grass derived biochar (pyrolysis temperature 600 ^{o}C).

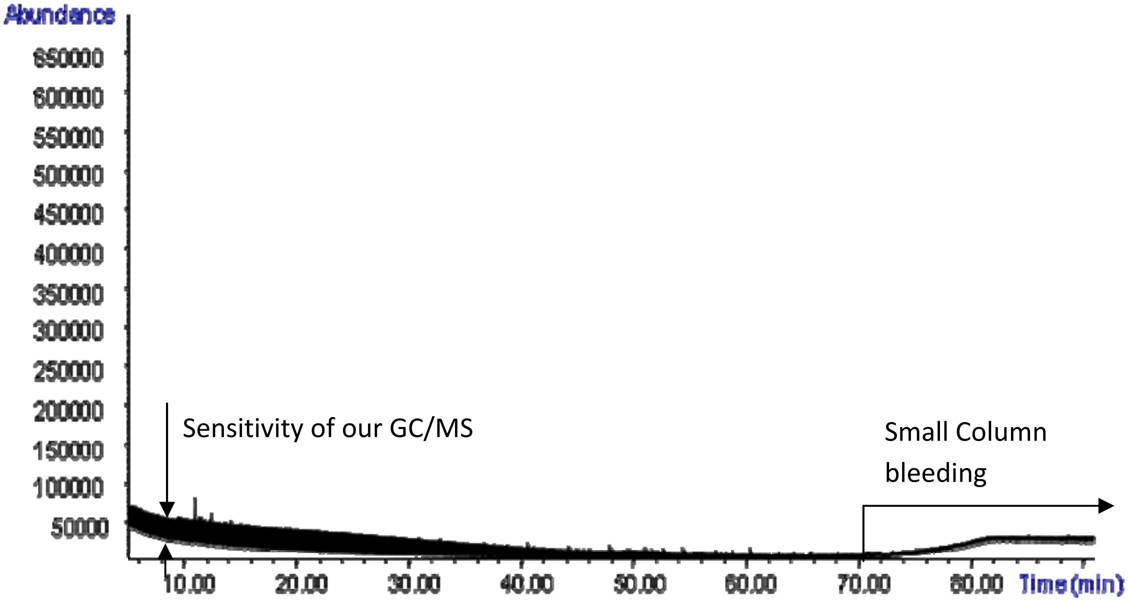


Figure A13. Wood pellet derived biochar (pyrolysis temperature 350 °C).

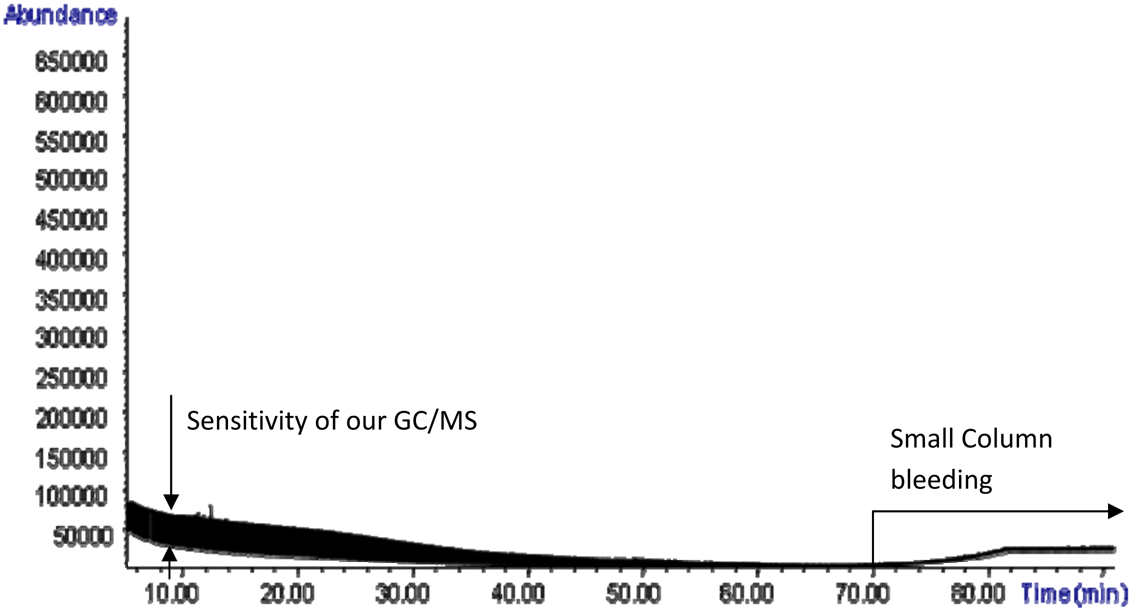


Figure A14. Wood pellet derived biochar (pyrolysis temperature 425 °C).

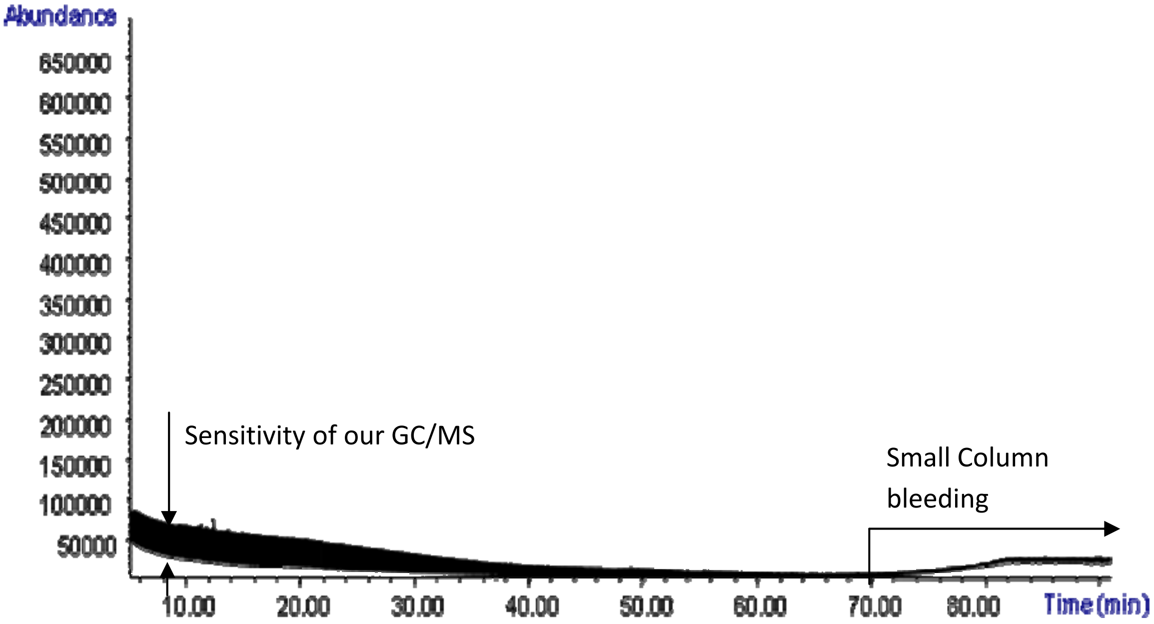


Figure A15. Wood pellet derived biochar (pyrolysis temperature 500 ^{o}C).

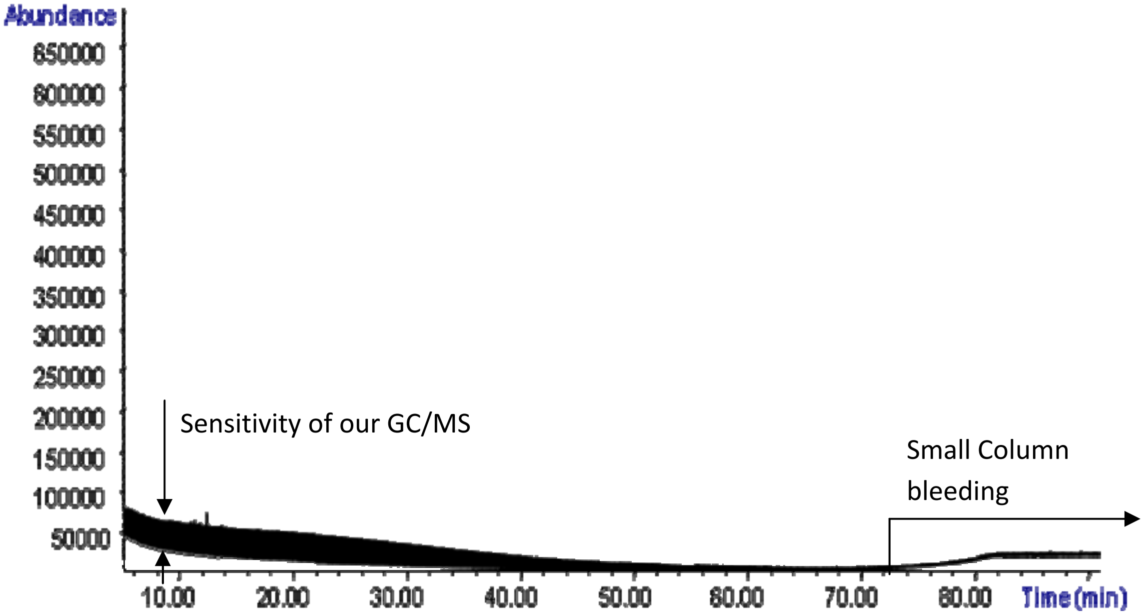


Figure A16. Wood pellet derived biochar (pyrolysis temperature 600 ^{o}C).

APPENDIX B. Biochar characterization and effect on soil and plant growth

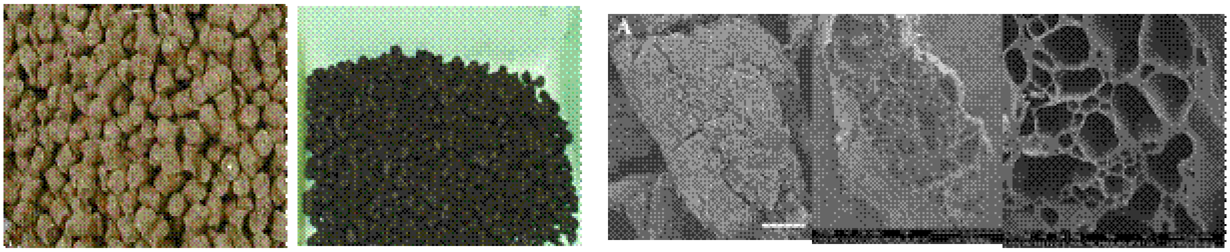
Table B1. Predicted and measured total C and resistant C pools for soils amended with biochar at four application rates. Quincy, Naff, and Palouse soils. Values used in construction of Figures 4.2 and 4.3.

		Quincy Sand				**Naff Silt loam**				**Palouse Silt loam**			
		Total C		Resistant C		Total C		Resistant C		Total C		Resistant C	
Biochar	Rate	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured
	Mg ha^{-1}	------------------ mg C kg soil^{-1} -------------------				------------------ mg C kg soil^{-1} -------------------				------------------ mg C kg soil^{-1} -------------------			
Switch grass	0	4300	4300	2120	2120	18010	18010	11547	11547	23160	23160	16846	16846
	9.8	6546	2600	4556	4390	20256	19940	13983	16500	25406	26030	19282	22370
	19.5	8733	4590	6928	5050	22443	22626	16355	20820	27593	28280	21654	23900
	39.0	13165	8860	11735	12870	26875	27780	21162	22330	32025	32000	26461	27770
Digested Fiber	0	4300	4300	2120	2120	18010	18010	11547	11547	23160	23160	16846	16846
	9.8	6800	2510	4814	4980	20510	20664	14241	14900	25660	25520	19540	19600
	19.5	9235	4860	7438	6900	22945	22893	16865	17500	28095	29400	22164	23500
	39.0	14170	9870	12755	9900	27880	26546	22182	23190	33030	38060	27481	29960
Softwood Bark	0	4300	4300	2120	2120	18010	18010	11547	11547	23160	23160	16846	16846
	9.8	7063	3320	4921	3300	20773	21359	14348	15550	25923	30200	19647	21880
	19.5	9753	5690	7648	5130	23463	23019	17075	18220	28613	35520	22374	23290
	39.0	15205	9440	13175	9610	28915	30219	22602	26430	34065	36480	27901	35150

Wood	0	4300	4300	2120	2120	18010	18010	11547	11547	23160	23160	16846	16846
Pellets	9.8	7264	5620	5103	4390	20974	20844	14530	17850	26124	26320	19829	21090
	19.5	10150	7100	8008	6940	23860	24332	17435	23730	29010	34960	22734	28840
	39.0	16000	11200	13895	12870	29710	34236	23322	30040	34860	38250	28621	30820

Table B2. Predicted and measured total C and resistant C pools for soils amended with biochar at four application rates. Thatuna and Hale soils. Values used in construction of Figures 4.2 and 4.3.

		Thatuna Silt loam				**Hale Silt loam**			
		Total C		Resistant C		Total C		Resistant C	
Biochar	Rate	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured
	Mg ha^{-1}	----------------- mg C kg soil^{-1} -------------------				----------------- mg C kg soil^{-1} -------------------			
Switchgrass	0	26860	26860	16423	16423	39880	39880	29180	29180
	9.8	29106	28340	18859	21830	42126	43670	31616	30360
	19.5	31293	31041	21231	26300	44313	44100	33988	34210
	39.0	35725	37641	26038	29460	48745	48630	38795	41050
Digested Fiber	0	26860	26860	16423	16423	39880	39880	29180	29180
	9.8	29360	29641	19117	25500	42380	42630	31874	31170
	19.5	31795	30368	21741	26970	44815	44680	34498	34190
	39.0	36730	37146	27058	28200	49750	49880	39815	41620
Softwood Bark	0	26860	26860	16423	16423	39880	39880	29180	29180
	9.8	29623	28331	19224	19460	42643	42450	31981	31040
	19.5	32313	31881	21951	19950	45333	44500	34708	32110
	39.0	37765	34888	27478	26340	50785	49630	40235	41940
Wood Pellets	0	26860	26860	16423	16423	39880	39880	29180	29180
	9.8	29824	28400	19406	18480	42844	43340	32163	34120
	19.5	32710	30274	22311	23460	45730	45670	35068	35520
	39.0	38560	38640	28198	33350	51580	51460	40955	44870



Pellets

Charred Pellets
500 °C

Micrographs of Char
Boateng, 2008

Figure B1. Photos of wood pellets used in laboratory and greenhouse studies. Micrographs courtesy of Dr. Boateng, USDA-ARS.

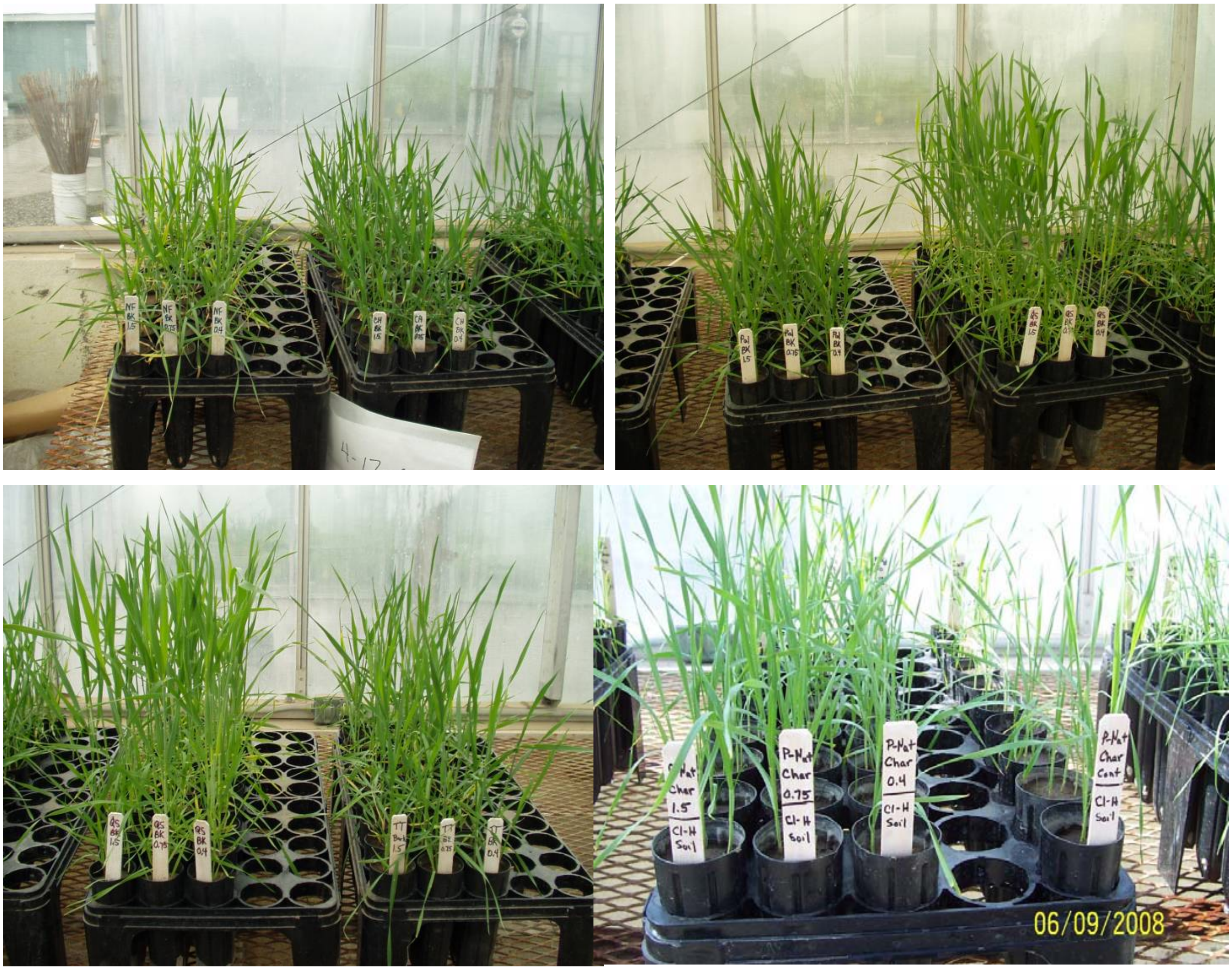


Figure B2. Photographs of greenhouse trials. Planted variety was Eden spring wheat.

Appendix C. Biochar economic analysis supporting materials.

Appendix for Chapter 5

Optimal temperature for fixed prices

The objective is to maximize the sum of the revenues from the two outputs minus the input costs, by choosing temperature:

$$\max_{T} V = P_c C(T,Z) + P_L L(T,Z) - K \quad , \tag{A1}$$

Assuming that *C* and *L* are increasing at a decreasing rate in *T*, the temperature that maximizes *V* satisfies the following condition:

$$\frac{P_L}{P_C} = -\frac{C'(T)}{L'(T)} , \tag{A2}$$

where $C'(T)$ and $L'(T)$ is the marginal productivity of *T* for the production of *C* and *L*, respectively. The left hand side of equation (2) represents the ratio of changes in L and C in response to changes in *T*, and the equation shows that this value is equal to the price ratio at the optimal *T*.

Given the quadratic forms shown in equations (5a) and (5b), the estimated marginal productivity measures in equations used in (2) and (4) are

$$C'(T_i) = \alpha_1 + 2\alpha_2 T_i \tag{A3a}$$

$$L'(T_i) = \beta_1 + 2\beta_2 T_i . \tag{A3b}$$

From these equations, the optimal temperature can be solved. For the fixed price case, given equations 2, 8a, and 8b, the optimal T for a given set of fixed prices can be solved as

$$T^*(P_C, P_L) = -\frac{\alpha_1 P_C + \beta_1 P_L}{2(\alpha_2 P_C + \beta_2 P_L)} \tag{A4}$$

subject to boundary conditions (corner solution restrictions). This optimal temperature will maximize revenues from the sale of both bio-oil and biochar given the prices for these two products.

Optimal temperature for temperature dependent prices

Allowing for price to vary as a function of temperature, the maximization problem in equation (1) can be recast as

$$\max_{T} V = P_C(T)C(T,\boldsymbol{Z}) + P_L(T)L(T,\boldsymbol{Z}) - K \ , \tag{A5}$$

and the optimality conditions analogous to equation (2) are

$$\left(P_C'(T)C(T) + P_C(T)C'(T)\right) = -\left(P_L'L(T) + P_L(T)L'(T)\right). \tag{A6}$$

Because prices are now a function of temperature, there is no constant price ratio to compare relative productivity to as in equation (A2). However, the interpretation of this optimality condition is similar. The right hand side represents the revenue received (or lost) from biochar from a unit increase in temperature, and the left hand side represents the revenue lost (or received) from bio-oil from a unit increase in temperature. The marginal revenue gains from one of the products equals the marginal revenue losses from the other at the optimal temperature.

Derivation of product transformation curves

From equations 2a and 2b in the main text, note that for any observation *i*, $\boldsymbol{\alpha}_0'\boldsymbol{Z}_i$ and $\boldsymbol{\beta}_0'\boldsymbol{Z}_i$ are scalars (constants not dependent on temperature) and can be thought of as data dependent intercepts in the quadratic relationship between temperature and biochar or bio-oil, respectively. The symbols $\boldsymbol{\alpha}_0$ and $\boldsymbol{\beta}_0$ will be used below to represent $\boldsymbol{\alpha}_0'\boldsymbol{Z}_i$ and $\boldsymbol{\beta}_0'\boldsymbol{Z}_i$ respectively, or a subset of these elements. All variables in ***Z*** are indicator variables in our regressions, each of which taking the value 1 in an observation if the category applies, and zero otherwise. Therefore, the parameters α_0 and β_0 depend on what feedstock and pyrolysis type is of interest for the calculations. For example, if forest products and fast pyrolysis is of interest, then α_0 equals the parameter associated with forest products, in the fast pyrolysis equation, which is $\alpha_0 = 80.67$ (Table 5.2).

The product transformation curve *C(L)* can be derived by first solving for the inverse of *L(T);* that is, solving equation (5b) for *T* in terms of *L*. This is a quadratic in *T*, so there are two solutions based on the quadratic formula. However, only one of these solutions is consistent with profit maximization in this setting, and which solution is appropriate depends on the shape of *C(T)*. Given the empirical results provided below, the economically valid solution for temperature in terms of bio-oil quantity (that is, the inverse of *L(T)*) is

$$T(L) = \frac{-\beta_1 + \sqrt{\beta_1{}^2 - 4\beta_2(\beta_0 - L)}}{2\beta_2} \tag{A7}$$

The right hand side of (6) is then substituted into equation (5a), which provides the product transformation curve:

$$C(L) = \alpha_0 + \alpha_1 T(L) + \alpha_2 T(L)^2 + \boldsymbol{\alpha}'\boldsymbol{Z}. \tag{A8}$$

Optimal temperature given price functions

Substituting (8a), (8b) and $P_G'(T) = \delta_1$ and $P_L'(T) = \gamma_1$ (derived from equations (10a) and (10b) in the text) into optimality condition (A6) provides

$$\begin{aligned}&\left(\delta_1(\alpha_0 + \alpha_1 T + \alpha_2 T^2) + (\delta_0 + \delta_1 T)(\alpha_1 + \alpha_2 2T)\right)\\ &\qquad = -\left(\gamma_1(\beta_0 + \beta_1 T + \beta_2 T^2) + (\gamma_0 + \gamma_1 T)(\beta_1 + \beta_2 2T)\right).\end{aligned} \tag{A9}$$

This can be rewritten as $AT^2 + BT + C = 0$, where $A = 3(\delta_1\alpha_2 + \gamma_1\beta_2)$,
$B = \left((\delta_1\alpha_1 + 2\delta_0\alpha_2 + \delta_1\alpha_1) + (\gamma_1\beta_1 + 2\gamma_0\beta_2 + \gamma_1\beta_1)\right)$ and $C = (\delta_1\alpha_0 + \delta_0\alpha_1) + (\gamma_1\beta_0 + \gamma_0\beta_1)$.
The optimal temperature within the economic temperature range (based on the quadratic formula) is.

$$\mathrm{T}^{**} = (2\mathrm{A})^{-1}\left(-\mathrm{B} + \sqrt{\mathrm{B}^2 - 4\mathrm{AC}}\right) \tag{A10}$$

where *A*, *B*, and *C* are defined directly above.

Appendix for Chapter 6

Table C1. Sources of Pyrolysis Data

Study	Feedstock biomass
A. Fast Pyrolysis	
Darmstadt, Hans, Dana Pantea, Lydia Summchen, Ulf Roland, Serge Kaliaguine, and Christian Roy. 2000. "Surface and Bulk Chemistry of Charcoal Obtained by Vacuum Pyrolysis of Bark: Influence of Feedstock Moisture Content." *Journal of Analytical and Applied Pyrolysis,* 53:1-17.	Maple bark, softwood bark
Demirbas, Ayhan. 2002. "Analysis of Liquid Products from Biomass via Flash Pyrolysis." *Energy Sources*, 24:337–345.	Yellow pine, tobacco stalk
Dogan Gullu. 2003. "Effect of catalyst on yield of liquid products from Biomass via pyrolysis." *Energy Sources*, 25(8):753-765.	Yellow pine, hazelnut shell, tea factory waste, tobacco stalk
Drummond, Ana-Rita F. and Ian W. Drummond. 1996. "Pyrolysis of Sugar Cane Bagasse in a Wire-Mesh Reactor." *Industrial and Engineering Chemistry Research*, 35(4):1,263-1,268.	Sugarcane bagasse
Kang, Bo-Sung, Kyung Hae Lee, Hyun Ju Park, Young-Kwon Park, Joo-Sik Kim. 2006. "Fast Pyrolysis of Radiata Pine in a Bench Scale Plant with a Fluidized Bed: Influence of a Char Separation System and Reaction Conditions on the Production of Bio-oil." *Journal of Analytical and Applied Pyrolysis*, 76:32–37.	Radiata pine
Garcia-Perez, Manuel, Xiao Shan Wang, Jun Shen, Martin J. Rhodes, Fujun Tian, Woo-Jin Lee, Hongwei Wu, and Chun-Zhu Li. 2008. "Fast Pyrolysis of Oil Mallee Woody Biomass: Effect of Temperature on the Yield and Quality of Pyrolysis Products." *Industrial and Engineering Chemistry Research*, 47(6):1,846-1,854.	Pine pellets
Ioannidou, O., A. Zabaniotou, E.V. Antonakou, K.M. Papazisi, A.A. Lappas, and C. Athanassiou. 2009. "Investigating the Potential for Energy, Fuel, Materials and Chemicals Production from Corn Residues (Cobs and Stalks) by Non-catalytic and Catalytic Pyrolysis in Two Reactor Configurations." *Renewable and Sustainable Energy Reviews,* 13:750–762.	Corn cob

Table C1. Sources of Pyrolysis Data (continued)

Study	**Feedstock biomass**
A. Fast Pyrolysis (continued)	
Luo, Zhongyang, Shurong Wang, Yanfen Liao, Jinsong Zhou, Yueling Gu, and Kefa Cen. 2004. "Research on Biomass Fast pyrolysis for Liquid Fuel." *Biomass and Bioenergy*, 26:455–462.	P. indicus (wood feedstock)
Scott, Donald S., Jan Piskorz, and Desmond Radlein. 1985. "Liquid Products from the Continuous Flash Pyrolysis of Biomass." *Industrial and Engineering Chemistry Process Design and Development*, 24(3): 581-588.	Poplar aspen cellulose, corn stover, wheat straw
Scott, Donald S., Piotr Majerski, Jan Piskorz, and Desmond Radlein. 1999. "A Second Look at Fast Pyrolysis of Biomass — The RTI Process." *Journal of Analytical and Applied Pyrolysis*, 51:23–37.	Poplar sawdust, spruce sawdust, sugarcane bagasse, sorghum bagasse, wheat chaff, sunflower hulls, wheat straw, flax shives, newsprint, fine paper, pulp mill waste, peat moss
Tsai, W.T., M.K. Lee, and Y.M. Chang. 2006. "Fast Pyrolysis of Rice Straw, Sugarcane Bagasse and Coconut Shell in an Induction-Heating Reactor." *Journal of Analytical and Applied Pyrolysis*, 76:230-237.	Rice straw, sugarcane bagasse, coconut shell
Wang, Xiaoquan, Sascha R. A. Kersten, Wolter Prins, and Wim P. M. van Swaaij. 2005. "Biomass Pyrolysis in a Fluidized Bed Reactor. Part 2: Experimental Validation of Model Results." *Industrial and Engineering Chemistry Research*, 44(23):8,786-8,795.	Pine, beech, bamboo
Zanzi, Rolando, Krister Sjöström,Emilia Björnbom. 2002. "Rapid Pyrolysis of Agricultural Residues at High Temperature." *Biomass and Bioenergy*, 23:357–366.	Wheat straw-untreated, wheat straw-pellets, olive waste (from oil production), birch wood

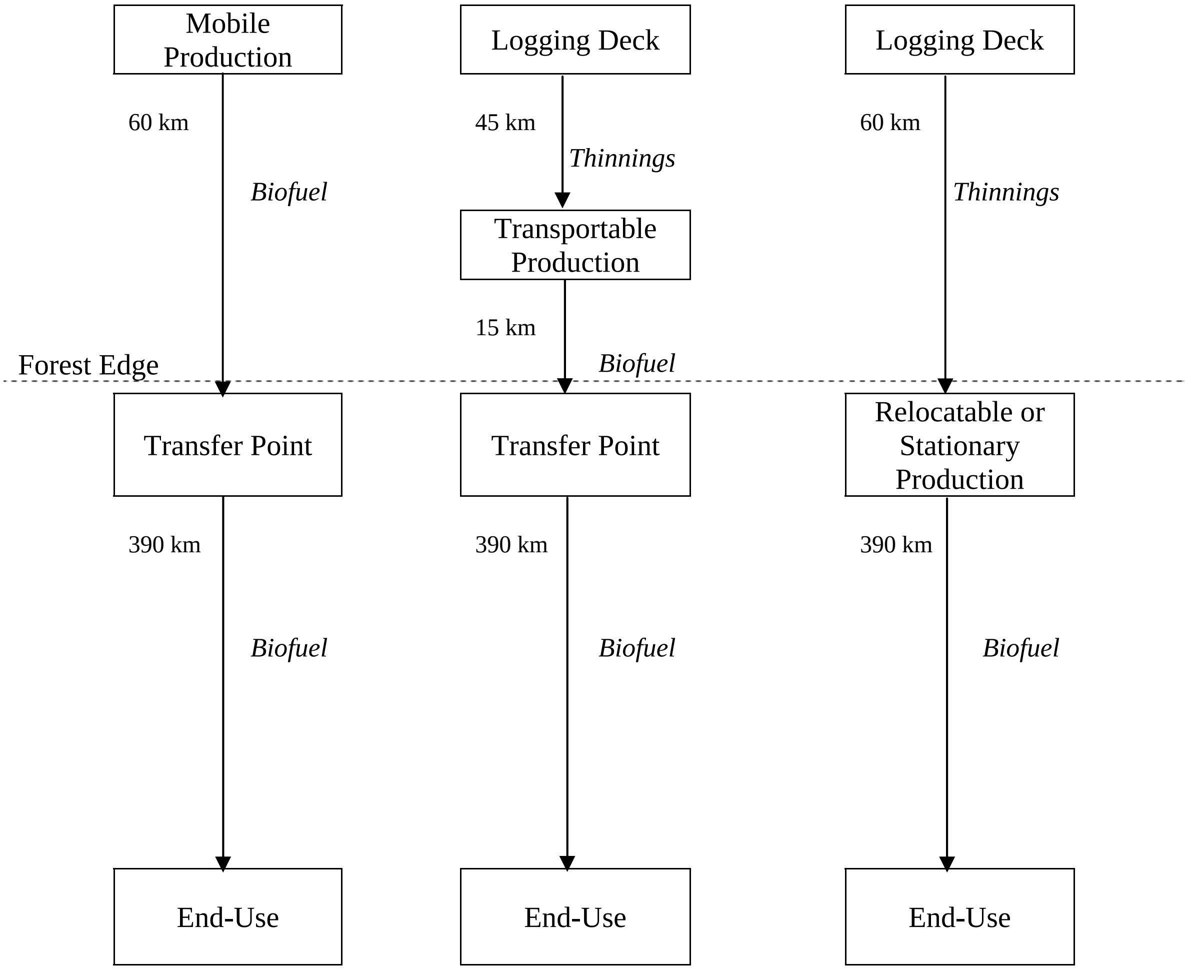
Table C1. Sources of Pyrolysis Data (continued)

Study	Feedstock biomass
Slow Pyrolysis	
Asadullah, M., M.A. Rahman, M.M. Ali, M.S. Rahman, M.A. Motin, M.B. Sultan, and M.R. Alam. 2007. “Production of Bio-oil from Fixed Bed Pyrolysis of Bagasse.” *Fuel*, 86:2,514-2,520.	Sugarcane bagasse
Chen, G., J. Andries, H. Spliethoff and D.Y.C. Leung. 2003. “Experimental Investigation of Biomass Waste (Rice Straw, Cotton Stalk, and Pine Sawdust) Pyrolysis Characteristics.” *Energy Sources*, 25:331–337.	Rice straw, cotton stalk, and pine sawdust
Garcia-Perez, Manuel, Thomas T. Adams, John W. Goodrum, Daniel P. Geller, and K. C. Das. 2007. “Production and Fuel Properties of Pine Chip Bio-oil/Biodiesel Blends.” *Energy and Fuels*, 21:2,363-2,372.	Pine chips, pine pellets
Ioannidou, O., A. Zabaniotou, E.V. Antonakou, K.M. Papazisi, A.A. Lappas, and C. Athanassiou. 2009. “Investigating the Potential for Energy, Fuel, Materials and Chemicals Production from Corn Residues (Cobs and Stalks) by Non-catalytic and Catalytic Pyrolysis in Two Reactor Configurations.” *Renewable and Sustainable Energy Reviews*, 13:750–762.	Corn cob
Sensoz, Sevgi. 2003. “Slow Pyrolysis of Wood Barks from *Pinus brutia* Ten. and Product Compositions.” *Bioresource Technology*, 89:307–311.	Pine bark
Sensoz, Sevgci and Mukaddes Can. 2002. “Pyrolysis of Pine (*Pinus brutia* Ten.) Chips: 1. Effect of Pyrolysis Temperature and Heating Rate on the Product Yields.” *Energy Sources*, 24:347-355.	Pine Chips
Williams, Paul T. and Serpil Besler. 1996. “The Influence of Temperature and Heating Rate on the Slow Pyrolysis of Biomass.” *Renewable Energy*, 7(3):233-250.	Pine wood
Zandersons, J., J. Gravitis, A. Kokorevics, A. Zhurinsh, O. Bikovens, A. Tardenaka, and B. Spince. 1999. “Studies of the Brazilian Sugarcane Bagasse Carbonisation Process and Products Properties.” *Biomass and Bioenergy*, 17:209-219.	Sugarcane bagasse

Table C2. Assumptions about transportation (adapted from Polagye et al., 2007; Polagye, 2009). See also Figure C1.

Production Facility	Forest transportation – Link 1: Logging deck to transfer point OR production facility	Forest transportation – Link 2: Production facility to transfer point	Long-haul transportation: Forest edge production or transfer point to end use
Mobile			
Link distance (one-way)	60 km	0	390 km
Feedstock moved	244,718 wet tons	0	1,096,000 wet tons
Distance driven (round trip)[a]	3,589,202 km	0	27,657,964 km
No. of trips	29,910	0	35,459
Round trip distance	120 km	0	780 km
Entire operation			
No. of drivers per truck	1	0	1
No. of trucks required	27.5	0	45.5
Labor hours	108,250	0	358,372
Fuel consumption	448,650 gallons	0	2,881,038 gallons
Oil consumption	44,865 gallons	0	288,104 gallons
Total transportation cost	$6.2 million	0	$23.5 million
Transportable			
Link distance (one-way)	45 km	15 km	390 km
Feedstock moved	1,096,000 wet tons	342,535 wet tons	342,535 wet tons
Distance driven (round trip)[a]	12,056,000 km	1,255,963 km	8,664,005 km
No. of trips	133,956	41,865	11,082
Round trip distance	90 km	30 km	780 km
Entire operation			
No. of drivers per truck	1	1	1
No. of trucks required	97.5	14.5	14.2
Labor hours	384,345	57,322	112,003
Fuel consumption	1,507,000 gallons	156,995 gallons	900,417 gallons
Oil consumption	150,700 gallons	15,700 gallons	90,042 gallons
Total transportation cost	$19.3 million	$3.2 million	$7.4 million
Relocatable or Stationary			
Link distance (one-way)	60 km	0	390 km
Feedstock moved	1,096,000 wet tons	0	340,069 wet tons
Distance driven (round trip)[a]	16,074,667 km	0	8,581,758 km
No. of trips	133,956	0	11,002
Round trip distance	120 km	0	780 km
Entire operation			
No. of drivers per truck	1	0	1
No. of trucks required	123	0	14.1
Labor hours	484,812	0	111,196
Fuel consumption	2,009,333 gallons	0	893,933 gallons
Oil consumption	200,933 gallons	0	89,393 gallons
Total transportation cost	$24.6 million	0	$7.3 million

Figure C1. Transportation options (adopted from Polagye *et al.,* 2007).



Notes: In-forest transportation is from the deck to the transfer point *or* production facility. It is provided by rugged container trucks. In-forest transportation costs are included in the "total cost of pyrolysis production." Long-haul transportation is from forest edge production or transfer point to end use. Large semi-trailer trucks are used.

Table C3. Annual costs and returns of biochar and bio-oil production, Mobile Facility.

Item	Quantity	Unit	Price or Cost (2008)	Value or Cost (2008)
Gross Returns				**$66,693,592.76**
Biochar	84,392	ton	$114.05	$9,625,277.88
Bio-oil	53,838,033	gallon	$1.06	$57,068,314.88
Operating Costs				
Feedstock handling				**$29,141,619.20**
Harvest	1,096,000	ton	$20.00	$21,920,000.00
Deck Loading				
Fixed Operating Cost				*$588,436.61*
Variable Operating Cost				*$2,320,788.35*
Facility Unloading *(involves unloading, chipping and debarking)*				
Fixed Operating Cost				*$643,075.37*
Variable Operating Cost				*$3,684,752.68*
Biofuel production				
Fixed Operating Cost				**$21,080,465.24**
Maintenance				*$11,711,369.58*
Overhead				*$9,369,095.66*
Variable Operating Cost				**$89,370,246.19**
Power				
Diesel fuel	*3,481*	*gal*	*$3.80*	*$2,582,097.12*
Diesel generator maintenance				*$1,344,462.21*
Labor	*8,760*	*hour*	*$30.00*	*$85,433,854.64*
Waste disposal (ash)				*$0.00*
Mobile operations				*$9,832.22*
Total Variable Costs (excluding transportation cost)				**$139,607,764.45**
Net Returns above Variable Costs (excluding transportation cost)				**-$72,914,171.69**
Fixed Costs (Annualized capital cost):				
Deck loading capital cost				$482,927.66
Facility unloading capital cost				$615,158.60
Biooil and biochar production capital cost				$56,410,728.31
Mobility				*$3,984,214.10*
Pre-treatment				*$21,820,345.56*
Fast pyrolysis				*$24,144,308.84*
Emissions (particulate) control				*$6,461,859.81*
Total Fixed Costs				**$57,508,814.57**
Total Costs (excluding transportation cost)				**$197,116,579.02**
Returns to Risk (excluding transportation cost)				**-$130,422,986.26**
Transportation Cost				

In forest transportation				**$6,945,511.56**
Capital cost (truck)				*$1,025,670.61*
Operating cost				
Fuel consumption	*448,650*	*gal*	*$3.80*	*$1,706,216.99*
Oil consumption	*44,865*	*gal*	*$3.30*	*$148,009.73*
Labor	*108,250*	*hr*	*$30.00*	*$3,247,510.14*
Repair and maintenance				*$768,280.74*
Transfer of material				*$0.00*
Insurance				*$11,432.69*
Tire cost				*$38,390.67*
Long-haul transportation				**$28,258,457.09**
Capital cost (truck)				*$3,211,088.78*
Operating cost				
Fuel consumption	*2,881,038*	*gal*	*$3.80*	*$10,956,587.08*
Oil consumption	*288,104*	*gal*	*$3.30*	*$950,454.40*
Labor	*358,372*	*hr*	*$30.00*	*$10,751,146.92*
Repair and maintenance				*$2,210,617.73*
Insurance				*$13,338.13*
Tire cost				*$165,224.06*
Production Cost and Return including in forest transportation cost only				
Total Variable Cost				**$145,527,605.40**
Returns to Risk (over Variable Cost)				**-$78,834,012.64**
Total Cost				**$204,062,090.58**
Returns to Risk (over Total Cost)				**-$137,368,497.83**
Production Cost and Return including in forest transportation and long-haul transportation cost				
Total Variable Cost				**$170,574,973.72**
Returns to Risk (over Variable Cost)				**-$103,881,380.96**
Total Costs				**$232,320,547.68**
Returns to Risk (over Total Cost)				**-$165,626,954.92**

Table C4. Annual costs and returns of biochar and bio-oil production, Transportable Facility.

Item	Quantity	Unit	Price or Cost (2008)	Value or Cost (2008)
Gross Returns				**$89,504,517.31**
Biochar	84,392	ton	$114.05	$9,625,277.88
Bio-oil	75,357,773	gallon	$1.06	$79,879,239.43
Operating Costs				
Feedstock handling				**$27,613,128.52**
Harvest	1,096,000	wet ton	$20.00	$21,920,000.00
Deck Loading				
Fixed Operating Cost				*$588,436.61*
Variable Operating Cost				*$2,320,788.35*
Facility Unloading *(involves unloading, chipping and debarking)*				
Fixed Operating Cost				*$469,976.71*
Variable Operating Cost				*$2,321,643.76*
Biofuel production				
Fixed Operating Cost				**$10,754,245.86**
Maintenance				*$5,974,581.03*
Overhead				*$4,779,664.82*
Variable Operating Cost				**$24,135,458.73**
Power				
Diesel fuel	*32,106*	*gal*	*$3.80*	*$2,454,565.35*
Diesel generator maintenance				*$1,278,058.18*
Labor	*8,760*	*hour*	*$30.00*	*$10,566,229.05*
Waste disposal (ash)				*$0.00*
Mobile operations				*$9,836,606.15*
Total Variable Costs (excluding transportation cost)				**$62,510,550.00**
Net Returns above Variable Costs (excluding transportation cost)				**$26,993,967.31**
Fixed Costs (Annualized capital cost):				
Deck loading capital cost				$482,927.66
Facility unloading capital cost				$591,285.53
Biofuel production capital cost				$28,778,057.51
Mobility				*$2,769,897.21*
Pre-treatment				*$9,009,262.90*
Fast pyrolysis				*$14,557,924.05*
Emissions (particulate) control				*$2,440,973.35*

Total Fixed Costs				**$29,852,270.70**
Total Costs (excluding transportation cost)				**$92,362,820.70**
Returns to Risk (excluding transportation cost)				**-$2,858,303.39**
Transportation Cost				
In forest transportation				**$25,467,534.32**
Capital cost (truck)				*$2,998,053.19*
Operating cost				
Fuel consumption	*1,663,995*	*gal*	*$3.80*	*$6,328,174.36*
Oil consumption	*166,400*	*gal*	*$3.30*	*$548,952.07*
Labor	*441,667*	*hr*	*$30.00*	*$13,250,022.78*
Repair and maintenance				*$2,007,929.08*
Transfer of material				*$159,623.61*
Insurance				*$18,143.18*
Tire cost				*$156,636.06*
Long-haul transportation				**$8,840,848.35**
Capital cost (truck)				*$1,003,568.76*
Operating cost				
Fuel consumption	*900,417*	*gal*	*$3.80*	*$3,424,286.67*
Oil consumption	*90,042*	*gal*	*$3.30*	*$297,047.64*
Labor	*112,003*	*hr*	*$30.00*	*$3,360,080.00*
Repair and maintenance				*$690,889.30*
Insurance				*$13,338.13*
Tire cost				*$51,637.84*
Production Cost and Return including in forest transportation cost only				
Total Variable Cost				**$84,980,031.14**
Returns to Risk (over Variable Cost)				**$4,524,486.17**
Total Cost				**$117,830,355.03**
Returns to Risk (over Total Cost)				**-$28,325,837.71**
Production Cost and Return including in forest transportation and long-haul transportation cost				
Total Variable Cost				**$92,817,310.73**
Returns to Risk (over Variable Cost)				**-$3,312,793.42**
Total Costs				**$126,671,203.38**
Returns to Risk (over Total Cost)				**-$37,166,686.07**

Table C5. Annual costs and returns of biochar and bio-oil production, Relocatable Facility.

Item	Quantity	Unit	Price or Cost (2008)	Value or Cost (2008)
Gross Returns				**$88,929,293.24**
Biochar	84,392	ton	$114.05	$9,625,277.88
Bio-oil	74,815,109	gallon	$1.06	$79,304,015.35
Operating Costs				
Feedstock handling				**$27,616,708.71**
Harvest	1,096,000	wet ton	$20.00	$21,920,000.00
Deck Loading				
Fixed Operating Cost				*$588,436.61*
Variable Operating Cost				*$2,320,788.35*
Facility Unloading *(involves unloading, chipping and debarking)*				
Fixed Operating Cost				*$481,544.25*
Variable Operating Cost				*$2,313,656.41*
Biofuel production				
Fixed Operating Cost				$7,175,376.47
Maintenance				$3,986,320.26
Overhead				$3,189,056.21
Variable Operating Cost				$15,366,105.54
Power: Grid electricity	*30,327,604*	*kWhr*	*$0.07*	*$7,890,751.62*
Labor	*8,760*	*hour*	*$30.00*	*$5,801,635.57*
Waste disposal (ash)				*$122,578.29*
Mobile operations				*$1,551,140.06*
Total Variable Costs (excluding transportation cost)				**$50,165,907.62**
Net Returns above Variable Costs (excluding transportation cost)				**$38,763,385.61**
Fixed Costs (Annualized capital cost):				
Deck loading capital cost				$482,927.66
Facility unloading capital cost				$647,840.75
Biofuel production capital cost				$18,311,750.11
Mobility				*$1,531,749.03*
Pre-treatment				*$4,609,562.91*
Fast pyrolysis				*$9,181,293.22*
Emissions (particulate) control				*$1,526,634.21*
Construction cost				*$1,462,510.74*
Total Fixed Costs				**$19,442,518.52**
Total Costs (excluding transportation cost)				**$69,608,426.15**
Returns to Risk (excluding transportation cost)				**$19,320,867.09**

Transportation Cost				
In forest transportation				**$28,062,511.84**
Capital cost (truck)				*$3,015,510.84*
Operating cost				
Fuel consumption	*2,009,333*	*gal*	*$3.80*	*$7,641,494.67*
Oil consumption	*200,933*	*gal*	*$3.30*	*$662,879.07*
Labor	*484,812*	*hr*	*$30.00*	*$14,544,358.40*
Repair and maintenance				*$2,019,621.24*
Transfer of material				*$0.00*
Insurance				*$6,710.49*
Tire cost				*$171,937.14*
Long-haul transportation of bio-oil				**$8,777,279.94**
Capital cost (truck)				*$996,341.89*
Operating cost				
Fuel consumption	*893,933*	*gal*	*$3.80*	*$3,399,627.80*
Oil consumption	*89,393*	*gal*	*$3.30*	*$294,908.55*
Labor	*111,196*	*hr*	*$30.00*	*$3,335,883.49*
Repair and maintenance				*$685,914.09*
Insurance				*$13,338.13*
Tire cost				*$51,265.99*
Production Cost and Return including in forest transportation cost only				
Total Variable Cost				**$75,212,908.63**
Returns to Risk (over Variable Cost)				**$13,716,384.61**
Total Cost				**$97,670,937.99**
Returns to Risk (over Total Cost)				**-$8,741,644.75**
Production Cost and Return including in forest transportation and long-haul transportation cost				
Total Variable Cost				**$82,993,846.68**
Returns to Risk (over Variable Cost)				**$5,935,446.56**
Total Costs				**$106,448,217.93**
Returns to Risk (over Total Cost)				**-$17,518,924.69**

Table C6. Annual costs and returns of biochar and bio-oil production, Stationary Facility.

Item	Quantity	Unit	Price or Cost (2008)	Value or Cost (2008)
Gross Returns				**$88,929,293.24**
Biochar	84,392	ton	$114.05	$9,625,277.88
Bio-oil	74,815,109	gallon	$1.06	$79,304,015.35
Operating Costs				
Feedstock handling				$27,452,926.42
Harvest	1,096,000	wet ton	$20.00	$21,920,000.00
Deck Loading				
Fixed Operating Cost				*$588,436.61*
Variable Operating Cost				*$2,320,788.35*
Facility Unloading *(involves unloading, chipping and debarking)*				
Fixed Operating Cost				*$557,762.53*
Variable Operating Cost				*$2,102,693.22*
Biofuel production				
Fixed Operating Cost				$3,702,470.56
Maintenance				*$2,056,928.09*
Overhead				*$1,645,542.47*
Variable Operating Cost				$11,766,845.80
Power: Grid electricity	*112,403,869*	*kWh*	*$0.07*	*$7,890,751.62*
Labor	*8,760*	*hour*	*$30.00*	*$3,753,515.89*
Waste disposal (ash)				*$122,578.29*
Mobile operations				*$0.00*
Total Variable Costs (excluding transportation cost)				**$42,958,997.06**
Net Returns above Variable Costs (excluding transportation cost)				**$45,970,296.18**
Fixed Costs (Annualized capital cost):				
Deck loading capital cost				$482,927.66
Facility unloading capital cost				$718,123.14
Biofuel production capital cost				$14,392,652.23
Mobility				*$0.00*
Pre-treatment				*$3,514,793.82*
Fast pyrolysis				*$6,677,792.49*
Emissions (particulate) control				*$1,237,712.10*
Construction cost				*$2,962,353.82*
Total Fixed Costs				**$15,593,703.03**
Total Costs (excluding transportation cost)				**$58,552,700.09**
Returns to Risk (excluding transportation cost)				**$30,376,593.15**

Transportation Cost				
In forest transportation				**$28,062,511.84**
Capital cost (truck)				*$3,015,510.84*
Operating cost				
Fuel consumption	*2,009,333*	*gal*	*$3.80*	*$7,641,494.67*
Oil consumption	*200,933*	*gal*	*$3.30*	*$662,879.07*
Labor	*484,812*	*hr*	*$30.00*	*$14,544,358.40*
Repair and maintenance				*$2,019,621.24*
Transfer of material				*$0.00*
Insurance				*$6,710.49*
Tire cost				*$171,937.14*
Long-haul transportation				**$8,777,279.94**
Capital cost (truck)				*$996,341.89*
Operating cost				
Fuel consumption	*893,933*	*gal*	*$3.80*	*$3,399,627.80*
Oil consumption	*89,393*	*gal*	*$3.30*	*$294,908.55*
Labor	*111,196*	*hr*	*$30.00*	*$3,335,883.49*
Repair and maintenance				*$685,914.09*
Insurance				*$13,338.13*
Tire cost				*$51,265.99*
Production Cost and Return including in forest transportation cost only				
Total Variable Cost				**$68,005,998.06**
Returns to Risk (over Variable Cost)				**$20,923,295.17**
Total Cost				**$86,615,211.93**
Returns to Risk (over Total Cost)				**$2,314,081.31**
Production Cost and Return including in forest transportation and long-haul transportation cost				
Total Variable Cost				**$75,786,936.12**
Returns to Risk (over Variable Cost)				**$13,142,357.12**
Total Costs				**$95,392,491.87**
Returns to Risk (over Total Cost)				**-$6,463,198.64**

Table C7. Fuel properties of wood based bio-oil, No. 2 heating oil and No. 6 heavy or residual fuel oil.

Parameter	Unit	Bio-Oil	No. 2 Heating Oil	No. 6 Heavy/Residual Fuel Oil
High Heating Value	MJ/kg	16-19	45.5	42.5
Density (15°C)	Kg/liter	1.2	0.865	0.986
Acidity	pH	2-3	—	—
Solids (char)	wt(%)	0.01-0.2	—	—
Moisture	wt(%)	20-25	—	< 0.5
Ash	wt(%)	<0.02	<0.01	0.02-0.08
Kinematic viscosity (60°C)	cSt	8	1.4-2.5	100-200

Source: Dynamotive (2007).

Table C8. Cost item as a percentage of the total production cost, by production facility

Item	Mobile	Transportable	Relocatable	Stationary
Operating or Variable Costs				
Feedstock handling:	**14.28%**	**23.44%**	**28.28%**	**31.70%**
Harvest	10.74%	18.61%	22.45%	25.31%
Deck Loading				
Fixed Operating Cost	*0.29%*	*0.50%*	*0.60%*	*0.68%*
Variable Operating Cost	*1.14%*	*1.97%*	*2.38%*	*2.68%*
Facility Unloading				
Fixed Operating Cost	*0.31%*	*0.39%*	*0.49%*	*0.67%*
Variable Operating Cost	*1.81%*	*1.97%*	*2.37%*	*2.36%*
Biofuel production:				
Fixed Operating Cost	**10.33%**	**9.13%**	**7.35%**	**4.28%**
Maintenance	*5.74%*	*5.07%*	*4.08%*	*2.38%*
Overhead	*4.59%*	*4.06%*	*3.27%*	*1.90%*
Variable Operating Cost	**43.80%**	**20.49%**	**15.73%**	**13.59%**
Power				
Diesel fuel	1.27%	2.08%	-	-
Diesel generator maintenance	0.66%	1.08%	-	-
Power grid electricity	-	-	8.08%	9.11%
Labor	41.87%	8.97%	5.94%	4.33%
Waste disposal (ash)	0.00%	0.00%	0.13%	0.14%
Mobile operations	0.005%	8.35%	1.59%	0.00%
Total Variable Costs (excluding transportation cost)	**68.42%**	**53.05%**	**51.36%**	**49.56%**
Fixed Costs (Annualized capital cost):				
Deck loading capital cost	0.24%	0.41%	0.49%	0.56%
Facility unloading capital cost	0.29%	0.50%	0.66%	0.86%
Biooil and biochar production capital cost	27.65%	24.43%	18.75%	16.62%
Mobility	*1.95%*	*2.35%*	1.57%	0.00%
Pre-treatment	*10.69%*	*7.65%*	4.72%	4.06%
Fast pyrolysis	*11.83%*	*12.36%*	9.40%	7.71%
Emissions (particulate) control	*3.17%*	*2.07%*	1.56%	1.43%
Construction cost			1.50%	3.42%
Total Fixed Costs (excluding transportation cost)	**28.18%**	**25.33%**	**19.90%**	**18.03%**
Total Costs (excluding transportation cost)	**96.60%**	**78.38%**	**71.26%**	**67.60%**

Transportation Cost:				
In forest transportation	**3.40%**	**21.62%**	**28.74%**	**32.40%**
Capital cost (truck)	*0.50%*	*2.54%*	*3.09%*	*3.48%*
Operating cost				
Fuel consumption	*0.84%*	*5.37%*	*7.82%*	*8.82%*
Oil consumption	*0.07%*	*0.47%*	*0.68%*	*0.77%*
Labor	*1.59%*	*11.25%*	*14.89%*	*16.79%*
Repair and maintenance	*0.38%*	*1.70%*	*2.07%*	*2.33%*
Transfer of material	*0.00%*	*0.14%*	*0.00%*	*0.00%*
Insurance	*0.01%*	*0.02%*	*0.01%*	*0.01%*
Tire cost	*0.02%*	*0.13%*	*0.18%*	*0.20%*
Production Cost and Return including in forest transportation cost only				
Total Variable Cost	**71.32%**	**72.12%**	**77.01%**	**78.49%**
Total Cost	**100.00%**	**100.00%**	**100.00%**	**100.00%**

References

Dynamotive. 2007. "General BioOil Information, Table 1." Available at: http://www.dynamotive.com/en/biooil/index.html.

Polagye, B.L. 2009. "Thinning Conversion Model." Model used in Polagye et al. (2007). A documented spreadsheet was requested from the author.

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Appendix for Chapter 7

Assumptions used to calculate the value of CO_2 offset

1. Case study: Eastern Whitman County, a high precipitation region (more than 18" per year)
2. Type of soil: Silt loam. We use the base pH = 4.5 in Collins (2008) for Palouse silt loam. To increase the soil pH of silt loam by 1.5 units (i.e., from 4.5 to 6), the requirements are:
   - 2.85 short tons of lime per acre (or 2.59 metric tons/acre)[1]; or
   - 33.75 short tons of biochar per acre (or 30.62 metric tons/acre)[2].

In Eastern Washington, only small amounts of agricultural lime are used. If there is a problem in soil pH, the recommended application rate is 1-3 short tons per acre.[3] Taking the minimum lime requirement (1 short ton per acre), we use the requirements mentioned above to increase the soil pH by 1 unit.

Note the conversion 1 metric ton = 1.10231131 short tons.

3. Representative farm in the enterprise budget for Eastern Whitman County is 2,500 acres.
   - Given a total of 84,392 metric tons of biochar produced by pyrolysis, then: $84{,}392 \text{ metric tons} * (\text{acre}/0.91 \text{ metric ton}) = 92{,}738 \text{ acres}$ can be supplied or 37 farms with 2,500 acres each.
4. Environmental benefits from using biochar as soil amendment
   - Avoided emissions for not using lime = 0.22 metric ton CO_2 per metric ton of limestone[4]
   - Biochar C sequestration = 0.8 ton per ton of carbon or 2.93 metric tons CO_2[5] per metric ton of biochar applied to the soil[6]

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[1] Source: California Plant Health Association (CPHA). 2002. Western Fertilizer Handbook, 9th edition. Danville, Illinois: Interstate Publishers, Inc.

[2] Source: H. Collins, unpublished data. Palouse silt loam soil analysis, biochar analyses.

[3] Source: Joan Davenport, personal communication, 2009

[4] Source: West, Tristram O. and Allen C. McBride. 2005. "The Contribution of Agricultural Lime to Carbon Dioxide Emissions in the United States: Dissolution, Transport and Net Emissions." *Agriculture Ecosystems and Environment*, 108:145-154.

[5] To convert from carbon to carbon dioxide, multiply by 44/12 (~3.67) (Blasing, T.J. *et al*., 2004. Estimates of Monthly CO_2 emissions and Associated 13C/12C Values from Fossil Fuel Consumption in the U.S.A. Available at: http://cdiac.ornl.gov/trends/emis_mon/emis_mon_co2.html.

[6] Based on biochar content of pine pellets. Source: Collins, Hal. 2008. "Use of Biochar from the Pyrolysis of Waste Organic Material as a Soil Amendment: Laboratory and Greenhouse Analyses." Quarterly report prepared for the Biochar Project (December 2008).

[A rough calculation was done to compare potential C sequestion from biochar (84,392 MT biochar = 247,268 MT CO_2 offset) to the emissions from the diesel fuel used in biochar production (loading, debarking, chipping: 326,000 gal; in-forest transport: 2,009000 gal; at 10.1 kg CO_2/gal diesel = 23,348 MT CO_2) using the details for a stationary facility (a high end estimate) from the Polagye study.]

5. Benefits *per acre* given lime or biochar applied to cropland:
   - Avoided emissions for not using lime =
     $2.59 \text{ metric tons of lime} * (0.22 \text{ metric ton } CO_2 / \text{metricton of lime}) \approx 0.57 \text{ metric ton } CO_2$
   - Biochar C sequestration =
     $58.63 \text{ metric tons of biochar} * (2.93 \text{ metric ton } CO_2/\text{metric ton of biochar})$
     $\approx 171.79 \text{ metric tons } CO_2$
6. Total value of CO_2 offset in Eastern Whitman County, using low and high ranges of CO_2 offset price (US$1 – US$31 per metric ton CO_2):

Table C9. Total value of CO_2 offset from biochar carbon sequestration.

	CO_2 offset price ($/metric ton CO_2)	CO_2 offset per acre (metric ton CO_2/acre)*	Representa-tive farm acres**	No. of farms**	Total value of CO_2 offset ($)***
Avoided emission	$1	0.57	2,500	37	$52,725
Biochar C sequestration	$1	89.72	2,500	37	$8,299,100
Total		*90.29*			*$8,351,825*
Avoided emission	$31	0.57	2,500	37	$1,634,475
Biochar C sequestration	$31	89.72	2,500	37	$257,272,100
Total		*90.29*			*$258,906,575*

*See number 6

**See number 4

***Total value of CO_2 offset = CO_2 offset price x CO_2 offset per acre x Representative farm acres x No. of farms