

1 **A decadal multi-site study of the effects of frequency and season of harvest on biomass**
2 **production from mallee eucalypts**

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14 **Abstract**

15 Mallee eucalypts are hardy, woody perennials that are being developed as a short-rotation
16 coppice crop in Australia for the production of eucalyptus oil, biofuels and other biomass
17 products. The economic viability of this prospective crop is dependent on its ability to
18 survive and regenerate following repeated harvesting of the above ground component. Here
19 we report on survival and biomass yield of mallee belt plantings of *Eucalyptus polybractea*,
20 *E. loxophleba* ssp *lissophloia* and *E. kochii* ssp *plenissima*, at 19 sites, under two harvest-
21 frequencies (3-8 year cycles) and harvest seasons (autumn or spring) over a decade from
22 2006-2015. 16 sites had post-harvest mortality ranging from 1.0% to 12.2% while the
23 remaining three sites with either shallow saline water tables or a silcrete hardpan failed.
24 Average site dry biomass yield across treatments ranged from 2.2 to 32.8 Mg ha⁻¹ yr⁻¹. Higher
25 yielding sites were generally characterised by pH between 3.8 and 8, EC_e below 15.0 dS m⁻¹
26 and high soil fertility. Lower yielding sites were generally near saline valley floors. After 7-
27 years, biomass yield from unharvested treatments exceeded the average cumulative yield of
28 harvest treatments at eight of the 16 sites, including all three *E. kochii* sites. For *E.*
29 *loxophleba*, significant interactions were found between season and frequency of harvest with
30 highest yields in long rotation spring treatments. There were also interactions between site
31 and frequency of harvest, which were mainly driven by the variable performance of the uncut
32 treatment. On average *E. loxophleba* yielded more biomass following spring harvests

33 whereas *E. kochii* yielded more following autumn harvests. *E. polybractea* yield was
34 unaffected by season or frequency of harvest; however, harvest treatments yielded more
35 biomass than uncut treatments. After 10 years, at eight of the nine sites subjected to three 3-
36 year cycles, no decline in biomass yield was observed. The site that declined in production
37 was attributed to depletion of a sandplain aquifer by extensive mallee plantings. Overall, the
38 results from this decadal study indicate that in warm-temperate semi-arid areas, such as the
39 south-west of WA, mallees biomass can be harvested sustainably at most sites even in short
40 (3-year) rotation cycles.

42 **Keywords:** bioenergy crops, belt-plantings, carbon sequestration, mallee eucalypts, multiple
43 harvest cycles, oil mallee, short-rotation coppice, tree mortality.

45 1. Introduction

46 The issues of sustainability in agriculture and climate change are driving development of
47 options to improve the performance of agricultural systems (Foley *et al.*, 2011). Perennial
48 biomass crops have potential to be profitable and may also improve the sustainability of
49 intensive annual crop/pasture agriculture (Brandes *et al.*, 2016; Brandes *et al.*, 2018; Dale *et*
50 *al.*, 2016; VanLoocke *et al.*, 2016). Here we present biomass yield data from three decades of
51 investment in the domestication of native mallee eucalypts for use as short-rotation coppice
52 crops in the wheatbelt agricultural region in the south west of Western Australia. This
53 development was motivated by the prospect of being able to better manage sustainability
54 problems in traditional farming systems with the targeted integration of new perennial crops,
55 but without any reduction in the economic viability of the farm (Bartle, 2009; Bartle &
56 Abadi, 2009; Barton, 2000; URS, 2008).

58 The major sustainability problem in the Western Australian (WA) wheatbelt is dryland
59 salinity (GHD, 2019), arising from the small change in the water balance that followed 20th
60 century conversion of some 15 million hectares of native vegetation to agriculture based on
61 annual crops and pastures (George *et al.*, 1997; George, 1992; Hatton *et al.*, 2003; Peck &
62 Hurle, 1973). The native woody perennial vegetation is adapted to exploit any subsoil water
63 infiltration (Robinson *et al.*, 2006; Verboom & Pate, 2006) and this allowed a large storage of
64 cyclic salt to accumulate (Hingston & Gailitis, 1976). The conversion to annual plant
65 agriculture permits some deep soil water penetration, slow accumulation of groundwater and
66 mobilisation of stored salt (George, 1992). Large areas of Western Australian farmland have
67 already been degraded by this process, and it is projected that over several decades some 30%
68 of the landscape could be affected (Simons *et al.*, 2013) with adverse regional consequences
69 for infrastructure, water resources and biodiversity protection (George *et al.*, 2008).

71 The process of water infiltration into WA wheatbelt soil profiles and the movement of
72 groundwater is dispersed and locally variable (George, 1992). Lefroy and Stirzaker (1999)
73 considered the options to achieve complementarity from tree crops in the farm setting, i.e. to
74 segregate, integrate or rotate. For salinity mitigation, integration in the form of widely
75 separated, permanent, mallee belts on the recharging proportion of the farm was adopted as
76 likely best practice for prime cropland. However, this could be complemented by segregated
77 stands of mallee forests on poorer quality land. Design of mallee belt layout needs to achieve
78 economically competitive biomass yields and contribute to salinity control, and as far as
79 possible deliver other on-farm benefits including: reduction in wind erosion and provision of
80 stock shelter (Baker *et al.*, 2018; Bird *et al.*, 1992; Sudmeyer *et al.*, 2002; Sudmeyer & Scott,
81 2002); reduction of waterlogging (Ellis *et al.*, 2006; Rundle & Rundle, 2002; Silberstein *et*

82 *al.*, 2002); protection and complementation of remnant native vegetation (Smith, 2009); and
83 managing greenhouse gas emissions (McGrath *et al.*, 2016; Wu *et al.*, 2007).

85 Mallee eucalypts are a genetically diverse group within the genus *Eucalyptus*, with about 300
86 species widely distributed across the southern semi-arid region of Australia (Nicolle, 2006).
87 They are tall shrubs or low trees that characteristically have multiple stems arising from a
88 large below-ground lignotuber (Eastham *et al.*, 1993; James, 1984; Wildy *et al.*, 2000b). The
89 lignotuber of mallee eucalypts is well endowed with meristematic tissue, an adaptation that
90 enables prolific coppicing after decapitation by fire or drought, and enables regeneration after
91 harvest (Noble, 1982; Noble, 2001; Noble & Diggle, 2014; Wildy & Pate, 2002).

93 Confidence in the potential of including mallee as a farm crop developed initially from native
94 woodland stands of *E. polybractea* harvested on short rotations in both New South Wales
95 (NSW) and Victoria. This commenced about a century ago to provide the international
96 market for high cineole containing eucalyptus oil (Coppin & Hone, 1992; Davis, 2002). In
97 recent decades this industry expanded into production from plantations established on former
98 farmland (Davis 2002).

100 In addition to cineole production, mallee eucalypts have been the focus of research as a
101 bioenergy feedstock crop to mitigate climate change (Bartle & Abadi, 2009; McGrath *et al.*,
102 2016; O'Connell *et al.*, 2007; Shepherd *et al.*, 2011). Many WA mallee species were screened
103 for high biomass yield potential and leaf cineole content. Subspecies of both *E. loxophleba*
104 L.A.S. Johnson & K.D. Hill and *E. kochii* C.A Gardner, were identified as prospective
105 candidates (Wildy *et al.*, 2000a; Wildy *et al.*, 2000b). Together with *E. polybractea*, these
106 three species of mallee eucalypts, hereafter referred to as 'mallee', provide a semi-arid

107 climate analogue for the northern hemisphere cool temperate short rotation coppice species
108 willow and poplar (Dickmann, 2006; Volk *et al.*, 2016) and perennial grasses in the
109 Mississippi Basin (Brandes *et al.*, 2018; VanLoocke *et al.*, 2016).

110 Early studies investigating fire and harvest of natural stands of mallee provide an indication
111 of survival and biomass yield responses to various harvest regimes. In the pastoral region of
112 NSW (mean rainfall 250 mm/year, evaporation 2400 mm/year) mallee mortality rates were
113 sensitive to the frequency of 'harvest' (Noble, 1982; Noble, 1989a, 1989b; Noble & Diggle,
114 2014); the effect was more pronounced when harvests were undertaken in autumn compared
115 to spring. In a later study, Milthorpe *et al.* (1998) subjected a 1-year old plantations of
116 *E. polybractea* and *E. kochii* in Condobolin NSW (mean rainfall 460 mm/year, evaporation
117 1800 mm) to annual harvest for 5-years. Yield improved on the second harvest, but thereafter
118 declined from 6 to 2 Mg ha⁻¹. Similarly, Davis (2002) observed failing vigour after 9-years of
119 annual harvests for *E. polybractea* at West Wyalong NSW (mean rainfall 480 mm/year and
120 evaporation 1600 mm). These observations suggest implications for mallee biomass
121 production arising from the choice of season and frequency of harvest, especially in more
122 arid regions.

123 Wildy and Pate (2002) and Wildy *et al.* (2004b) examined the mallee root system responses
124 to harvest. They demonstrated that newly harvested trees (*E. kochii* ssp *plenissima*) showed
125 loss of fine root (<2 mm) biomass, arrested production of roots, secondary thickening of
126 structural roots, and an increasing shoot to root ratio to restore a functional balance. The
127 recovery of root biomass to pre-harvest levels took 1.7- to 2.5-years. Spring harvests showed
128 earlier and stronger root and shoot growth than late summer harvest.

129 The growth of individual trees and tree stands through time have been well described e.g.
130 Richards (1959). In the general growth function, a tree grows slowly at an early age, reaches
131 exponential growth at middle age and then declines with old age (e.g. Johnson and Abrams
132 (2009), Zhao-gang and Feng-ri (2003)). In a coppice system, the growth function model is
133 reset after harvesting. Thus, a key driver of biomass production is likely to be the frequency
134 of harvest and, to maximise production, management decisions can be imposed to align
135 timing of harvest with growth rate. Estimations have been made concerning when to harvest
136 mallee under short-rotation. For instance, Bartle and Abadi (2009) proposed a conceptual
137 model where mallee are first harvested at 5-years of age, then every subsequent 3-years. Yu
138 *et al.* (2015) conducted a life cycle analysis based on harvest at 7-years with subsequent
139 harvests every 4- to 5-years. Both of these cases contain models where biomass estimations
140 were based on best available data and stability of productivity over time was inferred.

141 This paper presents results of different harvest regimes at 19 sites, covering a range of
142 landforms and soil types across the WA wheatbelt, where mallee belts were monitored and
143 harvested over a 10-year period. A subset of these results have been previously presented in
144 research reports (Mendham *et al.*, 2012; Peck *et al.*, 2012). This paper re-analyses the
145 original data, with the inclusion of three additional years of biomass data, testing the
146 following hypotheses:

- 147 1. That frequency and season of harvest have no effect on biomass production or
148 mortality;
- 149 2. There is no decline in the biomass yield caused by the cumulative effect of regular
150 harvest.

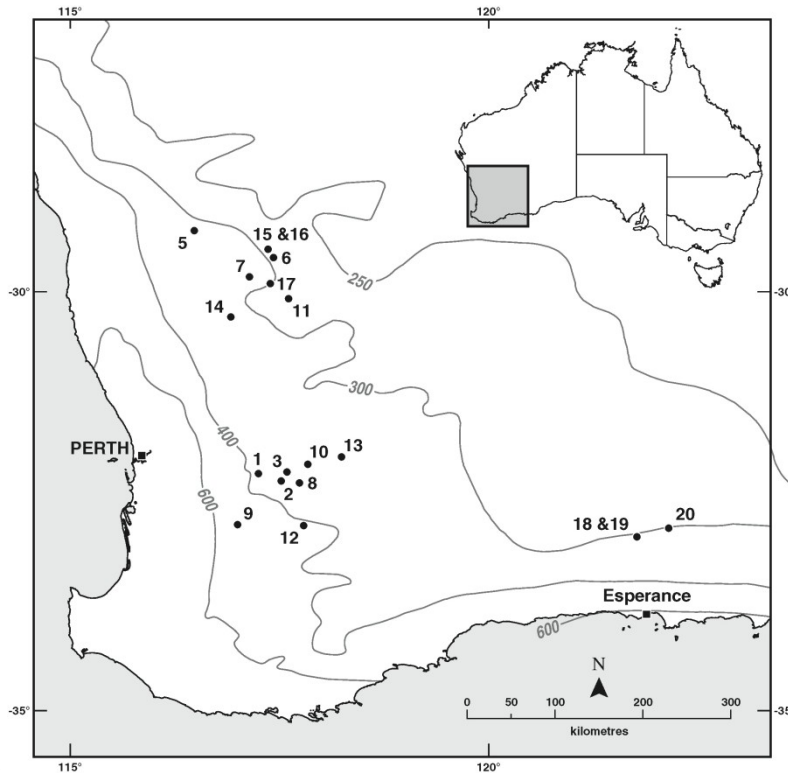
151 This paper also presents the allometric relationships used to calculate total dry biomass and
152 dry components (wood, bark, twig and leaf) of the three mallee species: *E. loxophleba* subsp.
153 *lissophloia*, *E. polybractea* and *E. kochii* subsp. *plenissima*.

154 2. Materials and Methods

155 This study concludes a long term research project that was set up across 19 sites with the dual
156 purpose of quantifying biomass production of mallee belts subjected to contrasting harvest
157 regimes, and to determine the competition imposed on adjacent annual crop and pasture over
158 the harvest cycle (Mendham *et al.*, 2012; Peck *et al.*, 2012; Sudmeyer *et al.*, 2012a). The
159 work reported here is principally concerned with mallee biomass production. Site 5 from the
160 previous reports was excluded from the statistical analysis, as this site traversed three distinct
161 site types rendering the 3 replications inadequate. Site names were left consistent with
162 previous reports to allow for further examination of data.

163 2.1 Species and study site

164 This study investigated the three major mallee species widely adopted for planting by farmers
165 in WA: *Eucalyptus loxophleba* subsp. *lissophloia*, *E. polybractea* and *E. kochii* subsp.
166 *plenissima*. These species will be hereafter referred to as E_{lox} , E_{pol} and E_{koc} respectively.
167 Typically E_{pol} has been planted in higher rainfall zones of the southern wheatbelt, E_{koc} has
168 been planted in the northern wheatbelt where it naturally occurs and E_{lox} has been planted
169 throughout the wheatbelt (*c.f.* Fig 1 and Table 1).



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171 Figure 1 – Location of mallee trial sites within the Western Australia wheatbelt; also shown are selected rainfall isohyets
 172 (grey line). The site numbers shown on the map correspond to those in Table 1.

173179

174 This study ran for 10-years (2006-2015) using 19 mallee belt plantings that had been
 175 established several years earlier by farmers in the WA wheatbelt (Fig. 1). For site details see
 176 Table 1. Sites were chosen to be representative of the range of species and environmental
 177 conditions where belt plantings of mallee had been undertaken (for detailed landscape and
 178 soil information see Table S1).

179

180 The wheatbelt has a Mediterranean climate with hot dry summers and mild wet winters. Over
 181 the duration of this experiment, mean annual rainfall ranged from 628 mm on the south-coast
 182 to 304 mm in the north-east, and evaporation increased from 1646 mm to 2575 mm (Table 1).

183 The crops and pastures of this region are predominantly non-irrigated, winter-growing
 184 annuals.

185 Table 1- Site characteristics and planting configuration for all field sites. Meteorological data obtained through SILO
 186 (Jeffrey *et al.*, 2001) datasets from 2005-2014. Site 4 was never established. Sites names have been kept consistent with
 187 previous publications for traceability.
 188195

Site	Lat (° S)	Long (° E)	Species	Year planted	Mean annual rainfall (mm)	Mean annual pan evaporative (mm)	Mean maximum temperature (° C)	Mean minimum temperature (° C)	Number of rows	Alley width (m)	Plot length (m)
1	-32.87	117.25	E _{pol}	1996	443	1781	23.4	10.0	2	70	20
2	-32.96	117.52	E _{lox}	1997	406	1775	23.3	9.9	2	20	20
3	-32.85	117.59	E _{lox}	2000	396	1811	23.4	9.9	3	50	20
5	-29.98	116.48	E _{lox}	1998	308	2577	27.0	12.4	4	>250	20
6	-30.30	117.43	E _{lox}	1999	304	2556	26.8	12.5	3	95	20
7	-30.52	117.14	E _{lox}	2000	305	2493	26.5	12.2	2	40	20
8	-32.99	117.73	E _{pol}	1998	396	1785	23.2	9.8	4	125-250	20
9	-33.48	117.00	E _{lox}	1999	486	1646	23.2	9.4	2	35	20
10	-32.76	117.83	E _{lox}	1998	364	1889	23.9	10.2	2	36	20
11	-30.78	117.61	E _{koc}	1999	322	2401	26.1	11.9	2	30-250	20
12	-33.49	117.79	E _{lox}	2000	417	1722	22.9	9.8	6	55	20
13	-32.67	118.24	E _{lox}	1997	362	1972	24.6	10.4	2	48	20
14	-30.01	116.91	E _{lox}	2000	340	2357	26.1	11.7	4	40-120	20
15	-30.21	117.36	E _{koc}	1998	319	2567	26.8	12.4	2	95	25
16	-30.18	117.37	E _{koc}	1994	324	2575	26.8	12.4	2	95	25
17	-30.60	117.39	E _{lox}	1999*	306	2466	26.4	12.2	2	50	25
18	-33.63	121.77	E _{pol}	2001	610	1929	22.8	11.2	6	90-100	25
19	-33.63	121.76	E _{pol}	2001	628	1935	22.8	11.4	6	120-140	25
20	-33.52	122.16	E _{lox}	2001	513	1951	22.6	10.8	6	150-250	25

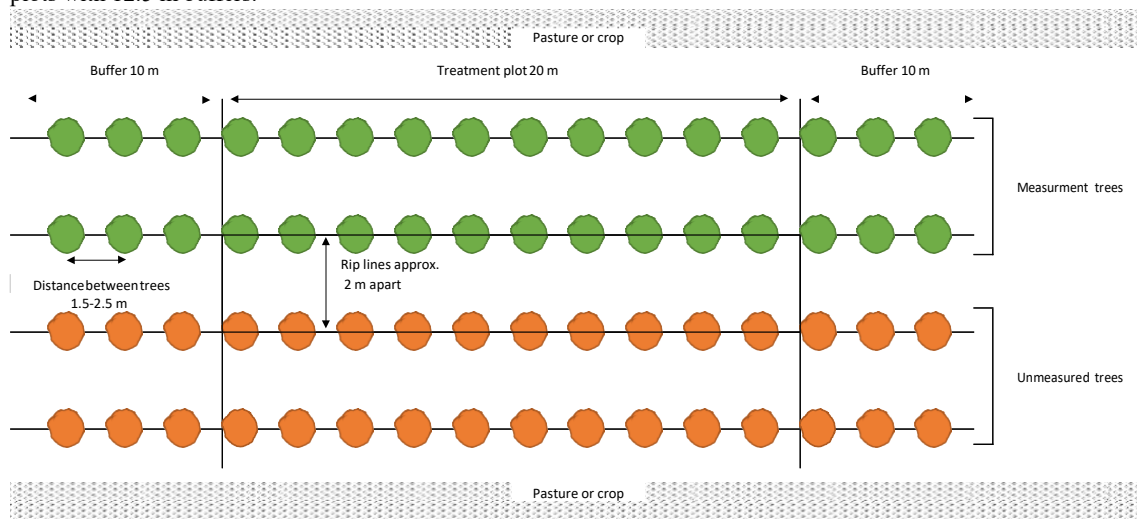
*Initially harvested in in Feb 2002 prior to trial

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 190
 191

2.2 Experimental design

192 All sites were planted in belt configurations of two, three, four or six rows within paddocks
 193 subject to rotations of annual crops and pasture. However, each plot within this study
 194 consisted of only two rows, an edge row and the adjacent row (Fig. 2). The plots ran along
 195 the belt and were either 20 m long with a 10 m buffer between plots or 25 m long with a 12.5
 196 m buffer.

197 Figure 2 – Schematic showing layout of a four-row mallee belt, and location of measurement plot and buffers. Mallee rows
 198 are planted on 0.5 m deep rip lines typically 2 m apart and a within-row spacing of between 1.5-2.5 m. Sites 15-20 had 25 m
 199 plots with 12.5 m buffers.



200
 201
 202 Each site consisted of 15 plots, three replicates of five treatments in a randomised block
 203 design. The four harvest treatments were arranged in a 2x2 factorial design with the addition
 204 of an uncut control treatment. There were two season of harvest treatments, spring and
 205 autumn; and two frequency of harvest treatments, 3- and 4-year. All mallee in each plot were
 206 measured annually and harvested in the allocated seasons. However, it became apparent prior
 207 to the second harvest that the allocated 3- and 4-year harvest frequencies were not viable on
 208 poorer sites due to concerns of mortality and increased unit costs of biomass harvesting.
 209 Harvest frequency was reduced until coppice biomass exceeded approximately 10 – 15 dry
 210 kg/tree to keep harvest cost of below AU\$30 Mg⁻¹ (Spinelli *et al.*, 2014). With these
 211 considerations, the final frequency of harvest treatments imposed were: short with a
 212 minimum of 3-years between harvests and long which was the short harvest cycle duration
 213 plus one year. The more productive sites (9 sites in total) completed three short and two long
 214 coppice cycles while the least productive sites only underwent one full cycle.

240 that was dominated by small mallee with bushy forms and multiple stems. For such uncut and
241 coppiced mallee, Crown Volume Index (CVI) was deemed a more accurate biomass
242 assessment method. CVI estimates the volume of the coppice in m³ as:

$$243 \quad CVI = H \times W_i \times W_j \quad [2]$$

244 Where H is the height and W_i and W_j are perpendicular, horizontal crown widths in cm. Site
245 17 had been harvested in February 2002, 4-years before the commencement of this project
246 and the EDRC method was used for the initial measurement.

247

248 Measurements at three of the nineteen sites were terminated due to high mortality and poor
249 performance. At Sites 6, 7 and 14 coppice measurement ceased in 2012, 2008 and 2009
250 respectively. Measurements continued for the uncut treatment until the conclusion of the
251 project at Site 6 whilst at Sites 7 and 14 uncut treatments were measured until 2011 (see
252 Table 7).

253 *2.5 Destructive measurements*

254 Biomass was harvested with a chainsaw close to ground level and weighed in a trailer fitted
255 with Ruddweigh 600 mm load bar (precision +/- 0.1 kg). Uncut and coppiced mallee were
256 selected using a stratified random selection method as detailed in (Snowdon *et al.*, 2002). The
257 uncut and coppiced mallee were stratified into 12 diameter or CVI size classes and samples
258 from each group were randomly selected. A range of 19-23 uncut and 21-145 coppice were
259 destructively sampled from each site (see S2 and S3 for more details). Trees for uncut
260 treatments were destructively sampled in 2006 with the initial spring and autumn harvests.
261 Most of the coppice were destructively sampled at first coppice harvest in 2009-2011.
262 Additional coppice and uncut mallee were destructively sampled during latter years when the
263 size of the mallee out-grew the range of the initial size classes, increasing the size range of

264 the allometric model. The additional uncut samples were harvested from areas of the planting
265 not part of the experiment.

266 *2.6 Partitioning and moisture content*

267 For all but site 14, uncut mallee were stratified into three size classes and two to four mallee
268 per size class were selected per site, as described by Snowdon *et al.* (2002), except at Site 13,
269 where only four trees were sampled. Total weight of wood with bark (>20 mm diameter over
270 bark), and twig with leaf (< 20 mm diameter over bark) were recorded. These were further
271 partitioned into four biomass components (wood, bark, leaf and twig). Sub-samples of each
272 of the four components were weighed in the field. The subsamples were transported to a
273 laboratory and oven dried at 70 °C. When the weights of the samples had stabilised, the final
274 weight was recorded. A similar method was applied to coppice with data collected from 11 of
275 the 19 sites.

276 *2.7 Mallee survival*

277 Gaps in belts were recorded at commencement in 2006 and later deaths were recorded
278 annually during biomass assessments. Percent survival was the difference between the mallee
279 counts at the initial and the subsequent years of measurement. Mallee deaths were verified
280 the following year and thus no new deaths were recorded in 2015, the last measurement year.
281 This method accommodated the occasional observation of delayed coppice regeneration.

282

283 *2.8 Allometry*

284 Mallee allometry has been published in Paul *et al.* (2016) and Paul *et al.* (2013b), however
285 new equations were developed for this study because of site and species bias inherent in
286 using generalised equations. Dry biomass components of uncut or coppiced mallee were

287 estimated by two-step allometric modelling. In the first step, generic and species-specific
288 allometric models were developed to estimate AGFB from EDRC/CVI. In the second step, a
289 further set of allometric models were developed to estimate dry components from AGFB. The
290 two models are described below:

$$291 \quad \ln(AGFB_{\text{Indiv}}) = \ln(a) + b * \ln(x) + \varepsilon \quad [3]$$

292 where $AGFB_{\text{Indiv}}$ is above ground fresh biomass of the individual mallee, a and b are
293 parameter estimates, x is *EDRC* in cm or *CVI* in m³ from Eq. 1 and 2, respectively and ε is the
294 error term. To estimate dry components further allometric equations were developed using:

$$295 \quad \ln(AGDBC_i) = \ln(c_i) + d_i * \ln(q) + e_i \quad [4]$$

296 where $AGDBC_i$ is above ground dry biomass for *component_i* (i.e., leaf, twig, bark or wood) of
297 the individual mallee, c_i and d_i are parameter estimates for *component_i*, q is *AGFB* and e_i is
298 the error term for *component_i* biomass model. In all cases, estimates a/c_i and b/d_i were
299 calculated using linear least-squares procedures. Due to the time-demand of data collection
300 for component partitioning, species-specific models were tested and site-level analysis was
301 omitted. General linear modelling (GLM) was used to test whether species improved the
302 performance of the models.

303

304 For all allometric equations, the residuals were checked for heteroscedasticity. Data from 10
305 uncut and 24 coppiced mallee were removed from analysis as those were deemed data entry
306 errors or were small individuals (*EDRC* or *CVI* < 26 mm or < 0.6 m³) which may not
307 conform to scaling laws (Enquist *et al.*, 2007). Two correction factors were assessed to
308 remove bias from back-transformation (Baskerville, 1972; Beauchamp & Olson, 1973) but in
309 this study the two methods had a maximum difference in biomass estimation of 0.67%, so the
310 more common methodology of Baskerville (1972) was used.

311 2.9 Plot biomass estimation

312 The individual biomass of uncut and coppiced mallee was calculated by converting EDRC or
313 CVI to fresh biomass (Eq. 3) then applying the component allometrics (Eq. 4) and summing
314 the partitioned dry components:

$$315 \quad \text{Total AGDB} = \sum_{i=1}^n C_i \quad [5]$$

316 where AGDB is above ground dry biomass, C_i is the dry weight of tree/coppice biomass
317 component, i : wood (>20 mm diameter over bark), bark, twig (<20 mm diameter over bark)
318 and leaf.

319

320 To standardise land area under different planting configuration and mallee size, the edge of
321 the plot adjacent to the crop/pasture was calculated as half the internal distance between rows
322 within a belt extended into the adjacent crop, as explored in Appendix 9 by Paul *et al.*
323 (2013a). Plot-level biomass estimates were divided by the total number of years of growth
324 and expressed in dry biomass per hectare per year ($\text{Mg ha}^{-1} \text{ yr}^{-1}$).

325

326 A preliminary analysis showed biomass yield symmetry between rows within a belt Figs S1-
327 20. For example, in a four row belt, row one biomass is equivalent to biomass from row four;
328 row two is equivalent to row three. This was tested from replicated datasets from 20 sites and
329 at 18 sites there was no difference between the stem diameters between the outer two rows
330 each side of a mallee belt in paired comparison t-tests ($P > 0.05$) (Fig. S1-S20). Therefore in
331 this study, to standardise biomass estimates between sites with a different number of rows,
332 sites with more than two-rows have been compensated with the additional biomass from the
333 unmeasured rows using belt symmetry principles (e.g. doubling the measured two-row
334 biomass from a four-row belt to estimate total biomass).

335

336 2.10 Statistical analysis

337 2.10.1 Treatment effect evaluation

338 Treatment effects were evaluated using general linear models:

339 $y_{ijklm} = s_i + r_k(s_i) + u_j + a_l(u_j) + f_m(u_j) + s_i.a_l(u_j) + a_l.f_m(u_j) + s_i.f_m(u_j) + s_i.a_l.f_m(u_j) + e_{ijklm}$ [6]

340 $y_{ijkm} = s_i + r_k(s_i) + u_j + f_m(u_j) + s_i.f_m(u_j) + e_{ijkm}$ [6a]

341

342 Where y is AGDB, s_i is the site, $r_k(s_i)$ is the replicate k nested within site i , u_j is the cut/uncut j
343 harvest treatment, a_l is the season l of harvest, f_m is the frequency m of harvest and e_{ijklm} is the
344 residual error. All main effects and interactions were nested within u_j . The site effect was
345 tested using rep (site) as an error term. Because the spring treatments were modified at most
346 sites after 7-years, two sets of analyses were performed to test: i) the effect of all treatments
347 (season of harvest and frequency of harvest) on the 7-year dataset (Eq 6), and ii) the effect of
348 frequency of harvest on the 10-year dataset with the season factor a_l excluded (Eq 6a).

349 Further, because each species occurred at one site only, separate analyses were done for each
350 species. Where necessary data were transformed using Box-Cox transformation to meet
351 assumptions of normality and variance homogeneity. Tukey-Cramer tests were used to
352 compare least square means (LSM) at different sites, treatments and site by treatment
353 interactions.

354

355 Eq. 6 was also used to test the factors responsible for mortality. The arcsine transformation
356 was used to approximate the model. Other models were tested, including binomial
357 distribution with logit link function but these specifications did not converge. Since the failed
358 sites were only measured for part of the experiment, two analyses were performed: i) a three-
359 year analysis that including the three failed sites excluding the effect of frequency of harvest

360 because none of the sites were harvested and ii) a 10-year analysis using Eq 6a. Site 6 was
361 excluded from the analysis because neither long autumn nor long spring treatments were
362 established.

363

364 *2.10.2 Relationships of mallee growth to environmental variables*

365 Stepwise multiple regression of annual growth on soil, climatic and landscape variables
366 (listed in Table S3), were carried out to identify environmental variables that explain
367 observed growth responses. Variables were included in the regression if they improved model
368 fit ($P < 0.05$). Collinearity was tested by checking the variance inflation factor with a cut off
369 of 10 (Chatterjee & Ali, 2015). Every site, including the failed sites, was included in this
370 analysis to identify site variable/s predicting poor performance.

371

372 All analyses reported here were performed using SAS v9.4 (SAS, 2017).

373

374 **3. Results**

375 *3.1 Estimation of mallee biomass*

376 Allometric models were used to estimate dry biomass in a two-step process. For the first step
377 of the estimation process (Eq. 3), species- and site-specific allometric models based on
378 EDRC in cm or CVI in m^3 explained between 79% and 98% of the variation in AGFB
379 (Tables 2, S4 and S5). For all species-specific and most of the site-specific models, the uncut
380 mallee models had a better fit than the coppice models.

381

382 The second stage of the allometric modelling (Eq. 4), estimated dry component biomass
383 (wood, bark, twig and leaf) from AGFB models and accounted for 87-98% of variances,
384 depending on component biomass (Tables 3 and 4). GLMs revealed species differences for

385 both uncut and coppiced mallee. For uncut mallee equations, there were significant
386 differences in both slope and intercept between species, primarily due to E_{lox} allometry being
387 different from allometries of the other two species (Table 3). Inclusion of species in coppice
388 allometries also improved fit of the component biomass models. The species effects were
389 realised in intercepts (Table 4). The biomass components changed with tree size for all
390 treatments and species. For the uncut treatment dry components across the species ranged
406 from 26.5 – 30.3% for wood, 3.9 – 7.5% for bark, 14.5 – 16.3% for twigs, and 8.9 – 10.6%
407 for leaves. For the coppice treatments, the respective ranges were 10.7 – 18.1% for wood, 2.9
408 – 3.4% for bark, 21.7 – 24.4% for twigs and 15.4 – 17.9% for leaves. Thus, in the harvested
409 treatments, foliage accounted for a larger percentage of total biomass than in the uncut
410 treatments, which conversely had a larger percentage of wood and bark.

411 Table 2- Parameterisation of allometric model for species-specific prediction of above ground fresh biomass (AGFB) of
412 uncut tree from ‘equivalent diameter near root collar’ (EDRC) in cm and coppice from Crown Volume Index (CVI) in m^3
413 (Eq. 3). Sample number (n), coefficient of determination (R^2), Mean Squared Error (MSE), and values in parentheses are
414 standard errors of parameter estimates.
415

Species	Treatment	n	AGFB range (kg)	Intercept (b)	Slope (a)	R^2	MSE
E_{koc}	Uncut tree	178	0.8 – 331.5	-2.315 (0.138)	2.471 (0.053)	0.926	0.058
E_{lox}	Uncut tree	724	0.5 – 702.0	-2.120 (0.054)	2.535 (0.025)	0.936	0.068
E_{pol}	Uncut tree	112	4.5 – 771.5	-2.008 (0.154)	2.463 (0.058)	0.943	0.052
E_{koc}	Coppice	156	1.0 – 107.3	0.786 (0.084)	0.956 (0.027)	0.892	0.033
E_{lox}	Coppice	775	0.1 – 152.5	-0.094 (0.043)	1.074 (0.014)	0.877	0.067
E_{pol}	Coppice	508	0.1 – 316.0	0.221 (0.050)	1.055 (0.015)	0.902	0.066

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420 Table 3 – Allometric models for estimating above ground dry components (wood, bark, twig and leaf) of uncut mallee from
 421 AGFB (Eq. 4). Numbers in parentheses are standard errors. Sample sizes and the largest biomass per uncut mallee for each
 422 species model were: E_{koc} n = 25, upper domain = 327.7 kg, E_{lox} n = 89, upper domain = 702 kg, and E_{pol} , n = 34 and upper
 423 domain = 683.8.

Component	Species	Intercept (d_i)	Slope (c_i)	MSE	R ²
Wood	$E_{pol}&E_{koc}$	-2.640 (0.092)	1.271 (0.016)	0.039	0.978
	E_{lox}	-2.295 (0.140)	1.224 (0.034)	0.036	0.98
Bark	E_{pol}	-4.180 (0.126)	1.173 (0.030)	0.042	0.973
	E_{koc}	-2.556 (0.284)	1.006 (0.064)		
	E_{lox}	-3.197 (0.152)	0.990 (0.038)		
Twig	$E_{pol}&E_{koc}$	-1.190 (0.098)	0.858 (0.018)	0.047	0.947
	E_{lox}	-1.296 (0.045)			
Leaf	$E_{pol}&E_{koc}$	-0.909 (0.118)	0.695 (0.021)	0.064	0.897
	E_{lox}	-0.991 (0.052)			

424 Table 4 – Allometric models for estimating above ground dry components (wood, bark, twig and leaf) of coppiced mallee
 425 from AGFB (Eq. 4). Numbers in parentheses are standard errors. Sample sizes and the largest biomass per coppice for each
 426 species model were: E_{koc} n=17, upper domain = 77.8 kg; E_{lox} n= 75, upper domain = 49.8 kg; and E_{pol} , n= 59 and upper
 427 domain =194 kg.
 428

Component	Species	Intercept (d_i)	Slope (c_i)	MSE	R ²
Wood	$E_{pol}&E_{lox}$	-3.424 (0.213)	1.408 (0.052)	0.119	0.878
	E_{koc}	-3.753 (0.097)			
Bark	$E_{koc}&E_{lox}$	-4.520 (0.109)	1.303 (0.046)	0.094	0.877
	E_{pol}	-4.798 (0.177)			
Twig	$E_{koc}&E_{pol}$	-0.801 (0.091)	0.822 (0.021)	0.023	0.939
	E_{lox}	-0.955 (0.030)			
Leaf	$E_{koc} & E_{lox}$	-1.298 (0.136)	0.896 (0.032)	0.051	0.87
	E_{pol}	-1.422 (0.121)			

429

430 3.2 Mortality

431 Mortality varied from about 1% to 45% across sites; the highest mortalities (>30%) occurred
 432 at valley floor Sites 6 and 7 which had saline ground water close to the surface or Site 14
 433 with a silcrete hardpan at a depth 2-4 m, while the lowest mortality rates were observed at
 434 sites with relatively low soil constraints (Fig. 3a and 3b).

435

436 By the end of the study, E_{koc} had overall mortality rate of 6.2%. The season of harvest had
 437 more effect on survival than frequency of harvest, with spring treatment mortality of 9.1%
 438 compared to autumn harvest treatment of 3.4% or uncut treatment of 6.0% ($P<0.05$) (Table
 439 5). There was a site by season interaction ($P<0.05$) due to elevated spring mortality at Site 15

440 (23.1%) and the uncut treatment at Site 16 (10.0%). Most of the spring mortality was from
441 the initial harvest. Using the 3-year dataset, there was a significant site by season effect
442 ($P>0.05$) due to high spring mortality at Sites 15 and 11 with no spring deaths at Site 16.
443 However, season as a main effect proved more significant ($P<0.0005$) primarily due to the
444 high mortality of the spring treatments compared to the consistently low mortality of the
445 autumn harvest (Table 5). Site was also significant with mortality of 7.3% at Site 15 when
446 compared to 0.5% at Site 16 ($P<0.05$) (Fig.3a).

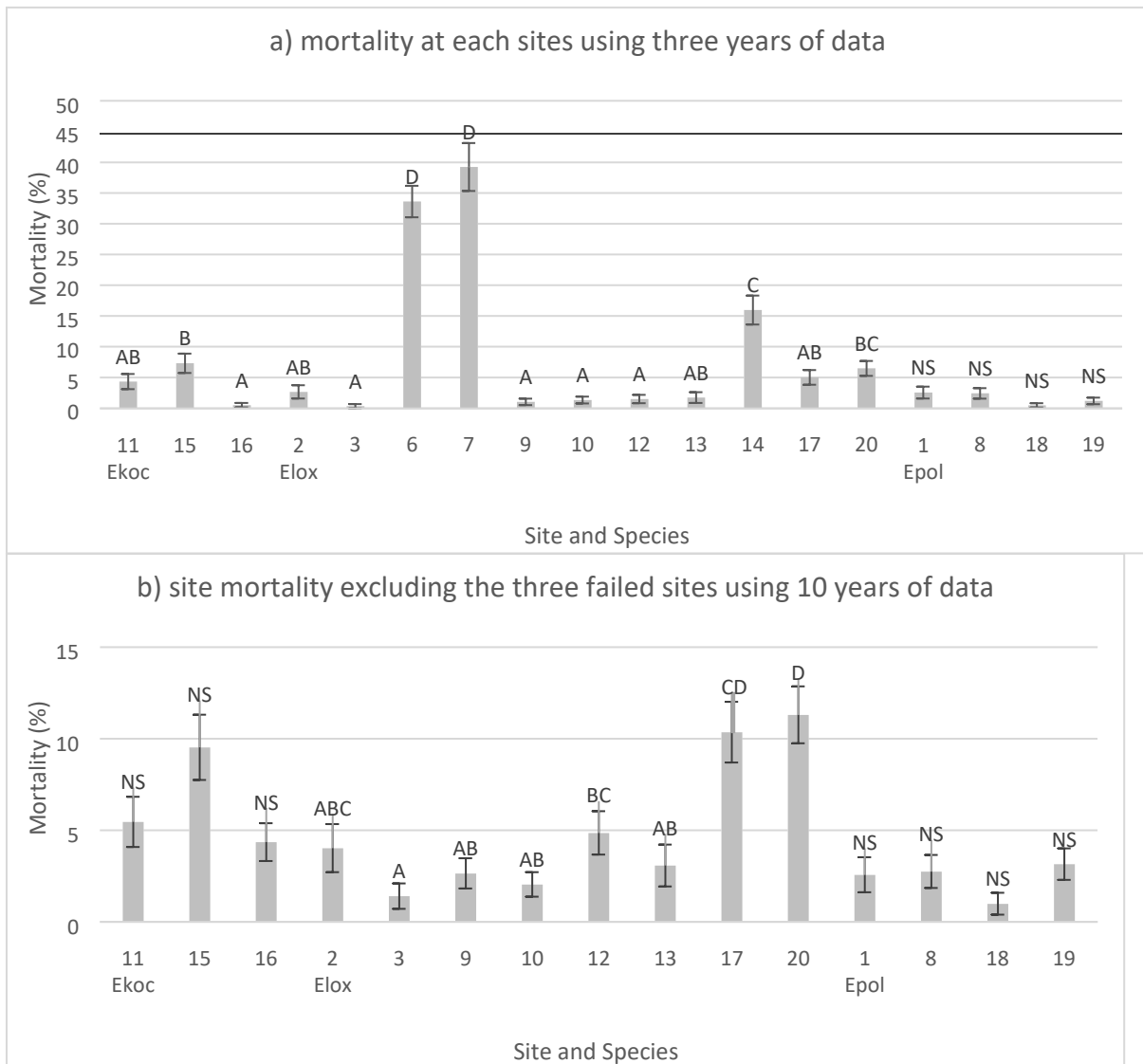
447

448 In contrast to the E_{koc} sites, by the end of the study, E_{lox} had very low spring mortality (2.9%),
449 less than half the mortality of the autumn harvest treatments (7.9%) with season being highly
450 significant ($P<0.001$) (Table 5). The site effect was also significant ($P<0.05$) ranging from
451 1.3% at Site 3 to 11.3% at Site 20 (Fig. 3b). Two separate analyses of the mortality data were
452 carried out after 3-year; the three failed sites were analysed separately to reduce the impact of
453 mortality on the successful sites (Fig. 3a). In the first analysis using the failed site data only,
454 season of harvest had a significant effect on mortality in the spring treatments (51.3%)
455 compared to the autumn treatments of (23.3%) ($P<0.01$). In the second analysis that excluded
456 the failed sites, there was a significant site by season interaction ($P<0.05$) with mortality at
457 Sites 17 and 20 autumn treatments of 11.2% and 7.5% respectively, compared to Sites 3 and
458 10 which had mortality of under 1.0%. Season as a main effect was highly significant
459 ($P<0.01$) with mortality of 4.1% across autumn treatments compared to 1.6% for the spring
460 treatments. The site effect was also highly significant ($P<0.0001$) mainly due to mortality of
461 under 2% at Sites 3, 9, 10, 11 and 13 compared to 6.5% and 5% at sites 17 and 20
462 respectively.

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464 E_{pol} had low mortality rate throughout the trial period; neither site nor harvest treatments
 465 impacted on its survival.

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Figure 3 – Mortality (%) by site and species averaged across all harvest treatments (\pm s.e.). a) analysis included all trial sites using 3-years of data and b) analysis excluded three failed sites and used 10-year data sets. Within a species, site means that are followed by different letters signify a difference in mortality at $P < 0.05$. Site was not significant (NS) for E_{koc} or E_{pol} sites.

477 The annual mortality of coppice and uncut treatments was not uniform. For coppiced mallee
 478 treatments, mortality rates peaked the first year after the initial harvest for E_{lox} and E_{pol} at
 479 1.9% and 1.6% respectively whereas E_{koc} mortality rate peaked 2-years after the initial

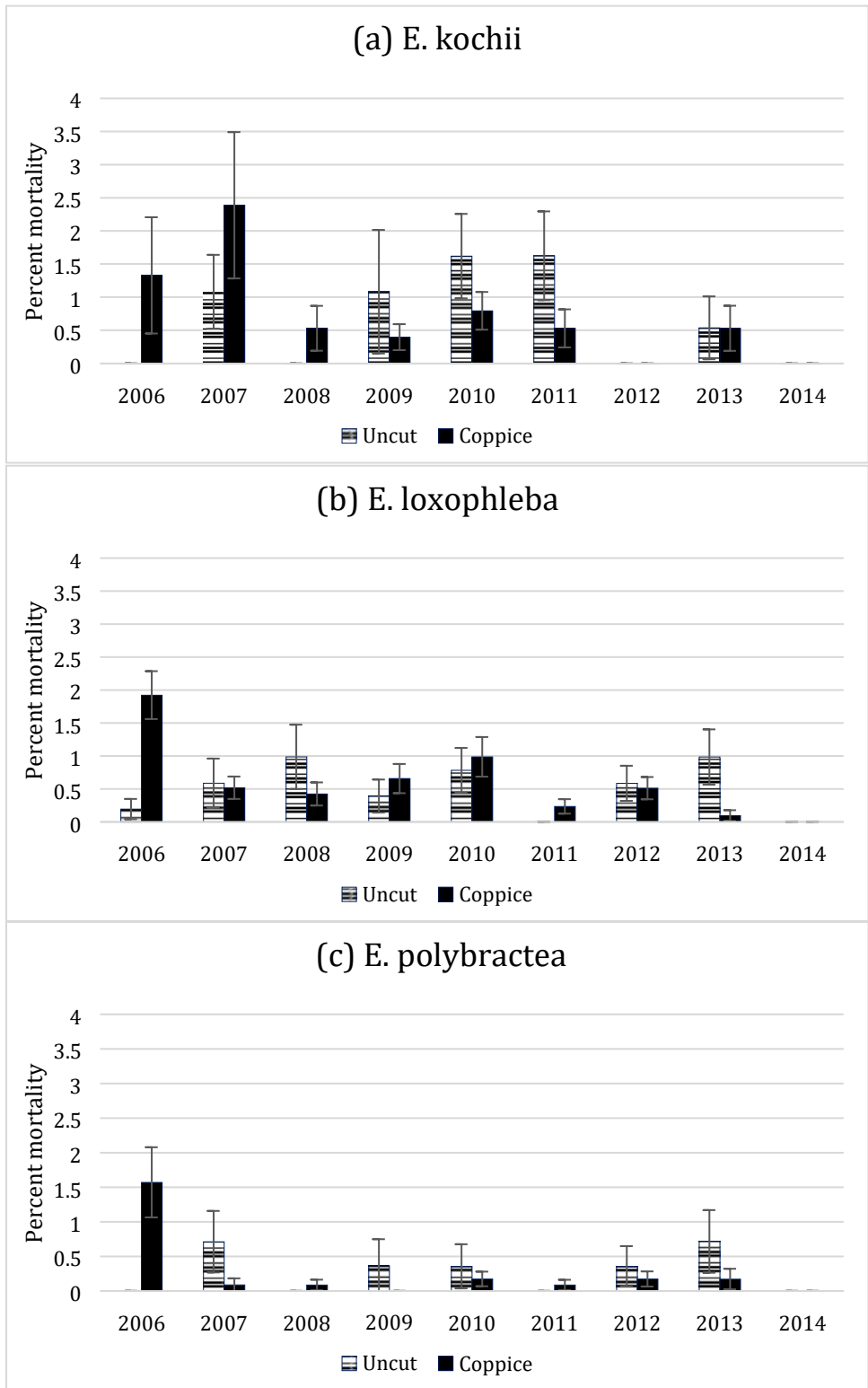
480 harvest at 2.5% (Fig. 4). There was a weaker trend observed in the uncut treatments with
 481 lower mortality rates occurring for each species throughout the trial period.

482

483 Table 5 – Effects of harvest regimes (season and frequency) on mallee mortality using 3-years of data for the failed sites, 3-
 484 years of data for the successful sites (excluding the three failed E_{lox} sites) and 10-year data. Mortality means of treatments
 485 are followed by different letters are significantly different at P< 0.05 based on Tukey’s HSD test.

Species	FreOfHarv	3 Year Data Failed Sites			3 Year Data Successful Sites			10 Year Data		
		Autumn	Spring	Control	Autumn	Spring	Control	Autumn	Spring	Control
E _{koc}	Control						1.1 ^{AB}			6.0 ^{AB}
	Long				0.5 ^A	7.1 ^{BC}		4.0 ^{AB}	7.1 ^{AB}	
	Short				0.0 ^A	9.3 ^C		2.8 ^A	10.9 ^B	
E _{lox}	Control			5.4 ^A			1.8 ^A			4.9 ^A
	Long	12.7 ^{AB}	34.6 ^{BC}		3.4 ^{AB}	1.5 ^A		6.9 ^{AB}	2.6 ^A	
	Short	30.8 ^B	62.3 ^C		4.7 ^B	1.7 ^A		8.2 ^B	3.2 ^A	
E _{pol}	Control						0.7 ^{NS}			2.5 ^{ns}
	Long				1.4 ^{NS}	2.1 ^{NS}		2.7 ^{ns}	3.1 ^{ns}	
	Short				0.7 ^{NS}	2.8 ^{NS}		1.1 ^{ns}	2.8 ^{ns}	

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Figure 4 - Mortality of all coppice and uncut treatments (\pm s.e.) of three mallee species (a) *E. kochii*, (b) *E. loxophleba* and (c) *E. polybractea* for each year. Only autumn coppice treatments were used after 2012. The three failed E_{lox} sites were excluded from analysis.

493 *Annual biomass production*

494 Annual biomass data was used to analyse all the spring and autumn treatments after 7-years
495 because at many sites the spring treatments were modified. The frequency of harvest of all
496 autumn and uncut treatments over 10 annual measurements were analysed separately.

497 *3.2.1 E_{koc} sites*

498 For the 7-year spring/autumn analysis, there was greater than a three-fold yield difference
499 between the highest and lowest yielding sites ($P < 0.0001$) that remained for the duration of the
500 experiment (Table 6). For 7-year analysis with all treatments, the uncut and autumn
501 treatments significantly outperformed the spring treatments ($P < 0.001$) as seen at Sites 11 and
502 15. Additionally, the uncut treatment produced more biomass than the coppice treatments
503 after 7-years ($P < 0.005$); however, these differences were not significant after 10-years. There
504 were no differences in annual growth rate between the frequency of harvest treatments at 7-
505 and 10-years, nor were any interactions present.

506 *3.2.2 E_{lox} sites*

507 Similar to the E_{koc} result, site was the most important factor influencing yield ($P < 0.0001$) at
508 the 7- and 10-yr results with a three-fold difference between the highest and lowest yielding
509 sites (Table 7). There was also a significant difference between harvest seasons; however,
510 there was a reversal of the performance of the treatments compared to the E_{koc} sites in that the
511 spring coppice yielded more biomass than the uncut treatments or autumn treatments
512 ($P = 0.005$). This difference was not realised across all sites, with Site 13 showing the opposite
513 trend. There was no significant interaction between site and season. There was no difference
514 between frequency of harvest treatments but there were significant interactions between
515 frequency of harvest and season ($P < 0.005$), in which the autumn treatment yield was higher
516 under the short rotation, whereas the spring treatments benefited from longer harvest cycles.
517 Excluding the failed sites, there was a significant interaction between performance of the

518 harvested and uncut treatments and site ($P < 0.0001$) for both the 7- and 10-year analyses. At
519 five of the eight sites (Sites 2, 3, 9, 12 and 20) all coppice treatments outperformed the uncut
520 treatments whereas the reverse was found at Sites 10, 13 and 17. However, the main effect of
521 harvested or uncut treatment was not significant in the 7-year analysis but the coppice
522 treatments yielded more biomass in the 10-year analysis ($P = 0.01$).

523 *3.2.3 E_{pol} sites*

524 The E_{pol} sites included the highest yielding sites across this study and there was a two- to
525 three-fold difference between site yields ($P < 0.0001$) (Table 8). There was no effect of season
526 and frequency of harvest, but there were interactions between site and the harvested or uncut
527 treatments ($P < 0.001$). Higher yields were observed for all coppice treatments at Sites 8 and
528 18 and three of the four coppice treatments at Site 1. In contrast, at Site 19 the uncut
529 treatment outperformed the coppice treatments ($P < 0.05$). Across all sites, the main effect of
530 harvesting compared to the uncut treatment was significant ($P = 0.0001$) with more biomass
531 produced following harvesting. For the 10-year analysis, there was no difference between the
532 yield of frequency of harvest treatments but the interaction and main effect that were
533 observed at 7-yr persisted to 10-yr $P < 0.001$ and $P = 0.005$ respectively.

534 Table 6 – Annualised increments of total dry biomass yield ($\text{Mg ha}^{-1} \text{yr}^{-1}$) of E_{koc} for each treatment and harvest cycle. The
 535 bracketed numbers are the duration in years of the harvest cycle. Tukey’s tests were performed to test difference between
 536 site, treatment and site by treatment interaction - means with the same letter do not differ at the 0.05 significance level. Tests
 537 for all treatments are given in the 7-year column, and tests for autumn and uncut treatments are given in 10-year column.

Site	Season	Frequency	7-year	10-year	Cycle 1	Cycle 2	Cycle 3
11 ^C	Autumn	Short	4.8 (6) ^{FG}	4.8 (9) ^E	4.5 (7)	5.6 (2)	
	Spring	Short	3.0 (6) ^G		3.0 (6)		
	Autumn	Long	4.2 (6) ^G	3.7 (9) ^E	3.4 (8)	6.0 (1)	
	Spring	Long	3.5 (6) ^G		3.5 (6)		
	Control	Control	5.3 (6) ^{EFG}	4.9 (9) ^{DE}			
15 ^B	Autumn	Short	9.4 (6) ^{DEF}	10.2 (9) ^{BC}	10.3 (5)	10.0 (4)	
	Spring	Short	4.6 (6) ^G		5.2 (5)	1.9 (1)	
	Autumn	Long	9.4 (6) ^{DEF}	8.9 (9) ^{CD}	9.4 (6)	8.1 (3)	
	Spring	Long	4.8 (6) ^G		4.8 (6)		
	Control	Control	10.1 (6) ^{CDE}	9.1 (9) ^C			
16 ^A	Autumn	Short	17.0 (6) ^{AB}	14.9 (9) ^A	18.6 (3)	15.4 (3)	10.6 (3)
	Spring	Short	13.1 (6) ^{BCD}		12.3 (3)	13.8 (3)	
	Autumn	Long	15.7 (6) ^{AB}	14.1 (9) ^{AB}	16.8 (4)	12.0 (5)	
	Spring	Long	14.3 (6) ^{BC}		14.4 (4)	14.1 (2)	
	Control	Control	19.5 (6) ^A	15.9 (9) ^A			

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 545 Table 7 – Annualised increments of total dry biomass yield ($\text{Mg ha}^{-1} \text{yr}^{-1}$) of E_{lox} for each treatment and harvest cycle. The
 546 bracketed numbers are the duration in years of the harvest cycle. Tukey’s tests were performed to test difference between
 547 site, treatment and site by treatment interaction - means with the same letter do not differ at the 0.05 significance level. Tests
 548 for all treatments are given in the 7-year column, and tests for autumn and uncut treatments are given in 10-year column.
 549

Site	Season	Frequency	7-year	10-year	Cycle 1	Cycle 2	Cycle 3
2 ^C	Autumn	Short	9.7 (6) ^{BCDEF}	8.6 (9) ^{BC}	9.7 (6)	6.2 (3)	
	Spring	Short	8.1 (6) ^{CDEFG}		8.1 (6)	6.7 (2)	
	Autumn	Long	7.7 (6) ^{FG}	7.5 (9) ^{CD}	7.1 (7)	8.6 (2)	
	Spring	Long	7.1 (6) ^{FGH}		6.2 (7)	4.7 (1)	
	Control	Control	5.6 (6) ^{HIJKL}	5.3 (9) ^F			
3 ^C	Autumn	Short	7.6 (6) ^{FG}	7.7 (8) ^{CD}	7.7 (3)	7.5 (3)	8.0 (2)
	Spring	Short	7.5 (6) ^{FG}		6.5 (3)	8.5 (3)	
	Autumn	Long	6.4 (6) ^{GHIJ}	7.1 (8) ^{CDE}	6.7 (4)	7.4 (4)	
	Spring	Long	8.1 (6) ^{DEFG}		8.6 (4)	7.1 (2)	
	Control	Control	4.9 (6) ^{JKLM}	5.5 (8) ^F			
9 ^A	Autumn	Short	10.3 (6) ^{BCD}	10.0 (9) ^{AB}	8.9 (3)	11.6 (3)	9.4 (3)
	Spring	Short	12.3 (6) ^{AB}		8.5 (3)	16.1 (3)	
	Autumn	Long	10.1 (6) ^{BCDE}	10.3 (9) ^{AB}	9.1 (4)	11.2 (5)	
	Spring	Long	14.6 (6) ^A		11.2 (4)	21.4 (2)	
	Control	Control	8.8 (6) ^{CDEF}	7.6 (9) ^{CD}			
10 ^A	Autumn	Short	6.4 (6) ^{GHIJ}	6.5 (9) ^{DEF}	5.7 (5)	7.4 (4)	
	Spring	Short	7.8 (6) ^{EFG}		6.2 (5)	15.9 (1)	
	Autumn	Long	8 (6) ^{DEFG}	7.4 (9) ^{CD}	8.0 (6)	6.1 (3)	
	Spring	Long	10.7 (6) ^{BC}		10.7 (6)		
	Control	Control	12.1 (6) ^{AB}	11.0 (9) ^A			

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Site	Season	Frequency	7-year	10-year	Cycle 1	Cycle 2	Cycle 3
12 ^E	Autumn	Short	4.2 (6) ^{KLM}	3.9 (9) ^G	4.2 (6)	3.2 (3)	
	Spring	Short	5.1 (6) ^{JKL}		5.1 (6)	3.0 (2)	
	Autumn	Long	4.2 (6) ^{KLM}	3.7 (9) ^G	3.7 (7)	3.7 (2)	
	Spring	Long	4.3 (6) ^{KLM}		3.1 (7)	1.7 (1)	
	Control	Control	2.4 (6) ^N	2.2 (9) ^H			
13 ^B	Autumn	Short	7.7 (6) ^{FG}	7.8 (9) ^{CD}	8.4 (3)	7.0 (3)	8.0 (3)
	Spring	Short	6.7 (6) ^{GHI}		6.5 (3)	6.9 (3)	
	Autumn	Long	6.2 (6) ^{GHIJ}	7.2 (9) ^{CDE}	6.9 (4)	7.4 (5)	
	Spring	Long	6.6 (6) ^{GHI}		7.1 (5)	4.3 (1)	
	Control	Control	10.2 (6) ^{BCDE}	10.7 (9) ^{AB}			
17 ^B	Autumn	Short	7.1 (6) ^{IHK}	7.1 (9) ^{EF}	7.6 (3)	6.7 (3)	7.2 (3)
	Spring	Short	5.7 (6) ^{KLM}		5.2 (3)	6.1 (3)	
	Autumn	Long	6.8 (6) ^{JKLM}	7.1 (9) ^F	7.0 (4)	7.1 (5)	
	Spring	Long	8.5 (6) ^{GHI}		8.9 (4)	7.7 (2)	
	Control	Control	10.1 (6) ^{EFG}	9.1 (9) ^{CDE}			
20 ^D	Autumn	Short	4.6 (5) ^{KLM}	6.7 (8) ^F	6.7 (6)	6.9 (2)	
	Spring	Short	4.2 (5) ^{LM}		5.3 (5)		
	Autumn	Long	3.9 (5) ^M	4.7 (8) ^G	4.7 (8)		
	Spring	Long	5.2 (5) ^{JKL}		6.5 (5)		
	Control	Control	3.7 (5) ^M	3.9 (8) ^G			
5	Autumn	Short			12.6 (4)	12.4 (4)	
	Spring	Short			5.3 (4)	10.1 (2)	
	Autumn	Long			9.8 (5)	12.6 (4)	
	Spring	Long			12.1 (5)	4.8 (1)	
	Control	Control			12.5 (9)		
6	Autumn	Short			4.9 (3)	3.7 (3)	
	Spring	Short			0.3 (3)	0.8 (2)	
	Autumn	Long			6.1 (4)	3.0 (2)	
	Spring	Long			4.7 (5)		
	Control	Control			17.6 (9)		
7	Autumn	Short			0.3 (2)		
	Spring	Short			0.1 (2)		
	Control	Control			0.7 (5)		
14	Autumn	Short			1.1 (3)		
	Spring	Short			0.5 (2)		
	Autumn	Long			0.8 (3)		
	Spring	Long			0.3 (2)		
	Control	Control			3.9 (5)		

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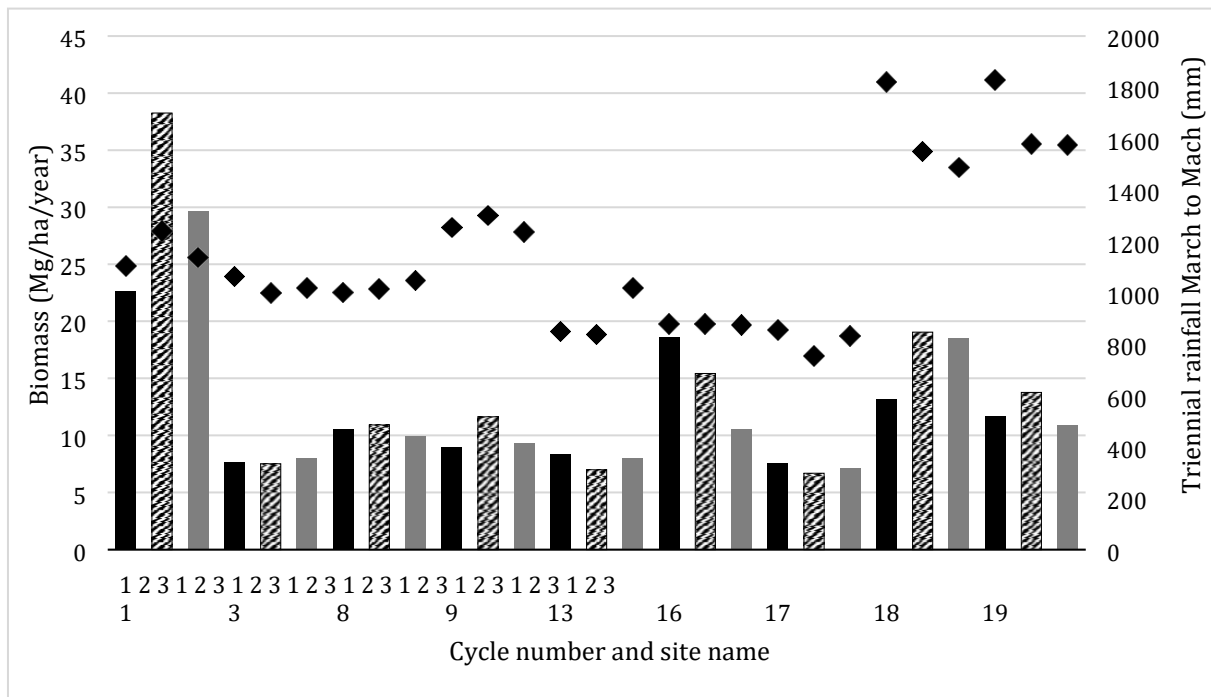
556 Table 8 – Annualised increments of total dry biomass yield ($\text{Mg ha}^{-1} \text{yr}^{-1}$) of E_{pol} for each treatment and harvest cycle. The
 557 bracketed numbers are the duration in years of the harvest cycle. Tukey’s tests were performed to test difference between
 558 site, treatment and site by treatment interaction - means with the same letter do not differ at the 0.05 significance level. Tests
 559 for all treatments are given in the 7-year column, and tests for autumn and uncut treatments are given in 10-year column.
 560

Site	Season	Frequency	7-year	10-year	Cycle 1	Cycle 2	Cycle 3
1 ^A	Autumn	Short	30.4 (6) ^A	30.2 (9) ^A	22.7 (3)	38.3 (3)	29.7 (3)
	Spring	Short	28.2 (6) ^A		14.7 (3)	41.7 (3)	
	Autumn	Long	29.3 (6) ^A	32.8 (9) ^A	28.5 (4)	36.3 (5)	
	Spring	Long	19.8 (6) ^{AB}		15.8 (4)	27.9 (2)	
	Control	Control	25.5 (6) ^A	23.7 (9) ^A			
8 ^D	Autumn	Short	10.7 (6) ^{GH}	10.5 (9) ^{DEF}	10.6 (3)	10.9 (3)	9.9 (3)
	Spring	Short	10.4 (6) ^H		9.2 (3)	11.5 (3)	
	Autumn	Long	11.2 (6) ^{FGH}	10.7 (9) ^{DEF}	10.8 (4)	10.6 (5)	
	Spring	Long	11.7 (6) ^{EF}		11.2 (4)	12.7 (2)	
	Control	Control	7.1 (6) ^I	7.4 (9) ^G			
18 ^B	Autumn	Short	16.1 (6) ^{CDEF}	16.9 (9) ^{BC}	13.2 (3)	19.1 (3)	18.5 (3)
	Spring	Short	16.7 (6) ^{CDE}		12.3 (3)	21.2 (3)	17.0 (2)
	Autumn	Long	17.6 (6) ^{CD}	18.7 (9) ^B	14.1 (4)	22.3 (5)	
	Spring	Long	19.4 (6) ^{BC}		14.0 (4)	27.8 (4)	
	Control	Control	16.5 (6) ^{CDEF}	15.6 (9) ^{BCD}			
19 ^C	Autumn	Short	12.7 (6) ^H	12.1 (9) ^F	11.7 (3)	13.8 (3)	10.9 (3)
	Spring	Short	14.0 (6) ^{EF}		12.9 (3)	15.0 (3)	11.5 (2)
	Autumn	Long	13.2 (6) ^{GH}	11.5 (9) ^{EF}	10.2 (4)	12.5 (5)	
	Spring	Long	14.4 (6) ^{DEFGH}		9.6 (4)	17.1 (4)	
	Control	Control	15.3 (6) ^{DEFG}	13.9 (9) ^{CDE}			

561

562 3.3 Yield comparison across multiple cycles

563 By the conclusion of this experiment, nine sites had undergone three complete cycles of 3-
 564 year autumn harvests and biomass yield was stable except for Site 1, 16 and 18 (Fig. 5). Sites
 565 1 and 18 produced less biomass in the first harvest cycle. Site 16 was the only site that
 566 showed progressive decline over the three harvest cycles.



567 Figure 5 – Annualised dry biomass yield ($\text{Mg ha}^{-1} \text{ year}^{-1}$) for all sites under three 3-year harvest cycle regimes. Solid black
 568 bars represent cycle one, pattern bars cycle two and grey bars cycle 3. Total rainfall for each 3-year cycle from autumn to
 569 autumn (March to March) is represent by diamonds. Site 3 was removed in 2014 and the last 3-year rotation was limited to
 570 2-years of data.

571 *3.4 Relationships of mallee growth to environmental variables*

572 Stepwise multiple linear regression of biomass on environmental variables identified soil
 573 and/or climate factors that accounted for some of the variation in biomass across sites and
 574 species. While the growth of uncut controls and coppice treatments were affected by some
 575 common factors, coppice growth variation was also influenced by variation in soil nutrients
 576 status and climatic factors. For uncut mallee biomass, soil pH, salinity constraints and soil
 577 carbon status accounted for over half the biomass variance across sites and species (Eq. 7):

581
$$T = 28.16 - 3.37 \text{ MpH} - 0.227 \text{ MEc} + 0.007 \text{ OC}, \quad R^2_{\text{ad}} = 0.56 \quad [7]$$

582 Where T is biomass of the uncut control treatment ($\text{Mg ha}^{-1} \text{ yr}^{-1}$), MpH is maximum pH
 583 (CaCl_2), MEc is maximum soil electrical conductivity ($\text{EC}_e \text{ dS m}^{-1}$) and OC is organic carbon
 584 (g/m^3) of soil.

585 For coppice, the variability in biomass across sites and species was explained by a
 586 combination of soil and climate constraints (Eq. 8):

587 $C = 162.6 - 4.66 \text{ MpH} - 2.77 T_{\text{max}} - 0.269 \text{ MEc} + 0.102 \text{ N} + 0.007 \text{ OC} \quad R^2_{\text{ad}} = 0.72 \quad [8]$

588 Where C is coppice biomass ($\text{Mg ha}^{-1} \text{ yr}^{-1}$), MpH is maximum site pH (CaCl_2), T_{max} is

589 Maximum Temperature ($^{\circ}\text{C}$), MEc is maximum soil electrical conductivity (dS m^{-1}), N is

590 NO_3^- plus NH_4^+ (g/m^3), and OC is organic carbon (g/m^3) of soil.

591

592 **4. Discussion**

593 The data presented here show substantial variation in both biomass yield and mortality across

594 sites, associated with species, climatic and edaphic variables. There is no consistent effect on

595 biomass or mortality from frequency of harvest. However, there was a species response to

596 season of harvest. E_{koc} responded better to autumn harvest, E_{lox} performed better with spring

597 harvest and E_{pol} performed well in each season and displayed low mortality.

598

599 *4.1 Site effect*

600 The variation in climatic and edaphic factors across the 19 sites more strongly influenced

601 biomass production than the treatments imposed. The combination of rainfall, evaporation

602 and soil depth has been found to accurately predict biomass production of juvenile mallee

603 plantings (Wildy *et al.*, 2000a). In this study, we found that most biomass yield variance (56-

604 72%) was accounted for by edaphic (pH, EC_e , N and organic C) and climate (T_{max}) variables.

605 The impacts of pH, EC_e and T_{max} on yield were negative, while soil nutrients (N and OC) had

606 positive effects. Although climate is a key determinant of plantation productivity in the WA

607 wheatbelt by virtue of its impact on landscape water balance (Brooksbank *et al.*, 2011;

608 Robinson *et al.*, 2006; Smettem & Harper, 2009; Sudmeyer *et al.*, 2004; Wildy *et al.*, 2004a),

609 our findings emphasise the importance of localised, edaphic factors controlling water and

610 nutrient availability and uptake by mallee at any given site.

611

612 Soil pH was a good predictor of growth for both uncut and coppiced treatments indicating
613 that the studied mallee species prefer acidic soils. pH varied across the sites from 3.6 to 9.1.
614 Symonds *et al.* (2001) found in a nursery trial that many eucalypt species prefer acidic
615 conditions, including E_{pol} which produced significantly less biomass above a pH of 7.6. The
616 distribution of some endemic eucalypt species or provenances are restricted by soil pH, and
617 perform poorly when grown out of their natural range (Anderson & Ladiges, 1978; Ladiges
618 & Ashton, 1977; Parsons & Specht, 1967). This suggests that pH should be considered in
619 species and site selection, and that agricultural soils too acidic and expensive to ameliorate
620 for other crops may be suitable for mallee.

621

622 Another factor that reduced yield across the sites was soil salinity which has been shown,
623 especially in combination with waterlogging, to reduce growth and survival of plants
624 (Barrett-Lennard, 2003). Site 11 exhibited the highest soil salinity of 36.6 dS m^{-1} but had a
625 dry profile, whereas Sites 6, 7, 10, 12, 15, and 17 all had high salinity with shallow saline
626 groundwater (Peck *et al.*, 2012). These root zone soil constraints may have contributed to the
627 high mortality at two of the failed sites (Sites 6 and 7) and to low biomass yield at the other
628 sites. In contrast, Site 1, which was located mid-slope and considered to have access to fresh
629 groundwater at 6-10 m (Peck *et al.*, 2012), had the highest yield. Of the three mallee species,
630 E_{lox} is considered to be moderately salt-tolerant and can survive at $EC_e 30.0 \text{ dS m}^{-1}$ (Pepper &
631 Craig, 1986). Brooksbank (2011) found that E_{pol} and E_{koc} will not use saline groundwater
632 exceeding 16.1 dS m^{-1} whereas E_{lox} actively sourced groundwater at 30.1 dS m^{-1} .

634 E_{lox} was most commonly planted on lower slopes and valley floors, reflecting its natural
635 occurrence on such sites. However, under agricultural use such sites have been compromised
636 by the accumulation of saline groundwater and as for conventional annual crops, have

637 reduced yield. At Sites 6 and 7 (<5 m elevation above adjacent saline discharge area)
638 establishment was achieved, but high mortality occurred after first harvest. In contrast, the
639 uncut treatment at Site 7 achieved yields of 17.6 Mg ha⁻¹ yr⁻¹. These sites had soil salinities of
640 15.2 and 20.0 dS m⁻¹ respectively, suggesting that E_{lox} salt tolerance is reduced as a result of
641 harvesting. There are perennial grazing plant options for salt affected valley floor sites
642 (Barrett-Lennard *et al.*, 2006; Bennett *et al.*, 2009), but these sites may be usefully bounded
643 on lower slopes by plantations of E_{lox} to be harvested on longer cycles. The four E_{pol} sites had
644 relatively deep soil profiles and were only saline at depth (>6 m) and could be considered
645 relatively unconstrained by soil salinity. Mallee plantings will span multiple soil types and it
646 is inevitable that yield variability will occur.

Nitrogen (NO³⁻ and NH⁴⁺) and organic carbon had a positive effect on growth. It was thought
that nutrient supply might only slowly become limiting because all sites were within fertilised
annual cropping and sheep-grazed legume-based pastures. However, the level of nutrient
651 removal appears too great especially for N and P, and fertiliser application will be required
652 following harvesting (Grove *et al.*, 2007; Yu *et al.*, 2015). Soil sampling occurred between
653 the first and the second harvests at most sites. Soil organic carbon was positively correlated
654 with biomass production for both the coppice and unharvested treatments. This suggests that
655 concentrations of organic carbon were unaffected by biomass removal. However, the
656 presence of nitrogen in the coppice model suggests removal of biomass may have reduced
657 available soil nitrogen pools. Also, poor inherent site soil fertility may have limited growth
658 from the time of establishment. In 2012 the spring treatments for 10 sites were harvested and
659 then converted to nutrient trials. The addition of 320 kg/ha of ammonium sulphate, 230 kg/ha
660 of double phosphate and 85 kg/ha of nitrate of potash between the rows in both 2012 and
661 2013 increased biomass production in 2014 by 11% per annum (Spencer *et al.*, unpublished

662 data). This supports the growth model indication that soil nutrition constrains biomass
663 production and that this might be mitigated with application of fertilizer or biomass ash
664 (Grove *et al.*, 2007).

665

666 *4.2 Frequency of harvest*

667 The short and long frequencies of harvest exhibited high survival and strong coppice vigour
668 with no downward trend in yield after consecutive harvests. Excluding the three failed sites,
669 mortality for the duration of the project, across all treatments, was 4.7%. These results
670 contrast with other studies which reported mortality of up to 100% (Noble & Diggle, 2014) or
671 progressive declines in productivity (Milthorpe *et al.*, 1998; Wildy & Pate, 2002) under more
672 frequent harvest regimes. In our study, coppice mortality following the initial harvests in
673 2006 and 2007 accounted for 46% of overall mortality. The peak mortality at first harvest
674 appears to be induced by the harvest, because mortality rates in the uncut treatments
675 remained steady. Harvest mortality was mostly confined to smaller trees, and appears to have
676 had little effect on biomass yield. In 2010, there was a slight increase in mortality where
677 many sites received about half their average annual rainfall.

678

679 It has been suggested that carbohydrate root reserves in WA flora have an important role in
680 the capacity to resprout (Bell *et al.*, 1996). Wildy and Pate (2002) found that with removal of
681 foliage from *E kochii* every three months, starch was a poor predictor of subsequent biomass
682 production and mortality. They also found the reduction of starch reserves persisted for 12-18
683 months after harvest. Hence to minimise mortality risk, a minimum 3-year harvest interval
684 was chosen in this study. It was anticipated that this would also deliver sufficient biomass to
685 facilitate development of low cost, high volume harvest systems (Abadi *et al.*, 2012). No

686 trend was observed within sites to suggest a penalty in annual yield under the shorter harvest
687 frequency.

688

689 Excluding the three failed sites, the frequency of harvest resulted in sustainable biomass
690 production, at higher yielding sites. Site 1 displayed large variation between cycles peaking at
691 cycle two with $38.3 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ (dry weight) with lower yields at cycles one and three. Site
692 16 showed progressive declines in yield for the 3-year autumn harvest coppice treatment
693 from 18.6 to $10.6 \text{ Mg ha}^{-1} \text{ yr}^{-1}$. There was no progressive decline in rainfall over this period
694 and no other site displayed a declining yield trend (Fig. 5). Site 16 is just upslope from the
695 boundary between the sandplain landform and the in-situ weathered profiles over the igneous
696 basement. These junctions are often the site of discharge from perched sandplain aquifers,
697 that are readily depleted with localised tree planting (George, 1990). Investigations of this
698 site reported in Bennett *et al.* (2005) and Pracilio *et al.* (2006) support the conclusion that the
699 sandplain aquifer had been exhausted by the extensive mallee planting of which Site 16 was
700 part. These sites would be optimally managed by matching plantation area to the discharge
701 volume of the aquifer.

702

703 There was a species response to harvest with E_{koc} seemingly the least tolerant, especially
704 following spring harvests. At each E_{koc} site, the uncut treatments yielded more biomass than
705 the coppice treatments. In contrast, most E_{pol} and E_{lox} sites yielded more biomass under
706 coppice regimes, however, this was not consistent between sites. The juxtaposition of an E_{pol}
707 belt adjacent to Site 16, an E_{koc} belt, provided an opportunity to observe the consequence of
708 the drying out of the shallow aquifer on two different mallee species (Bennett *et al.*, 2005;
709 Pracilio *et al.*, 2006). While E_{koc} showed progressive decline in harvest yield, E_{pol} suffered
710 extensive drought death. This vulnerability of E_{pol} to the hotter/drier climate of the northern

711 wheatbelt (evaporation >2500 mm and rainfall <350 mm) has been widely observed in farmer
712 plantings. E_{pol} is native to central Victoria and southern NSW (evaporation 1600 mm and
713 rainfall 480 mm) and in the absence of sufficient water it is prone to mortality (J. Bartle, D.
714 Huxtable and B. Spencer personal observations). In contrast, E_{koc} is a native species in this
715 region and although it showed a decline in biomass at Site 16, no widespread death was
716 recorded. When comparing the two species drought responses, E_{pol} increases root growth
717 thereby capturing more annual rainfall whereas E_{koc} reduces leaf area (Brooksbank, 2011) .
718 These adaptations seem to favour E_{koc} in the northern wheatbelt, where this species can
719 survive without groundwater supply but increase growth rate by ten-fold when additional
720 groundwater is available (Brooksbank *et al.*, 2011). However, without additional ground
721 water, the zone of transition for E_{pol} selection lies where the aridity index (ratio of annual
722 rainfall to annual evaporation) is about 0.2. Similar contrasting drought responses and growth
723 rates have been found in other tree species in this region (Mitchell *et al.*, 2013).

724

725 *4.3 Season of harvest*

726 Large-scale markets for mallee biomass will require nearly continuous supply of biomass to
727 minimise storage costs (Abadi *et al.*, 2012); hence harvest may need to occur at any time of
728 the year. The seasonal rainfall and temperature cycles in the south west of WA are likely to
729 influence the response of mallee crops to harvest. It has been shown that below ground
730 carbohydrate reserves in unharvested mallee are lower in summer than spring (Wildy & Pate,
731 2002) and lower survival rates are observed with autumn harvests (Milthorpe *et al.*, 1994;
732 Noble, 1982; Noble & Diggle, 2014). Thus, it was hypothesised that the autumn harvest
733 would produce less biomass and higher mortality than spring harvest. Our results showed no
734 consistent adverse impacts of autumn harvest, refuting our hypothesis. Our study had longer
735 harvest intervals than the works cited above and the 3-year harvest cycle appears to avoid

736 depleting stand vigour. However, this study found differential species responses to season of
737 harvest. E_{koc} sites yielded more biomass with autumn treatments and this could be attributed
738 to shorter rainfall period in the northern wheatbelt where all the E_{koc} sites were located. In
739 contrast, the E_{lox} sites produced more biomass with spring harvests. The failed E_{lox} sites (6, 7
740 and 14) did produce less biomass with higher mortality following spring harvests compared
741 to the uncompromised trials. These sites were all in the northern wheatbelt where only one
742 E_{lox} site survived (Site 17). More research is needed to establish the northern range of E_{lox} for
743 production of biomass, especially on sub-optimal sites. There was no seasonal effect of
744 biomass production at the E_{pol} sites.

745

746 Without the stress of harvest, it was expected that uncut treatments would exhibit higher
747 survival and this was generally observed. With respect to harvested mallee, our results
748 indicate that season had a greater effect on mortality than frequency of harvest; E_{koc} sites
749 exhibited higher spring losses whereas greater losses of E_{lox} occurred in autumn, consistent
750 with previous studies (Noble, 1982; Noble & Diggle, 2014). Native herbivorous spring
751 beetles (*Liparetrus* spp.) were observed at sites in the north-eastern wheatbelt, where all of
752 the E_{koc} sites were located, and herbivory of emergent coppice foliage may have contributed
753 to higher spring mortality. The four E_{pol} sites exhibited low mortality whereas Milthorpe *et al.*
754 (1994) found elevated mortality from E_{pol} from autumn harvests but this was attributed
755 mainly to waterlogging after a flood event. It appears that mortality reflected seasonal factors,
756 especially at a species-level.

757

758 *4.4 Biomass yield*

759 Caution should be taken when directly comparing the biomass yield between sites with
760 different planting configurations. The mallee plantings selected for this experiment were

761 chosen from established plantings reflecting the landholder's site selection, planting design
762 and management. Selection focussed on stands that were seen as adequately representative of
763 overall performance and fell within the narrow-belt specification of planting row number and
764 within-row spacing. It was necessary to estimate actual yield of standing biomass for belts
765 ranging from 2 to 6 planting rows. When comparing the yield between 2-row belt and belts
766 with more than 2-rows, Mendham *et al.* (2012) and Peck *et al.* (2012) doubled the yield of the
767 outer row of sites containing more than 2-rows because the inner rows had on average only
768 65-70% the biomass of outer rows. However, subsequent spacing trial data suggests that the
769 outer row biomass from treatments containing more than 2-rows have about 90% of the
770 biomass of a 2-row belt (B. Spencer *et al.*, unpublished data). Nevertheless, a tree in a 2-row
771 belt will have greater access to water and nutrient resources and will not be subjected to the
772 additional competition imposed by sites containing more than 2-rows. Hence the biomass
773 yield estimates for 2-row belts will be inflated when compared to sites of more than 2-rows.
774

775 In this study, biomass is reported as dry weights, with fresh mallee biomass, depending on
776 size and site, varying between 36% and 48% in water content. Most mallee studies report
777 fresh biomass, making direct comparisons difficult. Mallee growth rates, reported as dry mass
778 or adjusted to 40% moisture, are in the range of 1-25 Mg ha⁻¹ yr⁻¹ (Bennett *et al.*, 2015;
779 Brooksbank, 2012; Carter & White, 2009; Grove *et al.*, 2007; Pracilio *et al.*, 2006; Sudmeyer
780 & Hall, 2015). For most of our sites, the growth rates were within the above range, although
781 at some sites considerably higher rates were observed. These sites may reflect the age of
782 plantings. The project was initiated in 2006 on established plantings that were then between
783 five and 12-years of age and all mallee plantings were older than any of those referred to
784 above.

785

786 This study confirms that E_{pol} is capable of high biomass production in the high rainfall/low
787 evaporation south-western wheatbelt region. E_{lox} is well adapted to the central and eastern
788 wheatbelt on mid to lower slopes, but three sites failed due to the presence of either silcrete
789 hardpan or shallow saline groundwater. E_{koc} sites were restricted to upper slope sandplain
790 soils in the northern wheatbelt, but can deliver reasonable yields (3-16 Mg ha⁻¹ yr⁻¹), although
791 only one study site was subjected to the 3- and 4-year harvest regime. It is important to match
792 species to site types as they have different tolerances to salinity and water requirements
793 (Brooksbank, 2011). There is potential for siting plantations of E_{lox} on the transition zone
794 from saline valley floor to lower slopes and for E_{koc} on sand plain seepage areas in the central
795 and northern wheatbelt regions. Productivity of all three species is constrained by shallow
796 saline groundwater and by the scattered occurrence of silcrete hardpan.

797

798 *4.5 Capacity to coppice*

799 Mortality at harvest has been reported for other species of eucalypts grown for biomass. The
800 4.7% mortality in this project compares to other studies where 99% of *E. camaldulensis* and
801 *E. dunnii* coppiced within 1-year post-harvest (Grunwald & Karschon, 1974; Li *et al.*, 2012).
802 In contrast, mortality over 25% has been recorded for *E. globulus* at 15 months post-harvest
803 (Whitlock *et al.*, 2003) and *E. grandis* 20 months post-harvest (Little & Toit, 2003).
804 However, these mallee data were for multiple harvest cycles over a longer time period than
805 the other studies.

806

807 The effect of genetic variation in coppicing has not been reported for these three mallee
808 species. However, there is evidence from other eucalypts that it may be important. Whitlock
809 *et al.* (2003) for instance, found significant variation between the coppicing of sub-races of *E.*
810 *globulus* post-harvest and Borzak *et al.* (2016) found, for the same species, that larger

811 lignotubers exhibited lower mortality and faster growth. Our results indicate a spike in
812 coppice mortality after the first harvest that did not occur in subsequent harvests. Establishing
813 the heritability of coppicing vigour of families or sub-races could potentially reduce post-
814 harvest mortality and increase production.

815

816 *4.6 Economic considerations of harvest*

817 There are three economic questions that need to be addressed before harvesting: the market
818 for biomass products; the cost of harvest; and the competition imposed by mallee belts on
819 adjacent crops and pasture. The components of biomass (leaf, twig, bark, wood) change with
820 the species and the size of the uncut or coppiced mallee, providing scope to manipulate
821 biomass composition by varying the frequency of harvest. The component allometric
822 regressions demonstrate more frequent harvests increase the percentage of leaf while
823 reducing the wood fraction. Depending on prices for the components, and available markets
824 for biofuels and extractives such as cineole (Davis, 2002), manipulating frequency of harvest
825 could be important for economic optimisation. There are boundaries to harvest frequency due
826 to mortality risk if too frequent and harvester capability if too infrequent. Cycle duration will
827 influence the competition that mallee belts impose on adjacent crop or pasture. Sudmeyer *et*
828 *al.* (2012a) demonstrated greater competition on adjacent annual crops occurs with larger
829 mallee, and that competition is reduced after harvest for up to five years. However, the
830 ultimate assessment of economic viability will need to include a holistic assessment of all on-
831 and off-farm benefits that have been a major motivation for development of a woody
832 perennial crop (Bartle & Abadi, 2009).

833

834 *4.7 Conclusion*

835 This study reports that dry weight biomass yields ranged from 2.2 to 32.8 Mg ha⁻¹ yr⁻¹. All
836 three species planted at sites not limited by saline water or silcrete hardpan consistently
837 produced woody biomass that could be used for a range of products and services. The
838 frequencies of harvest imposed did not compromise biomass production and except for three
839 sites, mortality was generally low and independent of frequency of harvest. There was a
840 species response to season of harvest where E_{lox} performed better following spring harvests
841 whereas E_{koc} had higher mortality with lower yields. E_{pol} was unaffected by season and
842 frequency of harvest imposed.

843 This study confirms that E_{pol} is a high biomass producer provided it is planted in higher
844 rainfall and lower evaporation regions. E_{lox} is an adaptable species and can tolerate moderate
845 salinity, but planting too close to saline water tables reduces productivity and may result in
846 high mortality after harvest. E_{koc} sites were restricted to sandplain soils in the northern
847 wheatbelt, but can deliver reasonable yields (3-16 Mg ha⁻¹ yr⁻¹), although only one study site
848 was subjected to the 3- and 4-year harvest regime. Mallee belt plantings will span multiple
849 soil types and it is inevitable that yield variability will occur. It is important to match species
850 to site types as they have different tolerances. Frequency of harvest will affect biomass
851 component composition and hence utility and value. Soil factors including pH, EC_e, shallow
852 saline water tables and soil nutrition were found to strongly influence biomass production.
853 These results have implications for initial site selection for mallee plantings and management
854 decisions regarding timing of harvest.

855

856 **Acknowledgements**

857 Many farmers and research workers were involved in the project over its 10-years duration,
858 with major inputs from Adam Peck, Wayne O'Sullivan and Wally Edgecombe. Wayne
859 O'Sullivan, Daniel Mendham and Adam Peck provided critique of early drafts.

860 The state government of Western Australia provided funds and staff to manage this project
861 over 10-years through the DBCA. Rob Sudmeyer through DPIRD was responsible for soil
862 collection and analysis. We also thank the Salinity CRC, Future Farm Industries CRC,
863 RIRDC and Natural Heritage Trust for financial support.

864 The authors would also like to acknowledge the contribution of an Australian Government
865 Research Training Program Scholarship in supporting this research.
866 Finally, the authors thank two anonymous reviewers who provided important comments that
867 helped improve the manuscript.
868

869

870 **References**

871

- 872 Abadi, A., Bartle, J., Giles, R., & Thomas, Q. (2012). Supply and delivery of mallees. In C. Stucley, S.
873 Schuck, R. Sims, J. Bland, B. Marino, M. Borowitzka, A. Abadi, J. Bartle, R. Giles, & Q. Thomas
874 (Eds.), *Bioenergy in Australia: Status and Opportunities* (1st ed., pp. 140-172). St Leonards,
875 NSW, Australia: Bioenergy Australia Limited. Available at
876 <https://researchrepository.murdoch.edu.au/id/eprint/36149/>.
- 877 Anderson, C., & Ladiges, P. Y. (1978). A comparison of three populations of *Eucalyptus obliqua*
878 L'Hérit. growing on acid and calcareous soils in southern Victoria. *Australian Journal of*
879 *Botany*, 26(1), 93-109.
- 880 Baker, T., Moroni, M., Mendham, D., Smith, R., & Hunt, M. (2018). Impacts of windbreak shelter on
881 crop and livestock production. *Crop and Pasture Science*, 69(8), 785-796.
- 882 Barrett-Lennard, E. (2003). The interaction between waterlogging and salinity in higher plants:
883 causes, consequences and implications. *Plant and Soil*, 253(1), 35-54.
- 884 Barrett-Lennard, E., George, R., Hamilton, G., Norman, H., & Masters, D. (2006). Multi-disciplinary
885 approaches suggest profitable and sustainable farming systems for valley floors at risk of
886 salinity. *Australian Journal of Experimental Agriculture*, 45(11), 1415-1424.
- 887 Bartle, J. (2009). Integrated production systems. In I. Nuberg, B. George, & R. Reid (Eds.),
888 *Agroforestry for Natural Resource Management* (pp. 267-280). Collingwood: CSIRO.
- 889 Bartle, J. R., & Abadi, A. (2009). Toward sustainable production of second generation bioenergy
890 feedstocks. *Energy & Fuels*, 24(1), 2-9.
- 891 Barton, A. (2000). The oil mallee project: a multifaceted industrial ecology case study. *Journal of*
892 *Industrial Ecology*, 3(2-3), 161-176.
- 893 Baskerville, G. (1972). Use of logarithmic regression in the estimation of plant biomass. *Canadian*
894 *Journal of Forest Research*, 2(1), 49-53.
- 895 Beauchamp, J. J., & Olson, J. S. (1973). Corrections for bias in regression estimates after logarithmic
896 transformation. *Ecology*, 54(6), 1403-1407.
- 897 Bell, T. L., Pate, J. S., & Dixon, K. W. (1996). Relationships Between Fire Response, Morphology, Root
898 Anatomy and Starch Distribution in South-west Australian Epacridaceae. *Annals of Botany*,
899 77(4), 357-364.
- 900 Bennett, D., Speed, R. J., & Taylor, P. (2005). *Goodlands oil mallee study: drill completion and*
901 *preliminary hydrogeological interpretation*. Resource Management Technical Report 293.
902 Department of Agriculture WA. Perth: State of Western Australia.
- 903 Bennett, R. G., Mendham, D., Ogden, G., & Bartle, J. (2015). Enhancing tree belt productivity through
904 capture of short-slope runoff water. *GCB Bioenergy*, 7(5), 1107-1117.
- 905 Bennett, S. J., Barrett-Lennard, E., & Colmer, T. (2009). Salinity and waterlogging as constraints to
906 saltland pasture production: a review. *Agriculture, Ecosystems & Environment*, 129(4), 349-
907 360.
- 908 Bird, P., Bicknell, D., Bulman, P., Burke, S., Leys, J., Parker, J., Sommen, F., & Voller, P. (1992). The
909 role of shelter in Australia for protecting soils, plants and livestock. *An International Journal*
910 *Incorporating Agroforestry Forum*, 20(1), 59-86.
- 911 Borzak, C. L., Potts, B. M., & O'Reilly-Wapstra, J. M. (2016). Survival and recovery of *Eucalyptus*
912 *globulus* seedlings from severe defoliation. *Forest Ecology and Management*, 379, 243-251.

- 913 Brandes, E., McNunn, G. S., Schulte, L. A., Bonner, I. J., Muth, D., Babcock, B. A., Sharma, B., &
 914 Heaton, E. A. (2016). Subfield profitability analysis reveals an economic case for cropland
 915 diversification. *Environmental Research Letters*, 11(1), 014009.
- 916 Brandes, E., McNunn, G. S., Schulte, L. A., Muth, D. J., VanLoocke, A., & Heaton, E. A. (2018).
 917 Targeted subfield switchgrass integration could improve the farm economy, water quality,
 918 and bioenergy feedstock production. *GCB Bioenergy*, 10(3), 199-212.
- 919 Brooksbank, K. (2011). *Oil Mallees: Physiology and Growth Under Variable Water Availability in Low*
 920 *Rainfall Agroforestry Systems*. (Doctoral dissertation), University of Western Australia, Perth,
 921 Australia.
- 922 Brooksbank, K. (2012). *Hydrological Impacts and Productivity Interactions of Integrated Oil Mallee* 923
Farming Systems: Landscape Scale Effects of Dispersed Mallee Plantings. RIRDC Report no
 924 11/161. Barton ACT: Rural Industries Research and Development Corporation.
- 925 Brooksbank, K., Veneklaas, E. J., White, D., & Carter, J. (2011). Water availability determines
 926 hydrological impact of tree belts in dryland cropping systems. *Agricultural Water*
 927 *Management*, 100(1), 76-83.
- 928 Carter, J. L., & White, D. A. (2009). Plasticity in the Huber value contributes to homeostasis in leaf
 929 water relations of a mallee Eucalypt with variation to groundwater depth. *Tree Physiology*,
 930 29(11), 1407-1418.
- 931 Chatterjee, S., & Ali, H. S. (2015). *Regression analysis by example*. New Jersey: John Wiley & Sons.
- 932 Chojnacky, D. C., & Milton, M. (2008). Measuring carbon in shrubs. In *Field Measurements for Forest*
 933 *Carbon Monitoring* (pp. 45-72): Springer.
- 934 Coppen, J., & Hone, G. (1992). *Eucalyptus oils: a review of production and markets (NRI Bulletin 56)*.
 935 Chatham, UK: University of Greenwich, Natural resources institute.
- 936 Dale, V. H., Kline, K. L., Buford, M. A., Volk, T. A., Smith, C. T., & Stupak, I. (2016). Incorporating
 937 bioenergy into sustainable landscape designs. *Renewable and Sustainable Energy Reviews*,
 938 56, 1158-1171.
- 939 Davis, G. R. (2002). Cultivation and production of eucalypts in Australia: with special reference to the 940
 leaf oils. In J. J. W. Coppen (Ed.), *Eucalyptus: The Genus Eucalyptus* (pp. 183-201): Taylor and
 941 Francis.
- 942 Dickmann, D. I. (2006). Silviculture and biology of short-rotation woody crops in temperate regions:
 943 Then and now. *Biomass and Bioenergy*, 30(8), 696-705.
- 944 Eastham, J., Scott, P., Steckis, R., Barton, A., Hunter, L., & Sudmeyer, R. (1993). Survival, growth and
 945 productivity of tree species under evaluation for agroforestry to control salinity in the
 946 Western Australian wheatbelt. *Agroforestry Systems*, 21(3), 223-237.
- 947 Ellis, T. W., Leguedois, S., Hairsine, P. B., & Tongway, D. J. (2006). Capture of overland flow by a tree
 948 belt on a pastured hillslope in south-eastern Australia. *Soil Research*, 44(2), 117-125.
- 949 Enquist, B. J., Kerkhoff, A. J., Stark, S. C., Swenson, N. G., McCarthy, M. C., & Price, C. A. (2007). A
 950 general integrative model for scaling plant growth, carbon flux, and functional trait spectra.
 951 *Nature*, 449(7159), 218.
- 952 Foley, J., Ramankutty, N., Brauman, K., Cassidy, E., Gerber, J., Johnston, M., Mueller, N., O'Connell,
 953 C., Ray, D., West, P., Balzer, C., Bennett, E., Carpenter, S., Hill, J., Monfreda, C., Polasky, S.,
 954 Rockström, J., Sheehan, J., Siebert, S., Tilman, D., & Zaks, D. (2011). Solutions for a cultivated
 955 planet. *Nature*, 478(7369), 337.
- 956 George, R. (1990). Reclaiming sandplain seeps by intercepting perched groundwater with eucalypts.
 957 *Land Degradation & Development*, 2(1), 13-25.
- 958 George, R., Clarke, J., & English, P. (2008). Modern and palaeogeographic trends in the salinisation of
 959 the Western Australian wheatbelt: a review. *Soil Research*, 46(8), 751-767.
- 960 George, R., McFarlane, D., & Nulsen, B. (1997). Salinity threatens the viability of agriculture and
 961 ecosystems in Western Australia. *Hydrogeology Journal*, 5(1), 6-21.
- 962 George, R. J. (1992). Hydraulic properties of groundwater systems in the saprolite and sediments of
 963 the wheatbelt, Western Australia. *Journal of Hydrology*, 130(1-4), 251-278.

- 964 GHD. (2019). A New Direction for Salinity Management in Western Australia: A Consultative Review.
 965 Retrieved from
 966 [https://www.agric.wa.gov.au/sites/gateway/files/A%20New%20Direction%20for%20Salinity](https://www.agric.wa.gov.au/sites/gateway/files/A%20New%20Direction%20for%20Salinity%20Management%20in%20Western%20Australia%20-%20A%20Consultative%20Review_1.pdf)
 967 [%20Management%20in%20Western%20Australia%20-](https://www.agric.wa.gov.au/sites/gateway/files/A%20New%20Direction%20for%20Salinity%20Management%20in%20Western%20Australia%20-%20A%20Consultative%20Review_1.pdf)
 968 [%20A%20Consultative%20Review_1.pdf](https://www.agric.wa.gov.au/sites/gateway/files/A%20New%20Direction%20for%20Salinity%20Management%20in%20Western%20Australia%20-%20A%20Consultative%20Review_1.pdf)
- 969 Grove, T., Mendham, D., Rance, S., Bartle, J., & Shea, S. (2007). *Nutrient management of intensively* 970
 971 *harvested oil mallee tree crops*. RIRDC. Publication No 07/084. Barton ACT: Rural Industries
 972 Research and Development Corporation.
- 972 Grunwald, C., & Karschon, R. (1974). Effect of seed origin on coppice regeneration in *Eucalyptus*
 973 *camaldulensis* Dehn. *Silvae Genetica*, 23(5), 141-144.
- 974 Hatton, T., Ruprecht, J., & George, R. (2003). Preclearing hydrology of the Western Australia
 975 wheatbelt: target for the future. *Plant and Soil*, 257(2), 341-356.
- 976 Hingston, F., & Gailitis, V. (1976). The geographic variation of salt precipitated over Western
 977 Australia. *Soil Research*, 14(3), 319-335.
- 978 James, S. (1984). Lignotubers and burls—their structure, function and ecological significance in
 979 Mediterranean ecosystems. *The Botanical Review*, 50(3), 225-266.
- 980 Jeffrey, S. J., Carter, J. O., Moodie, K. B., & Beswick, A. R. (2001). Using spatial interpolation to
 981 construct a comprehensive archive of Australian climate data. *Environmental Modelling &*
 982 *Software*, 16(4), 309-330.
- 983 Johnson, S. E., & Abrams, M. D. (2009). Age class, longevity and growth rate relationships: protracted
 984 growth increases in old trees in the eastern United States. *Tree Physiology*, 29(11), 1317-
 985 1328.
- 986 Ladiges, P. Y., & Ashton, D. (1977). A comparison of some populations of *Eucalyptus viminalis* Labill.
 987 growing on calcareous and acid soils in Victoria, Australia. *Australian Journal of Ecology*, 2(2),
 988 161-178.
- 989 Lefroy, E., & Stirzaker, R. (1999). Agroforestry for water management in the cropping zone of
 990 southern Australia. *An International Journal Incorporating Agroforestry Forum*, 45(1), 277-
 991 302.
- 992 Li, B., Arnold, R., Luo, J., & Li, Z. (2012). Genetic variation in growth, cold tolerance and coppicing in
 993 *Eucalyptus dunnii* in trials in Hunan, China. *Australian Forestry*, 75(4), 215-224.
- 994 Little, K. M., & Toit, B. d. (2003). Management of *Eucalyptus grandis* coppice regeneration of
 995 seedling parent stock in Zululand, South Africa. *Australian Forestry*, 66(2), 108-112.
- 996 McGrath, J. F., Goss, K. F., Brown, M. W., Bartle, J. R., & Abadi, A. (2016). Aviation biofuel from
 997 integrated woody biomass in southern Australia. *Wiley Interdisciplinary Reviews: Energy and*
 998 *Environment*, 6(2).
- 999 Mendham, D., Bartle, J., Peck, A., Bennett, R., Ogden, G., McGrath, G., Abadi, A., Vogwill, R.,
 1000 Huxtable, D., & Turnbull, P. (2012). *Management of Mallee Belts for Profitable and Sustained*
 1001 *Production*. Crawley Australia: Future Farm Industries Cooperative Research Centre.
- 1002 Milthorpe, P., Brooker, M., Slee, A., & Nicol, H. (1998). Optimum planting densities for the
 1003 production of eucalyptus oil from blue mallee (*Eucalyptus polybractea*) and oil mallee (*E.*
 1004 *kochii*). *Industrial Crops and Products*, 8(3), 219-227.
- 1005 Milthorpe, P., Hillan, J., & Nicol, H. (1994). The effect of time of harvest, fertilizer and irrigation on
 1006 dry matter and oil production of blue mallee. *Industrial Crops and Products*, 3(3), 165-173.
- 1007 Mitchell, P. J., O'Grady, A. P., Tissue, D. T., White, D. A., Ottenschlaeger, M. L., & Pinkard, E. A.
 1008 (2013). Drought response strategies define the relative contributions of hydraulic
 1009 dysfunction and carbohydrate depletion during tree mortality. *New Phytologist*, 197(3), 862-
 1010 872.
- 1011 Nicolle, D. (2006). A classification and census of regenerative strategies in the eucalypts (Angophora,
 1012 Corymbia and *Eucalyptus*—Myrtaceae), with special reference to the obligate seeders.
 1013 *Australian Journal of Botany*, 54(4), 391-407.

- 1014 Noble, J. (1982). Significance of fire in the biology and evolutionary ecology of mallee *Eucalyptus*
1015 populations. In W. R. Barker & P. J. M. Greenslade (Eds.), *Evolution of the flora and fauna of*
1016 *arid Australia* (pp. 153–166). Adelaide: Peacock Publications.
- 1017 Noble, J. C. (1989a). Fire regimes and their influence on herbage and mallee coppice dynamics. In J.
1018 C. Noble & R. A. Bradstock (Eds.), *Mediterranean landscapes in Australia: mallee ecosystems*
1019 *and their management* (pp. 168-180). Melbourne: CSIRO.
- 1020 Noble, J. C. (1989b). Fire studies in mallee (*Eucalyptus* spp.) communities of western New South
1021 Wales: the effects of fires applied in different seasons on herbage productivity and their
1022 implications for management. *Austral Ecology*, *14*(2), 169-187.
- 1023 Noble, J. C. (2001). Lignotubers and meristem dependence in mallee (*Eucalyptus* spp.) coppicing
1024 after fire. *Australian Journal of Botany*, *49*(1), 31-41.
- 1025 Noble, J. C., & Diggle, P. J. (2014). Population biology of coppicing plants: survival of mallee
1026 (*Eucalyptus* spp.) populations exposed to contrasting fire and cutting regimes. *Australian*
1027 *Journal of Botany*, *61*(7), 552-557.
- 1028 O'Connell, D., Batten, D., O'Connor, M., May, B., Raison, J., Keating, B., Beer, T., Braid, A., Haritos, V.,
1029 Begley, C., Poole, M., Poulton, P., Graham, S., Dunlop, M., Grant, T., Campbell, P., & Lamb, D.
1030 (2007). *Biofuels in Australia : an overview of issues and prospects*. RIRDC Publication Number
1031 07/071. Canberra: Rural Industries Research and Development Corporation.
- 1032 Parsons, R., & Specht, R. (1967). Lime chlorosis and other factors affecting the distribution of
1033 *Eucalyptus* on coastal sands in southern Australia. *Australian Journal of Botany*, *15*(1), 95-
1034 105.
- 1035 Paul, K., Roxburgh, S., Chave, J., England, J., Zerihun, A., Specht, A., Lewis, T., Bennett, L., Baker, T.,
1036 Adams, M., Huxtable, D., Montagu, K., Falster, D., Feller, M., Sochacki, S., Ritson, P., Bastin,
1037 G., Bartle, J., Wildy, D., Hobbs, T., Larmour, J., Waterworth, R., Stewart, H., Jonson, J.,
1038 Forrester, D., Applegate, G., Mendham, D., Bradford, M., O'Grady, A., Green, D., Sudmeyer,
1039 R., Rance, S., Turner, J., Barton, C., Wenk, E., Grove, T., Attiwill, P., Pinkard, E., Butler, D.,
1040 Brooksbank, K., Spencer, B., Snowdon, P., O'Brien, N., Battaglia, M., Cameron, D., Hamilton,
1041 S., McAuthur, G., & Sinclair, J. (2016). Testing the generality of above-ground biomass
1042 allometry across plant functional types at the continent scale. *Global change biology*, *22*(6),
1043 2106-2124.
- 1044 Paul, K., Roxburgh, S., Raison, J., Larmour, J., England, J., Murphy, S., Norris, J., Ritson, P.,
1045 Brooksbank, K., Hobbs, T., Neumann, C., Lewis, T., Read, Z., Clifford, D., Knoch, L., Rooney,
1046 M., Freudenberger, D., Jonson, J., Peck, A., Giles, R., Bartle, J., McAuthur, G., Wildy, D.,
1047 Lindsay, A., Preece, N., Cunningham, S., Powe, T., Carter, J., Bennett, R., Mendham, D.,
1048 Sudmeyer, R., Rose, B., Butler, D., Cohen, L., Fairman, T., Law, R., Finn, B., Brammar, M.,
1049 Minchin, G., van Oosterzeeand, P., & A., L. (2013a). *Improved estimation of biomass*
1050 *accumulation by environmental plantings and mallee plantings using FullCAM*. Report for
1051 Department of Climate Change and Energy Efficiency. CSIRO Sustainable Agriculture
1052 Flagship, Canberra, Australia.
- 1053 Paul, K. I., Roxburgh, S. H., Ritson, P., Brooksbank, K., England, J. R., Larmour, J. S., John Raison, R.,
1054 Peck, A., Wildy, D. T., Sudmeyer, R. A., Giles, R., Carter, J., Bennett, R., Mendham, D. S.,
1055 Huxtable, D., & Bartle, J. R. (2013b). Testing allometric equations for prediction of above-
1056 ground biomass of mallee eucalypts in southern Australia. *Forest Ecology and Management*,
1057 *310*, 1005-1015.
- 1058 Peck, A., & Hurlle, D. H. (1973). Chloride balance of some farmed and forested catchments in
1059 southwestern Australia. *Water Resources Research*, *9*(3), 648-657.
- 1060 Peck, A., Sudmeyer, R., Huxtable, D., Bartle, J., & Mendham, D. (2012). *Productivity of mallee*
1061 *agroforestry systems under various harvest and competition management regimes*. RIRDC.
1062 Publication No 11/162. Canberra. Australia: Rural Industries Research and Development
1063 Corporation.

- 1064 Pepper, R., & Craig, G. (1986). Resistance of Selected Eucalyptus Species to Soil Salinity in Western
1065 Australia. *Journal of Applied Ecology*, 977-987.
- 1066 Pracilio, G., Smettem, K. R., Bennett, D., Harper, R. J., & Adams, M. L. (2006). Site assessment of a
1067 woody crop where a shallow hardpan soil layer constrained plant growth. *Plant and Soil*,
1068 288(1-2), 113-125.
- 1069 Richards, F. (1959). A flexible growth function for empirical use. *Journal of Experimental Botany*,
1070 10(2), 290-301.
- 1071 Robinson, N., Harper, R., & Smettem, K. R. J. (2006). Soil water depletion by Eucalyptus spp.
1072 integrated into dryland agricultural systems. *Plant and Soil*, 286(1-2), 141-151.
- 1073 Rundle, P. J., & Rundle, B. F. (2002). A case study of farm-based solutions to water logging and
1074 secondary salinity in southwestern Australia. *Agricultural Water Management*, 53(1-3), 31-
1075 38.
- 1076 SAS. (2017). Version 9.4. SAS Institute Inc., Cary, NC, USA.
- 1077 Shepherd, M., Bartle, J., Lee, D. J., Brawner, J., Bush, D., Turnbull, P., Macdonel, P., Brown, T. R.,
1078 Simmons, B., & Henry, R. (2011). Eucalypts as a biofuel feedstock. *Biofuels*, 2(6), 639-657.
- 1079 Silberstein, R., Bartle, G., Salama, R., Hatton, T., Reggiani, P., Hodgson, G., Williamson, D., & Lambert,
1080 P. (2002). Mechanisms and control of water logging and groundwater flow in the
1081 'Ucarro' sub-catchment. *Agricultural Water Management*, 53(1-3), 227-257.
- 1082 Simons, J., George, R., & Raper, P. (2013). *Dryland Salinity. In: Report card on sustainable natural*
1083 *resource use in agriculture*. Western Australia: Department of Agriculture and Food Western
1084 Australia.
- 1085 Smettem, K., & Harper, R. (2009). Using trees to manage local and regional water balances.
1086 *Agroforestry for natural resource management*. CSIRO, Collingwood, 37-52.
- 1087 Smith, F. P. (2009). Assessing the habitat quality of oil mallees and other planted farmland
1088 vegetation with reference to natural woodland. *Ecological Management & Restoration*,
1089 10(3), 217-227.
- 1090 Snowdon, P., Raison, R. J., Keith, H., Ritson, P., Grierson, P., Adams, M., Montagu, K., Bi, H., Burrows,
1091 W., & Eamus, D. (2002). *Protocol for sampling tree and stand biomass*. Technical Report No.
1092 31. Canberra. Australia: Australian Greenhouse Office.
- 1093 Spinelli, R., Brown, M., Giles, R., Huxtable, D., Relaño, R. L., & Magagnotti, N. (2014). Harvesting
1094 alternatives for mallee agroforestry plantations in Western Australia. *Agroforestry Systems*,
1095 88(3), 479-487.
- 1096 Sudmeyer, R., Adams, M., Eastham, J., Scott, P., Hawkins, W., & Rowland, I. (2002). Broadacre crop
1097 yield in the lee of windbreaks in the medium and low rainfall areas of south-western
1098 Australia. *Australian Journal of Experimental Agriculture*, 42(6), 739-750.
- 1099 Sudmeyer, R., Daniels, T., Jones, H., & Huxtable, D. (2012a). The extent and cost of mallee-crop
1100 competition in unharvested carbon sequestration and harvested mallee biomass
1101 agroforestry systems. *Crop and Pasture Science*, 63(6), 555-569.
- 1102 Sudmeyer, R., Daniels, T., Van Burgel, A., Jones, H., Huxtable, D., & Peck, A. (2012b). Tree and crop
1103 competition effects. In A. Peck, R. Sudmeyer, D. Huxtable, J. Bartle, & D. Mendham (Eds.),
1104 *Productivity of mallee agroforestry systems: the effect of harvest and competition*
1105 *management regimes* (pp. 59-85). RIRDC. Publication No 11/162. Canberra: Rural Industries
1106 Research and Development Corporation
- 1107 Sudmeyer, R., & Scott, P. (2002). Characterisation of a windbreak system on the south coast of
1108 Western Australia. 2. Crop growth. *Australian Journal of Experimental Agriculture*, 42(6),
1109 717-727.
- 1110 Sudmeyer, R., Speijers, J., & Nicholas, B. (2004). Root distribution of *Pinus pinaster*, *P. radiata*,
1111 *Eucalyptus globulus* and *E. kochii* and associated soil chemistry in agricultural land adjacent
1112 to tree lines. *Tree Physiology*, 24(12), 1333-1346.

- 1113 Sudmeyer, R. A., & Hall, D. J. (2015). Competition for water between annual crops and short rotation
 1114 mallee in dry climate agroforestry: The case for crop segregation rather than integration.
 1115 *Biomass and Bioenergy*, 73, 195-208.
- 1116 Symonds, W., Campbell, L., & Clemens, J. (2001). Response of ornamental Eucalyptus from acidic and
 1117 alkaline habitats to potting medium pH. *Scientia horticulturae*, 88(2), 121-131.
- 1118 URS. (2008). *Oil mallee industry development plan for Western Australia*. Perth. Western Australia:
 1119 Forest Products Commission.
- 1120 VanLoocke, A., Twine, T. E., Kucharik, C. J., & Bernacchi, C. J. (2016). Assessing the potential to
 1121 decrease the Gulf of Mexico hypoxic zone with Midwest US perennial cellulosic feedstock
 1122 production. *GCB Bioenergy*, 9(5), 858-875.
- 1123 Verboom, W., & Pate, J. (2006). Evidence of active biotic influences in pedogenetic processes. Case
 1124 studies from semiarid ecosystems of south-west Western Australia. *Plant and Soil*, 289(1-2),
 1125 103-121.
- 1126 Volk, T. A., Heavey, J. P., & Eisenbies, M. H. (2016). Advances in shrub-willow crops for bioenergy,
 1127 renewable products, and environmental benefits. *Food and Energy Security*, 5(2), 97-106.
- 1128 Whittock, S., Apiolaza, L., Kelly, C., & Potts, B. (2003). Genetic control of coppice and lignotuber
 1129 development in Eucalyptus globulus. *Australian Journal of Botany*, 51(1), 57-67.
- 1130 Wildy, D. T., Bartle, J. R., Pate, J. S., & Arthur, D. J. (2000a). Sapling and coppice biomass production
 1131 by alley-farmed 'oil mallee' Eucalyptus species in the Western Australian wheatbelt.
 1132 *Australian Forestry*, 63(2), 147-157.
- 1133 Wildy, D. T., & Pate, J. S. (2002). Quantifying above-and below-ground growth responses of the
 1134 western Australian oil mallee, Eucalyptus kochii subsp. plenissima, to contrasting
 1135 decapitation regimes. *Annals of Botany*, 90(2), 185-197.
- 1136 Wildy, D. T., Pate, J. S., & Bartle, J. R. (2000b). Variations in composition and yield of leaf oils from
 1137 alley-farmed oil mallees (Eucalyptus spp.) at a range of contrasting sites in the Western
 1138 Australian wheatbelt. *Forest Ecology and Management*, 134(1), 205-217.
- 1139 Wildy, D. T., Pate, J. S., & Bartle, J. R. (2004a). Budgets of water use by Eucalyptus kochii tree belts in
 1140 the semi-arid wheatbelt of Western Australia. *Plant and Soil*, 262(1), 129-149.
- 1141 Wildy, D. T., Pate, J. S., & Sefcik, L. T. (2004b). Water-use efficiency of a mallee eucalypt growing
 1142 naturally and in short-rotation coppice cultivation. *Plant and Soil*, 262(1-2), 111-128.
- 1143 Wu, H., Fu, Q., Giles, R., & Bartle, J. (2007). Production of mallee biomass in Western Australia:
 1144 energy balance analysis. *Energy & Fuels*, 22(1), 190-198.
- 1145 Yu, Y., Bartle, J., Mendham, D., & Wu, H. (2015). Site Variation in Life Cycle Energy and Carbon
 1146 Footprints of Mallee Biomass Production in Western Australia. *Energy & Fuels*, 29(6), 3748-
 1147 3752.
- 1148 Zhao-gang, L., & Feng-ri, L. (2003). The generalized Chapman-Richards function and applications to
 1149 tree and stand growth. *Journal of Forestry Research*, 14(1), 19-26.
- 1150