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Review article

THE EFFECT OF BIOCHAR ON PLANT DISEASES: WHAT SHOULD WE LEARN WHILE DESIGNING BIOCHAR SUBSTRATES?

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Abstract. The increasing demand for soilless substrates and rising environmental concerns about the use of non-renewable resources such as peat has led to the search for alternative constituents of growing mixtures for containerized plants. In this report we reviewed the works concerning biochar as constituent of growing media, targeting its influence on plant growth and plant disease. Biochar mostly has positive or neutral influences on plant growth compared with peat media when present in concentrations higher than 25% (v:v). However, studies of biochar influence on plant disease reveals that while lower concentrations (≤1%) of biochar often suppressed several diseases, higher concentrations (≥3%) were mostly ineffective or induced plant disease. For use as horticultural peat replacement, it is recommended that biochar feedstocks and concentrations be standardized and the potential effect of biochar on plant disease be considered, so that growers can rely on consistent and reproducible biochars for desired effects.

Keywords: *Clavibacter michiganensis*, damping-off, disease control, foliar pathogen, hormesis effect, organic amendments, plant nurseries, peat replacement, root rot, soilborne pathogens.

Introduction

Research and development into biochar, the application of charcoal to soil, has been increasing substantially over the last decade. The major driver of interest is biochar's longevity in the soil, with many biochar types having estimated half-lives of 100s to 1000s of years or more. This means that by adding biochar to soil, carbon that originated in the atmosphere as CO_2 can be sequestered, leading to a desirable carbon removal from the atmosphere. In addition to this benefit, an increasing number of studies point to positive influences of biochar addition to soil, such as increased cation exchange capacity in organic matter-poor soils (Silber *et al.* 2010; Cornelissen *et al.* 2013; Obia *et al.* 2015), increased nutrient and water retention in light soils (Glaser *et al.* 2002; Haider *et al.* 2016), improvement in pH of acidic soils (Yamato *et al.* 2006; Chan *et al.* 2007), enrichment in beneficial soil microorganisms (Kolb *et al.* 2009; Kolton *et al.* 2011), and reductions in greenhouse gas emissions (Kammann et al., this issue). Several pot and field trials have shown that adding different biochars to soils can enhance productivity and performance of crops such as wheat, maize, cucumber, bean, tomato, strawberry, and sweet pepper (Graber *et al.* 2010; Meller Harel *et al.* 2012; Cornelissen *et al.* 2013; Jaiswal *et al.* 2014; Jaiswal *et al.* 2015; De Tender *et al.* 2016), including when the biochar is used as a fertilizer carrier (Joseph *et al.* 2013) or has been previously loaded with nutrients e.g. by co-composting (Kammann *et al.* 2015). In contrast, a number

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of studies have shown no effect of biochar on crop yields (Jeffery *et al.* 2011; Ruysschaert *et al.* 2016), and some have also shown that biochar additions to soil can have unwanted effects on crop productivity, often due to tying up of nitrogen (Kammann *et al.* 2015; Haider *et al.* 2016), particularly in clay-rich fertile soils. Other works have pointed to biochar inactivation of soil-applied pesticides (Graber, Kookana 2015) and to soil contamination arising from biochar addition. Seeing that biochar has such a long half-life and that cannot be removed once it has been applied, it seems prudent to take small measured steps in its deployment, before widespread use.

A convenient "pre-soil" stage and research playground may be the addition of biochar to detached soilless growth media for partial peat replacement or peat-free growth media improvement. This idea has a number of advantages over the approach of widespread application to field soils, particularly in the initial stages:

1. Horticultural media can be used more easily as a model system for studying different aspects of biochar types and doses, including very general phenomena but also for fine tuning;
2. Horticultural crops are generally high return crops, which can justify investment in biochar more readily than extensive, low return field crops;
3. It is low risk and although not always strictly mimicking field studies, it still may assist us to detect some general phenomena and to outline the biochar positive borders. In addition, if there are any unexpected negative impacts of the added biochar on plant performance and health, no permanent damage to non-renewable soil resources has been done;
4. Usually, the culture turnover time is faster than the field and can comprise several cultures per year, speeding up the gain of knowledge and experience;
5. Economically successful implementation of biochar in horticultural detached media can have a positive impact on both industries;
6. The pyrolysis/biochar platform may be a welcome green solution for local nursery wastes;
7. Successful implementation of biochar in nursery media will encourage more extensive use of biochar in the future, and its benefits will be more easily quantified after gaining valuable experience in the nursery setting;
8. Peat deposits, which are non-renewable resources, are over-exploited. The growth media industry and various R&D initiatives have been trying to replace peat for a couple of decades, with limited success. Biochar as a partial peat replacement, or tool for improving the performance of peat-free alternative growth media, may help achieve this goal.

This last point, biochar as a potential peat replacement, has been examined in detail in a companion paper in this volume (Kern et al., this issue) and will not be examined here. The emphasis of the current communication is the effect of biochar additions to detached soilless media and the unrecognized influence it may have on plant susceptibility to diseases caused by plant pathogens, as plant protection is an economically very important aspect of modern horticulture.

1. Current state of the art

Biochar as a component of soilless substrates has been tested in several experimental systems; data are summarized in Table 1. Studies were conducted with various types of biochars, and several works involved combinations of biochar with other supplements such as mycorrhiza and fertilizers (Conversa *et al.* 2015), and humic acid products

Table 1. List of studies that involve biochar as a peat replacement in soilless media. Data include the range of concentrations in which biochar was found to be beneficial or non-harmful to plant growth are presented in the 2nd column. Concentrations at which negative effects on plant growth were detected are presented in the 3rd column

Crop	Beneficial impact (% biochar)	Negative impact (% biochar)	Reference
Blanket flower (*Gaillardia* spp.)	25	50	Dumroese *et al.* (2011)
Calathea (*Calathea insignis*)	20–35		Zhang *et al.* (2014)
Calathea (*Calathea rotundifola*)	50	>50	Tian *et al.* (2012)
Crown of Thorns (*Euphorbia x Lomi*)	15–60		Fascella (2015)
Horse-shoe pelargonium (*Pelargonium zonale*)	30	70	Conversa *et al.* (2015)
Kale (*Brassica oleracea L.* var. *acephala*)	1–5		Kim *et al.* (2016)
Lettuce (*Lactuca sativa*)	38–70		Mendez *et al.* (2015)
Lettuce (*L. sativa*)	50–75		Nieto *et al.* (2016)
Sunflower (*Helianthus annuus*)	25–75	100	Steiner and Harttung (2014)
Tomato (*Solanum lycopersicum*) & Marigold (*Tagetes erecta*)	5		Vaughn *et al.* (2013)

(Zhang *et al.* 2014). The studies tested elevated ratios of biochar: growth media (mostly peat) occasionally reaching very high biochar percentages (>60%) (Steiner, Harttung 2014; Mendez *et al.* 2015; Nieto *et al.* 2016). Analyses included chemical properties and various parameters of plant growth and other measurements such as chlorophyll (Fascella 2015). In most cases, biochar had a neutral or positive influence on plant growth compared with peat media when present in concentrations lower than 30% (v:v) (Dumroese *et al.* 2011; Conversa *et al.* 2015), and in some works even a much higher concentration was found to be not harmful (Fascella 2015; Mendez *et al.* 2015; Nieto *et al.* 2016). However, all of these studies focused on plant survival and several growth parameters, and did not consider the influence on plant diseases.

A positive influence of biochar on reducing plant diseases such as rust in wheat and mildew in other crops was first reported some 170 years ago (Allen 1847) and drew attention in the last decade where several pathosystems were studied by different groups worldwide (Elad *et al.* 2010; Elmer, Pignatello 2011; Jaiswal *et al.* 2014; Copley *et al.* 2015; Jaiswal *et al.* 2015). Pathosystems included both foliar pathogens and soil borne pathogens (Elad *et al.* 2011; Graber *et al.* 2014a). Lately, Bonanomi *et al.* (2015) reviewed and summarized the data from 13 pathosystems that tested the effect of biochar on plant disease. In their analysis, they reported that 85% of the studies showed a positive influence of biochar in reducing plant disease severity, 12% had no effect, and only 3% showed that biochar additions were conducive to plant disease. However, their analysis did not consider the fact that many of these studies revealed that plant susceptibility/resistance to disease was dependent on the crucial factor of the biochar dose.

In Table 2, we inspected the systems reviewed in Bonanomi *et al.* (2015) and additional newer studies. We summarized the data from 15 pathogens (fungi, oomycetes and nematodes) in 30 different pathosystems (i.e. plant/pathogen system). We then compared the effect of the highest tested biochar concentration on disease severity to the effect of the unamended control and also to the biochar concentration which had the most positive effect on disease suppression. The data show that for 60% of the pathogens and in 70% of the pathosystems, the highest tested biochar concentrations (ranging in most cases between 0.5 to 5%) had neutral to negative effects on plant disease, compared with the control or with the maximally effective biochar concentration, thus demonstrating the start of an inverted U-shaped biochar dose/response curve (that may also be described as negative quadratic relationship curve) in the majority of systems (Jaiswal *et al.* 2014, 2015). Moreover, several studies on biochar in detached growing media reported that while relatively low concentrations (≤1%) of biochar suppressed the diseases (Jaiswal *et al.* 2014, 2015; Huang *et al.* 2015), higher concentrations (3%) were mostly ineffective or even accelerated plant disease (Jaiswal *et al.* 2014, 2015; Copley *et al.* 2015; Huang *et al.* 2015). These studies currently encompass 12 different hosts and 5 different biochars including biochars with very different characters in terms of mineral content, alkalinity, and carbon content, suggesting that most, if not all, plant disease responses would eventually show such inverted U-shaped dose/response relationships if biochar dose would be further increased.

Interestingly, this effect was less obvious in foliar pathogens where only 2 out of 6 pathosystems (33%) demonstrated potential U-shaped relationships (Elad *et al.* 2010, 2011; Meller Harel *et al.* 2012) but was very common in the soilborne pathogen pathosystems (20 out of 24 pathosystems, 83%). As the experiments with the foliar pathogens showed milder susceptibility response (and for only one pathogen (B. cinerea)) and were not tested at concentrations relevant to partial peat replacements (>10%), a nursery tray experiment was conducted with the foliar bacterial pathogen *Clavibacter michiganesis* subsp *michiganesis*, the causal agent of bacterial canker of tomato plants. The following experiment was conducted twice: tomato seeds (Cv. *Fantasia*) were grown in a commercial nursery growing mixture with added biochar concentrations (0, 3, 6 and 18% w/w). Biochar was produced from greenhouse wastes of pepper plants (chemical and physical property of the biochar are described by Graber *et al.* (2014b)). Seedlings were grown under commercial condition with foliar fertigation. Twenty-one days after sowing, seedlings at the second leaf stage were transferred from the nursery to the laboratory and sprayed with 10^8/ml of the bacterial pathogen *C. michiganensis* and placed in 25 °C growth chambers. After 8 days, disease symptoms appeared as white blisters on the leaves and disease severity was evaluated as the number of blisters on each plant which has been shown to be a reliable disease severity assessment method (Frenkel *et al.* 2016). While no differences were detected in plant biomass, the disease symptoms in the unamended control was 8.6 lesions/plants, and were not significantly lower at 3% and 6% biochar (6.4 and 9.4 lesions/plant). However, the disease symptoms were significantly more severe at a higher biochar concentration of 18% when compared with the unamended control (15.1 *versus* 8.6 lesions/plants, respectively; Fig. 1). In this experiment, not only did the biochar have no positive effect at any tested concentration, but it had a negative effect at the highest one, demonstrating additional evidence for a U shape dose response for foliar pathogens and strengthening the point that high concentrations of biochar in growth media might be problematic also in the presence of a foliar pathogen.

Table 2. List of the studies that tested biochar in growth media on soilborne and foliar plant diseases. The last column gives the biochar concentration which exhibits negative influence on plant health compared with the control (no biochar) or compared with the biochar concentration having the most positive effect on disease suppression treatment, therefore representing the phenomena of the U-shape dose response

Pathogen	Host plant	Feedstock of biochar	Reference	Biochar % needs attention
Botrytis cinerea (F)[1]	*Lycopersicum esculatum*	Citrus wood (3, 5%) Eucalyptus wood (0.5, 1, 3%) Olive pomice (0.5, 1, 3%) Greenhouse waste (0.5, 1, 3%)	Elad *et al.* (2010) Elad *et al.* (2011) Mehari *et al.* (2015)	N[2] 3% N
	Capsicum annum	Greenhouse waste (0.5, 1, 3%)	Elad *et al.* (2010)	N
	Fragia x ananassa	Citrus wood, Greenhouse waste (3, 5%) Holm oak (1, 3%)	Meller Harel *et al.* (2012) De Tender *et al.* (2016)	N N
Colletotrichum acutatum (F)	*Fragia x ananassa*	Greenhouse (1, 3%)	Meller Harel *et al.* (2012)	N
Leveilulla taurica (F)	*C. annum*	Citrus wood (1, 3%)	Elad *et al.* (2010)	3%
Podosphora aphanis (F)	*Fragia x ananassa*	Citrus wood, Greenhouse waste (1, 3%)	Meller Harel *et al.* (2012)	N
Fusarium oxysporum f.sp asparagi (S)	*Asparagus sp.*	Commercial Quest biochar (0.5, 1.5, 3%)	Elmer and Pignatello (2011)	N
		Coconut charcoal (10, 30%)	Matsubara *et al.* (2002)	N
Fusarium oxysporum f.sp lycopersici (S)	*L. esculatum*	Wood & Green waste biochar (3% v/v)	Akhter *et al.* (2015) Akhter *et al.* (2016)	3% (v/v)[3]
Meloidogyne graminicola (Root knot nematodes; (S)	*Oryza sativa*	Oak wood (0.6, 1.2, 2.5, 5%)	Huang *et al.* (2015)	5%
Phytophthora cactorum (S)	*Acer rubrum*	Wood (0.5, 10, 20%)	Zwart and Kim (2012)	>5%
Phytophthora cinnanomi (S)	*Quercus rubra*	Wood (0.5, 10, 20%)	Zwart and Kim (2012)	>5%
Pythium ultimum (S)	*C. annum, Ocimum basilicum*	Spruce bark (50% v/v)	Gravel *et al.* (2013)	50% (v/v)
Plasmodiophora brassica (S)	*Brassica rapa*	Miscanthus (0.4, 0.8%)	Knox *et al.* (2015)	0.5%
Pratylenchus penetrans (root lesion nematodes; (S))	*Daucus carota*	Pine wood (0.8%) Pine bark (0.92) Wood (1.24%) Spelt husks (0.64%)	George *et al.* (2016)	0.8%
Ralstonia solanacearum (S)	*L. esculatum*	Municipal waste (0, 20%) Peanuts shells (2%)	Nerome *et al.* (2005) Lu *et al.* (2016)	N N
Replant disease (S)	*Prunus persica*	Wood 10, 20% (v/v)	Atucha and Litus (2015)	N
Rhizoctonia solani (S)	*Cucumis sativus* *Phaseolus vulgaris*	Greenhouse waste and Eucalyptus wood (0.5, 1, 3%)	Jaiswal *et al.* (2014) Jaiswal *et al.* (2015)	1% 3%
	Glycine max, Pisum sativum, Beta vulgaris, Medicago sativa, C. annum, L. esculatum, C. sativus, Raphanus sativus, D. carota, Allium ampeloprasum	Maple bark (1, 3, 5%)	Copley *et al.* (2015)	3%

[1] The letter F relates to foliar pathogens and the letter S to soil borne pathogens.
[2] The letter N represents studies where no significant negative effect was detected in any concentration compare with the control or with the biochar concentration with the most positive effect on disease control treatment.
[3] Concentration of biochar was determined as wt:wt unless otherwise stated as v:v.

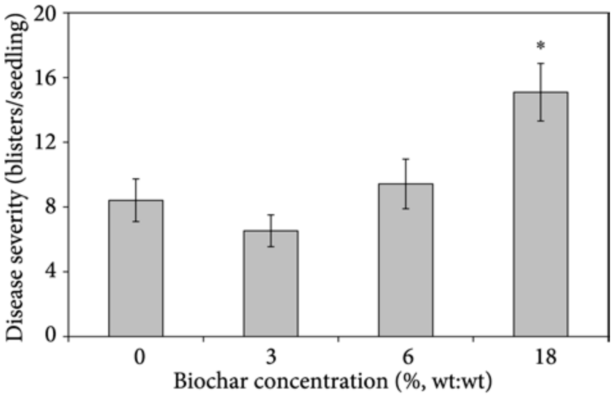

Fig. 1. The influence of increasing greenhouse waste biochar concentrations (w/w) on the disease severity caused by *Clavibacter michiganensis* subsp. *michiganensis* on tomato seedlings. Tomato cv. *Fantasia* was grown from seeds in commercial nursery. 17 days after sawing, seedlings were inoculated until runoff with 10^8 CFU/ml. Disease severities as white blisters on leaves were counted on each plant 8 days after inoculation. Vertical lines = Standard error. Asterisk represents treatment which is significantly different from the rest of the treatments by using Tukey HSD test (α = 0.05)

2. The shifted dose response between plant growth and disease response

Jaiswal *et al.* (2015) noted that not only is plant resistance to disease frequently biochar-concentration-dependent, but also that in many instances, an unwanted effect on plant growth and biomass occurred at relatively higher biochar doses (Rondon *et al.* 2007; Rajkovich *et al.* 2012; Spokas *et al.* 2012). Moreover, even when high biochar content has positive impacts on plant growth, there will be potentially irreversible damage if plant disease emerges and spreads. It has been noted that biochar dose-response curves for plant growth and plant disease are frequently shifted relative to each other along the biochar dose axis, with diseased plants being much more sensitive to higher biochar doses than healthy plants. Jaiswal *et al.* (2015) described this phenomenon while testing the impacts of biochars produced from greenhouse wastes and from eucalyptus wood chips on beans and cucumbers infected with the soilborne pathogen *R. solani*. In that study, biochar concentrations up to 3% by weight resulted in higher plant biomass in healthy plants, but in diseased plants, the biochar was beneficial only up to 1 wt %. Jaiswal *et al.* (2015) termed this phenomenon the "Shifted R_{max}–Effect", where R_{max} refers to the biochar dose at which there is a maximum growth response (G–R_{max}) and maximum disease reduction (D–R_{max}). This finding was later corroborated in additional reports. Akhter *et al.* (2015) described a similar phenomenon using 3% green waste biochar, wherein tomato root and shoot length were both increased in disease-free growing medium while the same biochar concentration was found to be conducive to diseases caused by the pathogen *F. oxysporum lycopersici*.

We postulate that the "Shifted R_{max}–Effect" underlies the reports (Viger *et al.* 2014) of positive effects of high biochar doses (4.2 and 8.4%) on Arabidopsis growth and concomitant down-regulation of defense-related genes. Viger *et al.* (2014) found that when *Arabidopsis thaliana* plants were subjected to increasing amounts of biochar mixed with soil, the leaf area, rosette diameter and root length were stimulated between 50 to 150 percent. By checking the response of more than 10,000 genes of *A. thaliana*, they suggested that up-regulation of genes involved in the brassinosteroids and auxin pathways, both known as growth-promoting hormones and signaling molecules, was a key to the growth stimulation observed in biochar treatments. However, the positive impacts of biochar were coupled with negative findings for a suite of genes that are known to determine the ability of a plant to withstand attack from pests and pathogens. These defense-related genes were consistently down-regulated following biochar application to the soil, including genes that regulate jasmonic acid, salicylic acid and ethylene pathways. The shifted R_{max} paradigm also could resolve apparent contradictions between Viger *et al.* (2014) and an earlier report by Meller Harel *et al.* (2012), which showed improved strawberry plant growth, decreased disease susceptibility, and up-regulation of defense-related genes in systems at relatively lower biochar doses (1 and 3 wt %; (Meller Harel *et al.* 2012).

These examples may all be related to wide range of materials that stimulate positive effects at low concentrations but cause toxicity and inhibition at higher doses (hormesis effect) (Jaiswal *et al.* 2014; Kammann, Graber 2015). As an example, low doses of an herbicide such as glyphosate might be used to beneficially modulate plant growth, development, or composition. At higher concentrations, glyphosate is a highly effective herbicide (Kortekamp 2011). Biochars can contain a plethora of small and large organic molecules that may individually or in combination have hormone-like or phytotoxic activities that are dose dependent. One example is the emission of ethylene from some biochars (Spokas *et al.* 2010). The plant hormone ethylene plays a significant role at low doses both as a plant growth promotor and in promoting plant defenses against various stressors. At higher concentrations, its influence on those aspects is negative (Kammann, Graber 2015). Different dose/response curves to ethylene concentrations for plant growth and plant defense could potentially be one of the mechanisms that explain the shifted R_{max} effect. The hormesis effect might also be related to macro and micro nutrients that are well known to influence disease severity along with plant growth, but are not necessarily correlated to the same positive ranges. The hormesis effect on plant disease is still widely unknown and needs to be further investigated. Hormesis might be caused by organic compounds that are abundant in some biochars, as a function of the biochar feedstock and preparation temperatures (Spokas *et al.* 2012). Some compounds may cause minor stresses at low concentrations and hence prime systemic resistance defenses, but at higher concentrations may be toxic or directly weaken the root and collar region of the plant. Such stresses and minor wounding may be the weak point that provides soil borne pathogens with favorable conditions to successfully attack and penetrate the mechanical defense layer of the root surface (Jaiswal *et al.* 2014, 2015). This possibility should be tested as one hypothesis for why foliar pathogens seem to be less sensitive to higher biochar concentrations than soilborne pathogens.

3. The challenge of the U shape effect: how to use biochar in soilless media

Considering the frequent U-shaped biochar dose/response curves, we suggest that caution should be taken before using biochar as an extensive peat replacement at high concentrations. We suggest that at the current stage, biochar be considered a supplemental additive at lower doses, where in many cases it improves plant performance against pathogens. This approach is at odds with the idea that biochar can make up a substantial proportion of the soilless media and serve to replace peat on a large scale.

While it is true that plant nurseries take strict sanitation and control measures and therefore disease risks may be considered low, there are several bacterial and fungal diseases that are highly problematic during the nursery stage, including *Xanthomonas campestris* (Krauthausen *et al.* 2011); *C. michiganesis* (Frenkel *et al.* 2016) and oomycetes pathogens such as *Pythium aphanidermatum* (Hendrix, Campbell 1973). Moreover, biochar positive or negative effects on plant responses may be long-lived, as suggested by Elmer and Pignatello (2011) and Elmer (2016), who reported a decrease in asparagus plant size in the second year of their experiment.

Moreover, as previously found (Jaiswal *et al.* 2014, 2015), different biochars have different optimum application rates for disease suppression. There is not yet any "one concentration fits all" paradigm that can be adopted for biochar application in soilless culture. This requires more studies of individual crop-pathogen-biochar systems. More importantly, it is essential to understand the mechanisms that are involved in disease suppression and promotion under biochar addition, in order to develop methods that will encompass a range of optimum application protocols. Some or all of the following mechanisms may be operating: i) induced resistance; ii) alteration of beneficial microbial communities; iii) nutrient content and supply; and iv) hormesis effects of biochar-derived phytohormones. In the meanwhile, care should be taken to standardize biochar feedstocks, production conditions, and concentrations, so that growers can rely on consistent and reproducible biochars for the desired effects.

Last, we believe that an additional approach should involve testing a range of treatments that might stretch the positive boundaries of biochar application in substrates. These means may include pre-treatment of biochar substrates with physical and biological enhancers and combining biochar with other growing media alternatives such as compost (Akhter *et al.* 2015; Kammann *et al.* 2015). The benefits of such combinations have yet to be shown in rigorous scientific studies and indeed provide a big challenge to the desired standardization process. This approach may also include addition of beneficial microorganisms: biological control agents and plant growth promoting bacteria. There are already several works which investigated the role of arbuscular mycorrhizal fungi combinations with biochar plant pathogens, and usually reported that biochar increased the density of arbusular mycorrhiza (Elmer, Pignatello 2011; Lecroy *et al.* 2013; Akhter *et al.* 2015) and plant growth promoting bacteria (Saxena *et al.* 2013). However, very few works have included biological control agents (Postma *et al.* 2013), such that additional known agents like *Trichoderma harzianum* and commercial bacillus strains can be tried. Another aspect worthy of research involves whether, in the presence of biochar, doses of fungicides and other pesticides in plant nurseries can be reduced. It may also be that damage caused by soil fauna such as nematodes may be reduced when biochar is added to the potting medium (George *et al.* 2016); this should be further explored.

Conclusions

In summary, biochar as a peat replacement in high concentrations may pose a hidden risk by weakening the plants' defenses or predisposing the roots to pathogen attack if applied in concentrations that are too high. Determining the safe limits of biochar concentrations in pathosystems that are common in nurseries and soilless culture systems may help stretch limits of beneficial (i.e., economically meaningful) biochar use in horticulture. Such benefits are needed if biochar is to have a role as partial peat replacement or as improver of peat-less alternative growth media.

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References

Akhter, A.; Hage-Ahmed, K.; Soja, G.; Steinkellner, S. 2015. Compost and biochar alter mycorrhization, tomato root exudation, and development of *Fusarium oxysporum* f. sp *lycopersici*, *Frontiers in Plant Science* 6: 529. https://doi.org/10.3389/fpls.2015.00529

Akhter, A.; Hage-Ahmed, K.; Soja, G.; Steinkellner, S. 2016. Potential of Fusarium wilt-inducing chlamydospores, in vitro behaviour in root exudates and physiology of tomato in biochar and compost amended soil, *Plant and Soil* 406: 425–440. https://doi.org/10.1007/s11104-016-2948-4

Allen, R. L. 1847. *A Brief Compend of American Agriculture*. 2nd ed. New York: C. M. Saxton. https://doi.org/10.5962/bhl.title.20151

Atucha, A.; Litus, G. 2015. Effect of Biochar Amendments Peach Replant Disease, *Hortscience* 50: 863–868.

Bonanomi, G.; Ippolito, F.; Scala, F. 2015. A "black" future for plant pathology? Biochar as a new soil amendment for controlling plant diseases, *Journal of Plant Pathology* 97: 223–234.

Chan, K. Y.; Van Zwieten, L.; Meszaros, I.; Downie, A.; Joseph, S. 2007. Agronomic values of greenwaste biochar as a soil amendment, *Australian Journal of Soil Research* 45: 629–634. https://doi.org/10.1071/SR07109

Conversa, G.; Bonasia, A.; Lazzizera, C.; Elia, A. 2015. Influence of biochar, mycorrhizal inoculation, and fertilizer rate on growth and flowering of Pelargonium (*Pelargonium zonale* L.) plants, *Frontiers in Plant Science* 6: 429. https://doi.org/10.3389/fpls.2015.00429

Copley, T. R.; Aliferis, K. A.; Jabaji, S. 2015. Maple bark biochar affects *Rhizoctonia solani* metabolism and increases damping-off severity, *Phytopathology* 105: 1334–1346. https://doi.org/10.1094/PHYTO-08-14-0231-R

Cornelissen, G.; Martinsen, V.; Shitumbanuma, V.; Alling, V.; Breedveld, G. D.; Rutherford, D. W.; Sparrevik, M.; Hale, S. E.; Obia, A.; Mulder, J. 2013. Biochar effect on maize yield and soil characteristics in five conservation farming sites in Zambia, *Agronomy* 3: 256–274. https://doi.org/10.3390/agronomy3020256

De Tender, C. A.; Debode, J.; Vandecasteele, B.; D'Hose, T.; Cremelie, P.; Haegeman, A.; Ruttink, T.; Dawyndt, P.; Maes, M. 2016. Biological, physicochemical and plant health responses in lettuce and strawberry in soil or peat amended with biochar, *Applied Soil Ecology* 107: 1–12. https://doi.org/10.1016/j.apsoil.2016.05.001

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. https://doi.org/10.1016/j.biombioe.2011.01.053

Elad, Y.; Cytryn, E.; Meller Harel, Y.; Lew, B.; Graber, E. R. 2011. The biochar effect: plant resistance to biotic stresses, *Phytopathologia Mediterranea* 50: 335–349.

Elad, Y.; David, D. R.; Meller Harel, Y.; Borenshtein, M.; Ben Kalifa, H.; Silber, A.; Graber, E. R. 2010. Induction of systemic resistance in plants by biochar, a soil-applied carbon sequestering agent, *Phytopathology* 100: 913–921. https://doi.org/10.1094/PHYTO-100-9-0913

Elmer, W. H.; Pignatello, J. J. 2011. Effect of biochar amendments on mycorrhizal associations and Fusarium crown and root rot of asparagus in replant soils, *Plant Disease* 95: 960–966. https://doi.org/10.1094/PDIS-10-10-0741

Elmer, W. H. 2016. Effect of leaf mold mulch, biochar, and earthworms on mycorrhizal colonization and yield of asparagus affected by Fusarium crown and root rot, *Plant Disease* 100: 2507–2512. https://doi.org/10.1094/PDIS-10-15-1196-RE

Fascella, G. 2015. Growing substrates alternative to peat for ornamental plants, in Md. Asaduzzaman (Eds.). *Soilless Culture-Use of Substrates for the Production of Quality Horticultural Crops*. InTech, 47–67.

Frenkel, O.; Bornestein, M.; Shulhani, R.; Sharabani, G.; Sofer, M.; Abo-Moch, F.; Lofthouse, M.; Manulis-Sasson, S.; Shtienberg, D. 2016. Secondary spread of *Clavibacter michiganensis* subsp. *michiganensis* in nurseries and the conditions leading to infection of tomato seedlings, *European Journal of Plant Pathology* 144: 569–579. https://doi.org/10.1007/s10658-015-0795-4

George, C.; Kohler, J.; Rillig, M. C. 2016. Biochars reduce infection rates of the root-lesion nematode Pratylenchus penetrans and associated biomass loss in carrot, *Soil Biology* & *Biochemistry* 95 11–18. https://doi.org/10.1016/j.soilbio.2015.12.003

Glaser, B.; Lehmann, J.; Zech, W. 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal – a review, *Biology and Fertility of Soils* 35: 219–230. https://doi.org/10.1007/s00374-002-0466-4

Graber, E. R.; Frenkel, O.; Jaiswal, A. K.; Elad, Y. 2014a. How may biochar influence severity of diseases caused by soilborne pathogens?, *Carbon Management* 5: 169–183. https://doi.org/10.1080/17583004.2014.913360

Graber, E. R.; Kookana, R. S. 2015. Biochar and retention/efficacy of pesticides, in J. Lehmann (Eds.). *Biochar for environmental management: science and technology*. London: Earthscan Books Ltd, 655–678.

Graber, E. R.; Meller Harel, Y.; Kolton, M.; Cytryn, E.; Silber, A.; David, D. R.; Tsechansky, L.; Borenshtein, M.; Elad, Y. 2010. Biochar impact on development and productivity of pepper and tomato grown in fertigated soilless media, *Plant and Soil* 337: 481–496. https://doi.org/10.1007/s11104-010-0544-6

Graber, E. R.; Tsechansky, L.; Lew, B.; Cohen, E. 2014b. Reducing capacity of water extracts of biochars and their solubilization of soil Mn and Fe, *European Journal of Soil Science* 65: 162–172. https://doi.org/10.1111/ejss.12071

Gravel, V.; Dorais, M.; Menard, C. 2013. Organic potted plants amended with biochar: its effect on growth and Pythium colonization, *Canadian Journal of Plant Science* 93: 1217–1227. https://doi.org/10.4141/cjps2013-315

Haider, G.; Steffens, D.; Müller, C.; Kammann, C. I. 2016. Standard extraction methods may underestimate nitrate stocks captured by field-aged biochar, *Journal of Environmental Quality* 45(4): 1196–1204. https://doi.org/10.2134/jeq2015.10.0529

Hendrix, F.; Campbell, W. 1973. Pythiums as plant pathogens, *Annual Review of Phytopathology* 11: 77–98. https://doi.org/10.1146/annurev.py.11.090173.000453

Huang, W. K.; Ji, H. L.; Gheysen, G.; Debode, J.; Kyndt, T. 2015. Biochar-amended potting medium reduces the susceptibility of rice to root-knot nematode infections, *BMC Plant Biology* 15: 267. https://doi.org/10.1186/s12870-015-0654-7

Jaiswal, A. K.; Elad, Y.; Graber, E. R.; Frenkel, O. 2014. Rhizoctonia solani suppression and plant growth promotion in cucumber as affected by biochar pyrolysis temperature, feedstock and concentration, *Soil Biology & Biochemistry* 69: 110–118. https://doi.org/10.1016/j.soilbio.2013.10.051

Jaiswal, A. K.; Frenkel, O.; Elad, Y.; Lew, B.; Graber, E. R. 2015. Non-monotonic influence of biochar dose on bean seedling growth and susceptibility to *Rhizoctonia solani*: the "Shifted Rmax-Effect", *Plant and Soil* 395: 1–16. https://doi.org/10.1007/s11104-014-2331-2

Jeffery, S.; Verheijen, F. G.; Van Der Velde, M.; Bastos, A. C. 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis, *Agriculture, Ecosystems & Environment* 144: 175–187. https://doi.org/10.1016/j.agee.2011.08.015

Joseph, S.; Graber, E. R.; Chia, C.; Munroe, P.; Donne, S.; Thomas, T.; Nielsen, S.; Marjo, C.; Rutlidge, H.; Pan, G. X.; Li, L.; Taylor, P.; Rawal, A.; Hook, J. 2013. Shifting paradigms: development of high-efficiency biochar fertilizers based on nano-structures and soluble components, *Carbon Management* 4: 323–343. https://doi.org/10.4155/cmt.13.23

Kammann, C.; Graber, E. R. 2015. Biochar effects on plant ecophysiology, in J. Lehmann, S. Joseph. *Biochar for environmental management: science and technology*. London: Earthscan Books Ltd, 391–419.

Kammann, C. I.; Schmidt, H. P.; Messerschmidt, N.; Linsel, S.; Steffens, D.; Muller, C.; Koyro, H. W.; Conte, P.; Stephen, J. 2015. Plant growth improvement mediated by nitrate capture in co-composted biochar, *Scientific Reports* 5: 12. https://doi.org/10.1038/srep11080

Kammann, C.; Ippolito, J.; Hagemann, N.; Borchard, N.; Cayuela, M. L.; Estavillo, J. M.; Fuertes-Mendizabal, T.; Jeffery, S.; Kern, J.; Novak, J.; Rasse, D.; Saarnio, S.; Schmidt, H. P.; Spokas, K.; Wrage-Mönnig, N. Biochar as a tool to reduce the agricultural greenhouse-gas burden – knowns, unknowns and future research needs, *Journal of Environmental Engineering and Landscape Management* (this issue).

Kern, J.; Tammeorg, P.; Shanskiy, M.; Sakrabani, R.; Knicker, H.; Kammann, C.; Tuhkanen, E.-M.; Smidt, G.; Prasad, M.; Tiilikkala, K.; Sohi, S.; Gascó, G.; Steiner, C.; Glaser, B. Synergistic use of peat and charred material in growing media – an option to reduce the pressure on peatlands?, *Journal of Environmental Engineering and Landscape Management* (this issue).

Kim, H. S.; Kim, K. R.; Yang, J. E.; Ok, Y. S.; Kim, W. I.; Kunhikrishnan, A.; Kim, K. H. 2016. Amelioration of horticultural growing media properties through rice hull biochar incorporation, *Waste and Biomass Valorization* 7(3): 1–10.

Knox, O. G. G.; Oghoro, C. O.; Burnett, F. J.; Fountaine, J. M. 2015. Biochar increases soil pH, but is as ineffective as liming at controlling clubroot, *Journal of Plant Pathology* 97: 149–152.

Kolb, S. E.; Fermanich, K. J.; Dornbush, M. E. 2009. Effect of charcoal quantity on microbial biomass and activity in temperate soils, *Soil Science Society of America Journal* 73: 1173–1181. https://doi.org/10.2136/sssaj2008.0232

Kolton, M.; Harel, Y. M.; Pasternak, Z.; Graber, E. R.; Elad, Y.; Cytryn, E. 2011. Impact of biochar application to soil on the root-associated bacterial community structure of fully developed greenhouse pepper plants, *Applied and Environmental Microbiology* 77: 4924–4930. https://doi.org/10.1128/AEM.00148-11

Kortekamp, A. 2011. *Unexpected side effects of herbicides: modulation of plant-pathogen interactions*. INTECH Open Access Publisher.

Krauthausen, H. J.; Laun, N.; Wohanka, W. 2011. Methods to reduce the spread of the black rot pathogen, Xanthomonas campestris pv. campestris, in brassica transplants, *Journal of Plant Diseases and Protection* 118: 7–16. https://doi.org/10.1007/BF03356375

Lecroy, C.; Masiello, C. A. Rudgers, J. A.; Hockaday, W. C.; Silberg, J. J. 2013. Nitrogen, biochar, and mycorrhizae: alteration of the symbiosis and oxidation of the char surface, *Soil Biology & Biochemistry* 58: 248–254. https://doi.org/10.1016/j.soilbio.2012.11.023

Lu, Y.; Rao, S.; Huang, F.; Cai, Y.; Wang, G.; Cai, K. 2016. Effects of biochar amendment on tomato bacterial wilt resistance and soil microbial amount and activity, *International Journal of Agronomy*. Article ID 2938282. https://doi.org/10.1155/2016/2938282

Matsubara, Y.; Hasegawa, N.; Fukui, H. 2002. Incidence of Fusarium root rot in asparagus seedlings infected with arbuscular mycorrhizal fungus as affected by several soil amendments, *Journal of the Japanese Society for Horticultural Science* 71: 370–374. https://doi.org/10.2503/jjshs.71.370

Mehari, Z. H.; Elad, Y.; Rav-David, D.; Graber, E. R.; Harel, Y. M. 2015. Induced systemic resistance in tomato (Solanum lycopersicum) against *Botrytis cinerea* by biochar amendment involves jasmonic acid signaling, *Plant and Soil* 395: 31–44. https://doi.org/10.1007/s11104-015-2445-1

Meller Harel, Y.; Elad, Y.; Rav-David, D.; Borenstein, M.; Shulchani, R.; Lew, B.; Graber, E. R. 2012. Biochar mediates systemic response of strawberry to foliar fungal pathogens, *Plant and Soil* 357: 245–257. https://doi.org/10.1007/s11104-012-1129-3

Mendez, A.; Paz-Ferreiro, J.; Gil, E.; Gasco, G. 2015. The effect of paper sludge and biochar addition on brown peat and coir based growing media properties, *Scientia Horticulturae* 193: 225–230. https://doi.org/10.1016/j.scienta.2015.07.032

Nerome, M.; Toyota, K.; Islam, T.; Nishijima, T.; Matsuoka, T.; Sato, K.; Yamaguchi, Y. 2005. Suppression of bacterial wilt of tomato by incorporation of municipal biowaste charcoal into soil, *Soil Microorganisms* 59: 9–14.

Nieto, A.; Gasco, G.; Paz-Ferreiro, J.; Fernandez, J. M.; Plaza, C.; Mendez, A. 2016. The effect of pruning waste and biochar addition on brown peat based growing media properties, *Scientia Horticulturae* 199: 142–148. https://doi.org/10.1016/j.scienta.2015.12.012

Obia, A.; Cornelissen, G.; Mulder, J.; Dorsch, P. 2015. Effect of soil pH increase by biochar on NO, N2O and N-2 production during denitrification in acid soils, *Plos One* 10 (9): e0138781. https://doi.org/10.1371/journal.pone.0138781

Postma, J.; Clematis, F.; Nijhuis, E. H.; Someus, E. 2013. Efficacy of four phosphate-mobilizing bacteria applied with an animal bone charcoal formulation in controlling *Pythium aphanidermatum* and *Fusarium oxysporum f.sp radicis lycopersici* in tomato, *Biological Control* 67: 284–291. https://doi.org/10.1016/j.biocontrol.2013.07.002

Rajkovich, S.; Enders, A.; Hanley, K.; Hyland, C.; Zimmerman, A. R.; Lehmann, J. 2012. Corn growth and nitrogen nutrition after additions of biochars with varying properties to a temperate soil, *Biology and Fertility of Soils* 48: 271–284. https://doi.org/10.1007/s00374-011-0624-7

Rondon, M. A.; Lehmann, J.; Ramirez, J.; Hurtado, M. 2007. Biological nitrogen fixation by common beans (*Phaseolus vulgaris L.*) increases with bio-char additions, *Biology and Fertility of Soils* 43: 669–708. https://doi.org/10.1007/s00374-006-0152-z

Ruysschaert, G.; Nelissen, V.; Postma, R.; Bruun, E.; O'toole, A.; Hammond, J.; Rödger, J. M.; Hylander, L.; Kihlberg, T.; Zwart, K.; Hauggaard-Nielsen, H.; Shackley, S. 2016. Field applications of pure biochar in the North Sea region and across Europe. *Biochar in European Soils and Agriculture.* Routledge, 99–135.

Saxena, J.; Rana, G.; Pandey, M. 2013. Impact of addition of biochar along with Bacillus sp. on growth and yield of French beans, *Scientia Horticulturae* 162: 351–356. https://doi.org/10.1016/j.scienta.2013.08.002

Silber, A.; Levkovitch, I.; Graber, E. R. 2010. pH-dependent mineral release and surface properties of cornstraw biochar: agronomic implications, *Environmental Science and Technology* 44: 9318–9323. https://doi.org/10.1021/es101283d

Spokas, K. A.; Baker, J. M.; Reicosky, D. C. 2010. Ethylene: potential key for biochar amendment impacts, *Plant and Soil* 333: 443–452. https://doi.org/10.1007/s11104-010-0359-5

Spokas, K. A.; Cantrell, K. B.; Novak, J. M.; Archer, D. W.; Ippolito, J. A.; Collins, H. P.; Boateng, A. A.; Lima, I. M.; Lamb, M. C.; Mcaloon, A. J.; Lentz, R. D.; Nichols, K. A. 2012. Biochar: a synthesis of its agronomic impact beyond carbon sequestration, *Journal of Environmental Quality* 41: 973–989. https://doi.org/10.2134/jeq2011.0069

Steiner, C.; Harttung, T. 2014. Biochar as a growing media additive and peat substitute, *Solid Earth* 5: 995–999. https://doi.org/10.5194/se-5-995-2014

Tian, Y.; Sun, X. Y.; Li, S. Y.; Wang, H. Y.; Wang, L. Z.; Cao, J. X.; Zhang, L. 2012. Biochar made from green waste as peat substitute in growth media for *Calathea rotundifola cv. Fasciata*, *Scientia Horticulturae* 143: 15–18. https://doi.org/10.1016/j.scienta.2012.05.018

Vaughn, S. F.; Kenar, J. A.; Thompson, A. R.; Peterson, S. C. 2013. Comparison of biochars derived from wood pellets and pelletized wheat straw as replacements for peat in potting substrates, *Industrial Crops and Products* 51: 437–443. https://doi.org/10.1016/j.indcrop.2013.10.010

Viger, M.; Hancock, R. D.; Miglietta, F.; Taylor, G. 2014. More plant growth but less plant defence? First global gene expression data for plants grown in soil amended with biochar, *GCB Bioenergy* 7: 658–672.

Yamato, M.; Okimori, Y.; Wibowo, I. F.; Anshori, S.; Ogawa, M. 2006. Effects of the application of charred bark of Acacia mangium on the yield of maize, cowpea and peanut, and soil chemical properties in South Sumatra, Indonesia, *Soil Science and Plant Nutrition* 52: 489–495. https://doi.org/10.1111/j.1747-0765.2006.00065.x

Zhang, L.; Sun, X. Y.; Tian, Y.; Gong, X. Q. 2014. Biochar and humic acid amendments improve the quality of composted green waste as a growth medium for the ornamental plant Calathea insignis, *Scientia Horticulturae* 176: 70–78. https://doi.org/10.1016/j.scienta.2014.06.021

Zwart, D. C.; Kim, S. H. 2012. Biochar amendment increases resistance to stem lesions caused by Phytophthora spp. in tree seedlings, *Hortscience* 47: 1736–1740.

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