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Bio-mitigation of carbon following afforestation of abandoned salinized farmland

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Abstract

As the global demand for food continues to increase, the displacement of food production by using agricultural land for carbon mitigation, via either carbon sequestration, bioenergy or biofuel is a concern. An alternative approach is to target abandoned salinized farmland for mitigation purposes. Australia, for example, has 17 million ha of farmland that is already or could become saline. At a representative, salinized, low rainfall (350 mm yr^{-1}) site at Wickepin, Western Australia, we demonstrate that afforestation can mitigate carbon emissions through either providing a feedstock for bioenergy or second generation biofuel production and produce salt-tolerant fodder for livestock. A range of factors markedly affect this mitigation. These include hydrological conditions such as salinity, site factors such as slope position and soil properties and a range of silvicultural factors such as species, planting density and age of the planting. High density (2000 stems ha^{-1}) plantings of *Eucalyptus occidentalis* Endl. produced a mean total biomass of 4.6 t ha^{-1} yr^{-1} (8.5 t CO_2-e ha^{-1} yr^{-1}) averaged over 8 years. *Atriplex nummularia* Lindl. produced a mean total biomass of 3.8 t ha^{-1} yr^{-1} (6.9 t CO_2-e ha^{-1} yr^{-1}) averaged over 4 years and approximately 1.9 t ha^{-1} yr^{-1} of edible dry matter annually to 8 years of age. With differences in salt tolerance between *E. occidentalis* and *A. nummularia*, we propose an integrated approach to treating salinized sites that takes salinity gradients into account, replicates natural wetland ecosystems and produces both fodder and biomass. Continued mitigation is expected as the stands mature, assuming that growth is not affected by the accumulation of salt in the soil profile. Such carbon mitigation could potentially be applied to salinized farmland globally, and this could thus represent a major contribution to global carbon mitigation without competing with food production.

Keywords: *Atriplex nummularia*, bioenergy, biofuel, carbon sequestration, *Eucalyptus occidentalis*, lignocellulosic, second generation

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Introduction

Afforestation of farmland represents a major method of mitigating rising atmospheric carbon dioxide contents, either through carbon sequestration or via the substitution of fossil fuels with bioenergy (Schlamadinger & Karjalainen, 2000; Canadell & Raupach, 2008). Although afforestation alone is unlikely to allow resolution of global carbon imbalance (Pacala & Socolow, 2004) it nonetheless represents a useful contribution. Current interest and developments with second generation biofuel technologies may further increase the demand for land used for carbon mitigation. For example, biofuels developed from cellulosic feedstocks show promise, not only with respect to yield, but also in relation to fossil fuel displacement and subsequent CO_2 removal (Schmer *et al.*, 2008).

Widespread afforestation may, however, result in competition between carbon mitigation and other land uses, in particular food production (Gunther, 2009). This conflict in land use is likely to increase with increasing world population and per capita food consumption. An alternative approach is to consider biomass production from abandoned or poorly productive agricultural land. To date, there are few data to support the cost-effectiveness, or otherwise, of this proposition. Studies in relation to global biomass energy and the use of abandoned farmland show Australia as having potentially large areas of abandoned farmland (Fischer & Schrattenholzer, 2001; Campbell *et al.*, 2008; Wicke *et al.*, 2011) however, these are based on generalized models rather than specific regional data sets. Similarly, several research and development gaps were

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identified for Australia's second generation biofuels industry by Warden & Haritos (2008). Of these, provision of biomass feedstock was identified as an area that required particular attention.

Globally, many regions experience salinization, with soil salinity being prevalent in more than 100 countries (Rengasamy, 2006) and across a range of climates (Marcar & Khanna, 1997). Globally, the impact of human land use has resulted in an estimated 74 Mha of salinized agricultural land (Dregne *et al.*, 1991), of this area 43 Mha is irrigated land and 31 Mha is secondary salinization of nonirrigated land.

Across major regions of southern Australia the removal of deep-rooted native vegetation (perennials) and replacement with shallow rooted agricultural crop and pasture species (annuals) has resulted in increased recharge to groundwater. A subsequent rise in water tables and mobilization of salt stores has led to the development of dryland or secondary salinity (George *et al.*, 1999; National Land and Water Resources Audit 2001). In Australia, it is projected that around 17 Mha of agricultural land will be salt affected by 2050 (National Land and Water Resources Audit 2001).

Two general plant-based approaches have been used to treat salinized farmland in Australia, these being either afforestation using salt-tolerant trees or revegetation with forage shrubs. Both approaches attempt to gain some economic return from salt-affected farmland, while removing excess soil moisture and restoring landscape hydrological balances (George *et al.*, 1999). On salinized land, the replanted species must be tolerant to both water logging and high levels of soil salinity (Barrett-Lennard, 2003). Although there have been many studies to identify suitable tree species for reclamation of saline farmland (Marcar *et al.*, 1995; Benyon *et al.*, 1999; Niknam & McComb, 2000), and some have pointed out the benefits of using salinized lands for fuel-wood production (e.g. El-Lakany, 1986), there are few data on biomass production for carbon mitigation potential. Of potential halophytic shrubs, saltbush (*Atriplex* spp.) has been the most extensively examined due to its salt tolerance and its nutritional potential as an alternative fodder for livestock (Norman *et al.*, 2004). Biomass estimates reported from many of these studies relate mostly to edible dry matter (EDM) and not total biomass.

This article examines the carbon mitigation potential from abandoned salinized farmland (or saltland) treated with *Eucalyptus occidentalis* and *Atriplex nummularia*, and the influence of both site (e.g. salinity) and silvicultural factors on yield to 8 years of age. These data are discussed in relation to both potential feedstock for second generation biofuel production and production of salt-tolerant fodder crops.

Materials and methods

Location

The study site, was located near Wickepin, Western Australia, approximately 240 km east of Perth (117°41′47.13″E; 32°23′24.67″S) the State capital. This site was selected as having soils and landforms representative of the general region (McArthur, 1991), which has a semi-arid Mediterranean climate, with a seasonal drought from November to April, a mean annual rainfall (1889–2001) of 365 mm yr^{-1} and mean annual pan evaporation of 1789 mm yr^{-1}. The mean rainfall during the 8 years of the experiment was 303 mm yr^{-1}.

Experimental design

A salt scald had developed in a valley floor during the previous two decades on land originally cleared for farming in the early 1900s, and this consisted of a bare, hypersaline area which has been extensively eroded with fringing less-saline areas (Fig. 1). *Eucalyptus occidentalis*, *A. nummularia*, *Allocasuarina huegeliana* Miq. and *Acacia celastrifolia* Benth. were planted adjacent to the salt scald in June 2001 at planting densities of 500 and 2000 stems ha^{-1} in a randomized complete block design, consisting of two replicate blocks (one either side of a salt scald), each with eight treatments and three replicates. Plants were germinated and grown in containers for approximately 6 months, then transplanted into 50 cm high mounds within 40 × 40 m treatment plots.

Allocasuarina huegeliana and *A. celastrifolia* performed very poorly and were not subsequently measured throughout the trial. *Acacia celastrifolia* was grazed by stock and some plots were completely destroyed. *Allocasuarina huegeliana* survived grazing but growth was very poor in comparison to *E. occidentalis* and *A. nummularia*. This article therefore focuses on the performance of the latter two species.

Biomass estimation

Measurements. Measurements were made of all treatments on an annual basis, to obtain estimates of biomass. Predictor variables used in the development of allometric relationships were measured on all *E. occidentalis* trees and *A. nummularia* (saltbush) shrubs within 20 × 20 m permanent measurement plots. Plots of this size were considered unlikely to be affected by edge effects between contrasting treatments. For *E. occidentalis* attributes measured included diameter over bark at 10 and 130 cm above ground, total tree height and for *A. nummularia* crown length and width measured perpendicular to each other, height and crown base height. The measurement was carried out at the same time each year to ensure there was time for crown regrowth of *A. nummularia* following summer grazing. Survival was estimated as a proportion of the plants alive at the time of measurement compared to the number initially planted.

Allometric equations. Species specific allometric equations for *E. occidentalis* were applied from a previous study in the same farming region and on plantings with the same planting

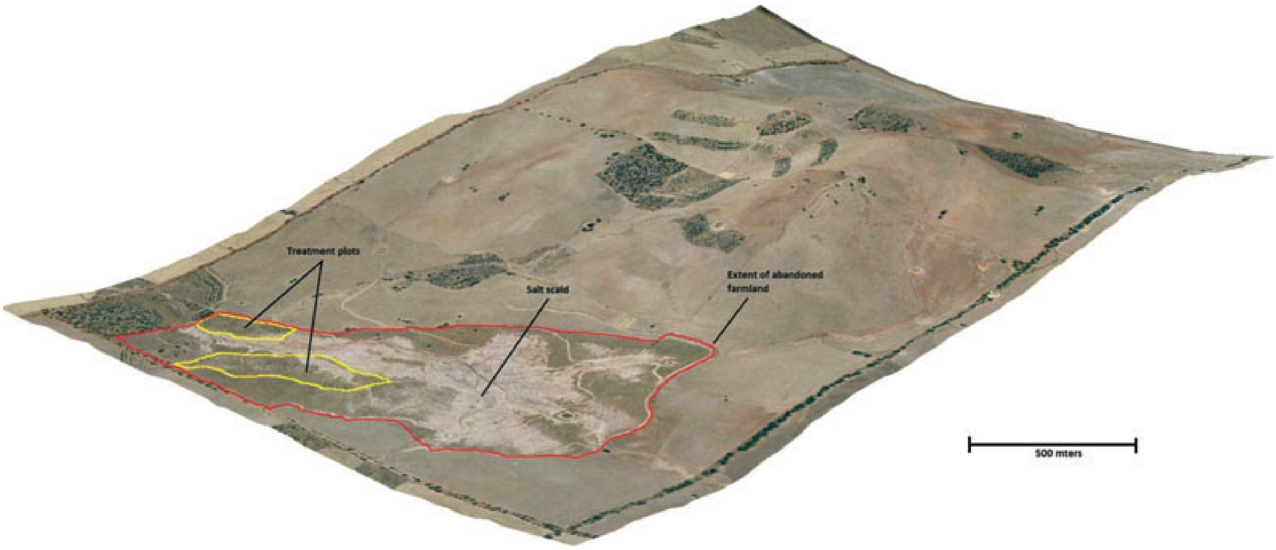

Fig. 1 Aerial photograph of the Wickepin experimental site (117°41′47.13″E; 32°23′24.67″S), overlaid on a digital elevation model, showing the salt scald and location of the experimental plots.

density (Sochacki *et al*., 2007). These equations predicted whole tree, leaf, stems and root biomass from tree height and diameter over bark at 10 cm above ground. For *A. nummularia,* allometric equations were developed from biomass sampling carried out in June 2005. Equations were derived using the same procedure as Sochacki *et al.* (2007) with respect to equation fitting and goodness-of-fit tests.

Above-ground biomass sampling (A. nummularia)

A total of 12 permanent measurement plots were sampled, with the five plants sampled from within each plot covering the dynamic range of sizes. Crown width, length, shrub height and crown base height were measured to calculate a crown volume index (CVI) for regression analysis. Stem diameter was also measured at 10 cm above ground height (D_{10}) and a diameter equivalent calculated (Avery & Burkhart, 1983). The fresh weight of each saltbush was measured and a whole branch sub-sample collected for moisture determination and to determine wood and leaf proportions. Sub-samples were placed in calico bags and oven dried at 70 °C to constant weight. Moisture ratios were derived to convert total saltbush fresh weight to oven dry weight. A subset of the oven dry samples were stripped of leaves and small stems <2 mm with this fraction representing the proportion of EDM as described by Andrew *et al.* (1976).

Below-ground sampling (A. nummularia)

For the estimation of below-ground biomass the roots of two plants from each plot were excavated to a depth of 30–50 cm, using a 1.5 tonne excavator. Soil was placed on a sieving table having a mesh size of 50 mm and roots collected as described by Ritson & Sochacki (2003). Roots were excavated to a minimum diameter of approximately 5 mm, roots of lesser diameter were not sampled as it was difficult to associate these to the individual trees being sampled.

Estimation of stand carbon sequestration

Carbon sequestration was estimated from dry biomass by (1) assuming a carbon content of the dry biomass of 50% (Gifford, 2000) and (2) converting this to carbon dioxide equivalents on the basis of molecular weight.

$$\mathrm{CO_2} - \mathrm{e} = \mathrm{D}b \times \mathrm{C}b \times 3.67$$

,

where D*b* is the oven dry biomass, C*b* is the default carbon proportion of dry biomass (50%) and 3.67 is the atomic mass ratio of carbon dioxide to carbon for CO_2 (44/12).

Soil salinity measurements

Apparent soil electrical conductivity (ECa) was measured using a Geonics EM38 electromagnetic induction meter. The EM38 values were used in a relative manner to compare treatments. The apparent electrical conductivity of the salt scald was measured in early winter 2005 and again in the winter of 2009. Measurements were made within the measurement plots both on the tree mound and in the adjacent alley. At each measurement location, the EM38 was used in both horizontal (EM38 H) and vertical mode (EM38 V). In 2005, EM38 measurements were also taken along a 100 m transect starting at the salt scald fringe and extending across the treatment plots in order to identify if a salinity gradient was present.

Statistical analysis

Plot data were investigated by analysis of variance and Pearson's correlations using XLSTAT statistical software.

Results

Allometry for A. nummularia

A total of 54 shrubs were sampled for the development of allometric equations for *A. nummularia*, of which 22 were sampled for below-ground biomass. Shrubs sampled ranged from 1 to 45 kg total dry weight with an average of 19% EDM and a root to shoot ratio of 0.22 (Table 1).

Above-ground biomass followed a linear trend in relation to CVI with very similar relationships being observed for both the 500 and 2000 stems ha^{-1} treatments (Fig. 2). The data for the 500 and 2000 stems ha^{-1} treatments were combined for the development of allometric equations, for both the above-ground and below-ground biomass (Table 2). Only above-ground biomass was estimated annually following recovery from grazing and is assumed to provide an estimate of crown volume unaffected by grazing. Estimation of below-ground biomass using CVI as a predictor variable would only be applicable to the initial sampling year as subsequent grazing would affect crown volume but not root biomass. An allometric equation for below-ground biomass was also developed using D_{10} as a predictor (Table 2).

Table 1 Characteristics of *Atriplex nummularia* shrub biomass (kg plant^{-1}) sampled for allometric equations. *n* is the number of samples, SE is the standard error

		Biomass (kg plant^{-1})		
Attribute	*n*	Range	Mean	SE
Above ground (B_{ag})	54	0.6–42.9	10.5	1.4
Below ground (B_{bg})	22	0.1–9.2	3.0	0.6
Total (B_t)	22	0.9–45.0	13.5	2.9

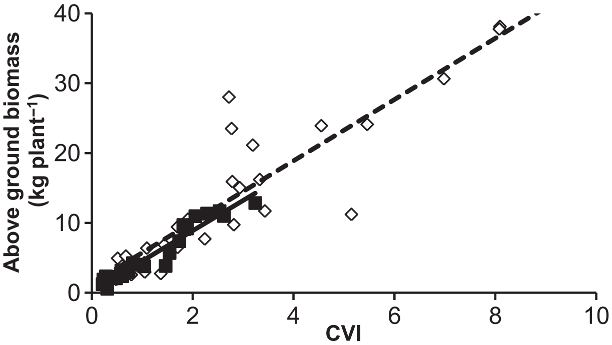

Fig. 2 Relationship between crown volume index (CVI) and above-ground biomass (kg plant^{-1}) for the *Atriplex nummularia* shrubs sampled from the 500 (◊) and 2000 (■) stems ha^{-1} treatments for the development of allometric equations.

Survival and tree growth

Survival of *E. occidentalis* was consistently around 85% for both the 500 and 2000 stems ha^{-1} treatments (Fig. 3a, b). For *A. nummularia* survival was between 86% and 89% for the 500 and 2000 stems ha^{-1} treatments, respectively (Fig. 3c, d). The highest mean total biomass yields for *E. occidentalis* were 18 and 37 t ha^{-1} for the 500 and 2000 stems ha^{-1} treatments respectively at 8 years (Fig. 3a, b). Total average biomass yields were significantly greater ($P < 0.05$) for the 2000 stems ha^{-1}, compared to the 500 stems ha^{-1} treatments for all years measured (4–8 years of age).

Above-ground biomass yields for *A. nummularia* did not increase over time (Fig. 3c, d) possibly as these plots were grazed by sheep each summer. The greatest above-ground biomass yields were achieved from the 2000 stems ha^{-1} treatment, with yields of 11 t ha^{-1} at 4, 6 and 8 years. The greatest mean above-ground biomass yield for the 500 stems ha^{-1} treatment was 10 t ha^{-1} at 8 years. There were no significant differences in mean total biomass yield between the two planting densities for any given year measured (2005–2009). Below-ground biomass yield for *A. nummularia* was estimated for the first measurement year (4 years) at 1.9 and 3.7 t ha^{-1} for 500 and 2000 stems ha^{-1} respectively, for subsequent years below-ground biomass was not estimated.

Total biomass yields of *E. occidentalis* for the 2000 stems ha^{-1} treatments were significantly correlated with soil apparent electrical conductivity as measured with the EM38 H at 4 years ($r = -0.9$, $P < 0.05$) and 8 years after establishment ($r = -0.93$, $P < 0.05$). A negative linear relationship is evident for both the 500 and 2000 stems ha^{-1} treatments (Fig. 4a, b). EM38 H (mS m^{-1}) readings taken along a 100 m transect extending across treatment plots from the fringe of the salt scald were negatively correlated with distance from the salt scald for both tree mounds ($r = -0.75$, $P < 0.0001$) and for measurements taken in the tree alley ($r = -0.84$, $P < 0.0001$) (Fig. 5). EM38 H measurements from the alley were also significantly ($P < 0.0001$) higher than the mounds.

Discussion

Biomass production

The areas adjacent to the salt scald had been effectively abandoned to agriculture but *E. occidentalis* produced a mean of 4.6 t ha^{-1} yr^{-1} (8.5 t CO_2-e ha^{-1} yr^{-1}) after 8 years, with plot values ranging as high as 5.9 t ha^{-1} yr^{-1} (10.8 t CO_2-e ha^{-1} yr^{-1}). This is within the range of 1–10 t ha^{-1} yr^{-1} reported on poor soils unsuitable for agriculture in other studies (Hoogwijk

Table 2 Allometric equations for the prediction of above-ground (B_{ag}) and below-ground biomass (B_{bg}) in *Atriplex nummularia*, including a range of goodness-of-fit indices as for Sochacki *et al.* (2007). These were based on the crown volume index (CVI) and diameter of the stem at 10 cm above ground (D_{10}). *n* is the number of samples, r^2 the coefficient of determination, FI is fit index, SE standard error of estimate and CV (%) is the coefficient of variation

Component	*n*	Pred. var.	Allometric equation	r^2	FI	SE	CV (%)
Above-ground biomass	54	CVI	$B_{ag} = 0.494 + 4.607*\mathrm{CVI}$	0.97	0.97	1.34	14
Below-ground biomass	22	D_{10}	$B_{bg} = 0.0874*D_{10}^{1.6163}$	0.56	0.47	0.87	28

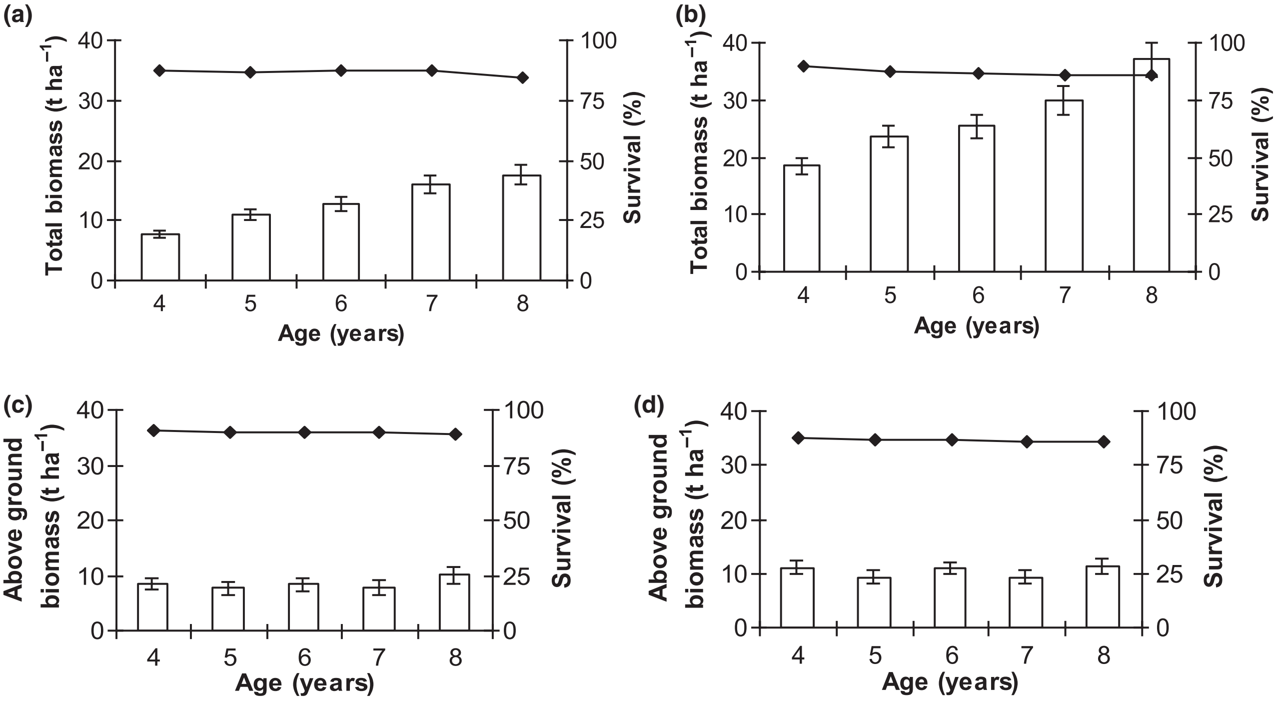

Fig. 3 Total biomass (t ha^{-1}) and survival (%) of *Eucalyptus occidentalis* planted at (a) 500 stems ha^{-1} and (b) 2000 stems ha^{-1}. Above-ground biomass and survival of *Atriplex nummularia* planted at (c) 500 stems ha^{-1} and (d) 2000 stems ha^{-1}. Error bars are standard error.

et al., 2003). *A. nummularia* was planted into large mounds in close proximity to the salt scald, with total standing above-ground biomass of between 9 and 11 t ha^{-1} between years 4 and 8, of which 19% was fodder. Fodder production from this species has received considerable attention as an alternate and complementary animal feed during the typically dry summer period this region experiences. In conjunction with other pastures, *Atriplex* plantings have also provided additional nutrition for sheep during autumn (Barson *et al.*, 1994). Approximately 1.9 t ha^{-1} yr^{-1} of edible fodder was produced on this site and this is comparable to other studies (Benjamin *et al.*, 1995; Abu-zanat *et al.*, 2004).

Biomass production was affected by both stocking density and soil salinity. Biomass production by *E. occidentalis* was higher at 2000 stems ha^{-1} than at 500 stems ha^{-1}. However, at 2000 stems ha^{-1} biomass production was affected by soil salinity levels but not at 500 stems ha^{-1}. The response of *E. occidentalis* to soil salinity at 500 stems ha^{-1} differs from the observations of Benyon *et al.* (1999) and Marcar *et al.* (2003). Benyon *et al.* (1999) reported a 10% reduction in height of *E. occidentalis* at a root zone salinity of 10 dS m^{-1} while Marcar *et al.* (2003) reported no growth decline up to an EC$_e$ of 10 dS m^{-1}. In this study, published calibration curves for the EM38 developed for soils of this region (Bennett & George, 1995) were used to produce estimates of soil salinity. Based on the EM38 values, the soil salinity was in excess of 10 dS m^{-1}, yet no significant response was observed for the 500 stems ha^{-1} *E. occidentalis* treatments. Marcar *et al.* (1995) reported marked variations in the response of different prove-

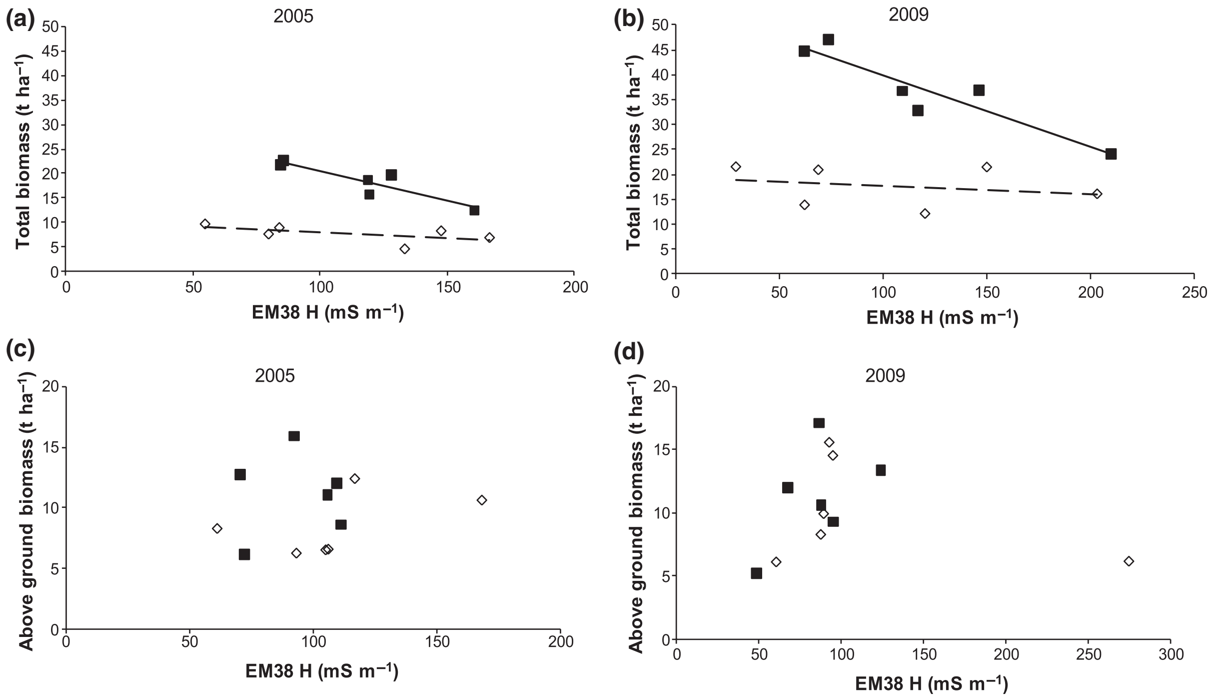

Fig. 4 Relationships between total biomass and soil conductivity in 2005 and 2009 for *Eucalyptus occidentalis* (a and b) and *Atriplex nummularia* (c and d) for 500 (◊) and 2000 (■) stems ha^{-1} treatments.

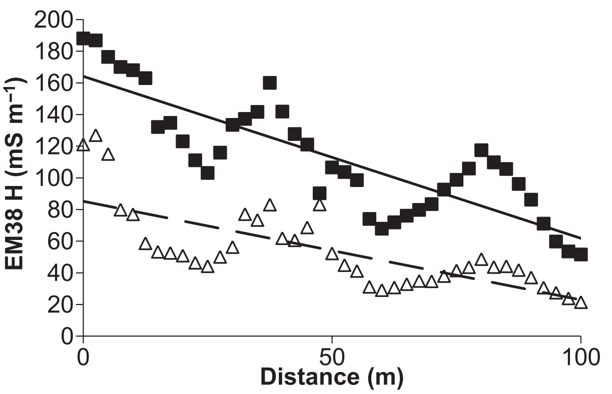

Fig. 5 Soil conductivity along a 100 m transect extending from the salt scald fringe, across treatment plots as measured with an EM38 (8 years after establishment) for mounds (Δ) and tree alleys (■).

nances of *E. occidentalis* to soil salinity and this may explain these results.

Although some halophytes show improved growth under mildly saline conditions (Stirzaker *et al.*, 2002), there was no significant effect of soil salinity levels on biomass production of *A. nummularia*. Soil electrical conductivity levels indicate a reduced level of salinity in mounds compared with the inter-row region and this may have reduced any effects of soil salinity. Salt concentrations are reduced following winter rains due to leaching of salt from the mounds back into the subsoil, an effect apparent in comparisons of salinity in the mounds and adjacent alleys in Fig. 5. Mounding has been used in other saltland planting studies and has been effective in leaching salt from the seedling root zone (Marcar *et al.*, 1995). The good growth of *A. nummularia* on these sites and the lack of a salinity response implies that this species may tolerate being planted in closer proximity to the hypersaline salt scald and thus utilize more of the abandoned farmland.

Future plantings

There are many reports of different growth rates for different species along salinity gradients (van der Moezel *et al.*, 1988; Niknam & McComb, 2000) and these are commonly associated with ecological successions such as in local saline wetlands. *Atriplex* species are reputed to have much greater salt tolerance that *Eucalyptus*, and indeed, this is the observation under natural conditions in south-western Australia, where *Atriplex* species occur on the beds of relict playas with fringing salt-tolerant eucalypts (Harper & Gilkes, 2004). It may thus be possible to design land treatments for salinized sites that take such gradients into account and replicate the ecological successions that occur in wetland ecosystems. *A. nummularia* could, for example, be planted into mounds in close proximity to salt scalds in conjunction with

E. occidentalis adjacent and upslope to these plantings. *A. nummularia* has a limited effect on water table levels (Slavich *et al.*, 1999) but is able to tolerate high salinity levels, coupled with *E. occidentalis*, a high water use species. The combined application of these two species would produce (1) fodder for livestock and (2) biomass for bio-energy or biofuel feedstock and potentially utilize excess soil water and help reduce water logging. Coppicing of harvested trees may be an option to minimize turn-around between rotations and eliminate the need for further soil disturbance through replanting. Marcar *et al.* (2003) report good coppice re-growth for *E. occidentalis* from cut stumps three years after thinning.

A key factor for carbon mitigation will be whether trees can persist on such sites and not be affected by salt accumulation (Stolte *et al.*, 1997). Archibald *et al.* (2006) report on the growth and survival of 25 year old trees adjacent to salt scalds in this region, with these still persisting despite some salt accumulation in their root zones, however these results may be quite site specific. If such salt-affected areas are planted as short rotation tree crops (Harper *et al.*, 2010) as opposed to long-term stands, salt accumulation will be less critical to mitigation performance. The sustainability of plantations on saline discharge sites is dependent on many interacting factors, which can only be resolved through further investigation. In this landscape position afforestation is most likely to have a minimal, if any, effect on ground-water levels and landscape hydrology (George *et al.*, 1999). Afforestation, however, will help to stabilize degraded parts of the landscape and has the potential to positively improve soil quality through the addition of soil carbon, which is typically reduced on salinized soils as a result of reduced vegetative cover (Wong *et al.*, 2010).

Biofuel feedstock potential

With predictions of salinity in Australia affecting up to 17 million hectares (National Land and Water Resources Audit 2001) and poor economic returns from moderately saline farmland areas, the use of these marginal or abandoned farmland areas for carbon mitigation warrants further investigation. If the results presented in this article are indicative of abandoned saline farmland in Australia then there is potential to produce considerable amounts of feedstock for lignocellulosic or second generation biofuel without competing with food production. Of the 17 Mha predicted to become affected by salinity, there will be areas that will not be suitable for carbon mitigation by afforestation, for example hypersaline areas and forest reserves. At the average growth rates reported in this study, and assuming production from half of the salinized area, and a conversion rate of 95 L t^{-1} of biomass (Sims *et al.*, 2010) an 8 year rotation of *E. occidentalis* would potentially produce 3.5 million tonnes of liquid biofuel per year. This is approximately 8% of Australia's 2009 fossil fuel use (BP 2010). Australia's current biofuel production is approximately 0.5% of total transport fuel and does not impinge on food production, however, if biofuel mandates are introduced, feedstocks required for biofuel production may compete with food production (O'Connell *et al.*, 2009).

Global potential

The potential of applying *E. occidentalis* in conjunction with *A. nummularia* to salinized areas in other regions is yet to be investigated. *Atriplex* species have been trialed in many countries and regions including North Africa (El Aich, 1992), Egypt (Fayed *et al.*, 2010) and Israel (Benjamin *et al.*, 1995). *A. nummularia* has been selected due its high growth rate and palatability for livestock. Reported yields range from 11 t ha^{-1} (Benjamin *et al.*, 1995) in arid regions (northern Negev, Israel) to 23 t ha^{-1} (Barrett-Lennard & Malcolm, 1995) for irrigated plots in Australia. In the San Joaquin Valley, California, *A. nummularia* was irrigated with saline water (18 dS m^{-1}) and produced 15.6 t ha^{-1} biomass from four successive total harvests (Watson & O'Leary, 1993). The performance of species in field trials result from a range of soil and climatic conditions and management scenarios and these need to be taken into account in the development of regional or global estimates. For example, mounding, fertilizer application and local conditions such as waterlogging will all have an effect on yield. In comparison, the use of salt-tolerant *Eucalypt* species on salinized farmland in regions outside Australia is limited and data relate predominantly to *E. camaldulensis* Dehnh (Marcar *et al.*, 1995). The use of *E. occidentalis* for saltland plantings is less well documented, despite this species having a higher tolerance to soil salinity than *E. camaldulensis* (Marcar *et al.*, 1995). Benyon *et al.* (1999) reported a 10% reduction in height growth of *E. camaldulensis* with soil salinity as low as 2 dS m^{-1}. However, for *E. occidentalis*, a 10% reduction in height was only evident at 10 dS m^{-1} with similar responses observed for stem diameter and crown volume.

This highlights the need for further studies and the synthesis of data from different regions globally. The performance of species in relation to site-specific conditions will provide invaluable input data for modeling global estimates of biomass yield. Salt-affected regions globally cover a range of soil and levels of salinity and therefore yield from afforestation would be affected accordingly. Wicke *et al.* (2011) report on global potential of bioenergy from salt-affected land based on the Harmonized World Soil Database (HWSD) and reported an average global biomass yield of 3.1 oven dry t ha^{-1} yr^{-1}, based on yields from three species including *E. camaldulensis*. In that study, Australia is reported as having 169 Mha of salt-affected land and the average biomass yield for Australia is estimated at 7.6 oven dry t ha^{-1} yr^{-1}, twice the global average. Clearly this estimate of salt-affected land is very different to local predictions of salinity in Australia of 17 Mha (National Land and Water Resources Audit 2001), the lack of data for Australia and the accuracy of the HWSD is questionable, thus highlighting the need for species specific regional data sets and accurate global soil data for modeling of global bioenergy potential. To estimate the global bioenergy potential of *E. occidentalis* and *A. nummularia* would require modeling of soil and climatic inputs, regional yield data and management regimes and species attributes that are beyond the scope of this study.

Nonetheless, it is obvious from this and other studies (Dornburg *et al*., 2010; Wicke *et al*., 2011) that considerable potential exists for bioenergy production from salinized farmland and given the threat increasing soil salinity has on global food production, further research is warranted. Similarly, given the tolerance of *A. nummularia* to salinity, the utilization of this species in bioenergy production could also be usefully examined.

Conclusions

In this study, we have demonstrated the potential of salinized abandoned farmland in providing carbon mitigation through biomass for bioenergy or as a future lignocellulosic feedstock. The commercial production of second generation biofuels from lignocellulosic biomass is promising and supplies of biomass feedstocks are obviously crucial to the success of commercial production; abandoned salinized farmland is therefore a potential feedstock source for this future industry. Mitigation can thus occur without displacing food production, and using combinations of *Eucalyptus* and *Atriplex* species may not only provide some mitigation but also produce fodder for livestock. Further research is required to extend the results of this study across broader areas of salinized land, determine the long-term viability of such land treatments and examine the greenhouse gas balances of harvested and grazed systems on abandoned farmland. It will be imperative that species be tested in different soil and climatic regimes in order to improve regional data sets for global estimates.

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