Biochar Potential To Enhance Forest Resilience, Seedling Quality, and Nursery Efficiency

R. Kasten Dumroese, Deborah S. Page-Dumroese, and Jeremiah R. Pinto

Research Plant Physiologist, National Nursery Specialist, U.S. Department of Agriculture (USDA), Forest Service, Rocky Mountain Research Station (RMRS), Moscow, ID; Research Soil Scientist, USDA Forest Service, RMRS, Moscow, ID; Research Plant Physiologist, Tribal Nursery Specialist, USDA Forest Service, RMRS, Moscow, ID.

Abstract

Land managers face a mounting variety of challenges, including how to efficiently dispose of excessive woody residues on forest sites (especially in the Western United States), maintain and improve soil productivity, improve forest resilience to changes in climate (especially as it pertains to drought and fire), and increase the effectiveness of reforestation activities. The use of biochar, a charcoal that is not readily degraded and is made specifically for land application, may have a role in meeting these challenges. Moreover, biochar may provide nursery managers with opportunities to produce seedlings for reforestation and restoration in a more sustainable way, particularly by reducing irrigation inputs, as evidenced through several trials summarized here.

Figure 1. Burning large slash piles can cause long-term damage to soil. (Photo by USDA Forest Service 2012)

Introduction

Many forests, especially those in the Western United States, face management challenges related to wildfire, insect and disease outbreaks, and invasive species because of overstocked or stressed stands (Weatherspoon and Skinner 2002). The nexus of these challenges facing land managers is what to do with the resulting excessive wood on forest sites that has little or no economic value. This wood comes from precommercial thinning of overstocked stands to reduce fire hazard, tremendous loss of standing timber to drought and bark beetle infestation (i.e., 29 million trees in the Sierra Nevada as of 2015), and conventional thinning and logging (Thibodeau et al. 2000, Fettig et al. 2019). Combined, these activities have created, literally, mountains of slash that are eventually burned (figure 1). Although slash pile burning is an economical method for disposing of undesired woody residues, burning can wreak havoc on the soils beneath piles, often rendering them unproductive for decades (figure 2). In addition, smoke and particulates contribute to air quality issues, and release of CO_2 adds to climate change. An alternative is to burn these residues under controlled conditions, thereby reducing emissions, generating bio-energy, and sequestering carbon (Jones et al. 2010, Page-Dumroese et al. 2017).

Burning residues under controlled conditions can create biochar (charcoal made for land application) and currently the interest in using woody forests residues, mill shavings, and invasive woody species to make biochar is increasing. Widespread use of this technique is limited, however, because transportation costs to bioenergy facilities where biochar can be made by pyrolysis (burning in the absence of oxygen) can be expensive. On-site production, however, is possible and encouraged (Page-Dumroese et al. 2017). In general, the carbon (C) concentration of the biochar is about double that of the original feedstock, but each type of feedstock and burn conditions creates unique biochar

Figure 2. Slash pile burn openings (non-green dots) created when large piles were burned 50 years ago. (Photo by USDA Forest Service 2010)

(table 1). Biochar derived from burning wood usually has a pH that is compatible with plant growth, whereas some feedstocks, such as poultry litter, yield biochar with very high (>8) pH (table 1). The benefits of adding biochar to soil are many, including an increase in water- and nutrient-holding capacity while sequestering C belowground (Page-Dumroese et al. 2016b). Although biochar is a form of organic matter, it persists much longer in the soil profile than litter or humus because it is charred. It has high cation exchange capacity and has been suggested for use in plant propagation (e.g., Dispenza et al. 2016, Dumroese et al. 2018).

Furthermore, many soils have lost appreciable soil organic matter from overgrazing, cultivation, forest harvesting, and erosion (Lal 2009). These soils could benefit from biochar additions during reforestation because it adds a highly recalcitrant form of C and promotes long-lasting effects (e.g., retention of cations, anions, and water; Thomas and Gale 2015). For example, biochar, wood ash, and biochar mixed with manure were applied on restoration sites in the Lake States and resulted in increased soil water-holding capacity and cation exchange capacity, and increased seedling growth (Richard et al. 2018).

Forestry Trials – On-site Creation and Use

Biochar is made by burning biomass under controlled conditions. Commonly, it is created in

Table 1. Examples of carbon and nitrogen concentrations, pH, and electrical conductivity (EC) in biochar created from woody residues from the Western United States (from Page-Dumroese et al. 2016b).

Tree species or species mix		Production method	Carbon (%)	Nitrogen (%)	pH	EC (µS/cm)
Mixed conifer	Primarily ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) and Douglas-fir (Mirb.) Franco	Improved slash pile	28	0.22	7.5	150
Mixed conifer	Primarily ponderosa pine and Douglas-fir	Gasifier	89	0.26	8.1	103
Fire-killed salvage	Mixed conifer but primarily ponderosa pine	Gasifier	94	0.34	7.4	258
Beetle-killed salvage	Mixed conifer but primarily ponderosa pine	Mobile pyrolysis	86	0.18	8.1	90
Oregon white oak	*Quercus garryana* (Douglas ex Hook.)	Mobile pyrolysis	87	0.62	7.9	180
Scotch broom	*Cytisus scoparius* (L.) Link	Mobile pyrolysis	80	0.51	7.5	235
Western redcedar	Thuja plicata (Donn ex D. Don)	Mobile pyrolysis	92	0.30	5.4	789
Twoneedle pinyon pine and common juniper	*Pinus edulis* (Englem.) and *Juniperus communis* (L.)	Metal kiln	76	0.50	6.5	330
Pacific madrone	*Arbutus menziesi*i (Pursh)	Mobile pyrolysis	85	021	4.5	789
Ponderosa pine		Fast pyrolysis/byproduct of bioenergy	85	0.74	7.5	197
Russian-olive	*Elaeagnus angustifolia* (L.)	Rotary kiln	73	1.69	7.6	190

large-scale bioenergy facilities by using pyrolysis (low-oxygen conditions) or gasification (partial oxidation of biomass). Both of these methods create high C biochar that has a small particle-size (<4 mm; Anderson et al. 2013) making it an excellent soil amendment, but these methods are often not amenable for small landowners and nursery managers, or for processing low- or no-value woody biomass created from restoration harvest operations.

Numerous biochar trials have been installed in the West. These trials have shown that biochar added to soil on many forest, rangeland, and mine reclamation sites can decrease the number and amount of invasive species (Adams et al. 2013, Bueno et al. 2019), increase water-holding capacity (Basso et al. 2013, Page-Dumroese et al. 2016b), and decrease greenhouse gas emissions (Sarauer et al. 2019) while concurrently sequestering C belowground.

Biochar can be applied with a biochar spreader (Page-Dumroese et al. 2016a), manure spreader, tractor, or by hand. On forested sites, biochar is not incorporated into the soil, but moves into the mineral soil with rain or snow melt. During tree planting in the Lake States, biochar was applied in the planting hole (Richard et al. 2018) and was shown to increase water-holding capacity. On agricultural sites, biochar is incorporated using available equipment. Recommendations for how much biochar to apply, however, largely depend on the soil texture and organic matter content. For example, a loamy-textured soil with abundant organic matter may benefit from only a small amount of biochar (~1 ton/ac [2,242 kg/ha]), but a coarse-textured, low fertility, low organic matter soil could benefit from 10 tons/ac (22,417 kg/ha). Although we have experimented with applying greater quantities, we have observed that large amounts of biochar can be detrimental to water infiltration into the soil and immobilization of nitrogen (N) (Page-Dumroese et al. 2015, 2018).

To avoid the economic costs of transporting woody residues to bioenergy facilities, we have been examining other ways to create biochar for wildland soil use. Three that show promise are better-designed slash piles, kilns, and air-curtain burners.

Slash piles

Properly constructed slash piles can maximize the creation of biochar to be distributed on wildland sites. The best slash piles have logs with the largest diameters at the bottom of the pile (with some gaps between them to encourage air flow) and smaller material piled perpendicularly on top (figure 3).

Grapplers can be used to build the piles, which are then lit from the top, allowing the fire to burn downward. Once the flames have gone out, the pile is extinguished with either soil or water to maximize the amount of char, rather than ash. After the biochar has cooled, it can be raked around the site. This method has four advantages:

1. Potential for greater air flow to dry wood.
2. Limited moisture wicking up from the soil into the wood.
3. Construction time is similar to other pile-building methods.
4. Limited soil impacts.

As noted in table 1, the biochar created in slash pile burns can be low in C, but on sites low in organic matter, this biochar can still provide additional water-holding capacity.

Kilns

Kilns (e.g., figure 4) have been used for centuries to make charcoal. They can be earth-covered pits or mounds, or made from bricks, metal, or concrete. Kilns work in batch jobs in which the feedstock is added, burned, quenched, and the charcoal removed and spread on the soil. Some kilns can be highly portable to use for on-site biomass processing. Mini-kilns, such as those made by Wilson Biochar Associates (www.wilsonbiochar.com) are ideal for small landowners interested in conservation stewardship or soil enhancement projects. These small kilns can be operated by one or two people. Depending on the type and size of kiln, processing can take hours to days to complete. Newer rotary kilns (Utah Forest News 2015) can be used for large-scale operations, but wood must be chipped before adding it to the kiln (Page-Dumroese et al. 2017). This equipment is housed in a shipping container so it can be relatively portable.

Kilns produce relatively high C biochar (table 1). Unless the biomass is chipped before burning, however, the resultant biochar can be chunky and slow to incorporate into the soil.

Figure 3. Slash pile built to maximize biochar production. Note the larger diameter logs at the bottom; they help keep the heat away from the soil surface and provide maximum airflow. (Photo by USDA Forest Service 2011)

Air Curtain Burners

Air curtain burners are an alternative to burning wood in slash piles. These are usually used for large-scale projects, but the burners come in different sizes (https://airburners.com). A series of blowers push air across the top of the fire box to create an air curtain, recirculating gases and particulates back into the fire for secondary combustion. Similar to kilns, air burners work in batch jobs. In air curtain burners, wood is burned continually, forming some biochar, but the primary product is wood ash unless the fire is quenched. This equipment can be used to rapidly dispose of fresh or dried woody residues, but because the air burners are heavy, equipment is needed to dump the ash out. Although the ash has value as a fertilizer, it does not have the high water- and nutrient-holding capacity of biochar.

Figure 4. Kiln used to convert juniper slash into biochar. (Photo by Eric Roussel, Nevada Division of Forestry 2016)

Nursery Trials

One way to increase the conversion of forest woody residues into biochar is to expand markets for using bioenergy and biochar. Biochar from woody biomass has been used to increase agricultural crop, grass, and urban tree growth (Jones et al. 2012, Scharenbroch et al. 2013). Because of these benefits, an obvious potential market for biochar is use in nurseries, especially if it could replace expensive, non-sustainable ingredients in growing substrates, such as Sphagnum peat moss, perlite, or vermiculite (Dumroese et al. 2011). Woody biomass can create high-quality biochar that is 70- to 90-percent C and, when used as a medium for plant production, can help sequester C belowground while improving soil properties. Using biochar can be an efficient way to sequester C because, once added to nursery growing media, biochar becomes part of the root plug already destined to be outplanted. Thus, the transportation and burial costs are already included *de facto* (Dumroese et al. 2011). We have conducted a series of trials to examine the potential of using biochar in container seedling substrates as summarized in the following sections.

Trial 1 – Pelletizing Biochar to Facilitate Handling

We examined the chemical and physical properties of biochar to determine its feasibility for growing seedlings. Because fine-granular biochar can be very dusty, we pelletize biochar with a wood flour binder, hypothesizing that the larger pellets may also provide benefit in the medium (Dumroese et al. 2011). We replaced Sphagnum peat moss with biochar from 25 to 75 percent by volume. At the 75-percent peat / 25-percent biochar level, we saw less shrinkage of the medium during the growing season (i.e., it was more stable than 100-percent peat), but rates of pelleted biochar > 25 percent yielded poor results because the pellets swelled excessively when irrigated (Dumroese et al. 2011).

Trial 2 – Pelletized versus Granular Biochar: Impacts on Seedling Growth

As a follow-up to the first trial, we looked at ponderosa pine growth with the pelleted biochar and the biochar in its original, fine-granular, non-pelleted form and added at the same rates described above (Dumroese et al. 2018). We were very strict with irrigation and N fertilization to avoid confounding the treatments. Irrigation occurred to all seedlings at the same dry-down percentages and we applied a discrete amount (mass) of N per week, at both a low (to achieve 20 mg N total for the experiment) and a high (i.e., normal, 80 mg N) rate; the low rate was used to see if biochar could improve fertilizer use efficiency. Because of expansion problems with pellets identified in the first trial, and very poor seedling growth observed with any pellet treatment (data not shown; see figure 6 in Dumroese et al. 2018), the likely scenario for nursery managers is just to use biochar in powder/fine granular form. In this form, medium pH ranged from 5.0 to 6.7 moving from 25- to 75-percent biochar in the medium. On the first irrigation, the volume of the 100-percent peat treatment shrank about 10 percent, but addition of biochar reduced that shrinkage to just 3 to 5 percent, suggesting that biochar helps maintain porosity. Adding 25- or 50-percent biochar reduced irrigation frequency 12 and 25 percent, respectively (Dumroese et al. 2018). At the low N rate, seedling growth was poorer with any addition of biochar (figure 5). At the high rate of N, adding 25-percent biochar had no effect on height, slightly increased root collar diameter (RCD), reduced shoot biomass, and increased root biomass (Dumroese et al. 2018).

Recalling that we held the fertilizer N rate constant (in terms of mass), we must add a caveat to our findings. Our data suggest that early in the crop cycle, biochar likely absorbs N on its cation exchange sites. Under a production scenario where nursery staff are monitoring growth against a target growth curve, a prudent manager could readily do some real-time nutrient manipulations to keep the crop growing on target.

In figure 6, for example, all seedlings were given the same mass of N and the same amount of water. If, however, they were grown operationally and the nursery manager regularly compared actual growth with target growth, and subsequently tailored the culturing regime to meet the target growth curve (by adding more N), we hypothesized that seedling quality could be maintained across a range of biochar additions.

Trial 3 – Using Granular Biochar in an Adaptive Way

To test the hypothesis framed at the conclusion of Trial 2, we added 25, 46, and 43 percent more N to the seedlings growing with 25-, 50-, and 75-percent granular biochar treatments at the 80 mg N rate to keep them on their target growth curves. Our results reveal that any short-term nutrient problems associated with the high cation exchange capacity (or some other factor) of the

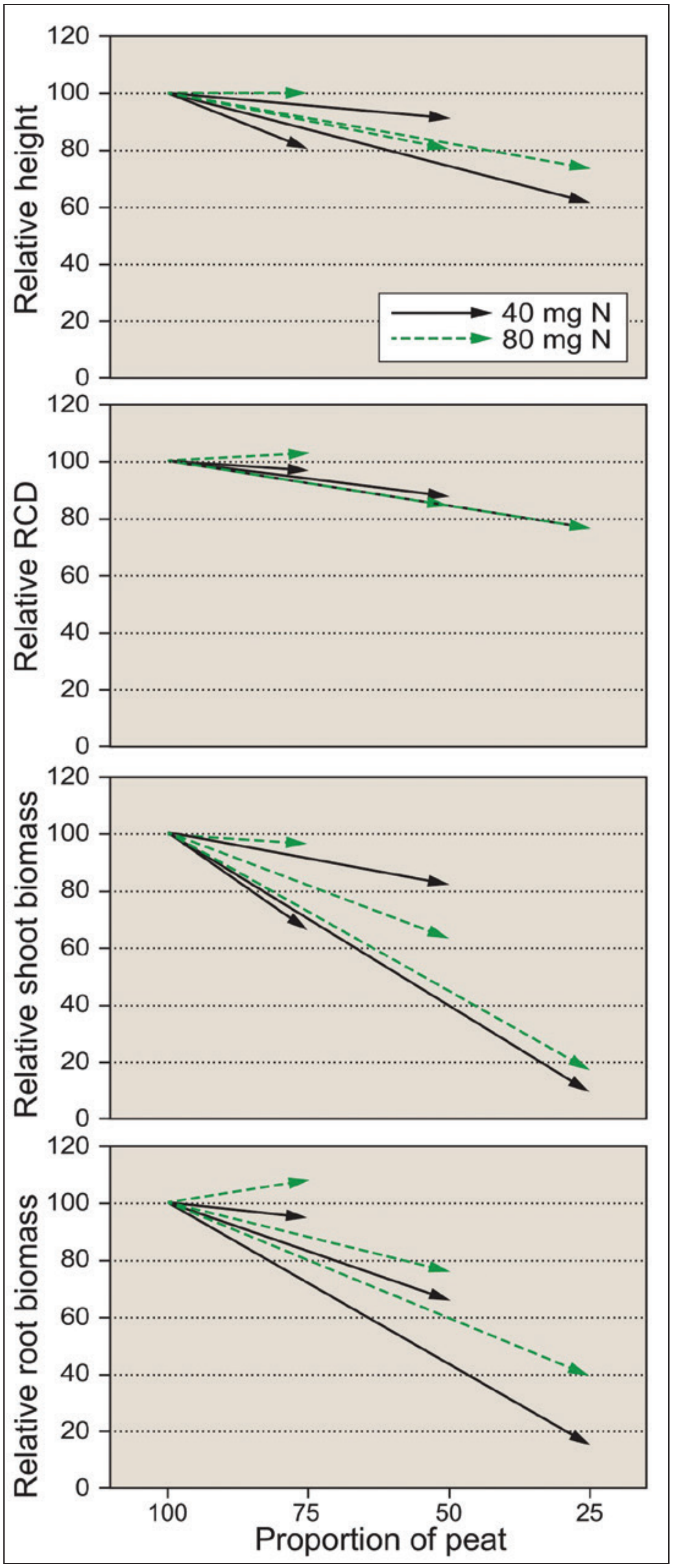

Figure 5. Vectors represent relative changes in seedling morphology of seedlings grown in a biochar-amended substrate compared to the control with 100-percent peat. X-axis reflects percentage of peat; Y-axis reflects relative value of the treatment to the control (i.e., 100-percent relative value is the value obtained with the 100-percent peat). In general, downward pointing arrows indicate morphologies smaller than the control. (Modified from Dumroese et al. 2018)

biochar can be overcome by manipulating the fertigation regime (figure 7). Remember that the seedlings shown in figures 6 and 7, grown with 25-percent addition of biochar by volume, yielded similar seedlings to those grown in the 100-percent peat control at the same high rate of N (which was really the "normal" rate of N we typically use to produce ponderosa pine) (Dumroese et al. 2018). Although we have not tested composting biochar, research indicates that mixing biochar with compost can initially charge the cation exchange sites of the biochar (Agegnehu et al. 2017). Pre-charging the biochar may avoid the lag in early growth we observed in Trial 2 and mitigate the need to manipulate N levels, as done in Trial 3.

Trial 4 – Testing More Species Than Pine

This trial also used biochar powder from a woody feedstock (Matt et al. 2018). Because of our results with 25-percent granular biochar in previous trials, we bracketed our rates in this experiment around that value, and replaced peat with biochar at rates of 0, 15, 30, and 45 percent (by volume). We also looked at three plant forms (i.e., tree, forb [an annual and a perennial], and grass). Ponderosa pine was the tree, pinkfairies (*Clarkia pulchella* Pursh) was the annual forb, blanketflower (*Gaillardia aristata* Pursh) was the perennial forb, and Idaho fescue (*Festuca idahoensis* Elmer) was the grass. We strictly controlled the N rate and irrigation to ensure all treatments were given the same amounts. In this trial, we found similar biomass (shoot, root, total) regardless of biochar rate for everything except the grass, which performed poorer than the control when any rate of biochar was added (Matt et al. 2018). A notable result from

Figure 6. Left to right: Seedlings grown with 0-, 25-, 50-, or 75-percent granular biochar at the 80-mg N rate. (Photo by R. Kasten Dumroese 2010)

Figure 7. Short-term nutrient problems can be overcome by manipulating the fertigation regime. Left to right: Seedlings grown with 0-, 25-, 50-, or 75-percent granular biochar and receiving 80, 100, 117, and 114 mg N, respectively, in order to achieve the same overall growth as the control (i.e., 80 mg N). (Photo by R. Kasten Dumroese 2010)

this trial was the reduced irrigation frequency afforded by the biochar (table 2; Matt et al. 2018).

Trial 5 – Biochar and Symbiotic Organisms

Our last trial examined whether biochar had any effects on the development, growth, and function of rhizobia during nursery production. Rhizobia are micro-organisms that form symbiotic relationships with legumes (Fabaceae), converting atmospheric N into a form useful to their host plants. In this trial, our host plant was black locust (*Robinia pseudoacacia* L.), and we amended *Sphagnum* peat moss with 5-percent (by volume) granular biochar. Our preliminary results revealed that biochar had no effect on the abundance of rhizobia or their ability to fix atmospheric N, but that biochar produced from gasification yielded larger seedlings than those grown with biochar from pyrolysis (unpublished data).

Table 2. Number of irrigation events, as triggered by a 75-percent container capacity threshold (from Matt et al. 2018, using Dumroese et al. 2015; scientist method; actual change in water mass).

	Biochar (% by volume)			
	0	15	30	45
Clarkia pulchella	38	36	32	27
Festuca idahoensis	31	26	21	20
Gaillardia aristata	53	51	44	41
Pinus ponderosa	49	44	39	37

Outplanting Seedlings with Biochar

An early study found benefits in the addition of biochar at planting (Richard et al. 2018). The benefits were hypothesized to include improved soil water-holding capacity dynamics, increased nutrient retention, and enhanced carbon sequestration. In a growth chamber study, we found no marked differences in growth of Norway spruce (*Picea abies* [L.] Karst.) seedlings transplanted into an alluvial silty soil amended up to 60 percent by volume with biochar (Heiskanen et al. 2013). This suggests that biochar may be added to mineral soils without detrimental effects to outplanted seedlings.

We outplanted, on a forest site in Alabama, longleaf pine (*Pinus palustris* Mill.) and loblolly pine (*Pinus taeda* L.) seedlings that were grown in containers with two sources of granular biochar (mixed conifer and proprietary) at rates from 0 to 20 percent by volume. After three growing seasons, we observed no differences in survival or growth (unpublished data).

Management Implications

Soil scientists, land managers, and nursery managers have an incredible opportunity to convert excess woody biomass that would normally be burned in slash piles into a high-carbon product and use it for soil restoration or as a component in growing media for native seedling production. Biochar can be a replacement for other forms of organic matter, but has the advantage of being highly recalcitrant, has a high cation-exchange capacity, can reduce leaching, and increases soil water-holding capacity. Furthermore, it sequesters C belowground, reduces the volume of woody residues and fire risk, and, because of the low N content, can limit invasive species. Most biochars have a relatively high pH and can also help remediate sites with a low pH by acting as a liming agent. Biochar, when used in combination with other soil restoration efforts (e.g., mycorrhizae inoculants, compost), should reduce recovery time and plant failure.

REFERENCES

Adams, M.M.; Benjamin, T.J.; Emery, N.C.; Brouder, S.J.; Gibson, K.D. 2013. The effect of biochar on native and invasive prairie plant species. Invasive Plant Science and Management. 6: 197–207.

Agegnehu, G.; Srivastava, A.K.; Bird, M.I. 2017. The role of biochar and biochar-compost in improving soil quality and crop performance: a review. Applied Soil Ecology. 119: 156–170.

Anderson, N.; Jones, J.G.; 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.

Basso, A.S.; Miguez, F.E.; Laird, D.A.; Horton, R.; Westgate, M. 2013. Assessing potential of biochar for increasing water-holding capacity of sandy soils. GCB Bioenergy. 5: 132–143.

Bueno, A.; Pritsch, K.; Simon, J. 2019. Species-specific outcome in competition for nitrogen between invasive and native tree seedlings. Frontiers in Plant Science. 10: article 337, 17 p.

Dispenza, V.; De Pasquale, C.; Fascella, G.; Mammano, M.M.; Alonzo, G. 2016. Use of biochar as peat substitute for growing substrates of *Euphorbia* × *lomi* potted plants. Spanish Journal of Agricultural Research. 14: article e0908, 21 p.

Dumroese, R.K.; Heiskanen, J.; Englund, K.; Tervahauta, A. 2011. Pelleted biochar: chemical and physical properties show potential use as a substrate in container nurseries. Biomass & Bioenergy. 35: 2018–2027.

Dumroese, R.K.; Montville, M.E.; Pinto, J.R. 2015. Using container weights to determine irrigation needs: a simple method. Native Plants Journal. 16: 67–71.

Dumroese, R.K.; Pinto, J.R.; Heiskanen, J.; Tervahauta, A.; McBurney, K.G.; Page-Dumroese, D.S.; Englund, K. 2018. Biochar can be a suitable replacement for Sphagnum peat in nursery production of *Pinus ponderosa* seedlings. Forests. 9: article 232, 21 p.

Fettig, C.J.; Mortenson, L.A.; Bulaon, B.M.; Foulk, P.B. 2019. Tree mortality following drought in the central and southern Sierra Nevada, California, U.S. Forest Ecology and Management. 432: 164–178.

Heiskanen, J.; Tammeorg P.; Dumroese, R.K. 2013. Growth of Norway spruce seedlings after transplanting into silty soil amended with biochar: a bioassay in a growth chamber. Journal of Forest Science. 59: 125–129.

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.

Jones, D.L.; Rousk, J.; Edwards-Jones, G.; DeLuca, T.H.; Murphy, D.V., 2012. Biochar-mediated changes in soil quality and plant growth in a three year field trial. Soil Biology and Biochemistry. 45: 113-124.

Lal, R. 2009. Challenges and opportunities in soil organic matter research. European Journal of Soil Science. 60: 158–169.

Matt, C.P.; Keyes, C.R.; Dumroese, R.K. 2018. Biochar effects on the nursery propagation of 4 northern Rocky Mountain native plant species. Native Plants Journal. 19: 14–26.

Page-Dumroese, D.S.; Anderson N.M.; Windell, K.N.; Englund, K.; Jump, K. 2016a. Development and use of a commercial-scale biochar spreader. Gen. Tech. Rep. RMRS-GTR-354. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 10 p.

Page-Dumroese, D.S.; Busse, M.D.; Archuleta, J.G.; McAvoy, D.; Roussel, E. 2017. Methods to reduce forest residue volume after timber harvesting and produce black carbon. Scientifica. 2017: article 2745764, 8 p.

Page-Dumroese, D.S.; Coleman, M.D.; Thomas, S.C. 2016b. Opportunities and uses of biochar on forest sites in North America. In: Bruckman, V.J.; Varol, E.A.; Uzun, B.B.; Liu, J., eds. Biochar: a regional supply chain approach in view of mitigating climate change. Cambridge, UK: Cambridge University Press: 315–336. Chapter 15.

Page-Dumroese, D.S.; Ott, M.R.; Strawn, D.G.; Tirocke, J.M. 2018. Using organic amendments to restore soil physical and chemical properties of a mine site in northeastern Oregon, USA. Applied Engineering in Agriculture 34: 43–55.

Page-Dumroese, D.S.; Robichaud, P.R.; Brown, R.E.; Tirocke, J.M. 2015. Water repellency of two forest soils after biochar addition. Transactions of the ASABE. 58: 335–342.

Richard, R.P.; Potvin, L.R.; Kane, E.S.; Handler, S.D.; Smith, P.J.; Peterson, D. 2018. Biochar and wood ash amendments for forestry in the Lake States: field report and initial results. Journal of Forestry. 116: 222–227.

Sarauer, J.L.; Page-Dumroese, D.S.; Coleman, M.D. 2019. Soil greenhouse gas, carbon content, and tree growth response to biochar amendment in western United States forests. GCB Bioenergy. 11: 660–671.

Scharenbroch, B.C.; Meza, E.N.; Catania, M.; Fite, K. 2013. Biochar and biosolids increase tree growth and improve soil quality for urban landscapes. Journal of Environmental Quality. 42: 1372–1385.

Thibodeau, l.; Raymond, P.; Camiré, C.; Munson A.D. 2000. Impact of precommercial thinning in balsam fir stands on soil nitrogen dynamics, microbial biomass, decomposition, and foliar nutrition. Canadian Journal of Forest Research. 30: 229–238.

Thomas, S.C.; Gale, N. 2015. Biochar and forest restoration: a review and meta-analysis of tree growth responses. New Forests 46: 931–946

Utah Forest News. 2015. Lessons learned: developing and demonstrating a rotary kiln mobile pyrolysis reactor. Utah State University Forestry Extension. 19(2). https://forestry.usu.edu/files/utah-forest-newsletter/utah-forest-newsletter-2015-2.pdf (January 2020).

Weatherspoon, P.C.; Skinner, C.N. 2002. An ecological comparison of fire and fire surrogates for reducing wildfire hazard and improving forest he alth—a study plan. Association of Fire Ecology Miscellaneous Publication 1: 239–245.