OPPORTUNITIES AND USES OF BIOCHAR ON FOREST SITES IN NORTH AMERICA

Waste to Wisdom: Subtask 4.6.6

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Abstract: Biochar may be useful for restoring or revitalizing degraded forest soils and help with carbon sequestration, nutrient leaching losses, and reducing greenhouse gas emissions. However, biochar is not currently widely used on forested lands across North America. This chapter provides an overview of several biochar experiments conducted in North America and discusses the feasibility of using in-woods mobile pyrolysis systems to convert excess forest biomass into biochar. Biochar may be applied to forest sites in order to positively influence soil properties (nutrient leaching, water holding capacity), but its biggest benefit may be in facilitating reforestation of degraded or contaminated sites, and in sequestering carbon in soils. The majority of data on biochar applications on forest sites focus on seedling responses and short-term impacts on nutrients, physical property changes, or microbial changes. Long-term field research is necessary to determine water use, carbon sequestration, nutrient use, and greenhouse gas emissions and the subsequent alteration of forest growth and stand dynamics

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15.1 Introduction

Many North American forests face management challenges related to wildfire, insect and disease outbreaks, and invasive species, resulting in part from overstocked or stressed stands. These sources of forest stress are already being exacerbated by global climate change (Dale et al., 2001). For example, changes in the pattern, distribution, and severity of fire may result in large-scale impacts on species diversity and regeneration (Stocks, et al. 1998). Further, commercial forestry in many regions face challenges related to decreased commodity values and increasing operational expenses, such that the cost of biomass removal often exceeds its value, despite increasing interest in forest biomass utilization (Rummer et al., 2003). Large quantities of forest residues; including tops, limbs, cull sections, and unmerchantable round wood are potentially available for use in the production of energy, fuels, and biochar. These byproducts of forest operations could also be used to off-set the use of fossil fuels and reduce greenhouse gas emissions (Jones et al., 2010). In the western US, it was recently estimated that more than 11 million hectares of forestlands could benefit from fuel reduction treatments, yielding approximately 310 million dry tons for bioenergy production (Rummer et al., 2003).

Currently, forest restoration or rehabilitation treatments involve forest thinning and regeneration harvests that can produce 40-60 million dry metric tons of woody biomass per year (Buford and Neary, 2010). Reducing wildfire hazard by fuel reduction can be costly (Desrochers et al., 1993; Zamora-Cristales et al. 2014), but in-woods processing to create chips (Jones et al. 2010), slash forwarding to recover previously discarded material (Harrill and Han, 2010), or mobile pyrolysis (thermochemical conversion of wood; Anderson et al., 2013) may all be used to decrease costs. The use of in-woods fast pyrolysis is also one method to potentially produce a viable byproduct, biochar from 'waste' wood left on log landings or in slash piles (Dymond et al., 2010; Coleman et al. 2010). In addition sawmills and other wood product facilities produce large quantities of woody biomass in the form of chips, sawdust, bark, and wood shavings that could be used to create biochar at centralized bioenergy facilities.

Biochar is defined as "a solid material obtained from thermochemical conversion of biomass in an oxygen-limited environment" (IBI 2014), and can be analogous to charcoal naturally found in fire-prone ecosystems (DeLuca and Aplet, 2008). Biochar has been tested as a soil amendment in many agricultural systems (Lehmann and Joseph, 2009; Liu et al. 2014); however, there has been considerably less work on biochar in forest systems, and in particular few published field trials (Thomas and Gale, 2015). In addition to a long residence time that results in C sequestration, biochar can improve soil properties by enhancing cation exchange capacity, increasing water holding capacity, increasing soil pH as a liming agent, and reducing soil bulk density and physical resistance to water and gas flow within the soil matrix (Mukherjee and Lal, 2013). All of these properties are thought to play a role in enhancing plant growth in biochar-amended soils (Atkinson et al., 2010).

Production of biochar, coupled with new national and international policies that promote large-scale biomass utilization (Abbas et al., 2011), could potentially lead to changes in how forest soils and stands are sustainably managed (Homagain et al., 2014). Bioenergy coupled with biochar as a co-product is a promising alternative for green energy (Homagain et al., 2014). Removal of forest residues can improve stand health and reduce the risk of wildfire (IEA Bioenergy, 2002), but residues also may serve as essential habitat for wood decay fungi and other organisms (Siitonen, 2001), provide cover for wildlife, reduce soil erosion, and play an important role in soil nutrient dynamics and hydrology (Lattimore et al., 2009). Therefore, how much biomass is left or removed should take into account multiple management objectives and should be determined on a site-specific basis (Wood and Layzell 2003; Lamers et al., 2013).

Although biochar application in forest ecosystems may be logistically more challenging than in agricultural systems, forest sites are prime candidates for soil improvement from biochar additions (Page-Dumroese et al., 2009; Coleman et al., 2010; Jarvis et al., 2014). Biochar has the potential to reduce fire risks by removing highly flammable excess woody residues from forest sites, and improve soil water and nutrient retention, and to enhance vegetation growth through improved soil physical or chemical properties. In addition, since charcoal is a major component of the fire-adapted ecosystems as a result of wildfires or prescribed burns (Certini, 2005) application of biochar is expected to mimic many of the soil properties associated with wildfire-generated charcoal (Harvey et al., 1979; Deluca and Aplet, 2008; Matovic, 2011), and thus better emulate natural disturbance processes (Thomas 2013).

In this chapter we review current progress in biochar as applied to managed forest ecosystems in North America. We specifically address the properties of biochar generated from forest residues and wood “waste” material, management scenarios and objectives in which biochar is most likely to play a role, and the effects of biochar additions on forest soil properties and tree growth. Field studies on biochar effects in forests are few, and we present novel data from field trials conducted in the western US. We conclude with a discussion of barriers to applied use of biochar in the North American context, and of related research priorities.

15.2 Biochar production and general properties

Biochar can be produced in any number of ways including traditional kilns and earth mounds, as well as engineered systems for slow pyrolysis, fast pyrolysis, flash pyrolysis, gasification, and microwave pyrolysis (Brown, 2009; Garcia-Perez et al., 2011). Fast-pyrolysis biochar (involving rapid heating rates to peak temperatures) has been more readily available for field and lab testing and will be the focus of the following discussions. In addition to variation in pyrolysis methods, many different feedstocks can be used, such as mill residues (sawdust, bark, wood chips), slash, and thinning residues. All production methods and feedstocks will result in differences in biochar physical and chemical properties; likewise, the same method at a different temperature or residence time will yield biochar with differing properties. For example, biochar produced between 400°C-600°C generally has the least amount of hydrophobicity and highest water holding capacity, while those created under higher temperatures have much stronger hydrophobic tendencies (Kinney et al., 2012; Page-Dumroese et al., 2015).

Black carbon encompasses a spectrum of carbonaceous materials, including char, high-carbon ash, coke, and soot, a subset of which can be considered biochar (Spokas et al. 2011). Biochar itself varies greatly, and even biochar created from woody residues can be inconsistent in terms of chemical properties, with tree species being particularly important in determining char chemistry, pH, and EC. Table 1 lists chemical properties of several biochar samples produced from the same equipment (Abri Tech Incorporated, Namur, QC) operated by Biochar Products in Halfway, OR, USA, with similar residence times (5-7 minutes) and temperature ranges (388-450°C). In particular, the wide range of pH, electrical conductivity, macro- and micronutrients indicate that care should be taken to understand how soil properties might be altered after application of a given biochar.

Table 1. Select chemical properties, pH, and EC of biochar created from woody feedstocks in the western USA. Fast pyrolysis was conducted on each feedstock using the same reactor, feed rate, residence time, and temperature range. Mixed conifer consisted of 70% *Pseudotsuga menziesii* Mirb. Franco, 20% *Tsuga heterophylla* (Raf.) Sarg., and 10% *Abies concolor* (Gord. & Glend.) Lindl. ex Hilebr. Fire salvage consisted of 60% *Pseudotsuga menziesii,* 30% *Tsuga heterophylla*, and 10% *Abies concolor*. Material was salvaged 3 years after fire. Beetle-killed salvage material consists of 60% *Pinus contorta* Douglas ex Loudon and 40% *Pseudotsuga menziesii.*

Tree species or species mix	**Chemical Element**										
	N	**C**	**Ca**	**Mg**	**K**	**P**	**S**	**Fe**	**Zn**	**pH**	**EC**
	--- % ---		---- µg/g ---								
Mixed conifer	0.26	89	6700	990	3900	490	120	3900	33	8.1	103
Fire salvage	0.34	94	8700	1400	4600	730	200	9700	94	7.4	258
Beetle-killed salvage	0.18	86	5100	930	3400	280	120	13000	86	8.1	90
Quercus garryana Douglas ex Hook	0.62	87	35000	2300	8600	880	250	13000	65	7.9	180
Cytisus scoparious (L.) Link	1.10	94	8000	3100	12000	1300	270	6000	91	7.5	235
Thuja plicata Donn ex D.Don	0.31	92	9800	1300	4300	960	170	10000	65	5.4	789
Pinus edulis Englem. and *Juniperus communis* L.	0.50	76	5500	350	1200	200	<75	380	8	6.5	330
Arbutus menziesii Pursh.	0.21	85	4500	630	1600	240	96	8500	35	4.5	789
Mean	0.44	88	10413	1375	4950	635	175	8060	59	6.9	347
Coefficient of variation	69	7	97	66	73	63	39	55	53	19	82

15.3 Field applications

Large-scale, centralized biomass and biochar facilities require large quantities (potentially thousands of tons) of feedstock biomass each year and also require a transportation infrastructure to move biomass from a harvest unit to the facility and transport biochar to an application site. There are examples of such large-scale facilities in North America in situations where there is both feedstock availability and good access to markets for biochar. In many cases such large-scale facilities are not logistically or economically feasible; however, advanced thermochemical technologies currently being developed are targeted to small-scale demand and processing (Fransham and Badger, 2006; Biochar Solutions, 2011; Anderson et al., 2013). Using smaller scale, in-woods (or near woods) biochar processing is one alternative for creating biochar from 'waste' wood using residues that would normally be left on site (lop and scatter) or burned in slash piles. Both the economic feasibility and carbon benefits of these systems are enhanced by reducing transportation of low-value woody biomass. If excess forest residues are pyrolynzed, rather than burned in slash piles, large quantities of the byproduct biochar would result (Mohan et al., 2006).

Generating biochar from waste wood has additional advantages; soil damage is minimized when slash pile burning is avoided or minimized (Page-Dumroese et al., 2010) and there are fewer particulates and greenhouse gas emissions from pyrolysis as compared to slash burning (Anderson et al., 2013). Distributed, small-scale facilities would be able to make biochar from local sources and have the potential to allow individuals to match biochar properties to particular site. Matching biochar may be particularly useful for remediation of specific soil chemical or physical properties (Novak et al., 2009). In addition to in-woods pyrolysis systems, other in-woods portable equipment for feedstock preparation, such as dryers, chippers, grinders, and pellet mills would potentially provide the means for moving slash and processing it into biochar that can be applied on-site or sold as a commercial product.

Unlike agricultural soils where biochar can be added and tilled into the soil profile, application of biochar on forest sites is more difficult since trees, stumps, and downed wood hinder movement across a harvest unit. However, in managed forests log landings, skid trails, abandoned roads, or abandoned mine land soils all require some form of restoration. Biochar added to the surface or mixed into the mineral soil during restoration activities (e.g., decompaction, or invasive species removal) can help increase water storage, reduce leaching, or improve bulk density (Ippolito et al., 2012) and can be applied with existing forest harvest equipment. However, biochar application should not disturb the surface organic horizons (Page-Dumroese et al., 2010). Ease of biochar application will depend on the equipment used to make the char where material size varies from several centimeters to sub-millimeters. Fine-textured biochar could potentially be applied to forest sites using modified agricultural machinery similar to that used in forest liming, as has been widely practiced in high-value hardwood stands in Eastern North America (Long et al. 1997). Formal evaluations of use of spreaders for wood ash have indicated challenges in efficiency and uniformity (Wilhoit and Ling 1996). If biochar is pelletized on site, then use of a log forwarder-pulled pellet spreader could potentially be used on skid trails and throughout relatively open harvested stands (Figure 1). Pellets can be produced using fresh slash as a binder (Dr. K. Englund personal communication, Washington State University) and the spreader has the capability to be used on slopes (≤ 35%) with spread width and quantity adjusted based on need or terrain.

[Insert Figure 1a and 1b here]

Another important use for biochar in a forestry context is in mine tailings restoration. Abandoned hardrock mines dot much of North America, and in western US forested landscapes they are extraordinarily common. In many places, signs of their existence are simply holes in the ground or cliff wall; in other places there are square kilometers of unproductive, exposed tailing features. Environmental concerns with the latter scenario include soil instability, sediment transport into nearby streams, limited revegetation and natural succession processes that are extremely slow, or occurring with undesirable species. In cases of acid-generating metal-leaching tailings there are additional critical concerns involving soil and stream acidification and mobilization of toxic metals. Biochar amendments have the potential to reduce leaching and bioavailability of heavy metals such as copper, zinc, lead, and cadmium (Beesley et al., 2011, 2014; Bakshi et al., 2014), mainly as a result of char sorption characteristics and char effects on soil pH.

In areas where road salt is routinely applied to roads, biochar could be used to mitigate salt-induced stresses. In a greenhouse experiment, biochar applied at 50 t ha^{-1} alleviated salt-induced mortality in two herbaceous plant species (*Abutilon theophrasti* Medik. and *Prunella vulgaris* L.; Thomas et al., 2013). Changes to plant growth and survival were attributed to salt sorption rather than increased plant growth.

15.4 Biochar effects on forest soil properties

15.4.1 Physical properties

Biochar is highly porous and its application to forest soil can improve a range of soil physical properties including soil porosity, pore-size distribution, bulk density, moisture holding capacity, infiltration, and hydraulic conductivity (Atkinson et al., 2010; van Zweiten et al., 2012). Of particular importance to forestry operations are beneficial effects related to reduced soil bulk density on skid trails or log landings. In many areas road removal on National Forests in the USA is being used to restore ecosystem processes. Often roads are ripped to decompact the soil surface and this is typically done with a bulldozer pulling a plow over the roadbed or a grappler lifting the roadbed. Once the road surface has been decompacted, soil amendments can be either surface applied or mixed in. Removing old or unused roads presents an opportunity to use biochar to add organic matter, help maintain a lower bulk density by forming micro-aggregates (Verheijen et al., 2009), and help establish vegetation (Adams et al., 2013). In addition, mulching with biochar or other organic amendments may prevent the soil surface from sealing which might increase sedimentation and runoff (Luce, 1997; Bradley, 1997).

Direct empirical data from field trials in forests are limited. Data from a road decommissioning project in central Montana shows that after 2 years, biochar did not improve soil bulk density or soil moisture to a much greater extent than just ripping (Table 2), which is similar to other findings for soil physical properties (*e.g.*, Verjeoken et al., 2009). Although positive effects on soil hydrological properties have been found in agricultural systems, even at a rate of 47 Mg ha^{-1} in an apple orchard, biochar did not alter soil porosity or water holding capacity (Hardie et al., 2014).

Table 2. Mean ground cover and moisture content, bulk density, and organic matter content 2 years after road restoration and biochar additions in central Montana (standard errors in parentheses). Biochar was created using mobile fast pyrolysis at ~400°C. Feedstock was beetle-killed lodgepole (*Pinus contorta* Douglas ex Loudan). Asterisks indicate significant differences at $p<0.05$ as compared to the other treatments.

	Soil surface cover						
Treatment	**Bare Ground**	**Forbs**	**Grass**	**Organic horizon**	**Soil Moisture content in August**	**Soil organic matter**	**Soil bulk density**
				------ percent ------			$Mg\ m^{-3}$
25 Mg/ha biochar	65	10	10	4	12	4.8	0.91
10 Mg/ha biochar	62	7	8	3	10	3.5	0.92
2 Mg/ha biochar	69	9	9	9	10	4.3	0.91
2 Mg/ha biochar pellets	68	3	8	9	11	3.7	0.92
Ripping only	68	13	1	14	10	3.9	0.92
14 Mg/ha wood straw	44 *	5	7	1	13	2.7*	0.97
Untreated Road	13 *	6	81*	0	5*	2.9*	1.47*

15.4.2 Chemical properties

Nutrient transformations when biochar is added to the soil are dependent on the type and quality of biochar. During pyrolysis heating causes some nutrients to volatilize, especially at the surface of the biochar, while other nutrients become concentrated (DeLuca et al., 2012). Nitrogen is usually lost from the char during high-temperature pyrolysis (Tyron, 1948). High temperature (800°C) biochar produced from wood waste feedstocks generally shows higher pH, electrical conductivity, and extractable NO_3^- relative to low temperature (350°C) biochar; however, biochar density, extractable PO_4^-, and NH_4^+ are generally lower in high temperature biochars (Gundale and DeLuca, 2006). Biochar produced from wood waste material is generally high in soluble potassium, and to a variable extent in phosphorus and calcium. In a Northern hardwood forest Sackett et al. (2014) found an initial increase in soil available potassium following biochar additions, followed later by increases in soil available calcium and magnesium.

15.4.3 Biological properties

Recent research suggests that biochar commonly initially stimulates microbial communities, with this effect diminishing over time (Kuzyakov et al., 2009) as labile C is metabolized (Smith et al., 2010). Soil enzyme activity, similar to soil chemical and physical property changes, is related to biochar quality and soil type (Bailey et al., 2011). In a comparison of a forest soil (Andisol) and agricultural soil (Mollisol), enzymes responsible for decomposition processes decreased with increased biochar additions (Figure 2), but soil respiration was unaffected (Figure 3) indicating that organic matter is likely not lost as biochar is added to the soil.

[Insert Figures 2a-2e here]

[Insert Figure 3 here]

Soil microbial composition is also likely to change in response to biochar additions to forest soils. Biochar has sometimes been portrayed as being particularly beneficial to fungi (Ishii and Kadoya, 1994; Warnock et al., 2007); however, recent studies indicate that biochar additions result in increased soil bacterial populations and increased bacterial: fungal ratio in a variety of systems (Chen et al. 2013; Farrell et al. 2013; Gomez et al. 2014). In a Northern Hardwood forest soil only minor effects on soil microbial community structure were found with low rates of biochar addition (5 t/ha) with a small but significant increase in bacterial:fungal ratio (Noyce et al. 2015). Laboratory soil incubations in the same system showed pronounced shift in the soil microbial community at higher biochar addition rates (10 and 20 t/ha), with an increase in the bacterial: fungal ratio and a transient increase in Gram-negative bacteria (Perry et al. 2014).

15.4.4 Greenhouse gas flux

Biochar is thought to be an important potential tool for mitigating increasing atmospheric levels of CO_2: first, by sequestering carbon, and secondarily by increasing net primary productivity and reducing greenhouse gas emissions from the soil or plant materials. Studies of both soil CO_2 and methane flux (Rondon et al., 2006; Spokas et al., 2009; Stewart et al. 2013) have given conflicting data on the value of adding biochar. Biochar is generally expected to result in at least a transient increase in soil CO_2 efflux (sometimes termed “priming”) as a result of microbial responses to labile carbon and nutrients (Ameloot et al. 2013); some studies have also found increased soil C mineralization in response to char additions (Wardle et al. 2008). However, recent studies suggest highly variable responses, including “negative priming” effects in which biochar additions reduce soil respiration (Zimmerman et al. 2011; Jones et al. 2011; Ameloot et al. 2013). In agricultural systems biochar is expected to reduce soil methane emissions by enhancing soil porosity and oxygen levels; and indeed complete suppression of methane emissions from field plots in the tropics has been observed (Rondon et al., 2005). As noted previously, many of the responses associated with biochar added to soils will be dependent on both the original feedstock for biochar and the soil.

The limited data available on soil greenhouse gas flux responses to biochar amendments in forest systems likewise appear variable. Lab incubation studies with forest soils have found increases in soil respiration in the short term, but positive “priming” effects are commonly transient (Steinbeiss et al. 2009; Zimmerman et al. 2011), or show complicated dynamics (Mitchell et al. 2015). Responses are also highly dependent on soil type. For example, soil respiration from the forested Andisol and the agricultural Mollisol were different, but there was no response to the addition of biochar (Figure 3). In a 12-month laboratory incubation of temperate hardwood forest soils Sackett et al. (2014) found higher microbial respiration in soils treated with biochar from maple feedstocks than those soils treated with spruce feedstock biochar. Spokas and Reicosky (2009) noted that after testing 16 different biochars on agricultural, forest, and landfill changes in greenhouse gases were dependent on both soil and biochar. Field responses may also show strong deviations from lab incubations, since half or more of total soil CO_2 efflux is attributable to root respiration. Sackett et al. (2014) found no detectable effect of biochar additions on soil CO_2 efflux in a field trial, in spite of significant effects in lab incubations.

Forest soils, particularly those of upland temperate forests, are a globally significant sink for methane (Price et al. 2003); however, there is substantial heterogeneity in soil methane flux patterns in forest ecosystems linked to local variation in hydrology (Dalal and Allen 2008; Wang et al. 2013). Methane uptake by forest soils is thought to be strongly substrate-limited (Bradford et al. 2001; Dalal and Allen 2008; Wang et al. 2013), suggesting the importance of soil porosity and aeration. We are aware of only one field study that has tested biochar effects on soil methane uptake (Sackett et al. 2014); although this study did not find a significant effect, the biochar addition rate used was low (5 t/ha), and at the time of measurements biochar was not fully incorporated in the mineral soil.

15.4.5 Growth responses

There has been a rapid increase in studies examining plant growth responses to biochar additions: recent meta-analyses that now incorporate 100s of independent experiments suggest that agricultural crops show average increases in the range of 10-25% (Biederman and Harpole 2013; Liu et al. 2013). A recent meta-analysis restricted to tree response studies found an average 41% increase in biomass (Thomas and Gale 2015). However, it should be emphasized that both agricultural and forestry studies show high variability, with individual studies showing positive, negative, or no significant change in vegetative growth (Spokas et al., 2011). This variability arises due to inherent differences in the soil, fertilizer application, the nature of the biochar, and differences in responses among plant species. Biochar additions to infertile soil can improve cation exchange capacity (Cheng et al., 2006; Lee et al., 2010), but no or minimal changes in cation exchange have also been observed (Novak et al., 2009). Further, there are complex relationships between biochar and the soil matrix leading to altered pH, soil nutrient availability, and microbial communities (Major et al., 2010). In addition, vegetation responses may be delayed initially, followed by yield increases in subsequent years (Gaskin et al., 2010; Major et al., 2010). Delayed responses could be due to 'aging' of the biochar (e.g., oxidation; Spokas et al., 2011), or gradual losses of volatile organic compounds sorbed during pyrolysis (Spokas et al. 2010; Gale and Thomas 2015). Aging or weathering of biochar often results in alteration of the surface chemistry (Azargohar and Dalai, 2008; Nuithitikul et al., 2010), and in out-gassing of sorbed substances such as ethylene (Fulton et al. 2013), but there is commonly little documentation regarding handling, storage, or post-treatment of biochars.

A published review of tree responses to biochar mostly have involved laboratory and greenhouse trials (e.g., 14 of 17 studies included in meta-analysis by Thomas and Gale 2015). In the Inland Northwest, USA, we have several ongoing biochar field trials examining tree growth responses to biochar. Short-term (1-2 years) changes in diameter increment on two sites (Andisol and Inceptisol soil) were not significantly impacted by biochar additions (Figure 4a and 4b).

[Insert Figure 4a-4b here]

The Andisol is a fine-textured, highly-productive soil (Page-Dumroese et al. 2015) and here tree growth was not affected by biochar amendment, but could be improved by leaving the residual slash in place. This result is similar on the coarser-textured Inceptisol, but higher biochar application rates had a greater tree response. Again, tree growth in the biochar plots was not significantly different from the residual slash retention plots. On this relatively infertile soil type biochar with fertilization also did not offer additional growth gains. Longer-term (5 years) results from a coarse-textured Andisol in south-central Oregon also indicate that biochar application at 25 Mg ha^{-1} was similar to retaining forest residues (Figure 5). However, lower

[Insert Figure 5 here]

levels of biochar application were not as effective as slash retention for increasing growth but did increase height growth slightly over the control trees. For all forest sites, biochar was applied to the surface (on top of the existing forest floor) to limit soil disturbance and maintain nutrient cycling, and this may explain the lack of pronounced tree growth responses. To alter the mineral soil, biochar must first be transported through the forest floor to provide benefits of soil water retention and subsequent tree growth. While we have not seen large gains in productivity on our study sites, neither has tree growth been significantly reduced. In addition, at the application rate of 25 Mg ha^{-1} with approximately 80% C, 15 Mg C ha^{-1} was sequestered with no deleterious effects.

15.4.6 Invasive species

Biochar has the potential improve soil quality and thereby increase desirable species restoration by the addition of organic C. Biochar additions may also result in greater microbial uptake and immobilization of N (Perry et al., 2004). On a tallgrass prairie site in Minnesota, soil C additions resulted in a 54% reduction of weed biomass and a 7-fold increase in native prairie species biomass, which was attributed to a large reduction in soil N (Blumenthal et al., 2003). Other authors have noted similar results with C additions reducing weed growth and/or greater growth of desired species (Blumental et al., 2003; Perry et al., 2004; Grygiel et al., 2010). However, other studies have reported no effect on invasive or desired species after soil C additions (Corbin and D’Antonio, 2004; Mangold and Sheley, 2008), or found that C additions reduced growth of desired species (Averett et al., 2004). Rapid establishment of vegetation is important for ripped roads, skid trails or after harvest operations. Vegetation growth is one of the first signs of ecosystem recovery (Wright and Blaser, 1981). Disused roads are typically nutrient poor and commonly dominated by invasive species (Switalksi et al., 2004). The central Montana road decommissioning project started with most of the vegetation as invasive grasses. However, after ripping, forbs and native grass species were beginning to revegetate both the ripped only and the biochar plots after 2 years (Table 2). While this latter study does not show definitive increases in desirable species in response to biochar, biochar additions did not impede revegetation efforts.

15.5 General prospectus and critical research needs

The potential benefits of adding biochar to agricultural sites have received considerable recent attention (e.g., Spokas et al., 2011), but few studies to date have examined analogous approaches in the forestry sector. There is a clear need for long-term field trials examining a range of biochars, soils, and forest types. A repeated theme in the present review is that responses observed in short-term lab or greenhouse studies do not necessarily translate into comparable responses in the field. It is certainly the case that careful planning to match biochar with site properties can result in C sequestration and improved soil conditions such as organic matter content, porosity, and water hold capacity. No deleterious impacts of biochar additions on forest vegetation have been found to date, though effects on a broader range of forest organisms, such as soil invertebrates, have received almost no attention. Site access and transport considerations are certain to be of critical importance in all practical applications of biochar to managed forests. Highly impacted areas such as skid trails and log landings will likely be a priority for applications due to both potential benefits for site remediation, and ease of access. Pelletizing biochar improves the ease with which it can be applied and reduces dust and particulates in the air. In addition, pellets made with fresh slash return many nutrients inherent in the biomass back to the site thereby reducing the risk of nutrient depletion.

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Table captions:

Table 1. Select chemical properties, pH, and EC of biochar created from woody feedstocks in the western USA. Fast pyrolysis was conducted on each feedstock using the same reactor, feed rate, residence time, and temperature range. Mixed conifer consisted of 70% *Pseudotsuga menziesii* Mirb. Franco, 20% *Tsuga heterophylla* (Raf.) Sarg., and 10% *Abies concolor* (Gord. & Glend.) Lindl. ex Hilebr. Fire salvage consisted of 60% *Pseudotsuga menziesii,* 30% *Tsuga heterophylla*, and 10% *Abies concolor*. Material was salvaged 3 years after fire. Beetle-killed salvage material consists of 60% *Pinus contorta* Douglas ex Loudon and 40% *Pseudotsuga menziesii.*

Table 2. Average ground cover and moisture content, bulk density, and organic matter content 2 years after road restoration and biochar additions in central Montana. Biochar was created using mobile fast pyrolysis at ~400°C. Feedstock was beetle-killed lodgepole (*Pinus contorta* Douglas ex Loudan). Asterisks indicate significant differences from the other treatments at p<0.05.

Figure captions:

Figure 1. Pellets (A) made from biochar and logging slash and (B) being spread with a proto-type biochar spreader developed by the Missoula Technology Development Center, Missoula, MT. (photos by Deborah S. Page-Dumroese).

Figure 2. Changes in (A) soil moisture, (B) soil pH, (C) cellulase, (D), chitinase, and (D) phosphatease in biochar amended Andisol and Mollisol soil types after laboratory incubation. CQuest Biochar was used for amendment (Dynamotive, Vancouver, BC, Canada) was produced using fast pyrolysis of hardwood residue (McElligott, 2011). This biochar had a total surface area of 1.6 m^2 g^{-1}, 16-23% organic volatile compounds, and with 100% particle size distribution <2 mm in size, 95% of the particles <1 mm, and 60% of the particles <0.5 mm. Physical and chemical analyses at the University of Idaho indicated a bulk density of 0.33 Mg m^{-3}, a pH of 6.8, a cation exchange capacity of 30 $cmol^{(+)}kg^{-1}$, 62% total C, and 0.18% total N.

Figure 3. Biochar amendment changes to soil respiration in an Andisol and Mollisol after laboratory incubation. CQuest Biochar was used for amendment (See Figure 2).

Figure 4. Short-term diameter increment response to biochar, fertilizer, or slash retention on (A) Andisol or (B) Inceptisol soils in the Inland Northwest, USA. The Andisol location used CQuest Biochar for amendment (See Figure 2). The Inceptisol used char from Biochar Solutions, Inc. was produced using fast pyrolysis and a mixture of western conifer residues. The biochar had a total surface area of 12 m^2 g^{-1}, with particles sizes ranging from 6.5-0.2 mm; 80% of the particles were <2 mm in size (Anderson et al., 2013). Physical and chemical and chemical characteristics were conducted at the Rocky Mountain Research Station and indicated a bulk density of 0.13 Mg m^{-3}, a pH of 8.7, 76% total C, and 0.45% total N.

Figure 5. Five-year height growth response to biochar or slash retention on the Umpqua National Forest, Oregon, USA. Biochar was created by fast pyrolysis from a fixed plant (Dynamotive) using mixed hardwood feedstock.