Effect of Biochar Amendments on Peach Replant Disease

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Abstract. The use of biochar as a soil amendment has generated interest all over the world, and it has been advocated as a means to improve soil fertility and sequester carbon. The objective of this study was to test if the use of pinewood biochar could reduce the detrimental effects of replant disease (RD) on peach tree growth and biomass production. An RD-susceptible peach rootstock, Lovell, was grown in soil from a peach replant site (control), sterilized soil (sterilized), and biochar-amended soil at 10% and 20% (v/v) [low biochar (LB) and high biochar (HB), respectively], all from the same site. Trunk diameter increase was measured weekly; total aboveground and belowground biomass was determined by harvesting a subsample of plants at 11, 22, and 33 weeks after planting. Soil samples, and foliar and root tissue samples were collected before each harvesting date and analyzed for nutrient content. Total aboveground and belowground biomass production was significantly higher in the biochar and sterilized soil treatment (S) compared with the control. Root carbon (C*) content was significantly greater in the HB treatment compared with the control. Soil nitrate-N was significantly greater in the HB treatment by the third harvesting date, and foliar magnesium (Mg) concentrations were significantly higher in both biochar treatments for all harvesting dates. The results from this study provide evidence that biochar may alleviate RD in peach trees.

Biochar is the carbon-rich solid coproduct of biomass pyrolysis, which has the potential to sequester carbon while improving crop yields and other ecosystem services when used as soil amendments (Lehmann, 2007b). It is produced from plant residue, manure, wood chips, and other wastes at high temperature and in the absence of oxygen. It is characterized by stable aromatic carbon structures, low oxygen and hydrogen-to-carbon ratios, low bulk density, moderate cation exchange capacity, high pH, and surface area (Lehmann, 2007a; Thies and Rillig, 2009). Studies have shown that soil amendments with biochar have improved soil fertility, as a result of an increase in pH of acid soils (Zwieten et al., 2010), or increase in nutrient retention as a result of cation adsorption (Liang et al., 2006). Biochar has reportedly changed soil biological properties and altered microbial community composition and abundance (Grossman et al., 2010; Liang et al., 2010; O'Neill et al., 2009). Changes in abundance of microorganisms in biochar-amended soil can be explained, in part, by the strong absorptive capacity of biochar toward organic compounds (Braida et al., 2003; Zhu and Pignatello, 2005), such

as allelopathic toxins, found in some replant soils (Patrick, 1955; Zhang et al., 2007).

Biochar additions to soil has shown to affect the severity of soilborne diseases in multiple crops (Elmer and Pignatello, 2011; Graber et al., 2014; Jaiswal et al., 2014a; Jaiswal et al., 2014b; Matsubara et al., 2002; Nerome et al., 2005; Zwart and Kim, 2012), suggesting that biochar could induce a systemic resistance response to pathogens in the soil, as well as pathogens confined to aboveground parts of plants (Elad et al., 2010; Harel et al., 2012; Zwart and Kim, 2012). Induced resistance (IR) is defined as a physiological state where the plant's defensive capacity against pathogens and pests is enhanced on exposure to biotic or abiotic stimuli (Vallad and Goodman, 2004). Two forms of IR have been described in plants: systemic acquired resistance (SAR) and induced systemic resistance (ISR). SAR can be triggered by chemical and biological elicitors, and is mediated by the phytohormone salicylic acid, and involves the synthesis of pathogenesis-related proteins (Durrant and Dong, 2004). ISR is triggered by plant growth promoting rhizobacteria and fungi on pathogen attack, and it depends on the phytohormones ethylene and jasmonic acid (Van Loon et al., 1998; Van der Ent et al., 2009). Systemic IR responses mediated by biochar could be the result of either or both chemical and biological factors, as biochars could themselves be the source of chemical inducer and/or they could alter the plant growth

promoting rhizobacteria and fungi community in the rhizosphere (Graber et al., 2014).

RD is a soilborne disease that affects young trees planted in sites where the same or closely related species were previously planted. RD of pome and stone fruits has been reported in all major fruit-growing regions in the world (Braun, 1991; Browne et al., 2006; Édin et al., 2004; Fan et al., 2008; Kandula et al., 2010; Mai and Abawi, 1981; Manici et al., 2003) and annual losses are estimated to be 10% to 20% in California (McKenry, 1999) and nearly \$100,000 (US) per hectare over a 10-year period in Washington State (Smith, 1995). Symptoms of RD, usually expressed shortly after planting, consist of stunted aboveground growth, dramatic reduction in aboveground and belowground biomass, and subsequent reduction in yield and orchard production life. Among factors implicated in RD etiology are soil pathogens including a variety of bacteria, fungi, oomycetes, and nematodes (Manici et al., 2003; Mazzola, 1998; Mazzola and Manici, 2012; Tewoldemedhin et al., 2011), as well as abiotic factors such as soil nutrient depletion, degradation of soil structure, and phytotoxicity from allelopathic toxins in plant roots (Browne et al., 2006; Hofmann et al., 2009; Zhang et al., 2007). As causes of RD are complex, and may differ from site to site (Mai and Abawi, 1981; Mazzola and Manici, 2012), there is no consistent single method to manage this problem (Merwin et al., 2001). The use of RD-tolerant rootstocks has become a valuable alternative for apple growers (Auvil et al., 2011; Isutsa and Merwin, 2000; Robinson et al., 2006); however, research on RD-tolerant rootstocks for stone fruits is ongoing and has yet to provide effective resistance to RD. Conventional management strategies have relied on broad-spectrum fumigants such as methyl bromide. However, with the global phaseout of this fumigant, and the lack of similarly effective alternatives to control RD in conventional and organic stone fruit production systems, there is an urgent need to find environmentally sound and sustainable solutions to RD.

This study investigates the effect of biochar on peach tree growth; biomass production and nutritional status under replant conditions. To our knowledge, this study is the first to look at the effect of biochar on peach RD.

Materials and Methods

Soil preparation. Soil was collected from the Western Colorado Orchard Mesa Research Station orchard in Grand Junction, CO. All soil samples were collected from the tree row of a recently removed peach orchard block at a sampling depth of 25 cm. The soil was a Turley clay loam (slope 0% to 2%, well drained, 10% calcium carbonate, 4% gypsum, nonsaline 0–0.2 mmhos/cm), derived from sandstone and shale. Soil was sieved through a 4-mm mesh and mixed with silica sand (effective size 1.1–1.15 mm) 1:1 (v/v) in a cement mixer to ensure adequate

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drainage and aeration in the growing containers. A portion of the soil mixture was used in the control (C) treatment, and another portion was autoclaved at 120 °C for 45 min, to suppress soil pathogen populations, and then used in the S treatment. Biochar used in this experiment was produced with pyrolysis of pinewood at 500–700 °C under anaerobic conditions by The Biochar Company (Berwyn, PA). The chemical and physical characteristics of the biochar are listed in Table 1. Biochar was mixed at 10% and 20% (v/v) with the soil mixture for the LB and HB treatments, respectively, equivalent to an application of 16 Mg·ha⁻¹ and 32 Mg·ha⁻¹ to the top 5 cm of soil. Soil mixtures were placed in 18.9-L containers.

Plant material. Rootstock liners of ‘Lovell’ were used because of their clear response to peach RD. Rootstocks were obtained from a commercial nursery in California. All rootstock liners were rated based on number and size of roots, and distributed evenly among treatments. Individual rootstocks were planted in 18.9-L containers and placed in a glass greenhouse with temperature ranging from 15 °C at night to 27 °C during daytime. Plants were irrigated as needed and fertilized twice a month with 200 mL of complete nutrient solution at a concentration of 5 g·L⁻¹ (30N–10P–10K) (Miracle Grow, Scotts Company, Marysville, OH) starting 2 weeks after planting. There were a total of 108 plants, with 27 replicates per soil treatment. For each treatment, plants were assigned randomly to three subsets for sequential destructive harvest at 11, 22, and 33 weeks after planting.

Plant growth measurements. To determine plant growth rate, the diameter of the main stem was measured at 12 cm above the soil surface weekly starting the day of planting. Total aboveground biomass and total root biomass were determined by harvesting a subset of plants (*n* = 9) per treatment at 11, 22, and 33 weeks after planting. Roots were washed free of adhering soil, and cleaned roots were placed in individual paper bags, dried for 2 d at 60 °C and weighed for dry biomass.

Leaf and root nutrient content. To determine plant foliar nutrient content, matured leaves were sampled a week before each destructive harvest date. Samples were sent to A&L Western Agriculture Laboratories (Modesto, CA) for a standard foliar plant analysis. A subsample of first- and second-order roots was collected during each destructive harvest, dried for 2 d at 60 °C and analyzed for total carbon (C*) and total nitrogen (N) by Dumas combustion methods (Sweeney, 1989).

Soil nutrient availability. Soil samples were collected before each destructive harvest date by compositing core samples taken from the full depth of soil in each container of plants scheduled for harvest. Samples were sent to A&L Western Agriculture Laboratories and analyzed for plant available nutrients.

Data analysis. A repeated measurement model (JMP, Version Pro 11; SAS Institute

Inc., Cary, NC) was used to analyze growth rate data from week to week. Biomass data, tissue, and soil nutrient content were analyzed as a one-way analysis of variance (ANOVA) due to significant interaction between treatments and harvest dates. When significant effects were indicated, means were compared using Tukey’s honestly significant difference (HSD) at *P* < 0.05.

Results

Plant growth and biomass production. Cumulative increase in stem diameter was significantly higher (Fig. 1, *P* < 0.001) in sterilized soil, followed by both biochar treatments and control. Total belowground biomass production did not differ among treatments for the first harvest (*P* = 0.215, Fig. 2), but was significantly higher for the HB treatments in comparison with control in

the second harvest; the control treatment produced significantly less (*P* < 0.001) belowground biomass than all the other treatments at the third harvest date. Aboveground

Table 1. Chemical and physical characteristics of the biochar applied.

	Wet basis	Dry basis
Moisture (%)	49.2	—
Organic C (%)	36.6	71.9
Inorganic C (%)	0.25	0.5
Total N (%)	0.3	0.6
Nitrate-N (mg·kg ⁻¹)	2.3	4.5
Total P (%)	0.19	0.38
Available P (mg·kg ⁻¹)	14	28
Total K (%)	0.39	0.79
Electric conductivity (dS·m ⁻¹)	0.69	—
pH (H ₂ O)	9.4	—
Bulk density (g·cm ⁻³)	0.64	0.32

Fig. 1. Cumulative increase in peach diameter (mm) from 0 to 33 weeks after planting under control (C), sterilized (S), low biochar (LB), and high biochar (HB) treatments. Data were analyzed using a repeated measurement model accounting for the overall effect of treatments throughout the 33 weeks of the study. Letters of mean separation were generated from Tukey’s honestly significant difference (HSD) test at *P* ≤ 0.05.

Fig. 2. Belowground biomass (g) production of 1-year-old peach rootstocks at 11, 22, and 33 weeks after planting under sterilized soil (S), control replant soil (C), and high biochar (HB) and low biochar (LB) treatments.

biomass production followed a pattern similar to belowground biomass production, with no significant differences among treatments during the first harvest ($P = 0.166$, Fig. 3). During the second harvest, aboveground biomass was significantly higher ($P = 0.007$) in the HB and S treatments, and by the third harvest the control treatment presented the

least aboveground biomass production ($P < 0.001$).

Root nutrient content. Roots in the HB treatments had significantly higher carbon (C*) concentration ($P = 0.008$, Fig. 4A) than roots from the control treatment plants, but were not statistically different from LB and S treatments. There were no differences

($P = 0.923$, Fig. 4B) among treatments with respect to root N content.

Foliar nutrient content. The N concentrations in foliar samples were lower in both biochar treatments than in the control treatment (Table 2), although not significantly different in C vs. LB during the first harvest date. Phosphorus (P) concentration was higher in the biochar treatments at the first and second harvest. Potassium (K) was significantly higher in HB treatment during the first and second harvest, but there were no significant differences at the third harvest. Magnesium was significantly higher in the biochar treatments for all three harvest dates. Micronutrients boron (B) and zinc (Zn) presented lower concentrations in the biochar treatments than in the control and S treatments.

Soil nutrient content. Nitrogen content in the HB treatment soil sample was significantly higher than S treatment for all the harvest dates (Table 3), and higher than in all other treatments at the third harvest date. No differences were observed for P and K in soil samples from the third harvest. Calcium (Ca) soil content was significantly higher in the control treatment than in the HB for the first and second harvest dates, but no differences were observed by the third harvest date. Micronutrient concentrations, with the exception of manganese (Mn), were significantly lower in HB soil compared with control and S treatments.

Discussion

This study showed that the growth of 'Lovell' peach rootstock in the biochar treatments and S treatment was significantly higher than the control (Figs. 1–3). Several studies have reported on the positive effects of biochar soil amendments on plant growth and productivity (Biederman and Harpole, 2013; Major et al., 2010), as well as on the severity of soilborne diseases (Elmer and Pignatello, 2011; Graber et al., 2014; Jaiswal et al., 2014a; Jaiswal et al., 2014b; Matsubara et al., 2002; Nerome et al., 2005; Zwart and Kim, 2012). Elmer and Pignatello (2011) observed an increase in root biomass production of asparagus established in replant soils treated with biochar, compared with a control. Similarly, Wang et al. (2014) reported that the application of biochar to replant soil improved the height and fresh weight of *Malus hupehensis* seedlings, as a result of a decrease in the concentration of phytotoxic phenolic compounds in the biochar treated soil. Detoxification of allelochemicals in replant soils through incorporation of biochar is likely due to the strong adsorptive capacity of biochar toward organic compounds (Zhu and Pignatello, 2005), rendering these allelopathic toxins ineffective in suppressing growth of nearby susceptible plants (Lehmann et al., 2011). Although soil phenolic compounds were not measured in this study, it has been reported that roots of peach trees produce phytotoxic metabolites affecting the reestablishment of

Fig. 3. Aboveground biomass (g) production of 1-year-old peach rootstocks at 11, 22, and 33 weeks after planting under sterilized soil (S), control replant soil (C), and high biochar (HB) and low biochar (LB) treatments.

Fig. 4. (A and B) Total carbon (%) and total nitrogen (%) of first- and second-order peach roots grown in sterilized soil (S), control replant soil (C), and high biochar (HB) and low biochar (LB) treatments. Total root C was significantly higher in the HB compared with C treatment ($P = 0.008$).

Table 2. Effects of biochar treatments on foliar nutrient concentration of peach trees under replant conditions. Data were analyzed using a one-way analysis of variance (ANOVA) model for each harvest date ($n = 9$ for all treatments at all harvests). When significant effect indicated among treatments, means were separated using Tukey's honestly significant difference (HSD) test [different letters indicate significant differences at $P \leq 0.05$ for control (C), sterilized soil (S), low biochar (LB) and high biochar (HB) treatments; NS = no significant difference].

Variable	First harvest				Second harvest				Third harvest			
	C	S	LB	HB	C	S	LB	HB	C	S	LB	HB
N (%)	4.2 ab	4.50 a	4.00 bc	3.90 c	4.30 a	4.10 ab	3.90 b	3.70 b	3.40 a	2.90 c	2.90 bc	3.10 b
P (%)	0.12 b	0.12 b	0.15 a	0.15 a	0.13 b	0.15 ab	0.15 ab	0.16 a	0.16 a	0.15 ab	0.15 ab	0.14 b
K (%)	2.40 b	2.50 b	3.20 a	3.40 a	3.08 c	2.90 d	3.25 b	3.73 a	3.00 NS	2.90	2.70	2.90
Ca (%)	1.87 NS	1.80	1.98	1.64	3.15 a	1.96 c	2.70 b	2.43 b	2.38 ab	2.05 b	2.64 a	2.37 ab
Mg (%)	0.54 b	0.53 b	0.80 a	0.83 a	0.66 c	0.50 d	0.77 b	0.90 a	0.52 b	0.50 b	0.6 a	0.70 a
Fe (ppm)	124.8 ab	117.3 a	60.3 ab	58.0 b	127.3 NS	119.8	133.3	111.3	106.5 ab	133.8 a	90.8 b	96.5 b
Mn (ppm)	62.8 NS	69.5	37.8	38.5	51.3 c	49.5 c	63.0 b	70.5 a	47.5 b	47.7 b	55.3 a	59.8 a
B (ppm)	32.3 b	35.0 a	28.8 c	25.0 d	34.5 b	39.0 a	31.8 bc	28.8 c	38.5 a	37.3 ab	33.8 bc	31.0 c
Zn (ppm)	36.5 a	43.5 a	18.0 b	21.8 b	34.5 a	31.0 ab	32.8 ab	24.3 b	28.0 a	26.0 ab	21.3 bc	21.5 c

Table 3. Effects of biochar treatments on soil nutrient concentration (ppm) of peach trees under replant conditions. Data were analyzed using a one-way analysis of variance (ANOVA) model for each harvest date ($n = 9$ for all treatments at all harvests). When significant effect indicated among treatments, means were separated using Tukey's honestly significant difference (HSD) test [different letters indicate significant differences at $P \leq 0.05$ for control (C), sterilized soil (S), and low biochar (LB) and high biochar (HB) treatments; NS = no significant difference].

Variable	First harvest				Second harvest				Third harvest			
	C	S	LB	HB	C	S	LB	HB	C	S	LB	HB
NO ₃ -N	157.3 ab	122.5 b	219.5 a	233.0 a	128.3 a	68.8 b	83.8 b	118.0 a	20.0 bc	16.3 c	26.3 b	58.8 a
P	45.3 NS	44.0	36.5	41.3	59.8 NS	70.0	106.0	76.0	70.8 NS	66.0	41.3	37.3
K	226.0 b	244.8 b	319.0 ab	360 a	368.5 a	360.0 a	321.8 ab	238.5 b	336.8 NS	313.8	383.3	343.8
Mg	172.8 b	171.3 b	235.5 a	282.8 a	149.3 NS	146.5	152.3	114.0	170.8 ab	224.5 a	150.5 ab	140.3 b
Ca	2,737 a	2,677 ab	2,355 bc	2,201 c	2,749 a	2,475 ab	2,443 ab	2,256 b	2,801 NS	2,770	2,756	2,525
Fe	4.5 ab	5.3 a	3.5 b	4.3 ab	5.8 c	6.3 bc	8.3 a	7.8 ab	8.3 a	8.3 a	5.5 ab	5.0 b
Zn	2.9 NS	1.9	1.3	1.0	1.9 c	2.2 ab	2.5 a	2.5 a	2.7 a	3.2 a	2.0 ab	1.4 b
Mn	2.3 NS	2.0	1.8	2.0	2.0 NS	1.8	2.0	2.0	2.0 a	1.3 b	1.3 b	2.0 a
B	0.7 ab	0.7 a	0.5 bc	0.4 c	0.9 NS	0.8	0.9	0.7	1.0 a	0.8 a	0.6 ab	0.5 b
pH	7.2 NS	7.2	7.4	7.3	7.3 NS	7.5	7.3	7.2	7.8 ab	7.9 a	7.8 ab	7.7 b

peach orchards (Proebsting and Gilmore, 1941), which could have been neutralized by the addition of biochar. However, even though abiotic factors such as phytotoxicity can aggravate replant symptoms, it is probably not the main cause of the RD at our study site, as demonstrated by the positive effect of soil sterilization on peach rootstock growth and biomass production (Figs. 1–3).

Yang et al. (2012) identified an extensive list of root-associated bacteria, fungi, and stramenopiles that correlated with peach RD symptoms. Biochar has been shown to alter soil biological community composition and abundance in various studies (Grossman et al., 2010; Kim et al., 2007; Lehmann et al., 2011; O'Neill et al., 2009), with implications for soil physical and chemical properties that can promote plant growth. Although there is no evidence that biochar would decrease the abundance of soil pathogens involved in RD, it has been shown that the addition of biochar positively affects the colonization of roots by beneficial microorganisms such as mycorrhizal fungi (LeCroy et al., 2013; Solaiman et al., 2010; Warnock et al., 2010). Warnock et al. (2007) argued that biochar could affect mycorrhizal colonization in plants by 1) altering soil chemical and physical properties, 2) favoring soil microbial populations that supports mycorrhizae, 3) sorption of signaling compounds or detoxification of allelochemicals that inhibit mycorrhizae colonization, and 4) protecting mycorrhizae from predators. In an asparagus replant study, Elmer and Pignatello (2011) reported that the addition of biochar, at similar rates to the

ones used in this study, significantly increased the colonization of roots by arbuscular mycorrhizal and resulted in increases in root weight and reductions in root lesions by pathogenic fungi. Likewise in our study, peach rootstock grown in replant soil amended with biochar had significantly higher root biomass production (Fig. 2). Even though there was no statistical differentiation between the HB and the S treatments at a significance level of $\alpha = 0.05$, root biomass of peach rootstock was significantly higher than the S treatment at $\alpha = 0.1$, which could be due to the beneficial effects of mycorrhizal colonization. In a study looking at apple root growth rates in relation to fungal colonization, Resendes et al. (2008) reported that the majority of new apple roots were colonized by either mycorrhizal or nonmycorrhizal fungi, but never colonized by both. This could be a result of mycorrhizal fungi selectively colonizing faster growing roots that receive more carbohydrates from the shoots, thus increasing the benefit to the mycorrhizal fungi (Resendes et al., 2008). If biochar promotes root colonization by mycorrhizal fungi, it could be expected that the treatments amended with biochar would have higher colonization of roots by mycorrhizal fungi, outcompeting pathogenic microorganisms found in replant soil, which could explain the positive effect on belowground biomass in the HB treatment in comparison with the S treatment. In fact, several studies (Elmer and Pignatello, 2011; Matsubara et al., 2010; Wacker et al., 1990) have reported that increased mycorrhizal colonization may act to

outcompete and suppress infection and disease in plants. It is also worth mentioning that C* content of roots in the HB treatment was greater than in the other treatments during the first 11 weeks after planting (Fig. 4), which could be attributed to greater colonization of mycorrhizal fungi in the faster growing roots that receive a greater fraction of carbohydrates from the shoots.

Recent studies have shown that biochar amendments can promote systemic resistance in certain pathosystems (Graber et al., 2014; Harel et al., 2012; Wacker et al., 1990). Induced systemic resistance is triggered by plant growth promoting rhizobacteria and fungi (Koike et al., 2003). If biochar increases root mycorrhizal colonization, it is possible that biochar additions are indirectly enhancing the plant's defensive capacity against soilborne pathogens present in replant soils. Mehari et al. (2015) reported that biochar-mediated root colonization by beneficial organisms plays an essential role in biochar-mediated induce resistance in tomato against gray mold. Biochar-mediated induce resistance has more than one mechanism of action, and studies in strawberries have reported that both chemical and biological factors are involved in the systemic responses of plants to biochar (Harel et al., 2012).

Although there were no strong trends on soil nutrient content, the HB treatment had significantly higher soil nitrate content during the last harvest (Table 3). In a soil relatively limited in available N, the higher retention of N associated with the biochar-amended treatments is consistent with other

studies (Güereña et al., 2013; Ventura et al., 2013). On the contrary, N concentrations in foliar tissue samples were consistently lower in the biochar treatments (Table 2), as reported by Elmer and Pignatello (2011); this may be due to the dilution effect of N in faster growing plant tissue, and not to differences in uptake of N among treatments (Jarrell and Beverly, 1981). Foliar contents of Mg and Mn were significantly higher in the biochar treatments (Table 2), which has also been reported by others (Elmer and Pignatello, 2011; Major et al., 2010; Wang et al., 2014). Research on asparagus has shown that increased levels of Mn are associated with disease suppression (Elmer, 1995, 2003). It is possible that these differences in nutrient content could have promoted a more disease-resistant plant in our study.

Conclusion

Based on the results of this study, application of biochar to replant soils may help protect peach trees from RD. Biochar-amended soils compared favorably with sterilized soils and had beneficial effects on aboveground and belowground biomass compared with an untreated control. However, before any recommendation on the use of biochar to suppress soilborne disease can be made, further research is needed, particularly on types and rates of biochar, and their interaction with different soil types, as well as large-scale studies under field conditions.

Literature Cited

- Auvil, T.D., T.R. Schmidt, I. Hanrahan, F. Castillo, J.R. McFerson, and G. Fazio. 2011. Evaluation of dwarfing rootstocks in Washington apple replant sites. *Acta Hort.* (ISHS) 903:265–271.
- Biederman, L.A. and W.S. Harpole. 2013. Biochar and its effects on plant productivity and nutrient cycling: A meta-analysis. *Glob. Change Biol. Bioenergy* 5:202–214.
- Brida, W.J., J.J. Pignatello, Y. Lu, P.I. Ravikovitch, A.V. Neimark, and B. Xing. 2003. Sorption hysteresis of benzene in charcoal particles. *Environ. Sci. Technol.* 37:409–417.
- Braun, P.G. 1991. The combination of *Cylindrocarpum lucidum* and *Pythium irregulare* as a possible cause of apple replant disease in Nova Scotia. *Can. J. Plant Pathol.* 13:291–297.
- Browne, G., J. Connell, and S. Schneider. 2006. Almond replant disease and its management with alternative pre-plant soil fumigation treatments and rootstocks. *Plant Dis.* 90:869–876.
- Durrant, W. and X. Dong. 2004. Systemic acquired resistance. *Annu. Rev. Phytopathol.* 42:185–209.
- Édin, M., P. Guigneault, C. Lavoisier, and C. Warot. 2004. Adaptation and renewal of apple orchards: How to replant successfully. *Infos-Citil.* 201:32–36.
- Elad, Y., D.R. David, Y.M. Harel, M. Borenshtein, H.B. Kalifa, A. Silber, and E.R. Graber. 2010. Induction of systemic resistance in plants by biochar, a soil-applied carbon sequestering agent. *Phytopathology* 100:913–921.
- Elmer, W.H. 1995. Association between Mn-reducing root bacteria and NaCl applications in suppression of Fusarium crown and root rot of asparagus. *Phytopathology* 85:1461–1467.
- Elmer, W.H. 2003. Local and systemic effects of NaCl on root composition, rhizobacteria, and Fusarium crown and root rot of asparagus. *Phytopathology* 93:186–192.
- Elmer, W.H. and J.J. Pignatello. 2011. Effect of biochar amendments on mycorrhizal associations and Fusarium crown and root rot of asparagus in replant soils. *Plant Dis.* 95:960–966.
- Fan, H., Z. Zhao, H. Liu, G. Zhao, X. Zhang, and Z. Zhang. 2008. Changes of soil nutrition in root zone and their effects on growth of the replanted apple. *Acta Hort. Sin.* 35:1727–1734.
- Graber, E.R., O. Frenkel, A.K. Jaiswal, and Y. Elad. 2014. How may biochar influence severity of diseases caused by soilborne pathogens? *Carbon Mgt.* 5:169–183.
- Grossman, J.M., B.E. O'Neill, S. Tsai, B. Liang, E. Neves, J. Lehmann, and J.E. Thies. 2010. Amazonian anthrosols support similar microbial communities that differ distinctly from those extant in adjacent, unmodified soils of the same mineralogy. *Microbiol. Ecol.* 60:192–205.
- Güereña, D., J. Lehmann, K. Hanley, A. Enders, C. Hyland, and S. Riha. 2013. Nitrogen dynamics following field application of biochar in a temperate North American maize-based production system. *Plant Soil* 365:239–254.
- Harel, Y.M., Y. Elad, D. Rav-David, M. Borenstein, R. Shulchani, B. Lew, and E.R. Graber. 2012. Biochar mediates systemic response of strawberry to foliar fungal pathogens. *Plant Soil* 357:245–257.
- Hofmann, A., L. Wittenmayer, G. Arnold, A. Schieber, and W. Merbach. 2009. Root exudation of phloridzin by apple seedlings (*Malus x domestica* Borkh.) with symptoms of apple replant disease. *J. Appl. Bot. Food Qual.* 82:193–198.
- Isutsa, D.K. and I.A. Merwin. 2000. Malus germplasm varies in resistance or tolerance to apple replant disease in a mixture of New York orchard soils. *HortScience* 35:262–268.
- Jaiswal, A.K., Y. Elad, E.R. Graber, and O. Frenkel. 2014a. Rhizoctonia solani suppression and plant growth promotion in cucumber as affected by biochar pyrolysis temperature, feedstock and concentration. *Soil Biol. Biochem.* 69:110–118.
- Jaiswal, A.K., O. Frenkel, Y. Elad, B. Lew, and E.R. Graber. 2014b. Non-monotonic influence of biochar dose on bean seedling growth and susceptibility to *Rhizoctonia solani*: The “Shifted Rmax-Effect.” *Plant Soil* 1–16.
- Jarrell, W. and R. Beverly. 1981. The dilution effect in plant nutrition studies. *Adv. Agron.* 34:197–224.
- Kandula, D.R.W., E.E. Jones, I.J. Horner, and A. Stewart. 2010. The effect of Trichoderma bio-inoculants on specific apple replant disease (SARD) symptoms in apple rootstocks in New Zealand. *Australas. Plant Pathol.* 39:312–318.
- Kim, J.-S., G. Sparovek, R.M. Longo, W.J. De Melo, and D. Crowley. 2007. Bacterial diversity of terra preta and pristine forest soil from the Western Amazon. *Soil Biol. Biochem.* 39:684–690.
- Koike, S., K. Subbarao, R.M. Davis, and T. Turini. 2003. Vegetable diseases caused by soilborne pathogens. UCANR (University of California Division of Agriculture and Natural Resources) Publications.
- LeCroy, C., C.A. Masiello, J.A. Rudgers, W.C. Hockaday, and J.J. Silberg. 2013. Nitrogen, biochar, and mycorrhizae: Alteration of the symbiosis and oxidation of the char surface. *Soil Biol. Biochem.* 58:248–254.
- Lehmann, J. 2007a. Bio-energy in the black. *Front. Ecol. Environ.* 5:381–387.
- Lehmann, J. 2007b. A handful of carbon. *Nature* 447:143–144.
- Lehmann, J., M.C. Rillig, J. Thies, C.A. Masiello, W.C. Hockaday, and D. Crowley. 2011. Biochar effects on soil biota—a review. *Biochar effects on soil biota—a review. Soil Biol. Biochem.* 43:1812–1836.
- Liang, B., J. Lehmann, D. Solomon, J. Kinyangi, J. Grossman, B. O'Neill, J.O. Skjemstad, J. Thies, F.J. Luizao, J. Petersen, and E.G. Neves. 2006. Black Carbon increases cation exchange capacity in soils. *Soil Sci. Soc. Amer. J.* 70:1719–1730.
- Liang, B.Q., J. Lehmann, S.P. Sohi, J.E. Thies, B. O'Neill, L. Trujillo, J. Gaunt, D. Solomon, J. Grossman, E.G. Neves, and F.J. Luizao. 2010. Black carbon affects the cycling of non-black carbon in soil. *Org. Geochem.* 41:206–213.
- Mai, W.F. and G.S. Abawi. 1981. Controlling replant diseases of pome and stone fruits in northeastern United States by preplant fumigation. *Plant Dis.* 65:859–864.
- Major, J., M. Rondon, D. Molina, S.J. Riha, and J. Lehmann. 2010. Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. *Plant Soil* 333:117–128.
- Manici, L.M., C. Ciavatta, M. Kelderer, and G. Erschbaumer. 2003. Replant problems in South Tyrol: Role of fungal pathogens and microbial population in conventional and organic apple orchards. *Plant Soil* 256:315–324.
- Matsubara, Y., N. Hasegawa, and H. Fukui. 2002. Incidence of fusarium root rot in asparagus [*Asparagus officinalis*] seedlings infected with arbuscular mycorrhizal fungus as affected by several soil amendments. *J. Jpn. Soc. Hort. Sci.* 71:370–374.
- Matsubara, Y., T. Okada, and A.S.M. Nahiyan. 2010. Tolerance to allelopathy and Fusarium disease, changes in antioxidant substance in mycorrhizal asparagus plants raised in decline soil. *Acta Hort.* (ISHS) 883:417–423.
- Mazzola, M. 1998. Elucidation of the microbial complex having a causal role in the development of apple replant disease in Washington. *Phytopathology* 88:930–938.
- Mazzola, M. and L.M. Manici. 2012. Apple replant disease: Role of microbial ecology in cause and control. *Annu. Rev. Phytopathol.* 50:45–65.
- McKenry, M. 1999. The replant problem and its management. Catalina Publishing, Fresno, CA.
- Mehari, Z., Y. Elad, D. Rav-David, E. Graber, and Y. Meller Harel. 2015. Induced systemic resistance in tomato (*Solanum lycopersicum*) against *Botrytis cinerea* by biochar amendment involves jasmonic acid signaling. Induced systemic resistance in tomato (*Solanum lycopersicum*) against *Botrytis cinerea* by biochar amendment involves jasmonic acid signaling. *Plant Soil* 1–14.
- Merwin, I.A., R. Byard, T.L. Robinson, S. Carpenter, S.A. Hoying, K.A. Iungerman, and M. Fargione. 2001. Developing an integrated program for diagnosis and control of replant problems in New York apple orchards. *N.Y. Fruit Qrtly.* 9:11–15.
- Nerome, M., K. Toyota, T. Islam, T. Nishijima, T. Matsuoka, K. Sato, and Y. Yamaguchi. 2005. Suppression of bacterial wilt of tomato by incorporation of municipal biowaste charcoal into soil. *Soil Microorganisms.* 59:9–14.
- O'Neill, B., J. Grossman, M.T. Tsai, J.E. Gomes, J. Lehmann, J. Peterson, E. Neves, and J.E. Thies. 2009. Bacterial community composition in Brazilian anthrosols and adjacent soils characterized using culturing and molecular identification. *Microbiol. Ecol.* 58:23–35.
- Patrick, Z.A. 1955. The peach replant problem in Ontario: II Toxic substance from microbial decomposition products of peach root residues. *Can. J. Bot.* 33:461–486.

- Proebsting, E.L. and A.E. Gilmore. 1941. The relation of peach root toxicity to re-establishment of peach orchards. *P. Amer. Soc. Hort. Sci.* 38:21–26.
- Resendes, M.L., D.R. Bryla, and D.M. Eissenstat. 2008. Early events in the life of apple roots: Variation in root growth rate is linked to mycorrhizal and nonmycorrhizal fungal colonization. *Plant Soil* 313:175–186.
- Robinson, T.L., G. Fazio, H.S. Aldwinckle, S.A. Hoying, and N. Russo. 2006. Field performance of Geneva® apple rootstocks in the Eastern USA. *Sodininkyste ir Darzininkyste* 25:181–191.
- Smith, T.G. 1995. Orchard update. *WSU Cooperative Extension Bulletin*, Pullman, WA.
- Solaiman, Z.M., P. Blackwell, L.K. Abbott, and P. Storer. 2010. Direct and residual effect of biochar application on mycorrhizal root colonisation, growth and nutrition of wheat. *Soil Res.* 48:546–554.
- Sweeney, R.A. 1989. Generic combustion method for determination of crude protein in feeds: Collaborative study. *J. Assoc. Offic. Anal. Chem.* 72:770–774.
- Tewoldemedhin, Y.T., M. Mazzola, I. Labuschagne, and A. McLeod. 2011. A multi-phasic approach reveals that apple replant disease is caused by multiple biological agents, with some agents acting synergistically. *Soil Biol. Biochem.* 43:1917–1927.
- Thies, J.E. and M.C. Rillig. 2009. Characteristics of biochar: Biological properties, p. 85–105. In: J. Lehmann and S. Joseph (eds.). *Biochar for environmental management: Science and technology*. Earthscan, Sterling, VA.
- Vallad, G.E. and R.M. Goodman. 2004. Systemic acquired resistance and induced systemic resistance in conventional agriculture. *Crop Sci.* 44:1920–1934.
- Van der Ent, S., S.C. Van Wees, and C.M. Pieterse. 2009. Jasmonate signaling in plant interactions with resistance-inducing beneficial microbes. *Phytochemistry* 70:1581–1588.
- Van Loon, L., P. Bakker, and C. Pieterse. 1998. Systemic resistance induced by rhizosphere bacteria. *Annu. Rev. Phytopathol.* 36:453–483.
- Ventura, M., G. Sorrenti, P. Panzacchi, E. George, and G. Tonon. 2013. Biochar reduces short-term nitrate leaching from a horizon in an apple orchard. *J. Environ. Qual.* 42:76–82.
- Wacker, T.L., G.R. Safir, and C.T. Stephens. 1990. Mycorrhizal fungi in relation to asparagus growth and Fusarium wilt. *Acta Hort. (ISHS)*. 271:417–422.
- Wang, Y., F. Pan, G. Wang, G. Zhang, Y. Wang, X. Chen, and Z. Mao. 2014. Effects of biochar on photosynthesis and antioxidative system of *Malus hupehensis* Rehd. seedlings under replant conditions. *Sci. Hort.* 175:9–15.
- Warnock, D.D., J. Lehmann, T.W. Kuyper, and M.C. Rillig. 2007. Mycorrhizal responses to biochar in soil—concepts and mechanisms. *Plant Soil* 300:9–20.
- Warnock, D.D., D.L. Mummey, B. McBride, J. Major, J. Lehmann, and M.C. Rillig. 2010. Influences of non-herbaceous biochar on arbuscular mycorrhizal fungal abundances in roots and soils: Results from growth-chamber and field experiments. *Appl. Soil Ecol.* 46:450–456.
- Yang, J.J., P.M. Ruegger, M.V. McKenry, J.O. Becker, and J. Borneman. 2012. Correlations between root-associated microorganisms and peach replant disease symptoms in a California soil. *PLoS One* 7:e46420.
- Zhang, J.H., Z.Q. Mao, L.Q. Wang, and H.R. Shu. 2007. Bioassay and identification of root exudates of three fruit tree species. *J. Integr. Plant Biol.* 49:257–261.
- Zhu, D. and J.J. Pignatello. 2005. Characterization of aromatic compound sorptive interactions with black carbon (charcoal) assisted by graphite as a model. *Environ. Sci. Technol.* 39:2033–2041.
- Zwart, D.C. and S.-H. Kim. 2012. Biochar amendment increases resistance to stem lesions caused by *Phytophthora* spp. in tree seedlings. *HortScience* 47:1736–1740.
- Zwieten, L.v., S. Kimber, S. Morris, K.Y. Chan, A. Downie, J. Rust, S. Joseph, and A. Cowie. 2010. Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. *Plant Soil* 327:235–246.