Determinants of the economic viability of mallee eucalypts as a short rotation coppice crop integrated into farming systems of Western Australia

Beren Spencer, Amir Abadi, John Bartle, Robert Sudmeyer, Sarah Van Gent, Mark Gibberd, Ayalsew Zerihun

Abstract
Mallee eucalypts are being developed as a short rotation coppice crop for integration into agricultural systems in the south-west of Western Australia. These have potential for biomass production for bioenergy, eucalyptus oil and generating carbon credits and to help control the extensive occurrence of dryland salinity. Some 12,000 ha of mallee planting has been undertaken since 1994, mostly in the form of wide-spaced, narrow belts within the annual agricultural system. Production and market data were used to estimate levelized costs (LC) of mallee biomass production under different harvest regimes across 11 sites from 2006 to 2012. We found LC ranged from AUD40 to AUD257 fresh Mg⁻¹. LC was most strongly determined by mallee production, followed by the crop/pasture rotation decisions of the landholder. Mallee harvest regime had minor impact on LC. Crop and pasture yield loss due to competition from the mallee belts accounted for 38% of costs, harvesting biomass was 32%, opportunity cost of the land occupied by the mallee belts was 16% while establishment and maintenance costs accounted for 14% of the costs. When income from carbon sequestered in mallee root biomass was included, the LC dropped by an average of 11% at the current Australian price of AUD15 Mg⁻¹ CO₂ equivalent (CO₂e). The income from carbon sequestered in root biomass alone is unlikely to make mallee agroforestry economically viable. Hence, income from harvested biomass in the form of feedstocks for industry or carbon credits is necessary to make mallee agroforestry commercially attractive. LC for unharvested mallee belts ranged from AUD33 to AUD237 Mg⁻¹. Where above- and below-ground biomass is converted to CO₂e at AUD15 Mg⁻¹, the LC drops to AUD11–AUD64, with three of 11 sites likely to be profitable. These three sites were characterized by high biomass production with low agricultural gross margins.

Keywords
agroforestry, alley cropping, carbon sequestration, competition zone, levelized cost, oil mallee, tree-crop competition
Integration of mallee eucalypts—which are lignotuberous Eucalyptus spp. with multi-stemmed growth form—into the dryland farming systems in the wheatbelt of Western Australia (WA) could help address several land degradation issues, in particular the on-farm impacts of dryland salinity and its adverse downstream consequences for water resources, conservation and infrastructure (Bartle et al., 2007; Clarke et al., 2002; George, 1990). Since the early 1990s, widespread test planting of mallee was undertaken with some 1,000 farmers establishing mallee belts on more than 12,700 ha of land (Bartle & Abadi, 2010; URS, 2008). However, the use of revegetation for salinity mitigation is contentious (George et al., 1999) and benefits will take decades to be realized and require extensive planting as part of an integrated farming system. Hence, mallee cropping must also generate an economic return to make it viable.

Selected mallee species have long been used for small-scale production of eucalyptus oil (Davis, 2002). Its major constituent, 1,8-cineole, has potential for large-scale markets in biofuels and industrial products (Barton & Tjandra, 1989; Mewalal et al., 2017; Soh & Stachowiak, 2002). Mallee biomass also has potential as bioenergy and biofuel feedstock (Barron & Zil, 2006; Garcia-Perez et al., 2008; McGrath et al., 2016; Wu et al., 2010; Yu et al., 2009) and biochar (Abdullah & Wu, 2009; Ding et al., 2016). More recently, the Australian Government Carbon Credits (Carbon Farming Initiative) Act 2011 provides opportunities for mallee plantings to generate revenue. In the United States, alley cropping has been estimated to have the potential to mitigate 82 Tg of CO2e per year (Fargione et al., 2016). More recently, the Australian Government Carbon Credits (Carbon Farming Initiative) Act 2011 provides opportunities for mallee plantings to generate revenue. In the United States, alley cropping has been estimated to have the potential to mitigate 82 Tg of CO2e per year (Fargione et al., 2018). In Australia, there are vast untapped agricultural areas with potential to mitigate CO2e using perennial crops, of which mallee is a strong candidate (Hobbs et al., 2009).

To date, efforts have focussed on assessing the utility of mallee agroforestry and optimization of design and production (Mendham et al., 2012; Peck et al., 2012). Leftroy and Stizacker (1999) proposed that widely dispersed belts of woody perennials were likely to be the most effective planting configuration for groundwater management. Mallee agroforestry plantings typically consist of belts of mallee with two to six rows separated by 40–100 m wide alleys of conventional crops and pasture (URS, 2008). Narrow belts (fewer rows of mallee) provide greater biomass productivity per unit of land occupied by the belt compared to wider belts or block plantings (Noorduijn et al., 2009; Paul et al., 2013; Spencer et al., 2020). However, narrower belts increase the area of interaction between mallee and the adjacent crop/pasture for a given area planted to mallee. Productivity of crops and pasture within 20 metres of the mallee belts is suppressed due to competition for water (Robinson et al., 2006; Sudmeyer et al., 2012; Sudmeyer & Hall, 2015). For this reason, Sudmeyer and Hall (2015) proposed segregation of mallee from agriculture to reduce the competition loss. Due to the prevalence of wide-spaced belt planting (URS, 2008), and to facilitate further adoption, the direct and/or indirect economic benefits of mallee production need to be quantified. Past economic studies have had limited long-term experimental data and have used simulation modelling of mallee belt growth and the interaction of belts with crops/pastures to estimate the likely costs and benefits of integrating mallee into the farming systems (Abadi et al., 2012; Bartle & Abadi, 2010). Using this modelling approach, Bartle and Abadi (2010) found that mallee agroforestry (harvested at year 5 and then every 3 years), when compared to agriculture, became profitable after 12 years at a selling price of AUD45 per fresh Mg. Subsequently, Abadi et al. (2012) modelled the economics of a mallee biomass production system and suggested that the cost of production was in the range of AUD53–AUD70 per Mg of fresh biomass with co-benefits valued at between AUD2 and AUD15 Mg−1.

This paper considers the economic viability of mallee in an agroforestry system using a decadal experiment providing yield data from mallee belts with six harvesting treatments across 19 sites (Spencer et al., 2019) and crop and pasture yields measured adjacent to the belts over 6 years (Sudmeyer et al., 2012). These data sets provide a unique opportunity to assess the economic viability of mallee using experimental data obtained from operational short rotation coppice systems with real-world management by farmers (Hauk et al., 2014). The aim of this study is to determine break-even prices of mallee biomass compared to conventional agriculture using levelized cost (LC) analysis. LC has been widely used to compare types of energy production (Edenhofer et al., 2012) and also been utilized in calculating the production cost of bioenergy and biofuel crops (Abadi et al., 2016; El Kasmioui & Ceulemans, 2013). LC is useful where the costs of production are known, but there is no active trading in local markets for the product (Peirson et al., 2002).

Four scenarios are explored: (a) income generated from agriculture alone, (b) income from harvested above-ground mallee biomass, (c) income from harvested above-ground biomass plus carbon sequestered in below-ground biomass, and (d) income from carbon sequestered in unharvested above- and below-ground biomass. Scenarios b, c and d included the costs associated with reduced agricultural production alongside the mallee belts. Sensitivity of the financial returns was assessed by adjusting key variables for a range of assumptions including discount rates, below-ground biomass estimates and carbon price.

2 | MATERIALS AND METHODS

2.1 | Study sites and species

This study includes 11 of 19 mallee trial sites originally established to determine mallee and agricultural yield from
alley farming systems (Spencer et al., 2019; Sudmeyer et al., 2012). Sites were established in 2006 with 5- to 12-year-old mallee belts on privately owned farms in the wheatbelt of WA (Figure 1; Table 1). For continuity, site names remain the same as in Spencer et al. (2019). Sites 6, 7 and 14 were excluded due to low survival and production following the first harvest (Spencer et al., 2019). Sites 2, 9 and 10 were excluded because the alley widths were too narrow (<40 m) to estimate open paddock yield. Sites 11 and 17 were excluded due to incomplete agricultural data sets (Sudmeyer et al., 2012). The belts were either 2, 3, 4 or 6 rows wide and the alley widths were between 48 and 250 m (Table 1). Further detail about the sites is published in two reports (Mendham et al., 2012; Peck et al., 2012).

The WA wheatbelt has a Mediterranean climate with dry hot summers and mild, cool and rainy winters. Mean annual rainfall ranged from 539 mm for the southerly sites to 321 mm for the northern sites (Table 1). The crops and pastures in the wheatbelt of WA are non-irrigated winter-growing annuals. The pastures are typically grazed with self-replacing merino sheep producing wool and meat. Crops and pastures are grown in annual rotations which can generally be characterized as cereal–pasture–pasture; cereal–pasture–cereal; cereal–legume–cereal; cereal–cereal–canola (Harries et al., 2015).

The three mallee species most widely planted by farmers in WA are represented in this study; *Eucalyptus loxophleba* subsp. *lissophloia* L.A.S. Johnson & K.D. Hill, *Eucalyptus polybractea* R. Baker and *Eucalyptus kochii* subsp. *plenissima* C.A. Gardener. These species will hereafter be referred to as $E_{lox}$, $E_{pol}$ and $E_{koc}$ respectively.

### 2.2 Experimental design

The experimental design at each site was a $2 \times 2$ factorial, plus unharvested plots, with three replicates. The factors, each with two levels, were frequency of harvest (short vs. long harvest cycles) and season of harvest (spring vs. autumn). Sites 1, 3, 5, 8, 12 and 15 had treatment plots that were 20 m long (along the mallee belt) with a 10 m buffer separating the plots, the remaining sites had 25 m long plots with a 12.5 m buffer. Prior to the establishment of this trial, no mallee had been harvested.

Initially, the frequency of mallee harvest treatments was 3 or 4 years, but at the less productive sites (12, 15 and 20), the second harvest was delayed to avoid the risk of high mallee mortality. At these sites, harvest frequency was extended to 6 years (Table 1).

Crop and pasture were grown in the alley adjacent to each mallee belt in rotations determined by the individual farmer at each site. Each year from 2006 to 2011, the yield of the crop or pasture was determined by harvesting plots parallel to and 2, 4, 6, 8, 12, 16, 20, 24 and 30 m from the mallee belt for each treatment replicate (Sudmeyer et al., 2012). For pasture paddocks, yield was assessed each year in September and is indicative of relative growth as a function of distance from mallee belts, not total annual pasture yield.

Above-ground mallee biomass yield data were derived and adjusted from Spencer et al. (2019) and summarized in Tables S4 and S5. First, fresh biomass data were used for the purpose of economic analysis, to be consistent with the on-farm gate price for unprocessed fresh woody biomass. Second, the 2 m wide crop exclusion zone (Figure 2) on both sides of the belt was added to account for the displaced cropping/pasture area. Thirdly, the biomass data are expressed as actual fresh harvest yield (Mg/ha) for each treatment rather than annualized increments (Mg ha$^{-1}$ year$^{-1}$).

Above-ground dry biomass was calculated for the unharvested treatments for carbon sequestration estimations as detailed in Spencer et al. (2019). Total biomass was calculated as the biomass produced over the 6 year length of the study.

### 2.3 Mallee carbon estimation

After harvest, mallee shed their fine roots but maintain the lignotuber and structural woody root architecture (Wildy & Pate, 2002). Below-ground biomass was estimated for each coppice treatment using the general mallee eucalypt allometric model from Paul et al. (2014). This model estimates...
below-ground biomass based on the height of the coppice; however, the accuracy of the model in estimating mallee below-ground biomass under frequent harvest management has not been exhaustively evaluated. Thus, to assess impact of possible under- or overestimation of mallee root biomass on LC estimates, a sensitivity analysis was carried out using three below-ground biomass estimates; the minimum, maximum and average over the 6 years of trial.

For the unharvested mallee plots, the carbon sequestered in the above- and below-ground biomass over the 6 years of trial period was estimated by assuming dry biomass to be 50% carbon. Below-ground biomass was calculated as a proportion of the above-ground biomass using the data from Brooksbank and Goodwin (in press).

### 2.4 Crop and pasture yield

The methodology for measurement of crop and pasture yield adjacent to the belt is described in Sudmeyer et al. (2012) and summarized in the Supplementary Materials.

Open paddock yield was determined as the average crop/pasture yield ≥20 m from mallee belt for all treatments given the greatest lateral extent of mallee competition was 18.7 m from the belt (Sudmeyer et al., 2012). To standardize yield across all sites and treatments, the yield in the competition zone (Figure 2; <20 m from the belts) was expressed as the percentage of the open paddock yield (relative yield; Sudmeyer et al., 2012).

The open paddock crop yields and relative yields used in this study were mostly derived from Sudmeyer et al. (2012) and are detailed in Table S1. However, at site 8 in 2008 and site 13 in 2010, crop data were not available. For such cases, average regional yield data from that growing season were used (Planfarm-Bankwest, 2007, 2008, 2009, 2010, 2011, 2012). When data were not collected for a particular treatment, the data were patched using the average yield proportion of the treatment relative to open paddock yield across all other measured years.

### 2.5 Economic analysis

The economic analysis was done over 6 years using reported estimates of returns and costs for mallee production (autumn and spring 2006–2012) and regional averages for crop and sheep enterprises (growing seasons 2006–2011). To standardize sites with different paddock dimensions and belt design, it was assumed that all sites were 100 ha in area assuming nil loss of crop area due to fences, tracks or other obstructions.
Alley and belt widths from each site were maintained and all belts were assumed to be straight and parallel.

At each site, the 100 ha paddock was divided into three components: (a) the mallee belt plus 2 m uncropped (exclusion zone) on either side of the belt; (b) the competition zone, being the area of mallee crop/pasture interaction 2–20 m from both sides of each belt; and (c) the area of open paddock outside the competition zone (Figure 2). The area of each component at each site is detailed in Table 2. Total mallee biomass was calculated by multiplying the yield per hectare for each treatment by the belt area at each site. The total crop/pasture yield was calculated by multiplying the total area of crop/pasture in both the competition zone and the open paddock (ha) by the respective yield (Mg/ha) and adding the quantities.

### 2.6 Production costs and prices for mallee biomass or carbon sequestration

The costs of production for mallee belts were estimated for establishment, maintenance and harvest. Establishment cost used in this study was AUD1,334 ha⁻¹ (Cooper et al., 2006) which was amortized over a period of 30 years per year using equivalent annual annuity:

\[
C = \frac{r \times NPV}{1 - (1 + r)^n},
\]

where \( C \) is equivalent annuity cash flow, \( r \) is the discount rate per period and is assumed to be 13%, \( NPV \) is the net present value of the establishment costs and \( n \) is the project life in years. \( NPV \) is used to account for the time value of funds invested in the paddock, including mallee and crops, over several seasons (Peirson et al., 2002). Maintenance cost was assumed to be AUD15 ha⁻¹ year⁻¹ or AUD55 ha⁻¹ following harvest (Cooper et al., 2006). Harvest cost was assumed to be AUD22 per chipped fresh harvested Mg which is the low end of the range as measured by Spinelli et al. (2014) using conventional forestry equipment and in the range estimated by Abadi et al. (2012). Storage and transport costs are assumed to be zero as biomass is assumed to be sold as fresh chips at the farm gate (El Kasmioui & Ceulemans, 2013). No harvest cost was applied to unharvested treatments which were assumed to be used for carbon sequestration.

#### Table 2

Breakdown of the 100 ha paddock into three components (in hectares) across all sites. Three components are area of mallee belt (including 2 m exclusion zone on either side of mallee belt), area where crop/pasture was subject to competition and the area of open paddock where crop/pasture was not subject to competition.

| Site number | Area mallee belt (ha) | Area competition zone (ha) | Area of open paddock (ha) |
|-------------|-----------------------|---------------------------|--------------------------|
| 1           | 8.4                   | 50.4                      | 41.2                     |
| 3           | 15.2                  | 68.4                      | 16.4                     |
| 5           | 4.0                   | 14.4                      | 81.6                     |
| 8           | 5.0                   | 18.0                      | 77.0                     |
| 12          | 21.0                  | 54.0                      | 25.0                     |
| 13          | 12.0                  | 72.0                      | 16.0                     |
| 20          | 7.0                   | 18.0                      | 75.0                     |
| 15          | 6.0                   | 36.0                      | 58.0                     |
| 16          | 6.0                   | 36.0                      | 58.0                     |
| 18          | 14.0                  | 36.0                      | 50.0                     |
| 19          | 9.8                   | 25.2                      | 65.0                     |

### 2.7 Production costs and prices for grain and sheep production

The operational costs associated with crop and sheep production were estimated using regional data for each experimental year (Planfarm-Bankwest, 2007, 2008, 2009, 2010, 2011, 2012). These costs are summarized in Table S2.

Crop prices for the WA regional export terminal (Kwinana) were obtained for 1 January (or as close as possible) for each year following the growing season (ABARE, 2015; Grain & Graze3, 2020). Sheep income was calculated as the sum of the wool and sheep returns per hectare for each region using industry benchmarks (Planfarm-Bankwest, 2007, 2008, 2009, 2010, 2011, 2012). Crop and sheep prices are detailed in Table S3.

The economic analysis used the actual crop yields (open paddock and competition zone) achieved at each site. Pasture yield was measured annually by Sudmeyer et al. (2012) and regional returns from sheep enterprises were used and discounted by relative pasture yield in the competition zone.

### 2.8 Economic model

Four scenarios were modelled: (a) base-case—exclusively agricultural with no mallee in the system, (b) agroforestry utilizing above-ground mallee biomass, (c) agroforestry utilizing above-ground mallee biomass plus below-ground biomass sequestered, (d) sequestration using unharvested mallee above- and below-ground biomass. The economic analysis presents estimates of the financial viability of each scenario by comparing the base-case model with agroforestry at each site and harvest treatment applied to a 100 ha area. LC analysis was used to determine the price of mallee biomass and sequestered carbon required for mallee agroforestry to break-even with agriculture. LC standardizes the unit price needed over time to break-even with
variable capital and operating expenses over several seasons (Peirson et al., 2002). LC, being a modified version of the net present value calculation, accounts for time value of money using a discount rate.

The model calculates gross margins (GM) in each year for both agroforestry and agricultural paddocks. The GM of the agricultural system and the crop/pasture component of the agroforestry system were calculated as crop and pasture income less production costs. Mallee production costs were calculated for each year. The annual break-even income required from mallee production was calculated by subtracting the mallee production cost and GM of the crop/pasture in the agroforestry system from the GM of the agricultural system.

To compare the agroforestry with the agricultural system over the 6 years of study, an LC analysis was performed by calculating the net present value of the annual break-even income and comparing this to the discounted mallee biomass production, using the following equation:

\[
LC = \sum_{i=0}^{n} \frac{(1+r)^{-i} \cdot A_i}{\sum_{i=0}^{n} (1+r)^{-i} \cdot Y_i}
\]

where \(LC\) is the leveled cost, \(t\) is time (in years), \(A_i\) is the break-even income of the agroforestry in year \(t\), and \(Y_i\) is mallee biomass yield in year \(t\).

A discount rate of 10% was utilized in the calculation of the LC for all scenarios. Sensitivity analysis was performed on the scenarios at low (7%) and high (13%) discount rates.

Sensitivity analysis was also conducted on CO2e price. There was no price on carbon in Australia in 2006 when this experiment commenced so the minimum price used per Mg CO2e was AUD15 based on the current Australian average price (Clean Energy Regulator, 2020), but AUD30 Mg\(^{-1}\) was also evaluated to reflect higher carbon prices elsewhere (Ramstein et al., 2019).

3 | RESULTS

The economic analysis presented here shows that the cost of mallee production integrated into an annual farming system in the wheatbelt of WA is driven by seven parameters: (a) site and its productivity, (b) frequency of mallee harvest, (c) season of mallee harvest, (d) the crop/pasture rotation used by the farmer, (e) discount rate, (f) CO2e price, and (g) the method of estimation of below-ground biomass in a coppice system.

3.1 | Scenario a—Agricultural paddock (base case)

Over the 6 years of this study, the crop/pasture rotations of farmers and the site productivity/seasons, GM from the 100 ha agricultural paddock ranged from a loss of AUD12,922 to a profit of AUD390,226 with an average of AUD114,598 (Table 3). The returns from cropping were consistently greater than from sheep enterprises due to the very low prices for wool and sheep meat over the study period (compare Tables S2 and S3). For instance, at sites 3 and 12, losses were incurred for the 5 years in pasture, yet were profitable for the year in crop (data not shown). Over this study, all other sites were profitable due to returns from 2 or more years of cropping.

3.2 | Scenario b—Agroforestry utilizing above-ground mallee biomass

Over 6 years, the break-even income required to offset mallee costs ranged from under AUD25,000 at site 5 to nearly AUD90,000 at site 19 (excluding site 16 with a truncated data set) (Table 3) with total fresh biomass production ranging from over 1,500 Mg at sites 1 and 18 to 150 Mg at site 15 (Table 3). There was a large range in productivity across all sites ranging from over 30 Mg ha\(^{-1}\) year\(^{-1}\) at site 1 to below 5 Mg ha\(^{-1}\) year\(^{-1}\) at site 15 (Table 3). The LC of mallee biomass production among the 11 sites also varied widely (>6-fold) ranging from AUD40 Mg\(^{-1}\) at site 1 to AUD261 Mg\(^{-1}\) at site 20 (Table 3). There were also considerable differences in LC of mallee biomass within sites across treatments; however, six of the 11 sites had under 20% difference between treatments.

Table 4 groups and compares sites by harvest treatments: those with a full set of harvest treatments (spring and autumn harvests at 3 and 4 years); those with either 3 or 4 years of harvest across different seasons; and low productivity sites with only one harvest in year 6. The LC were generally higher for spring harvests, an effect that was most pronounced at the low productivity sites (6 years of harvest) with a difference of AUD55 Mg\(^{-1}\). Regardless of season of harvest, on average, the LCs of the low productivity sites were double the LCs of the intermediate and high productivity sites. There were also higher LC for the longer harvest frequencies, especially between the 3 years (at AUD68–76 Mg\(^{-1}\)) and the 6 years of harvest frequencies (at AUD139–194 Mg\(^{-1}\)).

The cost of mallee in the agroforestry system was split between the direct costs of mallee establishment and maintenance, and harvesting and the indirect opportunity costs from foregone agricultural production on land occupied by the belts and the loss of yield due to mallee crop competition. Averaged across all sites and harvest treatments, competition costs accounted for approximately 38% of total costs, followed by harvest costs (32%), opportunity cost (16%) and establishment and maintenance costs (14%; Table 5 or Table S5 for individual harvest treatment data).
These costs, however, are not consistent between sites. Proportion of harvest costs was greatest at sites with high mallee production (sites 1, 3, 12 and 18). The opportunity cost was highest at site 19 which had a very high base-case scenario GM, while it was negative where a focus on sheep production incurred a net loss (sites 3 and 12; Tables S1 and S4). The remaining sites (5, 8, 13, 15, 16 and 20) incurred higher competition costs and were predominately cropped over the study period.
Sensitivity analysis was performed using low (7%), medium (10%) and high (13%) discount rates. This revealed only small differences (1%–4%) in LC among treatments at each site (Table S4). Across sites, the average difference in LC between high discount rate and low discount rate ranged from 1% at site 18 to 20% at site 12 and averaged 9.5% across all sites.

Across all sites and harvest treatments, there was a negative exponential relationship between total mallee biomass production and LC of mallee biomass with a coefficient of determination of 0.50 (Figure 3). This shows that the LC of biomass production is substantially greater at sites with lower productivity due to the diminishing marginal costs of production. There is a floor of LC of AUD58.6.

### Table 4

The averaged levelized cost of mallee biomass across sites for each harvest treatment. Sites are separated into groups with the full set of four treatments (frequency and season of harvest), those with either 3 or 4 years of harvests, and the low productivity sites with only 6 year harvest cycles. A discount rate of 10% was applied in the net present value calculation.

| Sites | Frequency of harvest (years) | Season of harvest | Levelized cost (AUD Mg\(^{-1}\)) |
|-------|-----------------------------|------------------|---------------------------------|
| 1, 3, 8, 13, 18 and 19 | 3 | Autumn | 70.2 |
| | 3 | Spring | 76.1 |
| | 4 | Autumn | 73.8 |
| | 4 | Spring | 78.3 |
| 5 and 16 | 3 or 4 | Autumn | 68.4 |
| | | Spring | 90.4 |
| 12, 15 and 20 | 6 | Autumn | 139.0 |
| | | Spring | 194.2 |

#### Figure 3

The levelized cost (LC) of fresh above-ground mallee biomass production across all 11 mallee sites and treatments including the unharvested treatments. Line of best fit is a power function, \( LC = 58.6 + 326*\exp{-0.005} \text{Mg} \) with a coefficient of determination of 0.50

### Table 5

The proportion of levelized cost, averaged across all harvest treatments, that is attributable to direct and indirect costs incurred when introducing mallee into the farming system. The direct cost of mallee includes establishment and maintenance and harvest. The indirect costs consist of the opportunity cost, being the land no longer available for crop, and the competition cost, being income lost from lower crop yields in the competition zone.

| Site | Direct costs (%) | Indirect costs (%) |
|------|------------------|--------------------|
|      | Establishment and maintenance cost | Harvest costs | Opportunity cost | Competition cost |
| 1    | 5                 | 51                | 12              | 32               |
| 3    | 25                | 50                | -5              | 30               |
| 8    | 10                | 27                | 21              | 42               |
| 13   | 9                 | 22                | 6               | 63               |
| 18   | 16                | 47                | 12              | 25               |
| 19   | 10                | 24                | 45              | 21               |
| 16   | 9                 | 40                | 8               | 43               |
| 5    | 11                | 25                | 20              | 44               |
| 12   | 42                | 44                | -6              | 20               |
| 15   | 7                 | 14                | 24              | 55               |
| 20   | 12                | 12                | 37              | 39               |
| Average | 14              | 32                | 16              | 38               |
| SD   | 11                | 14                | 16              | 14               |
| CV (%) | 75               | 44                | 100             | 36               |
increased to AUD30 Mg\(^{-1}\), this decreases the LC by between 6% and 54% with an average of 23%.

The difference in LC between the minimum and the maximum root biomass estimates averaged 8% or 17% Mg\(^{-1}\) CO\(_2\)e price of AUD15 or AUD30 respectively (Table S6). This ranged between 3% and 23% across all sites and treatments.

### 3.4 | Scenario d—Agroforestry with unharvested mallee sequestering carbon in AGB and BGB

The total above-ground mallee biomass produced over the 6 years of the trial ranged from 1,704 Mg at site 18 to 243 Mg at site 20 and averaged 709 Mg across all sites (Table 7),

### Table 6

| Site | Scenario b | Scenario d | Scenario b | Scenario d |
|------|-------------|-------------|-------------|-------------|
|      | $0 CO_2e$   | $15 CO_2e$  | $30 CO_2e$  | $15 CO_2e$  |
|      | Min BGB ($Mg^{-1}$) | Avg BGB ($Mg^{-1}$) | Max BGB ($Mg^{-1}$) | Min BGB ($Mg^{-1}$) | Avg BGB ($Mg^{-1}$) | Max BGB ($Mg^{-1}$) |
| 1    | 40–59       | 38–58       | 37–55       | 36–54       | 36–56       | 34–52       | 31–49       |
| 3    | 50–58       | 44–52       | 42–48       | 40–45       | 38–45       | 35–39       | 31–33       |
| 8    | 81–97       | 77–92       | 74–91       | 72–89       | 72–88       | 67–84       | 63–81       |
| 13   | 88–116      | 85–111      | 83–109      | 81–107      | 81–106      | 77–101      | 74–97       |
| 18   | 46–49       | 41–44       | 39–43       | 38–41       | 37–40       | 33–37       | 30–33       |
| 19   | 94–109      | 89–104      | 88–102      | 86–100      | 84–98       | 82–94       | 79–91       |
| 16   | 54–63       | 48–55       | 45–51       | 43–47       | 41–47       | 36–39       | 31–32       |
| 5    | 83–118      | 81–116      | 79–112      | 76–109      | 79–114      | 75–105      | 70–99       |
| 12   | 65–71       | 56–57       | 48–50       | 43–44       | 43–46       | 29–32       | 16–21       |
| 15   | 156–257     | 153–253     | 151–250     | 149–245     | 150–250     | 146–243     | 141–234     |
| 20   | 190–261     | 166–233     | 154–211     | 146–195     | 141–206     | 117–162     | 102–128     |

### Table 7

Productivity of unharvested mallee belts and the levelized cost for above-ground fresh biomass. Total Mg CO2e generated and CO2e productivity of above- and below-ground biomass of over 6 years at each site and the levelized cost with a 10% discount rate. Bold figures indicate sites that would be profitable with the current price of CO2e (AUD15 Mg\(^{-1}\)). Site 16 only included 3 years of data.
approximately 110 Mg less than the average harvested treatments from scenario b. For the unharvested belts, the undiscounted break-even mallee income ranged from AUD21,604 at site 3 (excluding site 16 with truncated data) to AUD75,349 at site 19, with an average of AUD39,947 across all sites (Table 3). This was about AUD12,000 less than the harvested treatments from scenario b mainly driven by the absence of harvest costs.

The LC of the unharvested belts under scenario b methodology ranged from AUD33 Mg\(^{-1}\) at site 1 to nearly AUD240 at site 20 (Table 7). Compared to the harvested belts, the LC of the unharvested mallee were cheaper at 6 of the 11 sites (cf. Tables 3 and 7). If mallee is grown solely to generate above- and below-ground carbon credits, then the LC ranged between AUD11 and AUD64 and averaged AUD29 Mg\(^{-1}\) CO\(_2\)e, a reduction across all sites ranging from 62% at both sites 18 and 19 and up to 83% at site 20. Lower LC were realized at sites with higher CO\(_2\)e productivity.

Across all sites, greater differences were observed between discount rates for the unharvested mallee agroforestry compared to the harvested mallee agroforestry (generally > 15%; Table S4). The proportion of costs of unharvested mallee belts was considerably different to the harvested mallee with higher average costs (66%), attributable to competition (Table S5).

### 4 | DISCUSSION

Understanding the economic consequences of integrating mallee belts into annual crop/pasture farming systems is essential for mallee agroforestry development. The data presented here show large site and regional differences in the LC of mallee biomass production or carbon credit production, but less variation arising from the management choices of season or frequency of harvest.

Mallee agroforestry systems can generate direct income by selling biomass, CO\(_2\)e or both. Under the Australian Carbon Farming Initiative, sequestration projects can generate carbon credits over 25 years of period, although the net abatement of CO\(_2\)e is reduced by 20% if the planting is removed before 100 years (Department of the Environment, 2015) and this applies to above- or below-ground biomass components. Over the trial, the above- and below-ground carbon sequestration by unharvested mallee would be profitable given current Australian CO\(_2\)e prices at three of the 11 trial sites. At AUD30 Mg\(^{-1}\) CO\(_2\)e, mallee agroforestry would have been profitable at seven sites.

In WA, crop and sheep enterprises generally generate annual positive cash flows while a coppice harvest regime for mallee generates periodic positive cash flows after harvest. This may well affect the willingness of landholders to grow the mallee or provide land to third parties to plant and harvest the mallee under a lease agreement. Given the 2006–2011 agricultural GM, four of the 11 study sites had a LC of mallee biomass production in the range AUD40–60 Mg\(^{-1}\). These sites were generally characterized by high biomass production or moderate biomass production with low agricultural GM. This price range may be economically attractive to farmers to sell into biomass processing markets to take advantage of the on-farm benefits of mallee crops. The remaining seven sites had levelized biomass costs ranging from AUD70 Mg\(^{-1}\), with two sites exceeding AUD200 Mg\(^{-1}\), and were less commercially attractive. There was a reduction in LC when below-ground biomass was used to generate carbon credits especially at AUD30 Mg\(^{-1}\) CO\(_2\)e, which although nearly double the current Australian price, is comparable to the price in some large carbon credit markets around the world (Ramstein et al., 2019).

Some caution needs to be exercised with these numbers as the opportunity cost and consequent LC of mallee biomass production was heavily influenced by crop/pasture rotation decisions of the landholders, with lower opportunity and competition costs associated with sheep grazing due to low wool and sheep prices over the study period (cf. Tables S2 and S3). This resulted in some sites with low biomass production with a low LC because the sites were in pasture for 5 of the trial 6 years. Conversely, two sites were moderately productive but had high LC due to high proportion of years where growers chose to grow grain crops. In the intervening years, there has been a substantial increase in returns for wool and sheep meat producers.

The sites with the lower LC were consistent with previous work on mallee economics. Abadi et al. (2012) estimated a range of AUD44–55 Mg\(^{-1}\) for biomass at the farm gate, or AUD53–70 Mg\(^{-1}\) including off-farm transport and supply chain costs. McGrath et al. (2016) showed that, excluding harvesting and delivery costs, mallee agroforestry would be marginally economic from AUD24 Mg\(^{-1}\), but AUD34 Mg\(^{-1}\) was required for large-scale adoption.

There are on-farm and natural resource management benefits of mallee integration including: dewatering the soil profile below and adjacent to belts (Robinson et al., 2006; Sudmeyer & Goodreid, 2007; Wildy et al., 2004) with potential to enhance salinity mitigation (Clarke et al., 2002; George, 1990); erosion control and provision of shade and shelter for stock which is especially useful during lambing (Abadi et al., 2012; Baker et al., 2018) and provision of shelter for crops (Baker et al., 2018; Bennell & Verbyla, 2008; Sudmeyer et al., 2002). Abadi et al. (2012) estimated the value of these benefits was between AUD2 and AUD13 per fresh Mg of mallee biomass produced, excluding payment for carbon sequestration. About 75% of the upper estimate was associated with mitigation of waterlogging which is
only frequent on particular soil types and in higher rainfall growing season (May–October in WA) and is becoming less common as average rainfall in the south-west of WA is diminishing (Asseng & Pannell, 2013). In estimating the required price per Mg of CO₂e to make agroforestry viable for carbon farming, Flugge and Abadi (2006) modelled the value of salinity mitigation at AUD5 Mg⁻¹ CO₂e.

The quantity of biomass produced per unit area has a large effect on the LC. The biomass productivity achieved at each site is a combination of several quantifiable factors, including season and frequency of harvest (Spencer et al., 2019) and planting configuration (number of rows, between row spacing and alley widths; Spencer et al., 2020). There are some less quantifiable factors, including reconfiguration of paddock shape, size and infrastructure to better integrate mallee belts. For instance, gains in mallee productivity could be realized by including small (40–50 cm) water retention bunds to capture any surface water flow. Experimental data show that after 3 years, belts with bunds produced 35% more biomass (Bennett et al., 2015). Spencer et al. (2019) found edaphic factors (EC, pH and nutrition) were strong predictors of productivity across the sites in this study. This decadal research project reveals declining mallee productivity with proximity to shallow saline water tables, and alkaline and nutrient-poor soils profiles. To reduce opportunity costs, mallee species have often been allocated suboptimal landscape positions, generally into saline valley floors. This economic analysis shows that, assuming a market for biomass, this paradigm should be questioned, with mallee capable of delivering greater financial reward to the landholder when planted in productive sites. Prospective mallee species have a range of site preferences indicating that matching species to site will generally improve mallee productivity and reduce opportunity costs. Wider belts (more rows) take up more paddock area and internal rows are suppressed by the larger trees in the external rows which have greater access to additional resources from the alley (Huxtable et al., 2012; Prasad et al., 2010; Spencer et al., 2020). Consequently, the internal rows have reduced the productivity per hectare of the belt. Fewer rows, or wider between-row spacing, may allow for shorter harvest frequencies will also improve cash flow. Fewer rows will also reduce the cost of harvest at the sites with less standing biomass because harvest costs have been found to be dependent on the standing biomass per km of belt (Spinelli et al., 2014). A prototype single-row chipper–harvester has been developed to reduce harvest cost using technology capable of processing the high wood density and multiple stems of mallee (Abadi et al., 2012; Goss et al., 2014). Harvesting single rows would be more cost-effective for single or double row belts.

Reducing belt width (i.e. number of rows) can reduce LC by increasing mallee productivity and reducing opportunity costs. Wider belts (more rows) take up more paddock area and internal rows are suppressed by the larger trees in the external rows which have greater access to additional resources from the alley (Huxtable et al., 2012; Prasad et al., 2010; Spencer et al., 2020). Consequently, the internal rows have reduced the productivity per hectare of the belt. Fewer rows, or wider between-row spacing, may allow for shorter harvest frequency intervals and generate earlier positive cash flows for investors with larger discount rate. Increased harvesting frequencies will also improve cash flow. Fewer rows will also reduce establishment and maintenance costs, and if using a single-row chipper–harvester, could further reduce harvest costs.

Results from this study rely on the accuracy of BGB estimates from allometric equations. The ‘best’ current model for estimating below-ground biomass of mallee is not species specific and uses mallee height which alone explains less than 50% of actual biomass (Paul et al., 2014). Large species differences have been found in unharvested root/shot ratios of the mallee species used in this study (Brooksbank & Goodwin, in press) which are likely to persist post-harvest. Furthermore, the allometric models are likely to underestimate mallee industry is likely to only be viable if it can deliver a continuous supply of biomass (Enecon, 2001) and growers may be limited in their choice of harvest season. To reduce competition costs, with increasing mallee size, the grower could increase the width of the exclusion zone; only cropping where returns are greater than input costs (Sudmeyer et al., 2012).

This study also demonstrates that longer harvest intervals increase LC. There was only a slight increase in LC when comparing the 3 years of harvests to the 4 years of harvests, but there was a much greater difference when comparing the 3 or 4 years of harvests to the 6 years of harvests. This is consistent with the finding that competition is positively correlated with tree height (Sudmeyer et al., 2002, 2012). The longer harvest frequencies will result in delayed returns from mallee production and a lower net present value.

Harvest costs account for almost a third of the total cost (32%) of mallee biomass production. These estimates were based on mallee harvesting using conventional forestry equipment. This study assumed a fixed harvesting cost, which would underestimate the cost of harvest at the sites with less standing biomass because harvest costs have been found to be dependent on the standing biomass per km of belt (Spinelli et al., 2014). A prototype single-row chipper–harvester has been developed to reduce harvest cost using technology capable of processing the high wood density and multiple stems of mallee (Abadi et al., 2012; Goss et al., 2014). Harvesting single rows would be more cost-effective for single or double row belts.
below-ground biomass because the models do not take into consideration the likely increase of biomass with subsequent harvests. A below-ground mallee root biomass conceptual model was proposed by Bartle and Abadi (2010) who suggest that below-ground biomass accumulates over time. This arises from the loss of fine root biomass with harvest (Wildy & Pate, 2002) and the considerable depth to which mallee roots can penetrate (Nulsen et al., 1986), and over regular harvests, additional woody root biomass sequestered between harvests would likely persist. Currently, no mallee allometry exists over multiple harvest cycles and further research is required to provide greater confidence in the below-ground biomass estimates.

Future research is required for multi-criteria mapping of the WA wheatbelt to locate land which could most benefit from mallee integration. For instance, such criteria include targeting areas that are most in need of salinity mitigation, with high suitability for mallee productivity, and where farmers could benefit from having shelter for sheep breeding. Such assessments have been undertaken for the agricultural sector in WA (DAFWA, 2013; Schoknecht, 2015) and could be adapted for mallee. For instance, in comparison to agricultural crops, mallee can tolerate and respond better to acidic soils (Spencer et al., 2019; Symonds et al., 2001). This assessment would also help investors who, for example, are looking for carbon offset projects, to have more confidence with where to grow mallee and the level of compensation required for landholders.

There are distinct advantages for both the coppice and unharvested system. Mallee are capable of stable biomass production with regular harvests (Davis, 2002; Spencer et al., 2019) but without harvest, the growth rates will slow reducing the rate of carbon sequestration while increasing competition to agriculture. Cash flows from the coppice system will occur with harvests, likely every 3–4 years, but in large operations, harvesting could be structured to provide annual income, although this will add annual costs for mobilizing harvesting equipment. Under current legislation, payments from sequestration occur at agreed reporting periods between 6 months and 5 years (Department of the Environment, 2014). The markets for biomass and carbon credits will ultimately determine whether the mallee will be harvested or left without harvest for 25 or 100 years, with our modelling suggests could be profitable based on carbon price.

5 | CONCLUSION

Mallee, integrated into a farming system, imposes additional costs on farmers, especially through competition and harvest costs, and, to a lesser extent, opportunity and establishment costs. For widespread adoption, farmers will require markets for biomass or carbon credits that equal or exceed the profitability of traditional agriculture.

Our estimates show that mallee can cost farmers from AUD40 to over AUD250 Mg⁻¹ of fresh biomass to produce. Lower LC are realized at sites with high mallee growth rates. The second most important determinant of LC was the relative returns from agricultural activities.

The LC could be reduced by 11% on average, if below-ground biomass was sold at the present CO₂e price in Australia. More accurate allometric models are required to estimate below-ground biomass, especially over multiple harvests. If Australia’s CO₂e price were aligned with other developed nations at AUD30 Mg⁻¹, the LC would be halved. Given the current carbon prices, the price generated by carbon from unharvested mallee at high productivity sites is already comparable with agricultural returns.

ACKNOWLEDGEMENTS

The authors would like to thank the teams from CALM/DEC and DAFWA who collected the mallee production and crop/pasture yield data. Dan Huxtable and Richard Mazanec were involved in early conceptual interpretation of data. The authors would like to thank the two anonymous reviewers who provided thoughtful comments and improve the manuscript. The authors would also like to acknowledge the contribution of an Australian Government Research Training Program Scholarship and Curtin Strategic Stipend Scholarship in supporting this research.

CONFLICT OF INTEREST

The authors declare no conflicts of interests in the subject matter discussed in this manuscript.

AUTHORS’ CONTRIBUTIONS

J.B. and R.S. designed the experiment responsible for the experimental data used in this study. B.S. and A.A. conceived the conceptual design of the study. S.V.G and B.S. built the economic model. B.S. drafted the manuscript. R.S., S.V.G, J.B., A.Z., A.A. and M.G. contributed to the final version of the manuscript.

DATA AVAILABILITY STATEMENT

Most data are available in article supplementary material or in these cited articles: Spencer et al. (2019) or Sudmeyer et al. (2012). Where the data are not available, data will be made available on reasonable request from the authors.

ORCID

Beren Spencer https://orcid.org/0000-0001-5475-0251

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.
Harries, M., Anderson, G. C., & Hüberli, D. (2015). Crop sequences in Western Australia: What are they and are they sustainable? Findings of a four-year survey. *Crop and Pasture Science, 66*(6), 634–647. https://doi.org/10.1071/CP14221

Hauk, S., Knoke, T., & Wittkopf, S. (2014). Economic evaluation of short rotation coppice systems for energy from biomass – A review. *Renewable & Sustainable Energy Reviews, 29*, 435–448. https://doi.org/10.1016/j.rser.2013.08.103

Hobs, T., Bennell, M., & Bartle, J. (2009). Developing species for woody biomass crops in lower rainfall Southern Australia: *FloraSearch* 3a. Publication No 09/043. Rural Industries Research and Development Corporation.

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.

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. https://doi.org/10.1016/S1364-8152(01)00008-1

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

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).

Mendham, D., Bartle, J., Peck, A., Bennett, R., Ogden, G., McGrath, G., Abadi, A., Vogwill, R., Huxtable, D., & Turnbull, P. (2012). Management of mallee belts for profitable and sustained production. *Future Farm Industries Cooperative Research Centre*.

Mewalal, R., Rai, D. K., Kainer, D., Chen, F., Kühlheim, C., Peter, G. F., & Tuskan, G. A. (2017). Plant-derived terpenes: A feedstock for specialty biofuels. *Trends in Biotechnology, 35*(3), 227–240. https://doi.org/10.1016/j.tibtech.2016.08.003

Noorduijn, S., Smettem, K., Vogwill, R., & Ghadouani, A. (2009). Relative impacts of key drivers on the response of the water table to a major alley farming experiment. *Hydrology and Earth System Sciences, 13*(11), 2095–2104. https://doi.org/10.5194/hess-13-2095-2009

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. https://doi.org/10.1111/j.1442-9993.1986.tb01406.x

Paul, K. I., Roxburgh, S. H., England, J. R., Brooksbank, K., Larmour, J. S., Ritson, P., Wildy, D., Sudmeyer, R., Raison, R. J., Hobbs, T., Murphy, S., Sochacki, S., McArthur, G., Barton, C., Jonson, J., Theiveyanathan, S., & Carter, J. (2014). Root biomass of carbon plantings in agricultural landscapes of southern Australia: Development and testing of allometrics. *Forest Ecology and Management, 318*, 216–227. https://doi.org/10.1016/j.foreco.2013.12.007

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., Knox, L., Rooney, M., Freudenberger, D., Jonson, J., Peck, A., ...Lothian, P. A. (2013). 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.

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

Peirson, G., Brown, R., Easton, S., & Howard, P. (2002). *Business Finance*. McGraw-Hill.

Planfarm-Bankwest. (2007). *Planfarm bankwest benchmarks 2006–2007*. Planfarm Pty Ltd and Bankwest Agribusiness Centre.

Planfarm-Bankwest. (2008). *Planfarm bankwest benchmarks 2007–2008*. Planfarm Pty Ltd and Bankwest Agribusiness Centre.

Planfarm-Bankwest. (2009). *Planfarm bankwest benchmarks 2008–2009*. Planfarm Pty Ltd and Bankwest Agribusiness Centre.

Planfarm-Bankwest. (2010). *Planfarm bankwest benchmarks 2009–2010*. Planfarm Pty Ltd and Bankwest Agribusiness Centre.

Planfarm-Bankwest. (2011). *Planfarm bankwest benchmarks 2010–2011*. Planfarm Pty Ltd and Bankwest Agribusiness Centre.

Planfarm-Bankwest. (2012). *Planfarm bankwest benchmarks 2011–2012*. Planfarm Pty Ltd and Bankwest Agribusiness Centre.

Prasad, J. V. N. S., Korwar, G. R., Rao, K. V., Mandal, U. K., Rao, C. A. R., Rao, G. R., Ramakrishna, Y. S., Venkatwarlu, B., Rao, S. N., Kulkarni, H. D., & Rao, M. R. (2010). Tree row spacing affected agronomic and economic performance of Eucalyptus -based agroforestry in Andhra Pradesh, Southern India. *Agroforestry Systems, 78*(3), 253–267. https://doi.org/10.1007/s10457-009-9275-1

Ramstein, C., Dominioni, G., Etchad, S., Lami, L., Quant, M., Zhang, J., Mark, L., Nierop, S., Berg, T., & Leuschner, P. (2019). *State and trends of carbon pricing 2019*. The World Bank.

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.

Schoknecht, N. (2015). Report card on sustainable natural-resource use in the agricultural regions of Western Australia. *Soil Research, 53*(6), 695–709. https://doi.org/10.1071/SR14267

Soh, M., & Stachowiak, G. W. (2002). The application of cineole as a grease solvent. *Flavour and Fragrance Journal, 17*(4), 278–286. https://doi.org/10.1002/ffj.1103

Spencer, B., Bartle, J., Abadi, A., Gibberd, M., & Zerihun, A. (2020). Planting configuration affects productivity, tree form and survival of mallee eucalypts in agroforestry systems. *Agroforestry Systems*. https://doi.org/10.1007/s10457-020-00543-0

Spencer, B., Bartle, J., Huxtable, D., Mazaneck, 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. https://doi.org/10.1016/j.foreco.2019.117576

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. https://doi.org/10.1007/s10457-014-9707-4

Sudmeyer, R., Adams, M., Eastham, J., Scott, P., Hawkins, W., & Rowland, I. (2002). Broadacre crop yield in the lee of windbreaks in the medium and low rainfall areas of south-western Australia. *Australian Journal of Experimental Agriculture, 42*(6), 739–750. https://doi.org/10.1071/EA02011

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.
Sudmeyer, R., & Goodreid, A. (2007). Short-rotation woody crops: A prospective method for phytoremediation of agricultural land at risk of salinisation in southern Australia. *Ecological Engineering*, 29(4), 350–361. https://doi.org/10.1016/j.ecoleng.2006.09.019

Sudmeyer, R. A., & Hall, D. J. (2015). Competition for water between annual crops and short rotation mallee in dry climate agroforestry: The case for crop segregation rather than integration. *Biomass and Bioenergy*, 73, 195–208. https://doi.org/10.1016/j.biombioe.2014.12.018

Symonds, W., Campbell, L., & Clemens, J. (2001). Response of ornamental Eucalyptus from acidic and alkaline habitats to potting medium pH. *Scientia Horticulturae*, 88(2), 121–131. https://doi.org/10.1016/S0304-4238(00)00202-8

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

Wildy, D. T., Bartle, J. R., Pate, J. S., & Arthur, D. J. (2000). 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. https://doi.org/10.1093/aob/mcf166

Wu, H., Yu, Y., & Yip, K. (2010). Bioslurry as a fuel. 1. Viability of a bioslurry-based bioenergy supply chain for mallee biomass in Western Australia. *Energy & Fuels*, 24(10), 5652–5659.

Yu, Y., Bartle, J., Li, C.-Z., & Wu, H. (2009). Mallee biomass as a key bioenergy source in Western Australia: Importance of biomass supply chain. *Energy & Fuels*, 23(6), 3290–3299. https://doi.org/10.1021/ef900103g

**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section.

**How to cite this article:** Spencer B, Abadi A, Bartle J, et al. Determinants of the economic viability of mallee eucalypts as a short rotation coppice crop integrated into farming systems of Western Australia. *GCB Bioenergy*. 2020;00:1–15. https://doi.org/10.1111/gcbb.12775