Wood Bioenergy and Soil Productivity Research

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Abstract Timber harvesting can cause both short- and long-term changes in forest ecosystem functions, and scientists from USDA Forest Service (USDA FS) 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 USDA 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 USDA FS scientists work to advance methods for soil quality monitoring and to inform international criteria and indicators. Current and future USDA 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 USA to lead in the sustainable production of woody biomass for bioenergy.

Keywords Woody biomass · Soil productivity · Biochar

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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 USA, 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 nineteenth 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 USA which could yield approximately 290–335 million Mg 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 FS has 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 FS has worked through the multiple USDA Biomass Research Centers to provide 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 soil 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).

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 [19, 20], but the extent, duration, degree, and distribution of the impacts are site, soil, and harvest method specific [21]. 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 [22], 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. One large-scale estimate suggests approximately 65 % of forest residues could be recovered with current timber harvest methods [25]. However, the Biomass Opportunity Supply Model (BIOS) was assessed between 6 and 50 % recovery rates from whole-tree even-aged management systems [26]. In a study in eastern Washington, approximately 30 % of forest residues were available but only 20 % could be recovered [27]. No matter how much is recovered, bioenergy harvesting allows for a greater utilization of each

Table 1 Nitrogen quantities (kg ha^{-1}) by pool in four representative forest types of the USA and Canada [94, 97]

Location	Forest type	Tree boles	Whole-trees	All organic matter	Soil[a]
British Columbia	Sub-boreal 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

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

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, conventional harvesting was compared to 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) [30]. Whole-tree harvesting followed by chopping and burning (the less intensive site preparation treatment) removed 186.4 kg N ha^{-1}, 18.6 kg P ha^{-1}, and 34.7 kg Ca ha^{-1}. Comparatively, the bole-only harvest with shearing, raking, and piling (the more intensive site preparation treatment) removed 711, 45.5, and 88.2 kg N, P, and Ca ha^{-1}, respectively. Thus, assessing the impact of biomass harvesting on soil productivity requires a complete analysis of treatments, not just a comparison of harvest intensities. Activities such as site preparation can have greater effects than harvesting. 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 US 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 USA 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 USA, 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 Organization of Petroleum Exporting Countries (OPEC) oil embargo forced the USA to consider alternatives, including woody biomass, to foreign petroleum. In 1976, the US 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 Dr. Earl Stone 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 symposium 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, Powers et al. [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 led by Dr. R.F. Powers 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 USA and Canada beginning in 1990 and continuing throughout the early 2000s across dozens of sites throughout most major timber-producing areas. Many of these sites and the research conducted therein where later incorporated into the USDA Biomass Research Center programs.

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 USA 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 USA 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 been attributed to causing reductions 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 USA [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 USA, understory plant diversity in loblolly pine plantations was not affected by either compaction or 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 USA, 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 nutrient deficiencies could still occur as canopy closure occurs. 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 soil health 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 5 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 years) 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 2 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 US pine-hardwood forest; compaction reduced earthworm density while organic matter removal slowed rates of recovery [78–80]. While earthworm density may be reduced by compaction, earthworm activity still proved to be an important natural mechanism for ameliorating soil compaction and restoring soil porosity [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, Gomez et al. [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. Siegel-Issem et al. [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]. Similar greenhouse approaches were used to study lodgepole pine and loblolly and longleaf pine responses respectively [85, 86]. Lodgepole pine was more influenced by water content at the range of bulk densities expected in field conditions [85], while longleaf pine root growth was more sensitive to both bulk density and water content than loblolly pine [86]. 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]. In-woods chipping [7], slash forwarding to recover previously discarded material [91], or treating biomass with mobile pyrolysis (*i.e.*, thermo-chemical conversion of wood) [92] are all potential treatments 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 tradeoff 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 have 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 and 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.

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

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

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. Research from 25 years of the Long-Term Soil Productivity experiment and other studies in conjunction with the USDA Biomass Research Centers have shown that while a few select sites may lose productive potential following intensive harvesting, most areas across the USA will likely show little reduction in productivity due to the greater removal of organic matter and nutrients or to soil compaction. 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.

References

1. Page-Dumroese DS, Jurgensen M, Terry TA (2010) Maintaining soil productivity during forest or biomass-to-energy thinning harvests in the western United States. West J Appl For 25:5–11
2. Dale VH, Joyce LA, McNulty S, Neilson RP, Ayres MP, Flannigan MD, Hanson PJ, Irland LC, Lugo AE, Peterson CJ, Simberloff D, Swanson FJ, Stocks BJ, Wotton BM (2001) Climate change and forest disturbances. Bioscience 51:723–734. doi:10.1641/0006-3568(2001)051[0723:CCAFD]2.0.CO;2
3. Millar CI, Stephenson NL (2015) Temperate forest health in an era of emerging megadisturbance. Science 349:823–826
4. USDA Forest Service (2005) A Strategic Assessment of Forest Biomass and Fuel Reduction Treatments in Western States. U.S. Department of Agriculture, Forest Service, Rocky Mountain

Research Station, Gen. Tech. Rep. RMRS-GTR-149., Fort Collins, CO

5. James SR, Dennell RW, Gilbert AS, Lewis HT, Gowlett JAJ, Lynch TF, McGrew WC, Peters CR, Pope GG, Stahl AB, James SR (1989) Hominid use of fire in the lower and middle Pleistocene: a review of the evidence. Curr Anthropol 30:1–26. doi:10.1086/203705

6. U.S. Energy Information Administration (2010) Annual Energy Review 2009. DOE/EIA-0384(2009) Washington, DC 408.

7. Jones G, Loeffler D, Calkin D, Chung W (2010) Forest treatment residues for thermal energy compared with disposal by onsite burning: emissions and energy return. Biomass Bioenergy 34: 737–746. doi:10.1016/j.biombioe.2010.01.016

8. US Department of Energy (2011) U.S. Billion-ton update: biomass supply for a bioenergy and bioproducts industry. ORNL/TM-2011/224 227.

9. Adams MB, Loughry LH, Plaugher LL (2004) Experimental forests and ranges of the USDA Forest Service. U.S. Department of Agriculture, Forest Service, Northeastern Research Station. Gen. Tech. Rep. NE-321, Newtown Square, PA

10. Page-Dumroese DS, Jurgensen MF, Curran MP (2010) Cumulative effects of fuel treatments on soil productivity. In: Elliot WJ, Miller IS, Audin L (eds) Cumulative watershed effects of fuel management in the Western United States. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Gen. Tech. Rep. RMRS-GTR-231., Fort Collins, CO, pp 164–174

11. Callaham MA, Scott DA, O'Brien JJ, Stanturf JA (2012) Cumulative effects of fuel management on the soils of eastern US. In: LaFayette R, Brooks MT, Potyondy JP, Audin L, Krieger SL, Trettin CC (eds) Cumulative watershed effects of fuel management in the Eastern United States. U.S. Department of Agriculture, Forest Service, Southern Research Station, Gen. Tech. Rep. SRS-161, Asheville, NC, pp 202–228

12. Greacen E, Sands R (1980) Compaction of forest soils. A review. Aust J Soil Res 18:163–189. doi:10.1071/SR9800163

13. Johnson CE, Johnson AH, Huntington TG, Siccama TG (1991) Whole-tree clear-cutting effects on soil horizons and organic-matter pools. Soil Sci Soc Am J 55:497–502

14. Marion GM (1979) Biomass and nutrient removal in long-rotation stands. In: Leaf AL (ed) Proceedings: Impact of Intensive Harvesting on Forest Nutrient Cycling, School of Forestry, SUNY-Syracuse, Syracuse, NY, pp 98–110

15. Alban DH, Perala DA, Schlaegel BE, Perala DA (1978) Biomass and nutrient distribution in aspen, pine, and spruce stands on the same soil type in Minnesota. Can J For Res 8:290–299. doi:10.1139/x78-044

16. Johnson DW, West DC, Todd DE, Mann LK (1982) Effects of sawlog vs. whole-tree harvesting on the nitrogen, phosphorus, potassium, and calcium budgets of an upland mixed oak forest. Soil Sci Soc Am J 46:1304–1309

17. Phillips DR, Van Lear DH (1984) Biomass removal and nutrient drain as affected by total-tree harvest in southern pine and hardwood stands. J For 82:547–550

18. Powers RF, Scott DA, Sanchez FG, Voldseth RA, Page-Dumroese DS, Elioff JD, Stone DM (2005) The North American long-term soil productivity experiment : findings from the first decade of research. For Ecol Manage 220:31–50. doi:10.1016/j.foreco.2005.08.003

19. Han H-S, Page-Dumroese DS, Han S-K (2006) Effects of slash, machine passes, and soil moisture on penetration resistance in a cut-to-length harvesting. Int J For Eng 17:11–24. doi:10.1080/14942119.2006.10702532

20. Han S-K, Han H-S, Page-Dumroese DS, Johnson LR (2009) Soil compaction associated with cut-to-length and whole-tree harvesting of a coniferous forest. Can J For Res 39:976–989. doi:10.1139/X09-027

21. Craigg TL, Howes SW (2007) Assessing quality in volcanic ash soils. In: Page-Dumroese DS, Miller RE, Mital J, Mcdaniel P, Miller D (eds) Volcanic-Ash-derived forest soils of the Inland Northwest: properties and implications for management and restoration. 9–10 Nov. 2005; Coeur d'Alene, ID. Proc. RMRS-P-44. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, pp 47–66

22. Ice G (2004) History of innovative best management practice development and its role in addressing water quality limited waterbodies. J Environ Eng 130:684–689. doi:10.1061/(ASCE)0733-9372(2004)130:6(684)

23. Ice G, McBroom M, Schweitzer P (2011) A review of best management practices for forest watershed biomass harvests with an emphasis on recommendations for leaving residual wood onsite. Center for Bioenergy Sustainability, Oak Ridge National Laboratory, Oak Ridge, TN

24. Biomass Research and Development Board (2011) Bioenergy feedstock best management practices: summary and research needs. Feedstock Production Interagency Working Group

25. Perlack RD, Wright LL, Turhollow AF, Graham RL, Stokes BJ, Erbach DC (2005) Biomass as feedstock for a bioenergy and bioproducts industry : the technical feasibility of a billion-ton annual supply. Oak Ridge National Laboratory, DOE/GO-102995-2135 ORNL/TM-2005/66.

26. Ralevic P, Ryans M, Cormier D (2010) Assessing forest biomass for bioenergy: operational challenges and cost considerations. For Chron 86:43–50. doi:10.5558/tfc86043-1

27. Oneil E, Lippke B (2009) Eastern Washington biomass accessibility. Report to the Washington State Legislature and Washington Department of Natural Resources, Seattle, WA

28. Korb JE, Johnson NC, Covington WW (2004) Slash pile burning effects on soil biotic and chemical properties and plant establishment: Recommendations for amelioration. Restor Ecol 12:52–62. doi:10.1111/j.1061-2971.2004.00304.x

29. Oswald BP, Davenport D, Neuenschwander LF (1998) Effects of slash pile burning on the physical and chemical soil properties of Vassar soils. J Sustain For 8:75–86. doi:10.1300/J091v08n01_06

30. Tew DT, Morris LA, Allen HL, Wells CG (1986) Estimates of nutrient removal, displacement and loss resulting from harvest and site preparation of a Pinus taeda plantation in the Piedmont of north Carolina. For Ecol Manage 15:257–267

31. Jang W, Keyes CR, Page-Dumroese DS (2015) Impact of biomass harvesting on forest soil productivity in the northern Rocky Mountains. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, RMRS-GTR-341., Fort Collins, CO

32. Keeves A (1966) Some evidence of loss of productivity with successive rotations of Pinus radiata in the south-east of South Australia. Aust For 30:51–63

33. Bormann FH, Likens GE, Fisher DW, Pierce RS (1968) Nutrient loss accelerated by clear-cutting of a forest ecosystem. Science 159:882–884

34. U.S. Laws, Statutes E. (1976) Public Law 94–588 National Forest Management Act. of 1976. (NFMA). Act of Ctt. 22, 1976. U.S.C. 1600.

35. U.S. Department of Agriculture FS (2015) Cut and Sold Reports. http://www.fs.fed.us/forestmanagement/products/sold-harvest/cut-sold.shtml. Accessed March 29, 2016.

36. Thomas JW (2011) The future of the national forests : who will answer an uncertain trumpet? Fair Chase 26:16–23

37. Leaf AL (1979) Proceedings: Impact of Intensive Harvesting on Forest Nutrient Cycling. College of Environmental Science and Forestry. SUNY, Syracuse, NY

38. Ballard R, Gessel SP (1983) IUFRO Symposium on Forest Site and Continuous Productivity. U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, Gen. Tech. Rep. PNW-163., Portland, OR

39. Kimmins JP (1977) Evaluation of the consequences for future tree productivity of the loss of nutrients in whole-tree harvesting. For Ecol Manage 1:169–183

40. Van Hook RI, Johnson DW, West DC, Mann LK (1982) Environmental effects of harvesting forests for energy. For Ecol Manage 4:79–94

41. McMinn JW, Nutter WL (1981) Energy wood harvesting: a study of promises and pitfalls. Georgia Forest Research Report 17

42. Smith CT (1995) Environmental consequences of intensive harvesting. Biomass Bioenergy 9:161–179

43. Stone EL (1979) Nutrient removals by intensive harvest—some research gaps and opportunities. In: Leaf AL (ed) Proceedings: Impact of Intensive Harvesting on Forest Nutrient Cycling. College of Environmental Science and Forestry, SUNY, Syracuse, NY, pp 366–382

44. Gessel SP, Lacate DS, Weetman GF, Powers RF (1990) Sustained Productivity of Forest Soils. Proceedings of the 7th North American Forest Soils Conference. University of British Columbia, Faculty of Forestry, Vancouver, BC

45. Powers RF, Alban DH, Miller RE, Tiarks AE, Wells CG, Avers PE, Cline RG, Fitzgerald RO, Loftus Jr. NS (1990) Sustaining site productivity in North American forests: problems and prospects. In: Gessell SP, Lacate DS, Weetman GF, Powers RF (eds) Sustained Productivity of Forest Soils. Proceedings of the 7th North American Forest Soils Conference. University of British Columbia, Faculty of Forestry, Vancouver, BC, pp 49–79

46. Dyck WJ, Mees CA (1989) Research Strategies for Long-Term Site Productivity. Proceedings, IEA/BE A3 Workshop, Seattle, WA. Forest Research Institute, New Zealand.

47. Tiarks AE, Powers RF, Alban DH, Ruark GA, Page-Dumroese DS (1993) USFS Long-term Soil Productivity National Research Project: a USFS Cooperative Research Program. In: Kimble JM (ed) Proceedings of the Eighth International Soil Management Workshop. U.S. Department of Agriculture, Soil Conservation Service, National Soil Survey Center, Lincoln, NE, pp 236–241

48. Ponder F Jr, Fleming RL, Berch SM, Busse MD, Elioff JD, Hazlett PW, Kabzems RD, Kranabetter JM, Morris DM, Page-Dumroese DS, Palik BJ, Powers RF, Sanchez FG, Scott DA, Stagg RH, Stone DM, Young DH, Zhang J, Ludovici KH, McKenney DW, Mossa DS, Sanborn PT, Voldseth RA (2012) Effects of organic matter removal, soil compaction and vegetation control on 10th year biomass and foliar nutrition: LTSP continent-wide comparisons. For Ecol Manage 278:35–54. doi:10.1016/j.foreco.2012.04.014

49. Scott DA, Eaton RJ, Foote JA, Vierra B, Boutton TW, Blank GB, Johnsen KH (2014) Soil ecosystem services in loblolly pine plantations 15 years after harvest, compaction, and vegetation control. Soil Sci Soc Am J 78:2032–2040. doi:10.2136/sssaj2014.02.0086

50. Fleming RL, Leblanc J, Hazlett PW, Weldon T, Irwin R, Mossa DS (2014) Effects of biomass harvest intensity and soil disturbance on jack pine stand productivity: 15-year results. Can J For Res 44:1566–1574

51. Gomez AG, Powers RF, Singer MJ, Horwath WR (2002) Soil compaction effects on growth of young Ponderosa pine following litter removal in California's Sierra Nevada. Soil Sci Soc Am J 66:1334–1343. doi:10.2136/sssaj2002.1334

52. Haywood JD (1994) Early growth reductions in short rotation loblolly and slash pine in Louisiana. South J Appl For 18:35–39

53. Stagg RH, Scott DA (2006) Understory growth and composition resulting from soil disturbances on the long-term soil productivity study sites in Mississippi. In: Connor KF (ed) Proceedings of the 13th biennial southern silvicultural research conference, U.S.

Department of Agriculture, Forest Service, Southern Research Station, Gen. Tech. Rep. SRS-92, Asheville, NC, pp 52–56

54. Scott DA, Stagg RH (2013) Plant community responses to soil disturbance and herbicide treatments over 10 years on the Texas LTSP study. In: Guldin JM (ed) Proceedings of the 15th biennial southern silvicultural research conference. U.S. Department of Agriculture, Forest Service, Southern Research Station, Gen. Tech. Rep. SRS-175, Asheville, NC, pp 21–27

55. Kershaw HM, Morris DM, Fleming RL, Luckai NJ (2015) Reconciling harvest intensity and plant diversity in boreal ecosystems: does intensification influence understory plant diversity? Environ Manage. doi:10.1007/s00267-015-0551-8

56. Reschke C, Host GE (2011) Effects of soil compaction and organic matter removal on ground-flora diversity : seventeen-year results from the Chippewa National Forest Long-term Soil Productivity Project. Technical Report NRRI/TR-2011/31. Natural Resources Research Institute, Duluth, MN

57. Kimmins JP (1989) Projecting our experience of the past to give us a vision of the future: the need for an appropriate research strategy. In: Dyck WJ, Mees CA (eds) Research Strategies for Long-Term Site Productivity. Proceedings, IEA/BE A3 Workshop, Seattle, WA. Forest Research Institute, New Zealand, pp 237–249

58. Ponder F Jr, Tadros M (2002) Phospholipid fatty acids in forest soil four years after organic matter removal and Soil compaction. Appl Soil Ecol 19:173–182. doi:10.1016/S0929-1393(01)00182-2

59. Axelrood PE, Chow ML, Radomski CC, McDermott JM, Davies J (2002) Molecular characterization of bacterial diversity from British Columbia forest soils subjected to disturbance. Can J Microbiol 48:655–674. doi:10.1139/w02-059

60. Axelrood PE, Chow ML, Arnold CS, Lu K, McDermott JM, Davies J (2002) Cultivation-dependent characterization of bacterial diversity from British Columbia forest soils subjected to disturbance. Can J Microbiol 48:643–654. doi:10.1139/w02-058

61. Chow ML, Radomski CC, McDermott JM, Davies J, Axelrood PE (2002) Molecular characterization of bacterial diversity in Lodgepole pine (Pinus contorta) rhizosphere soils from British Columbia forest soils differing in disturbance and geographic source. FEMS Microbiol Ecol 42:347–57. doi:10.1111/j.1574-6941.2002.tb01024.x

62. Shestak C, Busse MD (2005) Compaction alters physical but not biological indices of soil health. Soil Sci Soc Am J 69:236–246

63. Busse MD, Beattie SE, Powers RF, Sanchez FG, Tiarks AE (2006) Microbial community responses in forest mineral soil to compaction, organic matter removal, and vegetation control. Can J For Res 36:577–588. doi:10.1139/X05-294

64. Hassett J, Zak D (2005) Aspen harvest intensity decreases microbial biomass, extracellular enzyme activity, and soil nitrogen cycling. Soil Sci Soc Am J 69:227–235

65. Hartmann M, Howes CG, VanInsberghe D, Yu H, Bachar D, Christen R, Henrik Nilsson R, Hallam SJ, Mohn WW (2012) Significant and persistent impact of timber harvesting on soil microbial communities in Northern coniferous forests. ISME J 6:2199–218. doi:10.1038/ismej.2012.84

66. Cardenas E, Kranabetter JM, Hope G, Maas KR, Hallam S, Mohn WW (2015) Forest harvesting reduces the soil metagenomic potential for biomass decomposition. ISME J 1–12. doi: 10.1038/ismej.2015.57

67. Jordan D, Li F, Ponder F Jr, Berry EC, Hubbard VC, Kim KY (1999) The effects of forest practices on earthworm populations and soil microbial biomass in a hardwood forest in Missouri. Appl Soil Ecol 13:31–38

68. Carter MC, Dean TJ, Zhou M, Messina MG, Wang Z (2002) Short-term changes in soil C, N, and biota following harvesting

and regeneration of loblolly pine (*Pinus taeda* L.). For Ecol Manage 164:67–88. doi:10.1016/S0378-1127(01)00590-4

69. Ponder F (2005) Effect of soil compaction and biomass removal on soil CO_2 efflux in a Missouri forest. Commun Soil Sci Plant Anal 36:1301–1311. doi:10.1081/CSS-200056935

70. Tan X, Chang SX, Kabzems RD (2005) Effects of soil compaction and forest floor removal on soil microbial properties and N transformations in a boreal forest long-term soil productivity study. For Ecol Manage 217:158–170. doi:10.1016/j.foreco.2005.05.061

71. Tan X, Chang SX, Kabzems RD (2007) Soil compaction and forest floor removal reduced microbial biomass and enzyme activities in a boreal aspen forest soil. Biol Fertil Soils 44:471–479. doi:10.1007/s00374-007-0229-3

72. Mariani L, Chang SX, Kabzems RD (2006) Effects of tree harvesting, forest floor removal, and compaction on soil microbial biomass, microbial respiration, and N availability in a boreal aspen forest in British Columbia. Soil Biol Biochem 38:1734–1744. doi: 10.1016/j.soilbio.2005.11.029

73. Butnor JR, Johnsen KH, Sanchez FG (2006) Whole-tree and forest floor removal from a loblolly pine plantation have no effect on forest floor CO2 efflux 10 years after harvest. For Ecol Manage 227:89–95. doi:10.1016/j.foreco.2006.02.018

74. Foote JA, Boutton TW, Scott DA (2015) Soil C and N storage and microbial biomass in US southern pine forests: influence of forest management. For Ecol Manage 355:48–57. doi:10.1016/j.foreco.2015.03.036

75. Eaton RJ, Barbercheck M, Buford M, Smith W (2004) Effects of organic matter removal, soil compaction, and vegetation control on Collembolan populations. Pedobiologia 48:121–128. doi:10.1016/j.pedobi.2003.10.001

76. Battigelli JP, Spence JR, Langor DW, Berch SM (2004) Short-term impact of forest soil compaction and organic matter removal on soil mesofauna density and oribatid mite diversity. Can J For Res 34:1136–1149. doi:10.1139/x03-267

77. Bird SB, Coulson RN, Fisher RF (2004) Changes in soil and litter arthropod abundance following tree harvesting and site preparation in a loblolly pine (*Pinus taeda* L.) plantation. For Ecol Manage 202:195–208. doi:10.1016/j.foreco.2004.07.023

78. Jordan D, Ponder F Jr, Hubbard VC (2003) Effects of soil compaction, forest leaf litter and nitrogen fertilizer on two oak species and microbial activity. Appl Soil Ecol 23:33–41. doi:10.1016/S0929-1393(03)00003-9

79. Jordan D, Hubbard VC, Ponder F Jr, Berry EC (1999) Effect of soil compaction and organic matter removal on two earthworm populations and some soil properties in a hardwood forest. Pedobiologia (Jena) 43:802–807

80. Jordan D, Hubbard VC, Ponder F Jr, Berry EC (2000) The influence of soil compaction and the removal of organic matter on two native earthworms and soil properties in an oak-hickory forest. Biol Fertil Soil 31:323–328

81. Ponder F Jr, Li F, Jordan D, Berry EC (2000) Assessing the impact of Diplocardia ornata on physical and chemical properties of compacted forest soil in microcosms. Biol Fertil Soils 32:166–172. doi:10.1007/s003740000232

82. Gomez AG, Singer MJ, Powers RF, Horwath WR (2002) Soil compaction effects on water status of ponderosa pine assessed through 13C/12C composition. Tree Physiol 22:459–467

83. Siegel-Issem CM, Burger JA, Powers RF, Ponder F Jr, Patterson SC (2002) Seedling root growth as a function of soil density and water content. Soil Sci Soc Am J 69:215–226

84. Da_Silva AP, Kay BD, Perfect E (1994) Characterization of the least limiting water range of soils. Soil Sci Soc Am J 58:1775–1781

85. Blouin V, Schmidt M, Bulmer C, Krzic M (2004) Soil compaction and water content effects on lodgepole pine seedling growth in British Columbia. Proceedings of the 3rd Australian New Zealand Soils Conference, 5–9 December 2004, University of Sydney, Australia.

86. Scott DA, Burger JA (2014) Longleaf and loblolly pine seedlings respond differently to soil compaction, water content, and fertilization. Plant Soil 375:255–265. doi:10.1007/s11104-013-1929-0

87. Ludovici KH (2008) Compacting coastal plain soils changes midrotation loblolly pine allometry by reducing root biomass. Can J For Res 38:2169–2176. doi:10.1139/X08-060

88. Buford MA, Neary DG (2010) Sustainable Biofuels from Forests: Meeting the Challenge. Biofuels and Sustainability Reports. Ecol. Soc. Am, Washington, D.C

89. Desrochers L, Puttock D, Ryans M (1993) The economics of chipping logging residues at roadside: a study of three systems. Biomass Bioenergy 5:401–411. doi:10.1016/0961-9534(93)90035-3

90. Zamora-Cristales R, Sessions J, Boston K, Murphy G (2015) Economic optimization of forest biomass processing and transport in the Pacific Northwest USA. For Sci 61:220–234

91. Harrill H, Han H-S (2010) Application of hook-lift trucks in centralized logging slash grinding operations. Biofuels 1:399–408. doi:10.4155/bfs.10.16

92. Anderson N, Jones JG, Page-Dumroese D, McCollum D, Baker S, Loeffler D, Chung W (2013) A comparison of producer gas, biochar, and activated carbon from two distributed scale thermochemical conversion systems used to process forest biomass. Energies 6:164–183. doi:10.3390/en6010164

93. Dymond CC, Titus BD, Stinson G, Kurz WA (2010) Future quantities and spatial distribution of harvesting residue and dead wood from natural disturbances in Canada. For Ecol Manage 260:181–192. doi:10.1016/j.foreco.2010.04.015

94. Coleman M, Page-Dumroese D, Archuleta J, Badger P, Chung W, Venn T, Loeffler D, Jones G, McElligott K (2010) Can portable pyrolysis units make biomass utilization affordable while using bio-char to enhance soil productivity and sequester carbon? In: Jain TB, Graham RT, Sandquist J (eds) Integrated management of carbon sequestration and biomass utilization opportunities in a changing climate. Proc. of the 2009 National Silviculture Workshop, June 15–18 2009, Boise, ID. Proc RMRS-P-61. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, pp 159–168

95. Lehmann J, Joseph S (2015) Biochar for Environmental Management: an introduction. Biochar for Environmental Management - Science and Technology. Earthscan Press, London

96. DeLuca TH, Aplet GH (2008) Charcoal and carbon storage in forest soils of the Rocky Mountain West. Front Ecol Environ 6:18–24. doi:10.1890/070070

97. Liu X, Zhang A, Ji C, Joseph S, Bian R, Li L, Pan G, Paz-Ferreiro J (2013) Biochar's effect on crop productivity and the dependence on experimental conditions-a meta-analysis of literature data. Plant Soil 373:583–594. doi:10.1007/s11104-013-1806-x

98. Thomas SC, Gale N (2015) Biochar and forest restoration: a review and meta-analysis of tree growth responses. New For 46:931–946. doi:10.1007/s11056-015-9491-7

99. Mukherjee A, Lal R (2013) Biochar impacts on soil physical properties and greenhouse gas emissions. Agronomy 3:313–339. doi:10.3390/agronomy3020313

100. Atkinson CJ, Fitzgerald JD, Hipps NA (2010) Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. Plant Soil 337:1–18. doi:10.1007/s11104-010-0464-5

101. Abbas D, Current D, Phillips M, Rossman R, Brooks KN, Hoganson H (2011) Guidelines for harvesting forest biomass for energy: a synthesis of environmental considerations. Biomass Bioenergy 35:4538–4546. doi:10.1016/j.biombioe.2011.06.029

102. Homagain K, Shahi C, Luckai N, Sharma M (2014) Biochar-based bioenergy and its environmental impact in Northwestern

Ontario Canada: a review. J For Res 25:737–748. doi:10.1007/s11676-014-0522-6

103. Sims R, Taylor M, Saddler J, Mabee W (2008) From 1st to 2nd Generation Bio Fuel Technologies: an overview of current industry and RD&D activities. Organisation for Economic Cooperation and. Development/International Energy Agency, Paris, France

104. Siitonen J (2001) Forest management, coarse woody debris and saproxylic organism: Fennoscandian boreal forests as an example. Ecol Bull 49:11–41

105. Lattimore B, Smith CT, Titus BD, Stupak I, Egnell G (2009) Environmental factors in woodfuel production: opportunities, risks, and criteria and indicators for sustainable practices. Biomass Bioenergy 33:1321–1342. doi:10.1016/j.biombioe.2009.06.005

106. Wood S, Layzell D (2003) A Canadian Biomass Inventory: Feedstocks for a Bio-based Economy. BIOCAP Canada Foundation, Queen's University, Kingston, Ontario, Canada

107. Lamers P, Thiffault E, Paré D, Junginger M (2013) Feedstock specific environmental risk levels related to biomass extraction for energy from boreal and temperate forests. Biomass Bioenergy 55:212–226. doi:10.1016/j.biombioe.2013.02.002

108. Page-Dumroese DS, Abbott AM, Rice TM (2009) Forest Soil Disturbance Monitoring Protocol Volume II : Supplementary. U.S. Department of Agriculture, Forest Service, General Tech Report GTR-82b, Fort Collins, CO

109. Jarvis JM, Page-Dumroese DS, Anderson NM, Corilo Y, Rodgers RP (2014) Characterization of fast pyrolysis products generated from several western USA woody species. Energy Fuels 28:6438–6446. doi:10.1021/efS01714j

110. Certini G (2005) Effects of fire on properties of forest soils: a review. Oecologia 143:1–10. doi:10.1007/s00442-004-1788-8

111. Harvey AE, Larsen MJ, Jurgensen MF (1979) Comparative distribution of ectomycorrhiza in soils of three western Montana forest habitat types. For Sci 25:350–358

112. Matovic D (2011) Biochar as a viable carbon sequestration option: global and Canadian perspective. Energy 36:2011–2016. doi:10.1016/j.energy.2010.09.031

113. Brown R (2009) Biochar production technology. In: Lehmann J, Joseph S (eds) Biochar for Environmental Management - Science and Technology. Earthscan Press, London, pp 127–146

114. Garcia-Perez M, Lewis T, Kruger CE (2010) Methods for producing biochar and advanced biofuels in Washington State Part 1 : Literature review of pyrolysis reactors. Department of Biological Systems Engineering and the Center for Sustaining Agriculture and Natural Resources. Washington State University, Pullman, WA

115. Kinney TJ, Masiello CA, Dugan B, Hockaday WC, Dean MR, Zygourakis K, Barnes RT (2012) Hydrologic properties of biochars produced at different temperatures. Biomass Bioenergy 41:34–43. doi:10.1016/j.biombioe.2012.01.033

116. Page-Dumroese DS, Robichaud PR, Brown RE, Tirocke JM (2015) Water repellency of two forest soils after biochar addition. Trans ASABE 58:335–342. doi: 10.13031/trans.58.10586

117. Spokas KA, Cantrell KB, Novak JM, Archer DW, Ippolito JA, Collins HP, Boateng AA, Lima IM, Lamb MC, McAloon AJ, Lentz RD, Nichols KA (2012) Biochar: a synthesis of its agronomic impact beyond carbon sequestration. J Environ Qual 41:973. doi:10.2134/jeq2011.0069

118. McElligott K, Page-Dumroese DS, Coleman M (2011) Bioenergy production systems and biochar application in forests: potential for renewable energy, soil enhancement, and carbon sequestration. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Research Note RMRS-RN-46, Fort Collins, CO

119. Page-Dumroese DS, Coleman M, Thomas SC (2015) Opportunities and uses of biochar on forest sites in North America. Cambridge University Press, New York, NY

120. Lehmann J (2007) A handful of carbon. Nature 447:143–144. doi:10.1038/447143a