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Research Paper

Mitigation of carbon using *Atriplex nummularia* revegetation

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ABSTRACT

The use of abandoned or marginally productive land to mitigate greenhouse gas emissions may avoid competition with food and water production. *Atriplex nummularia* Lindl. is a perennial shrub commonly established for livestock forage on saline land, however, its potential for carbon mitigation has not been systematically evaluated. Similarly, although revegetation is an allowable activity to mitigate carbon within Article 3.4 of the United Nations Framework Convention on Climate Change's Kyoto Protocol, there is a paucity of information on rates of carbon mitigation in soils and biomass through this mechanism. For six sites where *A. nummularia* had been established across southern Australia four were used to assess changes in soil carbon storage and four were used to develop biomass carbon sequestration estimates. A generalised allometric equation for above and below ground biomass was developed, with a simple crown volume index explaining 81% of the variation in total biomass. There were no significant differences in soil organic carbon storage to 0.3 m or 2 m depth compared to existing agricultural land-use. Between 2.2 and 8.3 Mg C ha^{-1} or 0.2–0.6 Mg C ha^{-1} yr^{-1} was sequestered in above and below ground biomass and this translates to potential total sequestration of 1.1–3.6 Tg C yr^{-1} on saline land across Australia. Carbon income and forage grazing may thus provide a means to finance the stabilization of compromised land.

1. Introduction

Carbon dioxide (CO_2) levels have increased by 40% since pre-industrial times, and as a consequence global surface and ocean surface temperatures show a warming of 0.85 °C over the period of 1880–2012 (IPCC 2013). The increase in atmospheric CO_2 has mainly occurred through the combustion of fossil fuels and the conversion of forests to agriculture (Battle et al., 2000; Le Quéré et al., 2013). Across different emission scenarios the mean global surface temperature is projected to increase by between 1.5 °C and 3 °C relative to 1850–1900 by the end of the 21 st century (IPCC 2013).

A diverse range of policies, instruments and technologies are required to create a significant reduction in greenhouse gas (GHG) emissions and thus reduce the rate of temperature increase (IPCC 2014). The land sector both emits GHGs but also plays a central role in their mitigation (Bustamante et al., 2014; Smith et al., 2014). There are three main land sector approaches to mitigation: (1) the production of bioenergy from biomass to offset fossil fuel use (Chum et al., 2011), (2) carbon sequestration which is the transfer of atmospheric carbon dioxide into long-lived carbon pools in soils and plants (Lal 2008) and (3) the reduction in emissions from sources including deforestation, enteric fermentation in domestic animals and nitrogen fertilizers (Smith et al., 2014). Most research on land-based carbon mitigation has explored bio-sequestration via reforestation/afforestation, or storage in soils (Smith et al., 2014). Revegetation, which is the establishment of vegetation that does not meet the definition of a forest, is an allowable activity under Article 3.4 of the Kyoto Protocol (UNFCCC 1997), but is characterized by a lack of literature that quantifies its potential contribution to climate change mitigation (Smith et al., 2014).

Carbon sequestration is often viewed as a win–win situation, providing environmental co-benefits while also mitigating atmospheric CO_2 (Harper et al., 2007; Bustamante et al., 2014). However,

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Table 1
Summary of environmental features and sampling regime at each of the sites.

Site	Location		Planting Density	Rainfall	Salinity	Age of plantation	Number of plants sampled		Sampling methods	
	Lat. (°S)	Long. (°E)	(plants ha^{-1})	(mm)	(mS m^{-1})	(years)	AGB	BGB	AGB	BGB
Deniliquin	35.293	144.452	1250	337	–	5	14	14	F.H	Excavation + Cores
Monarto	35.717	139.848	1111	368	33	4	12	6	F.H	Excavation
Pithara	30.363	116.729	1411	315	192	11	14	0	F.H	–
Three Springs	29.622	115.649	892	382	288	13	12	0	F.H	–
Waikerie	32.433	117.394	635	248	23	4	9	9	F.H	Excavation
Wickepin	32.433	117.394	500, 2000	404	190	13	54	22	F.H	Excavation

Salinity measured with EM38; AGB: Above Ground Biomass; BGB: Below Ground Biomass; F.H: Full harvest.

concerns have been raised with respect to reforestation and competition for land (Haberl et al., 2014), water (Jackson et al., 2005), reduced biodiversity (Lindenmayer et al., 2012) and the displacement of other land uses (Mitchell et al., 2012). This increases pressure on food security, and may be most pronounced in developing countries where food shortages are more prevalent (Foley et al., 2005; Smith et al., 2014).

Utilising abandoned or degraded land for carbon mitigation provides an opportunity to utilise land that has marginal potential for other uses (Silver et al., 2000; Sochacki et al., 2012; Wicke et al., 2011). Campbell et al. (2008) estimated that 385–472 million hectares of land is abandoned globally and suggested that potential mitigation on abandoned land is greatest in Australia, Brazil, and the United States. Prolonged inappropriate agricultural practices are a common cause of land degradation (Powlson et al., 2011) and Australia has large areas of land that are abandoned because of improper farming practices, such as over clearing and overgrazing (Pannell and Ewing 2006). For example, large expanses of land have become saline, reducing the productivity of the affected land (Lefroy and Stirzaker 1999). It is estimated that 5.7 Mha of land across Australia has salinized or is at risk of becoming saline, with this increasing to 17 Mha by 2050 (National Land and Water Resources Audit, 2001).

A form of rehabilitation of saline land is the establishment of halophytic saltbush species (e.g. *Atriplex* spp.) (Smith 2008). These species are typically planted in areas of marginal value for cropping or grazing, because of their resistance to drought and tolerance of poor soil conditions (de Araújo et al., 2006; Slavich et al., 1999). *Atriplex nummularia* Lindl. is commonly used as forage for grazing ruminants during times of feed shortages, as peak foliage production occurs in summer when other feeds may be limited (Ben Salem et al., 2010). It follows that the majority of research involving this species has focussed on its use as livestock forage (Ben Salem et al., 2010; Glenn et al., 1998; Norman et al., 2004; Slavich et al., 1999).

The potential of *A. nummularia* established on abandoned and marginal agricultural land for carbon sequestration has not been formally published, despite the large amount of land potentially available for mitigation activities. The use of salt-land has however been considered for bioenergy production (Glenn et al., 1993; Sochacki et al., 2012; Wicke et al., 2011). Such a form of mitigation may be complementary to other forms of dryland carbon mitigation. Although mallee eucalypts are widely planted in Australian dryland carbon mitigation projects (Paul et al., 2015; Harper et al., 2017) these are not adapted to very saline soils.

Several assessments of the carbon mitigation potential of saltbush have remained in the grey literature (Issango et al., 2006; Montagu et al., 2003) or not been published at all. In this study, data from several of these studies and other unpublished data will be utilized, along with new field measurements. This study thus aims to explore the prospect of *A. nummularia* being used to sequester carbon on saline and poorly productive farmland in Australia by a) developing a more efficient method of estimating carbon in *A. nummularia* stands and in particular determining what explanatory variables contribute the most information to allometric relationships, b) producing an estimate of *A. nummularia* carbon sequestration potential at various sites across southern Australia, c) examining how carbon sequestered by *A. nummularia* is partitioned between soil organic carbon, and above and below ground biomass and d) examining factors such as planting density that affect the rates of sequestration by this species. This will allow policy makers, landholders and investors to determine whether carbon sequestration using this species is a viable carbon mitigation strategy, particularly in relation to other carbon mitigation approaches such as reforestation.

2. Methods

2.1. Sampling sites

Data were collected from six sites where *A. nummularia* had been established on farmland across southern Australia (Table 1, Fig. 1). These sites were considered representative of land that is marginal or degraded for typical agriculture in these areas. Across the six sites planting density varied from 500 to 2000 plants ha^{-1} and stand age ranged from 4 to 13 years at the time of sampling (Table 1).

The six sites all fell within the Australian temperate climate zone, using the Köppen classification system, with wet and mild winters, hot dry summers (BOM 2017) and mean annual rainfall ranging from 248 to 404 mm yr^{-1} (Table 1). The sites were grazed by sheep during late summer with edible dry matter (<2 mm stem size) removed. Plots were left to regrow and were measured in the following period, prior to grazing.

The sites were classified as saline or not saline based on soil measurements (Table 1). For Pithara, Three Springs and Wickepin a Geonics EM38 conductivity meter was used and for Monarto and Waikerie, salinity was measured on soil samples, and converted to EM38 equivalent values using the approach of McKenzie et al. (1989). No soil salinity data were available for Deniliquin.

2.2. Biomass sampling

The carbon mitigation potential of a planting is often calculated using allometric equations. These equations relate explanatory values such as height, crown width, or a crown volume index (CVI) to the above, below, or total biomass of a given individual plant. The use of these equations allows carbon mitigation to be calculated without the need for destructive sampling.

At each site saltbush plants were destructively sampled as described by Snowdon et al. (2002). Plants were randomly selected across the dynamic range of plant sizes to ensure data were representative. Potential predictor variables of shrub height, crown height, length and width were measured and applied in the development of allometric relationships. The number of plants sampled at each site is given in Table 1.

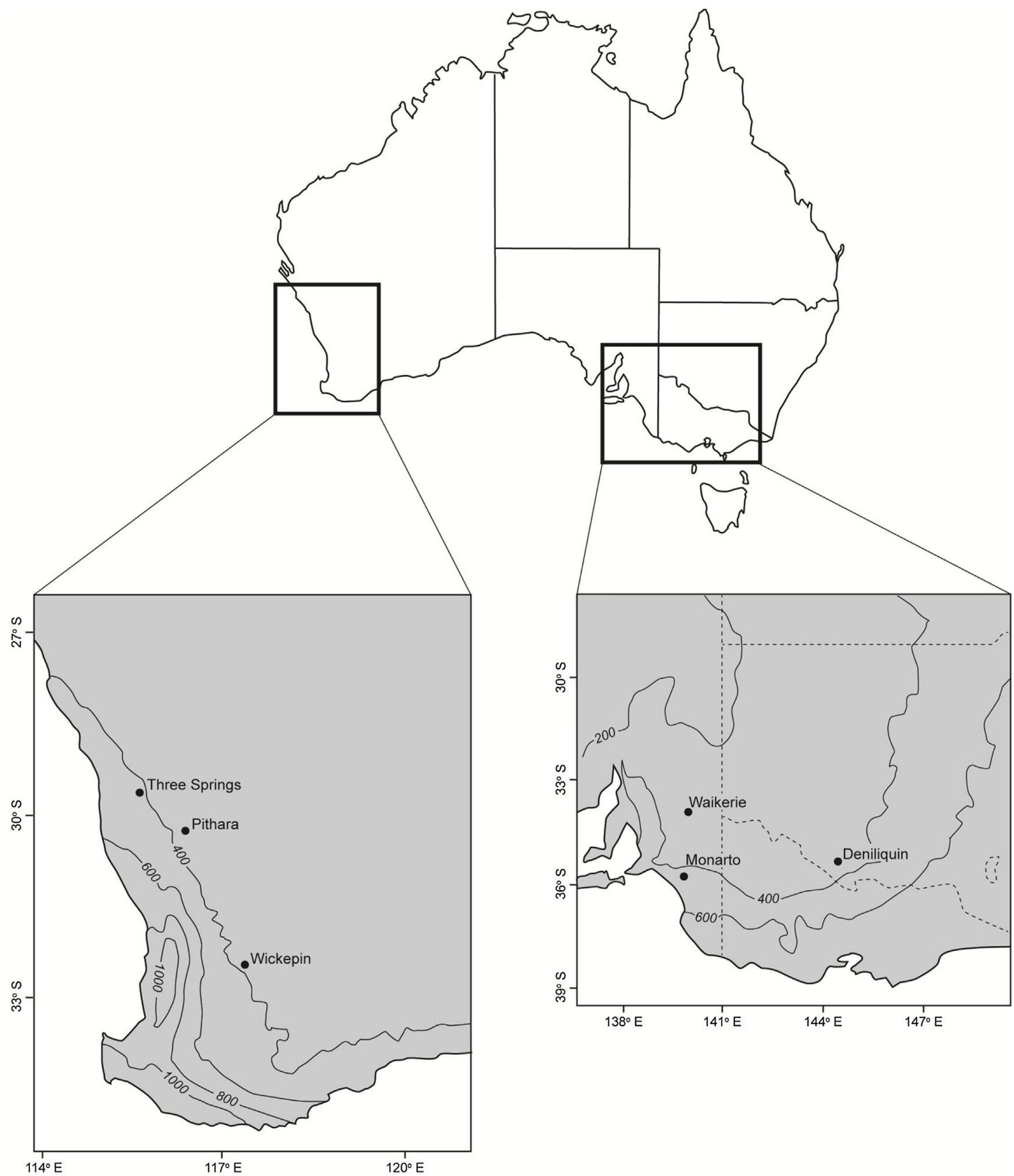

Fig. 1. Map showing position of sites sampled across southern Australia. Inset maps show more detailed positioning of sites with mean annual rainfall (mm/yr) isohyets. The Wickepin, Monarto, Waikerie and Deniliquin sites were used to develop the allometric model.

2.3. Above ground biomass

At Deniliquin, Monarto, Waikerie and Wickepin the above ground biomass (AGB) was separated into components of stems and leaves (Fig. 2). Given that *A. nummularia* is mostly used as a forage shrub the biomass of foliage was not used in carbon calculations. The total fresh weight of each component was recorded and subsamples (0.5–0.7 kg) of each component were collected, dried at 70 °C to constant dry weight and total dry weight determined. At Pithara and Three Springs the above ground biomass was not separated into different components but weighed whole and then sub-sampled to estimate oven dry weight using the procedures above.

2.4. Below ground biomass

At Wickepin, Monarto and Waikerie below ground biomass samples were taken by excavating soil by machine to 0.5 m and placing this on a sieving table overlaid with 50 mm square mesh as described by Ritson and Sochacki (2003) (Table 1). Samples were taken at the mid-point between adjacent shrub rows and the mid-point between shrubs within rows. All roots were collected to a

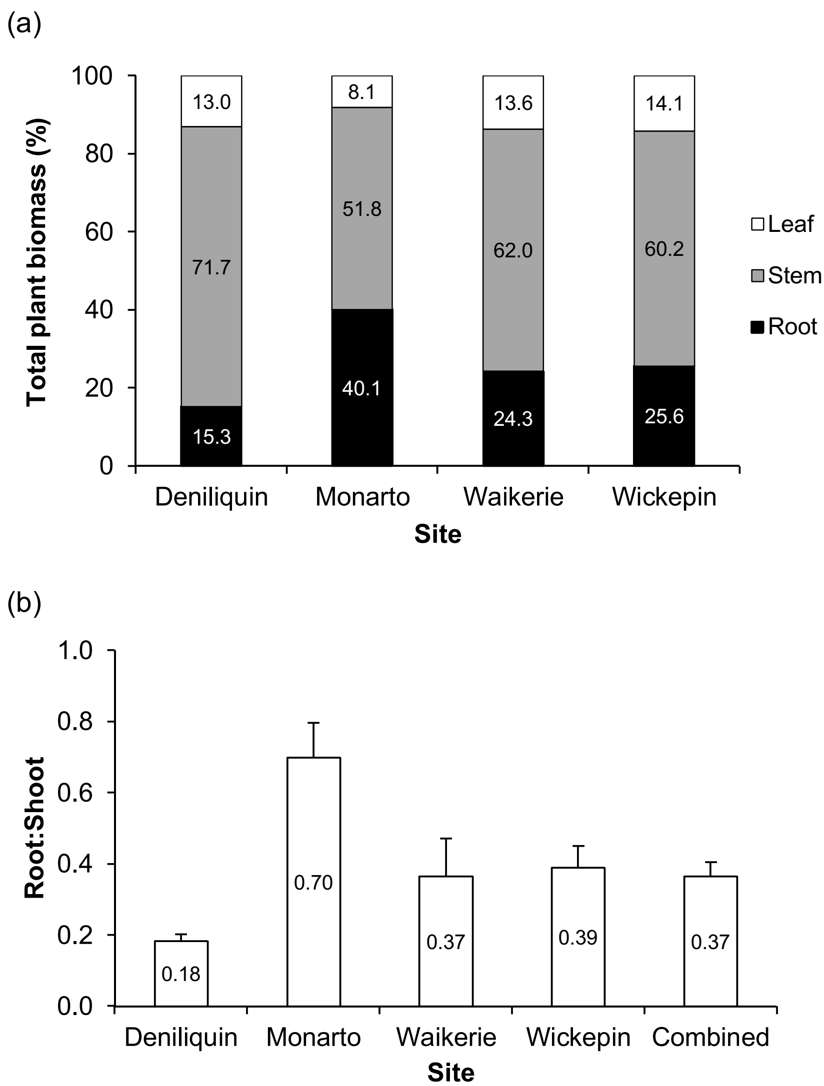

Fig. 2. Biomass data for each site. a) The mean percentage (%) of each biomass component at the four sites with above and below ground data and b) mean root to shoot ratio at each of the sites, and the mean when sites were combined. Bars are s.e.

minimum diameter limit of approximately 2 mm. Individual tap roots were excavated to a depth of 1 m. The roots were washed to remove any adhering soil and then dried, as described above, to determine the dry weight. Below ground biomass (BGB) was not measured at Pithara and Three Springs.

At Deniliquin, roots were sampled using a two stage method as described by Zerihun and Montagu (2004). The first stage involved soil coring for fine roots (<5 mm diameter) using a coring apparatus (Sochacki et al., 2007) with an internal diameter of 115 mm. Soil cores were collected to a depth of 1 m at increments of 0–0.1 m, 0.1–0.2 m, 0.2–0.3 m, 0.3–0.5 m and 0.5–1.0 m. Core samples were wet sieved to extract root material and dried at 70 °C. The second stage involved the excavation of sample plots as described above, to recover all roots ≥5 mm in diameter for all the sampled shrubs.

2.5. Soil organic carbon

To assess changes in soil organic carbon (SOC) stocks at Wickepin, Deniliquin, Waikerie and Monarto soil samples were collected within treatment plots using the sampling methods described below.

2.5.1. Wickepin

At Wickepin treatments consisted of replicated plots of two plant densities (500 and 2000 plants ha^{-1}) as described by Sochacki et al. (2012). It was assumed that any changes in SOC would most likely be evident under high density treatments (2000 plants ha^{-1}), thus only this treatment and the control were sampled. A coring apparatus (Sochacki et al., 2007) with an internal diameter of 115 mm was used to collect soil samples. Four control and six high density treatment plots were sampled. Four core samples were taken within each plot, one to a depth of 2 m, and three to a depth of 0.3 m. All cores were taken at a midpoint between the planting lines or approximately 1 m from the base of the saltbush shrub. The treatment plots were 40 × 40 m in size and cores were taken approximately 5 m inside the plot boundary to avoid edge effects. Depth intervals of coring were 0.1, 0.1–0.2 0.2–0.3, 0.3–0.6, 0.6–0.9, 0.9–1.2, 1.2–1.5, 1.5–1.8 and 1.8–2.0 m.

2.5.2. Deniliquin

For each plot at Deniliquin soil carbon concentration was measured on six bulked soil samples taken to a depth of 1 m. Four of these samples originated from bulking a subsample from the fine root sample cores. An additional two subsamples were taken from the soil bulk density samples. Samples were taken from the saltbush plots and control treatments were sampled from the adjacent pasture.

2.5.3. Waikerie and Monarto

Soil samples were taken in depth increments of 0.05, 0.05–0.1, 0.1–0.3, 0.3–0.6, 0.6–1.0, 1.0–1.5 and 1.5–2.0 m adjacent to saltbush plants using a 4.5 cm diameter soil corer. A total of 6 samples were collected for each plant at distances of 0.2, 1 and 2 m from the base of the plant and there were three replicates. Control samples were taken from pasture treatments at Monarto and from cropping treatments at Waikerie these being adjacent to the saltbush plots.

2.6. Soil analysis

Soil samples were air-dried in a glasshouse prior to C analysis. Bulk density (BD) was determined for each depth interval by drying a subsample to 105 °C and correcting for moisture content to determine BD based on the mass-volume relationship.

Soil samples were sieved through a 2 mm sieve and the >2 mm fraction collected and weighed. The total SOC of the <2 mm fraction was determined by the Leco combustion method, LECO CNS 2000 analyser, method 6B3 (Rayment and Higginson 1992). Soils were also tested for the presence of calcium carbonate (McKenzie et al., 2000). Total SOC mass was calculated from the bulk density and carbon concentration, to express the total carbon content of the soil after taking into account the presence of any coarse (>2 mm) fractions using an equivalent soil mass (ESM) within a specified soil depth as described by Wendt and Hauser (2013).

2.7. Carbon analysis of A. nummularia

Carbon content of *A. nummularia* was determined from 8 plants at Wickepin, 9 plants from Waikerie, and 14 plants at Deniliquin. Sample shrubs were selected randomly from within the sample plots, separated into leaves and stems then dried at 70 °C to constant weight. The analysis for carbon content was undertaken at a commercial laboratory, using the Leco combustion method (Rayment and Higginson 1992). The carbon content of roots at Waikerie was also determined using the same analytical procedure.

2.8. Carbon isotopic analysis

For soil from Deniliquin the stable carbon isotopic $\delta^{13}C$ was determined on the fine root samples from 0 to 10 cm depth using a Europa Scientific automated nitrogen carbon analysis mass spectrometer as detailed in Krull and Bray (2005). This was conducted to determine the contribution of saltbush plants to SOC pools. The relative proportions of fine roots of C4 plants (*A. nummularia*) and C3 plants (temperate pasture grasses) were estimated from the following equation (Ludlow et al., 1976):

$$\%C4 = ((\delta_s - \delta_{C3})/(\delta_{C4} - \delta_{C3}))x100 \qquad (1)$$

Where δ_s, δ_{C3}, and δ_{C4} are the $\delta^{13}C$ values of, the fine root sample, average of the C3 grass, and average of the C4 *A. nummularia.*

The $\delta^{13}C$ of soil samples from the 0–10 cm increment was analysed as detailed above. The relative proportions of derived soil organic carbon from of C4 plants (*A. nummularia*) and C3 plants (temperate pasture grasses) were estimated using Eq. (1), with δ_s being the $\delta^{13}C$ of the soil sample from either the saltbush or pasture plots.

2.9. Allometric equations

Allometric equations were developed using the biomass data from Wickepin, Monarto, Waikerie and Deniliquin (Fig. 3). Four

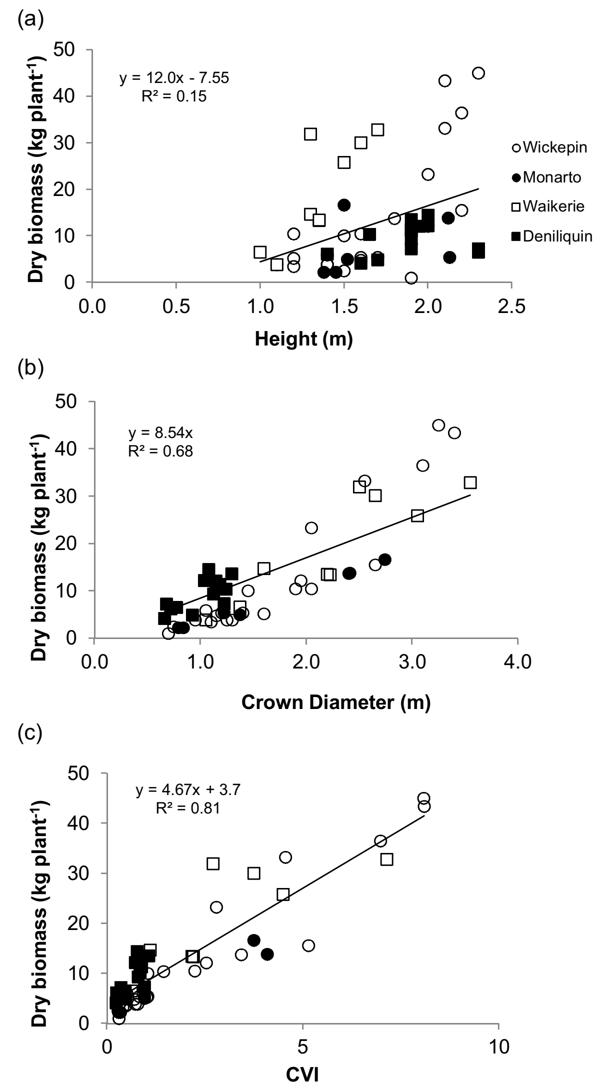

Fig. 3. Total dry biomass (TB) compared with the different plant growth estimators for all sites combined. a) height, b) crown diameter and c) crown volume index (CVI).

models (linear with y-intercept, linear with y-intercept as 0, logarithmic and exponential) were fitted according to apparent trends within the data. Models were tested using the extra sum of square F-test to select the model with the best fit to the data. A fit index, standard error of estimate and coefficient of variation were also used to determine the model with the best fit to the data (Table 2). Normality assumptions were tested on all models. To test whether an all-inclusive (combined) model was possible, a dummy variable was used to test whether the difference in site-specific slopes was significant. If the slopes were not significantly different the sites were pooled to derive a combined model. Likewise, if no significant difference was found between saline and non-saline sites these two categories were combined. Models were fitted and tested using the software package R-Studio (R Core Team, 2014).

2.10. Estimation of carbon sequestration

The allometric relationships (Table 2) were applied to predict the amount of carbon sequestered per plant in the stems and roots and takes into account that leaves are grazed on an annual basis and thus don't represent a permanent component of the carbon pools. Carbon sequestered was calculated by applying the allometric equations to stand data collected from permanent measurement

Table 2
Allometric equations for the prediction of above ground biomass (AGB), below ground biomass (BGB) and total biomass (TB) in *Atriplex nummularia*, including a range of goodness-of-fit statistics. These were based on the crown volume index (CVI), diameter (d) and height (h) of the plant.

	n	Allometric equation	R^2	FI	SE	CV (%)
AGB						
CVI	51	AGB = 3.11 * CVI + 2.53	0.79	0.74	3.39	33.9
BGB						
CVI	51	BGB = 0.80 * CVI + 1.12	0.59	0.59	0.99	37.3
TB						
Height	51	TB = 12.0 * h – 7.55	0.15	0.15	7.16	56.6
Diameter	51	TB = 8.54 * d	0.68	0.68	4.41	34.8
CVI	51	TB = 4.67 * CVI + 3.7	0.81	0.81	3.34	26.4

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.

plots to estimate the carbon storage in biomass at the different sites. Variation in stand density and age was considered when calculating sequestration per unit area over time.

Parameters to be applied as biomass predictor variables for *A. nummularia* were measured at all sites, these included shrub height, width and length. At Wickepin permanent measurement plots (0.04 ha) within larger treatment plots were assessed. Similarly, at Three Springs and Deniliquin 0.02 ha measurement plots were established while the Pithara site had 0.03 ha measurement plots. Given that the plots were of a known area and planting density, the data collected from these sites was then used to calculate carbon sequestration for each site.

The allometric equations were applied to the measured saltbush plants to estimate their total biomass. This was converted to carbon using the determined carbon content of components (Table 3) and carbon yield (Mg ha^{-1}) was then calculated based on the planting density.

$$C = Db\text{x}\text{Pc} \tag{2}$$

where:
C = Carbon, Db = dry biomass, Pc = carbon percentage of component.

2.11. Statistical analysis

Root to shoot ratios were analysed using one-way analysis of variance, with Tukey's honest significant difference post-hoc to determine site differences. This test was also used to compare the difference in carbon content (%) of the biomass components between the three sites. Normality assumptions were reviewed using Levene's test of equal variance and an examination of QQ plots. If data did not fulfil the normality assumptions, Welch&s (1990) correction was used, as this test does not assume equal variance.

To test the differences in carbon sequestered across the different sites the Welch analysis of variance test, and Games-Howell post hoc test were used if the data did not satisfy homogeneity of variance assumptions (Levene's test <0.05). This method was also used to test the effect of stand age and density in the long-term data from Wickepin.

3. Results

3.1. Saltbush partitioning

There was some variation in the proportion each plant component contributed towards total plant biomass at each site (Fig. 2a). Saltbush at Monarto had the highest percentage of roots (40.1%) compared to Wickepin (25.6%), Waikerie (24.3%), and Deniliquin (15.3%). The stems made up the largest proportion of the total biomass of shrubs sampled at all the sites (51.8 – 71.7%), while the leaves made up the least (8.1 – 14.1%) with Wickepin having the highest percentage (14.1%) of leaves (Fig. 2a).

Table 3
Carbon content (%) of the plant components with standard errors.

Site	Carbon content (%)		
	AGB		BGB
	Leaf	Stem	Root
Deniliquin	37.3 (±0.3)	46.7 (±0.3)	46.3 (±0.2)
Waikerie	36.5 (±0.3)	47.3 (±0.1)	45.7 (±0.2)
Wickepin	38.8 (±1.1)	49.2 (±0.2)	N.A
Combined average	37.3 (±0.6)	47.7 (±0.3)	46.0 (±0.2)

AGB: Above Ground Biomass; BGB: Below Ground Biomass.

3.2. Root to shoot ratios

The average root to shoot ratio at Monarto (0.70 ± 0.10) was significantly higher than that of Wickepin (0.39 ± 0.06) and Waikerie (0.37 ± 0.11) (Fig. 2b, $P < 0.05$). The Deniliquin plants had the smallest mean root to shoot ratio (0.18 ± 0.02), and this was significantly less than the average root to shoot ratios at Wickepin ($P < 0.05$) and Monarto ($P < 0.05$). The mean root to shoot ratio across all sites was 0.37 ± 0.04 (Fig. 2b).

3.3. Biomass allometric equations

Allometric equations were developed for the combined above and below ground biomass referred to here as total biomass (TB), above ground biomass (AGB) and below ground biomass (BGB) using an array of field measurements. No significant difference was found between the slopes of these regressions for saline and non-saline sites, and therefore these data were combined. Shrub height, width, length, and height to crown base were measured to develop a crown volume index (CVI) (Sochacki et al., 2012). Five different shapes (hemisphere, cylinder, cone, cube, pyramidal) were tested against field biomass data to determine the best shape to calculate crown volume.

CVI provided the strongest relationship with TB, with 81% of the variation in TB explained by variation in CVI (Fig. 3c, Table 2). Height provided the weakest relationship of the three estimators ($R^2 = 0.15$, Fig. 3a). Crown diameter was only slightly less predictive than CVI ($R^2 = 0.68$, Fig. 3b). As the CVI of a plant increases so do the relative variance in TB estimates.

3.4. Carbon content of *A. nummularia*

For the three sites the carbon content of the plant components was similar, although the carbon content of the stems at Wickepin (49.2%) was significantly higher than Waikerie (47.3%, $P < 0.001$). The leaf component had the lowest carbon content (Table 3) at all three sites, however the values of 36.5 and 38.8% at Waikerie

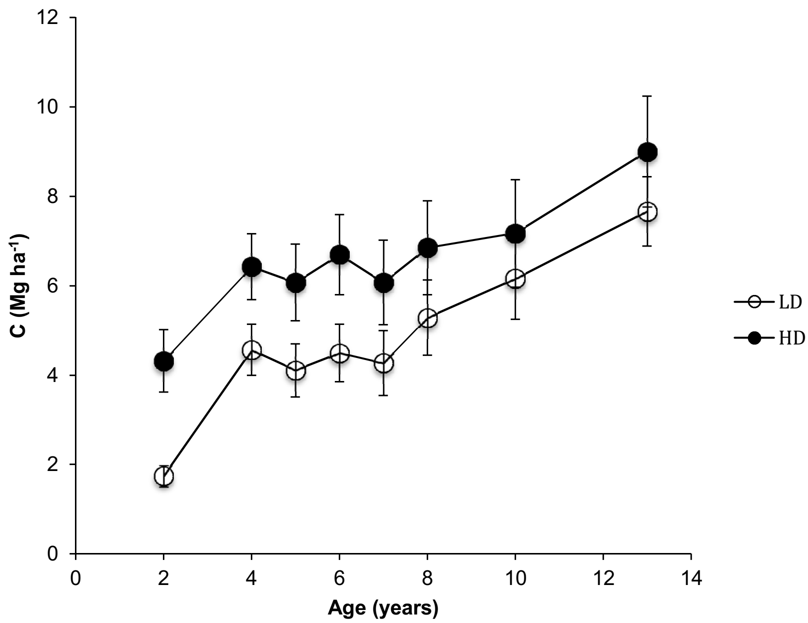

Fig. 4. Carbon sequestered over time at Wickepin for plots of two planting densities (LD: low density, 500 plants ha-1; HD: high density 2000 plants ha-1).

Table 4
Soil carbon storage (t C ha^{-1}) for different depth intervals (0-0.3, 0–3-2.0, 0–1.0 m). None of the paired comparisons between saltbush and pasture were significantly different.

Site	0–0.3 m		0.3–2.0 m		0–1.0 m	
	Pasture	Saltbush	Pasture	Saltbush	Pasture	Saltbush
Deniliquin	–	–	–	–	64.9	71.2
Monarto	43.44	45.39	31.08	35.16	–	–
Waikerie	15.39	14.65	35.69	38.14	–	–
Wickepin	27.91	27.67	22.00	22.52	–	–

– : indicates where data were not available for the given sampling depth.

Table 5
Estimates of carbon sequestration for the four saline sites using the AGB and BGB allometric equations. Standard errors are reported in brackets. Plot-scale estimates were not available for the non-saline sites at Waikerie or Monarto.

Site	Age	Carbon sequestration	
	yr	t C ha^{-1}	t C ha^{-1} yr^{-1}
Deniliquin	5	2.16(±0.10)	0.43(±0.02)
Pithara	11	2.27(±0.53)	0.20(±0.05)
Three Springs	13	4.79(±1.07)	0.37(±0.08)
Wickepin	13	8.33(±0.73)	0.64(±0.06)

and Wickepin were not significantly different ($P > 0.05$). The mean carbon content of the stems was significantly higher than the carbon content of the leaves (37.6 ± 0.64%, $P < 0.001$), and significantly higher carbon than the roots (45.7 ± 0.17%, $P < 0.001$).

3.5. Soil carbon storage

There were no significant differences in soil carbon storage between saltbush and control treatments at Wickepin, Deniliquin Waikerie or Monarto (Table 4). There was also no significant difference found at any of the depth intervals sampled. Carbon isotope analysis at Deniliquin indicated that the relative proportions of soil carbon (0–0.1 m) of C4 origin were 4.5% and 0% respectively in saltbush and pasture plots.

3.6. Carbon sequestration

Using Eq. (2) and converting the estimates of biomass yield on an area basis, the amount of carbon sequestered at the four saline sites ranged from 2.2–8.3 Mg C ha^{-1}, or 0.2–0.6 Mg C ha^{-1} yr^{-1} (Table 5).

At Wickepin, the effects of planting age and density on the rates of carbon sequestration were measured from 4 to 13 years after establishment. The cumulative amount of carbon sequestered across all densities increased from 3.0± 0.53 Mg C ha^{-1} when the planting was two years old, to 8.3± 0. 73Mg C ha^{-1} at 13 years of age (Fig. 4), with an apparent acceleration after eight years. Up to eight years the higher density planting sequestered more carbon, but there was no difference in the cumulative sequestration in the subsequent period (Fig. 4).

4. Discussion

4.1. Allometric relationships

An allometric equation was derived for the estimation of total (above and below ground) biomass across a range of differing sites southern Australia. There was no difference between saline and non-saline sites (Fig. 3c). Interestingly, crown diameter was only slightly less predictive ($R^2 = 0.68$) than CVI ($R^2 = 0.81$) (Figs. 3b, c). The use of this predictor to remotely sense rates of carbon sequestration via aerial based techniques has been assessed by Liu et al. (2017). The combined TB allometric can be used for the development of broad scale carbon estimates from field data and also provides a means of quickly estimating stand biomass.

4.2. Carbon composition of A. nummularia

The partitioning and carbon content of *A. nummularia* has not been previously reported in the formal literature. The leaf components comprise a small proportion of the total biomass of the plant (8–14%, Fig. 2a), and also have the smallest carbon contents (36.5% & 38.8%, Table 3). These carbon values were consistent across both saline (Deniliquin, Wickepin) and non-saline (Waikerie) environments and may thus represent a biological trait of *A. nummularia*. The partitioning of the plant components between leaves, stems and roots did not vary markedly between sites, except for the plants sampled at Deniliquin. The majority of the biomass at this site was found in the stems (51.8 – 71.7%) and roots (15.3 – 40.1%) across all the sites, with the root: shoot ratio at most sites greater than the IPCC default value of 0.2, ranging from 0.37 to 0.70 for Waikerie, Wickepin and Monarto. Only Deniliquin had a value similar to the default value. The combined root to shoot ratio (0.37) across all sites was higher than previously reported for *A. nummularia* by Jones and Hodgkinson (1970), who reported ratios of 0.18 and 0.20 for saltbush occurring in natural communities. The variation in root:shoot ratio may reflect site-specific characteristics, which could not be discerned in this study. Further research is required to extend these findings to other sites to determine possible relationships between root:shoot and site specific factors.

4.3. Carbon sequestration estimates

The annual rate of carbon sequestered by *A. nummularia* of 0.20–0.64 Mg C ha^{-1} yr^{-1} across the sites (Table 5) was modest when compared to the average rate for reforestation with *Eucalyptus occidentalis* on similar land of 2.2 Mg C ha^{-1} yr^{-1} (Sochacki et al., 2012). The carbon sequestration rates reported here are similar to those of Issango et al. (2006) who estimated the carbon sequestered by grazed (0.2 Mg C ha^{-1} yr^{-1}) and ungrazed (0.3 Mg C ha^{-1} yr^{-1}) *Atriplex undulata* on saline land in Wickepin.

At Wickepin, *A. nummularia* sequestered 8.3 Mg C ha^{-1} over a 13-year period, with no differences in sequestration with planting density after 8 years. The data reported here are limited to stands of age of 13 years, and therefore the evaluation of longer-term plantings and data are needed to provide an indication of the potential long-term carbon store of *A. nummularia*. Although Le Houérou (1992) suggested that saltbush growth may decline after 10 years there was no evidence of this at the Wickepin site; indeed growth accelerated in later years.

With an estimated 5.7 million ha of saline land in Australia potentially available for revegetation (National Land and Water Resources Audit, 2001), a first order estimate of carbon sequestration for Australia is 1.14–3.65 Tg C yr^{-1}. Globally, 77 million ha of saline land may be similarly available for revegetation (Munns et al., 1999), with a possible annual rate of carbon sequestration of 15.4–49.3 Tg C yr^{-1}. The yields reported here are smaller than the 5–10 Mg CO_2-eq ha^{-1} yr^{-1}(1.4–2.7 Mg C ha^{-1} yr^{-1}) over 10 years for woody forage shrubs estimated from the National Carbon Accounting Toolbox (AGO 2005) by Monjardino et al. (2010) with consequent over-estimates of farm productivity improvements by using forage shrubs.

4.4. Soil organic carbon

Changes in SOC levels in any cropping system will depend upon the quantity and quality of above and below ground plant C inputs, their decomposition rate and the management practices followed. Saltbush plants in the South Australian field experiments were grazed annually over a 4–8-week period at the end of summer (Descheemaeker et al., 2014; Revell et al., 2013), whereas at Wickepin saltbush was grazed at the end of summer effectively removing all leaf material. The lack of significant differences in SOC between saltbush treatments and agriculture controls may reflect the management regimes, the absence of sufficient litter fall and cycling of other necromass and high sampling errors due to a relatively low number of replicate soil cores taken per site.

There was no significant difference in the change in soil carbon storage to 0.3 m or indeed 2 m depth at Wickepin, and this is similar to what has been found for reforestation projects established on agricultural land in southern Australian environments (Harper et al., 2012; Hoogmoed et al., 2012). Also, the carbon isotopic analysis showed that only 4.5% of the soil carbon at Deniliquin originated from *A. nummularia*, suggesting that the turnover of carbon in these systems is low. There was no noticeable accumulation of litter at the sites, as they were all within grazing systems. Thus, it is recommended that SOC be omitted from carbon accounting of *A. nummularia* revegetation.

4.5. Carbon accounting

For carbon accounting purposes, the carbon that would be sold in a trading scheme is that which represents a permanent increment (Penman et al., 2003) compared to the previous land-use. Carbon accounts for revegetation with *A. nummularia* will include stems and roots, whereas leaves and soft stem components will not form a part of the net carbon storage. Carbon sequestration in leaves at all the sites was calculated at less than 0.1 Mg C ha^{-1} yr^{-1} (Fig. 2a), representing a minor component of the total carbon stocks. Grazing animals feed on the edible dry matter (leaves and stems <2 mm in diameter) (Andrew et al., 1976) and therefore carbon accounting for revegetation with *A. nummularia* will thus differ to reforestation projects, as not all of the biomass will be brought to account.

Although this study only examined carbon sequestration, revegetation with *A. nummularia* can also be valuable forage for summer grazing and land stabilization (Monjardino et al., 2010). Additionally, if saltbush is established on low value land, the opportunity cost or land rental associated with this conversion will be less than carbon mitigation activities (e.g. reforestation) on productive farmland (Townsend et al., 2012). The land conservation benefits and grazing potential from revegetation thus would need to be factored into any economic and sustainability analysis. There are potentially large areas of land that could be treated due to existing salinity or with limited other land-use options (Harper et al., 2007; Harper et al., 2017) and it may be possible to bundle the benefits from environmental service markets, such as carbon mitigation, together with grazing and salinity amelioration (Bennett et al., 2014) values. Importantly, such a system may represent one of the few economically viable options for saline land.

4.6. Future research

Ruminants that graze *A. nummularia* will also emit methane that will need to be included in any carbon accounting of saltbush grazing systems. The present version of the Australian National Carbon Accounting Toolbox for estimating carbon sequestration in different systems does not include estimates for woody shrubs such as saltbush (DEE, 2017). In addition, *A. nummularia* establishment may affect soil greenhouse gas emissions. *A. nummularia* is predominantly planted on saline, waterlogged soils and these soils are presumed to emit methane (Le Mer and Roger 2001), however the rates of methane emissions across the southern Australian sites are unknown as is the impact of reducing waterlogging through revegetation. Neither grazing nor soil emissions were investigated in this study and these are areas on which future research could focus.

5. Conclusions

Further work is required to refine the estimates of carbon sequestration, at both site specific and aggregate scales for grazing shrub species on abandoned or compromised land. Nonetheless, this study found that revegetation with *A. nummularia* presents an opportunity to sequester carbon on land that has marginal value for other uses. Apart from providing grazing value this will also provide environmental co-benefits such as stabilizing degraded farmland. Revegetating saline land with *A. nummularia* does not displace farm production but provides forage for grazing ruminants particularly during the typical end of summer feed shortage. Although there were modest amounts of carbon stored in the above and below ground biomass there are large areas of saline land and a first order estimate of the potential for carbon sequestration using *A. nummularia* on saline land in Australia is between 1.12–3.65 Tg C yr^{-1}. The respective estimate globally across 77 million ha of abandoned saline land is 12.5–47.3 Tg C yr^{-1}.

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