# DOES BIOCHAR IMPROVE ESTABLISHMENT OF TREE SEEDLINGS IN SALINE SODIC SOILS?

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**Abstract**

Reforestation of saline sodic soil is increasingly undertaken as a means of reclaiming otherwise unproductive agricultural land. Currently, restoration of degraded land is limited to species with high tolerances of salinity. Biochar application has the potential to improve physical, biological and chemical properties of these soils to allow establishment of a wider range of plants. In a glasshouse trial, we applied biochar made from *Acacia pycnantha* (5 t $ha^{-1}$) or no biochar to either a low ($EC_e$ 4.75 dS $m^{-1}$, ESP 6.9), moderate ($EC_e$ 27.6 dS $m^{-1}$, ESP 29.3) or high ($EC_e$ 49.4 dS $m^{-1}$, ESP 45.1) saline sodic soil. The regional common reforestation species *Eucalyptus viminalis* and *Acacia mearnsii* were planted as tubestock in to the soils. Early establishment indicators, including growth, plant condition and nutrition were assessed at the end of a simulated growing season, 108 days after biochar application. Application of biochar increased height, and decreased root:shoot and the concentration of Mn, N and S in plants of *E. viminalis* when grown in the highly-saline sodic soil. Biochar application increased the concentration of B in leaves of *E. viminalis* and increased the concentration of P, K and S in leaves of *A. mearnsii* when grown in the low saline sodic soil. The results confirm that there is potential for biochar to assist in reforestation of saline sodic soils.

**Keywords:** amelioration, afforestation, biochar, nutrition, remediation, revegetation

## Introduction

Over 30% of the world's soils are saline and/or sodic making them unproductive, with the area of salinized land continually increasing (Rengasamy, 2006). Reforestation is an important tool for mitigating dryland salinity and land degradation (George, *et al.*, 2012). In addition, reforestation improves biodiversity and conservation values, provides income to land holders through forest resources, carbon credits and offset schemes, and successfully remediates and reclaims land that is otherwise unproductive (Bartle, *et al.*, 2007; Lal, 2008; Schirmer & Bull, 2013; Smith, 2008). As soil degradation is a global issue, there is currently much research into reclamation and amelioration of saline and/or sodic soils (e.g. Ahmad, *et al*., 2011; Oo, *et al*., 2013; Srivastava, *et al*., 2014). Reforestation of saline and sodic soils is an approach that can be applied internationally (Lal, 2008).

The high cation content of saline and/or sodic soils limits plant growth, making them unusable for production agriculture (Naidu, *et al.*, 1995; Rengasamy, 2006). Plants living in sodic and/or saline soils are likely to experience conditions outside of the normal range, including both nutrient toxicity and deficiencies due to excess sodium and other cations in the soil, a high pH, reduced redox potential (Curtin & Naidu, 1998), and increased osmotic stress (Semple, *et al.*, 2008; Stiller, 2009). Sodic soils, which have weak structure, also contain water and nutrients that are inaccessible to plants, and provide poor root zone aeration (Curtin & Naidu, 1998; Rengasamy, 2006). Together, this can result in damaged and poor root growth, reduced shoot growth, necrosis and ultimately plant death (Curtin & Naidu, 1998; Rengasamy, 2006; Semple, *et al.*, 2008; Stiller, 2009).

Some species can tolerate saline and sodic soil conditions, making them suitable for reforestation. This includes some species from, but are not limited to, the following genera: *Eucalyptus* and *Acacia* (Dale & Dieters, 2007; Jackson & Bird, 2008; Marcar & Crawford, 2004), *Casuarina* and *Melaleuca* (Dunn, *et al.*, 1994; Marcar & Crawford, 2004); *Albizia*, *Azadirachta*, *Dalbergia*, *Terminalia* (Tripathi & Singh, 2005); *Prosopis* (Bhojvaid & Timmer, 1998); *Atriplex* (Nedjimi, 2014; Smith, 2008); and *Taxodium* specifically bred for salt tolerance (Stiller, 2009). There are species within these genera that are more sensitive to saline and sodic soils (Dunn, *et al.*, 1994; Stiller, 2009). These plants can show visible indicators of stress and poor plant health (e.g. chlorosis, wilting, poor growth, abscission, necrosis and death) (Jackson & Bird, 2008; Marcar & Crawford, 2004), related to the characteristics of saline and sodic soils. The success of reforestation on saline sodic soils depends on careful species selection for soil and site conditions (Jackson & Bird, 2008) and can also be improved through soil amelioration prior to reforestation.

Biochar is often promoted as a way of ameliorating degraded soils (Atkinson, *et al.*, 2010; Barrow, 2012; Lehmann, *et al.*, 2011). Biochar is produced by the pyrolysis of naturally derived organic matter, such as manure or wood chip, in a low oxygen environment to form a high-carbon product that can be applied to soil (Lehmann & Joseph, 2009). Biochar has been shown to increase mesoporosity, field available water and reduce bulk density of saline sodic bauxite wastes (Jones, *et al.*, 2010). Biochar has been found to reduce salt stress through sorption, improving productivity of *Prunella vulgaris* and *Abutilon theophrasti* (Thomas, *et al.*, 2013). Application of biochar to soils can also improve nitrogen and phosphorous availability (Atkinson, *et al.*, 2010; Barrow, 2012; Joseph, *et al.*, 2010), which is important for nutrient-limited sodic soils. Biochar amendments are known to increase abundance of mycorrhizas

and improve microbial community structure (Lehmann, *et al.*, 2011). Increased arbuscular mycorrizal (AM) associations are linked directly to improved plant growth in saline soils (Al-Karaki, 2006; Ahanger *et al.*, 2014).

Research in forest ecosystems has focused on changes to soil physiochemical properties due to charcoal produced following fires in plantations and native forests (Atkinson, *et al.*, 2010; DeLuca, *et al.*, 2006) and not the addition of biochar. The limited studies of saline sodic soils amended with biochar have focused on the yield and productivity of crop and other herb species (e.g. Lashari et al. 2013; Thomas et al. 2013). Until now, there have been no tests of benefits of biochar addition to improve the success (growth, condition or nutrition of plants) of reforestation and particularly not on saline sodic soils.

Here, we determined if the application of biochar improves growth, condition and nutrition of seedlings during establishment of tree plantings on three different saline sodic soils. Seedlings of two species commonly used in reforestation in southeastern Australia, *Acacia mearnsii* and *Eucalyptus viminalis*, were grown in a glasshouse trial, with and without the addition of biochar derived from a local native species *Acacia pycnantha*. This trial will provide crucial information on the potential for a combined amendment-reforestation method to reclaim salinized land.

## Methods and materials

### Site description

Soils and plants used in this study were sourced from western Victoria, Australia (see Table 1), due to its prevalence of saline sodic soils. The climatic averages for the

hottest month of the year (February) are 22.3 – 26.3 °C maximum and 11.6 – 13.3 °C minimum, and a rainfall of between 578 - 909 mm $year^{-1}$ (Bureau of Meterology, 2014). Temperatures increase and rainfall further from the coast. The focus of the soils in this research are Sodosols (Isbell, 1996), which are soils with an exchangeable sodium percentage (ESP) > 6%. The soils used in this trial are predominantly grazed for meat and fibre (cattle and sheep), and dairy production, with limited remnant forest or reforestation. The areas that were sampled were historically classed as Grassy Woodlands, previously dominated by *Eucalypt sp.* with an open canopy and ground cover including grasses and herbs. Otherwise they were historically classed as wetlands that were predominately grassed with scattered trees.

**Soil collection and preparation**

Saline sodic soils used in this study were from three sites in the regions of Darlington, Dundonald and Grassmear (Table 1). At each of the three sites, approximately 300 kg of soil from the 0 – 10 cm layer was collected from a single location using a tractor. The soil from each site was placed into its own bulk bag, with all soils kept separate for the duration of the experiment, including preparation prior to use. Any large organic debris, including maize residue, was removed, and the soil crushed and sieved to < 10 mm and homogenised thoroughly. The soil was then air-dried prior to experimental set up.

Key physicochemical properties of these soils (Table 1) were analysed as follows: pH (1:5 water), EC (1:5), exchangeable Na and exchangeable sodium percentage (ESP), exchangeable K, B and Mn, Colwell-P (Rayment & Higginson, 1992); total carbon

(TC) and total nitrogen (TN) by LECO CNS2000 Analyser; sulfur, ammonium and nitrate-N (modified Morgan extract)(Wolf & Beegle, 2009).

All three soils were saline sodic, with an ESP > 6 and a saturated electrical conductivity ($EC_e$) > 4 dS $m^{-1}$, based on the definitions of Rengasmy (2006) and Murphy (2002). The texture class, using the ribbon test, was determined as being loam for all soils. $EC_e$ was determined using the standard equation and conversion table in Hazelton and Murphy (2007), where $EC_e$ = EC 1:5 x 9.5 (Table 1). All three soils had varying amounts of salinity and sodicity (Table 1), and included: a low saline sodic (LS), moderately saline sodic (MS), and highly saline sodic (HS).

**Biochar**

A biochar was produced from wood chip of *Acacia pycnantha* (Golden Wattle) in a continuous reactor pyrolyser operated by Biochar Energy Systems, Australia. Approximately 15 kg of dry *A. pycnantha* wood chips were placed in a mixer. Phosphoric acid (20%, 500 mL) was sprayed onto the surface of the wood chip, and 500 g bentonite (Arumpo Bentonite Pty Ltd, Victoria, Australia) was added to the wood chip. Phosphoric acid (10%, 1:1 solution to biochar) was added to the blends to oxidise the surface of the biochar whilst concomitantly stabilising carbonyl groups and improving loss of H from the biochar surface (Chia *et al*., 2014). Bentonite was added to the biochar during production to increase dehydration and oxidation (Chia *et al*., 2012). The mixture was then homogenised in the mixer for 30 min. The wood chip, clay and phosphoric acid mix was then added to the pre-heated pyrolyser (550 ˚C) for carbonisation in an oxygen-limited environment. The charring temperature was between 450 - 480 ˚C. Large particles of the denser/wetter wood chip that were

not fully pyrolysed were discarded. The general characteristics of the biochar are in Table 1, and methods of analysis were the same as for soil.

**Plants**

Seedlings of two species, *A. mearnsii* (a nitrogen fixer) and *E. viminalis* were chosen for this experiment. The chosen species are common in tree plantings in Western Victoria. A variant of *E. viminalis* was found to have a salinity tolerance of between 4 - 8 dS $m^{-1}$ (Jackson & Bird, 2008). *Acacia mearnsii* has a salinity tolerance between $EC_e$ 2 - 4 dS $m^{-1}$, with reduced growth expected when $EC_e$ > 4 dS $m^{-1}$ and reduced survival when $EC_e$ > 10 dS $m^{-1}$ (Jackson & Bird, 2008; Marcar & Crawford, 2004; Marcar, *et al.*, 2003).

Seedlings were sourced from the Franklin Native Nursery in western Victoria. The seedlings were of the same local provenance to the soils used in this study, which is the typical approach used by land managers. At the start of the experiment, the 36 seedlings of *A. mearnsii* were 16 weeks old and the 36 seedlings of *E. viminalis* were 12 weeks old.

**Experimental design**

A randomised one-way treatment design was used in the glasshouse trial. Soils (LS, MS, HS) were used as a block, and located in three separate areas (left, middle and right) in the glasshouse. Within each block, half were treated as control (0 t $ha^{-1}$) and 5 t $ha^{-1}$ were incorporated to the other half of the soils. Two tubestock species (*A. mearnsii* or *E. viminalis*) planted into each soil and biochar combination. This gave a total of four treatments (+/- biochar with either *A. mearnsii* or *E. viminalis*), which

were then replicated six times within each soil. Randomisation of pots within soil blocks was done by species and biochar combination, where three replicate sets of the treatments were positioned at the back of the glasshouse, and three at the front of the glasshouse. Positions within the replicate set were fully randomised by treatment.

Free draining plastic pots (20 cm tall, radius of 9.8 cm), with a layer of gauze placed in the base to limit soil loss, were filled with 5 kg of either LS, MS or HS soils. Biochar was incorporated into the top 10 cm of the soil at a rate of 5 t $ha^{-1}$ (15.1 g per pot) to half of each soil. The application rate of 5 t $ha^{-1}$ biochar was chosen as an economically feasible rate for farmer application. These pots were then watered to 100% of field capacity (FC), pots were then weighed every second day, and allowed to equilibrate for 10 d to reach 60% FC. The weight of the plant was also subtracted from the pots prior to calculating the FC. A FC of 60% was chosen to ensure sufficient available water for the native plants (Weggler, *et al.*, 2008), whilst avoiding waterlogging. On the same day, each soil had six seedlings planted into soil with biochar, and six into soil without biochar. Potting mix surrounding the seedlings roots was retained during planting, as this reflects the common method used in field. The experiment began on the day of the planting and finished 106 d later.

During the trial, pots were weighed and watered every 2 - 3 d to maintain 60% FC and no less than 50% FC at any given time, with weight of the plant removed prior to FC calculation. The pots were maintained in glasshouse conditions for the entirety of the experiment. The climatic conditions were maintained at 25 °C during the day, and 10 °C at night, with natural light and a day length of between 9.5 – 11.5 hours during the study period (June to September of 2012). These parameters are similar to growing season conditions of the field site. Relative humidity was maintained at 60%.

**Plant monitoring**

Growth, condition and nutrition of plants were measured to understand the effect of biochar on improving establishment in early stages of reforestation. Plants were assessed at the time of planting (time 0 hereafter) and again at 106 d. Condition assessments followed those used by Marcar et al. (1989; 1995), and in this research included: a) percentage of leaves that had necrosis; b) percentage of leaves that had chlorosis; c) presence of abscission; d) presence of other diseases or stress indicators including yellow spots, not related to mites, and leaf curl; e) overall presence of disease and stress, as a total of the presence or absence of all indicators. Necrosis and chlorosis was calculated as the percentage of leaves affected by each condition compared to overall number of leaves. Abscission and other diseases were determined as either absence or presence for each plant.

Growth indicators measured included plant height, root and shoot biomass. Plant height was measured from the base of the stem at the soil surface to the top of the highest branch, just before the leaf petiole. Plants were cut at the soil surface and anything below this point was considered roots. Roots were washed thoroughly to remove potting mix and soil, with some loss of fine roots. This was unavoidable given the clay present in the soils. Root and shoot biomass was dried at 60 °C for 72 hr prior to weighing for dry biomass. Root to shoot ratio was then calculated.

Dried samples of the plants shoots (stems and leaves) were ground to a fine powder in a ball mill prior to analysis for plant nutrition. TN, TC and S were analysed by a LECO CNS2000 Analyser. Phosphorus, Ca, Na, K, Mg, Zn, Fe, Mn, Cu, B and Mo were analysed by undertaking microwave digestion with nitric acid and read on an ICP-MS.

## Data Analysis

All data analysis was undertaken using SPSS Version 21 (IBM Corporation, 2012). A restricted maximum likelihood (REML) was used to determine if there were significant effects of biochar on species response variables, including plant growth, condition and nutrition indicators. Growth variables included shoot and root mass, root:shoot ratio and the final plant height. Condition variables included % necrosis, % chlorosis, and presence or absence at end of the trial of abscission, other diseases, and overall disease and stress indicators. Nutrient variables included concentrations of N, P, K, S, C, Ca, Mg, Na, Cu, Zn, Mn, Fe, B and Mo. A REML was chosen for analysis due to heterogeneity of variance, as determined using residual plots. Unlike analysis of variance (ANOVA) that requires parametric and homogenous data, REML analysis can use heterogeneous non-parametric data. The REML was applied to each soil and plant species combination; being low, medium and highly saline sodic soil, with either *A. mearnsii* or *E. viminalis*, giving a total of six REMLs. Plant and soil combinations were not compared. Biochar was the fixed factor, and side and position of the replicates in the glasshouse as random effects. The species and soils are highly dissimilar, and thus analysed individually to ensure there is no masking of effects. Pairwise comparisons were undertaken using least significant differences (LSDs). Where P-values were significant, F-values were checked against appropriate orthogonal contrasts.

## Results

The results are only discussed as the effect of biochar on the individual soil-plant type combinations, and no comparison is made between plant or soil types. The addition of biochar to the highly saline sodic (HS) soil significantly ($P = 0.018$) increased the height of *E. viminalis* by an average of 5.1 cm and also significantly ($P = 0.001$) reduced the root:shoot ratio by 0.1 (Table 2). Biochar had no other effect on plant growth variables (height, biomass, root:shoot) or condition indicators (necrosis, chlorosis, abscission, other and overall) in any of the soil (LS, MS or HS) and plant type (*E. viminalis* or *A. mearnsii*) combinations (Table 2). During root cleaning, nodules were only observed in two seedlings of *A. mearnsii* grown in LS and these nodules were confined to the original potting mix, which was retained when planting the seedlings. No other plants in any soils had nodules.

Biochar application had significant effects on some aspects of plant nutrition, which were soil-plant specific (Tables 3 and 4). In LS, *A. mearnsii* also had significantly higher concentrations of leaf tissue P ($P = 0.02$), K ($P = 0.004$) and S ($P < 0.001$) with biochar application than without (Table 3). Also in LS, *E. viminalis* had significantly ($P = 0.032$) higher B concentration in leaf tissue with biochar application, with an increase of 2.8 mg $kg^{-1}$ compared to plants without biochar (Table 4).

In HS, *A. mearnsii* had significantly ($P = 0.048$) higher concentrations of Na in leaf tissue, by a factor of 4.2, with biochar application compared to without (Table 3). The Na in plant tissue ranged from 0.3 – 0.8% in low and moderate soils (Table 3), similar to the 0.8% in the tissue of *A. mearnsii* from highly saline sodic soil without biochar addition. Also in HS, *E. viminalis* with biochar application had significantly lower concentrations of TN ($P = 0.031$), S ($P = 0.003$) and Mn ($P = 0.01$) in leaf tissue

compared to those without biochar (Table 4), with these averages (2% N, 0.19% S, 76.8 mg $kg^{-1}$ Mn) closer to plant tissue concentrations in the LS (1.9% N, 0.2% S, 23.8 mg $kg^{-1}$ Mn) and MS (2.1% N, 0.2% S, 83.7 mg $kg^{-1}$ Mn), irrespective of biochar addition. There were no significant changes in nutrition of either species in the MS soil (Table 3 and 4).

## Discussion

The international importance of large-scale development of reforestation to reclaim salinized land has been discussed in the Introduction. The adverse effects of high salinity have been shown in the reduced growth of *Eucalypt sp*. (Niknam & McComb, 2000), and in the observations of necrosis and death of *E. viminalis* when irrigated with ≥ 300 mol $m^{-3}$ NaCl (Marcar, 1989). No amelioration attempts to improve *Eucalyptus* and *Acacia sp*. reforestation in saline sodic soils have been reported, and the effects of biochar appear to have been restricted to reports on the improved growth of the herb *Prunella vulgaris* and yield increases of wheat grown in saline soils (Lashari, *et al.*, 2013; Thomas, *et al.*, 2013). The increased height and decreased root:shoot response of *E. viminalis* to biochar addition in the highly saline sodic soil are thus similar to previous findings (Lashari, *et al.*, 2013; Thomas, *et al.*, 2013). The improvement in growth is most likely related to sorption of salts by the biochar.

The application of biochar to highly sodic soils decreased the concentration of Mn, N and S in *E. viminalis* plants, which may have been related to improved fungal associations with biochar addition. *Eucalyptus* species are not known to physiologically regulate S uptake, and low S can lead to reductions in leaf area and height (Wilson & Murray, 1994). Furthermore, Mn toxicity is known to cause reduced

biomass in *Eucalyptus* species (Guo, *et al.*, 2002). Poorer growth indicators with higher plant tissue Mn and S were found here for *E. viminalis* plants without biochar addition. This lack of regulation is the result of mechanisms in *Eucalyptus* species that minimise loss and maximise uptake of nutrients due to their adaptation to nutrient poor environments (Wilson & Murray, 1994; Guo, *et al.*, 2002). However, ectomycorrhizas have associations with *Eucalyptus* species (Kariman, *et al.*, 2012) and are well known to down regulate nutrients when the plant may not have its own mechanism (Jourand, *et al.*, 2014; Lehto, *et al.*, 2010). The harsh conditions of saline soils are known to limit fungal and bacterial associations with plants (Ahanger, *et al.*, 2014; Nadeem, *et al.*, 2014), and this association may have been absent in the highly-saline sodic soil. As the low and moderate saline sodic soils both had higher concentration of Mn (Table 1) and lower leaf tissue Mn than the highly saline sodic soil, this suggests the lower ESP and $EC_e$ of these soils allowed for mycorrhiza associations that regulate Mn uptake. As biochar addition to soil improves habitat and conditions for fungal or bacterial associations (Warnock et al. 2007; Lehmann et al. 2011) and reduces salinity through sorption (Lashari, *et al.*, 2013; Thomas, *et al.*, 2013), this may have created conditions that promote fungal associations in the highly saline sodic soil. This would have resulted in the down regulation of N, Mn and S closer to the concentrations in leaves of *E. viminalis* in the low and moderately saline sodic soils, and improved growth. The exact mechanism involved in the reduction of plant tissue Mn, N and S is unclear and warrants further examination.

There was an increased uptake of B in *E. viminalis* in the low sodic saline soil (Table 4), indicating changes to available B with biochar addition. Biochar application is known to increase plant available nutrients in soil (Atkinson, *et al.*, 2010; Chan, *et al.*, 2008; Joseph, *et al.*, 2010), and the exchangeable B present in the biochar (Table 1)

would have contributed to the soils B availability. As there was 11.9 mg $kg^{-1}$ exchangeable B in the biochar and 1.1 mg $kg^{-1}$ exchangeable B in the low saline sodic soil (Table 1), there would be a an absolute maximum of 0.2 mg $kg^{-1}$ increase in exchangeable B with a biochar addition of 5 t $ha^{-1}$, increasing exchangeable B to 1.3 mg $kg^{-1}$. However, the increase of B in plant tissue was 2.8 mg $kg^{-1}$, which is higher than the maximum amount related to biochar input (0.2 mg $kg^{-1}$), and thus another biochar-soil interaction must have contributed. Ectomycorrhizas are known to have associations with *Eucalyptus* species (Kariman, *et al.*, 2012) and regulate B uptake in forest tree species (Lehto, *et al.*, 2010). In conjunction with this, ectomycorrhizas are known to increase in abundance and/or plant associations with the addition of biochar (Warnock, *et al.*, 2007). Thus, the potential for an increased association with ectomycorrhizas with biochar addition could explain the additional increase in the uptake of B in *E. viminalis*.

The increased plant tissue P, K and S in *A. mearnsii* in the low saline sodic soil (Table 3) is related to an increase in available nutrients with biochar application, as has been reported previously (e.g. Chan, *et al.*, 2008; Joseph, *et al.*, 2010; Tagoe, *et al.*, 2008). With biochar applied at a rate of 5 t $ha^{-1}$ to the soil, there would be a maximum increase of 21.4 mg $kg^{-1}$ Colwell-P, 6.3 mg $kg^{-1}$ S and 3.42% K (using data from Table 1), which is sufficient to explain the increases in plant tissue P, K and S in *A. mearnsii*.

The addition of biochar to the highly-saline sodic soil resulted in a dramatic increase in the concentration of Na in *A. mearnsii* plant tissue. Similar to the concentration of Mn and S in *E. viminalis* plant tissue, the concentration of Na in plant tissue from low and moderate saline sodic soils was similar to that from highly saline sodic soil without biochar addition. This suggests that the biochar in the highly saline sodic soil

influenced the uptake of Na, but only when Na levels in soil are already extremely high (ESP > 40). However, the maximum increase of Na to soil from biochar can only be 0.2 % (calculated using Table 1). As Na was 4.2 times higher in plants when biochar was added to the soil, a change in a fungal and bacterial association that regulates Na uptake is more likely. Fungal associations with plants are known to regulate uptake of Na from saline soils (Ahanger, *et al.*, 2014; Al-Karaki, 2006; Mardukhi, *et al.*, 2011; Nadeem, *et al.*, 2014). This regulation and association is most likely to be occurring in this study, across all soils where Na in plant tissue is low (< 0.8%). However, biochar, is known to alter fungal associations, including changes in the percentage presence of N-fixing and non-N-fixing AMF (Rondon *et al.*, 2007; Warnock *et al.*, 2007). The addition of biochar in the highly saline sodic soil may have resulted in a shift to species that do not regulate the uptake of Na, and thus caused an increase in plant tissue Na. Although plant condition and growth in this establishment phase was similar between all soils tested both with and without biochar, accumulation of Na in plant tissue can cause poor condition, stunted growth and eventually death (Jackson & Bird, 2008; Marcar & Crawford, 2004; Marcar, *et al.*, 2003). The response to excess Na in *A. mearnsii* may be delayed until they are saplings. The mechanism related to the increased Na uptake in *A. mearnsii* with biochar addition in the highly saline sodic soil is unclear and further research on this mechanism is required.

Both species showed evidence of chlorosis, necrosis and leaf curl in the moderately and highly sodic soils, which is suggestive of osmotic stress and nutrient limiting impacts due to the saline sodic soil conditions (Marcar, 1989; Marcar, *et al.*, 1995; Rengasamy, 2006). The application of 5 t $ha^{-1}$ biochar had no beneficial effect on plant condition. An increased application rate of biochar may show further beneficial

effects on plant establishment, and have been reported to improve the ability of *Prunella vulgaris* to grow, but only at an application rate of 50 t $ha^{-1}$ (Thomas, *et al.*, 2013). This would, however, reflect a ten-fold increase in biochar use compared to what was undertaken here, and further consideration is necessary to determine if this is economically feasible for landholders.

Although our short-term trial found benefits of adding biochar in the establishment phase of reforestation, further beneficial effects of biochar application have been found three years after application (Jones, *et al.*, 2012) and after a five-crop rotation following a single biochar application (Liu, *et al.*, 2014). This suggests that the benefits of biochar may persist, and possibly increase, during the early development of these tree plantings on saline sodic soils.

## Conclusion

We found that two important reforestation species in temperate Australia, *E. viminalis* and *A. mearnsii*, had soil-specific responses to biochar addition. In low ($EC_e$ 4.75 dS $m^{-1}$, ESP 6.9) and highly ($EC_e$ 49.4 dS $m^{-1}$, ESP 45.1) saline sodic soils, biochar generally had a positive effect on conditions for plant establishment in reforestation at commercially feasible application rates of 5 t $ha^{-1}$. Application of biochar to moderately ($EC_e$ 27.6 dS $m^{-1}$, ESP 29.3) saline sodic soils has no detrimental effect. This finding is particularly important for highly saline sodic soil, which is extremely degraded. This research demonstrates that biochar has the potential to improve reforestation success on extremely degraded land, resulting in greater areas of land that can be potentially reclaimed. Harnessing an understanding of the most

appropriate use of biochar to restore degraded lands can increase biodiversity, provide alternative income sources and global carbon sinks.

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## Table Captions

**Table 1 – Characteristics, including pH, electrical conductivity (EC), saturated electrical conductivity (ECe), total carbon (TC), total nitrogen (TN), exchangeable sodium percentage (ESP), nitrate-N ($NO_3^-$-N), ammonium-N ($NH_4^+$-N), Colwell phosphorus (Colwell-P), exchangeable potassium (K), sulfur (S), boron (B) and manganese (Mn), of the three compromised soils including low saline sodic (LS), moderately saline sodic (MS), highly saline sodic (HS), and the Golden Wattle biochar. The latitude and longitude and land use of each soil are included. [A] The high Colwell-P value of the biochar is a result of phosphoric acid addition during pyrolysis.**

**Table 2 – Average (mean ± standard error, *N*=6) of plant growth and condition variables for each soil and species combination by biochar rate (0 or 5 t ha$^{-1}$). This includes height, shoot and root biomass, root:shoot, presence or absence of abscission or other conditions, presence or absence of all conditions, percentage of leaves with necrosis or chlorosis. Soils are low sodic (LS), moderately sodic (MS) and highly sodic (HS). Abscission, other and overall plant condition indicators are presented as absence or presence. * is used when there is a significant difference (*P* < 0.05) between biochar treatments.**

**Table 3 – Average (mean ± standard error, *N*=6) of nutrition variables for *Acacia mearnsii* in each soil, by biochar rate (0 or 5 t ha$^{-1}$). These include nitrogen (N), phosphorus (P), potassium (K), sulfur (S), carbon (C), calcium (Ca), magnesium (Mg), sodium (Na), copper (Cu), Zinc (Zn), manganese (Mn), iron (Fe), boron (B) and molybdenum (Mo). Soils are low sodic (LS), moderately sodic (MS) and highly sodic (HS). * is used to denote a significant difference (*P* < 0.05) between biochar treatments within the same soil.**

**Table 4 – Average (mean ± standard error, *N*=6) of nutrition variables for *Eucalyptus viminalis* in each soil, by biochar rate (0 or 5 t ha$^{-1}$). These include nitrogen (N), phosphorus (P), potassium (K), sulfur (S), carbon (C), calcium (Ca), magnesium (Mg), sodium (Na), copper (Cu), Zinc (Zn), manganese (Mn), iron (Fe), boron (B) and molybdenum (Mo). Soils are low sodic (LS), moderately sodic (MS) and highly sodic (HS). Soil is low sodic (LS), moderately sodic (MS) and highly sodic (HS). * is used to denote a significant difference (*P* < 0.05) between biochar treatments within the same soil.**

622 **Tables – in order**

623 Table 1

| | Soil | | | Biochar |
|---|---|---|---|---|
| | **LS** | **MS** | **HS** | |
| **Latitude and Longitude** | 37.93 ºS 143.06 ºE | -38.29 ºS 142.53 ºE | -37.47 ºS 144.79 ºE | NA |
| **Land Use** | Maize, Grazing | Restoration | Grazing, Restoration | NA |
| **pH** | 7.6 | 8.7 | 8.6 | 7.4 |
| **EC (ds $m^{-1}$)** | 0.5 | 2.9 | 5.2 | 1.1 |
| **ECe (ds $m^{-1}$)** | 4.75 | 27.6 | 49.4 | NA |
| **TC (%)** | 5.3 | 2.7 | 2 | 66 |
| **TN (%)** | 0.5 | 0.3 | 0.2 | 0.8 |
| **ESP** | 6.9 | 29.3 | 45.1 | 13.5 |
| **$NO_3^-$-N (mg $kg^{-1}$)** | 64.9 | 4.7 | 11.9 | 28 |
| **$NH_4^+$-N (mg $kg^{-1}$)** | 10.8 | 12.3 | 14.2 | 7.2 |
| **Colwell-P (mg $kg^{-1}$)** | 154.2 | 17.8 | 62.4 | 1427.4[A] |
| **K (%)** | 1.6 | 4 | 4.5 | 22.8 |
| **S (mg $kg^{-1}$)** | 20.7 | 200.2 | 663.2 | 421.2 |
| **B (mg $kg^{-1}$)** | 1.1 | 3 | 5.71 | 11.9 |
| **Mn (mg $kg^{-1}$)** | 19.7 | 55.3 | 9.7 | 20.5 |

624 Table 2

| | *A. mearnsii* | | | | | | *E. viminalis* | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Soil** | **LS** | | **MS** | | **HS** | | **LS** | | **MS** | | **HS** | |
| **Biochar Rate (t ha$^{-1}$)** | **0** | **5** | **0** | **5** | **0** | **5** | **0** | **5** | **0** | **5** | **0** | **5** |
| **Height (cm)** | 37.4±3.1 | 35.1±1.5 | 13.7±1.7 | 15.3±2.5 | 12.4±1.7 | 7.6±2.4 | 64.4±3.0 | 63.0±1.8 | 30.7±2.5 | 35.7±2.1 | 32.4*±1.8 | 37.5*±1.2 |
| **Shoot Biomass (g)** | 5.13±0.20 | 4.52±0.87 | 1.14±0.21 | 0.88±0.27 | 0.41±0.12 | 0.48±0.13 | 5.04±0.55 | 5.85±0.52 | 1.88±0.26 | 1.57±0.14 | 1.53±0.14 | 1.78±0.16 |
| **Root Biomass (g)** | 0.73±0.16 | 0.63±0.15 | 0.40±0.07 | 0.29±0.07 | 0.20±0.04 | 0.22±0.06 | 1.11±0.15 | 1.07±0.25 | 0.82±0.08 | 0.68±0.04 | 0.63±0.06 | 0.57±0.07 |
| **Root:Shoot** | 0.14±0.03 | 0.14±0.01 | 0.37±0.03 | 0.38±0.05 | 0.53±0.07 | 0.68±0.22 | 0.22±0.02 | 0.18±0.04 | 0.46±0.04 | 0.45±0.04 | 0.42*±0.02 | 0.32*±0.02 |
| **Abscission** | 0±0 | 0±0 | 0.33±0.21 | 0.33±0.21 | 0.67±0.21 | 0.50±0.22 | 0.33±0.21 | 0.17±0.17 | 0±0 | 0.17±0.17 | 0.67±0.21 | 0.33±0.21 |
| **Other** | 0±0 | 0±0 | 0±0 | 0±0 | 0±0 | 0.33±0.21 | 0.33±0.21 | 0.17±0.17 | 0.17±0.17 | 0.17±0.17 | 0±0 | 0±0 |
| **Overall** | 0±0 | 0±0 | 0.50±0.22 | 0.50±0.22 | 0.67±0.21 | 1.00±0.00 | 0.50±0.22 | 0.17±0.17 | 0.17±0.17 | 0.17±0.17 | 0.67±0.21 | 0.50±0.22 |
| **Necrosis (%)** | 0±0 | 0±0 | 0±0 | 0±0 | 0±0 | 3.70±3.70 | 0±0 | 0±0 | 0±0 | 0±0 | 2.75±1.78 | 3.55±1.65 |
| **Chlorosis (%)** | 0±0 | 0±0 | 25.18±12.45 | 13.10±8.33 | 26.98±9.23 | 22.22±16.48 | 0±0 | 0±0 | 0±0 | 0±0 | 0±0 | 0±0 |

625

626 **Table 3**

| Soil | LS | | MS | | HS | |
|---|---|---|---|---|---|---|
| Biochar Rate (t ha$^{-1}$) | 0 | 5 | 0 | 5 | 0 | 5 |
| N (%) | 3.1±0.1 | 3.1±0.1 | 2.7±0.1 | 2.7±0.1 | 2.9±0.1 | 2.8±0.1 |
| P (%) | 0.15*±0.005 | 0.16*±0.005 | 0.2±0.03 | 0.2±0.01 | 0.2±0.01 | 0.51±0.21 |
| K (%) | 0.9*±0.04 | 1.1*±0.04 | 0.9±0.09 | 1.0±0.1 | 0.9±0.08 | 0.76±0.09 |
| S (%) | 0.17*±0.003 | 0.20*±0.003 | 0.3±0.03 | 0.3±0.1 | 0.3±0.02 | 0.29±0.01 |
| C (%) | 44.3±0.2 | 44.5±0.2 | 45.2±0.5 | 45.2±0.3 | 44.6±0.3 | 43.7±0.4 |
| Ca (%) | 1.4±0.04 | 1.3±0.1 | 1.1±0.1 | 1.0±0.1 | 1.2±0.1 | 1.5±0.4 |
| Mg (%) | 0.2±0.01 | 0.2±0.01 | 0.4±0.03 | 0.4±0.04 | 0.3±0.01 | 0.44±0.12 |
| Na (%) | 0.3±0.02 | 0.3±0.04 | 0.8±0.28 | 0.6±0.1 | 0.8*±0.1 | 3.35*±1.06 |
| Cu mg kg$^{-1}$ | 4.9±0.4 | 5.6±0.6 | 13.4±1.3 | 12.6±0.5 | 12.1±1.5 | 21.7±8.3 |
| Zn mg kg$^{-1}$ | 16.8±1.0 | 17.8±0.9 | 22.6±3.2 | 19.8±1.3 | 22.0±3.0 | 65.1±30.5 |
| Mn mg kg$^{-1}$ | 11.9±0.8 | 10.5±0.8 | 34.7±6.9 | 27.4±4.9 | 18.7±1.3 | 28.8±7.5 |
| Fe mg kg$^{-1}$ | 194.8±19.7 | 208.8±26.1 | 523.0±206.1 | 474.8±184.5 | 382.7±55.1 | 1719.1±966.9 |
| B mg kg$^{-1}$ | 15.1±0.8 | 13.7±0.8 | 26.3±5.2 | 20.4±2.0 | 53.9±1.2 | 93.5±40.5 |
| Mo mg kg$^{-1}$ | 3.7±0.3 | 3.2±0.3 | 6.8±1.1 | 9.0±0.3 | 10.7±0.5 | 24.8±11.6 |

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628

629 **Table 4**

| Soil | LS | | MS | | HS | |
|---|---|---|---|---|---|---|
| Biochar Rate (t ha$^{-1}$) | 0 | 5 | 0 | 5 | 0 | 5 |
| N (%) | 1.9±0.2 | 2.1±0.1 | 2.1±0.1 | 1.9±0.1 | 2.3*±0.01 | 2.0*±0.01 |
| P (%) | 0.1±0.01 | 0.1±0.01 | 0.1±0.01 | 0.1±0.00 | 0.1±0.01 | 0.1±0.01 |
| K (%) | 0.9±0.04 | 0.9±0.1 | 0.7±0.03 | 0.7±0.02 | 0.6±0.04 | 0.7±0.1 |
| S (%) | 0.2±0.02 | 0.2±0.01 | 0.2±0.01 | 0.2±0.01 | 0.23*±0.01 | 0.19*±0.01 |
| C (%) | 45.0±0.3 | 45.6±0.3 | 47.0±0.2 | 47.0±0.2 | 45.9±0.4 | 46.1±0.4 |
| Ca (%) | 1.1±0.1 | 1.2±0.1 | 0.9±0.1 | 0.9±0.04 | 1.0±0.1 | 1.0±0.1 |
| Mg (%) | 0.2±0.01 | 0.3±0.01 | 0.3±0.03 | 0.4±0.01 | 0.3±0.01 | 0.3±0.02 |
| Na (%) | 0.2±0.03 | 0.2±0.01 | 0.3±0.02 | 0.4±0.01 | 0.6±0.04 | 0.7±0.1 |
| Cu mg kg$^{-1}$ | 6.5±0.6 | 11.4±3.7 | 9.8±0.1 | 10.0±0.6 | 10.3±0.6 | 12.3±1.3 |
| Zn mg kg$^{-1}$ | 31.9±3.3 | 38.4±2.4 | 26.4±2.1 | 24.0±0.9 | 25.6±1.9 | 25.6±1.2 |
| Mn mg kg$^{-1}$ | 23.8±2.1 | 29.1±3.4 | 83.7±12.3 | 85.3±3.5 | 116.1*±9.0 | 76.8*±9.6 |
| Fe mg kg$^{-1}$ | 172.4±95.5 | 131.0±20.6 | 155.2±23.8 | 128.0±8.7 | 141.2±11.1 | 387.7±121.7 |
| B mg kg$^{-1}$ | 17.3*±0.9 | 20.1*±1.1 | 23.8±1.8 | 27.8±1.6 | 48.4±2.9 | 43.7±5.9 |
| Mo mg kg$^{-1}$ | 0.9±0.2 | 0.9±0.1 | 1.4±0.1 | 1.4±0.1 | 1.8±0.1 | 3.0±0.6 |

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