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Eucalyptus globulus agroforestry on deep sands on the southeast coast of Western Australia: The promise and the reality

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ABSTRACT

Secondary salinisation is a growing problem in Western Australia, with 1.1 Mha of agricultural and public land now affected to some extent. During the 1980s and early 1990s it was widely believed that agroforestry offered one of the best hopes for reducing the area at risk from salinisation while improving the productivity of conventional agricultural enterprises and providing new sources of income to landholders. This paper details the hydrogeology, tree water use and the productivity of *Eucalyptus globulus*, crops and pastures in an agroforestry system on the south coast of Western Australia with deep sandy soils and rising groundwater.

The tree-belts directly occupied 10% of the catchment and the lateral spread of outer tree roots meant recharge was effectively eliminated over 20% of the catchment. However, groundwater at the site continued to rise for 13 years after the trees were planted. Sapflow and tree growth measurements showed that the trees did not access the brackish groundwater (>500 mg/L) present over most of the site. Consequently, tree growth was relatively poor (5 m^3/ha/yr for inner trees) and the estimated economic returns from pulpwood production were less than from agriculture. While the outer tree rows grew at 8 times the rate of inner rows, this was at the expense of reduced crop and pasture growth in the adjacent 15–20 m wide competition zone (CZ). If the area of the CZ where agricultural production was less than breakeven is considered, then the outer tree rows grew at a similar rate (expressed on an area basis) as the inner rows. This suggests there was no economic advantage in growing pulpwood in belts rather than blocks at this site. Thinning the trees to 125 stems/ha allowed improved crop and pasture production and reduced wind erosion in the CZ, and facilitated greater growth rates of the remaining trees. It remains to be determined whether increased economic returns from the trees will compensate for the cost of thinning and pruning.

This study has shown that *E. globulus* is not a suitable agroforestry tree species for medium rainfall sites with deep sands and brackish groundwater, other tree species may be more suited to these sites and achieve better economic and hydrological outcomes for landholders.

1. Introduction

In the agricultural areas of southwestern Australia, the transition from native forest, woodlands and shrublands to agricultural systems based on annual crops and pastures has changed the hydrological balance. More water now percolates below the root zone of agricultural plants compared to native vegetation. This water can cause groundwater to rise, mobilizing salts stored in the soil. Consequently, secondary salinisation is a growing problem in Western Australia, with 1.1 Mha of agricultural and public land now affected to some extent (McFarlane et al., 2004) and the current best estimate suggesting that an additional 1.7–3.4 Mha are threatened by salinisation (George et al., 2006). Since the late 1970s there have been increasing scientific and industry driven efforts to address the problem in Australia. During the 1980s and early 1990s planting trees on agricultural land was widely promoted as one of the best methods for decreasing groundwater recharge and reducing the area at risk from salinisation. At that time there was limited Australian information about the actual impacts of planting trees into agricultural landscapes, but it was widely believed that limited re-afforestation could address salinity particularly where commercial tree species planted in shelterbelt layouts would improve the productivity of the conventional agricultural enterprises and provide new sources

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of income to landholders (Homes and Talsma, 1981; Scott, 1990, 1991; Bicknell, 1992; Robins et al., 1996; Burnage, 1996; Stirzaker and Lefroy, 1997).

This paper details the hydrogeology, tree water use and the productivity of *Eucalyptus globulus* Labill. (Tasmanian blue gum) and crops and pastures in an agroforestry system. The amenity and biodiversity values of the system were not assessed during this study. The tree-belts were planted in 1993, on a site on the south coast of Western Australia with deep sandy soils and rising groundwaters. The agroforestry system was designed with the aims of combating rising groundwater, increasing agricultural productivity by the provision of shelter and diversifying farm income with the establishment of a pulpwood or sawlog production enterprise. The success of this agroforestry system in achieving these aims is discussed in light of the results from this trial and published information from other sites in Australia in recent years.

2. Materials and methods

2.1. Site description

The trial site is located at Neridup, approximately 38 km northeast of the town of Esperance, Western Australia (122°14′57″E, −33°40′12″N). The trial site is located within a 300 ha externally drained sub-catchment on an undulating plain. The climate is temperate, with cool, wet winters and warm to hot, dry summers. Annual rainfall 5.8 km to the northeast averaged 553 mm between 1962 and 2005 and 549 mm between 1993 and 2005 (Fig. 1) (meteorological data accessed from Patched Point Dataset, maintained by the Queensland Department of Natural Resources and Mines).

The soil was classified as deep, fine-grained, yellow quaternary sands (basic, arenic, bleached-orthic Tenosol (Isbell, 1996; Nicholas, personal communication, 2000)) overlying orange/brown sandy clays at a depth of 2–5 m. Tertiary sediments from the Plantagenet Group of the Bremer Basin underlie the quaternary sands. The tertiary sediments consist of two distinct formations; Pallinup siltstone consisting of siltstone and spongolite which was deposited in a shallow marine environment overlying the deeper Werillup Formation consisting of dark coloured siltstone, sandstone, claystone and lignite deposited in a fluvial or estuarine environment (Cockbain, 1968). Beneath the sediments, Proteroizoic granite of the Albany-Fraser Orogen forms the basement rock (Morgan and Peers, 1973) that outcrops on the ridge tops and underlies the area planted to trees at depths greater than 45 m (Hall, 1989).

The site has a localized groundwater flow system (Coram, 1998) with an unconfined to semi-confined aquifer (Short, 2000). Groundwater occurs directly above the impervious basement rock and extends to within 5 m of the ground surface, with the aquifer having a saturated thickness of <50 m. In the southern part of the site, there was an isolated unconfined superficial aquifer perched on the sandy clays overlying the main aquifer. Saturated hydraulic conductivities range from 0.01 m/day in the tertiary sediments to 0.09 m/day in the weathered granite (Clarke et al., 2000). The source of salts in the groundwater is oceanic aerosols deposited with rainfall (Hingston and Gailitis, 1976) and accreted in the regolith over thousands of years (Johnston, 1987).

The native vegetation was cleared from the area during the early 1960s, and the land was predominantly used for grazing enterprises. Subsequent native vegetation regrowth was recleared in the mid 1980s to facilitate mixed cropping and grazing. Forty hectares of remnant native vegetation and regrowth still remain on non-arable ridge tops (Fig. 2). Crops in the area are typically sown in late May or early June and mature in mid–late November, pastures are based on annual legume and grass mixtures.

In 1993, *E. globulus* tree-belts were planted on 30 ha or 10% of the sub-catchment. Initially the silvicultural regime was aimed at harvesting pulpwood for paper manufacturing when the trees were 10 years old. Each tree-belt consisted of 10–12 rows of trees, with rows 5 m apart and trees spaced 2.4 m apart along the rows so that planting density was 840 stems per ha (SPH). The tree-belts were planted in a grid pattern oriented NE–SW or NW–SE (Fig. 2).

Between 1993 and 2000 wheat (*Triticum aestivum*), barley (*Hordeum vulgare*) and lupins (*Lupinus angustifolius*) were grown in rotation with pastures based on annual legume and grass mixtures. In 2001, lucerne (*Medicago sativa*) was sown and the subsequent permanent pasture was a mixture of lucerne and annual grasses.

2.2. Tree thinning, and fertiliser treatments

In 1999, it was decided to investigate the potential for changing the silvicultural regime from producing solely pulpwood to producing saw logs. To do this it was necessary to increase tree growth rates by reducing tree density and applying additional fertiliser. Accordingly, three tree density treatments were established with two of the densities also receiving additional nutrients in 1999 and 2001. Consequently there were the following five treatments:

- unthinned, approximately 800 SPH, and unfertilised (800−);
- unthinned, approximately 800 SPH, and fertilised (800+);
- thinned to approximately 400 SPH and fertilised (400+);
- thinned to approximately 125 SPH and unfertilised (125−);
- thinned to approximately 125 SPH and fertilised (125+).

In the thinned treatments, the poorest performing trees were removed and the best trees retained and pruned to 4 m height. At each fertiliser application the following nutrients were applied (kg/ha): N = 14.6, P = 4.2, K = 12.2, S = 14.4, Ca = 4.8, Cu = 0.06, Zn = 0.07, Mn = 0.24, Fe = 0.4, Mg = 0.72 and B = 0.01. Each treatment extended 50 m along the tree-belt.

Because of site constraints it was not possible to randomize treatments within replicate blocks. So treatments 125+, 125−, 400+, 850+ were established across the full width of the central tree-belt, with two 12-row wide and 50 m long blocks of each treatment randomly distributed along the central tree-belt (Fig. 2). The 12-row wide blocks were split into two 6-row wide plots; one on the northern side of the belt and the other on the southern. One 800+ and four 800− plots were established on the tree-belts to the north and south of the central belt (Fig. 2). This gave four plots 50 m long by 30 m (6 rows) wide for each treatment, two with northwest aspects and two with southeast aspects.

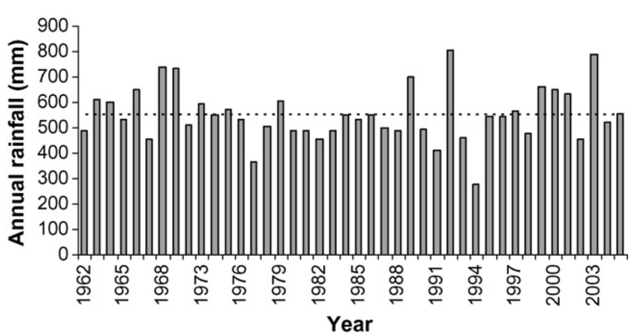

Fig. 1. Annual rainfall at 'Welcome Downs', 5.8 km to the northeast of the trial site, dotted line shows average annual rainfall over the period. Data courtesy of the Patched Point Dataset, maintained by the Queensland Department of Natural Resources and Mines.

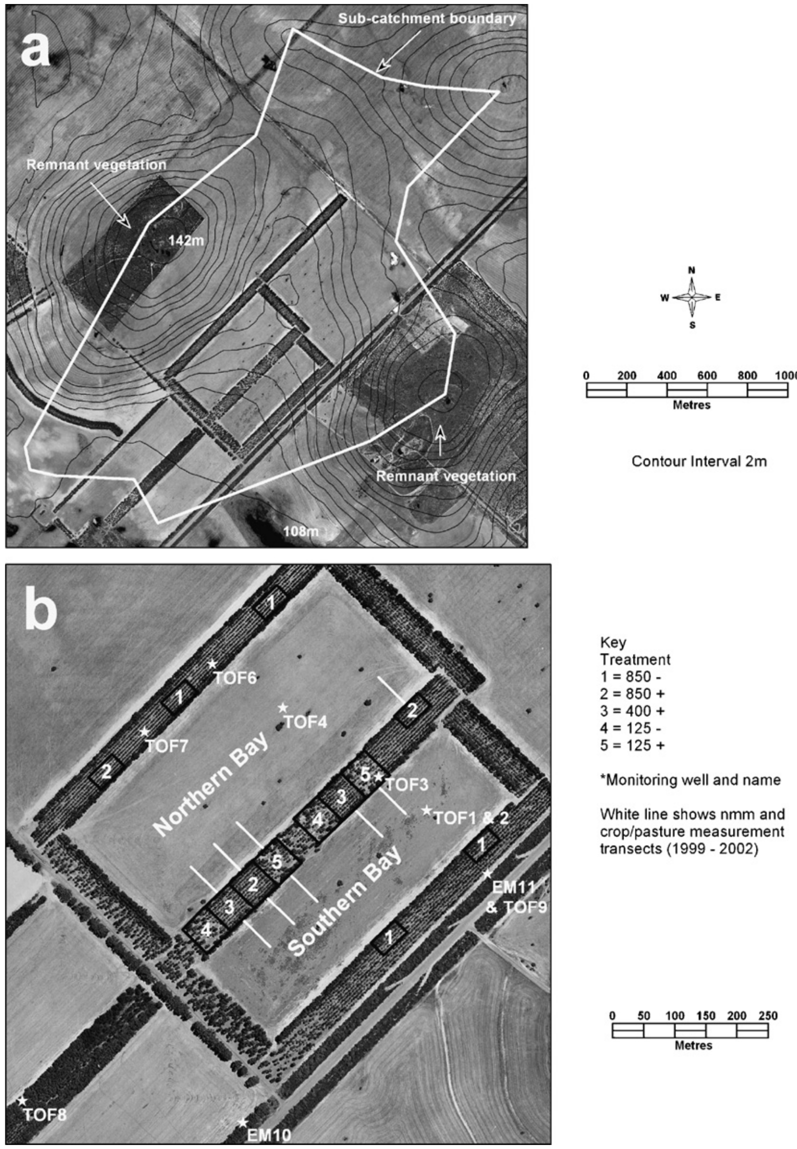

Fig. 2. Plan of sub-catchment showing (a) topographic contours, catchment divide and location of tree-belts and remnant vegetation and (b) location of treatment plots where the tree-belt had received additional fertiliser and was unthinned (800 stems per ha (SPH)) or had been thinned to 400 SPH or 125 SPH or was unfertilised and unthinned (800 SPH) or thinned to 125 SPH (treatments 800+, 400+, 125+, 800− and 125−, respectively). Measurement transects for crop and pasture growth and soil water content as measured by neutron moisture meter (nmm) are shown as white lines and location of groundwater wells with a white star.

2.3. Windspeed

Windspeed was measured 50 m upwind (open) and 12 m (one multiple of tree height (*H*)) downwind of treatments 800+, 400+ and 125+ between 28 June 1999 and 23 August 1999. Measurements were made using Unidata™ cup anemometers mounted 2 m above the ground, sensors were monitored every 5 s and hourly averages recorded using Unidata PDL data loggers™. The effectiveness of the windbreaks was assessed by calculating the ratio of downwind windspeed at 1*H* to open windspeed. Only data for open winds stronger than 2 m/s with a direction normal ($\pm 10^{\circ}$) to the windbreak were used.

2.4. Tree growth

Tree growth was assessed in June or July each year from 1999 to 2003 and in March 2006. Tree height and stem diameter over bark at breast height (1.3 m) (DBH) were used to estimate stem volume by assuming the stem was conical in shape. Measurement plots were six tree rows wide, i.e. from the outermost tree row to the middle of the tree-belt, and 40 m long (measured along the tree rows) for the 125+, 125− and 400+ treatments and 30 m long for the 800+ and 800− treatments, with four replicates of each treatment. The volume of wood in the tree stems was calculated for the inner four tree rows, i.e. growth for a block planting of trees, and for the entire belt including the outer tree rows, i.e. the actual standing volume at the site. Twelve inner trees immediately adjacent to TOF8 were also measured once in 2003.

2.5. Tree water use

Tree water use was estimated between March 2000 and January 2003. Sap flow was determined using the compensation method to determine sap velocity (Swanson and Whitfield, 1981; Barrett et al., 1995; Morris et al., 1998) and the weighted average technique of Hatton et al. (1990) to determine sap flow. Heat pulse velocity was measured using Greenspan Loggers and SF300a probe sets. Four probes were installed on a single inner tree in one replicate of the 800+, 400+ and 125+ treatments, with probes installed at breast height on the northern, southern, eastern and western sides of each stem. Each probe was installed at a different depth into the sapwood of the tree. Sap velocity was measured and logged every 30 min. Probes were reinstalled in the same tree on a 2–3-month interval. New trees were selected and the interval between reinstalling probes was reduced to 6–8 weeks beginning in late 2001. An additional probe and sensor set was installed in an outer tree in the 800+ treatment between February 2001 and March 2002, this was moved to an inner tree between March 2002 and January 2003.

The volume fractions of sapwood and water were 0.31 and 0.62, respectively, as calculated by Archimedes' principle (Anon., 1996). The time at which flow was considered to be effectively zero was determined using the cut-branch method (Anon., 1996). The width of the wound around the probes was measured through the transverse plane (Barrett et al., 1995). An 8, and two 3-year-old trees were felled 2 months and 10 days, respectively, after installing probes and sections taken through the sapwood. The mean wound width in these trees was 0.46 mm on each side of the hole giving a total wound width of 2.93 mm.

Sap velocity was estimated when no data were collected. For the 125+ (2–22/3/2000 and 16/1/2001–22/3/2001) and 400+ (2–22/3/2000, 30/8/2000–8/10/2000 and 16/1/2001–22/3/2001) treatments, the relationship with the sap velocity of the 800+ treatment on the days immediately before and after the period of missing data was used. For the 800+ treatment (2–22/3/2000, 30/8/2000–8/10/2000 and 16/1/2001–22/3/2001) sap velocity of the 400+ treatment was used. In each case, the linear regressions explained 81–92% of the variability in sap velocity between treatments.

Over the course of the experiment, sapwood area was determined for 12, 10 and 11 trees in the 800+, 400+ and 125+ treatments, respectively. The width of the heartwood, sapwood and cambium was determined by taking four cores from each tree stem using a 5 mm diameter increment corer. Heartwood was indicated by the presence of tyloses in the vessels and an acid indication when tested by pH indicator Dimethyl yellow. These data were used to determine the relationship between DBH and sapwood area (sapwood area = $0.2357\text{DBH}^{2.1896}$, $r^2 = 0.95$). This relationship was used with the tree diameter data collected to determine tree growth, to estimate the total sapwood area in each treatment.

The sap flow velocity system overestimated transpiration by 4% when tested using the 'cut tree method' (Anon., 1996). To determine the variability of sap velocity, five trees in the 800+ treatment (four inner and one outer) were measured over 6 weeks in August–September 2001 and 8 weeks in January–March 2002. The sap velocities of individual trees averaged over the spring and summer periods were within $\pm 12\%$ and $\pm 9\%$, respectively, of the mean value for all five trees. For inner trees, there was no correlation between sap velocity and sapwood area (tree size). However, sap velocity of the tree in the outer row was 1.5 times greater than for inner trees. This was also the case for the outer tree measured between February 2001 and March 2002.

The water use of all of the inner trees in a particular treatment was estimated by multiplying the total sapwood area of the inner trees by the sap velocity of the measured tree. To estimate the water use of the entire tree-belt, the sap velocity of the measured outer tree in the 800+ treatment (26/1/2001–19/3/2002) was multiplied by total sapwood area of the outer rows of treatments 400+ and 800+. For the periods 3/3/2000–25/1/2001 and 20/3/2002–31/12/2002, the sap velocity of the measured inner tree was multiplied by 1.5 to estimate the sap velocity of the outer trees in the 800+ and 400+ treatments. For the 125+ treatment, all of the trees were considered 'edge' trees and no correction factor was applied to sap velocity for the outer trees.

2.6. Soil water content

Soil water content was determined using a Campbell Pacific Nuclear™ neutron moisture meter during the growing season in 1999 and 2000, and throughout the year in 2001 and 2002. In 1999, PVC access tubes were installed in transects running perpendicular to the central tree-belt in three replicates of the 125+, 400+ and 800+ treatments (Fig. 2). The access tubes were installed to a depth of 3.5 m in the second row of the tree-belt and 12, 24 and 48 m from the tree-belts. Calibration equations for each soil horizon were determined in the field to a depth of 1.7 m using wet and dry soil profiles (Greacen, 1981). Count ratio explained 96, 98 and 81% of the variability in volumetric soil water content at depths of 0–0.2, 0.2–0.4 and >0.4 m, respectively.

2.7. Crop and pasture productivity

In 1995, wheat yield was measured at 5 m intervals along a northwest–southeast oriented transect running across the centre of the northern bay. In 1997, wheat yield was measured along transects perpendicular to each of the tree-belts in the northern bay (i.e. they had SE, SW, NW and NE aspects). Measurements were made at 0.5, 1, 1.5, 2, 2.5, 3, 3.5 and 4H from each tree-belt and were replicated 3 times for each aspect. Wheat, lupins, lucerne pasture and lucerne pasture were measured in both the northern and southern bays from 1999 through to 2002, respectively. Measurements were made at 0.5, 1, 1.5, 2, 2.5, 3, 4 and 5H adjacent to the same three replicates of the 125+, 400+ and 800+ treatments at which groundwater measurements were made (Fig. 2).

Wheat and lupin grain yield was determined by harvesting 1.6 m wide by 25 m long plots running parallel to the tree-belts at each measurement distance. Lucerne pasture was established between the tree-belts in 2001 and was measured in December 2001 immediately prior to being grazed by sheep. In 2002, the standing pasture biomass was measured at regular intervals throughout the growing season using the visual assessment method of Campbell and Arnold (1973). These assessments did not account for grazing between measurement dates.

To facilitate comparisons across years, crop and pasture yield were expressed relative to yield 3–5H from the tree-belts. Crop and pasture production more than 3H from the trees was considered to be unaffected by tree competition. This assumption was based on the measured extent of competition next to trees at other sites and the extent of tree roots at this site (Sudmeyer et al., 2002b, 2004).

2.8. Groundwater monitoring network

Two mineral exploration holes (EM10 and EM11) were drilled at the site in 1988, using a reverse circulatory air core rig. These were subsequently cased and groundwater depth and salinity monitored quarterly. The depth drilled and other details of each well are shown in Table 6. To determine the impact of the tree-belts on groundwater depths, a further eight groundwater monitoring wells (TOF1–9) were installed along a transect crossing the site, and perpendicular to the groundwater flow direction, in 1993 using a solid stem auger rig (Fig. 2). Each well at the site was cased with 40 mm diameter, class 9 PVC with 2 m of slotting over the lower section screened with 2–3 mm gravel, the remaining annulus was back filled with drill cuttings and plugged with cement just below the surface. Regolith samples from the drill holes were analysed to determine salt content using electrical conductivity (EC 1:5 at 25 °C) and chloride (Cl^-) titration. Groundwater levels in the wells were monitored quarterly between 1994 and 2003 and once in 2006.

2.9. Statistical analysis

Tree growth on the two sides of the central tree-belt for all treatments was tested using a *T*-test. Differences in tree growth between treatments were assessed using analysis of variance, with two replicates for each measurement (average of values on each side of central tree line, or adjacent plots in the 800− treatment). Topographic height was used as a covariate. The effect of tree density and distance from the trees on soil water content was also assessed using analysis of variance with the topographic height of each measurement transect as a covariate. All analyses were carried out using GenStat Edition 8 (© Lawes Agricultural Trust, Rothamsted Experimental Station, Hempstead, Hert, UK).

Groundwater depth data were analysed using HARTT (Hydrograph Analysis—Rainfall and Time Trend) to determine trends in groundwater depth and to separate the effects of atypical rainfall events from the underlying time trend (Ferdowsian et al., 2001).

3. Results

3.1. Windspeed

Windspeed at 1*H* was reduced by 60, 14 and 1% in the lee of tree-belts with densities of 800, 400 and 125 SPH, respectively.

3.2. Tree growth

The basal area and stem volume of trees in the outer rows of the tree-belts were significantly greater compared to trees in inner rows ($P < 0.05$), differences in growth between the two sides of the central tree-belt were not significant (data not presented). In the 800 SPH treatments, basal area and stem volume of the two outer rows was greater than the combined basal area (Fig. 3) or stem volume of the inner 10 rows. However, if the 15–20 m wide competition zone next to the tree-belts where agricultural production was reduced is included in the area occupied by the belt, then the outer tree rows grew at a similar rate (expressed on an area basis) as the inner rows (Fig. 4).

Thirteen-year-old inner trees grew at a mean rate of 4.3–4.9 m^3/ha/yr in the 800− and 800+ treatments (respectively), in contrast unthinned 10-year-old inner trees near TOF8 grew at 37 m^3/ha/yr.

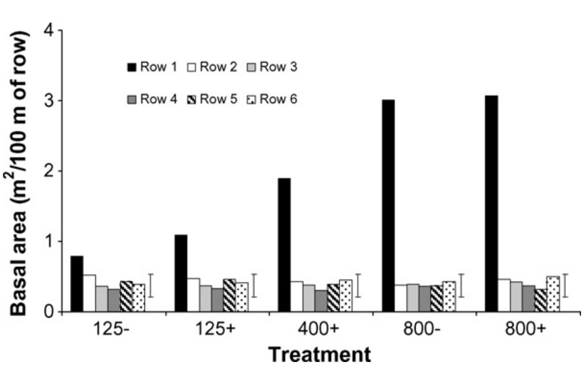

Fig. 3. Total basal area of trees growing along 100 m of row in 12-row ***E. globulus*** belts with various thinning and fertiliser treatments in 2003. Row 1 is the outer row and row 6 is the innermost. Values are for fertilised plots with tree densities of 800, 400 and 125 stems per hectare (SPH) (treatments 800+, 400+ and 125+, respectively) or unfertilised with tree densities of 800 and 125 SPH (treatments 800− and 125−, respectively). Bars show least significant differences (***P*** < 0.05) for row by treatment interactions.

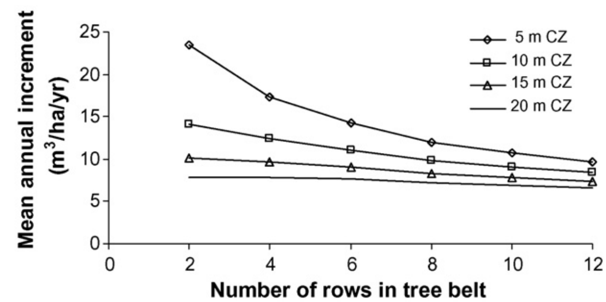

Fig. 4. Mean annual increment of 13-year-old ***E. globulus*** belts with 2–12 tree rows. The area occupied by the belts has been calculated including a competition zone (CZ) on either side of the belt ranging from 5 to 20 m wide.

Table 1
Stem volume in 1999 and 2006 of 12 row *E. globulus* tree-belt or inner rows only (block planting)

Year	Belt/block	Stem volume (m^3/ha)					
		800+	800−	400+	125+	125−	LSD
1999	Inner trees	19a	20a	15ab	7b	7b	9
	Tree-belt#	35a	40a	24ab	11b	10b	14
2006	Inner trees	63	56	63	56	58	17
	Tree-belt#	136a	121a	118a	79b	79b	38

Values are for fertilised plots with tree densities of 800, 400 and 125 stems per hectare (SPH) (800+, 400+ and 125+, respectively) or unfertilised with tree densities of 800 and 125 SPH (800− and 125−, respectively). Values in the same row followed by a different letter are significantly different at $P < 0.05$. Difference in volume significant at $P = 0.841$ for inner trees and $P = 0.057$ for entire tree-belt. Least significant differences (LSD) at $P < 0.05$ are given.
Calculated for area of belt and 5 m wide competition zone.

Thinning significantly reduced the basal area and stem volume of the outer rows as nearly all of the trees removed were large, but had less effect on inner rows as most of the larger trees were retained (Fig. 3). Consequently in 1999, thinning significantly reduced the stem volume of the entire tree-belt and inner rows of the 125 SPH treatments but not the 400+ treatment compared to the 800 SPH treatments (Table 1). By 2006, differences in stem volume among treatments were still significant for the entire tree-belt but not for inner rows (Table 1).

Over the period 1999–2006, all treatments showed similar increases in the stem volume for both the entire tree-belt and inner trees (Table 2). This was achieved by trees in the 125 SPH

Table 2
Increase in diameter at breast height (DBH) and stem volume between 1999 and 2006 of 12 row *E. globulus* belt or inner rows only (block planting)

	Treatment					
	800+	800−	400+	125+	125−	LSD
Inner trees						
DBH (mm)	52a	47a	78a	175b	181b	51
Stem volume (m^3/ha)	44	36	48	49	51	14
Entire tree-belt#						
DBH (mm)	68a	61a	111a	195b	201b	49
Stem volume (m^3/ha)	101	82	93	70	68	31

Values are for fertilised plots with tree densities of 800, 400 and 125 SPH (800+, 400+ and 125+, respectively) or unfertilised plots with tree densities of 800 and 125 SPH (800− and 125−, respectively). Values in the same row followed by a different letter are significantly different at $P < 0.05$. Least significant differences (LSD) at $P < 0.05$ are given.
Calculated for area of belt and 5 m wide competition zone.

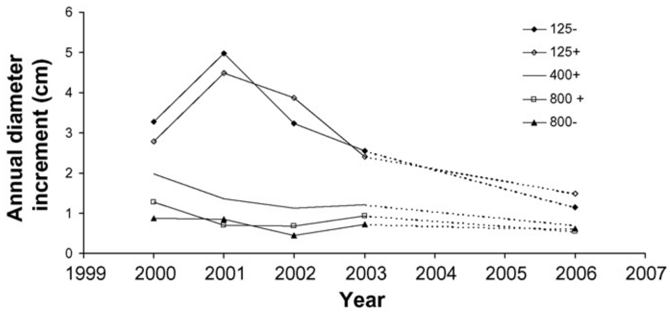

Fig. 5. Annual diameter increment (at breast height, over bark) of inner rows of ***E. globulus*** belts. The value for 2006 is the mean of growth over the period 2003–2006. Values are for fertilised plots with tree densities of 800, 400 and 125 stems per hectare (SPH) (treatments 800+, 400+ and 125+, respectively) or unfertilised with tree densities of 800 and 125 SPH (treatments 800− and 125−, respectively).

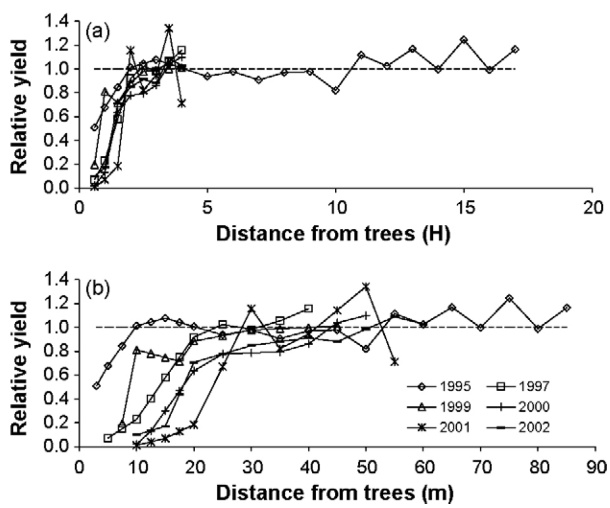

Fig. 6. Grain (1995–2000) or pasture yield (2001 and 2002) at various distances from unthinned ***E. globulus*** tree-belts (800 stems per ha, treatments 800+ and 800−) expressed relative to yield at 3–5 times the tree height (***H***) from the trees, plotted as a function of (a) ***H*** and (b) distance in metres.

treatments producing significantly greater diameter growth than trees in the 800 and 400 SPH treatments (Table 2). Most of the greater diameter growth occurred in the 3 years immediately after thinning, by 5–7 years after thinning the diameter growth of thinned and unthinned treatments was similar (Fig. 5).

The addition of fertiliser did not significantly increase tree growth in the 800 or 125 SPH treatments (Table 2).

3.3. Crop and pasture growth

There was no increase in crop yield in the most protected part of the bay (0–10*H*) in 1995 (Fig. 6). Within 1.5*H*, unthinned tree-belts (800 SPH) suppressed crop or pasture growth by more than 10% (relative to yield at 3–5*H*) in 1995 (2 years after planting) and within 3*H* by 2002 (9 years after planting) (Fig. 6a). While the width of the competition zone was relatively constant when expressed as a multiple of tree height (1.5–3*H*), in absolute terms it expanded from 7.5 to 35 m over this period (Fig. 6b). There was a strong correlation between the density of tree roots in the top 0.5 m of the soil profile and crop and pasture yield in the competition zone, though reductions in yield extended about 0.5*H* beyond the measured lateral extent of tree roots (relative yield = $-0.066 + 1.061 \times 0.996577^{\text{root density}}$, $R^2 = 0.96$, $P < 0.001$, tree root data from Sudmeyer et al., 2004).

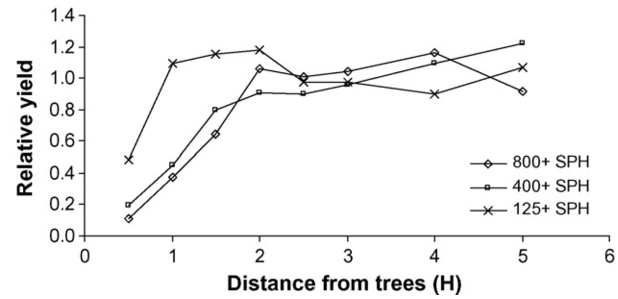

Fig. 7. Average agricultural yield adjacent to tree-belt for 4 years after thinning trees from 800 to 400 or 125 stems per ha (SPH) (treatments 800+, 400+ and 125+, respectively). Yields expressed relative to average yield at 3–5 times the height of the trees (***H***) from the tree-belt.

Table 3
Tree water use over the period 3 March 2000 to 31 December 2002 as estimated from sap velocity measurements

Area of over which water use estimated	Total water use (mm)		
	125 SPH	400 SPH	800 SPH
Inner trees only	858	926	1041
Tree-belt with 35 m wide competition zone	500	964	1417

Total rainfall over this period was 1496 mm.

Thinning tree-belts to 125 SPH increased average agricultural yields for at least 4 years after thinning. Average yield within 3*H* of tree-belt with 125 SPH was 98% of yield at 3–5*H*, compared to 70% for tree-belt with 800 or 400 SPH (Fig. 7).

3.4. Tree water use

For the purposes of estimating water use, the area occupied by the belt was taken to include the adjacent agricultural land on either side of the tree-belt into which tree roots extended and crop and pasture yields were reduced. Tree roots extended 2*H* from the tree stems, this was 26 m in 2000 increasing to 30.5 m in 2003. Accordingly, the water use of the unthinned belt (800 SPH) was similar to rainfall over the area of the belt and root zone, however, water use of the inner trees was less than rainfall (Table 3). For the entire tree-belt, the larger trees at the edge of the belt dominated water use in the 800+ treatment as the sapwood area of outer tree rows was 1.6 times greater than the total sapwood area of the inner eight tree rows and sap velocity of outer trees was 1.5 times greater than for inner trees. Consequently thinning had a greater effect on the water use of the whole tree-belt compared to inner trees only.

The water use of inner trees was less in the 125+ and 400+ treatments compared to the 800+ treatment for 1 year after thinning but similar for all treatments in the second and third years after thinning (Fig. 8). Tree water use was less than potential evaporation for all treatments (Fig. 8).

3.5. Soil water content

Soil water content (SWC) was greatest in September 2000 (Fig. 9) following above-average rainfall in summer through to early winter. Subsequently, there was a general trend for SWC maxima to decline as annual rainfall declined from 659 mm in 1999 to 454 mm in 2002. The maximum storage capacity of the top 2 m of the profile was about 200 mm/m (September 2000) with 90 mm/m plant available; estimated as the difference between the wettest profile and driest profile (November 2002) 48 m from the trees.

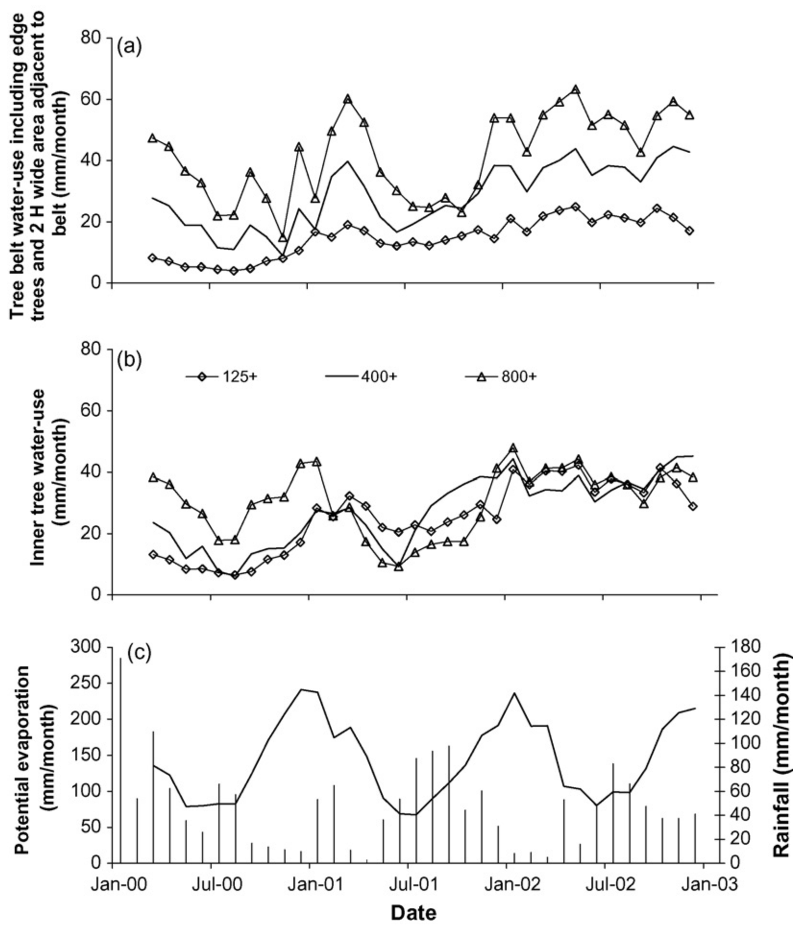

Fig. 8. Estimated monthly water use of ***E. globulus*** that have received additional fertiliser and with densities of 125, 400, and 800 SPH (treatments 125+, 400+ and 800+, respectively) in: (a) 12-row belts including the 2*H* wide competition zone next to belt, (b) inner trees of belt, i.e. water use of block planting and (c) potential evaporation (solid line) and rainfall (bars). Rainfall and evaporation data accessed from Patched Point Dataset, maintained by the Queensland Department of Natural Resources and Mines.

When measurement began in July 1999, differences in SWC to 3.75 m depth were non-significant for treatment by distance interactions or among treatment means (Table 4). However, across all treatments, mean SWC was less under the trees compared to 12, 24 or 48 m from the tree-belt. This difference was primarily due to drier soil between 2.0 and 3.5 m depth under the trees. Mean SWC to 2.0 or 0.5 m depth under the trees was not significantly different from mean SWC values outside the tree-belt (data not presented).

Changes in SWC to 3.75 m depth between July 1999 and January 2003 were not significant when treatment by distance interactions were compared or mean values for each treatment were compared (data not presented). However, across all treatments, mean SWC increased under the trees and decreased 12, 24 and 48 m from the trees (Table 5). Again these differences were largely due to SWC between 2 and 3.5 m depth increasing more under the tree-belt compared to at 12, 24 or 48 m from the tree-belt. Changes in mean SWC to 2.0 or 0.5 m depth under the trees were not significant compared to values outside the tree-belt.

The increase in SWC below 2 m depth in the part of the trial site where SWC was measured was largely due to rising groundwater from in situ recharge to the watertable by rainfall. After July 2000, rising groundwater brought the soil below 2.5 m to field capacity under the southwestern half of the tree-belt (data not presented). It is not possible to attribute the greater increase in SWC under the trees compared to outside the tee-belt to the establishment of lucerne pasture in 2001. Rising groundwater and declining annual rainfall over the period 1999–2002 confounded assessment of the effect of lucerne establishment, with the trend for SWC to increase over time under the trees and decrease 24 and 48 m from the trees evident prior to April 2001 (Table 5).

3.6. Regolith salt content

Chloride content in the regolith ranged from 100 mg/kg in the sands to 500 mg/kg in the deeper sandy clays. The electrical conductivity ranged from 0.2 dS/m in the sands to 3.2 dS/m in the sandy clays.

3.7. Groundwater

In 1994, groundwater depth ranged between 1.5 m (TOF8) below ground level and 7.9 m (TOF4) (Table 6). By 2006, depths ranged from 2.7 m at the topographically lowest point (EM10) to 4.4 m on the mid-slope (TOF4), with groundwater in TOF8 falling below the base of the well casing in 1998 (Fig. 10). The groundwater salinity in the main aquifer was brackish (2700–4100 mg/L) (Table 6), with salinity increasing with depth (Fig. 11b). The groundwater salinity in the isolated perched aquifer was fresh (490 mg/L). Groundwater horizontal gradients were low, ranging from 0.2% (TOF4–9) to 0.6% (EM11 and EM10).

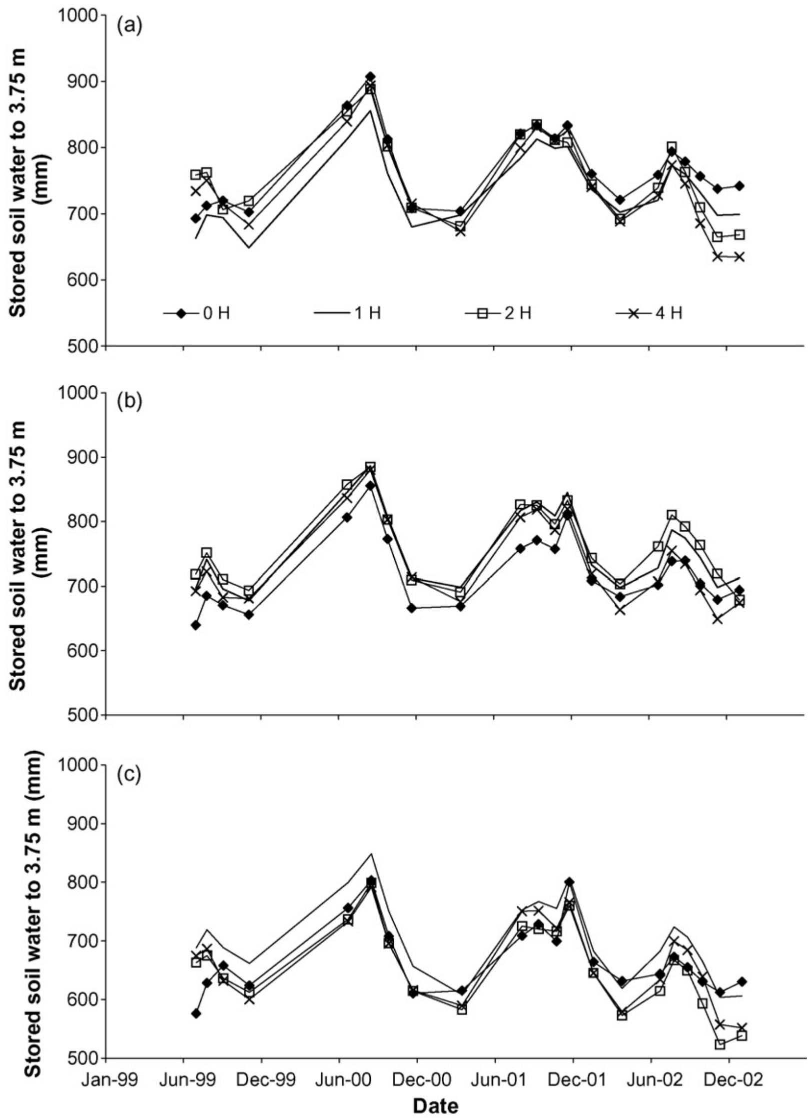

Fig. 9. Soil water storage to 3.75 m within the tree-belt and 1, 2, 4*H* (1*H* = 12 m) from tree-belt with 800 SPH (a), and thinned to 400 (b) and 125 SPH (c).

Groundwater in all of the monitoring wells that intercepted groundwater, except TOF8, rose at average rates between 0.1 and 0.3 m/yr (Table 6). Steeper rises than the long-term average trends in groundwater levels are evident in the groundwater hydrographs during the above average rainfall years of 1989, 1992, 1999, 2000, 2001 and 2003 (Fig. 11a), indicating that most groundwater recharge occurred episodically during and after years of above-average rainfall. The only indication of trees influencing the groundwater depth was in well TOF8 located in the perched freshwater aquifer, where the groundwater fell at a rate of 0.1 m/yr (Fig. 11a).

Table 4
Stored soil water to 3.75 m on 29/7/1999, within and at various distances from tree-belts which had received additional fertiliser and had densities of 800, 400 and 125 SPH (treatments 800+, 400+ and 125+, respectively)

Treatment	Stored soil water (mm) at various distances from tree-belt				
	Within belt	12 m	24 m	48 m	All distances
800+	702	671	769	734	721
400+	622	679	701	675	669
125+	585	697	672	683	659
All treatments	636a	682b	713b	700b	

Least significant differences ($P < 0.05$) were 82, 38 and 73 mm for treatment by distance, distance only or treatment only interactions, respectively. Values in the same row followed by a different letter are significantly different ($P < 0.05$).

Table 5
Change in soil water content (SWC) to 3.75, 2.0 and 0.5 m depth between 29/7/1999 and 10/1/2003 and to 3.75 m depth between 3/4/2001 and 10/1/2003 at various distances from tree-belts

Depth (m)	Period	Change in soil water (mm) at various distances from tree-belts				LSD	*P*
		Within belt	12 m	24 m	48 m		
3.5	July 1999–January 2003	53a	−10b	−85c	−80c	40	<0.001
2.0		−92	−115	−118	−127	28	0.101
0.5		−44	−42	−44	−45	18	0.577
3.5	April 2001–January 2003	26a	4ab	−23b	−26b	37	0.026

Values are means for treatments 800+, 400+ and 125+, positive values indicate an increase in SWC, and negative values a decrease. Values in the same row followed by a different letter are significantly different ($P < 0.05$). Least significant differences (LSD) at $P < 0.05$ are given.

Table 6
Depth of drilling and well casing, groundwater depth at start and end of monitoring period, total dissolved solids (TDS) in 2006, groundwater depth trends (positive values upward, negative values downward) and *T*-tests for calculated groundwater trends

Well ID	Depth drilled (m)	Casing depth (m)	Groundwater depth (m)		TDS (mg/L)	Groundwater depth trend (m/yr)	*P*
			20/01/1994	10/10/2006			
EM10	44.0	6.5	5.0[a]	2.7	2700	0.1	<0.001
EM11	36.0	15.5	10.8[a]	5.3	4100	0.3	0.007
TOF1	45.0	30.5	7.1	4.2	6800	0.3	<0.001
TOF2	7.7	7.3	6.9	4.4	3100	0.3	0.001
TOF3	10.0	8.9	7.3	4.5	3300	0.3	0.002
TOF4	10.0	9.4	7.9	4.4	2900	0.3	0.013
TOF5	21.0	Not cased	–	–	–	–	–
TOF6	5.5	5.1	Dry	Dry	–	–	–
TOF7	6.8	5.8	Dry	Dry	–	–	–
TOF8	3.5	3.2	1.5	Dry	490[b]	−0.1	0.003
TOF9	8.0	7.2	Dry	5.4	3300	0.1	0.203

[a] 08/06/1988.
[b] 20/01/1994.

4. Discussion

The *E. globulus* agroforestry system at this site was not successful in achieving the intended goals of providing a commercially viable pulpwood crop within 10 years, halting groundwater rise or improving agricultural production through the provision of shelter. The first goal was not met because *E. globulus* at this site grew at only 25% of the rate forecast by the plantation industry in the region. The second goal was not met because *E. globulus* was unable to utilize brackish groundwater at the site. The failure to meet the third goal was due to a more general problem of agroforestry systems in the medium and low rainfall areas of Western Australia—that of agricultural losses due to tree/crop competition exceeding any gains from microclimate improvement (Sudmeyer et al., 2002b; Oliver et al., 2005). Each of these goals and outcomes are discussed in detail below.

Stirzaker et al. (1999) suggested that tree-belts with access to groundwater could be spaced at 400 m intervals on deep sands to balance recharge and discharge at a paddock scale. However, water use by the inner trees at this site was only 60–70% of rainfall, suggesting they made little use of groundwater. While interception losses, evaporation from the soil surface and water use by annual plants would have added to measured transpiration from the tree-belts (White et al., 2002; Benyon et al., 2006), it is unlikely that total evapotranspiration would have exceeded rainfall in the centre of the belts or under block plantings with similar soil and groundwater. While the tree-belts directly occupied 10% of the catchment, the lateral spread of outer tree roots and consequent greater sapwood area and sap velocity of outer compared to inner trees meant recharge was effectively eliminated over 20% of the catchment. It should be noted that Taylor et al. (2001) reported very similar ratios of inner to outer tree water use for *E. globulus* growing in belts; i.e. the sap velocity of outer trees was 1.5–1.6 times that of inner trees, which they attributed to outer trees having increased access to soil water and possibly enhanced advection of dry air. Despite this, groundwater data from this and other sites (George et al., 1999; Stirzaker et al., 1999) shows that without trees directly using groundwater, eliminating recharge from 20% of a catchment will generally not halt groundwater rise.

Increasing groundwater salinity with depth and low saturated hydraulic conductivities and gradients restricting groundwater flow, suggest that rainfall was directly recharging the aquifer in situ causing groundwater levels to rise. While *E. globulus* have been shown to use groundwater if it has low salinity, is shallow and is in a transmissive aquifer (Benyon et al., 2006), the small response in tree growth to additional nutrients at this site and annual transpiration rates that were less than annual rainfall, suggests that access to fresh water may have limited growth over most of the site. Where groundwater was fresh and shallow (TOF8) trees grew at 7 times the rate measured elsewhere at the site and groundwater showed a falling trend. It should be stressed that this area of greater growth was very limited, with tree growth rapidly

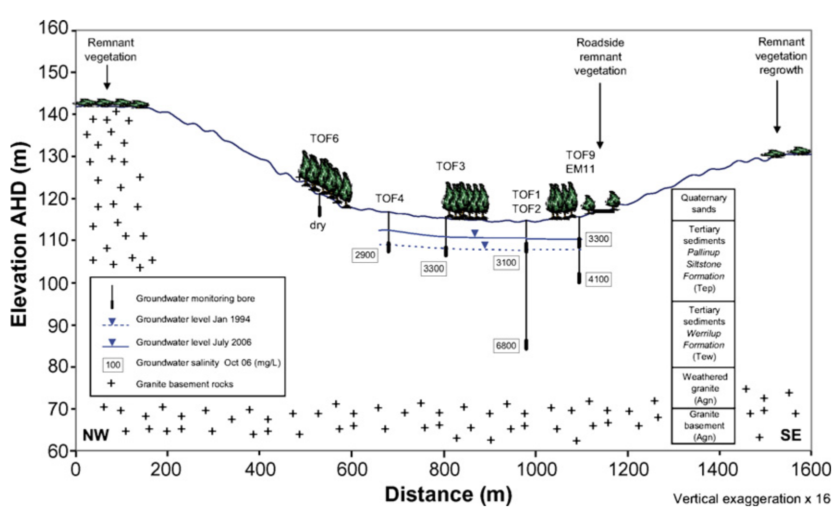

Fig. 10. Hydrological cross-section illustrating bore transect, groundwater depth (m) (January 1994 and July 2006) and salinity (TDS, mg/L).

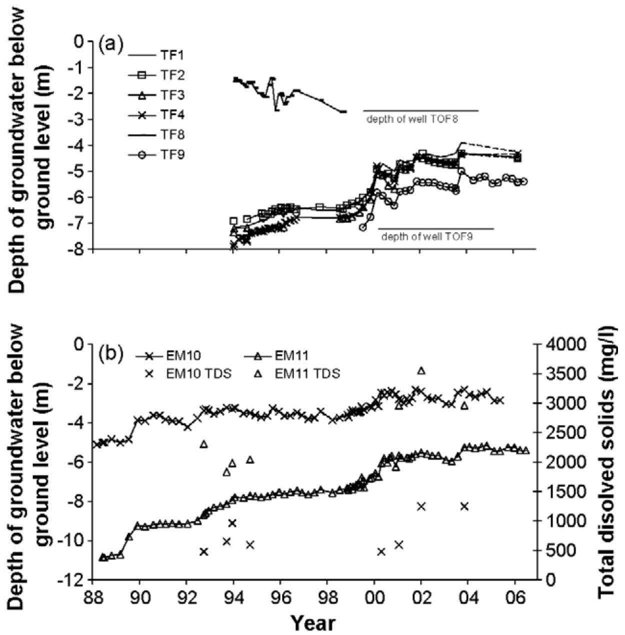

Fig. 11. Depth of groundwater below ground level and salinity (TDS) in wells (a) TOF1–4, 8 and 9 and (b) EM10 (lower slope/depression) and EM11 (mid-slope).

declining to <5 m^3/ha/yr as the depth of sandy topsoil decreased to <0.5 m deep to the southwest of TOF8 or the accessible groundwater became more saline to the north. These data, and other studies, suggest that *E. globulus* was unable to make use of the brackish groundwater (2700–4100 mg/L), at the site due to the species' comparatively low salinity tolerance (Greenwood et al., 1985; Hookey et al., 1987 (cited in Raper, 1998); Marcar et al., 2003). Rooting depth, or clay subsoil alone should not have prevented access to groundwater across the site as rising groundwater intersected sands previously dried by tree roots. Measurements at other sites on the south coast have shown *E. globulus* accessing soil water to 4 m, three of those into Pallinup siltstones similar to those found at this site (Sudmeyer and Goodreid, 2007), and at least 5 m into clays at a site near Albany (Sanford et al., 2003).

The inability of *E. globulus* to utilize marginal to brackish groundwater has implications in the broader context of the Esperance sandplain, where there is relatively little opportunity for *E. globulus* to be planted with access to fresh groundwater and trees will have to grow at commercial rates solely with access to stored soil water and annual rainfall. Growth rates at this site are similar to those measured at other sites in the region (Harper et al., 1999; Sudmeyer unpublished data), but are less than 1996 best estimates of growth in the region (9–20 m^3/ha/yr, Burnage, 1996) or current estimates by a plantation timber company with 50 000 ha of *E. globulus* plantations in the region (21 m^3/ha/yr, Integrated Tree Cropping; www.treecrop.com.au accessed September 2006).

Evaluating the economics of forestry enterprises in the Esperance region is somewhat speculative as commercial tree harvesting has not yet commenced. That said, the growth rates of unthinned trees in this study (5 m^3/ha/yr for inner trees, i.e. a block planting) mean that economic returns from pulpwood production would be less than from agriculture, and would probably not breakeven (i.e. costs exceed returns). An independent economic analysis of various forestry options for the region commissioned by the South East Forest Foundation (SEFF), suggested that landholders who bore all of the costs associated with an *E. globulus* pulpwood enterprise could expect an Annual Equivalent Return (AER) of \$24/ha/yr from trees growing at 12 m^3/ha/yr (Jones, personal communication, 2006). This compares with an estimated AER from agriculture on deep sandy soil of \$30/ha/yr for a sheep enterprise or \$121/ha/yr for a continuous cropping enterprise.

As discussed previously, there is some advantage to growing trees in belts in terms of the increased water use of the edge trees, Albertson et al. (2000) also discussed the possibility of varying the number of tree rows in *E. globulus* belts (i.e. the ratio of inner to outer tree rows) to manipulate productivity. While this would appear to be beneficial at this site where the outer tree rows grew at 6 times the rate of inner rows, there was no benefit when the area occupied by the tree roots adjacent to the belts was considered in an estimate of biological or economic productivity, particularly in light of the competition between trees and agriculture for resources. When the 15–20 m wide area next to the belts where agricultural production was less than breakeven (Sudmeyer and Flugge, 2005) is included in the area occupied by the belt, then the outer tree rows grew at a similar rate (expressed on an area basis) as the inner rows. Indeed, given that crop and pasture losses greater than 10% extended 35 m from the trees 7–9 years after planting, and that the outer trees were heavily branched and would require additional management to facilitate harvesting, there appears to be no economic advantage in growing pulpwood in belts rather than blocks at this site.

Soil water content is typically less under and adjacent to trees belts compared to under agricultural rotations (Hall et al., 2002; Robinson et al., 2002; Sanford et al., 2003; Unkovich et al., 2003). At this site in 1999 and early 2000, SWC below 2 m was less under the trees compared to outside the tree-belt but similar in the top 2 m of the soil profile. Rising groundwater brought the soil to field capacity below 2.5 m over the lower half of the site after 2000, so this trend of drier soil under the trees was no longer evident. The relative uniformity of soil water content in the top 2 m of the profile is attributed to the limited capacity of the sands to store plant available water (90 mm/m), combined with high infiltration rates. Consequently, a limited amount of rainfall was stored then rapidly depleted, with trees or crops reducing soil water content in the top 2 m of the profile to similar levels. Highly permeable sands with low plant available water content where rainfall rapidly moved through the profile to become unavailable as it entered the brackish groundwater aquifer may also explain the relatively low ratio of transpiration/rainfall for inner trees at the site.

While soil water contents in the top 2 m of the profile were similar at 12, 24 and 48 m, trees and crop or pasture competed for water within 3*H* and crop and pasture yield was negatively correlated to the density of unthinned tree roots. It was not possible to reduce tree/crop competition by severing lateral tree roots (root pruning) in the deep sands (Sudmeyer et al., 2002a), as root pruning merely encouraged the development of deeper lateral tree roots (Sudmeyer et al., 2004). In most years it is unlikely that microclimate changes due to shelter from the tree-belts would have improved crop and pasture growth sufficiently to offset these losses in the competition zone. The lack of positive crop response to shelter in 1995 accords with other studies in Western Australia showing that the principle benefit of windbreaks is ameliorating wind erosion, and subsequent "sand blasting" (Jones and Sudmeyer, 2002; Sudmeyer et al., 2002b; Oliver et al., 2005).

While the sandy soils of the site are highly erodible, soil erosion was not a problem in nearby well-managed paddocks with similar soils and no windbreaks. In fact, the tree-belts created something of a soil erosion problem as tree competition resulted in an area of bare soil next to the trees (visible as white strips alongside the trees in Fig. 2). Soil deflation was evident on the northwest sides of the tree-belts by 2006. Thinning the trees to 125 SPH reduced tree competition so allowing vegetation to stabilize the soil next to the belts despite the thinned belts reduced ability to reduce wind-speed.

Besides reducing wind erosion alongside the trees, thinning trees to 125 SPH, offered other benefits. Firstly, it greatly reduced tree/crop competition for at least 4 years, moving the economic breakeven point for crops and pasture 7 m closer to the trees and increasing agricultural returns by $ 208/yr/km of tree-belt (both sides) (Sudmeyer and Flugge, 2005). Secondly, it increased the growth rate of inner trees, so trees at 125 SPH had an average DBH of 178 mm compared to 49 mm for trees at 800 SPH. The disadvantages of thinning were reduced water use by the entire tree-belt, which may have allowed additional recharge, reduced shelter from the tree-belt and the cost of thinning.

Clearly the cost of thinning and pruning the remaining trees would have to be offset by increased economic returns from the trees. If the increased growth rate could be maintained over the full harvest cycle (presumably by repeated thinning) it would approach the expected growth rate of *Pinus pinaster* (8–9 m^3/ha/yr) in a sawlog regime currently being promoted by the Forest Products Commission (FPC) (Jones, personal communication, 2006). Further work is required to determine if repeated thinning can maintain *E. globulus* growth rates, and so to produce economically viable timber products, and determine if tree/crop competition increases over time as the basal area of the remaining trees increases. Alternatively, other tree species may be more suited to these deep sands and achieve better economic and hydrological outcomes for the landholder than growing *E. globulus*.

5. Conclusions

This study has shown that *E. globulus* is not a suitable agroforestry tree species for medium rainfall sites with deep sands and brackish groundwater. While *E. globulus* can reduce or eliminate recharge on the area directly occupied by the trees and lateral roots, *E. globulus*' inability to use slightly brackish groundwater means it cannot be used in strip plantings to halt rising or reduce groundwater levels. This combined with sub-economic growth rates and competition losses alongside the tree-belts makes *E. globulus* unsuited to agroforestry applications in this environment. Further work is required to establish if other tree species which can make use of slightly brackish groundwater are better suited to this application.

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