doi:10.2489/jswc.2022.0603A

FEATURE

Forest management and biochar for continued ecosystem services

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New approaches to managing climate change uncertainty rely on integrating innovative forest management practices with adaptive management techniques and robust decision-support strategies. Forest management alternatives for a changing climate can enhance ecosystem health and sustainability while ensuring the flow of ecosystem services, such as water, wildlife, biodiversity, recreation, and ecosystem resilience. Ideally, these methods will help reverse the decline in ecosystem function from associated ecological disturbances, such as drought, wildfire, insects, diseases, or invasive species. Forests are important because they are a source for food, fiber, medicine, water, and biofuels for more than one billion people. In addition, forests protect soil and water quality, host more than three-quarters of terrestrial biodiversity, and help combat climate change impacts (FAO 2020).

Sustainable forest management results in healthy and productive ecosystems that provide goods and services to current and future generations. Ecosystem services include (1) *provisioning services* such as food, water, clean air, wood, grasslands (open space), and fiber; (2) *regulating services* that affect climate, floods, disease, wastes, and water quality and quantity; (3) *cultural services* that provide recreational, aesthetic, and spiritual benefits; and (4) *supporting services* such as soil formation, photosynthesis, and nutrient cycling (Millennium Ecosystem Assessment 2005; Smyth 2014). With these ecosystem services in mind, approaches to forest management can include actions directed to the conservation and sustainability of ecosystems and their contributions to enhance human well-being and benefits.

One method to increase ecosystem services is by incorporating biochar into forest management practices. Biochar is a carbon (C)-rich, fine-grained, porous substance, produced by thermal decomposition of biomass under oxygen (O_2)-limited conditions and at relatively low temperatures (i.e., below 700°C [1,292°F) with the intent of use in soil applications (Greco et al. 2019). Biochar is an emerging industry with high potential for development in the United States. Currently, the USDA Forest Service is promoting sustainable forest management in areas at a high risk for wildland fire with the use of low (or no)-value woody biomass for biochar production as one option. Biochar can be used for waste management, renewable energy, C sequestration, greenhouse gas emission reduction, and soil and water remediation; it may also improve soil quality and crop productivity. In addition, C sequestered during biochar applications, "in combination with sustainable biomass production, can be C-negative and therefore used to actively remove carbon dioxide (CO_2) from the atmosphere, with potentially major implications for mitigation of climate change" (Lehmann and Joseph 2009).

Sustainable forest management provides the raw materials for biochar production used to restore degraded soil productivity, water retention, or for soils that have some degree of soil erosion or contamination. This practice is important as a tool to sustain forest and agricultural ecosystems and mitigate the impacts of a changing environment. In this article, we provide a rationale to promote biochar production from "waste" wood to restore ecosystem services for improved soil formation, water retention, and C sequestration.

BACKGROUND

The objective of sustainable forest management is to ensure that goods and services derived from forests meet present-day and long-term needs (Duncker et al. 2012). Forest ecosystems are impacted by natural disturbances and human influence, but the impacts can be minimized by managing for appropriate stand structure by using forest harvesting or controlled burning. Restoration of overstocked forest stands involves judicious use of silvicultural operations (Oliver and Oliver 2018), and the economic benefits are enhanced ecosystem services that can be realized through wildfire cost savings, improved watershed health, and enhanced recreational opportunities, which increase revenue and reduce costs for surrounding communities. Improved ecosystem services also enhance C sequestration, habitat creation and preservation, and watershed health (Ecological Restoration Institute 2010).

Current forest management in the United States is conducted to maximize environmental and ecosystem services (Rodriguez and Conje 2022) and is conducted using a *multiresource approach* to protect biodiversity, soil, water, wildlife, sacred sites, endangered species, fragile ecosystems, wilderness areas, and aesthetics. By protecting site features, forests purify air and water, regulate climate, and control nutrient cycles, which are essential for life (Daily 1997; Binder et al. 2017).

In the United States, catastrophic wildfires have been increasing in frequency, intensity, and geographical coverage during the last decade, partially resulting from changing environmental conditions (Liu et al. 2013). For example, an increase in the length of the fire season from a few months to nearly all year coupled with intensive drought periods, overstocked forest stands, and low intensity forest management created an unbalanced forest ecosystem susceptible to insect and disease attacks with high tree mortality. This situation is expected to worsen because of climate change, putting property and lives

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Received June 3, 2022.

in danger while disrupting ecosystem services and prompting an urgent need for forest restoration treatments, including fuel reduction and salvage logging of dead trees. One way to decrease catastrophic fires and their impacts on ecosystem services is through forest management that alters stand structure and density, composition, and growth (Smith 1986). However, one drawback of silvicultural treatments, under current conditions, is that not all trees removed are economically attractive to the forest industry because they have limited use and value. This lack of forest industry, economic gains, or potential uses often results in large piles of woody residues that are burned without consideration of creating byproducts (Page-Dumroese et al. 2017). Burning large slash piles can impact under-pile soil processes and hydrologic function, thereby lowering burn scar productivity for residual trees. Burning also becomes a source for increased CO_2 and particulate emission.

One option for reducing slash piles is to make biochar. Conversion of this wood into biochar provides revenue, offers a path to long-term C sequestration, and improves ecosystem services. Making biochar on-site (or near site) lowers transportation costs of moving unmerchantable woody material to a pyrolysis unit and can be used to improve forest soils or transported within a watershed (Page-Dumroese et al. 2017). This activity has advantages for forest soil restoration because current efforts to convert biomass normally burned in slash piles to biochar can result in a 10% to 35% (volume) increase of C in the soil. Biochar C is more stable and has a lower risk of releasing CO_2 or other greenhouse gases into the atmosphere (Hernandez-Soriano et al. 2016). Biochar also increases soil water-holding capacity, making the soil less prone to drought and more resilient and productive. Amending sites with biochar during farming or on forest, range, or mines sites further protects biochar from degradation as it becomes part of the stable C pool (Kimetu and Lehmann 2010).

Currently, the potential for biochar production from federal lands has not been fully explored, but there is up to 334 dry Mt (368 million dry tn) of forest wastes and residues produced each year on a sustainable basis (Buford and Neary 2010). Under a high-yield scenario, wastes and residues increase from 483 dry Mt (532 million dry tn) in 2022 up to 1.15 dry Gt (1.27 billion dry tn) in 2040 that could be sustainably produced each year (US Department of Energy 2016). This could be particularly beneficial for federal lands in the western United States if these materials are used for biochar production, where appropriate.

SOIL FORMATION AND NUTRIENT RETENTION

Healthy soils are foundational to agriculture and forestry production and essential for food, feed, fiber, clean water, and clean air (Borrelli et al. 2017; FAO 2019). Therefore, soil degradation and soil loss should be avoided or minimized to maintain ecosystem services, which is cheaper than rehabilitating soils after degradation has occurred (FAO and ITPS 2015). However, 75 Gt (82 billion tn) of fertile soil is lost every year to erosion, leading to losses of 12 Mha (30 million ac) of soil (FAO and IAEA 2017). Estimated erosional losses of cultivated and noncultivated cropland in 2007 was 959.9 ± 14.9 Mt y^{-1} (1,058.1 ± 1.64 million tn yr^{-1}) from water and 765.1 ± 37.8 t y^{-1} (843.4 ± 41.7 tn yr^{-1}) from wind (USDA NRCS 2007). This indicates the need for intensive conservation practices to avoid erosion and increase soil formation. Biochar applications can reduce wind and water erosional losses and provide options for sustainable soil management by improving upon existing best management practices (Lehman and Joseph 2009).

Soil organic matter (SOM) reaches equilibrium with the current environment, but it responds quickly to human-induced changes, making this property central to sustainable management (FAO and ITPS 2015). Biochar from nonmerchantable woody biomass adds long-lasting SOM and leads to considerably greater amounts of C than applications of un-charred organic matter (Lehman et al. 2006). Biochar influences soil-forming processes that govern the accumulation, transformation, and translocation of soil constituents and hence, in the long-term, can modify soil pedogenic activity, morphology, and productivity (Richter 2007). Biochar improves soil structure, texture, porosity, particle size distribution and density, and has a high degree of chemical and microbial stability (Atkinson et al. 2010).

In addition to the benefits previously mentioned, biochar can provide refugia for beneficial soil microorganisms (Gul et al. 2015; Sheng and Zhu 2018), bind cations and anions, and enhance macronutrient (nitrogen [N] and phosphorus [P]) availability (Carlson et al. 2015). Other soil changes associated with biochar applications are increased soil pH, electrical conductivity, and cation exchange capacity (Zhao et al. 2013). Biochar can also reduce ammonium (NH_4) leaching, nitrous oxide (N_2O) emissions, and other pollutants (Xu et al. 2017). There may also be reductions in soil mechanical impedance (Uzi et al. 2019). The greatest benefits of biochar are found when it is added to low fertility, contaminated (Rodriguez and Page-Dumroese 2021), or low SOM soils (El-Naggar et al. 2019; Shabaan et. al. 2018). Strategic biochar application to soils can augment agronomic, environmental, and economic benefits while also reducing woody residues from timber harvest operations. Actions that restore soil ecosystem services on agricultural and forest lands are increasingly critical in the face of climate change (Lal 2022), and biochar applications could help to restore ecological integrity caused by anthropogenic activities in both rural and urban areas.

SOIL WATER RETENTION

The global water cycle has been altered by climate change, thereby affecting water quality and quantity, and streamflow timing. It also causes indirect effects on water resources by the altering the extent and severity of wildfire and subsequent forest mortality (Furniss et al. 2010), infiltration, and water storage in the soil profile. Using biochar on degraded soils is an opportunity to alter soil physical properties resulting in subsequent increases in water-holding capacity, plant-available water (Rasa et al. 2018), infiltration, and hydraulic conductivity (Atkinson et al. 2018; Kang et al. 2022). With an increase in soil aggregation, water infiltration, and water-holding capacity due to biochar, it is possible to reduce agricultural irrigation amounts and costs, especially in semiarid environments (Spokas et al. 2012). Forest management activities, biochar, and water are of paramount importance, because over 644,000 km (400,000 mi) of streams, over 1.4 Mha (3.5 million ac) of lakes and wetlands, and over half of the nation's hydroelectric power supplies in the contiguous United States originate in national forests managed by the USDA Forest Service (Tidwell 2016). In short, the greatest water benefits from biochar additions are in coarse- and medium-textured soils (Razzaghi et al. 2020), and biochar can contribute to effective soil water management and conservation (Blanco-Canqui 2017).

CARBON SEQUESTRATION

Biochar production systems can sequester C, generate heat energy, and create negative emissions. Newer biochar production technologies can also produce biodiesel for heavy duty road transport, hauling logs, or tilling fields. According to the National Academy of Sciences, biological C sequestration can be achieved through afforestation, changes to agricultural practices, soil C sequestration, application of biochar to soil, and the combination of soil biochar additions and bioenergy with C capture and storage technology (NAS 2018). In addition to potential soil benefits, biochar and other co-products from biochar production, such as bio-oil and biogas, have also been studied for their potential climate change mitigation benefits. Recent assessments estimate that using woody residues to create biochar could sequester between 0.6 and 11.9 Gt CO_2 y^{-1} (0.7 and 13.1 billion tn CO_2 yr^{-1}), depending on the availability of biomass for biochar production using CO_2 removal rates of 2.8 to 3.3 Gt CO_2 y^{-1}(3.1 to 3.6 billion tn CO_2 yr^{-1}) (Fuss et al. 2018). Climate change mitigation requires a reduction of emissions and deployment of low-C technologies between now and 2050. Biochar creation from forest biomass could contribute to "negative emissions" (Cowie et. al 2019), and the thermal conversion of biomass to biochar creates a product with much slower mineralization than the original biomass source, which delivers long-term C sequestration.

FOREST MANAGEMENT AND BIOCHAR

Supporting forest biomass for biochar production could decrease the risk of catastrophic fires, increase forest management to restore resilient and healthy stands, reduce drought, and improve rural economies. In addition, biochar production technologies can increase energy supplies, bioproducts from renewable biomass sources, and above- and belowground C sequestration. Forest management influences negative emissions technologies and C sequestration by (1) changing residual tree growing space by increasing the allocation of that space, water, and nutrients for increased growth and (2) using the removed unmerchantable biomass to create biochar. Changes in forest management methods can increase forest C retention from 0.03 to 1.6 Gt y^{-1} (0.03 to 1.8 billion tn yr^{-1}). In addition, afforestation and reforestation efforts can change ecosystem C in a range of 0.001 to 2.25 Gt y^{-1} CO_2 (0.001 to 2.48 billion tn yr^{-1}) (NAS 2019). Biochar has the potential to mitigate climate change (Lehman and Joseph 2015).

CHALLENGES, OPPORTUNITIES, AND RESEARCH NEEDS

Barriers to biochar production and use are not the lack of an adequate supply of forest biomass or the lack of conversion technologies. Rather, the difficulties lie in finding economical methods to convert biomass to biochar and bioenergy and add value to byproducts. Currently, nonmerchantable residues remaining from harvest operations or stand thinning add to the large volume of biomass found at log landings and they are burned to decrease fire risk. This method wastes energy, C, and nutrients while also increasing smoke and particulate emissions. Therefore, developing efficient conversion processes for turning excess biomass into beneficial bioenergy and biochar is worth exploring. Biochar production at a variety of scales (e.g., portable kilns, moderate-scale pyrolysis, fixed plants) within or near forest sites is now possible. The key biochar advantage is a reduction of accumulated forest biomass while simultaneously reducing wildfire risk and improving soil quality. In addition, biochar produced on or near forest lands could establish a pathway for agricultural soils to benefit from biochar additions, and this creates another market for timber purchasers to consider when bidding on harvest units.

Current biochar markets are not fully developed, but the potential to supply biochar to improve water retention, C, and soil productivity on agricultural lands could be of great importance into the future as the drought conditions persist. It could also be important to restore soil productivity to overused soil in farmlands, degraded forest soils, unvegetated mine sites, or expand range forage opportunities. This potential should be explored through mechanisms that facilitate biochar adoption.

Research needs are varied depending on biomass production (biomass recollection) systems, transportation methods, bio-hub availability (forest industry clusters), and biochar production systems (techno-economic assessment of different production options and assessment of portable and fixed production systems at different scales). Furthermore, characterization of woody biochar applications for different environmental uses, developing of standards for those uses, and other environmental assessments around biochar production, such as production system air pollution, are needed. A research roadmap that defines solutions to address climate change has been proposed (Amonette et al. 2021) and is a starting place for gathering information needed by private and governmental decision makers to increase biochar deployment while also maintaining ecosystem services and environmental health.

DISCLAIMER

The findings and conclusions in this publication are those of the authors and should not be construed to represent any official USDA or US government determination or policy.

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