Opportunities for biochar production to reduce forest wildfire hazard, sequester carbon, and increase agricultural productivity of dryland soils

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Project Dates
Start: July 1, 2015
End: June 30, 2018
Duration: 36 Months

Project Costs

Year 1	Year 2	Year 3
$125,857	$96,219	$27,390

Total: $249,466

Abstract

Widespread concerns regarding the impact of wildfires on rural communities have prompted fuel reduction treatments across forested landscapes. To offset the cost of wildfire mitigation previous efforts proposed that low-value timber could be used as a feedstock for bioenergy production. Unfortunately, this scenario is capital intensive and often economically challenging in the Pacific Northwest. However, recent advances in steep slope harvesting technology promise to reduce the cost of hazard reduction treatments. Simultaneously, an enormous potential demand for biochar, a soil amendment that increases crop productivity, improves water efficiency, and promotes carbon sequestration, has arisen. This demand could be satisfied with a local facility that couples consumption of low-value timber with biochar production. By extending economic, social, and ecological benefits from forest restoration to enhanced crop production; biochar offers a huge opportunity where dryland crops, water scarcity, green-energy delivery grids, and high fire-hazard forests share the same landscape, as they do in the Klamath Basin. A forest-origin biochar strategy will only be suitable if it is *technically feasible, logistically scalable, economically competitive, and environmentally beneficial*. Our proposal deeply explores these issues to create a win-win scenario for wildfire mitigation, carbon sequestration, and agroecosystem health. This multidisciplinary landscape-level study optimizes treatment, facility, and agricultural application locations to *promote forest restoration, forest-related employment, increased agricultural competitiveness, and carbon sequestration*. By supporting the development of forest-to-farm biochar markets, this proposal has the potential to impact management and inform policy for Oregon and IWFL stakeholders, while exerting College of Forestry leadership for this emerging forest product.

1. Introduction, scope and main objectives

Over the last twenty years, carbon dioxide emissions have rapidly risen, placing Earth's climate on a trajectory toward rapid environmental change. The current US Administration is committed to strategies that mitigate climate change (White House 2013), including reducing the impacts of wildfire and fostering carbon sequestration, all while maintaining agricultural and forest productivity. It is estimated that 80 million ha of federal and state forest and rangelands face the risk of large-scale wildfire and are therefore in dire need of fuel reduction treatments and ecosystem restoration (GAO 1999). Although programs that address wildfire risk reduction typically involve thinning low-value trees (DOE 2011), there are few strategies for the economical and environmentally sustainable use of the resulting biomass. Therefore, biomass is typically burned on site, releasing carbon into the atmosphere where it contributes to climate change. An alternative strategy involves utilizing the biomass from wildfire risk reduction efforts to produce biochar (Fig 1). Biochar, a carbon-rich by-product of bioenergy production, is typically produced by slow pyrolysis or gasification of biomass. Because of its persistence in soils, the production of biochar from forest-origin residues is widely recognized as a viable carbon sequestration strategy. Moreover, the use of biochar as a soil amendment has been shown to improve soil quality and plant productivity by increasing moisture retention, raising pH, increasing ion exchange capacities, improving water infiltration, and increasing the fertility of highly weathered soils (Biederman and Harpole, 2013). The volume of biochar required to effectively amend these soil properties is quite high (between 20 and 116 mTon/ ha) (Trippe et al. 2015), and although there are several boutique facilities that are capable of producing small quantities of biochar, facilities for producing biochar in larger quantities (>10,000 tons per year) are rare. Therefore, the limited availability of biochar restricts the ability of growers to apply biochar to subprime agricultural lands just as the limited demand for forest harvest residues restricts the ability of foresters to fund restoration projects. Although a forest-origin biochar strategy pairs these reciprocal needs, it will only be suitable for adoption if it is *technically feasible, logistically scalable, economically competitive, and environmentally beneficial*.

Our proposed study aims to evaluate these critical aspects of a forest-to-field biochar production chain in the Upper Klamath Basin of Oregon and northern California (Sprague River, Williamson River, Upper Klamath Lake, Lost River, Upper Klamath East, and Butte Creek sub-basins) (Fig 2a).

To accomplish this, we have developed a multidisciplinary landscape-level study that pairs large-scale biochar production with newly emerging steep slope harvesting technology to overcome economic and ecological barriers that have previously limited the ability to profitably combine fire hazard reduction with green energy production. Overall, this study jointly explores optimization of wildfire hazard reduction treatments, biochar facility locations, and agricultural field applications to promote forest restoration, forest-related employment, increased agricultural competitiveness, and carbon sequestration.

The specific aims of the study are:

Aim 1: Optimize woody biomass biochar feedstock collection and transport, and biochar production and application in the Upper Klamath Basin.

Aim 2: Evaluate the physical properties of forest-origin biochar and its function as a soil amendment.

Aim 3: Optimize fire hazard reduction in the context of biochar production.

Aim 4: Identify the long-term carbon consequences of an optimized forest-to-field biochar production chain.

This proposal directly addresses IWFL themes of improving health of rural communities, increasing competitiveness of rural businesses, enhancing ecosystem health with a landscape approach, and increasing trust in active management of forest land.

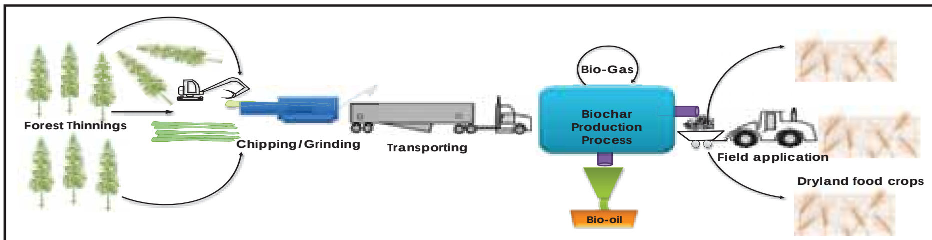

Fig. 1. Biochar supply chain from forest-to-farm.

Related Studies from Agriculture

Biochar is a highly persistent form of organic matter with demonstrated agronomic benefits. Although the agronomic benefits of biochar are the subject of many current investigations, biochars can have a tremendous range in physical and chemical properties. Emerging evidence suggests that the feedstock and the method by which the biochar is produced has a significant impact on ash content, percentage of fixed carbon, percent volatile matter, and pH, which collectively impact the ability of the biochar to ameliorate soil conditions that limit plant growth and yield. Potential benefits of biochar include increased water holding capacity, soil permeability, pH, and soil fertility, and reduced bioavailability of toxins. While very little is known about forest-origin biochar produced by microwave pyrolysis, one common attribute of biochars is their impressive ability to increase the water holding capacity (WHC) of soils. For example, we observed that when a soil with very little water holding capacity was amended (4%) with biochar, it contained twice the amount of moisture at the permanent wilting point than the non-amended control. Although similar gains in WHC can be achieved by with compost-based amendments, compost amendments are notably ephemeral, while the effects of biochar amendment have the potential to persist for decades to centuries. Although a full evaluation of this biochar will ultimately determine the most appropriate agricultural markets for biochar use, we anticipate that increased WHC alone will significantly increase crop yield and decrease irrigation requirements. Therefore, regions like the Upper Klamath Basin, which are perennially impacted by drought, are prime agricultural markets for biochar amendments.

One barrier to large-scale use of biochar as an agricultural amendment is the unknown cost associated with a limited supply. McCarl et al. (2009) evaluated the use of biochar produced from corn residues in a small stationary plant. They considered agricultural productivity increases and savings in fertilizer. Biochar had an estimated a breakeven cost of about $40/tonne of biochar when tied to a 5% increase in wheat productivity. We expect our analyses will indicate that a higher per tonne value can be placed on biochar. This prediction is based on recent studies that demonstrated that the addition of biochar to highly weathered soils produces wheat with double or triple the biomass of plants grown in non-amended soil (K.M. Trippe, personal communication). Furthermore, we expect that when biochar is applied to high value crops, that the breakeven point for biochar production will be significantly increased over the values estimated by McCarl et al. (2009). Our optimism regarding the impacts of biochar on agricultural productivity is also based on a recent meta-analysis of 371 independent biochar studies (Biederman and Harpole, 2013). This study determined that despite variability in climate, soil type, biochar properties, and cropping systems, biochar amendments on average increased plant productivity, crop yield, and total soil carbon and concluded that biochar appeared to be a "win-win-win solution" for energy, agroecosystem function, and carbon storage.

Related Studies from Forestry

Hazard reduction to make forests more resistant and resilient to wildland fire consists of reducing canopy density/continuity, reducing ladder fuels, and rearranging or removing surface fuels (particularly fine fuels). Successful hazard reduction is often measured in the ability to raise the minimum wind speed required to cause individual trees to torch (torching index) and raise the minimum wind speed required to support fire spread through forest crowns (crowning index). Silvicultural prescriptions to achieve these objectives typically focus on (1) treating or removing fuels and vegetation that permit fire to reach the tree canopy; and (2) harvesting small-to-intermediate trees that permit fire to spread through a canopy and then contribute to rapid re-accumulation of surface fuels. These two approaches collectively create horizontal and vertical fuel discontinuities that moderate fire behaviour under most conditions.

One of the greatest challenges is applying these treatments to a forest landscape in such a way that the value from harvested forest products can economically support a significant portion of the forest treatment. Developing a hazard reduction program involves (1) understanding the current forest condition and the development of fuels categories over time, (2) understanding fire behaviour as a function of forest condition/fuels, topography and prevailing weather conditions, and developing prescriptions that would improve tree resistance and forest resilience, (3) calculating the cost of these forest treatment options, (4) calculating the value of the products that are derived from the forest treatment, and (5) assigning the forest treatments in an efficient way to achieve land management objectives.

This proposed project will build upon several related landscape-scale research efforts. The two most relevant studies are Daugherty and Fried (2007) and Granatstein et al. (2009). Daugherty and Fried (2007) focused on jointly optimizing selection of fuel treatments and site selection of forest based bioenergy facilities for landscape-scale fire hazard reduction. They concentrated on the use of biomass for electrical energy production. Their analytical framework is FIA BioSum, a mixed integer linear programming model that combines the spatial location of Forest Inventory Analysis (FIA) plots, a spatial simulation of haul cost distances, fuel treatment prescriptions, and possible facility locations. It is a single-period model for which the decision variables are hectares assigned to a fuel treatment. Biomass transfer variables are used to account for transportation costs to each possible facility. It is similar previously developed models, but differs in levels of detail. Its harvest cost component relies on STHARVEST (Fight et al. 2003), the latest variant of which is embedded in FRCS (Fight et al. 2006.). However, steep slope harvesting technologies in STHARVEST do not include information or data reflecting the world trend toward steep slope feller-bunchers, harvesters, or forwarders.

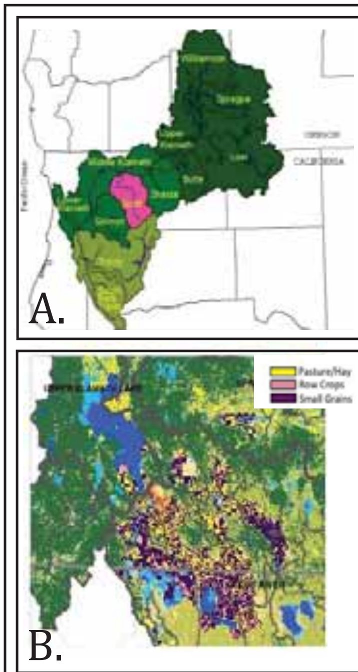

Fig. 2a. Upper and Lower Klamath Basin vicinity map. **Fig 2b**. Part of Upper Klamath Basin showing forest and primary agricultural uses.

Daugherty and Fried (2007) found, for timber prices and electrical power prices typical of the 2004-2005 period, fuel reduction could support 23 to 47 20 MW cogeneration plants. They found that the combined timber plus power had a total net revenue of $6-9 billion over 10 years with the biomass contributing about 15-27% of the total revenue and that plants smaller than 20 MW were not competitive. The capital investment in a 20 MW plant is $40-50 million and requires about 150,000 BDT or 250,000 green tons. Feedstock cost to the power plant appears to have been about $15-18 per BST ($25-$30 per green ton) to calculate power plant net revenues. A significant portion of the power plant feedstock costs were being carried by solid wood products.

Granatstein et al. (2009) evaluated the applicability and performance of biochar made from Washington state forest residue feedstocks on Washington state agricultural soils. They estimated the availability of forest residuals at 7.4 million tonnes/year. Using a stylized analysis of forest thinnings, they evaluated the economics of stationary, relocatable, transportable, and mobile pyrolysis facilities for the production of bio-oil and biochar relying heavily on earlier work by Polygye et al. (2007). Granatstein et al. found that the economics favoured a large stationary plant, with costs increasing with relocatable, transportable, and mobile plants, respectively. Using their assumptions, biochar had a value of $40/ton for agricultural uses. Under 2009 cost assumptions, only the stationary plant was profitable. They concluded that the highest value use for large-scale production of biochar was US$90/ton based on its energy value for power generation.

2. Research location and methods

This project will focus on the optimal siting of a stationary biochar plant in the Upper Klamath Basin (Fig 2a; here after referred to as the Klamath).

Our approach jointly optimizes the application of wildfire hazard reduction treatments, soil amendments, and carbon sequestration by (1) evaluating the cost of undertaking biomass treatments using state of the art harvesting technology, (2) building on previous USDA Forest Service efforts that define hazard reduction treatments for forests in the Klamath, (3) using decision support transportation optimization from forest to plant, and plant to agricultural field and (4) evaluating alternative plant sites using Capex and Opex estimates with our industrial cooperators.

Aim 1. Optimizing woody biomass biochar feedstock collection and transport in the Upper Klamath Basin.

The ability to offset forest restoration treatment costs depends heavily on the value/characteristics of the trees being removed, handling costs, and proximity to facilities, which in the case of the

Klamath, depends largely on the cost-effectiveness of thinning on steep slopes. Daugherty and Fried (2007) found that harvesting was a major cost using conventional technologies, however, the technology for mechanized harvesting on steep slopes has made major advances in the last 10 years. With appropriate sale planning, harvesters and forwarders have been shown to have good productivity and relatively low environmental impacts on slopes to 70% (Fig 3), even without cable assist (Zamora et al. 2014a). Cable-assist add-ons to harvesters and forwarders permit harvesters and forwarders to maintain traction on steep surfaces while providing equipment stability, operator safety, and reducing soil disturbance. Because harvesting costs are a fraction of costs associated with conventional cable logging equipment (Flint 2013), several equipment manufacturers are developing purpose-built cable assisted harvesters as well as post manufacture add-ons. In small wood (< 16 inches Dbh), harvesters-forwarders were only 20-25% of the cost of conventional cable yarding when operating on steep slopes (up to 65%). Flint also found even where cable yarding was used, if harvesters were permitted to bunch for cable yarders, overall stump-to-truck costs were 50% of those associated with conventional cable yarding techniques.

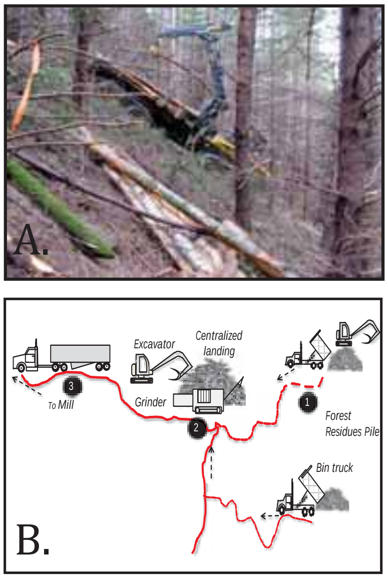

Fig. 3. A. Steep slope thinning in western Oregon (Zamora et al. 2014a). **B.** Comminution and transport options common in western Oregon (Zamora et al. 2014b)

Steep slope harvester-forwarder technology could be a game-changer for forest restoration activities in the PNW given the ability to more cheaply access biomass on the landscape. Lee Miller has commented that possibly one-half of the cable yarders in Oregon may be displaced by steep slope ground-based operations, and has recently acquired a cable-assisted harvester and a cable-assisted forwarder to explore this potential. In order to understand, model, and apply forest restoration strategies using new steep slope harvesting technologies, we will conduct a shift level productivity study of Miller Timber Services harvesting operations. They have previously agreed to participate in an OSU-led steep slope safety study for a National Institute for Health and Safety grant. Pending funding, we would be able to leverage the data collected in that study and apply it to the questions proposed here. Likewise, we have two additional opportunities to collect data for productivity and soil disturbance impacts by working with federal mangers. One would be a production study on the Siuslaw NF to start in August/September and the other on the Winema/Freemont to start in Fall, 2015. For the Winema/Freemont study, we also have the opportunity to leverage funding from the Northwest Advanced Renewables Alliance (NARA).

The ability to offset forest restoration treatment costs depends heavily on the value/characteristics of the trees being removed, handling costs, and proximity to facilities (hauling costs). To obtain highest value, integrated forest operations for sawlog and biomass are undertaken with sorting done either in the field, or at the landing, or at a sort yard (Vitorelo et al. 2012, Harrill and Han 2012, Han et al. 2011). Processors in the field offer greater opportunity to retain nutrients at the field site, which is particularly important on lower productivity sites. More efficient access to and handling of materials more proximate to centralized facilities all increase the potential for increased scope and pace of fuels reduction and ecological restoration treatments. Our modelling would use similar logic to allocate logs to biochar production among other uses. Transportation options from forest to plant can be an important cost element, particularly in steep terrain (Sessions et al. 2010). To reduce transportation costs, forest biomass could be comminuted at roadside or in a central yard (Fig 3) by either chipping or grinding to increase bulk density as well as to prepare biomass for biochar production. Several decision support systems for transportation of biomass from forest to plant are available (Zamora et al. 2014b, Harill and Han 2010). The lowest cost system depends primarily on truck access, biomass concentration along the road system, and distance to plant. We will use the methods of Zamora et al. (2014b) to choose among competing biomass comminution and transport options. Transportation from plant to farm will likely use large on-highway end-dump or side-dump trailers depending upon characteristics of the unloading site.

To develop the significant components for the overall economic feasibility of utilizing biochar in agricultural soils we will estimate costs for building the biochar production facility, develop operating costs of the production facility over and above woody biomass raw material costs, and estimate added processing costs of converting the biochar into a form suitable for agricultural field application. We will begin by preparing supporting documentation for estimating establishment and production costs for producing biochar in an industrial-scale facility located in the Klamath. Our production technology partner, BSEI, currently operates a pilot plant, which employs their proprietary microwave-based technology for producing biochar from woody biomass. Their expertise will be drawn on to develop a detailed description of a commercial facility capable of producing 10,000 to 15,000 bdt/y of biochar. Components of this definition will include: narrative description, process flow diagram, list of major equipment required for material handling, energy generation and management, production, and pollution control, description of site and building requirements, material and energy balance for converting biomass into biochar and process energy, electrical power requirements, and a general arrangement drawing. We will then seek input from vendors and contractors to prepare a Class 30 estimate of the capital cost for building the facility on a suitable industrial site identified by BSEI in the Klamath.

The strategy for full utilization of purchased forest biomass influences the overall economics of the operation and its energy balance. It is our intent to design a facility that will produce only biochar products. The BSEI technology yields approximately one-third of the biomass input into saleable biochar. Most of the rest leaves the reactor either as producer gas rich in CO and H, and condensable oils, tars, and water vapor; collectively referred to as bio-oil. Since further processing of these liquid products adds cost and complexity, and markets for them are currently undeveloped, we will design the production facility for their immediate combustion and capture the energy to dry raw material and generate electrical power to run the microwave generator and plant motors. Consequently, the plant's energy center will need to be capable of burning process wastes in solid (hogfuel), liquid (bio-oil), and gaseous (producer gas) forms. Whether or not the plant will be essentially energy self-sufficient, or require additional operational energy inputs (beyond start-up and back-up needs) will be determined by the energy balance.

We will also explore options for delivering the biomass to agricultural markets in an appropriate form for broad-scale application. Our partner Walking Point Farms is an active player in the agricultural supplement supply chain. Their current expectation is that the market will require raw biochar to be modified to reduce dusting and improve handling characteristics. They have pioneered a number of ways for doing this, including pelletizing, prilling, and seed coating technologies, with some promising results. We will draw on their expertise to estimate the cost of utilizing these technologies, either as additional unit operations built-in to the biochar production plant, or as value-added operations conducted at a third-party facility. We will also expand the plant definition to support estimation of all other operational cost requirements, including production and maintenance, labor, replacement parts and facility maintenance, utilities and fuels, supervision and management, legal and permits, sales and administration, and other typical costs. From this, along with the capital estimate and the range of expected delivered cost of the raw material, we will generate a *pro forma* cost statement for the facility showing total costs for producing biochar, in a form suitable for broad-scale agricultural use, on a per ton basis for input into the biochar production and application cost model.

Tasks:

A1.1 A literature review of national and international studies done with tethered harvesters and forwarders

A1.2 A shift level productivity study Summer/Fall 2015 of Miller Timber Services operations on the Alsea District of the Siuslaw combined with soil impact and tension measurement

A1.3 A shift level productivity study Fall 2015 with a MS student of Miller Timber Services operations on the Winema/Freemont NF combined with soil impact and tension measurement

A1.4 Harvest model development

A1.5 Establish costs for building the biochar production facility on a specific site

A1.6 Develop operating costs of the production facility over and above raw material costs

A1.7 Estimate added processing costs of converting the biochar into a form suitable for agricultural field application.

Aim 2. Evaluating the physical properties of forest-origin biochar and its function as a soil amendment

Because the properties of biochar are variable and because biochars persist in soils, the International Biochar Initiative recommends that all biochars meet specific parameters regarding basic physiochemical and soil enhancement properties. Therefore, a typical array of tests that determine the qualities of this (or any other) persistent soil amendment will be conducted, including: (1) Proximate analysis to determine the percentages of volatile matter, ash, and fixed C, (2) bulk density and hydraulic conductivity, (3) elemental analysis of plant micro-, and macronutrients, volatile organics, and heavy metals as determined by inductively coupled plasma optical emission spectrometry (4) analysis of plant-available nutrients (NO3, NH4, P, K, incubation- N, and mineralizable N and cation exchange capacity), and (5) analysis of pH and char conductivity. These analyses will provide a complete description of basic properties of the forest-origin char and will inform subsequent studies.

A recent meta-analysis of biochar studies indicated that biochar amendments increase plant productivity and yield (Biederman and Harpole, 2013). However, the degree to which biochar impacts crop productivity is largely based on the physiochemical properties discussed earlier. Therefore, greenhouse experiments will be conducted to determine the specific impact that forest-origin biochar has on the productivity of plants and on the dynamics of soil water and carbon. Wheat is one of the most economically important crops grown in Oregon ($368 million), and a proxy for the small grains that dominate Klamath agriculture (Fig 2). Greenhouse experiments will be conducted with soil collected from a Klamath field that is currently used to grow row crops under an irrigated water regime. The soil will be amended (4% or 9% amendment rate) either with pelleted or with unprocessed biochar. In all cases, the amendment will be equally mixed into the soil prior to planting. Non-amended controls will also be planted and monitored. Prior to planting, the amended and non-amended soils will be sampled and analysed for WHC and for total carbon. Each pot will be planted with four wheat seeds, two of which will be removed from the pot post-germination. Each treatment will be replicated 5 times and, using a completely randomized block design, placed in the greenhouse. Plants will be grown with supplemental lighting with a 16h extended day length for 150 days or until they reach maturity. Subsequently, the above ground portion of the plants will be harvested, dried, and weighed to determine if there is a significant difference in plant productivity between treatments.

Previous studies have estimated that the application of 0.9 Pg of biochar to agricultural soils can sequester 1.8 Pg CO_2-carbon equivalents by reducing CH_4, CO_2, and N_2O emissions (Woolf et al. 2010). However, it is not yet clear if these estimates are valid among biochars with variable physiochemical properties. Although long-term studies of forest-origin biochars are outside the scope of this proposal, it is important to inform the carbon model described in Aim 4 with values that are meaningful for the biochar and the soil type specified in the model. Therefore, carbon emissions will be monitored during and subsequent to the greenhouse studies described above. Carbon fractionation experiments combined with monitoring of greenhouse gas emissions will collectively determine if the forest-origin carbon remains in the stable carbon pool or if it is respired by heterotrophic microbes. To accomplish this, CO_2 and N_2O emissions will be periodically monitored throughout greenhouse experiments. After harvest, soil samples will be removed from the pots with the wheat roots intact. These samples will be incubated for 90 days in the laboratory under a constant temperature and periodically monitored for CO_2 and N_2O concentrations. After 90 days we expect that all of the labile carbon will be respired from the soil cores. We will then use centrifugation techniques to determine the fraction of carbon that belongs to the intermediate carbon pool. The remaining carbon will be assigned to be the stable carbon pool. These values will serve to parameterize the carbon accounting model proposed in Aim 4.

Tasks:

A2.1 Analyse the physiochemical properties of microwave-produced biochar

A2.2 Determine the effect of biochar amendments on soil moisture dynamics

A2.3 Evaluate the effect of biochar amendment on carbon dynamics and greenhouse gas emissions.

Aim 3. Optimizing fire hazard reduction in the context of biochar production in the Klamath.

The prescription assignment model used in this proposal will be similar to Daugherty and Fried (2007), but will differ in several important ways. The decision variables will be the number of acres of each FIA plot that will receive a hazard reduction prescription, but the harvesting costs will be based upon the proportion of acres on different topographies within the vicinity of the plot, rather than the description of the plot center (Vogler 2014). This classification would build off of current GIS methodology developed under a USDA NIFA NARA project that combines road locations with topography to provide an estimate of the number of acres of each terrain type in the immediate area of the plot center. Although the actual plot centers are not available, we believe the distortion is not significant at the scale of this assessment.

As a starting point, we will use the hazard reduction treatments developed by Daugherty and Fried (2007), archived at the PNW Station, to understand potential feedstock supply from treated FIA plots. Additional treatments and refinements will be added based on regional modelling experience and interactions with area collaboratives and managers designing current treatments (e.g. ecological forestry). For example, we can explore the impact of diameter caps on economic and ecological/fire behaviour viability of treatments. Landscape-level fire risk will be evaluated with Flammap and similar emerging GIS products.

The landscape transport model will use the RENO decision support model developed under NARA to determine the most cost effective methods of comminution and delivery of biomass to alterative plant locations. The plant locations can be considered a transshipment point on the transportation network to the agricultural field. Sessions and Paredes (1987) considered sort yard locations to increase product values through a two-phase procedure that used network analysis to solve the first phase and either mixed integer or linear programming to solve the second phase. We will embed the road network within the allocation model to better understand transportation costs to alternative sort yard, facility locations, and farm destinations.

<u>Tasks</u>

A3.1 Develop assignment model methodology

A3.2 Assemble GIS and FIA data sets

A3.3 Develop and modify silvicultural prescriptions across the landscapes

A3.4 Complete assignment model development.

Aim 4. Identifying the long-term carbon consequences of an optimized forest-to-field biochar production chain

Among the most exciting and widely touted claims regarding biochar is its potential to mitigate climate change (Gurwick et al. 2013; Jeffery et al. 2015). Unlike other bioenergy operations, which depend on construed fossil-fuel off-sets in order to be considered a net carbon sink (Ter-Mikaelian et al. 2015), biochar promises to increase terrestrial carbon stores by converting labile organic matter (i.e. that largely destine for the atmosphere in a matter of months to years) to highly recalcitrant organic matter (i.e. that which may remain terrestrially sequestered for decades or centuries). Moreover, the energy required to perform this conversion can be derived in part, or entirely, from the biomass itself (De Gryze 2010; Stewart et al. 2013). For these reasons biochar projects, which may be economically sustainable in their own respect, have the added advantage of being possibly rewarded by regulatory systems aimed at promoting carbon sequestration and penalizing operations which reduce terrestrial carbon stocks (De Gryze, 2010). At the moment, there is no US-sanctioned certification process by which biochar operations could be financially credited for carbon sequestration, however the regulatory system defining the market value of carbon sequestration is evolving rapidly at the state level. Therefore, being able to evaluate the carbon consequences of biochar operations, like that being considered here for the Klamath, is a critical facet of our proposed feasibility assessment. To that end, we propose to model the origin and fate of forest carbon in the Klamath as it moves from forest through biochar production and eventually to agricultural soils.

Model structure and parameterization To perform this analysis we will employ a temporally-dynamic ecosystem model that tracks carbon from forest to biochar production facility to agricultural soil pools (Fig 1). This model has been successfully used to evaluate the impact of timber harvest, fuels reduction, and natural disturbance on net ecosystem carbon balance (Campbell et al. 2012), and will be modified for this study to include a biochar pool, fed by forest fuels and sent to agricultural soil pools. Default parameters describing the carbon flow associated with fuels treatments and forest growth are widely available and can be specified to reflect specific operations. Parameters describing the energy costs associated with feedstock recovery and transportation are also widely available and can be specified to reflect the delivery networks. Currently, the most variable and uncertain parameters are those involving the biochar conversion efficiencies and soil residence time (Gurwick et al. 2013). We will rely on our industrial partners to provide biochar conversion efficiencies associated with specific facilities proposed for the Klamath, and compare these to alternate documented values (De Gryze 2010). Biochar soil residence time, and its secondary effects on the residence of native soil organic matter, will be derived from the soil incubation studies.

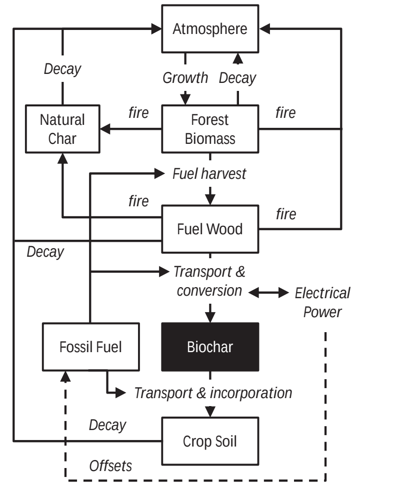

Fig. 4. Proposed carbon model for evaluating the production of biochar from forest fuel treatments and its application into crop soils.

Simulation scenarios

Ultimately, the amount of carbon sequestration (or emissions) attributed to a regional biochar operation will depend on the baseline used. For instance, future carbon markets may opt to view biochar feedstock as an inevitable by-product of forest restoration activities and therefore carbon neutral at their point of generation. Alternatively regulations may view forest biomass reduction as a carbon debt attached to the whole operation. Or, as some European markets have determined, biochar production itself may be considered business-as-usual, crediting operations only for how much carbon is retained in the char and its subsequent lifecycle. Once parametrized, we will compare the outcome of four different model scenarios. These are: 1) No action wherein forest fuels remain *in situ* and are subject probabilistic combustion in wildfire (sub-scenario 1a: subject to wildfire; sub-scenario 1b: no wildfire); 2) fuel reduction only wherein harvests are applied as specified by existing operational plans for Klamath-region forests with residues left on site (sub-scenario 2a: lop-and-scatter left to rot; sub-scenario 2b: pile-and-burn); 3) biochar production involving feedstock transport to optimally-located biochar plant and conversion into biochar (sub-scenario 3a: conventional pyrolysis; sub-scenario 3b: microwave-initiated pyrolysis); and 4) agricultural application involving biochar transport to crop fields and soil incorporation. (sub-scenario 4a: relatively acidic crop soils; sub-scenario 4b: relatively basic crop soils)

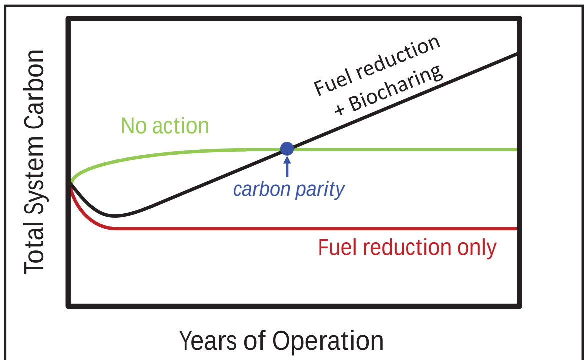

Fig 5. Hypothetical model output illustrating the effects of converting forest fuels into biochar. Losses in forest biomass associated with repeated fuel removal are eventually overcome by the cumulative sequestration of forest origin carbon in stable biochar products. True atmospheric parody occurs when biochar sequestration first surpasses the no-action scenario.

Evaluation and anticipated results

First, the biochar soil sequestration rate will be evaluated for a range of possible production efficiencies and soil resonance times. Second, fossil fuel consumption will be evaluated for a range of logistical scenarios. Finally, the system-wide impact of biochar production will be evaluated by in a manner similar to Mitchell et al. (2012), wherein the accumulation of total carbon associated with any particular intervention is compared to no-action scenarios. As illustrated in Figure 5, this approach will reveal the elapsed time required for operations to pay-back losses in forest biomass and reach the carbon sequestration parity point. While these modelling exercises are designed specifically to assess forest-to-field biochar feasibility, results are also germane to ongoing efforts aimed at understanding relationship between fire and ecosystem carbon storage. Recent advances in our understanding of combustion and post-fire decomposition have greatly improved our understanding of how prescribed fire and wildfire influence net ecosystem carbon balance (Campbell et al, 2007, 2012), however the role of charcoal in this process remains poorly understood. Results from this project will help fill this critical knowledge gap.

Tasks:

A4.1 Structure carbon flow model
A4.2 Parametrize carbon flow model with default values and those provided in Aims 1-3
A4.3 Evaluate carbon consequences of forest-to-field biochar production chains in the Klamath.

3. Anticipated outcomes

This proposal has the potential to positively impact management and inform policy for Oregon and IWFL stakeholders by evaluating if large-scale biochar production is *technically feasible, logistically scalable, economically competitive, and environmentally beneficial* at the landscape scale. Likewise, if our model suggests that biochar production meets these minimum criteria, it could potentially trigger industrial interest in supporting the development of forest-to-farm biochar markets, benefiting rural economies that are typically based on forest and agricultural commodities. It exerts College of Forestry leadership for this emerging forest product with national and international implications, and contributes new knowledge to the forest-to-field biochar supply chain with:

a) a collection and transportation model evaluating the potential for treating forest stands on steep slopes using state of the art harvesting and transport technologies,
b) a biochar production and application cost model,
c) a description of biochar properties through the proposed industrial process and feedstock sufficient to identify target soils, application rates, and crop response,
d) a description of effect of biochar on water holding capacity of Klamath soil,
e) an estimation of the carbon sequestration potential of forest-origin biochar,
f) a landscape-level wildland fire hazard reduction assignment model, including a carbon accounting framework,
g) an improved consideration of black carbon stocks in ecosystem models for evaluation of alternate management and product pathway scenarios and consequences for carbon sequestration, and
h) a sensitivity study using the biochar supply chain decision support model to identify the level of a wildfire hazard reduction program whose direct costs could be offset by receipts from a combination of carbon credits and agricultural productivity increases given varying assumptions of agricultural productivity responses and carbon sequestration credits.

4. Outreach activities

Outreach activities will involve publications in basic and applied science journals, the NW Fire Science Consortium, a website, and knowledge will be extended to growers through field days, workshops, and extension newsletters. Where ever possible, growers will be invited to field days where they will be shown crops grown in biochar amended soil, different biochar application methods, and benefits of biochar. We will collaborate with OSU extension to present information on biochar and assist interested growers in the transition to biochar farming, to provide advice in fire hazard reduction prescription development, and to communicate project results to stakeholders. A video will be developed for demonstrating the potential for steep slope harvest operations.

Our team includes the Biomass Coordinator at ODF, and other investigators that are active in regional organizations focused on the expanded utilization of forest biomass, including the Oregon Forest Biomass Working Group, the Oregon State-Wide Wood Energy Team, and the Northwest Biochar Working Group. The information gained from this study will be disseminated directly to target audiences in agriculture and forest restoration through presentations, white papers, and other professional interactions. Our collaborator, Walking Point Farms, is focused on the development of biochar-based products for commercial agriculture. They are therefore well positioned to make direct use of the information we generate to stimulate market expansion.

5. Timeline

AIM.TASK	Year One	Year Two	Year Three
A1.1 A literature review of tethered harvesters and forwarders	X		
A1.2 Productivity study of Miller Timber Services operations on Siuslaw NF steep slope forwarder and harvester	X		
A1.3 Productivity study of Miller Timber Services operations on Winema/Freemont NF steep slope forwarder and harvester	X		
A1.4 Harvest model development	X		
A1.5 Establish costs for building the biochar production facility	X	X	

A1.6 Develop operating costs of the production facility over and above raw material costs	X	X	
A1.7 Estimate added processing costs of converting the biochar into a form suitable for agricultural field application.	X	X	
A2.1 Analysis of biochar properties	X	X	
A2.2. Greenhouse pot experiments	X	X	
A2.3 Carbon sequestration analyses	X	X	
A3.1 Develop assignment model methodology	X	X	
A3.2 Assemble GIS and FIA data sets	X	X	
A3.3 Develop silvicultural prescriptions	X	X	
A3.4 Complete assignment model development	X	X	
A4.1 Structure carbon flow model	X	X	X
A4.2 Parametrize carbon flow	X	X	X
A4.3 Evaluate carbon consequences	X	X	X
Project Report			X

6. Integration

This proposal directly addresses IWFL themes by (a) protecting communities from wildfire, strengthening the base for local employment in forest restoration activities, and enhancing the competitiveness of the farming sector (b) Increasing the competiveness of forest owners by providing a market for low-value wood/residues and increasing the competitiveness of farmers by improving land productivity and water efficiency, (c) enhancing ecosystem health by increasing forest resilience, sequestering carbon in agricultural soils, and improving water efficiency on agricultural lands, and (d) contributing to a scientific basis for biochar use in agricultural soils with emphasis on the Klamath.

Unlike past efforts which have addressed individual components of a field-to-forest biochar chain, this proposed study promises to integrate diverse expertise and perspectives from the disciplines of operations engineering, economics, landscape management, soil biology, and ecosystem science. While we are fortunate to have such diverse expertise here in the College of Forestry, project cooperation at this level has, to date, been more theorized than realized. We see this project as a unique opportunity to integrate our talents in ways that have not been fully realized in the past.

7. Partner linkages and support

IWFL themes are addressed by merging a broad spectrum of expertise, philosophies, and perspectives. Our proposed collaboration represents each department with CoF and brings external perspectives from agriculture, ODF, and two industrial collaborators. CoF PI's are John Sessions (FERM), John Bailey (FERM) John Campbell (FES), and David Smith (WSE). Agricultural, microbial, and soil science expertise is provided by Kristin Trippe (USDA ARS) and Stephen Machado (OSU Agricultural Experiment Station). Daniel Leavell is with the Klamath Basin Extension and Research Center (KBREC). Marcus Kauffman (ODF) is a Biomass Resource Specialist at the ODF and chair of the Oregon Forest Biomass Working Group. Leavell, Machado, and Kauffman would assist in developing the outreach plan for forest and agricultural landowners. Our Industrial collaborators are Rolly Liu of BSEI Inc., and Chris Tenney of Walking Point Farms LLC. BSEI Inc. operates a microwave-driven biochar plant in Yunnan, China (Dehong CHON Pyrolsate) and recently established headquarters in Portland, OR. They will provide technical support for developing capital and operating expenditures for potential plant sites. BSEI will also prepare and ship biochar samples for experimental use. Walking Point focuses on specialized fertilizers and delivery systems. They will provide technical support related to application technologies of biochar to agricultural soils and will pellet BSEI biochar for experimental use. In kind contributions from outside source total $238,597, from ARS ($92,000), BSEI ($50,000), Walking Point Farms ($15,000), and the ODF ($10,000). Combined with in-kind contributions from OSU faculty, the match to IWFL funding is approximately 96% of the requested budget.

8. Interaction with IWFL Board Members

We solicited support from all Board Members. We received input from 16 of the 20 Board Members. We distilled the input and feedback from the Board Members into 19 points with a team response as to how the issues raised by Board Members were addressed in the full proposal. The specific questions and team responses are on file at CoF.

Bibliography

Biederman, L. and W.S. Harpole, 2013. Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. GCB Bioenergy (2): 202-214.

Campbell, J.C., D.C. Donato, D.A. Azuma, and B.E. Law. 2007. Pyrogenic carbon emission from a large wildfire in Oregon, USA. Journal of Geophysical Research-Atmospheres. 112(G4): No. G04014.

Campbell, J.L., M.E. Harmon, and S.R. Mitchell. 2012. Can fuel reduction treatments really increase forest carbon sequestration by reducing future fire emissions? Frontiers in Ecology and the Env.. 10(2):83-90.

De Gryze, S. 2010. Evaluation of the opportunities for generating carbon offsets from soil sequestration of biochar. An issues paper com. by the Climate Action Reserve. Terra Global Capital LLC. San Fran, CA.

Daugherty, P. and J. Fried. 2007. Jointly optimizing selection of fuel treatments and siting of forest biomass-based energy production facilities for landscape-scale fire haz. red. INFOR. 45(1): 17-30.

De Gryze, S. 2010. Evaluation of the opportunities for generating carbon offsets from soil sequestration of biochar. An issues paper comm by the Climate Action Reserve. Terra Global Capital LLC. SanFransisco, CA.

DOE 2011. Billion Ton Study-Update: Biomass supply for a bioenergy and bioproducts industry.

Fight, R., X. Zhang, and B. Hartsough. 2003. Users Guide for STHARVEST: Software to estimate the cost of harvesting small timber. USDA FS, Gen. Tech. Rpt., PNW-GTR-582, Portland, OR.

Fight, R.D., B. Hartsough, and P. Noordijk. 2006. Users guide for FRCS: fuel reduction cost simulator software. Gen. Tech. Rep. PNW-GTR-668. Portland, OR: USDA, Forest Service, Pacific Northwest Research Station.

Flint, B. 2013. Analysis of operational characteristics of biomass extraction on steep terrain in western Oregon. M.S. thesis, Oregon State University, Corvallis. 175 pp.

GAO 1999. Western national forests: A cohesive strategy is needed to address catastrophic wildfire threats. Rep to the Subcom on Forests and Forest Health. House of Rep. GAO/RCED-99-65 60 pp.

Granatstein, D., C. Kuger, H. Collins, et al, 2009. Use of biochar from the pyrolysis of waste organic material as a soil amendment. Final proj. rept. Ctr. for Sustaining Agri and Nat Res, WSU, Wenatcheee, 168 pp.

Gurwick NP, Moore LA, Kelly C, Elias P. 2013. A Systematic Review of Biochar Research, with a Focus on Its Stability in situ and Its Promise as a Climate Mitigation Strategy. PLoS ONE 8(9).

Han, H.-S., T. Bilek, J. Dramm, D. Loeffler, and D. Calkin. 2011. Financial feasibility of a log sort yard handling small-diameter logs: A preliminary study. West. J. App For. Vol.26(4):174-182.

Harrill, H. and H.-S. Han. 2012. Productivity and cost of integrated harvesting of wood chips and sawlogs in stand conversion operations. Int J of For Res. Article ID: 893079 (Open Journal), 10p.

Jeffery, S., T. Bezemer, G. Cornelisson, et al. 2015. The forward in biochar research: targeting trade-offs between the potential wins. Global Change Biology – Bioenergy (7):1-13.

McCarl, B., C. Peacocke, R. Chrisman, C. Kung, and R. Sands. 2009. Econ of biochar production, util and greenhouse gas offsets, p. 341-358 in J. Lehmann S. Joseph (ed) Biochar for Env Mgt. Earthscan. London.

Mitchell, S.R., M.E. Harmon, and K.B. Oconnell. 2012. Carbon debt and carbon sequestration parity in forest bioenergy production. Global Change Biology- Bioenergy. 4, 818–827

Polygye, B., K. Hogson, and P. Maltea. 2007. An economic analysis of bio-energy options using thinnings from overstocked forests. Biomass and Bioenergy 31:105-125.

Sessions, J. and G. Paredes. 1987. A soln. meth. for the sort yard loc. prob. in for. oper. For Sci 33(3):750-762.

Sessions, J., J. Wimer, F. Costales, and M. G. Wing. 2010. Engineering Considerations in Road Assessment for Biomass Operations in Steep Terrain. West. J. of Applied Forestry 25(3):144-153.

Stewart, C.E. J. Zheng, J. Botte, and M. Francesca. 2013. Co-generated fast pyrolysis biochar mitigates greenhouse gas emissions and increases C seq. in temp. soils. Global Change Biology- Bioenergy 5, 153–164.

Trippe, K., S. Griffith, G. Banowetz, and J. Whitaker. 2015. Changes in acid farm soil chemistry following wood and grass biochar amendments. Agr. J (in press). Pub online 6 Mar. 2015. doi:10.2134/agronj14.0593.

Vitorelo, B., H.-S. Han W. Elliot. 2012. Productivity and cost of integrated harvesting for fuel reduction thinning. Forest Products Journal, Vol. 61(8):664–674.

Vogler, K. 2014. Sustainable biomass supply from fuel reduction treatments: A biomass assessment of federally owned land in eastern Oregon. M.S. Thesis, OSU, Corvallis. 117 p.

Ter-Mikaelian, M., S. Colombo, and J. Chen. 2015. The Burning Question: Does Forest Bioenergy Reduce Carbon Emissions? A Review of Common Misconceptions about For. Carb. Accounting. J. For 113: 000-000.

White House 2013. Climate change and President Obama's action plan. Last accessed January 2, 2015. http://www.whitehouse.gov/share/climate-action-plan.

Woolf, D., J.E. Amonette, F.A. Street-Perott, J. Lehmann, S. Joseph. 2010, Sustainable biochar to mitigate global climate change. Nature Communications, doi: 10.1038/ncomms1053.

Zamora, R., P. Adams, and J. Sessions. 2014a. Ground-based thinning on steep slopes in Western Oregon: Soil exposure and strength effects. Forest Science 60(5):1014-1020.

Zamora, R., J. Sessions, K. Boston and G. Murphy 2014b. Economic Optimization of Forest Biomass Processing and Transport. Forest Science. http://dx.doi.org/10.5849/forsci.13-158