WOOD BIOENERGY AND SOIL PRODUCTIVITY RESEARCH

Waste to Wisdom: Subtask 4.2.1 and 4.6.2

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Abstract:

Timber harvesting of can effect both short- and long-term changes in forest ecosystem functions, and scientists from U.S.D.A. Forest Service Research and Development (FS R&D) have been studying these processes for many years. Biomass and bioenergy markets alter the amount, type, and frequency at which material is harvested, which in turn has similar yet specific impacts on sustainable productivity. The nature of some biomass energy operations provides opportunities to ameliorate or amend forest soils to sustain or improve their productive capacity, and FS scientists are leading the research into these applications. Research efforts to sustain productive soils need to be verified at regional, national, and international scope, and FS scientists work to advance methods for soil quality monitoring and to inform international criteria and indicators. Current and future FS research ranges from detailed soil process studies to regionally important applied research and to broad scale indicator monitoring and trend analysis, all of which will enable the U.S. to lead in the sustainable production of woody biomass for bioenergy.

Introduction

Many North American forests face wildfire, insect and disease outbreaks, and invasive species, resulting in part from overstocked or stressed stands [1]. These sources of forest stress are already being exacerbated by climate change [2]. For example, changes in the pattern, distribution, and severity of fire may result in large-scale impacts on species diversity and regeneration [3]. Further, commercial forestry in many regions face challenges related to decreased commodity values and increasing operational expenses, such that the cost of timber harvesting often exceeds its value, despite increasing interest in forest biomass utilization [4].

Bioenergy from wood has been used for about a half-million years [5], initially for cooking and heating. Today, wood energy supplies about 9% of the worldwide demand for energy and is the single largest renewable energy source, equal to all other renewable sources combined. In addition, about 30% of the world's population depends on wood for their primary source of energy. In the United States, wood was the sole source of human-harnessed energy until 1850, and remained the main source until coal became the primary source in the late 19th century [6]. Wood has been an important source of energy, and will continue to be for the foreseeable future. Large quantities of forest residues, including tops, limbs, cull sections, and non-merchantable round wood are potentially available for use in the production of energy, fuels, biochar and other bioproducts, offsetting the use of fossil fuels and reducing greenhouse gas emissions [7]. Currently, there are approximately 303 million hectares of forestland in the US which could yield approximately 320 million dry tons of forest residues for bioenergy production [8].

However, increasing harvest intensity to include biomass for bioenergy or other uses risks altering energy and nutrient cycles, soil quality, and other associated ecosystem services and attributes. The USDA Forest Service and partners have been studying the impacts of intensive forest harvesting on long-term sustainability for years on various experimental forests and other research installations [9]. Researchers and managers work closely together to understand how various woody biomass products, such as biochar, can be incorporated into management strategies and practices to maintain and improve forest productivity and health. Finally, as the leader for forest biomass and bioenergy research, the USDA Forest Service provides practical science to develop best management practices to improve stand productivity and health. This manuscript will provide an overview of the issues surrounding site productivity, incorporation of multi-use products like biochar into forest management practices, and the broader efforts of maintaining and enhancing forest health and productivity.

Impacts of intensive harvesting on site productivity

Increased forest product utilization inherent in woody biomass extraction has been linked to a multitude of impacts on altered energy cycles, short-and long-term hydrology, and a number of soil properties and processes impacted by increasing the number of stand entries and removing additional wood. Most physical effects are the result of compaction and other forms of soil disturbance, which can increase in both extent and intensity if multiple entries are needed for traditionally merchantable wood as well as residues and non-merchantable wood [10,11]. This additional disturbance can reduce porosity, which limits movement of air, water and nutrients in the soil and negatively impact root growth, microbial activity and potentially reduce tree growth [12]. Soil chemistry and fertility are altered primarily by removing nutrients in harvested organic matter and from changes in nutrient leaching following harvest [13]. The loss of nutrient capital and organic matter due to biomass harvesting is of particular concern to sustaining site productivity and carbon sequestration potential.

Logging residues, or the remainder of the standing tree after the removal of the merchantable bole, contain a disproportionately high nutrient concentration relative to the bole. Similarly, smaller and younger trees contain higher nutrient concentrations than older trees and deciduous trees generally contain more than conifers [14]. Since most plant nutrients are located in the branches and foliage, whole-tree harvesting can remove as much as three times the nutrients as conventional bole-only harvesting where tops are left on site [15–18]. However, the majority of site nutrients are contained in the forest floor and mineral soil (Table 1).

Table 1. Nitrogen quantities (kg ha^{-1}) by pool in four representative forest types of the United States and Canada [18,19]

Location	Forest	Tree boles	Whole-trees	All organic matter	Soil[1]
British Columbia	Subboreal spruce	195	253	1068	1630
Idaho	Mixed conifer	190	410	846	1222
Louisiana	Loblolly pine	134	229	352	796
California	Mixed conifer	218	609	1064	4578

[1]Soil was sampled to 20, 30, 30, and 40 cm for the British Columbia, Idaho, Louisiana, and California soils, respectively

Harvesting operations can also cause ground disturbance via tractors, excavators, trucks, and other wheeled or tracked vehicles. These disturbances result in a number of physical changes, such as compaction, soil mixing, and altered surface hydrology [20,21], but the extent, duration, degree, and distribution of the impacts are site, soil, and harvest method specific [22]. Soil disturbances can alter soil chemical, physical, and biological properties and hydrological function as well as affect residual tree root growth and function. Harvesting woody biomass can result in additional traffic and soil disturbance, and woody biomass is often used to mitigate soil physical disturbances and sediment movement. Harvest operations that place economic value on all of the woody biomass products often leave fewer residues on site for ecological functions and erosion control. Best management practices often suggest that some portion of the non-merchantable material such as branches and foliage be left distributed on site to mitigate disturbance, protect the soil and reduce or prevent erosion (Ice, 2004)[FS1], and numerous states have developed or are developing best management practices for biomass harvesting [23,24].

In practice the potential quantity of wood harvested is rarely realized; forest residue recovery varies widely depending on a number of factors. For example, [25] estimated that approximately 65% of forest residues could be recovered with current timber harvest methods. However, the Biomass Opportunity Supply Model (BIOS), assessed between 6 and 50% recovery rates from whole-tree even-aged management systems [26]. In a study in eastern Washington, [27] note that although approximately 30% of forest residues were available, only

20% could be recovered. No matter how much is recovered, bioenergy harvesting allows for a greater utilization of each tree as well as smaller trees which were previously considered non-merchantable.

Many National Forests have become overstocked due to fire suppression or limited cutting. When these forests are thinned, the non-merchantable biomass serves as fuel for wildfires and therefore, this material is often burned to reduce fuels, which may also alter soil physical and chemical properties [28,29]. In addition, biomass is often removed to facilitate regeneration [1]. The specific treatments vary among region and forest type, but often include some form of mechanical removal or comminution and may often be followed by burning. These site preparation treatments often incur even more nutrient removal than harvesting for biomass would. In a loblolly pine (*Pinus taeda* L.) stand in North Carolina, [30] compared conventional harvesting vs. whole-tree harvesting (which included hardwood removals) and conventional site preparation (roller-drum chopping followed by broadcast burning) to intensive site preparation (shearing, raking, and piling). Whole-tree harvesting followed by chopping and burning removed 186.4 kg ha^{-1} N, 18.6 kg ha^{-1} P, and 34.7 kg ha^{-1} Ca. Comparatively, the bole-only harvest with shearing, raking and piling removed 711, 45.5, and 88.2 kg ha^{-1} N, P, and Ca, respectively. Thus, assessing the impact of biomass harvesting on soil productivity requires a complete analysis of treatments, not just a comparison of harvest intensities. In some ecosystems and soils after bioenergy harvest activities, long-term soil nutrient pool depletion has been found to be negligible and is projected to be at or above pre-harvest levels before the next rotation [31]. In some U.S. systems, this type of comparison has been studied for several decades, and this long-term research is vital to our understanding of biomass harvesting impacts.

While research on the impacts of harvesting organic components of the forest on nutrient cycling has been conducted since at least the late 1800s, interest in the U.S. peaked in the 1970s for a host of reasons. First, a number of major research findings were noting the potential impact of forest harvesting on nutrients and productivity. One study of second-rotation

Radiata pine (*Pinus radiata* D.Don) stands in South Africa indicated widespread declines in productivity due to organic matter reductions and subsequent declines in soil fertility [32], and, in the U.S., landmark research at the USFS Hubbard Brook Experimental Forest indicated clearcutting increased nutrient losses [33]. Secondly, several socioeconomic and political issues were accelerating harvesting and increasing interest in biomass harvesting. In 1973, the OPEC oil embargo forced the U.S. to consider alternatives, including woody biomass, to foreign petroleum. In 1976, the U.S. Congress passed the National Forest Management Act [34], which required the Department of Agriculture to conduct research to ensure that forest management practices did not degrade the productive capacity of the land. At the same time, timber production from the National Forests was rapidly rising to its highest level of over 13 billion board feet in 1976 [35], and in 1980 was projected to reach over 20 billion board feet by 2030 [36].

Major manuscripts, reviews and symposia were held over the next two decades related to the effects of forest management on productivity [37–41] and a host of symposia were sponsored by the International Energy Agency (IEA) [42]. While scientists developed increased understanding of the basic site processes, few studies had followed growth after harvest to determine actual productivity change and little direct evidence had been produced to answer the questions posed by Earl Stone [FS2]in his evaluation of research gaps in 1979 [43] :

1. What levels of nutrient removal can our soil-forest systems sustain with no or only minor decrease in productivity capacity? What elements will become limiting first in the face of accelerated removals, and how will soils or forest types differ in response?
2. How can we objectively predict the nature and magnitude of possible decreases in productivity, and what measures can be devised to avoid or mitigate such decreases, or even to increase productivity?

3. What will be the physical consequences, if any, of more frequent traffic by heavy harvesting equipment, and lower returns of organic matter to the soil?
4. What unplanned secondary changes are likely as a result of altered nutrient circulation; as for example, in species composition, habitat diversity or pest problems?

One landmark symposia was held in 1988 as the 7th North American Forest Soils Conference [44], and it holistically evaluated the state of knowledge on sustainable soil productivity. As part of this symposium, [45] reviewed the evidence available at that time for actual productivity declines. They found that of the scant evidence indicating productivity declines, reductions in site organic matter and/or soil porosity were common among the situations. In addition, limitations in modeling, chronosequences, and retrospective research [46] prompted the group lead by Bob Powers [FS3]to design a long-term study aimed at answering some of these most difficult questions related to harvesting and soil productivity. This experiment, termed the Long-Term Soil Productivity (LTSP) experiment [45,47], was intended to provide scientific progress toward an understanding of mechanisms related to sustaining soil productivity in managed forests as well as practical guidelines for managers. While not specifically designed to test the impacts of biomass harvesting, its design was ideal for testing specific issues inherent in biomass harvesting (e.g., soil organic matter removal and compaction within a climatic gradient).

Unlike most forest soil disturbance and harvesting studies, the LTSP experiment did not test specific harvesting technologies or silvicultural treatments. It imposed gradients ranging from minimal disturbance of site organic matter and soil porosity change to maximum disturbance. Thus, it did not compare operational “conventional” harvesting to “biomass” harvesting, but it did compare a minimum level of site organic matter removal, bole-only harvesting (only the locally merchantable bole was removed) to complete tree removal (similar, although more intensive than operational “biomass” harvesting) and complete aboveground organic matter removal (including forest floor removal, but stumps and coarse roots were not removed). Similarly, soil porosity loss was not accomplished by testing “wet-weather harvesting” to “dry harvesting” with current mechanical technologies. Gradients of porosity reduction were imposed from no traffic on plots to severe porosity reductions, and were applied to the entire plot. These treatments were conducted during the harvest of mature forest stands on National Forests and partner lands throughout the U.S. and Canada beginning in 1990 and continuing throughout the early 2000s across dozens of sites throughout most major timber producing areas.

This experiment represents the most widespread, coordinated, long-term test of varying levels of harvest intensity on soil productivity in the world, and has been maintained as a grass-roots effort by the scientists and land managers since the mid-1990s. The oldest site, installed on the Palustris Experimental Forest in central Louisiana, was just measured for its 25th year of growth response. This study network, which also encompasses many affiliate studies using amelioration or other silvicultural treatments, provides one of the most comprehensive tests of the basic questions posed by Stone (1979) available.

First, when considered across the entire network, which includes forest types such as southern pine and mixed pine-hardwood in the South, aspen (*Populus tremuloides* Michx.) and black spruce (*Picea mariana* (Mill.) Britton, Sterns, & Poggenb.) in the northern U.S. and Ontario, mixed conifers in California, Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) in the Rocky Mountains and in the Pacific Northwest, and various conifers and aspen throughout British Columbia, productivity is little affected by nutrient and organic matter removals through the first 10 years [48]. Most of these data are from stands that have not yet reached canopy closure and thus maximum nutrient stress, but data from the oldest stands on fairly infertile sites indicate similar resilience . By age 15, the 13 sites in the southeastern U.S. had all been at canopy closure for several years, yet productivity was reduced by whole-tree harvesting only on the most infertile sites [49]. Similarly, jack pine (*Pinus banksiana* Lamb.) growth was not reduced after across 9 sites following whole-tree harvesting [50].

Second, soil porosity reductions (compaction) have decidedly mixed effects on productivity. In most cases, compaction has had little to no significant impact on early survival or productivity [48]. In contrast, a few soils with clayey soil textures have reported declines in young tree growth due to compaction [51] while productivity increased on loamy and coarse-textured soils after compaction due to improvements in water holding capacity or other physical attributes [48]. Compaction effects across a range of textures in southern pine sites resulted in increased tree productivity due to a reduction in competing vegetation [49].

Plant diversity has had little impact on soil productivity, and treatments have had varying impacts on plant diversity. Monocultures, especially conifer monocultures, have reductions[FS4] in soil productivity. These concerns were initiated by the German “Spruce sickness” of the late 1800s [45] in which soil porosity and productivity declined following the planting of spruce monocultures in lowland clay soils where beech was previously growing. Similar concerns were associated with the decline of second-rotation pine stands in Australia and the southeastern U.S. [32,52]. As such, one aspect of many of the LTSP locations was the inclusion of a split-plot treatment in which the non-crop trees and competing vegetation were controlled manually or with herbicides. Overwhelmingly, crop tree biomass was greater where competing vegetation was controlled through 10 years across all forest types, and total stand biomass was greater on all but a few sites naturally dominated by shrub biomass at early stages of stand development [48]. At this early stage, no negative soil impacts have been reported due to creating monocultures at any sites. In addition, several investigators have been exploring questions related to how the organic matter and compaction treatments might affect plant diversity as well as how plant diversity may be affecting measures of soil quality and forest health. Across the southeastern U.S., understory plant diversity in loblolly pine plantations was not affected by either compaction nor whole-tree harvesting at age 15 years [49], but some species were positively or negatively affected by the more intense disturbances [53,54]. Those positively affected were generally early-successional shrubs, while those negatively affected were later-successional tree species. Across several black spruce sites in Ontario, the impact of harvest intensity on diversity depended on soil type; diversity increased on loamy soils with whole-tree harvesting while it decreased on peat soils due to warmer microclimates where slash was lower [55]. In the aspen forests of the north-central U.S., harvesting intensity has had no impact on plant diversity through 17 years but compaction has increased diversity by increasing early successional and invasive species while reducing forest ground flora [56].

That these treatments, which included the complete removal of all aboveground organic matter and nutrients, failed to induce widespread losses in tree productivity is a clear indication of the resistance and resilience that healthy, managed forests maintain. However, 15 years is still quite young relative to most rotation ages, and forest soils research is replete with long-term studies contradicting early results and vice versa. Furthermore, while these descriptive results are paramount to assessing the relative importance of management actions on soil productivity, the LTSP and affiliated studies have also provided an exceptional design for process-level testing. The combination of descriptive and process-level testing will help answer the question "what will happen in the future under a given set of management and environmental conditions"[57]. Process-level work that has been incorporated into the LTSP design includes studies that evaluate changes to decomposition rates and soil biology, and attempts to explain plant responses to soil compaction using mechanistic-based models and process-level studies on soil fertility.

A number of investigators have studied the impacts of intensive harvesting on microbial community properties, processes, and ecology using a variety of techniques. Overwhelmingly, these studies have shown the effects of harvesting have stronger initial and long-term impacts than any particular treatment. The majority of studies through the first five years post-harvest indicate few substantial changes in microbial structure due to compaction or organic matter removal treatments [58–64]. More recent studies in British Columbia show a long-lasting reduction in fungal communities and genes associated with decomposition in response to both compaction and forest floor removal [65,66]. Similarly, microbial population size and activity has shown mixed effects in response to compaction and organic matter removal, with the majority of studies finding few consistent or long-term responses [67–73]. One notable exception is a study from a loblolly pine forest in Texas which showed long-term (>15 yrs) reduced microbial C and N in plots where forest floor was removed [74].

In addition to these examples of microbial communities and microbially-mediated nutrient transformations, additional research has been conducted on mesofauna, primarily earthworms, Collembola and Acari to understand organic matter turnover and natural compaction amelioration. Organic matter removal reduced Collembola in some coastal plain loblolly pine forests [75] and subboreal spruce forests [76] and altered mite populations and diversity [76] following treatment. In another loblolly pine forest, however, Collembola and Acari had similar abundance within two years following organic matter removal treatments[77]. Compaction, however, had comparatively little impact on Collembola and Acari. The opposite occurred for earthworms in a central U.S. pine-hardwood forest; compaction reduced earthworm density while organic matter removal slowed rates of recovery [78–80]. Earthworms, as expected, proved to be an important mechanism for ameliorating compaction [81].

Several investigators have studied the impact of compaction on root growth directly and related this to soil type, tree species, and water availability. In California, [51,82] examined the relative impact of soil texture on water availability and the resulting impact on tree water stress and growth, and found that compaction improved water availability on coarse-textured soils but reduced it on fine-textured soils. [83] modeled root growth as a function of gradients in bulk density and soil water content for three tree species and four soil types, and found the responses were predictably soil- and species-specific yet followed principles of the Least-Limiting Water Range[84]. [85] and [86] used similar greenhouse approaches to study lodgepole pine and loblolly and longleaf pine responses, respectively. Lodgepole pine was more influenced by water content at the range of bulk densities expected in field conditions (Bouin et al., 2004), while longleaf pine root growth was more sensitive to both bulk density and water content than loblolly pine (Scott and Burger, 2013). These process-level studies on root growth were confirmed by a study of mid-rotation loblolly pine in North Carolina which showed no aboveground growth response to soil compaction, but root growth, especially tap root growth, was significantly reduced [87].

Overwhelmingly, responses in microbial properties and activity, nutrient transformations, root growth capacity, and tree growth to reductions in soil porosity and site organic matter have been relatively minor across the wide variety of soils and ecosystems studied. Longer-term monitoring and continued process-level studies are needed to help understand how to identify and manage the few site types sensitive to these disturbances. Biomass markets need not result in only negative impacts, though. Some biomass products can themselves be used to improve soil productivity.

Biochar

Forest restoration, bioenergy production, or rehabilitation treatments involve forest thinning that can produce 40-60 million dry metric tons of woody biomass per year [88]. However this can be costly [89,90]. Using in-woods processing to create chips [7], slash forwarding to recover previously discarded material [91], or mobile pyrolysis (*i.e.,* thermochemical conversion of wood) [92] 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 [93,94]. 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" [95], and can be analogous to charcoal naturally found in fire-prone ecosystems [96]. Biochar has been tested as a soil amendment in many agricultural systems [95,97]; however, there has been considerably less work on biochar in forest systems, and in particular few published field trials [98]. 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 [99]. All of these properties are thought to play a role in enhancing plant growth and drought tolerance in biochar-amended soils [100].

Production of biochar, coupled with new state, national and international policies that promote large-scale biomass utilization [101], could potentially lead to changes in how forest soils and stands are sustainably managed [102]. Bioenergy coupled with biochar as a co-product is a promising alternative for green energy [102] and removal of forest residues can improve stand health and reduce the risk of wildfire [103]. The trade-off is that residues also serve as essential habitat for wood decay fungi and other organisms [104], provide cover for wildlife, reduce soil erosion, and, as mentioned previously, play an important role in soil nutrient dynamics and hydrology [105]. Therefore, how much biomass is left or removed should take into account multiple management objectives and should be determined on a site-specific basis [106,107].

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 [94,108,109]. Biochar manufacture and application has the potential to reduce fire risks by removing highly flammable excess woody residues from forest sites, improve soil water and nutrient retention, and 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 [110], application of biochar is expected to mimic many of the soil properties associated with wildfire-generated charcoal [96,111,112], and thus emulate natural disturbance processes [98].

Biochar can be produced using numerous methods which include traditional kilns and earth mounds, as well as engineered systems for slow pyrolysis, fast pyrolysis, flash pyrolysis, gasification, and microwave pyrolysis [113,114]. Fast-pyrolysis biochar (involving rapid heating rates to peak temperatures) is 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 400-600 °C generally has the least amount of hydrophobicity and highest water holding capacity, while those created under higher temperatures have much stronger hydrophobic tendencies [115,116]. Table 2 shows examples of the chemical composition of several biochars produced from the same equipment (Abri Tech Incorporated, Namur, QC) operated by Biochar Products in Halfway, OR, USA, with similar residence times (5-7 min) and temperature ranges (388-450 °C). In particular, the wide range of pH, electrical conductivity (EC), and macro- and micronutrients indicate that care should be taken to understand how soil properties might be altered after application of a given biochar.

Table 2. Selected chemical characteristics, pH, and electrical conductivity (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**
	--- wt % ---		---- µg g^{-1} ---								
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

A recent meta-analysis of tree response to biochar application found an average 41% increase in biomass [98]. However, forestry studies indicate high variability in their results, with individual studies showing positive, negative, or no significant change in vegetative growth [117]. This variability arises due to inherent differences in the soil, fertilizer application, the nature of the biochar, and differences in responses among plant species. In the Inland Northwest USA, there are several ongoing biochar field trials examining tree growth responses to biochar [118,119]. Short-term (1-2 years) changes in diameter increment on two sites (Inceptisol and Andisol soils) were not significantly altered by biochar additions, but 5 year growth gains after biochar addition were similar to leaving slash [119]. The advantage of using biochar is that it is a long-term organic matter addition once it migrates through the forest floor [120]; whereas slash will decompose within a short time, depending on climatic regime. Biochar is often applied to the surface (on top of the existing forest floor) to limit soil disturbance and maintain nutrient cycling which may be why forest sites have a slower response than agricultural sites.

The potential benefits from adding biochar to forest sites has not been fully researched for long-term impacts which examine a range of biochars, soils, and forest types. However, it is clear that avoiding atmospheric inputs of GHG from burning slash is critical for reducing climate change effects. Field trials in the western USA [119], show that there are no deleterious impacts of biochar additions on forest vegetation, although the broader range of effects on invertebrates, fungi, bacteria, and other organisms should also be studied. On-site (or near-site) production of biochar will facilitate soil applications after bioenergy harvesting. Highly impacted forest areas such as skid trails or log landings should be a priority for biochar applications since they have the potential for site remediation and ease of access.

Summary

The capacity of forests to continue supplying a variety of ecosystem services, such as timber, water, biodiversity, and carbon capture is fully dependent on the capacity of forest soils to support plant growth. Timber or biomass harvesting, because it alters natural energy, nutrient and hydrologic cycles, has the potential to reduce soils' productive capacity. Harvesting woody biomass for various products such as biochar improves the general health and sustainability of many forests by reducing stress and susceptibility to insects, pathogens, or wildfire. Biochar provides both a useful form of energy from wood while also producing a product similar to that produced from natural fire regimes that improves soil productivity. The USDA Forest Service and its partners have provided leadership in the research of both, as well as many other forest soil-related concerns.

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