Planting configuration affects productivity, tree form and survival of mallee eucalypt in farm forestry plantings

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Abstract

Mallee eucalypts have been extensively planted in the Western Australia wheatbelt for salinity mitigation and as a short-rotation coppice crop for the production of cineole and bioenergy feedstocks. Mallee has been planted in wide-spaced narrow belts (2-6 rows) within annual crops and pasture, but optimal planting configurations have not been determined. Here, we assess the biomass yield responses of *Eucalyptus loxophleba* ssp. *lissophloia* and *E. polybractea* to; four row treatments (1, 2, 4 and 6 row belts) and five within-row spacing treatments (1, 1.5, 2, 3 and 4 m). Thirteen years after planting, the row effects on plot-level biomass productivity of *E. loxophleba* ranged from 4.3 to 21.2 Mg ha^{-1} $year^{-1}$. For *E. polybractea*, both row number and within-row spacing affected yield, which ranged from 2.7 to 18.8 Mg ha^{-1} $year^{-1}$. For both species, the highest growth rates were observed in the one-row belts with shorter (<3 m) within-row spacing. Within the belts, reductions of growth rate were observed with additional rows, due to increased competition and significant suppression of internal rows; and with wider within-row spacing, due to lower initial planting density. However, when including the area between belts, wider belts generated more biomass. For both species, average tree size decreased with additional rows and shorter within-row spacing. For both species, the number of stems per tree increased with wider within-row spacing, and also for *E. polybractea,* with fewer rows. The substantial variation in productivity, tree size and form found in these results will affect harvestability and ultimately the economic viability of future mallee plantings.

Introduction

Over the last three decades research has been undertaken to develop woody perennial crops to complement annual crops and pastures in the Western Australian (WA) wheatbelt. Economically viable perennial crops could help mitigate dryland salinity (Olsen *et al.*, 2004; Bartle *et al.*, 2007; Bartle & Abadi, 2010). Lefroy and Stirzaker (1999) examined tree crop planting options for salinity management and concluded that integrated plantings would be preferred to segregated or rotated tree crop systems. In this case integrated plantings would take the form of wide-spaced narrow belts within the existing annual crop/pasture farming system.

Mallee eucalypts (hereafter referred to as mallee) are small, multi-stemmed lignotuberous trees. Mallee were selected as the most prospective woody perennials for crop development due to their ability to coppice after regular, short-cycle harvest. Some 300 native mallee species occur across the inland, lower annual rainfall (200-500 mm) regions of the southern states of Australia (Nicolle, 2006). Mallee attracted commercial interest from the early years of European settlement in Australia as a source of eucalyptus oil (extracted from the leaf by steam distillation). Species with leaf oil consisting predominantly of 1,8-cineole (hereafter referred to as cineole) were particularly favoured (Davis, 2002). There are a few current operations in Australia extracting eucalyptus oil from mallee species, from both native and cultivated stands, on coppice harvest cycles of 1 to 5 years. Historic markets for cineole focussed on non-prescription medical uses but recent work has shown promise for industrial scale use (Barton & Tjandra, 1989; Davis, 2002; Soh & Stachowiak, 2002; Leita *et al.*, 2010). High total oil, cineole-rich mallee species have been selected to suit the full range of edaphic and climatic conditions in the WA wheatbelt. Two of these are the subject of this work, *Eucalyptus polybractea* R.T Baker, native to New South Wales and Victoria, and *Eucalyptus loxophleba* Benth. subsp. *lissophloia* LAS Johnson & KD Hill, from WA. Both of these species readily coppice after harvest (Eastham *et al.*, 1993; Wildy *et al.*, 2000a; Spencer *et al.*, 2019). Recent interest in carbon sequestration by agroforestry systems to combat climate change (Harrison & Gassner, 2020) gave strong impetus to develop mallee for its carbon offset and bioenergy potential (Wu *et al.*, 2008; Abadi *et al.*, 2012; Yu *et al.*, 2015). Biofuels became a major research area with a particular focus on conversion to fuels by pyrolysis (O'Connell *et al.*, 2007; Garcia-Perez *et al.*, 2008; Wu *et al.*, 2009; McGrath *et al.*, 2016).

Integration of mallee into the wheatbelt farms has potential direct commercial returns. Other on-farm and regional benefits may also be substantial: hydrological control reducing salinity and waterlogging (Rundle & Rundle, 2002; Silberstein *et al.*, 2002; Ellis *et al.*, 2006; Robinson *et al.*, 2006); stock shelter and wind erosion control (Bird *et al.*, 1992; Sudmeyer & Scott, 2002a, 2002b; Baker *et al.*, 2018) and biodiversity benefits (Smith, 2009). However, mallee have extensive root systems and while their deep root penetration is beneficial (Nulsen *et al.*, 1986; Robinson *et al.*, 2006), their lateral roots spread well beyond the planted belts, creating a wide competition zone with the adjacent annual crops and pastures (Sudmeyer *et al.*, 2012). Economic analyses have been undertaken to help define the full range of costs and benefits (Cooper *et al.*, 2006; Abadi *et al.*, 2012).

The number of rows in a belt, plant spacing within the rows, and harvest frequency will all affect biomass yield and composition. In agroforestry plantings, shorter within-row spacing leads to smaller trees but greater yield (Karim & Savill, 1991; Dagar *et al.*, 2016). This within-row tree spacing effect has also been demonstrated in plantation forestry prior to canopy closure (Niemistö, 1995; DeBell & Harrington, 2002; Pinkard & Neilsen, 2003; West & Smith, 2019). The most common planting configuration for mallee has been 4-row belts, 40-100 m apart, with 2 m between rows and 1.5 m within-row spacing (URS, 2008; Bartle, 2009). The area between belts is commonly called the alley. A study across eight sites in WA with more than 2-rows, found yield reduction in internal rows of 60% for unharvested belts; and for harvested belts inner row suppression of up to 80% (Huxtable *et al.*, 2012). Evidence that 1- or 2-row belts may better utilise the land occupied indicates the need to better define the yield characteristics of these narrow belts (Prasad *et al.*, 2010; Paula *et al.*, 2013).

This study presents the results of two mallee spacing experiments consisting of four different numbers of rows, and five within-row spacing treatments. The aim is to determine:

1) the planting configuration that maximises mallee productivity by testing total biomass response to planting configurations; and
2) the effect of planting configuration on survival and tree form.

Methodology

Study site and Species

The experiments were established at two sites north of the town of Narrogin (32.93°S, 117.18°E, altitude 290-310 m) in the Western Australian wheatbelt. The wheatbelt has mild wet winters and hot dry summers. Annual average rainfall (1986-2015) for Narrogin was 447 mm, annual evaporation 1566 mm, average daily maximum temperature was 22.7 ^{o}C and average daily minimum temperature was 9.8 ^{o}C (Jeffrey *et al.*, 2001).

The experimental sites were selected considering suitability of soil types to the two selected mallee species: *E. polybractea* and *E. loxophleba* subsp. *lissophloia*, which are widely planted in the Western Australian wheat belt. These species will be hereafter referred to as E_{pol} and E_{lox} respectively. Each site consisted of only one of the two species. Both sites have similar landscape position and soil type, i.e. shallow valley floor landform in the Eastern Darling Range Zone and depositional profiles having duplex soils with deep grey sandy surface soil horizon to 1 m over sandy clay (Moore, 2001). Both sites were cleared of native vegetation several decades ago and converted to an agriculture based on well-fertilised annual crop/pasture rotations.

Both experiments were established in winter 2000. Prior to planting, weed control was carried out using glyphosate and simazine. Seedlings were planted into soil that had been ripped to a depth of 50 cm and rip-lines were 2 m apart.

Experimental design

Both experiments had a split plot design with four replicates and random allocation of main plots within each replicate, and sub-plots within the main plots (Fig. 1). The belt row configuration was the main plot treatment with four levels: 1, 2, 4 or 6 row belts. The distance between rows was maintained at 2 m as this is the minimum spacing required for a single row harvester to access internal rows. The main plots were divided into five within-row spacing treatments of 1, 1.5, 2, 3 or 4 m. At each main plot boundary there was a six-tree buffer while there was a three-tree buffer between the sub-plots. The larger buffer was used between the main plots as it represented a change in both tree-spacing and number of row treatments. Each sub-plot consisted of 12 trees distributed between the number of rows prescribed.

Two analyses were performed: firstly, to compare the productivity of each treatment on the area the mallee plots physically occupy; and secondly, to compare the productivity of each treatment including the alley area to determine mallee productivity of the entire paddock. These two approaches were used as both have limitations, the first analysis does not account for the area of influence the mallee belt has on the immediately adjacent agricultural land (called the competition zone) and the second approach does not account for the additional area foregone to agriculture that the wider belts occupy.

In the first analysis, to standardise the plot area of each treatment, the outer edge of the plot was calculated as half the internal distance between rows, as used by Paul *et al.* (2013a). Hence, the 2 m inter-row space had 1 m added to each side to derive plot area. The 1-row treatment was also allocated a 1 m edge to derive area. Consequently, the 1-row treatment is twice the length and half the width of the 2-row treatment; analogously the 1-row treatment was six times the length and one sixth the width of the 6-row treatment. This method allocates equivalent plot areas to different row treatments with the same spacing treatment. For instance, for a 1 m within-row spacing, the 1-row belt of 12 trees has a plot area of 24 m^2, 12 trees x 2 m^2 (1 m^2 each side of the belt) and the 6-row belt at 1 m within-row spacing also has a plot area of 24 m^2 (2 trees along the belt x 2 m between row x 5 internal rows plus 2 external tree x 2 rows x 1 m^2 for the external edge). However, plot area is modified by the within-row spacing treatments (Table 1).

In the second analysis, the alley area was included to calculate mallee productivity over the entire paddock. Alley widths at both experiments were approximately 50 m apart. The plot area, for instance, for a 1 m within-row spacing, the 1-row belt of 12 trees has a plot area of 0.06 ha (12 m x 50 m) whereas the 6-row belt at the same spacing has a plot area of 0.01 ha (2 m x 50 m) (Table 1).

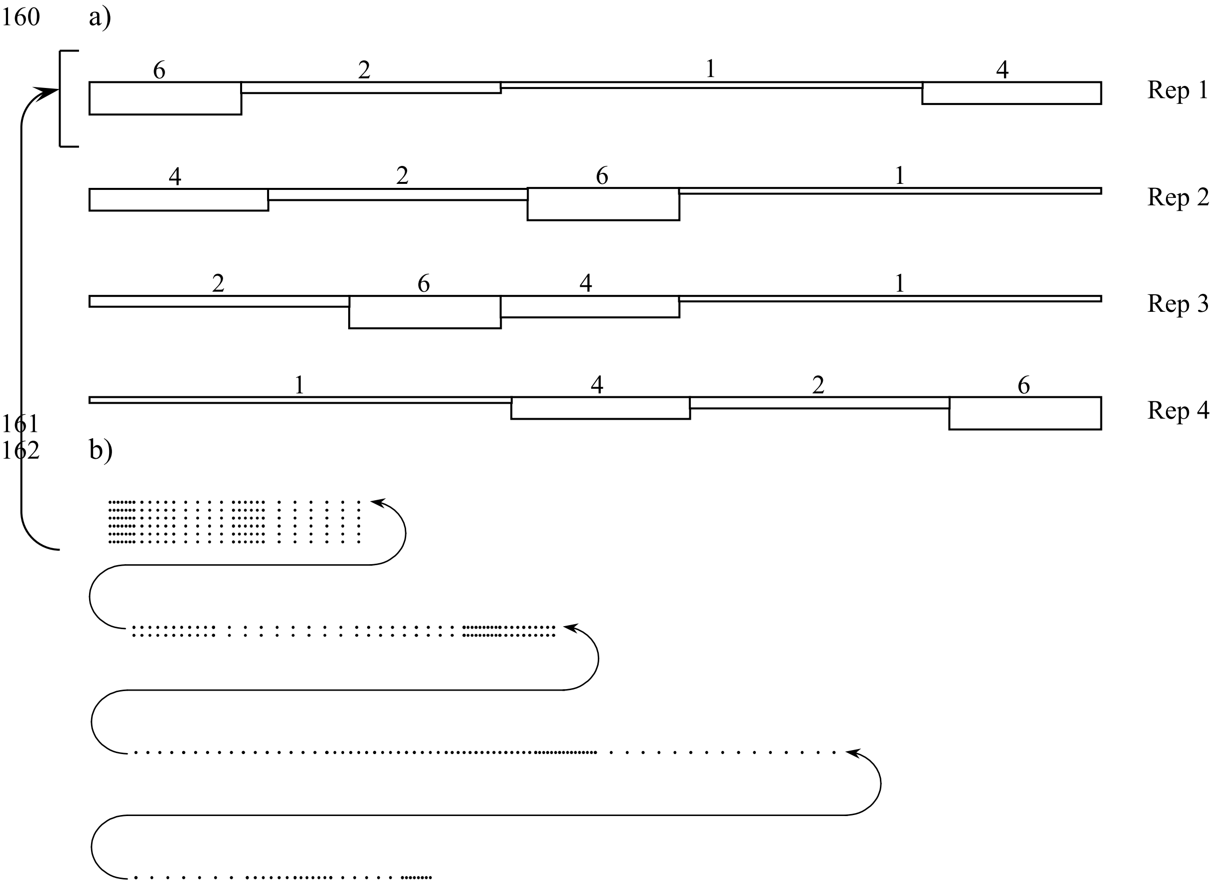

Figure 1 A schematic of the trial design and planting configuration: a) fully randomised allocation of main plot treatments (number of rows) within each replicate, and b) further randomised arrangement of the subplot (within-row spacing) treatments within the whole plot factor using replicate 1 as an example.

Table 1 Plot areas and stocking density (trees ha^{-1}) of within-row spacing treatments (m) for the plot-level scenario and the plot areas for each row-treatment and within-row spacing for the paddock-level scenario. The numbers refer to each replicate at the two experimental sites. Note that for the plot-level scenario, at a given within-row spacing, the plot area is the same for all four different row spacing treatments; see text in the Methods section for details.

	Plot-level scenario		Paddock-level scenario Row Treatment and plot area (ha)			
Within row spacing (m)	Plot area (ha)	Trees ha^{-1}	1-row belt	2-row belt	4-row belt	6-row belt
1	0.0024	5000	0.060	0.030	0.015	0.010
1.5	0.0036	3333	0.090	0.045	0.023	0.015
2	0.0048	2500	0.120	0.060	0.030	0.020
3	0.0072	1667	0.180	0.090	0.045	0.030
4	0.0096	1250	0.240	0.120	0.060	0.040

Estimating dry mass of trees

Diameters of each stem were measured in the winter of 2013 with a diameter tape at approximately 10 cm above ground level. All stems over 10 mm were measured. Fibrous bark, buttressing and swelling associated with low branching was avoided by slightly raising or lowering the measurement height. For multiple stemmed trees, the Equivalent Diameter (EDRC) method of Chojnacky and Milton (2008) was used to provide a single diameter:

$$EDRC = \sqrt{\sum_{i=1}^{n} \mathrm{drc}_i^2} \qquad [1]$$

Where *drc* equals the diameter of each stem and *n* equals the number of stems of each tree.

Mallee allometric equations developed by Spencer *et al.* (2019) were used to estimate dry biomass in a two-step process; first converting EDRC to above ground fresh biomass, then partitioning fresh biomass into oven dry wood, bark, twig and leaf. These data were then summed to estimate the dry biomass of the tree which was used to calculate standing dry biomass for each treatment and plot- and paddock-level scenarios. Other mallee eucalypt allometric equations were assessed; these include Paul *et al.* (2013b) which did not cover suitable size range for stem diameter, while the continental-scale multi-stemmed equation published Paul *et al.* (2016) underestimated biomass when compared to the species-specific equations generated by Spencer *et al.* (2019).

Statistical model

Treatment effects were evaluated by sites using mixed linear models using REML to estimate variance components in SAS 9.4 (SAS, 2017) with the following formula:

$$y_{ijk} = r_i + o_j + s_k + o_j \text{ x } s_k + o_j(r_i) + e_{ijk} \qquad [2]$$

Where y is the trait of interest (dry biomass ha^{-1}, number of stems or survival),

r_i is the replicate effect, o_j is the row treatment, s_k is the spacing treatment, o_j x s_k is the interaction between the row and the spacing treatments, and e_{ijk} is the residual error. Replicate and replicate nested with the main plot (row treatment) were specified as random effects. The proportion of trees that survived were analysed following arcsine transformation. Tree biomass was natural-log transformed to reduce heteroscedasticity and heterogeneity of variance. Prior to measurement, a fire had burnt one replicate of the 6-row treatment at the E_{pol} site. Additionally, at the E_{lox} site, two subplots (4 and 3 m spacing) of one replicate of the 1-row treatment had high mortality and the remaining trees had been damaged by termites modifying the growth form of the trees. The burnt and termite affected plot data were treated as missing observations in analysis.

Results

Planting configuration on mallee survival

Tree survival, averaged across treatments, was 86% (range: 69-94%) at the E_{lox} site while at the E_{pol} site it was 89% (range: 78-96%) (Fig. 2a). Significant differences in survival were observed at the E_{lox} site ($p < 0.05$) for the row treatments (Table 2), where there was 78% survival for the 1-row belts compared to above 86% for the other row treatments. No differences in survival were observed between treatments at the E_{pol} site.

Planting configuration affects productivity of mallee in agroforestry systems

For the plot-level scenario, across both experiments, the 1-row treatment produced significantly more biomass per unit area than the other row-treatments (Fig. 2b). Table 2 summarises the significance of the main- and sub-plot results at both sites. The number of row treatment had a highly significant effect on biomass production which ranged from 4.3 – 21.2 Mg ha^{-1} $year^{-1}$ at the E_{lox} site (p <0.0001) and 2.7 – 18.8 Mg ha^{-1} $year^{-1}$ at the E_{pol} site (p <0.001). There was a yield reduction with additional rows, with the highest yielding 1-row treatment producing more than twice the biomass of any of the 4 and 6-row treatments. The within-row spacing treatment was also highly significant at the E_{pol} site (p <0.0001) where the 1 m within-row spacing yield exceeded the other within-row spacing treatments. Although not significant, a similar trend was observed at the E_{lox} site except for the 1-row treatment. Across both sites and most row-treatments, the 3 and 4 m within-row spacing treatments consistently produced the least biomass. The interaction between row treatment and within-row spacing was not significant (Table 2).

For the paddock-level scenario, productivity ranged from 0.65 – 1.56 Mg ha^{-1} $year^{-1}$ at the E_{lox} site and from 0.43 – 1.86 Mg ha^{-1} $year^{-1}$ at the E_{pol} site with most biomass being generated at the wide belts (4- or 6-rows) with short within-row spacing (Fig. 2c). These wider belts produced significantly more biomass (p <0.01) than the 1- or 2-row treatments, with the 6-row belt, averaged across within-row spacing treatments, producing almost double the biomass of the 1-row belt at both sites. The within-row spacing treatments were highly significant at the E_{pol} site (p <0.0001) where, averaged across row-treatments, the 1 m within-row spacing belt yielded nearly twice the biomass compared to the 3 and 4 m within-row treatments. Analogous to the plot-level analysis, a similar trend occurred at the E_{lox} site, but was not significant. The interaction between row treatment and within-row spacing was also not significant.

The biomass production of the 4- and 6-row treatments were further analysed and there was a difference ($p < 0.0001$) in biomass production between the external and internal rows (Fig. 3). At both sites there were interactions ($p < 0.005$) between external and internal row biomass and the within-row spacing treatments, driven by the higher yields of the external rows at shorter within-row spacing. The short within-row spacing outperformed the wider spacing at the E_{pol} site ($p < 0.01$) while at the E_{lox} site, the 4-row treatment yielded nearly 2 Mg ha^{-1} year^{-1} more than the 6-row treatment ($p < 0.05$). At most within-row spacing treatments, there was at least a doubling, but up to a five-fold difference in biomass production of the external rows compared to the internal rows. This was much more pronounced for the higher density within-row spacing treatments.

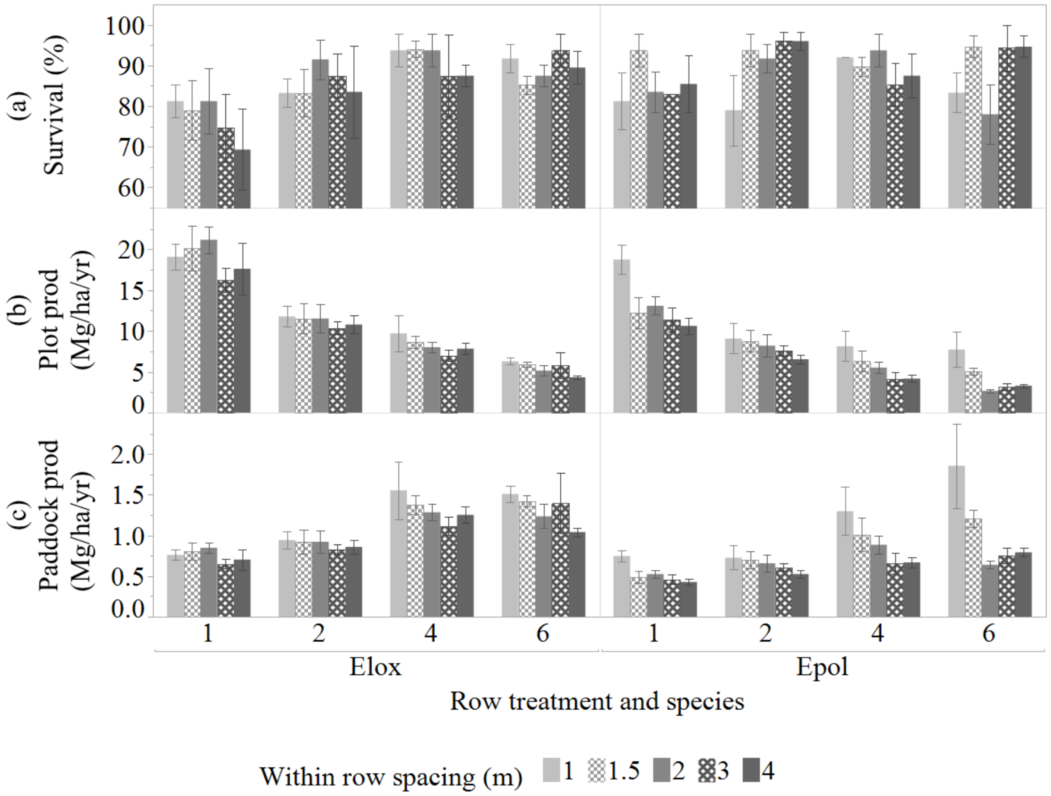

Figure 2 Effect of number of rows (1, 2, 4 and 6) and within-row spacing treatments on: (a) mallee survival; (b) plot-level productivity (Plot prod Mg ha^{-1} year^{-1}) which includes only the area occupied by mallee; and (c) paddock-level productivity (Paddock prod Mg ha^{-1} year^{-1}) which includes the alley area between mallee belts. All graphics refer to the *Eucalyptus loxophleba* subsp. *lissophloia* (E$_{\text{lox}}$) and *E. polybractea* (E$_{\text{pol}}$) sites near Narrogin, Western Australia. Error bars represent ± one standard error (n = 3 – 4).

Table 2 Linear mixed model analyses of arcsine-transformed survival, dry mallee productivity (Mg ha^{-1} yr^{-1}) of both plot and paddock scenarios, natural log transformed average dry tree biomass and the number of stems per mallee. *F*-values and numerator and denominator degrees of freedom in parentheses (ndf, ddf), for the fixed effects (row treatment, within-row spacing treatment and their interaction) for the *Eucalyptus loxophleba* subsp. *lissophloia* and *E. polybractea* spacing experiments near Narrogin, Western Australia. Significant test results are denoted as: * = $P < 0.05$; **= $P < 0.001$; *** = $P < 0.0001$).

	Eucalyptus loxophleba site					*Eucalyptus polybractea* site				
Effect	Survival	Productivity (plot)	Productivity (paddock)	ln (tree biomass)	Number of stems	Survival	Productivity (plot)	Productivity (paddock)	ln (tree biomass)	Number of stems
Fixed effects	*F* (ndf, ddf)	*F* (ndf, ddf)	*F* (ndf, ddf)	*F* (ndf, ddf)	*F* (ndf, ddf)	*F* (ndf, ddf)	*F* (ndf, ddf)	*F* (ndf, ddf)	*F* (ndf, ddf)	*F* (ndf, ddf)
Row	4.1 (3,9)*	30.1 (3,9) ***	10.3 (3,9)*	57.4 (3,9)***	3.7 (3,9)	0.8 (3,8)	20.1 (3,8)***	8.3 (3,8)*	30.6 (3,8)***	12.3 (3,8)**
Spacing	0.7 (4,46)	1.9 (4,46)	2.2 (4,46)	61.3 (4,46)***	6.2 (4,46)***	2.0 (4,43)	14.5 (4,43)***	15.5 (4,46)***	28.5 (4,43)***	5.8 (4,43)***
Row x Spacing	0.7 (12,46)	0.6 (12,46)	0.5 (12,46)	0.5 (12,46)	0.8 (12,46)	1.2 (12,43)	1.5 (12,43)	2.0 (12,43)	1.5 (12,43)	0.7 (12,43)

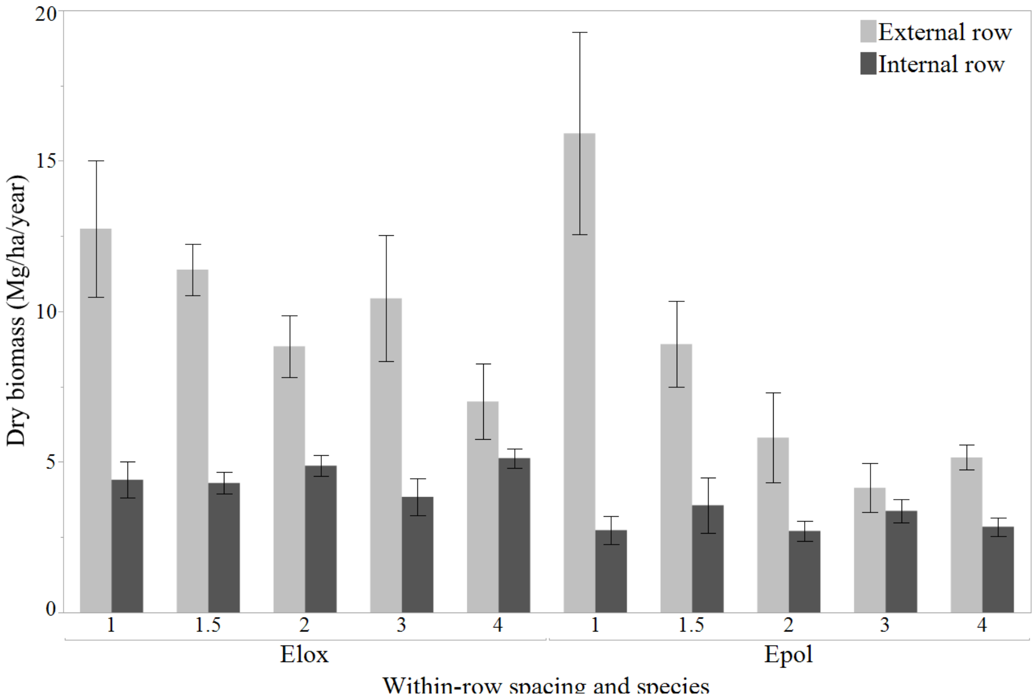

Figure 3 Yield responses of the internal and external rows of the combined 4- and 6-row treatments and within-row spacing treatments of *Eucalyptus loxophleba* subsp. *lissophloia* (E_{lox}) and *E. polybractea* (E_{pol}) at two sites near Narrogin, Western Australia. Error bars represent ± one standard error (n = 3 – 4).

Planting configuration affects individual tree size and number of stems

Average tree biomass varied significantly for both row number treatment and within-row spacing treatment (Table 2). Generally, for all row-number treatments and species, tree size increased with increasing within-row spacing such that the largest trees were observed in the 4 m within-row spacing (Fig 4a). However, for E_{pol} the 1- and 1.5-m within-row spacing treatments had similar productivity. For instance, at the E_{lox} site, the 1-row treatment had the smallest mallee at the 1 m within-row spacing and averaged 61 kg per tree, while at the 4 m within-row spacing, average tree size increased to 264 kg. The magnitude of difference between the within-row spacing treatments was generally two to four-fold greater at the 4 m spacing compared to the 1 m spacing. This difference was less pronounced at the E_{pol} site especially for the 6-row treatment. Trees on average were also largest in the 1-row treatment and smallest in the 6-row treatment although there was no statistical difference between the 4- and 6-row treatments at the E_{pol} site. The average tree biomass of the 1-row belt was three times the biomass of the 6-row treatment at both sites.

On average, E_{pol} had more stems per mallee compared to the E_{lox} site (2.8 vs 1.6 stems). The number of stems was significantly affected by within-row spacing at both sites (Table 2), with fewer stems per mallee at the denser within-row spacing treatments (Fig. 4b). At the E_{lox} site, this ranged from 1.4 stems at the 1 m within-row spacing to 1.8 stem at the 4 m within-row spacing; the corresponding figures for the same treatments at the E_{pol} site were 2.2 and 3.4 stems. The number of stems also varied significantly between the row treatments but only at the E_{pol} site. The 1-row treatment averaged 3.5 stems per mallee, which decreased to 2.3 stems per mallee in the 6-row treatment. This trend, although not significant, was also apparent at the E_{lox} site.

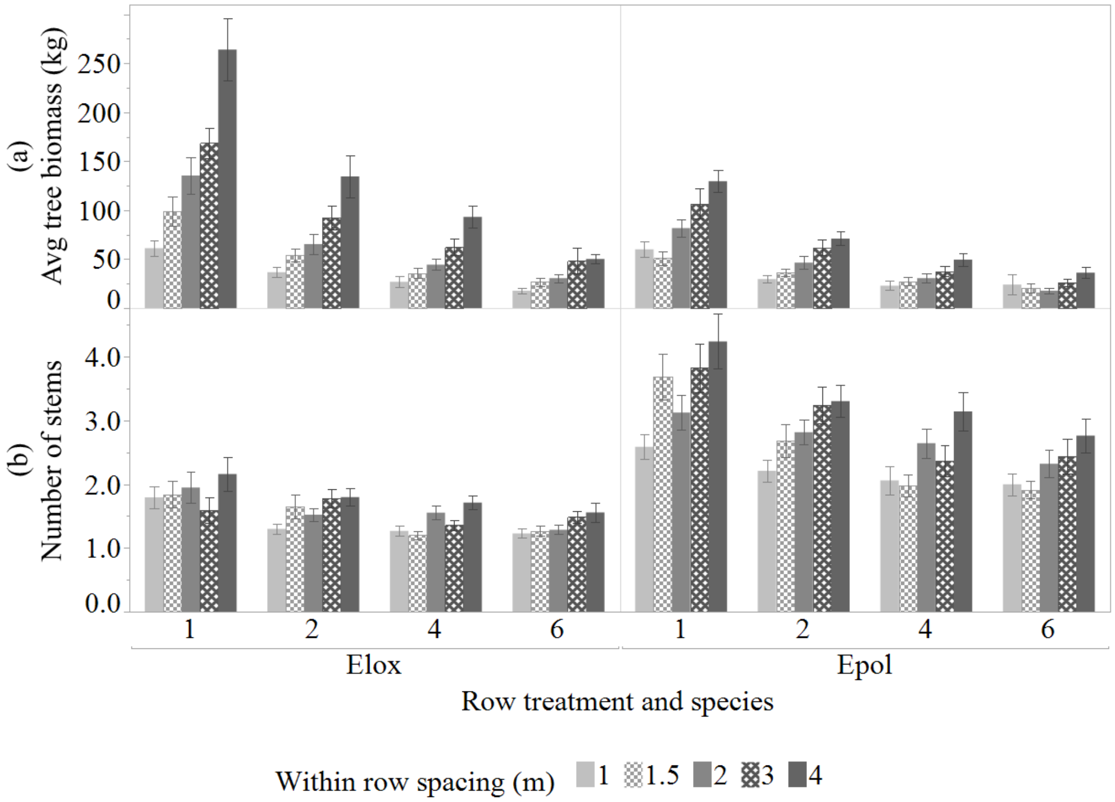

Figure 4 Effect of number of rows (1, 2, 4 and 6) and within-row spacing treatments on: (a) mallee size (kg dry biomass per tree); and (b) the number of stems per tree. Each graphic refers to the *Eucalyptus loxophleba* subsp. *lissophloia* (E_{lox}) and *E. polybractea* (E_{pol}) sites near Narrogin, Western Australia. Error bars represent ± one standard error (n = 3 – 4).

Discussion

Understanding the impact of planting configuration and tree belt design on productivity of tree crops may facilitate their optimal integration into farming systems. To help develop this knowledge we examined effects of planting configuration on productivity of two commonly planted mallee species within the Western Australian wheat belt. Our results revealed that the design of a mallee belt exerts significant impacts on several key attributes including productivity, tree size and form (stem number), and tree mortality. These are discussed below.

Biomass production

Productivity of the plot-level scenario of E_{lox} and E_{pol} in this study ranged from 2.7 to 21.2 Mg ha^{-1} yr^{-1}. These results are mostly within the range observed for unharvested mallee productivity study from 19 sites in the Western Australian wheatbelt (Spencer *et al.*, 2019). This study considers the impact of spacing configuration on productivity and found the productivity of the 1-row E_{lox} (>20 Mg ha^{-1} year^{-1} over 13 years) is the highest yield we have observed for this species. Biomass production per plot area, was affected by both the row treatment and within-row spacing. In this study, the 1-row treatment had significantly faster growth rates than the other treatments and productivity penalties were observed with additional rows and also with wider spacing.

The yield responses from the paddock-level scenario, in which wider belts produced more biomass than the narrower belts, were contrary to the plot level results. This was, however, expected: a 6-row belt from external stump to stump physically occupies 10 m, whereas a 2-row belt occupies only 2 m, which is a considerable difference with 50 m alley widths. This land is completely foregone to agriculture. The narrower-belts also have faster growth rates per tree. Competition imposed from unharvested mature mallee on the immediately adjacent agriculture has been found to extend a further 14 m from mature mallee belts (Sudmeyer *et al.*, 2012), however, it is unknown if belt width will impact competition extent.

A common finding between the plot- and paddock-level scenarios was that shorter within-row spacing treatments were generally more productive. In plantation forestry, Binkley (2004) hypothesised that prior to canopy closure suppression of growth through tree dominance is low and resource supply is high for all trees. At this stage the increase in biomass production is a function of stocking rate. As competition between trees begins, growth rate slows, with earlier onset of competition in higher density plantings, where less competitive individuals are suppressed. The application of this concept to narrow belts indicates that competition will lead to conspicuous asymmetry in size between trees, described as phase two of the Binkley (2004) model. This was indeed observed in these two spacing experiments where clear asymmetry was observed in 4- and 6-row treatment, especially comparing the external with internal rows.

The lower productivity observed from the internal rows of the 4- and 6-row treatments was caused by the suppression of growth rates from the external rows. This production penalty has been observed elsewhere for mallee and other species (Ritson, 2006; Prasad *et al.*, 2010; Huxtable *et al.*, 2012; Paula *et al.*, 2013) and is driven by the trees in the external rows having greater access to the additional resources especially light, nutrients and water.

The most likely reason for the slower growth rates of many planting configurations is the lack of available water. In the Western Australian wheatbelt, the annual potential evaporation (PET) can be up to five-fold the annual rainfall (at Narrogin annual PET is three and a half times the annual rainfall) and water has been shown to be a major limiting resource for mallee belts. Rainfall has not been shown to be a predictor of mallee productivity (Spencer *et al.*, 2019) probably because other water sources are available. For instance, Bennett *et al.* (2015) demonstrated by intercepting surface run-off by tree belts with small bunds, there was a 35% increase in biomass production. Mallee with access to fresh groundwater have shown up to ten times the biomass accumulation compared to those without access to groundwater (Wildy *et al.*, 2004; Brooksbank *et al.*, 2011). Access to these additional water sources are likely to benefit exterior trees with fewer rows and wider within-row spacing.

Work on other species in higher rainfall and lower insolation environments indicate that shading can limit tree growth (Long & Smith, 1984; Righi *et al.*, 2016; Pommerening & Sánchez Meador, 2018). Wildy and Pate (2002) found that shaded *E. kochii* coppice produced less biomass than unshaded coppice in the first year post-harvest. Shading could be a factor in mallee belts especially because the larger external trees may shade the smaller internal-row trees during winter when radiation is lower and water is more readily available. However, if shading was limiting growth, the internal trees from the denser within-row spacing treatments would be less productive than the internal trees of the wider within-row spacing. This was not observed at these two sites, where there was a reduction in productivity of external trees with wider spacing, but the internal trees remained similarly suppressed (Fig. 4). Indeed, eucalypts tend to be crown-shy thus making shading due to crown dominance unlikely in even aged plantings (Lane-Poole, 1936; Schönau & Coetzee, 1989).

Competition for nutrients is another factor that could affect productivity under different planting configurations. Both spacing trials were located on fertilised annual cropping paddocks and trees from external rows, narrower belts or wider spacing would have greater access to additional nutrients. Indeed, in plantation forestry, soil nutrition may vary considerably in small areas across a site resulting in varied growth rates (Thomson, 1986; Phillips & Marion, 2004). Recently, we showed soil organic carbon and nitrogen (NO_3^- and NH_4^+) were correlated with mallee biomass productivity in a multi-site long term study (Spencer *et al.*, 2019). Organic carbon is probably a surrogate for nutrient supply and water availability in sandy soils (Doran & Smith, 1987; Loveland & Webb, 2003). The nitrogen correlation was, however, limited to frequently harvested treatments where biomass removal has been shown to deplete soil nitrogen stores (Grove *et al.*, 2007; Yu *et al.*, 2015). However, in this study, neither spacing trial had been harvested.

For both mallee species, the plot-level growth rate per tree of the 1-row belt was markedly higher than for the 2-row belt even at double the within-row spacing. Similar but smaller responses have been observed elsewhere but on much younger trees (Prasad *et al.*, 2010; Paula *et al.*, 2013). The process involved in this highly divergent response is unclear, but it suggests that competition between rows is more pronounced than competition within rows. A likely explanation is that trees in multiple row belts are subject to the additional competition of the neighbouring row. Within a few years of planting, root systems will overlap, competition for resources within the belt area will strengthen and roots will grow into the adjacent agricultural land to acquire water and nutrients. This lateral root growth has been observed with crop suppression in the alley of unharvested mallee where there was a reduction in crop and pasture yield by 36% between 2 and 20 m from the mallee belts compared to open paddock yields in the Western Australian wheatbelt (Sudmeyer *et al.*, 2012). Such suppression of adjacent crops from agroforestry plantings have been widely observed in other countries (Rao *et al.*, 1991; Prasad *et al.*, 2010; Dagar *et al.*, 2016; Oliveira *et al.*, 2016).

Two metres between rows was generally viewed as the minimum distance for a harvester to access multiple row belts. This planting configuration was found to reduce mallee productivity compared to 1-row belts. Single-row belts may also reduce establishment costs and decrease the paddock area allocated to mallee while still achieving enhanced water use and some degree of salinity control. However, 2-row belts, compared to 1-row belts, may provide greater capacity to consume excess water and will be less porous, providing better stock shelter and wind erosion control. If the between-row spacing of 2 m was increased, this would reduce the penalty of the additional row and minimise the productivity difference between the 2- and 1-row belts.

Tree size and form

As the within-row spacing increases, the average tree size increases. Average tree size is also affected by mortality, that is, if mortality is high in a plot, the average tree size of survivors also increases. This was observed in the 1-row E_{lox} treatment where the average mallee biomass for the 4 m within-row spacing is more than 4-fold as large as the 1 m within-row spacing. This difference was due to both the increased spacing and higher mortality at the 4 m within-row spacing. Mortality at larger within-row spacing will make available additional space and resources resulting in larger mallee than mortality at shorter spacing. In these experiments, there was a large range of whole-tree biomass across spacing treatments. The smallest trees were in the 4- and 6-row treatments at shorter within-row spacing. This divergence in mallee size will affect harvestability and proportions of the biomass components.

Maximum tree size, tree form and production per kilometre of row and belt are factors in the harvest viability of a mallee belt system. Mallee is difficult to harvest, having high wood density (Ilic *et al.*, 2000) and have multiple stems. Poplar, willow, sugar cane or forage harvesters are not suitable for harvesting mallee with large stem diameters (Giles & Harris, 2003; Abadi *et al.*, 2012), but traditional forestry harvesters have been used (Spinelli *et al.*, 2014) and a prototype single-row chipper-harvester to improve harvesting efficiency has been developed and tested (Bartle, 2009; Goss *et al.*, 2014). Traditional forest harvesting equipment is more efficient with larger, taller trees. The chipper-harvester, being a continuously moving, integrated cutting-and-chipping operation, is mostly influenced by yield per kilometre of row, provided tree size range is below about 150 kg per tree. By varying the speed of the harvester, maximum efficiency can be maintained over a range of tree sizes, but overall harvest and transport (forwarding) efficiency is improved with high yields per kilometre of row (Abadi *et al.*, 2012). Tree form is less significant for the chipper harvester than it is for traditional forest harvesting and chipping, but an upright form is easier to handle.

In the current work, the number of stems per tree is used as a proxy for upright form, and the number of stems increased for both species and with wider spacing. This response is similar to that observed in eucalypt forestry trials where branch size is inversely proportional to stocking rates (Neilsen & Gerrand, 1999; Gerrand & Neilsen, 2000; Henskens *et al.*, 2001). Mallee belt design can therefore aim to use shorter within-row spacing to increase yield, reduce tree size and stem number. Concentrating biomass into fewer rows will reduce the total amount of biomass produced but may result in increased harvest efficiency for a chipper harvester because the biomass will be concentrated into fewer rows. In contrast, narrow belts would likely increase costs using traditional forestry equipment because additional travel distance would be required to process less biomass.

The strategy of maximising biomass while minimising tree size with shorter within-row spacing will alter the component partitioning of biomass with increased stemwood in larger trees (Paul *et al.*, 2017). Foliar cineole, has greater economic value than wood, twig and bark (Barton, 2000; Davis, 2002). Currently, for leaf oil production, whole trees are harvested in the paddock with the oil extracted via hydro-distillation or steam distillation (Wildy *et al.*, 2000b; Babu & Singh, 2009). Both traditional forestry harvesting equipment and single-row chipper-harvester process whole tree biomass on-site ready for transport. This material can then be delivered to a processing plant where the leaf material would be separated from the other fractions and cineole extracted (Enecon, 2001). The results from our study suggest there is scope to maximise leaf production by producing smaller mallee, without reducing mallee productivity. Where cineole production is a major objective, leaf biomass yield can be favoured by shorter within-row spacing. If a larger proportion of wood fraction is preferred then 1-row belts with larger within-row spacing can be used, but this may require conventional forestry harvesting equipment.

Conclusion

The two species in this experiment showed broadly similar production responses to both row-number and within-row spacing treatments. Single row belts with shorter within-row spacing have faster growth rates per tree than any other configuration, particularly for E_{pol}. However, wider belts generate more biomass but the internal rows display considerable suppression with reduced productivity and occupy more land. Closer within row spacing will favour leaf biomass production. If wood biomass is the target product, narrow belts with wider spacing should be considered.

Declaration

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Conflicts of interest

Authors declare that there are no conflicts of interest.

Availability of data and material

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Code availability

The SAS code generated during analysis from the current study are available from the corresponding author on reasonable request.

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References

Abadi, A., Bartle, J., Giles, R., & Thomas, Q. (2012). Supply and delivery of mallees. In C. Stucley, S. Schuck, R. Sims, J. Bland, B. Marino, M. Borowitzka, A. Abadi, J. Bartle, R. Giles, & Q. Thomas (Eds.), *Bioenergy in Australia: Status and Opportunities* (pp. 140-172). Bioenergy Australia Limited. Available at https://researchrepository.murdoch.edu.au/id/eprint/36149/, St Leonards, Australia.

Babu, G. D. K., & Singh, B. (2009). Simulation of Eucalyptus cinerea oil distillation: A study on optimization of 1, 8-cineole production. *Biochemical Engineering Journal, 44*(2-3), 226-231.

Baker, T., Moroni, M., Mendham, D., Smith, R., & Hunt, M. (2018). Impacts of windbreak shelter on crop and livestock production. *Crop and Pasture Science, 69*(8), 785-796.

Bartle, J. R. (2009). Integrated production systems. In I. Nuberg, B. George, & R. Reid (Eds.), *Agroforestry for Natural Resource Management* (pp. 267-280). CSIRO, Collingwood, Australia.

Bartle, J. R., & Abadi, A. (2010). Toward sustainable production of second generation bioenergy feedstocks. *Energy & Fuels, 24*(1), 2-9.

Bartle, J. R., Olsen, G., Cooper, D., & Hobbs, T. (2007). Scale of biomass production from new woody crops for salinity control in dryland agriculture in Australia. *International Journal of Global Energy Issues, 27*(2), 115-137.

Barton, A. F. M. (2000). The oil mallee project: a multifaceted industrial ecology case study. *Journal of Industrial Ecology, 3*(2-3), 161-176.

Barton, A. F. M., & Tjandra, J. (1989). Eucalyptus oil as a cosolvent in water-ethanol-gasoline mixtures. *Fuel, 68*(1), 11-17.

Bennett, R. G., Mendham, D., Ogden, G., & Bartle, J. R. (2015). Enhancing tree belt productivity through capture of short-slope runoff water. *GCB Bioenergy, 7*(5), 1107-1117.

Binkley, D. (2004). A hypothesis about the interaction of tree dominance and stand production through stand development. *Forest Ecology and Management, 190*(2-3), 265-271.

Bird, P., Bicknell, D., Bulman, P., Burke, S., Leys, J., Parker, J., Sommen, F., & Voller, P. (1992). The role of shelter in Australia for protecting soils, plants and livestock. *Agroforestry Systems, 20*(1), 59-86.

Brooksbank, K., Veneklaas, E. J., White, D., & Carter, J. (2011). Water availability determines hydrological impact of tree belts in dryland cropping systems. *Agricultural Water Management, 100*(1), 76-83.

Chojnacky, D. C., & Milton, M. (2008). Measuring Carbon in Shrubs. In *Field Measurements for Forest Carbon Monitoring* (pp. 45-72). Springer, New York, USA.

Cooper, D., Olsen, G., & Bartle, J. (2006). Capture of agricultural surplus water determines the productivity and scale of new low-rainfall woody crop industries. *Australian Journal of Experimental Agriculture, 45*(11), 1369-1388.

Dagar, J. C., Lal, K., Ram, J., Kumar, M., Chaudhari, S. K., Yadav, R. K., Ahamad, S., Singh, G., & Kaur, A. (2016). Eucalyptus geometry in agroforestry on waterlogged saline soils influences plant and soil traits in North-West India. *Agriculture, Ecosystems and Environment, 233*, 33-42.

Davis, G. R. (2002). Cultivation and production of eucalypts in Australia: with special reference to the leaf oils. In J. J. W. Coppen (Ed.), *Eucalyptus: The Genus Eucalyptus* (pp. 183-201). Taylor and Francis, London, UK.

DeBell, D. S., & Harrington, C. A. (2002). Density and rectangularity of planting influence 20-year growth and development of red alder. *Canadian Journal of Forest Research, 32*(7), 1244-1253.

Doran, J. W., & Smith, M. S. (1987). Organic matter management and utilization of soil and fertilizer nutrients. In R. F. Follett (Ed.), *Soil fertility and organic matter as critical components of production systems* (pp. 53-72). Soil Science Society of America. Special Publication No 19, Madison, USA.

Eastham, J., Scott, P. R., Steckis, R. A., Barton, A. F. M., Hunter, L. J., & Sudmeyer, R. J. (1993). Survival, growth and productivity of tree species under evaluation for agroforestry to control salinity in the Western Australian wheatbelt. *Agroforestry Systems, 21*(3), 223-237.

Ellis, T. W., Leguedois, S., Hairsine, P. B., & Tongway, D. J. (2006). Capture of overland flow by a tree belt on a pastured hillslope in south-eastern Australia. *Soil Research, 44*(2), 117-125.

Enecon, P. (2001). Integrated tree processing of mallee eucalypts. RIRDC Publication No 01/160. Rural Industries Research and Development Corporation, Barton, Australia.

Garcia-Perez, M., Wang, X. S., Shen, J., Rhodes, M. J., Tian, F., Lee, W.-J., Wu, H., & Li, C.-Z. (2008). Fast Pyrolysis of Oil Mallee Woody Biomass: Effect of Temperature on the Yield and Quality of Pyrolysis Products. *Industrial & Engineering Chemistry Research, 47*(6), 1846-1854.

Gerrand, A. M., & Neilsen, W. A. (2000). Comparing square and rectangular spacings in Eucalyptus nitens using a Scotch plaid design. *Forest Ecology and Management, 129*(1-3), 1-6.

Giles, R. C., & Harris, H. D. (2003). *Short Rotation Crops for Bioenergy; Proceedings of the IEA Bioenergy Task 30 Conference.* Paper presented at the Short Rotation Crops for Bioenergy, Tauranga, New Zealand.

Goss, K., Abadi, A., Crossin, E., Stucley, C., & Turnbull, P. (2014). Sustainable Mallee Jet Fuel: Sustainability and Life Cycle Assessment for Supply to Perth Airport, Western Australia. Project No DP36. Future Farm Industries CRC, Perth, Australia.

Grove, T., Mendham, D., Rance, S., Bartle, J., & Shea, S. (2007). Nutrient management of intensively harvested oil mallee tree crops. Publication No 07/084. Rural Industries Research and Development Corporation, Barton Australia.

Harrison, R. D., & Gassner, A. (2020). Agricultural lands key to mitigation and adaptation. *Science, 367*(6477), 518-518.

Henskens, F. L., Battaglia, M., Cherry, M. L., & Beadle, C. L. (2001). Physiological basis of spacing effects on tree growth and form in Eucalyptus globulus. *Trees, 15*(6), 365-377.

Huxtable, D., Peck, A., Bartle, J., & Sudmeyer, R. (2012). Tree biomass. In A. Peck, R. Sudmeyer, D. Huxtable, J. Bartle, & D. Mendham (Eds.), *Productivity of mallee agroforestry systems under various harvest and competition management regimes. Publication No. 11/162*. Rural Industries Research and Development Corporation, Barton, Australia.

Ilic, J., Boland, D., McDonald, M., Downes, G., & Blakemore, P. (2000). Wood density phase 1: state of knowledge. National Carbon Accounting System Technical Report No. 18. Australian Greenhouse Office. Australian Greenhouse Office, Canberra, Australia.

Jeffrey, S. J., Carter, J. O., Moodie, K. B., & Beswick, A. R. (2001). Using spatial interpolation to construct a comprehensive archive of Australian climate data. *Environmental Modelling & Software, 16*(4), 309-330.

Karim, A., & Savill, P. (1991). Effect of spacing on growth and biomass production of Gliricidia sepium (Jacq) Walp in an alley cropping system in Sierra Leone. *Agroforestry Systems, 16*(3), 213-222.

Lane-Poole, C. (1936). Eucalypt planting in South Africa. *Australian Forestry, 1*(1), 25-32.

Lefroy, E., & Stirzaker, R. (1999). Agroforestry for water management in the cropping zone of southern Australia. *Agroforestry Systems, 45*(1), 277-302.

Leita, B. A., Warden, A. C., Burke, N., O'Shea, M. S., & Trimm, D. (2010). Production of p-cymene and hydrogen from a bio-renewable feedstock–1, 8-cineole (eucalyptus oil). *Green Chemistry, 12*(1), 70-76.

Long, J. N., & Smith, F. W. (1984). Relation between size and density in developing stands: A description and possible mechanisms. *Forest Ecology and Management, 7*(3), 191-206.

Loveland, P., & Webb, J. (2003). Is there a critical level of organic matter in the agricultural soils of temperate regions: a review. *Soil Tillage and Research, 70*, 1-18.

McGrath, J. F., Goss, K. F., Brown, M. W., Bartle, J. R., & Abadi, A. (2016). Aviation biofuel from integrated woody biomass in southern Australia. *Wiley Interdisciplinary Reviews: Energy and Environment, 6*(2).

Moore, G. A. (2001). Soilguide (Soil guide): A handbook for understanding and managing agricultural soils. Bulletin 4343. Department of Agriculture and Food, Western Australia, Perth, Australia.

Neilsen, W. A., & Gerrand, A. M. (1999). Growth and branching habit of Eucalyptus nitens at different spacing and the effect on final crop selection. *Forest Ecology and Management, 123*(2), 217-229.

Nicolle, D. (2006). A classification and census of regenerative strategies in the eucalypts (Angophora, Corymbia and Eucalyptus—Myrtaceae), with special reference to the obligate seeders. *Australian Journal of Botany, 54*(4), 391-407.

Niemistö, P. (1995). Influence of initial spacing and row-to-row distance on the growth and yield of silver birch (*betula pendula*). *Scandinavian Journal of Forest Research, 10*(1-4), 245-255.

Nulsen, R. A., Bligh, K. J., Baxter, I. N., Solin, E. J., & Imrie, D. H. (1986). The fate of rainfall in a mallee and heath vegetated catchment in southern Western Australia. *Australian Journal of Ecology, 11*(4), 361-371.

O'Connell, D., Batten, D., O'Connor, M., May, B., Raison, J., Keating, B., Beer, T., Braid, A., Haritos, V., Begley, C., Poole, M., Poulton, P., Graham, S., Dunlop, M., Grant, T., Campbell, P., & Lamb, D. (2007). Biofuels in Australia: An Overview of Issues and Prospects. Rural Industries Research and Development Corporation, Barton, Australia.

Oliveira, C. H., Reis, G. G., Reis, M. G., Leite, H. G., Souza, F. C., Faria, R. S., & Oliveira, F. B. (2016). Dynamics of eucalypt clones canopy and Brachiaria brizantha production in silvopastoral systems with different spatial arrangements. *Agroforestry Systems, 90*(6), 1077-1088.

Olsen, G., Cooper, D., Huxtable, D., Carslake, J., & Bartle, J. (2004). Developing multiple purpose species for large scale revegetation. Search Project final report. NHT Project 973849. Department of Conservation and Land Management, Perth, Australia.

Paul, K., Roxburgh, S., Chave, J., England, J., Zerihun, A., Specht, A., Lewis, T., Bennett, L., Baker, T., Adams, M., Huxtable, D., Montagu, K., Falster, D., Feller, M., Sochacki, S., Ritson, P., Bastin, G., Bartle, J., Wildy, D., Hobbs, T., Larmour, J., Waterworth, R., Stewart, H., Jonson, J., Forrester, D., Applegate, G., Mendham, D., Bradford, M., O'Grady, A., Green, D., Sudmeyer, R., Rance, S., Turner, J., Barton, C., Wenk, E., Grove, T., Attiwill, P., Pinkard, E., Butler, D., Brooksbank, K., Spencer, B., Snowdon, P., O'Brien, N., Battaglia, M., Cameron, D., Hamilton, S., McAuthur, G., & Sinclair, J. (2016). Testing the generality of above-ground biomass allometry across plant functional types at the continent scale. *Global change biology, 22*(6), 2106-2124.

Paul, K., Roxburgh, S., Raison, J., Larmour, J., England, J., Murphy, S., Norris, J., Ritson, P., Brooksbank, K., Hobbs, T., Neumann, C., Lewis, T., Read, Z., Clifford, D., Kmoch, L., Rooney, M., Freudenberger, D., Jonson, J., Peck, A., Giles, R., Bartle, J., McAurthur, G., Wildy, D., Lindsay, A., Preece, N., Cunningham, S., Powe, T., Carter, J., Bennett, R., Mendham, D., Sudmeyer, R., Rose, B., Butler, D., Cohen, L., Fairman, T., Law, R., Finn, B., Brammar, M., Minchin, G., van Oosterzeeand, P., & A., L. (2013a). Improved estimation of biomass accumulation by environmental plantings and mallee plantings using FullCAM. Report for Department of Climate Change and Energy Efficiency. CSIRO Sustainable Agriculture Flagship, Canberra, Australia.

Paul, K. I., Roxburgh, S. H., & Larmour, J. S. (2017). Moisture content correction: Implications of measurement errors on tree-and site-based estimates of biomass. *Forest Ecology and Management, 392*, 164-175.

Paul, K. I., Roxburgh, S. H., Ritson, P., Brooksbank, K., England, J. R., Larmour, J. S., John Raison, R., Peck, A., Wildy, D. T., Sudmeyer, R. A., Giles, R., Carter, J., Bennett, R., Mendham, D. S., Huxtable, D., & Bartle, J. R. (2013b). Testing allometric equations for prediction of above-ground biomass of mallee eucalypts in southern Australia. *Forest Ecology and Management, 310*, 1005-1015.

Paula, R. R., Reis, G. G., Reis, M. G., Neto, S. N. O., Leite, H. G., Melido, R. C., Lopes, H. N., & Souza, F. C. (2013). Eucalypt growth in monoculture and silvopastoral systems with varied tree initial densities and spatial arrangements. *Agroforestry Systems, 87*(6), 1295-1307.

Phillips, J. D., & Marion, D. A. (2004). Pedological memory in forest soil development. *Forest Ecology and Management, 188*(1-3), 363-380.

Pinkard, E. A., & Neilsen, W. A. (2003). Crown and stand characteristics of Eucalyptus nitens in response to initial spacing: implications for thinning. *Forest Ecology and Management, 172*(2-3), 215-227.

Pommerening, A., & Sánchez Meador, A. J. (2018). Tamm review: Tree interactions between myth and reality. *Forest Ecology and Management, 424*, 164-176.

Prasad, J. V. N. S., Korwar, G. R., Rao, K. V., Mandal, U. K., Rao, C. A. R., Rao, G. R., Ramakrishna, Y. S., Venkateswarlu, B., Rao, S. N., & Kulkarni, H. D. (2010). Tree row spacing affected agronomic and economic performance of Eucalyptus -based agroforestry in Andhra Pradesh, Southern India. *Agroforestry Systems, 78*(3), 253-267.

Rao, M., Ong, C., Pathak, P., & Sharma, M. (1991). Productivity of annual cropping and agroforestry systems on a shallow Alfisol in semi-arid India. *Agroforestry Systems, 15*(1), 51-63.

Righi, C. A., Couderc, V., Pereira, C. R., & COUTO, H. T. Z. (2016). Responses of *Eucalyptus camaldulensis* sprouts to shade: an evaluation of canopy plasticity. *Experimental Agriculture, 52*(3), 346-358.

Ritson, P. (2006). Growth, yield and carbon sequestration of Pinus pinaster established on farmland in south-western Australia. Doctoral dissertation, University of Melbourne Melbourne.

Robinson, N., Harper, R., & Smettem, K. R. J. (2006). Soil water depletion by Eucalyptus spp. integrated into dryland agricultural systems. *Plant and Soil, 286*(1-2), 141-151.

Rundle, P. J., & Rundle, B. F. (2002). A case study of farm-based solutions to water logging and secondary salinity in southwestern Australia. *Agricultural Water Management, 53*(1-3), 31-38.

SAS. (2017). Version 9.4. SAS Institute Inc., Cary, NC, USA.

Schönau, A., & Coetzee, J. (1989). Initial spacing, stand density and thinning in eucalypt plantations. *Forest Ecology and Management, 29*(4), 245-266.

Silberstein, R., Bartle, G., Salama, R., Hatton, T., Reggiani, P., Hodgson, G., Williamson, D., & Lambert, P. (2002). Mechanisms and control of water logging and groundwater flow in the 'Ucarro'sub-catchment. *Agricultural Water Management, 53*(1-3), 227-257.

Smith, F. P. (2009). Assessing the habitat quality of oil mallees and other planted farmland vegetation with reference to natural woodland. *Ecological Management & Restoration, 10*(3), 217-227.

Soh, M., & Stachowiak, G. W. (2002). The application of cineole as a grease solvent. *Flavour and fragrance journal, 17*(4), 278-286.

Spencer, B., Bartle, J., Huxtable, D., Mazanec, R., Abadi, A., Gibberd, M., & Zerihun, A. (2019). A decadal multi-site study of the effects of frequency and season of harvest on biomass production from mallee eucalypts. *Forest Ecology and Management, 453*, 117576.

Spinelli, R., Brown, M., Giles, R., Huxtable, D., Relaño, R. L., & Magagnotti, N. (2014). Harvesting alternatives for mallee agroforestry plantations in Western Australia. *Agroforestry Systems, 88*(3), 479-487.

Sudmeyer, R., Daniels, T., Jones, H., & Huxtable, D. (2012). The extent and cost of mallee–crop competition in unharvested carbon sequestration and harvested mallee biomass agroforestry systems. *Crop and Pasture Science, 63*(6), 555-569.

Sudmeyer, R., & Scott, P. (2002a). Characterisation of a windbreak system on the south coast of Western Australia. 1. Microclimate and wind erosion. *Australian Journal of Experimental Agriculture, 42*(6), 703-715.

Sudmeyer, R., & Scott, P. (2002b). Characterisation of a windbreak system on the south coast of Western Australia. 2. Crop growth. *Australian Journal of Experimental Agriculture, 42*(6), 717-727.

Thomson, A. J. (1986). Trend surface analysis of spatial patterns of tree size, microsite effects, and competitive stress. *Canadian Journal of Forest Research, 16*(2), 279-282.

URS. (2008). Oil mallee industry development plan for Western Australia. Forest Products Commission, East Perth, Australia.

West, P., & Smith, R. (2019). Inter-tree competitive processes during early growth of an experimental plantation of Eucalyptus pilularis in sub-tropical Australia. *Forest Ecology and Management, 451*, 117450.

Wildy, D. T., Bartle, J. R., Pate, J. S., & Arthur, D. J. (2000a). Sapling and coppice biomass production by alley-farmed 'oil mallee' Eucalyptus species in the Western Australian wheatbelt. *Australian Forestry, 63*(2), 147-157.

Wildy, D. T., & Pate, J. S. (2002). Quantifying above-and below-ground growth responses of the western Australian oil mallee, *Eucalyptus kochii* subsp. *plenissima*, to contrasting decapitation regimes. *Annals of Botany, 90*(2), 185-197.

Wildy, D. T., Pate, J. S., & Bartle, J. R. (2000b). Variations in composition and yield of leaf oils from alley-farmed oil mallees (*Eucalyptus* spp.) at a range of contrasting sites in the Western Australian wheatbelt. *Forest Ecology and Management, 134*(1), 205-217.

Wildy, D. T., Pate, J. S., & Bartle, J. R. (2004). Budgets of water use by *Eucalyptus kochii* tree belts in the semi-arid wheatbelt of Western Australia. *Plant and Soil, 262*(1), 129-149.

Wu, H., Fu, Q., Giles, R., & Bartle, J. (2008). Production of mallee biomass in Western Australia: energy balance analysis. *Energy & Fuels, 22*(1), 190-198.

Wu, H., Yip, K., Tian, F., Xie, Y., & Li, C.-Z. (2009). Evolution of Char Structure during the Steam Gasification of Biochars Produced from the Pyrolysis of Various Mallee Biomass Components. *Industrial & Engineering Chemistry Research, 48*(23), 10431-10438.

Yu, Y., Bartle, J., Mendham, D., & Wu, H. (2015). Site Variation in Life Cycle Energy and Carbon Footprints of Mallee Biomass Production in Western Australia. *Energy & Fuels, 29*(6), 3748-3752.