Received: 28 August 2020 | Accepted: 12 October 2020
DOI: 10.1111/gcbb.12775

ORIGINAL RESEARCH

GCB-BIOENERGY BIOPRODUCTS FOR A SUSTAINABLE BIOECONOMY Open Access
WILEY

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

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Funding information
Curtin University of Technology; Australian Government Research Training Program

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} CO_2 equivalent (CO_2e). 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 CO_2e 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

1 | INTRODUCTION

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 CO_2e per year (Fargione et al., 2018). In Australia, there are vast untapped agricultural areas with potential to mitigate CO_2e 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). Lefroy and Stirzaker (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.

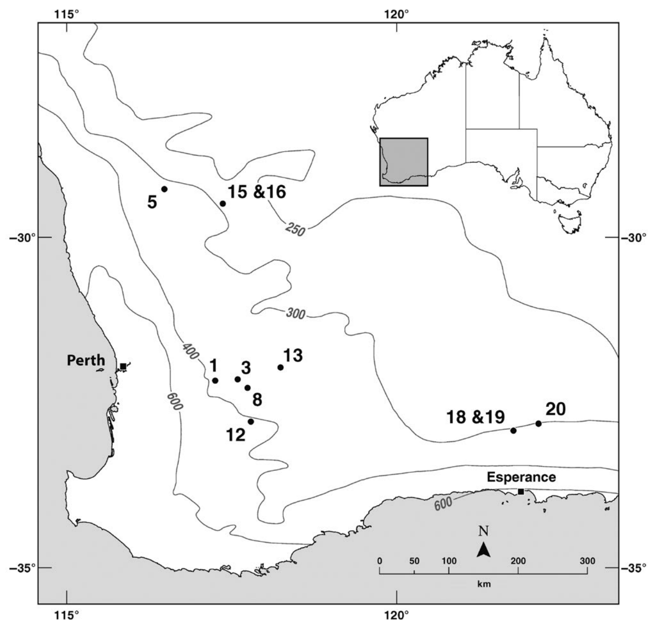

FIGURE 1 Location of mallee trial sites within the Western Australia wheatbelt; also shown are selected rainfall isohyets (grey line). The site numbers correspond to those in table 1 of Spencer et al. (2019)

2.2 | Experimental design

The experimental design at each site was a 2 × 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

TABLE 1 Site characteristics and planting designs for mallee trial sites including mallee species, year of planting, number of rows in each belt, the alley width between belts and the harvest frequency at each site. Mean annual rainfall (MAR) data from 1970 to 2011 were obtained through SILO data sets (Jeffrey et al., 2001)

Site number	Species	Year planted	Number of rows	Alley width (m)	Harvest frequency (years)	MAR (mm)
1	E_{pol}	1996	2	70	3 and 4	432
3	E_{lox}	2000	3	50	3 and 4	353
8	E_{pol}	1998	4	180	3 and 4	368
13	E_{lox}	1997	2	48	3 and 4	326
18	E_{pol}	2001	6	95	3 and 4	539
19	E_{pol}	2001	6	130	3 and 4	539
16	E_{koc}	1994	2	95	3	321
5	E_{lox}	1998	4	250	4	327
12	E_{lox}	2000	6	55	6	370
20	E_{lox}	2001	6	180	6	457
15	E_{koc}	1998	2	95	6	321

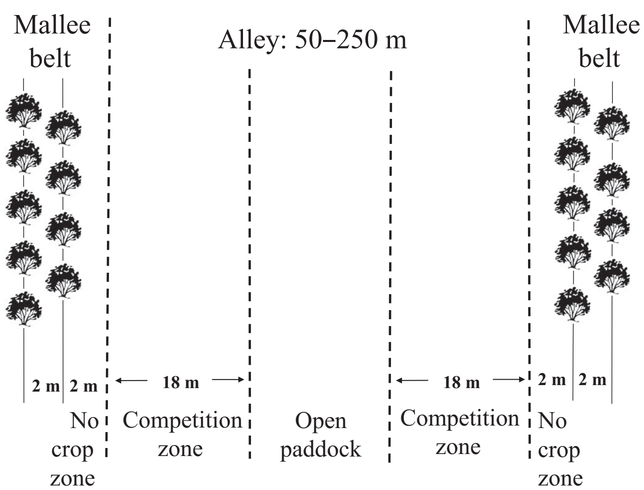

FIGURE 2 Schematic cross section of a two-row mallee belt with 2 m exclusion zones and an alley between the belts comprising of competition zones and open paddock

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:

$$C = \frac{r \times \text{NPV}}{1-(1+r)^{n}}, \tag{1}$$

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 agriculture 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:

$$\mathrm{LC} = \frac{\sum_{t=0}^{n} (1+r)^{-t} \,.\, A_t}{\sum_{t=0}^{n} (1+r)^{-t} \,.\, Y_t}, \tag{2}$$

where LC is the levelized cost, t is time (in years), A_t is the break-even income of the agroforestry in year t, and Y_t 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 b* and *d* at low (7%) and high (13%) discount rates.

Sensitivity analysis was also conducted on CO_2e price. There was no price on carbon in Australia in 2006 when this experiment commenced so the minimum price used per Mg CO_2e 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) CO_2e 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 harvests) 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).

TABLE 3 Gross margin (AUD) of the solely agricultural paddock and the break-even mallee income (AUD) required to offset the costs incurred by mallee from the agroforestry paddock compared to agricultural paddock over the 6 years of trial. The cost of mallee includes establishment, maintenance, harvesting, opportunity and competition costs. The production of fresh mallee biomass produced and mallee productivity over the trial for all treatments and the levelized cost for above-ground fresh biomass (AUD Mg^{-1}) using a 10% discount rate. Treatments varied between sites with either 3 and 4 years of harvest or 6 years of harvest regime. Site 16 had only one 3 years of harvest cycle

Site	Gross Margin ($)	Season of harvest	Frequency of harvest (years)	Costs of mallee ($)	Productivity (Mg ha^{-1} $year^{-1}$)	Mallee biomass (Mg)	Levelized cost ($ Mg^{-1})
1	94,288	Autumn	3	67,653	33.1	1,670	42.7
		Spring	3	73,097	30.6	1,540	52.2
		Autumn	4	61,187	32.3	1,629	40.1
		Spring	4	58,700	22.2	1,118	58.8
3	−12,922	Autumn	3	37,203	9.8	891	50.1
		Spring	3	38,656	9.6	874	54.2
		Autumn	4	35,248	8.1	743	57.9
		Spring	4	41,843	10.4	944	53.3
8	156,839	Autumn	3	34,239	14.5	436	82.4
		Spring	3	38,075	14.1	423	97.3
		Autumn	4	34,501	15.1	454	81.4
		Spring	4	40,571	15.8	475	93.1
13	27,752	Autumn	3	53,783	8.8	632	88.4
		Spring	3	56,644	7.6	550	110.3
		Autumn	4	50,708	7.0	507	106.1
		Spring	4	60,503	7.5	541	116.3
18	65,867	Autumn	3	74,939	18.7	1,573	48.5
		Spring	3	77,074	19.3	1,625	48.6
		Autumn	4	81,789	20.4	1,717	49.0
		Spring	4	83,290	22.4	1,884	45.6
19	390,226	Autumn	3	86,257	14.8	869	109.4
		Spring	3	82,043	16.3	957	94.1
		Autumn	4	85,522	15.4	904	107.9
		Spring	4	89,605	16.8	985	103.0
16	17,877	Autumn	3	16,231	17.2	309	54.1
		Spring	3	12,107	11.2	202	62.9
5	131,045	Autumn	4	29,761	16.2	388	82.7
		Spring	4	23,850	9.5	227	117.9
12	−12,922	Autumn	6	40,371	6.2	775	70.7
		Spring	6	45,348	7.4	936	64.7
15	146,155	Autumn	6	40,439	8.6	308	156.3
		Spring	6	32,246	4.2	150	256.9
20	256,371	Autumn	6	51,757	7.8	329	190.1
		Spring	6	45,671	5.1	216	261.0
Average	114,598			52,380	14.2	817	91.4
SD	117,291			21,445	7.5	510	54.3
CV (%)	100			40.9	52.7	62.4	59.4

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

3.3 | *Scenario c*—Agroforestry with above-ground production and below-ground carbon sequestration

When above-ground mallee biomass production plus carbon sequestration in below-ground biomass is considered, the LC of mallee biomass production is reduced (Table 6 or Table S6 for individual harvest treatment data). Compared to *scenario b*, a carbon price of AUD15 Mg^{-1} CO_2e at the average below-ground biomass estimate reduces the LC of biomass production by between 3% and 27% and averaged 12% across all sites and harvest treatments (Table S6). If the CO_2e price is

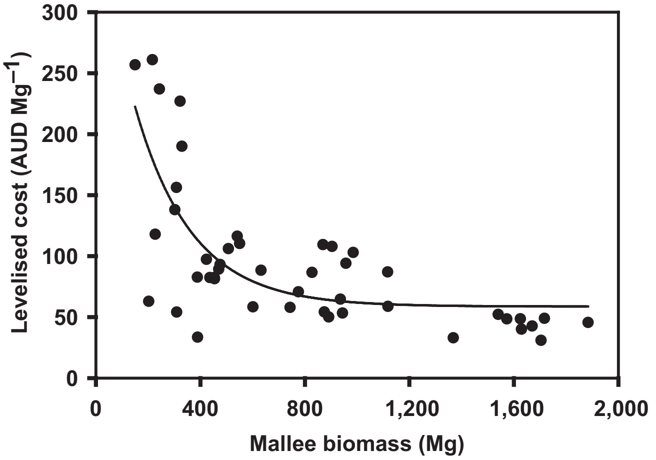

FIGURE 3 The levelized cost (LC) of fresh above-ground mallee biomass production across all 11 mallee sites and treatments including the unharvested treatments. Line of best fit is a power function, LC = 58.6 + 326*exp − 0.005 Mg with a coefficient of determination of 0.50

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

	Direct costs (%)		Indirect costs (%)	
Site	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

TABLE 6 The range of levelized costs (AUD Mg^{-1}) at each site across harvest treatments at a discount rate of 10%. Levelized cost from *Scenario b* is presented for comparison. Sensitivities were performed at AUD15 and AUD30 Mg^{-1} CO_2e. Sensitivities were also performed on the below-ground carbon biomass estimates with three categories: minimum below-ground biomass (Min BGB), average (Avg BGB) and maximum (Max BGB) over the 6 years of experimental data

	$0 CO_2e	$15 Mg^{-1} CO_2e			$30 Mg^{-1} CO_2e		
Site	*Scenario b*	Min BGB ($ 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 CO_2e generated and CO_2e 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 CO_2e (AUD15 Mg^{-1}). Site 16 only included 3 years of data

	Scenario b				*Scenario d*		
Site	Productivity (Mg ha^{-1} $year^{-1}$)	Total cost of mallee ($)	Mallee biomass (Mg)	Levelized cost (AUD Mg^{-1})	Total CO_2e (Mg)	CO_2e productivity (Mg ha^{-1} yr^{-1})	Levelized cost (AUD Mg^{-1} CO_2e)
1	27.1	34,345	1,368	33.0	2,526	50.1	**11.1**
3	6.6	21,604	601	58.4	1,138	12.5	19.2
8	10.1	32,707	302	138	506	16.9	51.1
13	11.5	57,008	827	86.6	1,666	23.1	26.7
18	20.3	45,256	1,704	30.9	2,804	33.4	**11.7**
19	19.0	75,349	1,117	87.0	1,825	31.0	33.1
16	10.8	12,486	389	33.5	889	49.4	**12.1**
5	18.9	29,759	453	82.4	922	38.4	25.2
12	3.7	26,313	470	89.3	877	7.0	29.7
15	8.9	58,451	322	227.0	889	24.7	63.8
20	5.8	46,138	243	237.0	911	21.7	39.3
Average	13.0	39,947	709	100.0	1,359	28.0	29.4
SD	7.3	18,486	487	72.5	749	14.1	16.9
CV (%)	56.4	46	69	72.3	55	50.2	57.0

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_2e 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), 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_2e, 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_2e 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_2e 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_2e 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_2e prices at three of the 11 trial sites. At AUD30 Mg^{-1} CO_2e, 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_2e, 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 CO_2e to make agroforestry viable for carbon farming, Flugge and Abadi (2006) modelled the value of salinity mitigation at AUD5 Mg^{-1} CO_2e.

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 be important in maximizing production and economic viability (Eastham et al., 1993; Wildy et al., 2000).

Mallee species productivity can be influenced by the season of harvest, with Spencer et al. (2019) showing E_{koc} more productive following autumn harvest, E_{lox} following spring harvest and no significant seasonal response for E_{pol}. This study showed that spring harvest resulted in higher LC of production (AUD83.4 Mg^{-1}) compared to autumn harvest (AUD99.4 Mg^{-1}). It supports Sudmeyer et al. (2012) who found that adjacent crop competition by mallee was reduced when harvest was undertaken before the growing season (i.e. in autumn) for both initial and second harvest. The mallee belts used in this study were between 5 and 12 years old before the initial harvest and therefore had well-advanced root systems with considerable lateral reach and depth (Robinson et al., 2006; Sudmeyer & Goodreid, 2007). Depletion of stored soil water by mallee prior to spring harvest would have increased competition between mallee and the adjacent annual crop, as well as exposing the mallee belt to harsher coppice regeneration conditions going into the dry summer, thereby increasing the spring LC. However, any large-scale 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.

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 wide 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 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 CO_2e price in Australia. More accurate allometric models are required to estimate below-ground biomass, especially over multiple harvests. If Australia's CO_2e 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.

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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. https://researchrepository.murdoch.edu.au/id/eprint/36149/

Abadi, A., Maynard, H., Arpiwi, N. L., Stucley, C., Bartle, J., & Giles, R. (2016). Economics of oil production from Pongamia (*Millettia pinnata*) for biofuel in Australia. *Bioenergy Research*, *9*(3), 874–883. https://doi.org/10.1007/s12155-016-9739-x

ABARE (2015). Rural commodities – Coarse grain. https://www.agriculture.gov.au/abares/research-topics/agricultural-commodities/agricultural-commodities-trade-data#20151067

Abdullah, H., & Wu, H. (2009). Biochar as a fuel: 1. Properties and grindability of biochars produced from the pyrolysis of mallee wood under slow-heating conditions. *Energy & Fuels*, *23*(8), 4174–4181.

Asseng, S., & Pannell, D. (2013). Adapting dryland agriculture to climate change: Farming implications and research and development needs in Western Australia. *Climatic Change*, *118*(2), 167–181. https://doi.org/10.1007/s10584-012-0623-1

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. https://doi.org/10.1071/CP17242

Barron, O., & Zil, K. (2006). *Katanning desalination demonstration plant: Business plan*. CSIRO.

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. https://doi.org/10.1504/IJGEI.2007.013652

Barton, A. F. M., & Tjandra, J. (1989). Eucalyptus oil as a cosolvent in water-ethanol-gasoline mixtures. *Fuel*, *68*(1), 11–17. https://doi.org/10.1016/0016-2361(89)90004-5

Bennell, M., & Verbyla, A. (2008). Quantifying the response of crops to shelter in the agricultural regions of South Australia. *Australian Journal of Agricultural Research*, *59*(10), 950–957. https://doi.org/10.1071/AR08188

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. https://doi.org/10.1111/gcbb.12207

Brooksbank, K., & Goodwin, A. (in press). A model of coppice biomass recovery for mallee-form eucalypts. *New Forests*.

Clarke, C., George, R., Bell, R., & Hatton, T. (2002). Dryland salinity in south-western Australia: Its origins, remedies, and future research directions. *Soil Research*, *40*(1), 93–113. https://doi.org/10.1071/SR01028

Clean Energy Regulator. (2020). Emissions reduction fund – Auction March 2020. http://www.cleanenergyregulator.gov.au/ERF/Auctions-results/march-20201108

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. https://doi.org/10.1071/EA04152

DAFWA. (2013). *Report card on sustainable natural resource use in agriculture*. Department of Agriculture and Food Western Australia.

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.

Department of the Environment. (2014). Carbon credits (carbon farming initiative) (measurement based methods for new farm forestry plantations) methodology determination 2014. http://www.comlaw.gov.au/1207

Department of the Environment. (2015). Carbon credits (carbon farming initiative – Reforestation and afforestation 2.0) explanatory statement. http://www.comlaw.gov.au/1077

Ding, Y., Liu, Y., Liu, S., Li, Z., Tan, X., Huang, X., Zeng, G., Zhou, L., & Zheng, B. (2016). Biochar to improve soil fertility. A review. *Official Journal of the Institut National De La Recherche Agronomique*, *36*(2), 1–18.

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. https://doi.org/10.1007/BF00705242

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S., & von Stechow, C. (2012). *Renewable energy sources and climate change mitigation. Special report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

El Kasmioui, O., & Ceulemans, R. (2013). Financial analysis of the cultivation of short rotation woody crops for bioenergy in Belgium: Barriers and opportunities. *Bioenergy Research*, *6*(1), 336–350. https://doi.org/10.1007/s12155-012-9262-7

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

Fargione, J. E., Bassett, S., Boucher, T., Bridgham, S. D., Conant, R. T., Cook-Patton, S. C., Ellis, P. W., Falcucci, A., Fourqurean, J. W., Gopalakrishna, T., Gu, H., Henderson, B., Hurteau, M. D., Kroeger, K. D., Kroeger, T., Lark, T. J., Leavitt, S. M., Lomax, G., McDonald, R. I., … Griscom, B. W. (2018). Natural climate solutions for the United States. *Science Advances*, *4*(11), eaat1869. https://doi.org/10.1126/sciadv.aat1869

Flugge, F., & Abadi, A. (2006). Farming carbon: An economic analysis of agroforestry for carbon sequestration and dryland salinity reduction in Western Australia. *Agroforestry Systems*, *68*(3), 181–192. https://doi.org/10.1007/s10457-006-9008-7

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.

George, R. (1990). Reclaiming sandplain seeps by intercepting perched groundwater with eucalypts. *Land Degradation & Development*, *2*(1), 13–25. https://doi.org/10.1002/ldr.3400020103

George, R., Nulsen, R., Ferdowsian, R., & Raper, G. (1999). Interactions between trees and groundwaters in recharge and discharge areas – A survey of Western Australian sites. *Agricultural Water Management*, *39*(2–3), 91–113. https://doi.org/10.1016/S0378-3774(98)00073-0

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.

Grain & Graze3. (2020). *Agricultural commodity prices*. http://agprice.grainandgraze3.com.au/1059

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

Hobbs, 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*(1), 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., Külheim, 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., Kmoch, 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., Venkateswarlu, 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., Ettehad, S., Lam, 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., 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. 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.

Crop and Pasture Science, *63*(6), 555–569. https://doi.org/10.1071/CP12129

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

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. https://doi.org/10.1023/B:PLSO.0000037058.85572.ba

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