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Biochar mitigates negative effects of salt additions on two herbaceous plant species

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ABSTRACT

Addition of pyrolyzed biomass ("biochar") to soils has commonly been shown to increase crop yields and alleviate plant stresses associated with drought and exposure to toxic materials. Here we investigate the ability of biochar (at two dosages: 5 and 50 t ha^{-1}) to mitigate salt-induced stress, simulating road salt additions in a factorial glasshouse experiment involving the broadleaved herbaceous plants *Abutilon theophrasti* and *Prunella vulgaris*. Salt additions of 30 g m^{-2} NaCl to unamended soils resulted in high mortality rates for both species. Biochar (*Fagus grandifolia* sawdust pyrolyzed at 378 °C), when applied at 50 t ha^{-1} as a top dressing, completely alleviated salt-induced mortality in *A. theophrasti* and prolonged survival of *P. vulgaris*. Surviving *A. theophrasti* plants that received both 50 t ha^{-1} biochar and salt addition treatments showed growth rates and physiological performance similar to plants without salt addition. Biochar treatments alone also substantially increased biomass of *P. vulgaris*, with a ~50% increase relative to untreated controls at both biochar dosages. Biochar did not significantly affect photosynthetic carbon gain (A_{max}), water use efficiency, or chlorophyll fluorescence (Fv/Fm) in either species. Our results indicate that biochar can ameliorate salt stress effects on plants through salt sorption, suggesting novel applications of biochar to mitigate effects of salinization in agricultural, urban, and contaminated soils.

1. Introduction

"Biochar" is the term given to pyrolyzed biomass (charcoal) when applied as a soil amendment intended to increase productivity or otherwise ameliorate soil properties (Lehmann et al., 2006). The potential of biochar to increase plant biomass and crop yields has been demonstrated in a number of tropical agricultural studies, with a recent meta-analysis of published studies finding that biochar treatments increased crop yields by an average of 10%, with larger effects observed on acidic and coarse-textured soils, and at high addition rates (Jeffery et al., 2011). It has also been demonstrated that increased crop yields over several years can result from a single biochar treatment (Major et al., 2010). Indeed, agricultural productivity is significantly enhanced in the "terra preta" soils of Brazil that were amended with charcoal more than 1000 years ago (Glaser et al., 2001).

Although detailed physiological mechanisms remain unclear (Atkinson et al., 2010), the properties accounting for favorable effects of biochars on productivity are thought to include high specific surface area, CEC, and, depending on pyrolysis conditions, microporosity (Thies and Rillig, 2009). In addition to enhancing water and nutrient retention in soils, these properties also enable biochars to adsorb a wide range of potentially toxic materials, including heavy metals (Beesley et al., 2010), pesticides (Kookana, 2010), and other contaminants (Rhodes et al., 2008; Beesley et al., 2010; Buss et al., 2011). The longevity of most biochars in the soil presents obvious advantages for bioremediation in comparison to other organic materials that break down more quickly (Bradshaw and Chadwick, 1980).

Mineral salts are an important plant stress factor, having adverse impacts on urban trees and road verges where salts are used for de-icing (Czerniawska-Kusza et al., 2004; Munck et al., 2010), on mine spoils, particularly in arid and semi-arid regions

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(Munns et al., 2006; Mendez and Maier, 2008), and in conditions of saltwater intrusion associated with land subsidence and rising sea levels (Williams et al., 1999). High soil salinity, and/or sodicity, affect an estimated 1.1 Gha, or more than 7% of the world's total land area (Wicke et al., 2011). Recent estimates indicate that salinization adversely affects approximately 30% of irrigated croplands (Chaves et al., 2009). Salinization reduces plant growth, thereby decreasing crop yields (Munns, 2002; Chaves and Oliveira, 2004; Chaves et al., 2009); especially severe growth inhibition is often observed in roadside vegetation (Davison, 1971).

The high capacity of activated charcoals to sorb a variety of salts has long been noted (Bartell and Miller, 1923), and charcoals have also been utilized in industrial desalination processes (e.g., Zou et al., 2008). However, the potential use of biochar as a soil amendment to mitigate salt-induced plant stress appears to have received essentially no prior research attention. In the present study we investigated the potential of biochar to mitigate salt impacts on plant performance, specifically in cases where salts are deposited on the soil surface as occurs with the use of de-icing salts. We employed a glasshouse experiment on two herbaceous plant species exposed to a factorial combination of biochar treatments and additions of commercial road salt. We hypothesized that biochar additions would improve plant performance overall, and that high biochar dosages in particular would ameliorate salt-related stress effects as indicated by plant survival, growth, and physiological performance.

Table 1
Physical and chemical properties of biochar used in experimental treatments. Means are given with standard deviations for 2–6 replicate measurements (where available).

Attribute	Value
Organic matter (%)	98.4 (0.05)
Ash (%)	1.6 (0.05)
Mineralized N (mg/g)	0.34 (0.43)
Extractable P (μg/g)	8.1 (0.37)
pH	6.18 (0.50)
Electrical conductivity (μS cm^{-1})	42.2 (6.2)
Cation exchange capacity (cmol kg^{-1})	16.2 (1.9)
Elemental composition	
C (%)	77.3
N (%)	0.163
S (%)	0.014
Ca (ppm)	2907
K (ppm)	3064
Mg (ppm)	565.8
P (ppm)	154.6
Particle size distribution	
<180 μm	3.6% (1.0)
180–250 μm	2.3% (0.6)
250–300 μm	1.4% (0.3)
300–500 μm	4.0% (0.9)
0.5–2.0 mm	39.3% (10.1)
2.0–2.8 mm	21.6% (1.0)
2.8–5.1 mm	24.5% (13.9)
>5.1 mm	3.4% (1.5)

2. Materials and methods

2.1. Growth conditions and experimental design

A glasshouse experiment was conducted at the University of Toronto, St. George Campus, using a completely randomized factorial design involving two plant species, *Abutilon theophrasti* Medik. (hereafter *Abutilon*) and *Prunella vulgaris* L. (hereafter *Prunella*), and two treatment factors: biochar and salt additions. The two plant species were selected for rapid growth and ease of cultivation; both are considered weedy invasive species in eastern North America. Seed of both species was germinated 3–4 weeks prior to the start of the experiment. *Abutilon* seed was obtained from Herbiseed Special Seeds (Twyford, UK); *Prunella* seed was germinated from the seed bank of upper soil horizons collected near the base camp of Haliburton Forest and Wildlife Reserve, Haliburton, Ontario, Canada (45°15′N, 78°34′W).

Biochar used in the experiment was generated using a batch pyrolysis system with feedstock consisting of 100% sawdust of American beech (*Fagus grandifolia*) harvested and processed at Haliburton Forest and Wildlife Reserve, Ltd. Low oxygen conditions were obtained in this system by flushing the pyrolysis reactor airspace with nitrogen gas. The system was run for ~3 h to completion of the pyrolysis reaction; the peak temperature obtained during pyrolysis was 378 °C. Biochar was air-dried, but not otherwise treated, following pyrolysis. Chemical and physical properties of biochar used are listed in Table 1. Moisture and ash content were determined following ASTM D1762-84 (ASTM, 2007). Gravimetric moisture content was obtained by drying biochar in a forced-air oven for 24 h at 105 °C. Samples were then placed in a muffle furnace at 500 °C for 4 h, cooled and weighed to obtain ash content. Mineralized N and extractable P were determined by K_2SO_4 extraction and colorimetric analysis using a flow injection analyzer. Biochar pH and EC were determined using a pH and conductivity electrode in a 1:1 by volume mixture of biochar and deionized water. Cation Exchange Capacity was determined using the ammonium acetate method (Chapman, 1965). The total P and cation data were obtained by way of a sulfuric acid digest (using Selenium dioxide as a catalyst) and analyzed by inductively-coupled plasma spectroscopy on a Spectro Genesis ICP-OES. C and N elemental analysis were run on an Elementar VarioMax and S on an Eltra Helios by combustion analysis. Determination of particle sizes by sieving followed ASTM D2862-97 (ASTM, 1999).

Three levels of biochar were applied in the study: 0 t ha^{-1} (untreated control), 5 t ha^{-1}, and 50 t ha^{-1}; the latter dosages correspond to low and moderately high addition rates used in prior agricultural studies (cf. Jeffery et al., 2011; Rajkovich et al., 2012). A commercial road salt (Sifto® Ice Salt) consisting of >99% NaCl and <1% impurities was used for salt addition treatments. The added salt treatment received 30 g m^{-2}, approximating single dosage exposures common in roadside environments where road salts are used (Davison, 1971; Booth et al., 2011). There were 5 replicate plants (1 plant/pot) per treatment: thus a total of 60 plants were used in the experiment (2 species × 6 treatments × 5 replicates). A commercial potting soil was used as the growth medium (Sunshine Professional Grow Mix #1: 70–80% sphagnum moss, perlite, dolomitic limestone, and gypsum), with a slow-release fertilizer (nutricote 16-10-10) added to approximate a nitrogen mineralization rate of 25 kg/ha over one growing season. Dosages for biochar, salt, and fertilizer were calculated relative to pot soil surface area (~200 cm^2/4-L pot). Biochar was added as a top-dressing: this application method has been used and is anticipated in the context of no-till agriculture, established perennial crops, natural vegetation, and forestry (Blackwell et al., 2009). Salt and fertilizer were added following the biochar applications, simulating soil surface deposition as would occur with road salts, salt spray, or soil-amendment-derived salts. Pots were allowed to drain freely; a layer of standard fiberglass window screening was placed at bottom of each pot to reduce soil particle loss.

Plants were grown for 63 days following soil amendment treatments, and were watered daily by a drip irrigation system to maintain soils near field capacity. Following final harvests, measurements of soil pH and electrical conductivity (EC) were made using a pH electrode and conductivity electrode in a 1:1 by volume mixture of the upper 2 cm of soil and deionized water. Similar measurements were made on biochar separated manually from soil.

2.2. Plant growth and physiological measurements

Plant survivorship, plant height (to the nearest cm), and estimated leaf area (cm^2) were recorded weekly throughout the experiment. Leaf area was calculated for each individual by measuring the length of every leaf to the nearest 1 cm, applying a species-specific allometric equation to estimate area/leaf, and summing these estimates across all leaves. The leaf area equation for *Abutilon* was that used in a previous study (Thomas et al., 1999): $A = 0.6519 \times L^{1.9523}$ (where A is leaf area in cm^2 and L is leaf length in cm). For *Prunella* we developed an equation using 30 harvested leaves (measuring leaf lamina length to the nearest 0.1 cm and leaf area to the nearest 0.01 cm^2 with a Licor LI-3000 leaf area meter). We compared equations of the form $A = a \times L^b$ and $A = a \times L^2$ fit using non-linear least squares, and selected the model with minimum AIC (using the nls (non-linear least squares) and AIC functions in R (R Core Team, 2012)). The resulting equation for *Prunella* was $A = 0.2398 \times L^2$ ($r^2_{adj} = 0.945$, $P < 0.0001$).

Physiological responses of *Abutilon* and *Prunella* to biochar and salt additions were examined through leaf-level gas-exchange and chlorophyll fluorescence parameters measured after 8 weeks of plant growth. Light-saturated photosynthetic rate (A_{max}), stomatal conductance (g_s), leaf transpiration (E) and leaf-level water-use efficiency (WUE) were measured between 8 and 11:00 AM local time using an LI-6400 Portable Photosynthesis system (Li-Cor, Lincoln, NE, USA). Triplicate measurements were made on the most recently developed fully-expanded leaf. A 6-cm^2 leaf cuvette was used; all surviving plants in the experiment were measured except those with leaf areas smaller than 6 cm^2. The system flow rate was set to 400 mmol/s, and CO_2 concentration of the sample set to 400 ppm; relative humidity in the chamber was kept at approximately 50%. A red light source (LiCor SI-355 red LED) with a photosynthetic photon flux density of 1000 μmol m^{-2} s^{-1} was used for measurements. Gas flux rates were monitored during measurements to ensure steady-state values prior to recording data. Chlorophyll fluorescence was measured on three leaves per plant for all surviving plants using a Walz miniPam fluorometer (Heinz Walz, Effeltrich, Germany). Plants were allowed to dark acclimate for >30 min at a light level <1 μmol m^{-2} s^{-1} of incident photosynthetically active radiation prior to measurements, and dark-adapted Fv/Fm (the ratio of variable to maximal fluorescence) was estimated using the saturation pulse method (Maxwell and Johnson, 2000).

At the end of the experimental growth period aboveground plant biomass was collected by cutting plants just above the root collar. Roots were then gently freed from soil particles, washed, and allowed to air-dry. Above- and belowground parts were then dried in a forced-air oven at 60 °C for 24 h prior to weighing. A count of reproductive parts (flower production in *Prunella*) was also made prior to the final harvest.

2.3. Statistical analysis

Plant survivorship was analyzed using a Cox proportional hazard model (Therneau and Grambsch, 2000); predictor variables included species, biochar and salt treatments, and all possible interactions. A repeated measures analysis of variance (ANOVA) was used to analyze changes in plant and height and leaf area. Simple one-way ANOVA was used to examine other growth and physiological responses to biochar additions; analyses were done separately for each species, omitting treatment cells in which low survivorship resulted in insufficient replication (<2 individuals per treatment × species combination). Where sufficient survivorship permitted, t-tests were used to compare differences between salt and no-salt treatments for each biochar addition. Preliminary analyses found no differences in soil and biochar characteristics between species at the end of the experiment; two-way ANOVA with biochar and salt as main effects was therefore used in this case. Post-hoc comparisons utilized the Tukey HSD test. A test for treatment effects on reproduction (number of flowers produced in *Prunella*) utilized a general linear model with Poisson error and log link functions. All statistical analyses were implemented in the R (R Core Team, 2012), using the R packages survival and nlme for the proportional hazard model and repeated-measures ANOVA, respectively.

3. Results

3.1. Effects on plant survivorship

Biochar and salt addition treatments had strong interactive effects on plant survivorship (Fig. 1; Table 2). In the Cox proportional hazard model analysis, biochar, salt, and biochar × salt terms were highly significant ($P < 0.0001$), as was the salt × species interaction term ($P = 0.0099$). Nearly all plants (29 of 30) that did not receive salt additions survived until the end of the experiment. For plants that did receive salt additions survivorship was strongly dependent on the amount of biochar added. Both species showed nearly 100% mortality within 10 days in response to salt additions in the no biochar and low biochar dosage (5 t ha^{-1}) treatments; however,

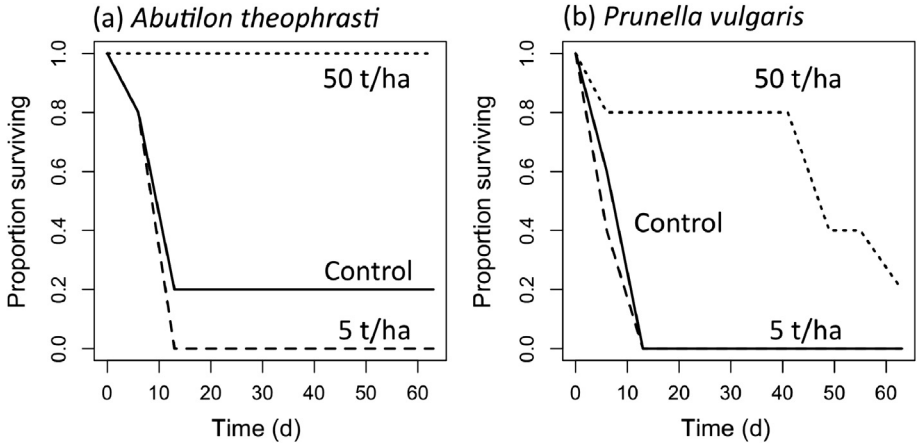

Fig. 1. Plant survivorship through time in (a) *Abutilon theophrasti*, and (b) *Prunella vulgaris*. Only salt addition treatments are plotted: solid lines indicate control treatment (no biochar added), dashed lines the 5 t ha^{-1} biochar treatment, and dotted lines the 50 t ha^{-1} biochar treatment.

Table 2
Analysis of deviance results for plant survivorship responses to biochar and salt additions in *Abutilon theophrasti* and *Prunella vulgaris*. The model fit is a Cox proportional hazards regression.

Factor	Log likelihood	Chi-square	d.f.	*P*
Null	−1486.0			
Salt	−1445.6	80.8797	1	<0.0001***
Biochar	−1433.4	24.3308	2	<0.0001***
Species	−1433.0	0.8785	1	0.3486
Salt × biochar	−1407.3	51.3648	2	<0.0001***
Salt × species	−1404.0	6.6471	1	0.0099**
Biochar × species	−1403.6	0.7060	2	0.7026
Salt × biochar × species	−1403.1	1.0404	2	0.5944

survivorship was high in the salt plus high biochar addition dosage (50 t ha^{-1}) treatment (Fig. 1). For *Abutilon*, survivorship in the salt plus high biochar addition dosage treatment was 100% throughout the course of the experiment. In *Prunella*, survivorship in the salt plus high biochar dosage treatment was initially high, but then declined following day 40 of the experiment (Fig. 1).

Biochar additions resulted in large increases in leaf area growth in *Prunella*, but did not produce detectable increases in *Abutilon* (Fig. 2): repeated-measures ANOVA indicated highly significant biochar × time interaction terms for *Prunella* ($F_{16,96} = 6.39$; $P < 0.0001$), but not for *Abutilon* ($F_{16,89} = 0.29$; $P = 0.9961$). Similarly, biochar additions resulted in significantly increased height growth in *Prunella* ($F_{16,96} = 2.79$; $P = 0.0010$), but not *Abutilon* ($F_{16,89} = 0.67$; $P = 0.8186$) (results not shown). *Prunella*, but not *Abutilon*, flowered by the end of the experiment; the latter showed substantially increased flower production in response to the high dosage biochar treatment ($\chi^2_{2,12} = 75.9$; $P < 0.0001$) (mean flowers per plant were 0.8, 0.0, and 8.6 in the control, 5 t ha^{-1}, and 50 t ha^{-1} treatments, respectively).

3.2. Physiological responses

Although biochar increased growth, physiological responses were generally not significant. Final biomass and physiological measurements could only be made in treatment combinations with sufficient survivorship: we therefore analyzed plant responses of both species to biochar in the absence of salt additions, and also compared plant performance between salt and no-salt treatments at the high biochar addition rate for *Abutilon* (Fig. 3, Table 3). Total

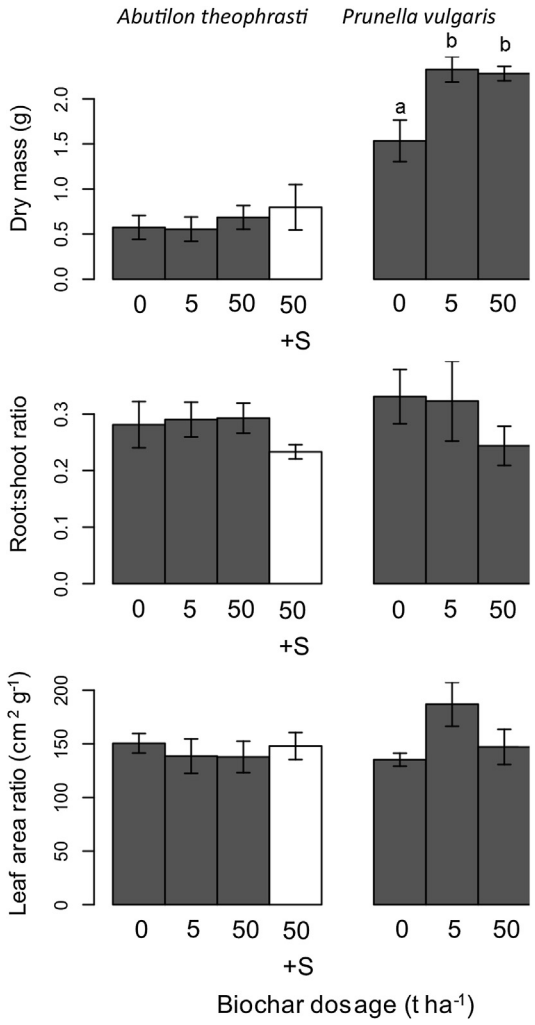

Fig. 3. Final plant biomass and related metrics (root:shoot ratio and leaf area ratio) in *Abutilon theophrasti*, and *Prunella vulgaris* in relation to biochar addition treatments. Shaded bars indicate treatments with no salt addition; open bars treatments with salt addition. Means are plotted ±1 SE. Letters indicate pairwise comparisons (based on Tukey HSD test) significant at $P < 0.05$ within a species.

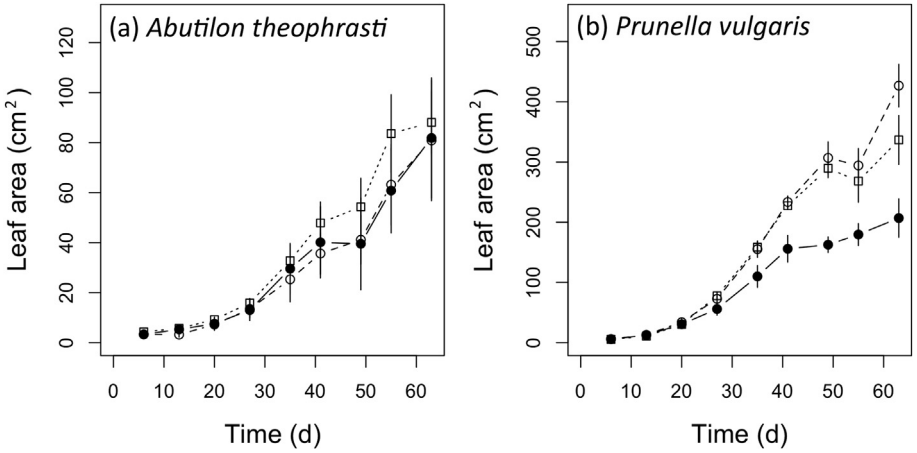

Fig. 2. Leaf area growth in (a) *Abutilon theophrasti*, and (b) *Prunella vulgaris*. Only the no-salt addition treatments are plotted: solid lines indicate control treatment (no biochar added), dashed lines the 5 t ha^{-1} biochar treatment, and dotted lines the 50 t ha^{-1} biochar treatment. Means are plotted ±1 SE.

Table 3
Responses of measured physiological parameters to biochar and salt addition treatments. Means are listed ±1 S.E. No statistically significant differences (among biochar treatments or between salt and no-salt treatments at the high biochar (BC) addition rate for *Abutilon*) were detected at $P < 0.05$. Abbreviations – A_{max}: light-saturated photosynthetic rate; g_s: stomatal conductance under light-saturated conditions; WUE: instantaneous water-use efficiency; Fv/Fm: ratio of variable to maximal chlorophyll fluorescence.

Treatment	N	A_{max} (μmol m^{-2} s^{-1})	g_s (mmol m^{-2} s^{-1})	WUE (mmol/mol)	Fv/Fm
Abutilon theophrasti					
Control	5	17.3 (1.2)	0.193 (0.017)	5.098 (0.225)	0.796 (0.002)
5 t ha^{-1} BC	4	16.1 (0.4)	0.183 (0.010)	4.658 (0.029)	0.789 (0.005)
50 t ha^{-1} BC	5	18.1 (0.6)	0.218 (0.007)	4.901 (0.110)	0.790 (0.009)
50 t ha^{-1} BC + salt	5	17.5 (1.1)	0.195 (0.026)	5.056 (0.132)	0.798 (0.002)
Prunella vulgaris					
Control	5	6.8 (0.5)	0.100 (0.019)	4.579 (0.440)	0.788 (0.005)
5 t ha^{-1} BC	5	7.0 (0.3)	0.108 (0.005)	4.365 (0.209)	0.782 (0.006)
50 t ha^{-1} BC	5	6.2 (0.4)	0.108 (0.013)	3.869 (0.504)	0.800 (0.003)

biomass in both biochar treatments was higher than the control in *Prunella* ($F_{2,12} = 7.49$; $P = 0.0078$), with increases of 52% and 49% in the 5 t ha^{-1} and 50 t ha^{-1} treatments, respectively (Tukey HSD comparisons significant at $P = 0.0124$ and $P = 0.0178$, respectively) (Fig. 3). There was a positive, but not significant biomass response in *Abutilon* as well (Fig. 3), with an increase of 19% in the 50 t ha^{-1} treatment relative to the control ($F_{2,13} = 0.28$; $P = 0.7602$). Neither species showed a significant response of root–shoot ratio to biochar treatments ($F_{2,12} = 0.8171$; $P = 0.4649$ for *Prunella*; $F_{2,12} = 0.0318$; $P = 0.9688$ for *Abutilon*). Leaf-level physiological variables examined (A_{max}, g_s, WUE, and Fv/Fm) likewise did not show a significant response to biochar treatments in either species (Table 3). There were also no detectable differences in physiological variables between salt addition and no-salt treatments under high (50 t ha^{-1}) biochar levels for *Abutilon* (Table 3).

3.3. Effects on soil properties

Neither biochar nor salt additions had a detectable effect on soil pH (mean pH = 7.48 ± 0.25 s.d.; $P > 0.05$ for all terms in ANOVA) (Table 4). In contrast, there were strong interactive effects of biochar and salt treatments on soil electrical conductivity (EC), which was used as a marker of dissolved NaCl in the soil solution ($F = 7.70$; $P = 0.0011$, for the salt × biochar term in ANOVA). EC was uniformly low (120–135 μS cm^{-1}) in biochar treatments without salt additions, but much higher (176–1171 μS cm^{-1}) in treatments with salt additions, with the highest EC found at the high dosage biochar treatment (Table 4). These results suggest that added NaCl was quickly washed through the control and low-dosage biochar treatments, resulting in transiently high ionic concentrations, but was initially sorbed and then more gradually desorbed in the high-dosage biochar treatment. Salt sorption was visibly apparent as a whitish crust within biochar in the high biochar addition treatments. Strong sorption of NaCl by biochar was clearly indicated by EC measurements of weathered biochar, with EC values ~2 and 20-fold higher than corresponding treatments without salt additions at 5 and 50 t ha^{-1}, respectively (Table 4).

4. Discussion

Our results indicate that addition of biochar derived from lignocellulosic material to soils can mitigate, or even eliminate, negative effects of salt addition on plant performance; however, mitigation of salt stress effects was evident only at the higher rate of biochar addition (50 t ha^{-1}). The two species examined had distinct responses to both biochar and salt additions. Biochar had a pronounced fertilization effect under glasshouse conditions generally favorable to plant growth and reproduction in *Prunella*. In contrast, *Abutilon* (which had higher variability among individuals) did not show a significant growth enhancement. However, salt-induced mortality in *Abutilon* was completely mitigated by the biochar treatment, and growth and physiological performance of surviving plants in the high biochar plus salt treatment closely approximated that observed in treatments where only biochar was added.

The sorptive properties of biochar appear to be largely responsible for most cases in which biochar acts to mitigate the impacts of plant stress, either by reducing exposure of plants to stress agents, or by ameliorating the stress responses of plants. For both heavy metals and organic pollutants, direct reductions in exposure due to sorption are presumed to be of primary importance (Beesley et al., 2010, 2011; Buss et al., 2011; Yu et al., 2009). Biochar can also substantially increase the water holding capacity of soils (Kammann et al., 2011; Karhu et al., 2011; Novak et al., 2012), and therefore improve the water status of plants, particularly during drought periods. Salts negatively impact plants through both osmotic effects and ionic toxicity (Munns and Tester, 2008), and enhanced water availability is expected to mitigate both of these effects. Thus, biochar's capacity to increase water availability may in part explain the amelioration of salt impacts observed in the present study. However, in the present experiment direct sorption of salt by biochar was visually apparent, and was indicated by large increases in biochar electrical conductivity in salt plus biochar treatments. Moreover, no effects of biochar on photosynthetic gas-exchange patterns were observed, as would be expected if biochar effects were mainly mediated by increased water availability. These

Table 4
Differences in soil and biochar properties (pH and EC) by biochar and salt addition treatments. Measurements were made at the end of the experiment. Data are pooled across species, and means listed ±1 S.E. Letters indicate pairwise comparisons (based on Tukey HSD test) significant at $P < 0.05$.

Treatment	N	Soil pH	Soil EC (μS cm^{-1})	Biochar pH	Biochar EC (μS cm^{-1})
Control	10	7.51 (0.09)	120 (39)[a]	–	–
5 t ha^{-1} BC	10	7.51 (0.08)	135 (17)[a]	7.70 (0.13)[a]	289 (76)[a]
50 t ha^{-1} BC	10	7.49 (0.06)	120 (29)[a]	8.04 (0.09)[b]	171 (39)[a]
Salt only	10	7.50 (0.07)	176 (73)[a]	–	–
5 t ha^{-1} BC + salt	10	7.51 (0.11)	323 (83)[a]	7.54 (0.19)[a]	606 (125)[b]
50 t ha^{-1} BC + salt	10	7.32 (0.06)	1171 (318)[b]	8.29 (0.12)[b]	5331 (3199)[b]

results suggest that the main mechanism for mitigation was sorption of NaCl resulting in reduced exposure. In the present experiment, the application of biochar as a top-dressing is likely to have enhanced its capacity to sorb salts (also introduced from above) relative to what would be observed if biochar was incorporated into the soil. This may be a realistic simulation in the case of road salt impacts and similar cases of deposition from above; however, other types of salt impacts, such as already saline soils, will almost certainly demand incorporation of biochars for amelioration.

The largest growth responses of plants to biochar additions are expected in situations of poor soil quality and nutrient status, high soil acidity, or low water holding capacity (Atkinson et al., 2010). The emerging literature generally supports this expectation, with larger benefits observed on relatively nutrient-poor, acidic, and coarse-textured soils (Jeffery et al., 2011). Mitigation of salt stress effects provides another example of this general trend. However, plant growth benefits of biochar have also been documented in relatively rich soils under favorable conditions (e.g., Rajkovich et al., 2012). The present study provides another such example: *Prunella*, grown in a commercial potting medium, showed a growth increase of ~50% in biomass at both biochar dosages relative to controls. This effect was not observed, however, in *Abutilon*, which showed only a marginal, non-significant growth response, suggesting high species-specificity of biochar effects.

Plant eco-physiological responses to biochar additions have been reported in relatively few studies, but are important to elucidate mechanisms for enhanced growth and other effects. Enhanced plant nutrient status, particularly increased N uptake, can result in increased growth through changes in resource allocation such as reduced root allocation (Ingestad and Ägren, 1991), and increased photosynthetic leaf-level carbon gain (Evans, 1989). The few existing studies on photosynthetic responses to biochar additions have emphasized increased leaf-level or whole-plant water-use efficiency (Buss et al., 2011), but the generality and mechanism(s) responsible for this effect are unclear. In the present study we detected no significant effects of biochar treatments on either leaf-level physiology or root–shoot partitioning, although *Prunella* shows a suggestive trend toward reduced root allocation under high biochar dosages (Fig. 3). Similar to other non-nutrient soil amendments, elucidation of the mechanisms for growth responses to biochar will likely require a range of techniques. The similarity of biochar to lime additions is informative, and suggests use of vector nutrient analysis (Gradowski and Thomas, 2008), or alternative approaches (Burke and Raynal, 1998) to deduce the relative importance of specific plant nutrient resources in driving observed responses.

5. Conclusions

We found that at high dosages, biochar can strongly mitigate or even eliminate stress impacts of salt additions on plants. Our results suggest novel uses of biochar application to mitigate salt stress in agriculture as well as other managed systems, such as urban forestry and ecological restoration sites. In each of these cases, biochar may represent a relatively inexpensive soil amendment that would provide multiple additional benefits such as enhanced water retention, cation exchange capacity, and carbon sequestration. Excess sodium has also been identified as a problem within biochars generated from Na-rich feedstocks such as food waste (Rajkovich et al., 2012), an issue that could potentially be addressed through mixing of biochar types to reduce Na^+ bioavailability. The results reported here provide a strong incentive for further studies of salt sorption and desorption by biochars, of biochar and salt responses of species varying in salinity tolerance, and, in particular, for direct field trials in salt-exposed systems.

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