The effects of biochars on the growth of *Zelkova serrata* seedlings in a containerized seedling production system

Min Seok Cho*, Loth Meng*, Ji-Hye Song*, Si Ho Han*, Kikang Bae* and Byung Bae Park*

*Forest Practice Research Center, National Institute of Forest Science, Pocheon 11187, Republic of Korea; Departments of Environment & Forest Resources, Chungnam National University, Daejeon 34134, Republic of Korea; ASEAN-ROK Forest Cooperation, Seoul 07236, Republic of Korea

**ABSTRACT**

Biochar has been used for soil improvement in agriculture; however, there are few studies of its uses in forestry. The purpose of this study was to investigate the effects of biochar, made from diverse feedstocks on the growth and chlorophyll content of *Zelkova serrata* seedlings, to identify optimal feedstocks in a containerized seedling production. Five resources were used for biochar: woodchips of *Pinus densiflora* and *Quercus acutissima*; cones of *Pinus koraiensis*; rice husks; and crab shells. The biochar was mixed with growing medium by 20% in volume and two levels of fertilization were applied. The height and root collar diameter of *Z. serrata* treated with wood chips of *P. densiflora* and *Q. acutissima* and rice husk were each significantly greater than those treated with pine cones and crab shells. The biomass responses and quality indexes were similar to those of height and root collar diameter. There were no significant differences in growth between fertilization levels. This study shows that biochar made from woodchips of *P. densiflora* and *Q. acutissima* and rice husk can be substituted for growing medium by 20% in a containerized seedling production system.

**Keywords**
Afforestation; fertilization; pine cone; rice husk; wood chip

**Introduction**

Biochar is a biomass derived black carbon, which is a byproduct of the anaerobic pyrolysis process. Biochar has been used as a soil amendment to: improve crop productivity; enhance soil physical and chemical quality; increase carbon sequestration in the soil; and filtrate percolating soil water mainly on agricultural soils (Johannes and Stephan 2009; Zhang et al. 2012). Usage of biochar additions has been suggested to mitigate the possible negative impacts of forest biomass removal by whole-tree harvest, pre-commercial thinning, and hazardous fuel reductions because of biochar’s carbon sequestration, nutrient supply, and liming effect. However, little is known about the consequences of biochar application to temperate forests as most research of biochar additions comes from agricultural systems (Wardle et al. 1998; McEligott et al. 2011; Spokas et al. 2012).

Biochar has been used for soil improvement and enhancing plant growth (Lehmann 2007), but also has potentially negative impacts on soil quality, such as N immobilization and increasing soil pH in alkaline soils (Lehmann et al. 2003; Novak et al. 2009). These effects depend on its unique physical, chemical, and biological properties, and its interactions with soil and plant communities. Because the properties of biochar vary by feedstock type and conditions of pyrolysis (Enders et al. 2012; Robertson et al. 2012; Mukherjee and Zimmerman 2013; Jindo et al. 2014), it is important to understand the characteristics of biochar prior to application.

The type of feedstock material is an important factor to determine the biochar’s effect on soil properties and plant growth, because its properties are affected by the nature of the original material. Rice husk and rice straw yield high biochar quantities with low carbon content and a low absorption characteristic relative to wood chips of *Malus pumila* and *Quercus serrata* (Jindo et al. 2014). The soil cation exchange capacity of manure-based biochar is greater than *Eucalyptus* biochar (Singh et al. 2012), but less for saturated hydraulic conductivities (Lei and Zhang 2013).

The purpose of this study was to investigate the effects of biochar made from diverse biomaterials on the growth and physiological properties of *Zelkova serrata* seedlings in a containerized seedling production system. Five biomaterials were used for biochar in this study: pine chip; oak chip; pine cone (byproducts from forestry); rice husk (from agriculture); and crab shell (from fishery). These biomaterials are regarded as industrial wastes unless used in a cost-effective and environmentally acceptable manner. *Zelkova serrata* seedlings were used to verify the effects of biochar in a containerized production system because of this species’ high economic value as commercial timber and as a street tree. This study aims to improve knowledge about which biomaterial can be used economically for seedling production in plantations.

**Materials and methods**

**Study sites and species**

The experiment was conducted in a greenhouse located in Chungnam National University, Daejeon, South Korea (36 22’N, 127 21’E). The temperature and humidity were measured from May to September 2015 with HOBO (U23 Pro v2, USA). Mean temperature was 22.5 °C and mean humidity was 78.6%.

*Zelkova serrata* seeds were germinated in March 2015 at the Forest Practice Research Center, National Institute of Forest Science and delivered to the greenhouse in Chungnam National University in early May 2015.

**CONTACT** Byung Bae Park bbpark@cnu.ac.kr

© 2017 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
Biochar production

In May 2015, the biochar was made using a wood roaster at the College of Agriculture and Life Sciences, Chungnam National University. This wood roaster automatically conveys sources and carbonizes at temperatures of 200 °C to 250 °C (Lee and Kang 2015). Pulverizing equipment was also used to grind carbonated materials into 0.1 mm in diameter. The feedstocks used were pine chip, oak chip, pine cone, rice husk, and crab shell. The dimensions of the pine chips and oak chips were 2 cm × 2 cm × 0.5 cm. For convenient carbonization, pine cone was broken into dimensions of 3 cm × 3 cm × 1 cm. All of the sources were dried at 65 °C for 72 h before carbonization in the wood roaster.

Biochar analysis

Moisture content, ash content, fixed carbon content, and volatility of biochar were the physical properties. Moisture content was determined by measuring the weight loss following furnace-dry of 3 g of biochar in a crucible at 150 °C for 24 h. Following the same procedure, the volatile matter and the ash content were determined at 450 °C and 750 °C, respectively.

For analyzing biochar’s chemical properties, the char samples were dried at 65 °C for 48 h; pH, EC, carbon (C), nitrogen (N), phosphorus (P), potassium (K), sodium (Na), calcium (Ca), and magnesium (Mg) were also determined. Biochar pH and EC were determined by diluting samples with distilled water at a ratio of 1:5. Total N was analyzed with the Micro-Kjeldahl method with a 1 g char sample. Available phosphorus (P₂O₅) was measured with the Lancaster method (Lancaster 1980). Exchangeable K⁺, Ca²⁺, Na⁺, and Mg²⁺ were determined in 1 N NH₄OAc extracts with an atomic absorption spectrometer (AA280FS, Varian, USA).

Experimental treatments

The experiment was designed as a 6 × 2 factorial experiment with Z. serrata: control for no treatment and five biochar types (pine chip, oak chip, pine cone, rice husk, and crab shell), and two levels of fertilization. Each treatment was applied to five replications in a completely randomized design.

The cells for Z. serrata were 6.8 cm in diameter and 15 cm in depth (400 mL). Each tray was 32 cm × 40 cm and contained 20 cells. The trays were placed on a platform 60 cm above the greenhouse floor. When cultivating the seedlings, we used a growing medium mixture of peat moss, perlite, and vermiculite at a ratio of 1:1:1 by volume. Eighty mL biochar was mixed with 320 mL of soil to make a 20% ratio. The seedlings were then planted with blank cells in between seedling cells; 10 seedlings per tray. On planting, the seedlings were of similar height at 6 cm.

Fertilization started on 28 May with two levels – 1 × fertilization (0.5g/L) and 2 × fertilization (1 g/L) at 110 mL per cell – of MultiFeed20 fertilizer (20N:20P₂O₅:20K₂O; Haifa Chemical, Israel) applied once per week for 10 weeks. Water irrigation was applied for 20 min every day. The positions of the trays were rotated every 2 weeks in order to reduce unknown environmental influences such as unequal water irrigation.

Growth measurements

During the experiments, the height and root collar diameter (rcD) of seedlings were measured every month from late May to late September. The height was measured from the ground to apical meristem, while the rcD was measured at 1 cm above the ground. The seedlings were harvested in October and divided into stem, leaf, and roots. The roots were washed with tap water in order to remove soil particles. All components were dried to a constant weight at 65 °C for 48 h.

Chlorophyll measurements

For measuring chlorophyll content, three healthy leaves from the third to fifth order from the top for each seedling were selected and measured by SPAD-502plus (MINOLTA, Japan). The measurements were taken only once in September.

Dickson’s quality index

Dickson’s quality index was estimated to measure the quality of seedlings as follows:

\[
\text{Quality index} = \frac{\text{SD}}{(\text{HD} + \text{SR})}
\]

where SD is seedling dry weight (g), HD is height (cm) to rcD ratio (mm), and SR is shoot dry weight (g) to root dry weight (g) ratio (Deans et al. 1989; Bayala et al. 2009; Park et al. 2015).

Statistical analysis

Analysis of variance (ANOVA) with Duncan’s multiple comparison tests was applied to test the effects of biochar and fertilization treatment on seedling height, rcD, dry weight, quality index, and chlorophyll contents. Only September measurements for height and rcD were used for ANOVA. All probabilities were tested at the significant level at 0.05.

Results

Biochar characteristics

Except for moisture content, the biochars’ physical properties were significantly different (Table 2). The range among bios was from 0.5% to 36.6% for ash, from 7.8% to 26.4% for fixed carbon, and from 51.4% to 79.9% for volatility. Of the five biochars, crab shell had the highest ash content and lowest carbon content; pine chip, oak chip, and pine cone

---

Table 1. Physical and chemical properties of the growing media before mixing with biochar (revised from Cho 2015).

| Bulk density (g m⁻³) | pH  | Electric conductivity (ds m⁻¹) | Organic matter (%) | Total N (%) | P₂O₅ (mg kg⁻¹) | CEC (cmol, kg⁻¹) |
|---------------------|-----|-------------------------------|-------------------|-------------|--------------|-----------------|
| 0.37                | 6.1 | 0.06                          | 4.0               | 0.08        | 3.0          | 0.3 3.3 2.5 24.3 |

Dickson's quality index was estimated to measure the quality of seedlings as follows:
had similar carbon; and rice husk and crab shell had lower volatility than the others by 25%.

Similarly, the chemical properties of the biochars were significantly different (Table 3). pH was highest for crab shell (8.8) and lowest for oak chip and pine cone (5.1). The EC had similar carbon; and rice husk and crab shell had lower volatility than the others by 25%.

The order of height and rcD growth was rice husk, pine cone, and crab shell from greatest to least, but this was not significantly different from one treatment to the next (Figures 1–2). Pine cone and crab shell treatment showed 66% and 28% of the height growth and 51% and 17% of the rcD growth of rice husk, respectively. For pine cone treatment, 2× fertilization increased height growth by 57% and rcD growth by 33% relative to 1× fertilization.

Biomass of leaf, stem, and root showed a similar pattern among biochars and fertilizer amounts (Table 4, Figure 3) similar to height and rcD growth. The highest total biomass of leaf, stem, and root showed a similar pattern among biochars and fertilizer amounts (Table 4, Figure 3) similar to height and rcD growth. The highest total biomass among biochars and fertilizer amounts (Table 4, Figure 3) was 5.8 times greater than that of crab shell. The 2× fertilization showed a minor increase in total biomass relative to the 1× fertilization (P = 0.08) except for rice husk. For pine chip and oak chip, 2× fertilization increased aboveground biomass by only 15%, but by 339% for pine cone and 585% for crab shell. However, root biomass was not significantly increased by fertilization except in the pine cone treatment.

Quality index and chlorophyll content

The order of quality index, which is one of the comprehensive indices to evaluate seedling quality, was rice husk, pine cone, and crab shell from greatest to least. However, the type of biochar treatment was not significantly different (Figure 4). The quality index of pine cone and crab shell was significantly lower than that of rice husk by 47% and 16%, respectively. The effect of fertilization treatment on quality index was not significant (Table 4).

Chlorophyll content was not statistically influenced by biochar or fertilization treatment (Figure 5). At 2× fertilization, chlorophyll content was lower for pine cone and crab shell than the others, but this was not significantly different.

Discussion

The greatest tree growth was observed for the rice husk biochar treatment at both fertilizations. Our findings are in agreement with other reports of biochar effects on tree growth: the type of feedstock significantly affected the properties of biochar and crop yield (Joseph et al. 2010). The biochar derived from rice husk showed a high ash content because of the high Si content in rice husk as found by Mukome et al. (2013). This property favors the formation of Si–C bonds, thus increasing the number of aromatic components. Therefore, the application of the rice husk biochar has been reported to enhance soil absorption capacity and water retention ability (Lei and Zhang 2013; Kalderis et al. 2014). Rice husk also contains a high concentration of nutrients such as P, Na, Ca, and Mg that can improve available nutrients, ultimately increasing tree growth at 1× fertilization in this study, which is half of the amount of normal fertilization (Cho 2015). This means available nutrients from adding rice husk biochar makes up for the low supply of nutrients at 1× fertilization. Sovu et al. (2012) also found that

Table 2. Physical properties of biochar.

| Biochar type | Moisture content | Ash (%) | Fixed carbon (%) | Volatility (%) |
|--------------|-----------------|---------|------------------|----------------|
| Pine chip    | 4.4 (0.1) c      | 1.9 (0.1) b    | 17.9 (0.5) b     | 75.8 (0.4) b   |
| Oak chip     | 3.2 (0.0) c      | 0.5 (0.0) b    | 16.4 (0.4) b     | 79.9 (0.4) b   |
| Pine cone    | 4.3 (0.0) c      | 1.1 (0.0) b    | 17.3 (0.3) b     | 77.2 (0.2) b   |
| Rice husk    | 3.9 (0.1) b      | 18.3 (0.6) b   | 26.4 (2.1) b     | 51.4 (2.6) b   |
| Crab shell   | 3.0 (0.0) c      | 36.6 (0.1) b   | 7.8 (0.2) b      | 52.7 (0.2) b   |

Parenthesis represent one standard error of the mean (n = 3). Different letters within a column represent significant differences among biochar types.

Table 3. Chemical properties of biochar.

| Biochar    | pH          | EC (ds m⁻¹) | Carbon (%) | N   | P  | K  | Na | Ca | Mg |
|------------|-------------|-------------|------------|-----|----|----|----|----|----|
| Pine chip  | 6.4 (0.1) b | 0.031 (0.026) b | 53.7 (0.1) b | 2.5 (0.7) b | 0.54 (0.08) b | 6.45 (1.11) b | 0.54 (0.05) b | 2.3 (0.4) b | 0.75 (0.11) b |
| Oak chip   | 5.10 (0.0) b | 0.282 (0.054) b | 52.2 (0.0) d | 0.7 (0.4) f | 0.94 (0.08) b | 0.97 (0.12) b | 0.64 (0.11) b | 10.3 (1.2) b | 0.83 (0.09) b |
| Pine cone  | 5.10 (0.0) b | 1.244 (0.191) b | 53.2 (0.1) b | 6.4 (0.1) b | 0.11 (0.00) c | 1.63 (0.03) b | 0.35 (0.02) b | 3.6 (0.5) b | 0.48 (0.01) b |
| Rice husk  | 6.3 (0.3) b  | 0.394 (0.147) b | 45.4 (0.1) b | 5.7 (0.1) b | 12.05 (0.08) b | 2.68 (0.10) b | 7.34 (0.59) b | 158 (7.1) b  | 10.38 (0.62) a |
| Crab shell | 8.8 (0.0) b  | 0.005 (0.000) b | 28.7 (0.2) b | 36.3 (0.3) b | 0.26 (0.04) d | 6.12 (0.15) b | 0.35 (0.07) b | 1.8 (0.3) b  | 0.78 (0.09) b |

Parenthesis represent one standard error of the mean (n = 3). Different letters within a column represent significant differences among biochar types.

Table 4. ANOVA table for growth parameters and chlorophyll content.

| Source of variable | Degree of freedom | Height | Root collar diameter | Leaf | Stem | Root | Total | Quality index | Chlorophyll content |
|--------------------|-------------------|--------|----------------------|------|------|------|-------|---------------|--------------------|
| Fertilization      | 1                 | 0.01   | 0.11                 | <0.01| 0.05 | 0.65 | 0.06  | 0.56          | 0.29               |
| Biochar type       | 5                 | <0.01  | <0.01                | <0.01| <0.01| <0.01| <0.01 | <0.01         | 0.06               |
| Fertilization × biochar type | 5 | 0.08 | 0.12 | 0.33 | 0.12 | 0.65 | 0.18 | 0.37 | 0.26 |
biochar treatment increased the diameter and height growth of all species tested, especially on some slow-growing tree species (Dipterocarpus alatus, Pterocarpus macrocarpus, and D. cochinchinesis) after 4 years on a degraded restoration field in Laos. However, the high ash content, about 40% of dry weight, of crab shell can cause a reduction of water retention capacity due to the high amount of chitin in the crab shell (Jung et al. 2005; Wang and Xing 2007). Therefore, crab shell biochar can have a low nutrient retention capacity affecting plant growth, especially when grown in small volume (400 mL) containers. In agronomical studies, the harmful effects have been reported by crab shell application on soil even though high content nutrients such as N and K: reduction of chickpea yields (Lauter et al. 1981) and reduction of nodulation and soybean growth (Ali et al. 1998) are due to leachable salts from crab shell.

Biochar made from forestry byproducts showed a greater volatile content than rice husk and crab shell due to high lignin contents in woody feedstocks produced at relatively low temperature (Enders et al. 2012; Jindo et al. 2014), which is consistent with the results of Mukome et al. (2013). Higher ratios of C/N and surface area were also reported in a softwood biochar than in a hardwood biochar, which can influence crop production. No relationships were found between plant responses and properties of biochar analyzed in this study, but low EC of pine cone biochar could cause low seedling growth. The growth of Z. serrata in the pine chip and oak chip treatments was comparable to that of seedlings grown in the rice husk treatment, but was significantly higher than the pine cone treatment.

This study did not aim to identify which biochar properties (e.g. pH, C content, or pore sizes of biochars) influence soil amendment and crop performance. However, this type of research should be done to evaluate the effect of biochar properties on different soil and plant responses. Biochar effects on soil and plant growth are not always positive (Chan and Xu 2009), but the ability of biochars to increase

![Figure 1](image1.png)

**Figure 1.** Height growth of *Zelkova serrata* at 1× fertilization (left) and 2× fertilization (right) across five biochars. Vertical bars represent one standard error of the mean (n = 5).

![Figure 2](image2.png)

**Figure 2.** Root collar diameter growth of *Zelkova serrata* at 1× fertilization (left) and 2× fertilization (right) across five biochars. Vertical bars represent one standard error of the mean (n = 5).
Figure 3. Leaf, stem, and root dry weight of *Zelkova serrata* at 1× fertilization (left) and 2× fertilization (right) across five biochars. Vertical bars represent one standard error of the mean (n = 5).

Figure 4. Seedling quality index of *Zelkova serrata* at 1× fertilization (left) and 2× fertilization (right) across five biochars. Vertical bars represent one standard error of the mean (n = 5).

Figure 5. Chlorophyll content of *Zelkova serrata* at 1× fertilization (left) and 2× fertilization (right) across five biochars. Vertical bars represent one standard error of the mean (n = 5).
water-holding capacity, reduce bulk density, and provide additional cation exchange sites can potentially improve seedling production conditions in small volume containers (Landis et al. 1990).

Conclusion
Biochar made from two wood chips and rice husk can improve soil quality and tree growth in a nursery system. This usage could increase economic benefits for forest managers by converting low-value biomaterials into locally available, environmentally-friendly products. This study found that wood chips and rice husk biochar are excellent amendments in a nursery production system, which can directly improve economic returns in tree seedling production.

Acknowledgments
We thank Youngtak Ko and Garam Lee for managing the greenhouse work, and Tom J. Kim for his help to improve the manuscript.

Disclosure statement
No potential conflict of interest was reported by the authors.

Funding
This project was partially carried out with support by the Research Fund of Chungnam National University.

References
Ali M, Horisuchi T, Miyagawa S. 1998. Effects of soil amendment with crab shell on the growth and nodulation of soybean plants (Glycine max Merr.). Plant Prod Sci. 1:119–125.
Bayala J, Dianda M, Wilson J, Ouedraogo S, Sanon K. 2009. Predicting field performance of five irrigated tree species using seedling quality assessment in Burkina Faso, West Africa. New Forest. 38:309–322.
Chan KY, Xu Z. 2009. Biochar: nutrient properties and their enhancement. In: Lehmann J, Joseph S, editors. Biochar for environmental management: science and technology. Abingdon: Earthscan; p. 67–84.
Cho MS. 2015. Effects of growing density and cavity volume of container on growth performances and physiological characteristics of major temperate broad-leaved tree species in nursery and plantation stage [dissertation]. Daejeon, Republic of Korea: Chungnam National University.
Deans JD, Mason WL, Cannell MGR, Sharpe AL. 1989. Growing regimes for bare-root stock of sitka spruce, Douglas fir and scots pine. 1. Morphology at the end of the nursery phase. Forestry. 62:53–60.
Enders A, Hanley K, Whitman T, Joseph S, Lehmann J. 2012. Characterization of biochars to evaluate recalcitrance and agronomic performance. Bioresource Technol. 114:644–653.
Jindo K, Mizumoto H, Sawada Y, Sanchez-Monedero MA, Sonoki T. 2014. Physical and chemical characterization of biochars derived from different agricultural residues. Biogeoosciences. 11:6613–6621.
Johannes L, Stephen J. 2009. Biochar for environmental management: an introduction. In: Biochar for environmental management: science and technology. UK: Earthscan.
Joseph SD, Camps-Arbestain M, Lin Y, Munroe P, Chia CH, Hook J, van Zwieten L, Kimber S, Cowie A, Singh BP et al., 2010. An investigation into the reactions of biochar in soil. Aust J Soil Res. 48:501–515.
Jung WJ, Jo GH, Kuk JH, Kim KY, Park RD. 2005. Denitrification of crab shells by chemical and biological treatments. Biotechnol Bioproc E. 10:67–72.
Kalderis D, Kotti MS, Méndez A, Gascó G. 2014. Characterization of hydrochars produced by hydrothermal carbonization of rice husk. Solid Earth. 5:477–483.
Lancaster JD. 1980. Mississippi soil test method and interpretation. Mississippi Agricultural Experiment Station Mimeograph.
Landis TD, Tinus RW, McDonald SE, Barnett JP. 1990. Containers and growing media. In: The container tree nursery manual, vol. 2. Washington (DC): USDA Forest Service; Agriculture handbook, p. 674.
Lauter DJ, Munns DN, Clarkin KL. 1981. Salt response of chickpea as influenced by N supply. Agron J. 73:961–966.
Lee CG, Kang SG. 2015. A study on fuel characteristics of mixtures using torrefied wood powder and waste activated carbon. J Korean Wood Sci Wood Technol. 43:135–143.
Lehmann J. 2007. A handful of carbon. Nature. 447:143–144.
Lehmann J, Da Silva Jr JP, Steiner C, Nehls T, Zech W, Glaser B. 2003. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. Plant Soil. 249:343–357.
Lei O, Zhang R. 2013. Effects of biochars derived from different feedstocks and pyrolysis temperatures on soil physical and hydraulic properties. J Soil Sediment. 13:1561–1572.
McElligott K, Dumroese D, Coleman M. 2011. Bioenergy production system application in forest: potential for renewable energy, soil enhancement, and carbon sequestration. Res. Note RMRS-BN-46. Fort Collins (CO): U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station; 14p.
Mukherjee A, Zimmerman AR. 2015. Organic carbon and nutrient release from a range of laboratory-produced biochars and biochar soil mixtures. Geoderma. 193:122–130.
Mukome FND, Zhang X, Silva LCR. Six J, Parikh SJ. 2013. Use of chemical and physical characteristics to investigate trends in biochar feedstocks. J Agr Food Chem. 61:2196–2204.
Novak JM, Busscher WJ, Laird DL, Ahmeda M, Watts DW, Niandou MAS. 2009. Impact of biochar amendment on fertility of a southeastern coastal plain soil. Soil Sci. 174:105–112.
Park BB, Park GE, Bae K. 2015. Diagnosis of plant nutrient and growth responses on fertilization with vector analysis and morphological index. Forest Sci Technol. 111:1–10.
Robertson SJ, Rutherford PM, L. López-Gutiérrez JC, Massicotte HB. 2012. Biochar enhances seedling growth and alters root symbioses and properties of sub-boreal forest soils. Can J Soil Sci. 92:329–340.
Singh BP, Cowie AL, Smernik RJ. 2012. Biochar carbon stability in a clayey soil as a function of feedstock and pyrolysis temperature. Environ Sci Technol. 46:11770–11778.
Sowa MT, Savadogo P, Oden PC. 2012. Facilitation of forest landscape restoration on abandoned swidden fallows in Laos using mixed-species planting and biochar application. Silva Fenn. 46:39–51.
Sokas KA, Cantrell BK, Novak JM, Archer DW, Ippolito JA, Collins HP. 2012. Biochar: a synthesis of its agronomic impact beyond carbon sequestration. J Environ Qual. 41:973–989.
Wang X, Xing B. 2007. Importance of structural makeup of biopolymers for organic contaminant sorption. Environ Sci Technol. 41:3559–3565.
Wardle DA, Zackrisson O, Nilsson MC. 1998. The charcoal effect in boreal forests: mechanisms and ecological consequences. Oecologia. 115:419–426.
Zhang A, Bian R, Pan G, Cui L, Hussain Q, Li L, Zheng J, Zheng J, Zhang X, Han X, Yu X. 2012. Effects of biochar amendment on soil quality, crop yield and greenhouse gas emission in a Chinese rice paddy: a field study of 2 consecutive rice growing cycles. Field Crop Res. 127:153–160.