



Silviculture and water use of short-rotation mallee eucalypts

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Foreword

One desirable option for the remediation of salinity in dryland agricultural areas is the development of commercial tree crops to utilise excess water not used by annual crops and pastures. Tree crops able to resprout after repeated harvests carried out at short intervals may be economically and practically desirable. Oil mallee is potentially one such crop for the low-rainfall areas of the Western Australia wheatbelt.

Little is known of the silvicultural practices (cultivation techniques) for tree crops on short rotations in dry areas, or the amounts and sources of water used by trees belts in such environments. The trade offs encountered between leaving trees to grow uncut or harvesting for coppice regeneration are not well understood.

This study details experiments aimed at building a basis for harvest regimes to be designed. It also generated detailed water budgets for coppiced and uncut tree belt at an alley-farmed oil mallee trial site at Kalannie, Western Australia, over a two year period.

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This report, a new addition to RIRDC's diverse range of over 900 research publications, forms part of our Agroforestry and Farm Forestry R&D program, which aims to integrate sustainable and productive agroforestry within Australian farming systems.

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Executive Summary

The use of annual crops and pastures in cleared wheatbelt landscapes in Western Australia leads to excessive recharge of groundwater and hence rising water tables and secondary salinity. Current interest in deep-rooted woody perennials now centres around the development of commercial tree crops as an economical strategy for removing excess water from agricultural landscapes.

‘Mallees’ are multi-stemmed eucalypts possessing a lignotuber and are capable of being ‘coppiced’ i.e. harvested to ground level followed by regeneration of shoots. ‘Oil mallees’ are species mostly native to wheatbelt areas that have been identified to possess high leaf oil contents and have potential for the simultaneous production of activated carbon and eucalyptus oil and for residues to be used as biofuels. Based on general experience from the eucalyptus oil industry in eastern Australia, mallees should be capable of enduring repeated harvests. To date, approximately 23 million trees have been established by landholders in Western Australia keen to see the industry reach commercial status.

Limited information is available on management for productivity (‘silviculture’) of eucalypts in low rainfall (wheatbelt) areas and information is very scarce for trees managed as short-rotation coppice crops. The literature suggests that many trees species cut on very short rotations (1–3 years) lose vigour and incur high mortality. Here, a detailed case study of a single site near Kalannie, Western Australia, was investigated to begin building a knowledge base for the silviculture of short-rotation coppice crops in low-rainfall areas.

Our experiments into management for productivity confirmed that mallees are well adapted to resprout after repeated harvests through the development of large lignotubers and adequate starch reserves. After cutting, fine roots died back and root biomass remained stagnant for 1.5–2.5 years depending on season of cutting.

Spring cuts resulted in faster shoot regeneration and a more rapid return to growth for large roots than summer-cut trees. Mallees should not be cut on 1–2 year cycles since yields will be reduced due slow growth in the first year after cutting and the vigour of rootstocks will decrease, in turn affecting yields in future harvest cycles. Coppice rotations of approximately 3–4 years would probably give near-optimal yields and allow rootstocks to remain vigorous.

Relatively little is known of the effectiveness of trees in block plantings or in belts across paddocks (‘alley farming’) in reducing recharge to groundwater bodies. Recently, several case studies have been reported, mainly in higher rainfall areas. The present study adds to this new body of knowledge by assessing coppicing trees alongside uncut saplings at a particularly low-rainfall site as is typical of much of the eastern wheatbelt of Western Australia.

For the study of water use by tree belts, detailed graphical water budgets were constructed for a zone beginning in the middle of a tree belt and extending out into the adjacent alley. Water budgets were constructed for both saplings and coppiced trees at three sites within the paddock, one of which featured a fresh perched aquifer encountered at 4–5 m depth. All sites had a deep yellow sand upper horizon with a silicified hardpan at 5–7 m, below which extended a considerable depth of kaolin clay. The clay horizon had a moderately saline regional groundwater at 8–14 m depth.

Despite relatively small leaf areas on coppice shoots over the two years following decapitation, high leaf transpiration rates resulted in coppices using water at rates far in excess of that falling as rain on the tree belt area. Water budgets showed that 20 % of the study paddock would have been needed as 0–2 year coppices in 5 m wide twin-row belts in order to maintain hydrological balance over the study period. Maximum water use occurred where uncut trees were accessing a fresh perched aquifer, but where this was not present water budgets still showed transpiration of uncut trees occurring at

rates equivalent to 3–4 times rainfall incident on the tree belt canopy. With 5–7 yea old uncut trees, only 10 % of the paddock surface would have been required under 5 m wide tree belts to restore hydrological balance, but competition losses in adjacent pasture would have been greater.

Since deep yellow sands of the low-rainfall wheatbelt are considered to contribute disproportionately high recharge under crops and pastures, generally have only moderately saline groundwaters accessible by oil mallee roots and are considered marginal for traditional agricultural production, such areas would appear well suited to the production of woody biomass with deep rooted coppicing species such as *E. kochii*.

1. Introduction

Plantation forestry has traditionally not been practised in the semi-arid wheatbelt areas of Western Australia due to limitations to tree growth by low rainfall (300–450 mm per annum) and the better economic returns likely to be generated by conventional wheat and sheep farming in the region. However, the use of annual crops and pastures leads to excessive recharge of groundwater and hence rising water tables and secondary salinity (Peck and Williamson, 1987; George *et al.*, 1997). Current interest in deep-rooted woody and herbaceous perennials in the area now centres around the possible development of commercial tree crops in conjunction with crops and pastures as a plant-based strategy for removing excess water from agricultural landscapes (State Salinity Council, 2000).

Forestry undertaken in unirrigated semi-arid regions of the world often involves non-timber products such as paper pulp, fodder, reconstituted wood, biofuels and charcoal production, and may also involve future trading in environmental services such as salinity- and carbon-credits. Furthermore, where long-maturing timber is not required, reduced harvest intervals involved in short-rotation forestry practices are more likely to generate better economic returns, whether by harvesting of whole young (e.g. < 10 year-old) trees or use of species capable of coppicing repeatedly after cutting.

Growing trees in belts ('alley farming') through pastures has potential to overcome water limitations since trees can access water either directly from adjacent cleared areas under crops/pastures, or from perched aquifers or groundwater bodies that may be being recharged by water draining below crops and pastures in the alleys between tree belts.

Mallee eucalypts are characterised by multiple woody stems arising from an underground lignotuber (Kerr, 1925; James, 1984). The latter houses a large store of potential bud-forming sites carrying the capacity for rapid regeneration of a canopy after shoots are lost through fire or harvest. Mallees occur naturally across broad regions of southern Australia in areas of dry- to extra-dry-Mediterranean type climate with annual rainfall also in the range 300–450 mm. Mallees are very long-lived, with some species (e.g. the Meelup mallee, *Eucalyptus phylacis*) reaching ages possibly exceeding 6000 years (Rosetto *et al.*, 1999). They grow slowly (Walker *et al.*, 1989) and show excellent adaptations in relation to low nutrient soils, long periods of drought and seasonal high temperatures. These features include extensive, deeply-penetrating root systems (Nulsen *et al.*, 1986), a sclerophyllous habit and foliage exhibiting tight stomatal control and ability to withstand low leaf water potentials (Jones *et al.*, 1981; Myers and Neales, 1984).

'Oil mallees' have seen much research and development effort over recent years since they possess potential for commercially-driven revegetation in dry wheatbelt areas. Species that possess high levels of desirable oil compounds in their leaves have been identified (Brooker *et al.*, 1988; Eastham *et al.*, 1993; Wildy *et al.*, 2000a), most being native to parts of the Western Australian wheatbelt. Based on general experience from the eucalyptus oil industry in eastern Australia, it is envisaged that mallee eucalypts could be harvested on short-rotations as coppice crops for the production of eucalyptus oil for sale into existing pharmaceutical markets and possibly into solvent markets. More recently, shoot biomass from mallees was deemed suitable for simultaneous production of bio-electricity and activated carbon in addition to eucalyptus oil (Enecon Pty Ltd, 2001). To date, approximately 20 million trees have been established by land holders keen to see the industry reach commercial status.

Research has focussed on economic evaluation, harvesting machinery, processing technology, qualities and uses of leaf oils (Tjandra, 1986; Wildy *et al.*, 2000a), and site and species selection (Eastham *et al.*, 1993; Wildy *et al.*, 2000b). Both of the latter studies found *Eucalyptus kochii* subsp. *plenissima* and the closely related *E. horistes* to perform well on yellow sands in the central wheatbelt. This study looks to determine how to ensure continual high production of the shoot

biomass feedstock for the emerging industry, the importance of different water sources in sustaining this productivity and their effectiveness in controlling groundwater rise and thus further salinity.

In this report, two major sections of research have been presented: silviculture (Section 3) and water use (Section 4). Each contain a separate detailed methods subsection, but each of the many subsections relating to specific experiments and findings are written to contain a very brief description of aims and methods as well as results and brief interpretation of the implications. Sections 3 and 4 also contain a general summary dealing with general implications. A final short discussion (Section 5) is presented summarising the findings and bringing together management issues. Technical terms are listed in the Glossary (Section 6).

Three papers have been published in or submitted to scientific journals from the work shown in this report (Wildy and Pate, 2002; Wildy *et al.*, submitted-b; Wildy *et al.*, submitted-a).

2. Objectives

Limited information is available on silviculture of eucalypts as short-rotation coppicing tree crops, and data are even more scarce for mallees in dry areas. This study aims to address this deficiency using a detailed case study of a single site near Kalannie, Western Australia to provide a solid base for the management of short-rotation coppice crops in low rainfall areas.

Until recently, little was known of the effectiveness of trees in block plantings or in belts across paddocks ('alley farming') in reducing recharge to groundwater bodies. Lately, several case studies have been reported mainly in higher rainfall areas of the wheatbelt (e.g. Lefroy *et al.*, 2001; Knight *et al.*, 2002; Ward *et al.*, 2002; White *et al.*, 2002). The present study adds to this new body of knowledge by assessing coppicing trees alongside uncut saplings at a particularly low-rainfall site as is typical of much of the eastern wheatbelt of Western Australia.

3. Harvest regimes and productivity

3.1 Aims

Silvicultural practices, including timing of first cut, the interval between cuts, and the season of cutting, have a large affect on the long-term yields obtainable from a stand of mallees. This section shows data collected at the Kalannie trial site for *E. kochii* for 4- to 7-year-old saplings in comparison with trees coppiced in two contrasting seasons: late summer (February) and spring (October). Coppiced trees were either left to resprout after the initial harvest or were cut repeatedly at three month intervals. The data include time series of shoot and root biomass, starch concentrations, and the development of lignotubers with age.

This section aims to assess the impact of the timing of first and subsequent cuts, and the season of cutting, on above-ground biomass yield, below-ground growth, and the ability of trees to repeatedly resprout into the future.

3.2 Methods

3.2.1 Principal site

At the principal trial site (30°09'S, 117°12'E) near Kalannie, in the central wheatbelt of Western Australia, alley plantings of *E. kochii* subsp. *plenissima* had been established as seedlings in July 1994 immediately after ripping and scalping of topsoil to remove weeds. Fertilizer was not applied since the soil was of relatively high fertility through continuous use of fertilized crops of wheat and nitrogen-fixing lupins (*Lupinus* spp.). Each belt of trees consisted of two rows 2 m apart, with an average of 1.8 m spacings between trees within the rows. The average alley width available for crop/pasture between belts of trees was 90 m. Planting density was 2820 trees per hectare in that part of the land surface devoted to trees, or the equivalent of 121 trees/ha across the whole ecosystem at the time of planting. Since only 85 % of seedlings survived the dry year of establishment (238 mm in 1994), the effective density at the time of commencement of the study was reduced to 103 trees/ha. Our measurements were made between February 1999 and October 2001, that is, as trees aged from 4.6 through to 7.2 years.

The extra-dry Mediterranean climate (Beard, 1984) of the Kalannie region of the wheatbelt (Table 1) typically features hot, dry summers (December–February) and cool, wet winters (June–August). The long-term (74-year) annual average rainfall at Kalannie is recorded as 319 mm (Bureau of Meteorology, Australia). However, 1999 was an exceptionally wet year (504 mm falling at the principal study site) and unusually heavy summer rain fell in 1999-2000 and again in 2000-2001 (see Table 3.1). The soil at the principal study site was a gradational yellow sand (Gn 2.21: Northcote, 1979) overlying a siliceous hardpan at varying (1–8 m) depth across the study site.

3.2.2 Development of lignotubers meristematic bud reserves with age

Lignotuber development was studied in February 1999 by random sampling across a range of differently aged (0.6–4.6 year) plantings of as yet uncut saplings selected in the Kalannie area. All sites involved deep yellow sands similar to those at the principal site. Five trees of each age class were excavated, including one set of 4.6 year old trees from the principal study site referred to above. All bark down to cambium level was peeled off the lignotuber, surrounding stem and upper root to expose for counting the closely-spaced groups of pimple-like 'meristematic bud sites' (~1 mm diameter) typically encountered within each swollen region on or in the vicinity of the lignotuber.

3.2.3 Harvest treatments

At the principal study site, a random series of 100 m long quadrats of tree belt were selected and stems of all included trees cut with a chainsaw to 5 cm above ground level. The quadrats designated for cutting were sited within a fully randomised block design comprising 16 quadrats cut in late summer (February), a further 16 cut the following spring (October) of 1999, and a matching set of 16 quadrats of uncut saplings incorporated as controls. Following initial cutting, mortality was only 2.0 % and 0.5 % for trees cut in February and October, respectively.

In each of the 16 coppice quadrats used for the two seasons of cutting, most trees were allowed to regenerate naturally for the duration of the study (C_N treatment, Table 3.2) while two in each quadrat were subjected to additional decapitations on a 3-monthly basis (C_R treatment).

Table 3.1 Monthly rainfall and temperature data for Kalannie, Western Australia. Rainfall data for 1999 to 2001 (recorded at the principal trial site), and mean daily temperatures (the average of data recorded at Kalannie between 1999 and 2001) were both provided by Agriculture WA. The long-term (74-year) average monthly rainfall for Kalannie was supplied by the Bureau of Meteorology, Perth.

	J	F	M	A	M	J	J	A	S	O	N	D
1999 rainfall	25	4	113	11	147	49	40	22	29	18	20	26
2000 rainfall	56	0	156	4	3	15	40	19	17	0	0	11
2001 rainfall	72	22	7	0	24	2	51	18	19	7	11	0
Long-term av. rainfall	14	16	24	24	44	57	50	38	19	14	9	10
Mean max. daily temp.	33	33	29	26	21	18	16	17	21	25	29	34
Mean min. daily temp.	19	19	16	14	9	5	6	5	7	10	13	18

Table 3.2 Experimentation, general treatment codes, sampling frequency and numbers of replicates in the study of coppicing in *Eucalyptus kochii* subsp. *plenissima* at Kalannie, Western Australia. All measurements on decapitated trees were carried out both for plants first cut in February 1999 or in October 1999. Sampling frequency is indicated as 'final' for C_R where a single measurement was made at the end of the experiments (when ~15 % of plants had died, after approximately 12 months). These final measurements were then made on the remaining plants. For all treatments, the number of trees (replicates) sampled at each date is shown in brackets. Note that below-ground starch measurements were made between July 1999 and February 2001 only.

Code	Treatment	Measurements			
		Shoot biomass	Shoot number	Below-ground biomass	Below-ground starch
	Uncut saplings (control)	2- to 5-monthly (42)	-	2- to 5-monthly (10)	2- to 5-monthly (10)
C_N	Decapitated trees No further intervention	2- to 5-monthly (42 × 2 seasons)	3-monthly (16 × 2 seasons)	2- to 5-monthly (10 × 2 seasons)	2- to 5-monthly (10 × 2 seasons)
C_R	Repeated 3-monthly decapitation	3-monthly (32 × 2 seasons)	3-monthly (32 × 2 seasons)	final (10 × 2 seasons)	final (10 × 2 seasons)

3.2.4 Counts of resprouting shoots

Counts of numbers of shoot sprouts (equivalent to the fascicles of Noble, 2001) arising from lignotubers were made on 3-monthly intervals after decapitation (see schedule in Table 3.2). This was carried out non-destructively for C_N plants while for C_R plants, shoots were counted at the time of each 3-monthly decapitation.

3.2.5 Measurement of shoot and root biomass

Shoot biomass of (i) control uncut trees and (ii) trees regenerating naturally from cutting in February or October 1999 (C_N) was measured at ten sampling dates between February 1999 and February 2001 (see Table 3.2). At each sampling date, 42 randomly selected trees of these treatments were cut to 5 cm above ground level and weighed fresh in the field. Subsamples of leaf, twig and larger stems were collected, weighed fresh and then oven-dried to constant weight at 70°C for fresh:dry weight conversions. For C_R trees, shoot biomass produced after initial decapitation was measured at each further 3-monthly decapitation event. Shoots were oven-dried to constant weight at 70°C before weighing.

Below-ground biomass was excavated to assess root and lignotuber biomass using a bobcat which progressively transferred soil plus root material on to a mobile mechanical sifting device. The readily recognisable lignotuber was removed with a chainsaw at the point of root proliferation and weighed fresh. Root biomass was separated visually into lateral (flaking bark, straight) and sinker (non-shedding bark, contorted shape) roots. These were then weighed fresh, fed through a garden chipper, and a small subsample frozen immediately pending oven-drying for fresh:dry weight conversions and starch analysis (see below). A chainsawed section through the lignotuber was also frozen for starch analysis and fresh:dry weight conversions. For control saplings and C_N plants, the average ratio of lignotuber weight:rest-of-shoot weight for each treatment at each root sampling date was used to estimate total shoot biomass (i.e. shoot including lignotuber) of the corresponding 42 trees from a treatment and sampling date (described above).

Root and lignotuber biomass was sampled for control saplings and C_N trees from ten plants per treatment at each sampling date and at two- to five-month intervals during the study period. Root biomass of C_R plants was sampled for ten plants from each treatment at one final sampling date twelve months after the initial decapitation of the plants (February or October 2000) (Table 3.2).

The regularly employed root sampling procedure involved a 'standard' excavation 1 m deep and extending 1 m out from the tree stump into the untreed alley and similarly out to the midpoint between neighbouring trees (Fig. 3.1). To estimate the proportions of lateral and sinker root biomass not likely to be recovered by the 'standard' procedure, selected trees were subjected to a series of more 'extensive' excavations executed in 1 m stages to 4 m depth and 5 m out into alleys (see Fig. 3.1). These were carried out on three trees (including both uncut and coppicing plants) at 5 sampling occasions throughout the study period. Such excavations were found to harvest virtually all lateral root biomass and all but the lowermost parts of deeply penetrating sinker roots. By following the attenuation in recovery of sinker root biomass for each successive 1 m level of excavation it was estimated that unrecovered root biomass extending below the 4 m depth limit would be equivalent to only 4–8 % of the total root biomass of trees of the age class under study. Comparisons of data from these 'standard' and occasional 'extensive' excavations indicated that the standard (incomplete) excavation would typically recover 80 % of the lateral root biomass and 50 % of that of sinker roots.

Shoot:root dry weight ratios were determined for the excavated C_N coppice and saplings at each sampling date. Throughout the text, the terms 'root' refers to the full extent of the root system, excluding lignotuber biomass, while 'shoot' includes both the aerial canopy removed in a normal harvest procedure (leaf + stem) plus the shoot stump remaining above ground and the lignotuber. Conversely, the term 'below-ground biomass' refers to the calculated full extent of roots + lignotuber (i.e. that remaining after shoot harvest), and 'above-ground biomass' refers to the harvestable portion of stem above the lignotuber.

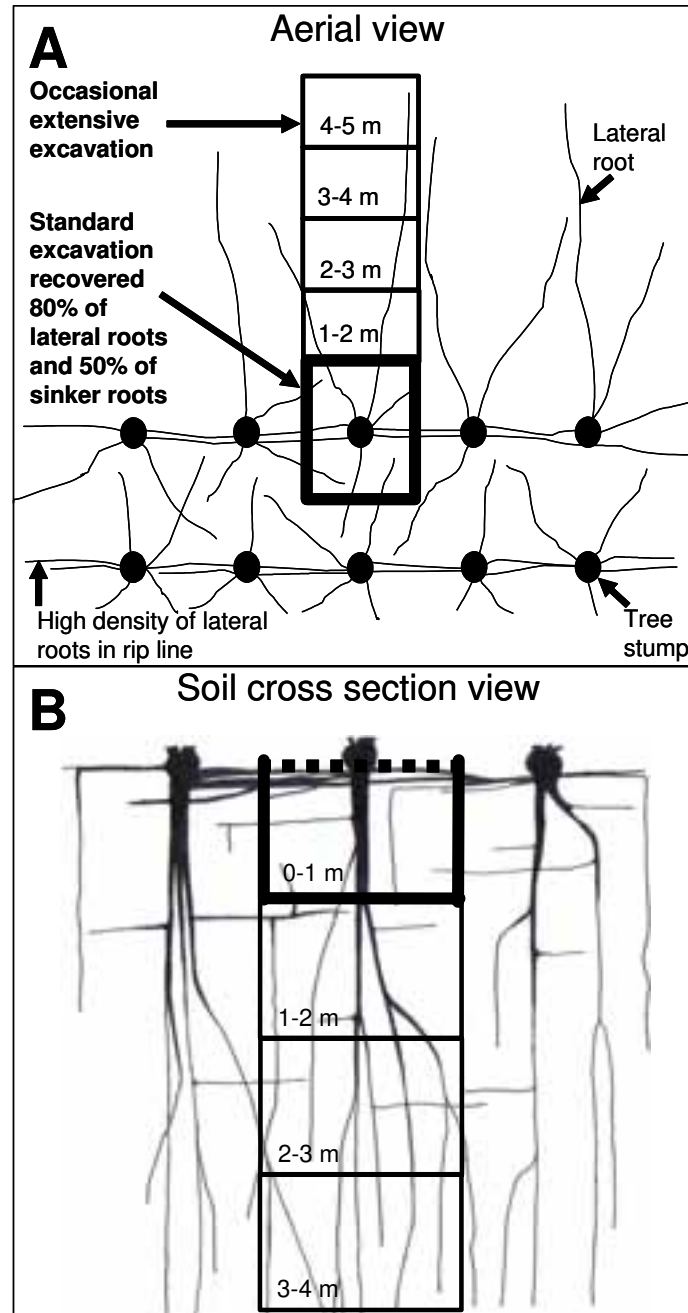


Figure 3.1 Stylized root systems and dimensions of excavations used in sampling root biomass for mallees grown in twin-row belts, as shown by an aerial view (A) and a cross-sectional view through the soil profile (B). The 'standard' excavation (bold lines) was 1 m deep and extended from midpoint between neighbours to 1 m out into the alley. Occasional 'extensive' excavations allowed regular standard excavations to be scaled-up to include all root biomass, which included the estimated 4–8 % of deeply penetrating sinkers that were not recovered in the extensive excavation.

3.2.6 Study of effect of coppicing on secondary growth of roots

An anatomically-based technique for evaluating possible inhibitory effects of cutting on root growth of coppiced (C_N) trees compared to uncut trees was initiated three months after setting up of the summer or spring coppice treatments (May 1999 or January 2000, respectively). It involved non-destructive exposure of one or two major sinker and lateral roots of each of 16 randomly selected

coppicing or uncut trees and removal of a small 0.5 cm² window of bark down to the cambium to expose the outer layer of xylem (sapwood). The portion removed in each case involved less than 12 % of the root circumference and was therefore unlikely to have a major deleterious effect on subsequent secondary growth of the root. Treated roots were re-covered with soil and left for 21 months (until February or October 2001). A 10 cm length of root including the ‘window’ was then collected and transversely sectioned to assess the extent of increase in root diameter underbark in undamaged radial sections of the root to that of the non-growing exposed portion underlying the window. Comparative estimates were thus made of the proportional extents to which secondary growth of roots of coppicing trees had been reduced over the 21 month period relative to that exhibited by uncut trees.

3.2.7 Starch concentrations and total starch reserves of below-ground biomass

For each tree excavated for root biomass between July 1999 and February 2001, starch concentrations were determined separately for lignotubers, lateral roots and sinker roots. Dried subsamples of material of each plant part were finely ground to pass through a final mesh width of 0.5 mm. Starch was extracted from a 0.1 g subsample using the perchloric acid method (Pucher *et al.*, 1948) and then assayed using the phenol method (Dubois *et al.*, 1956; Pate *et al.*, 1990) giving reproducible recoveries of starch, including both amylose and amylopectin. Starch concentrations in roots and lignotubers are given on a weight for weight basis (g starch per g organ dry matter) and are expressed as percentages.

Since determinations of starch in root biomass collected from standard excavations required extrapolations based on more extensive excavations, it was necessary to test whether starch concentrations in outer-lying root biomass differed appreciably from that obtained from more proximally located roots recovered in standard excavations. Three uncut saplings and coppicing C_N trees from both seasons of initial cutting were sampled in this way at July 2000 and February 2001. The resulting data (Table 3.3) showed general trends towards increased concentration of starch in root biomass with distance out along a lateral or down a sinker root (e.g. see Kolb and McCormick, 1991). An appropriate correction factor was therefore applied when scaling up starch contents of both lateral and sinker roots from a standard excavation to provide a more accurate assessment of total starch concentration (and consequently total starch storage) within the entire below-ground biomass of each tree investigated.

Table 3.3 Starch concentrations ($\pm$ standard error) in *Eucalyptus kochii* roots in the ‘standard’ excavation zone (see Fig. 3.2) and in the remainder of roots collected in ‘extensive’ excavations beyond the standard excavation zone.

	Uncut saplings (% of DM*)	February-cut coppice (% of DM)	October-cut coppice (% of DM)
Lateral roots			
in standard excavation	2.1 ($\pm$ 1.0)	1.4 ($\pm$ 0.4)	1.7 ($\pm$ 0.4)
beyond standard excavation	3.8 ($\pm$ 0.9)	2.6 ($\pm$ 0.9)	3.5 ($\pm$ 2.0)
Sinker roots			
in standard excavation	1.6 ($\pm$ 0.7)	1.6 ($\pm$ 0.7)	1.3 ($\pm$ 0.2)
beyond standard excavation	3.8 ($\pm$ 1.6)	1.2 ($\pm$ 0.5)	2.9 ($\pm$ 0.7)

*DM, dry matter

3.3 Above-ground biomass yields

3.3.1 Saplings

Above-ground biomass was calculated on a canopy-area basis. Sixty tonnes of oven-dried harvestable shoot biomass was produced after 7 years per hectare of tree belt as saplings. Shoot biomass of saplings at the Kalannie site increased at near-exponential rates during the period of study (Fig. 3.2).

For example, the increase in above-ground biomass between years 0 and 1 was approximately 1 t DM/ha, while between years 3 and 4 it was 6 t DM/ha and between years 5 and 6 approximately 13 t DM/ha. This increasing rate of increase is a common biological phenomenon for trees and other organisms: as canopies grow larger, they are able to capture more light and thus produce more sugars which in turn allow for even greater rates of new foliage production, causing a snowball effect. Eventually, the rate of increase would slow as the resources necessary to growth such as water or nutrients become scarce. It appeared that this did not occur until after age 7.

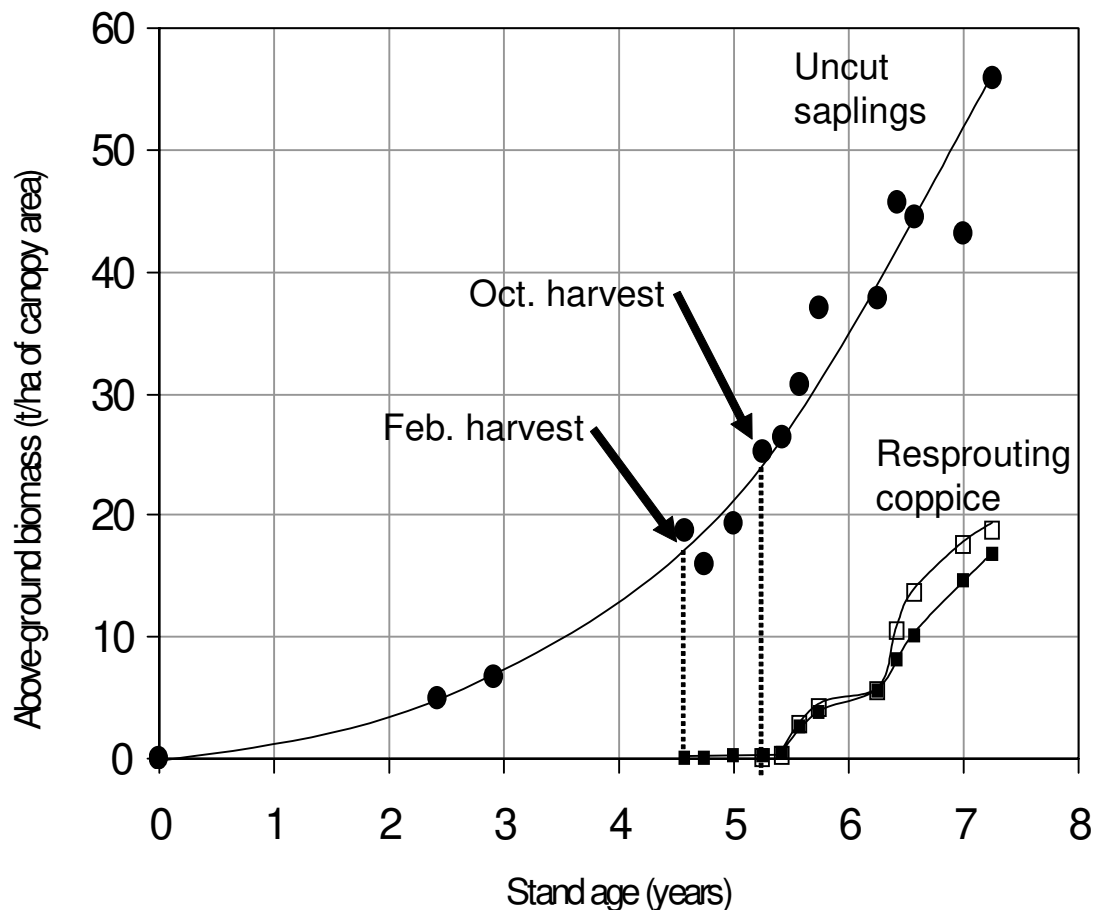


Figure 3.2 Harvestable above-ground biomass (dry matter) for *Eucalyptus kochii* as uncut saplings (circles) or coppice regenerating from a February cut (black squares) or an October cut (open squares) at the Kalannie trial site. Early sapling growth at ~age 3 was from a similar site nearby (data from Wildy et al. 2000b).

3.3.2 Coppiced trees

Trees cut in February 1999 showed little new growth during the following winter. In contrast, trees cut after winter, in October 1999, regenerated rapidly so both sets of coppicing trees showed similar above-ground biomass production in the months following October 1999.

The biomass growth by coppiced trees (Fig. 3.2) was generally low in the first year after cutting (2 t DM/ha for February-cut trees and 6 t DM/ha for October-cut trees), but this was greater than had been shown by seedlings when they were first planted (tree age 0–1 yr, 1 t DM/ha). Above-ground growth of coppiced trees in their first year was far lower than the biomass production that nearby saplings produced in the same time period (13 t DM/ha).

If large, rapidly growing trees are harvested there is thus a ‘penalty year’ while coppiced canopies regenerate slowly compared to the growth that would otherwise been generated by the intact canopy.

However, in the second year after harvest, growth rates were much higher and February-cut coppices produced 7 t DM/ha while October trees produced 10 t DM/ha. The study included a further 8 months of data collected for the earlier-cut February coppice, and this indicated that the relatively fast growth rates of coppice would continue through the third year.

3.3.3 Simulated yields under different harvest regimes

There is evidence to suggest that the rate of biomass accumulation after first harvest is relatively independent of the size or age for a given stand of trees (see section 3.8). For the purposes of the following exercise this is assumed to be the case. Using the measured regrowth rates for coppices over the two years, and further assuming that the biomass increase in the third year after harvest would be equivalent to the second year, a series of scenarios involving different possible harvest regimes could be demonstrated (Table 3.4).

The indication is that the age of first harvest doesn’t have as strong an effect on the overall yield at the end of a 15 year period as the interval between each subsequent harvest. Due to the ‘penalty year’ where coppice regrowth is slow in the first year, rotation lengths of 2 or 3 years are more favourable since the effect of the penalty year is diluted (Table 3.4).

The average annual yield over a period of time is termed the Mean Annual Increment (MAI) and is expressed as tonnes of above-ground dry matter per hectare of tree belt area per year. Table 3.4 suggests that a first cut at age 3 followed by annual cuts would yield a MAI of 3.6 t DM/ha/yr compared to an MAI of 5.8 t DM/ha/yr if there were a lesser number of 3 year rotations. The greatest MAI would theoretically result from a first cut at age 7 followed by 3 year rotations, yielding an MAI of 6.8 t DM/ha/yr.

These figures were calculated using the average figures for coppice regrowth occurring in February and October. If only October cuts were employed, these yields would be 30–40 % higher.

Table 3.4 Demonstration of the effect of harvest regime on yield over a ~15 year period at the Kalannie trial site for *Eucalyptus kochii*. The simulation uses data shown in Fig. 3.2 and assumes coppice regrowth rate is not affected by the size of the trees when first cut (see section 3.8). Note that *E. kochii* is probably not able to survive repeated harvests on 1 year intervals (see section 3.9) so yields would be lower than shown (indicated by *).

First harvest	Future harvests	Calculation	Average yield each year or MAI (t DM*/ha/yr)
at age 1 (1 t DM/ha)	14 × 1 yr interval* (4 t DM/ha at each harvest)	$\frac{1 \text{ t} + (14 \times 4 \text{ t})}{15 \text{ yr}}$	3.8*
	7 × 2 yr interval (12 t DM/ha at each harvest)	$\frac{1 \text{ t} + (7 \times 12 \text{ t})}{15 \text{ yr}}$	5.7
	5 × 3 yr interval (20 t DM/ha at each harvest)	$\frac{1 \text{ t} + (5 \times 20 \text{ t})}{16 \text{ yr}}$	6.3
at age 3 (7 t DM/ha)	12 × 1 yr interval* (4 t DM/ha at each harvest)	$\frac{7 \text{ t} + (12 \times 4 \text{ t})}{15 \text{ yr}}$	3.6*
	6 × 2 yr interval (12 t DM/ha at each harvest)	$\frac{7 \text{ t} + (6 \times 12 \text{ t})}{15 \text{ yr}}$	5.3
	4 × 3 yr interval (20 t DM/ha at each harvest)	$\frac{7 \text{ t} + (4 \times 20 \text{ t})}{15 \text{ yr}}$	5.8
at age 5 (22 t DM/ha)	10 × 1 yr interval* (4 t DM/ha at each harvest)	$\frac{22 \text{ t} + (10 \times 4 \text{ t})}{15 \text{ yr}}$	4.1*
	5 × 2 yr interval (12 t DM/ha at each harvest)	$\frac{22 \text{ t} + (5 \times 12 \text{ t})}{15 \text{ yr}}$	5.5
	3 × 3 yr interval (20 t DM/ha at each harvest)	$\frac{22 \text{ t} + (3 \times 20 \text{ t})}{14 \text{ yr}}$	5.9
at age 7 (48 t DM/ha)	8 × 1 yr interval* (4 t DM/ha at each harvest)	$\frac{48 \text{ t} + (8 \times 4 \text{ t})}{15 \text{ yr}}$	5.3*
	4 × 2 yr interval (12 t DM/ha at each harvest)	$\frac{48 \text{ t} + (4 \times 12 \text{ t})}{15 \text{ yr}}$	6.4
	3 × 3 yr interval (20 t DM/ha at each harvest)	$\frac{48 \text{ t} + (3 \times 20 \text{ t})}{16 \text{ yr}}$	6.8

*DM, dry matter

3.4 The effect of harvest on below-ground growth

3.4.1 Analysis of data

Excavations showed that trees had developed a number of deeply penetrating sinker roots originating directly below the stem and also from shallow lateral roots that radiated out from the stem base along rip lines and out in adjacent alleys (see Fig. 3.1). Most trees also possessed horizontally extending lateral roots that developed from sinker roots at depths down to 2–3 m. Lignotubers were calculated to comprise on average 17 % of total below-ground biomass compared with 41 % for lateral roots and 42 % for sinker roots.

Observations on excavated root systems of all harvested plants showed that large amounts of fine roots (<2 mm) had senesced soon after cutting. There was no increase in root biomass of coppiced trees for 2.5 years after cutting for February-harvested trees and 1.7 years for October-harvested trees (Fig. 3.3).

Trees that were repeatedly cut every three months had lower root biomass than at the time they were first cut. Occasionally, the root systems of these plants had also been attacked by fungi and borer insects. By contrast, root biomass increased three-fold for saplings over the same period (Fig. 3.3).

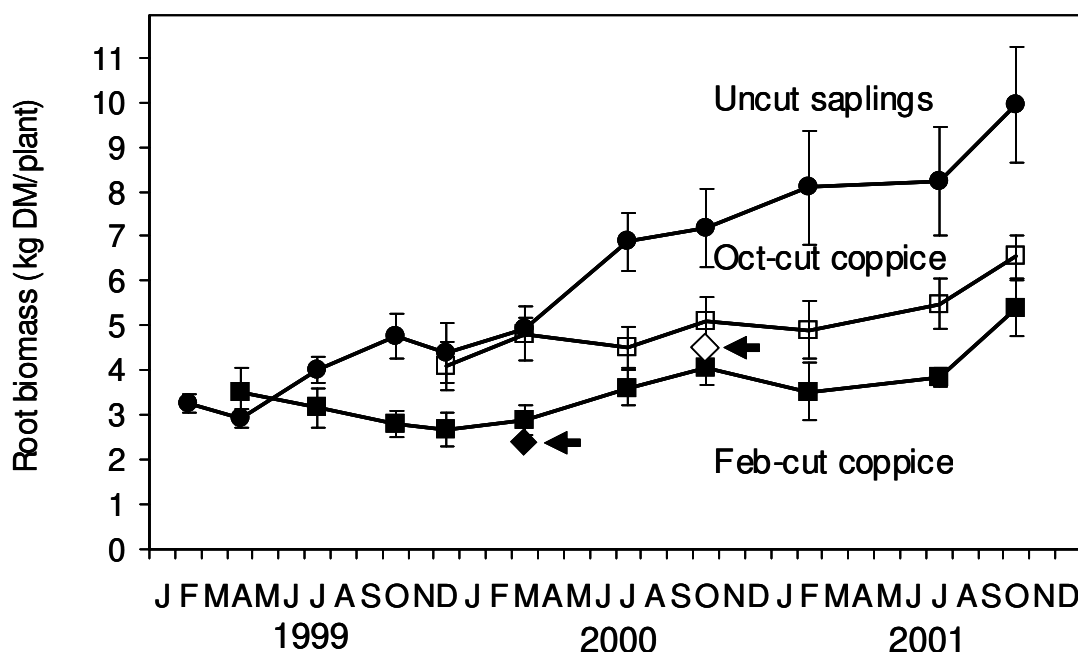


Figure 3.3 Root biomass (dry matter) for *Eucalyptus kochii* growing as uncut saplings (circles) or coppice regenerating from a February cut (black squares) or an October cut (open squares) at the Kalannie trial site. Arrows indicate trees that were repeatedly cutting on a three monthly basis after initial cutting in February 1999 (black diamond) or October 1999 (open diamond). Vertical bars represent ± 1 s.e.

We also measured the rate of thickening of large lateral and sinker roots for a 21 month period after each harvest (February or October) and compared it with the thickening of saplings over the same periods (Table 3.5). While saplings more or less doubled the cross sectional area of their major roots over the period, the cross sectional area of major roots of coppiced trees only increased by 14–30 %. Reductions of root growth following shoot removal are common in the published literature (Kny, 1894; Hodgkinson and Becking, 1977; Schroth and Zech, 1995; Crombie, 1997; Ruess *et al.*, 1998).

Table 3.5 Root thickening in *Eucalyptus kochii* over a 21 month period following a single decapitation in comparison with uncut controls (saplings). Data are expressed as the percentage increase in wood cross-sectional area. Standard errors are shown in brackets.

	Comparison 1		Comparison 2	
	February-cut coppice	Uncut sapling	October-cut coppice	Uncut sapling
Stem	–	88 (± 9)	–	213 (± 36)
Lateral roots	26 (± 10)	86 (± 17)	23 (± 9)	129 (± 23)
Sinker roots	14 (± 8)	74 (± 9)	30 (± 7)	70 (± 17)

The relatively low shoot:root biomass ratios of saplings of 2.5–3.6 (Fig. 3.4) indicate that this species has a relatively large root system in proportion to its shoot (cf. Dickmann and Pregitzer, 1992). Shoot:root ratios of coppiced trees increased continuously but failed to reach the original ratio of uncut saplings.

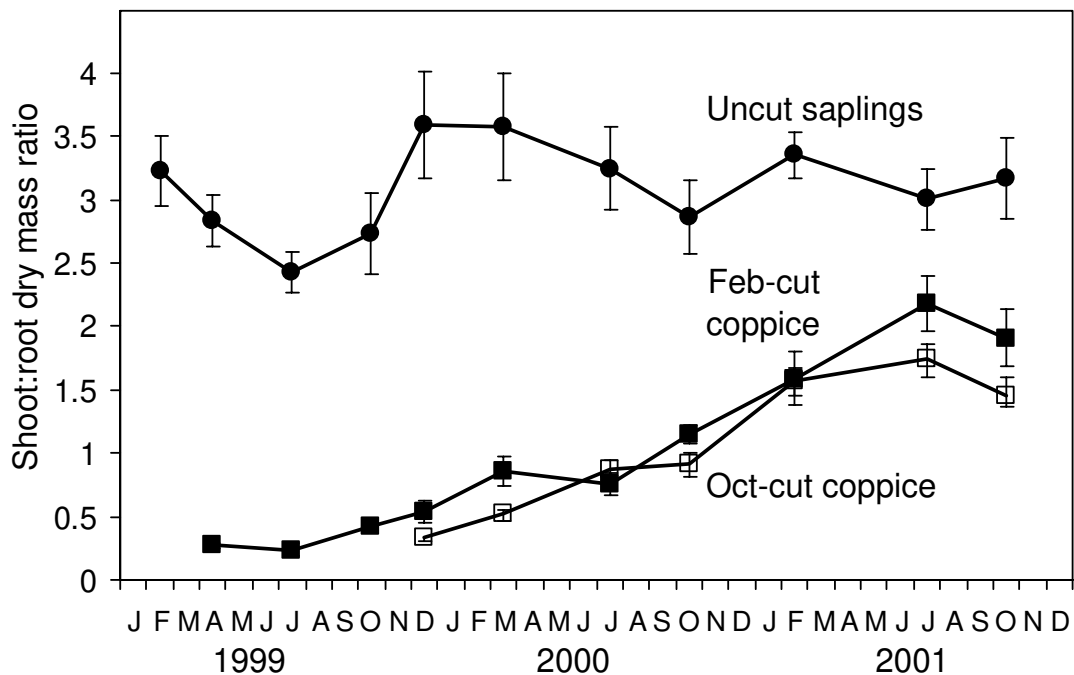


Figure 3.4 Shoot:root dry matter ratios of *Eucalyptus kochii* saplings (circles) or coppice regenerating from harvest in February 1999 (black squares) or October 1999 (open squares) at the Kalannie trial site.

3.4.2 Summary of effects of harvest on below-ground growth

A general scheme for the effect of coppicing on root growth was constructed using the data collected in this study and comparison with data of other published studies (Reidacker, 1973; Hodgkinson and Becking, 1977; Steinbeck and Nwoboshi, 1980; Reis and Kimmins, 1986; Kummerow *et al.*, 1990; Fownes and Anderson, 1991; Dickmann and Pregitzer, 1992; Schroth, 1995; Ruess *et al.*, 1998; Farrar and Jones, 2000). It is thought that *E. kochii* sheds fine root biomass after cutting, but the superstructure of the root system is retained. Soon after reformation of the canopy, fine roots may then start being produced again in balance with the regenerating shoot, but further investment in structural roots or lignotubers remains slow until the functional shoot:root ratio nears restoration.

The lack of new growth of new living tissues on larger roots is a cause of concern in coppiced trees. Individual living cells of tissues of any plant are not designed to last for a long period of time, and are constantly being replaced in properly-functioning organisms. While coppiced trees strive to rebuild their lost canopies, the bulk of new sugars are directed to the shoot and larger structural roots are utilised but do not actively grow until the shoot has been restored to some level.

If coppiced trees are cut repeatedly before secondary roots have the opportunity to grow new tissues (which did not occur to a large extent until after over two years after cutting) then the vigour of the ensuing coppice crop may be compromised by the aging rootstock from which it must regenerate again.

These data suggests that trees should be cut on rotation lengths of not less than 2–3 years. The effect of the season of cutting would also affect the vigour of rootstocks, since a more rapid regeneration from a spring cut would allow greater over all growth rates, both above- and below-ground, than would cutting in late summer just prior to the natural winter dormancy of shoot growth.

3.5 Season of harvest

Trees cut in February (late summer) showed markedly slower rates of recovery than trees cut in October (Fig. 3.2). Two years after the February cut, yield of coppice shoots would have been 10.0 t DM/ha, compared with 18.7 t DM/ha two years after the October cut. The difference was primarily attributable to the February-cut trees showing slow new growth in the autumn and winter immediately following harvest. During this period where the trees lacked vigour, weeds grew up through the small new canopies and insects partly defoliated some.

Noble (1989) has shown annual autumn harvests can debilitate and eventually kill mature mallees whereas mallees repeatedly cut in spring survived well. Milthorpe *et al.* (1994) found that autumn-harvested blue mallee (*E. polybractea*) also suffered high mortality.

The species' natural shoot extension growth phase is in spring and early summer when temperatures are optimal and soil moisture levels are greatest (Specht and Moll, 1983; Wildy *et al.*, 2000a). This usually begins in September–October and continues until January–February but is dependent on soil moisture levels (Fig. 3.5).

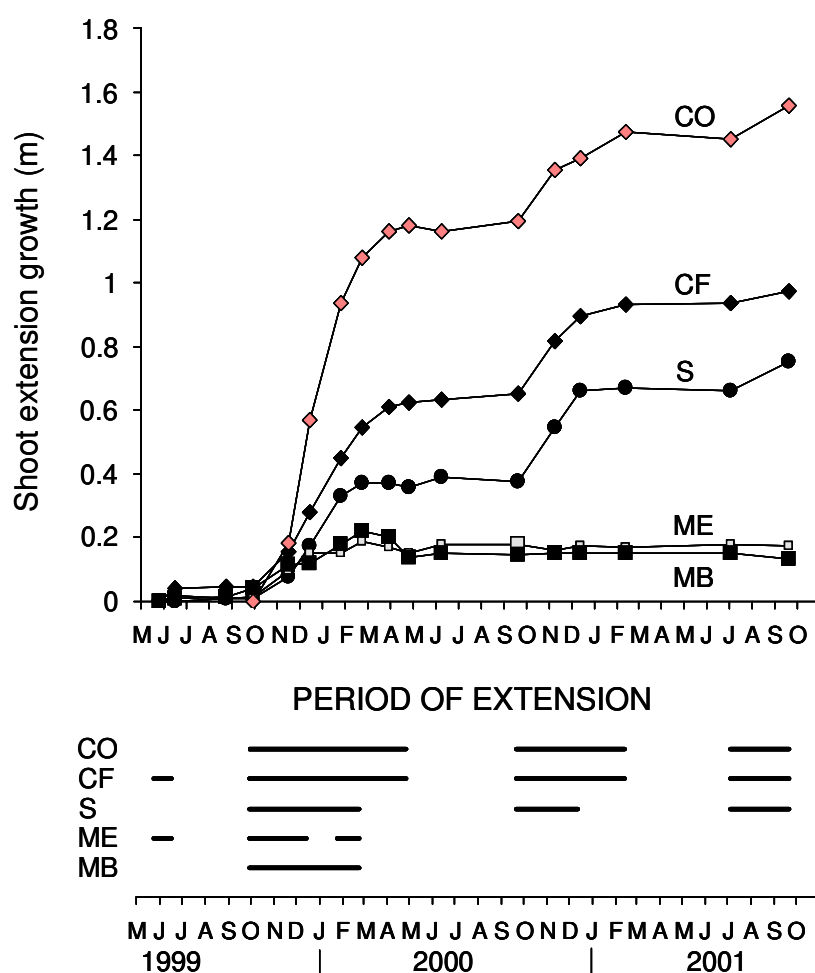


Figure 3.5 Profiles of shoot extension growth of leading shoots of *Eucalyptus kochii* growing as mature trees within remnant bush (MB) or edging cleared agricultural land (ME), or growing in belts through agricultural land as saplings (S) or young coppices cut in February 1999 (CF) or October 1999 (CO).

Cutting trees at the end of this period forces the regeneration of new shoots out of their natural cycle and when conditions are less favourable for shoot growth. Regrowth is slower (Fig 3.2) and rootstocks remain starved of photosynthates for longer (Figure 3.3). In contrast, cutting trees just prior to the natural growth period allows a new functional canopy to take advantage of the optimal growth season (e.g. see Murtagh, 1996).

3.6 Starch reserves and coppice regeneration

Starch is the major carbohydrate reserve material accumulated in woody plants such as *E. kochii* and provides an energy source for growth and respiration when photosynthesis alone is not sufficient e.g. during periods of rapid growth or when coppicing after harvest. We originally expected that starch reserves in below-ground parts of the plant would dictate the ability of the tree to regenerate after cutting and that rapid, repeated cutting would cause a fatal decline in starch reserves.

Starch concentrations of regularly excavated portions of below-ground biomass were significantly higher ($P < 0.001$) in saplings (mean of all starch samples 2.9 % of dry matter) than in coppiced trees regenerating from harvest in either February or October (1.4 % and 1.7 % respectively).

Lignotubers had significantly lower ($P < 0.05$) concentrations of starch (generally less than 1 %) than either lateral or sinker roots (Table 3.6). Combined with the fact that these comprise 17 % of biomass remaining after harvest, lignotubers would only have contributed 5–10 % of starch reserves available to recently cut plants.

Table 3.6 Starch concentrations measured in excavated portions of below-ground organs of uncut and naturally regenerating coppice of *Eucalyptus kochii* at Kalannie, Western Australia. Different letters designate significant differences ($P < 0.05$) between organs across all treatments using Tukey's pairwise comparison.

	Mean of all samples (% of DM*)	Range of all means across harvests (% of DM)
Uncut saplings		
Lignotuber	0.77 c	0.5 - 1.5
Lateral roots	3.59 a	1.7 - 5.4
Sinker roots	4.07 a	1.2 - 6.2
February-cut coppice		
Lignotuber	0.41 c	0.1 - 1.5
Lateral roots	1.81 b	0.9 - 3.9
Sinker roots	1.85 b	0.7 - 3.8
October-cut coppice		
Lignotuber	0.37 c	0.3 - 0.4
Lateral roots	2.21 b	1.2 - 4.6
Sinker roots	2.29 b	1.5 - 3.8

*DM, dry matter

Combining dry weight values for the full extent of below-ground biomass with the above starch concentration data (appropriately corrected for higher starch concentrations in outlying roots as shown in Table 3.3) gave calculated values for mean below-ground starch concentrations in the range of 2–6 % of dry matter for uncut saplings and 1–5 % for regenerating coppice (Fig. 3.6A). Saplings showed peak starch concentrations just prior to the period of main shoot extension growth in spring of 1999 and 2000, followed by a decline in starch content in summer.

Fluctuations in the total below-ground starch reserve pools (Fig. 3.6B) followed similar patterns except that the smaller root biomass of coppiced plants resulted in total starch reserves in below ground parts remaining significantly lower ($P < 0.05$) than those of uncut saplings until February 2001. October-cut trees possessed a significantly greater total below-ground starch store than the February-cut trees ($P = 0.003$) despite starch concentrations not varying significantly between the two (see Fig. 3.6A).

When plants cut repeatedly on a three month cycle were close to death they still possessed starch concentrations of 0.4–1.0 % of dry matter. Though low, these were only marginally below values shown by coppices regenerating after a single cut.

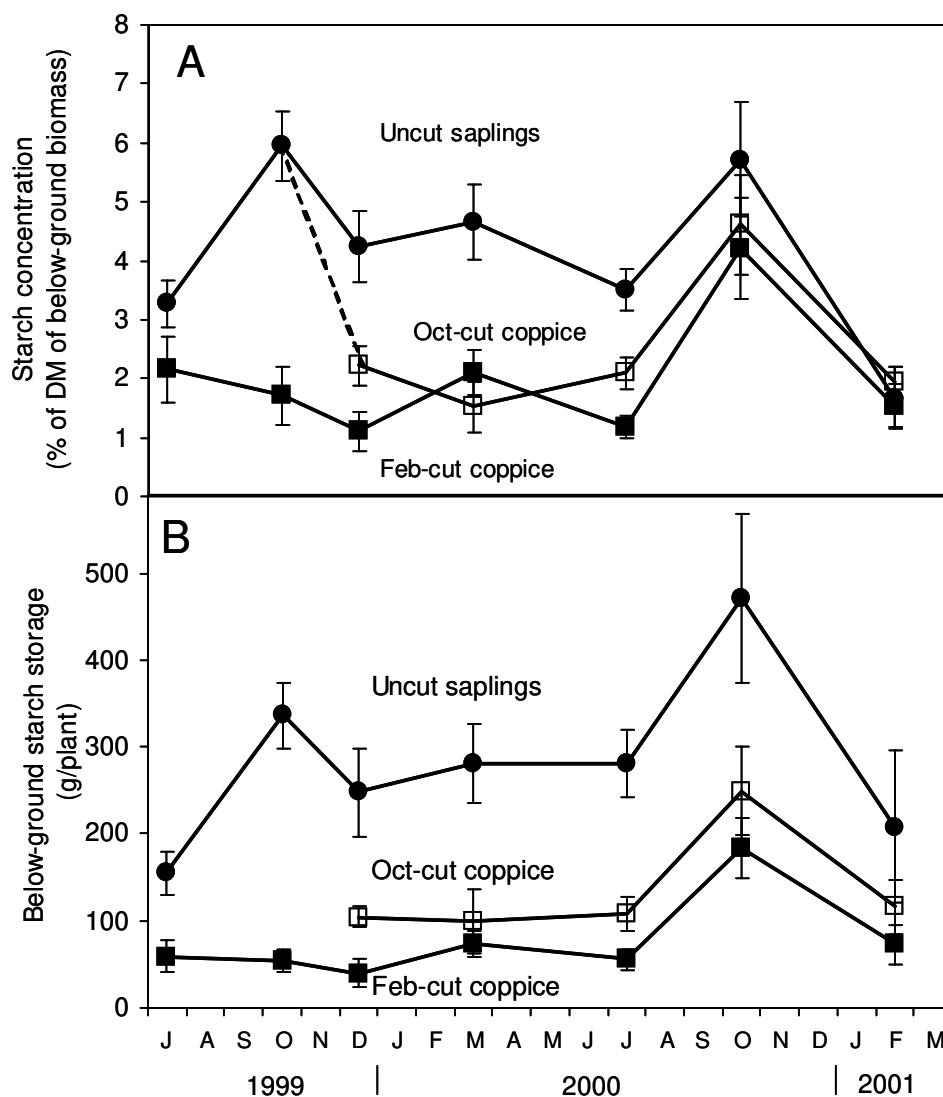


Figure 3.6 Changes in concentration (A) and total below-ground reserves (B) of starch in total below-ground biomass of 4- to 7-year old trees of *Eucalyptus kochii* left intact (uncut saplings, circles) or coppiced in summer (February 1999 cut, black squares) or the following spring (October 1999 cut, open squares). Dashed lines indicate the October cutting event. Vertical bars are ± 1 s.e.

Starch reserves were interpreted to provide the substrate for the early growth of the new shoots and the respiration of the root system before new shoots were formed. Soon after the new small canopy was produced, starch ceased to be utilised and the plants relied instead on photosynthates produced in the new leaves.

Evidence for this role for starch reserves is found firstly in the fact that starch concentrations dropped quickly immediately after decapitation but stayed at a constant low level thereafter, until gradually rebuilding 1–1.5 years after cutting. Secondly, while 0.9–2.5 kg of new shoot dry matter was produced in the first year by coppiced trees cut in February and October, respectively, only 0.1–0.2 kg of starch was lost in this period and would thus have contributed only a small fraction to the years total growth. Thirdly, strong relationships between starch concentrations and resprouting vigour often don't exist in the literature (see Chapin *et al.*, 1990; Hodgkinson, 1992).

Further evidence on the utilisation of starch following coppicing was found using natural carbon stable isotope ratios ($\delta^{13}\text{C}$) as tracer signals (see Farquhar *et al.*, 1989; Gleixner *et al.*, 1998; Terwilliger *et al.*, 2001). Starch extracted from roots and lignotubers at the time of cutting showed $\delta^{13}\text{C}$ signatures of -23.3 ‰ for February-cut trees and -23.6 ‰ for October-cut trees (Fig. 3.7A & B). The first new shoots produced on the stump possessed $\delta^{13}\text{C}$ values similar to starch, but then rapidly decreased to much lower values. These lower values (-26 to -27 ‰) are more typical of new photosynthates produced under low water stress by rapidly transpiring shoots (Farquhar *et al.*, 1989; Osório and Pereira, 1994).

A similar pattern was found when coppiced stumps were permanently shaded under multiple layers of shade cloth immediately after cutting (Fig. 3.7B). Even under low light levels when photosynthesis proceeded at very slow rates, starch appeared only to provide a substrate for new shoots in the first few months following cutting and then the plants reverted to relying on meagre current photosynthates.

These data further support the theory that starch is important only in the very early stages of coppicing. Adequate reserves for this purpose seem to be present regardless of the treatment of rootstocks.

In contrast to our initial hypothesis, we conclude that starch is not a controlling factor in the ability of *E. kochii* to resprout after cutting.

3.7 Lignotuber development with age

New stems form after cutting via meristematic bud sites on the lignotuber (e.g. see Burrows, 2002). These are clumps of cells located shallowly underneath the bark and protected by a surrounding sheath of woody tissue. We wished to determine the rate of development of these bud sites on young *E. kochii* trees and the proportion utilised in a coppicing cycle to ultimately determine whether these would have a bearing on cutting frequency.

Counts of meristematic bud sites on debarked lignotubers showed 2-yr-old plants to possess about 500, rising to about 1000 on 3-yr-old plants and then to 3000 per lignotuber on 5-yr old trees. When cut at age 4.6 (February cutting) or 5.2 (October cutting), stumps produced similar intensities of new coppice stem production, viz. 140–170 per lignotuber, representing only a small percentage of the available number counted previously (Fig. 3.8).

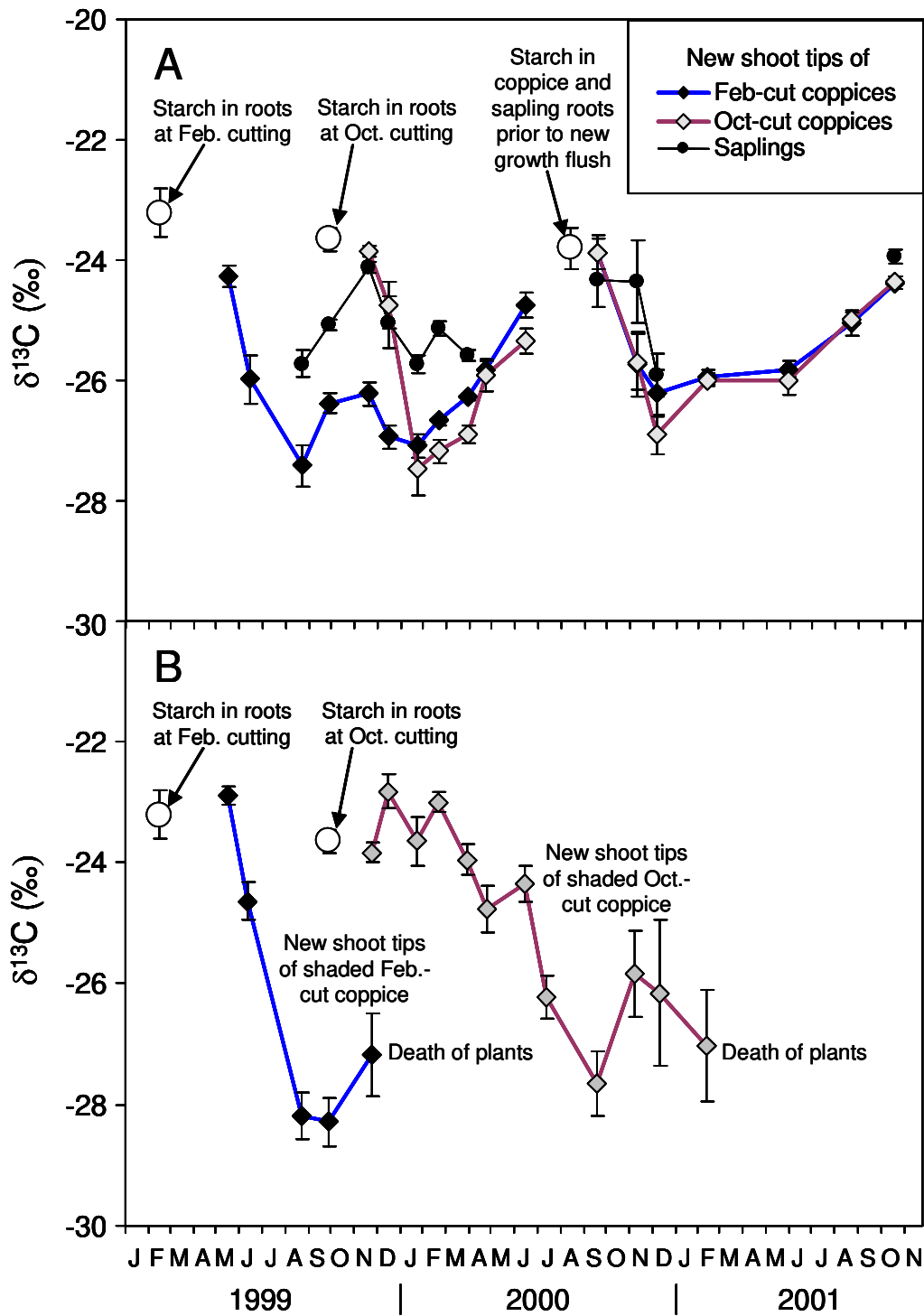


Figure 3.7 Carbon isotope discrimination values for starch extracted from bulk below-ground biomass and for dry matter of new shoot tips produced sequentially across each seasonal flush of growth for *Eucalyptus kochii*. Treatments in (A) all growing naturally, coppices in (B) shaded immediately after decapitation. Note that first formed shoots in a growth flush possess similar $\delta^{13}\text{C}$ signals to starch. Error bars indicate ± 1 s.e.

Repeated cutting of stumps on three-monthly intervals produced successive crops of new stems numbering 40–160 per lignotuber. The cumulative number of stems produced until death was approximately 400 per stump, equivalent to only 13 % of the number of meristematic bud sites available.

We conclude that lignotubers of *E. kochii* develop at an early age and provide a very large store of buds in readiness to produce successive new crops of shoots on stumps after harvest. When managing the species on short rotations, the size of the potential bud store needn't be taken into account. Similar findings have been reported for other woody taxa including eucalypt species (Sennerby-Forsse *et al.*, 1992).

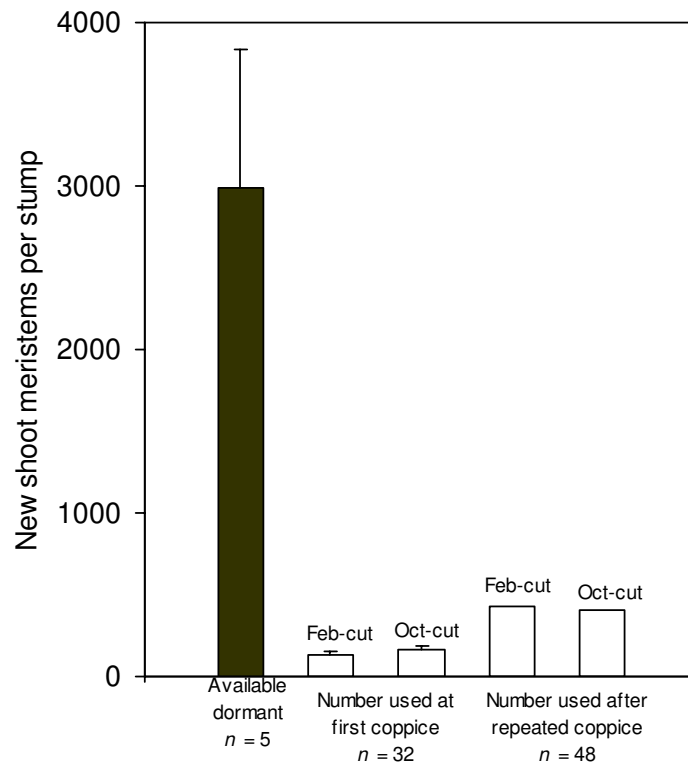


Figure 3.8 Number of meristematic bud sites on 5-year-old lignotubers and the number utilised firstly after a single coppicing event ($n = 32$) and the cumulative number used after repeated harvests ($n = 48$). Error bars indicate ± 1 s.e.

3.8 The relationship between resprouting ability and plant size

One might expect larger plants with larger stores of carbohydrates or bud sites to coppice faster after cutting than a smaller or younger plant (e.g. see Bellingham and Sparrow, 2000). If this were the case then harvests may need to be delayed to ensure rapid regrowth or a strong ability to endure repeated cutting.

Larger trees as a result of better genetics or site conditions will resprout better than smaller trees of the same age, for the same reasons that the saplings grew large initially (e.g. see Fig. 6 of Wildy *et al.*, 2000b). In other words, if trees are on a site where they can grow quickly as saplings, then they will grow quickly as coppice too.

However, where large plant size is due to age, there appears to be no relationship between the size of a tree and its ability to resprout. Put simply, at a given site a one year old tree is likely to regrow at the same rate as a five year old tree. The reasons for this are detailed below.

Firstly, the ultimate experiment to test this would be for sections of a large uniform planting of young trees to be cut in their first year, others at age two, a further set of trees at age three and so on, while measuring biomass of coppiced shoots following each years cutting. This was not attempted here but observations are that trees as young as one year old may coppice as vigorously as four or five year old trees (Max Waters pers. comm.). Two studies of coppicing *E. kochii* at Kalannie on deep yellow sands with a fresh perched water table are available (Wildy *et al.*, 2000b and the present study). These studies showed similar sapling growth rates. In the former study trees were cut in two seasons at age 2.5 and 3 and the coppice regrew at very similar rates as in the present study even though these trees were 3.7 and 5.2 years old.

Secondly, a review of the scientific literature also failed to find any evidence to support the hypothesis that older, larger trees at a site will be able to resprout better than younger trees. Indeed many species actually show a reduction in coppicing ability beyond a certain age (Blake, 1980). This is not the case for mallees, which are generally able to resprout vigorously even when very old (Noble, 1989; Milthorpe *et al.*, 1998). Coppice rates of mallees cut one year after planting can be high as well (Eastham *et al.*, 1993; Milthorpe *et al.*, 1994; Milthorpe *et al.*, 1998).

Thirdly, we elucidated the role of starch in coppicing in *E. kochii* in section 3.6 as being only important in the very early stages of shoot development after coppicing (e.g. one to three months) and having no quantitative effect on the rate of coppice growth. This would then suggest that even if larger plants did possess larger stores of starch, then this would not necessarily lead to more rapid coppice growth rates.

A good summary is to say ‘vigour begets vigour’ (Jacobs, 1955). In other words, vigorous plants will produce coppice biomass more rapidly than a less vigorous plant. This vigour may be due to either genetic ability of the individual or the site on which it is growing. However, given a particular genotype and site, older, larger plants will not resprout more vigorously than younger trees. It therefore appears that there is no evidence to consider the effect of age of trees on their subsequent resprouting ability when designing optimal harvest regimes.

Other implications would therefore be

- selecting fast growing saplings in breeding programs is likely to select indirectly for fast coppice growth rates too
- management practices promoting sapling vigour would presumably also lead to better coppice regeneration rates once cut. Thus minimizing grazing damage, spray drift etc and cutting in favourable seasons would keep trees as vigorous as site conditions would allow and impact on future coppice yields.

3.9 Sustaining rootstock vigour over successive harvests

Evidence in the published literature suggests that repeated cutting of temperate woody species can cause reductions in yield over a period of time, particularly if cut on very short rotations such as one to three years (Perala, 1979; Sennerby-Forsse *et al.*, 1992; Ceulemans and Deraedt, 1999; Liesebach *et al.*, 1999; Hytönen and Issakainen, 2001). For example, repeated cuts on one year intervals can result in decreasing yields and death of stumps.

It appears that mallees are also unable to tolerate repeated annual cuts. The data of Milthorpe *et al.* (1998) show *E. kochii* and *E. polybractea* shoot biomass yields to reduce after an initial increase when cut annually. The eucalyptus oil industry in eastern Australia employs harvests of 1.5–3 years

depending on season (Geoff Davis, pers comm.). There, they aim for the shortest possible rotation since this has the highest leaf proportion and thus the highest recoverable oil percentage. Experience over a century of cutting, sometimes on the same stands continuously, has found that shorter rotations cause reduced regrowth rates in subsequent rotations. This applies both for young stands and mature natural stands (Geoff Davis, pers comm.).

The reasons for the decline of repeatedly cut trees are not well understood but may involve

1. soil nutrient depletion (Nambiar, 1999)
2. contorted vascular pathways through coppice junctions (Del Tredici, 2001)
3. hormonal or biochemical imbalances (Vogt and Cox, 1970)
4. insufficient meristematic bud sites (Sennerby-Forsse *et al.*, 1992)
5. depleted carbohydrate reserves in rootstocks (Woods *et al.*, 1959)
6. rootstock photosynthate starvation (Steinbeck and Nwoboshi, 1980)
7. root senescence (Sims *et al.*, 1999)
8. rootstock disease or insect attack (Christersson *et al.*, 1992)

Of the possible reasons for decline in vigour, site nutrient depletion from repeated export of shoot biomass from the site (1) is unlikely to be a concern for belt-planted mallees since they are planted on fertilized ex-agricultural land and the alleys between the tree belts were regularly fertilized. Measurements of leaf gas exchange rates (not shown in this report) suggested that (2) was unlikely to be a major factor either. The possibility of (3) occurring was likely but beyond the scope of the study.

Regarding possibility (4), lignotubers possessed a large number of new sprout bud sites and only a relatively small fraction were activated at each coppicing event (detailed above in section 3.7) so these too are unlikely to limit the long-term vigour and survival of repeatedly cut trees. We concluded similarly for the role of starch reserves (5) in *E. kochii* (section 3.6).

Instead, possibilities 6–8 in the above list may be involved in the reduced vigour of trees cut on very short rotations. After repeated cutting, a reduced supply of photosynthates might result from a shortage in the tree while most energy is being directed into forming a new canopy (6), especially if the plant is struggling e.g. after being cut in an unfavourable season. Or another way of looking at it is that roots may be ‘less important’ in the context of the whole plant since there is a large root system but no shoots, so the large roots don’t develop further, slowly age and senesce (7). A weak rootstock will be more easily predated on or infected by diseases (8).

As detailed in section 3.4, shoot harvest essentially results in a large structural root system being retained that is not really necessary during the initial regeneration period. After cutting, smaller roots are shed but larger transporting roots are retained. Fine feeding roots are then grown directly from the structural roots to keep the small shoot supplied with water and nutrients. But most of the new canopy’s resources are being directed into rebuilding the shoot. In the meantime, the large structural roots are not actively growing since they are effectively oversized already, and they may remain in this state for 1.5–2.5 years (Fig. 3.3). If the tree was cut again before the larger roots had a chance to grow new tissues, then these roots would age, weaken, be attacked by fungi and insects, reducing the viability of the tree to function optimally.

In summary, the observed reducing yields after repeated cutting on short rotations in mallee eucalypts may be avoided by using rotation lengths greater than 2–3 years. This may be related to the vigour of larger roots on the remaining rootstock which do not actively grow until after 1.5–2.5 years.

3.10 Implications: harvest regimes for productivity and long-term yields

Table 3.7 *Summary of major conclusions affecting yield for Eucalyptus kochii grown on short-rotations and their implications for harvest regimes.*

Subject of consideration	Major points	Desirable rotation length
Harvestable shoot production	• age of first cut is not overly important • first year after cutting incurs ‘penalty year’ of slow growth • early growth is near-exponential (but this study did not quantify how many years after cutting this effect would last)	Ideally 3–4 years. Possibly longer still?
Rootstock vigour	• slow for first 1.5–2.5 years until shoot is restored • lack of new root growth if cut on short intervals may cause decline in rootstock vigour	at least 2–3 years
Season of harvest	• ideally harvests would be timed so that new canopy is formed at natural time of shoot formation coppice growth occurs (i.e. cut in late winter/spring)	increase next rotation length if cut in bad season (e.g. late summer/autumn); could decrease if cutting in late winter or spring
Starch reserves	• no large impact on harvest regime	nil
Bud sites for new shoots initiation	• no large impact on harvest regime	nil

In summary, our experiments into management for productivity confirmed that mallees are well adapted to resprout after repeated harvests through the development of large lignotubers and adequate starch reserves. The timing of the first cut is not overly important from the point of view of future production rates. Spring cuts resulted in faster shoot regeneration and a more rapid return to growth for large roots than late summer cut trees. Mallees should not be cut on 1–2 year cycles since yields will be reduced due to the penalty year after cutting and the vigour of rootstocks will decrease, in turn affecting yields in future harvest cycles. Coppice rotations of approximately 3 years would probably give near-optimal yields and allow rootstocks to remain vigorous. While the effect of further extending coppice rotations was not studied, it is thought that economic considerations would not allow longer rotation lengths, and water sources may also become scarce and slow the growth rates of larger trees.

4. Water use

4.1 Introduction

4.1.1 Rationale

Oil mallees are grown first as young saplings then coppiced repeatedly. Where coppiced trees are grown on a short-rotation basis their use of water may be too small to have an appreciable impact on groundwater recharge, as leaf areas of regenerating canopies will be small and transpiration rates accordingly reduced (Vertessy *et al.*, 1997; Jackson *et al.*, 2000). However, there is evidence that recently coppiced trees of a species can show higher rates of transpiration per unit leaf area than larger uncut trees (Blake, 1980) suggesting that performance in reducing rises in water tables may be underestimated.

Wherever trees have the potential to use considerable amounts of water in a semi-arid environment, access to sources other than rainfall will be paramount at certain times and stages of growth. This 'extra' water might be derived from unsaturated soil water where profiles penetrable by roots are deep, from perched aquifers, and from deep groundwater accumulating above the basement rock. The relative importance of these sources will depend on the ease of availability to trees which will be influenced by rooting habits, with both affecting their ability to exploit recharge waters and hence their productivity (Ong *et al.*, 1996).

It is generally considered that native bush within catchments is in overall hydrological balance and essentially utilises all the rain that falls on it (Nulsen *et al.*, 1986). Where tree plantations are established on former agricultural land, they tend to grow very quickly initially using rainfall plus accumulated stores after which growth rates become greatly reduced unless these additional resources of water are replenished by lateral flow. But lateral conductivities are negligible in unsaturated soil and also tend to be low for movement within large groundwater bodies (0.1–10 cm/day), particularly in the very flat (1–3 % slope) landscapes in the eastern wheatbelt (McFarlane *et al.*, 1993). Not surprisingly, therefore, growth rates of trees in plantation format would be expected to end up as low as those of the natural vegetation (e.g. 1–4 t dry matter/ha/yr) due to intense competition between closely spaced trees for water. In such cases the offsite hydrologic benefits are often limited to only 20–50 m from the canopy edge (George *et al.*, 1999).

Because of such concerns in plantations, belt plantings of trees through alleys of crops or pastures have been advocated (Kang *et al.*, 1990; Lefroy and Scott, 1994) to increase the proportion of the landscape directly accessed by tree roots. This would also lead to higher rates of growth on a canopy area basis compared to plantation grown trees. However alley plantings with large trees are well known to have deleterious effects on growth of adjacent crop or pasture species (Govindarajan *et al.*, 1996; McIntyre *et al.*, 1997).

The ideal situation would be for tree belts to utilise only that water that falls on or is stored below their projected canopies while also accessing free drainage of water from alleys by localised lateral flow of perched or deep groundwater. The worst case, on the other hand, would be where downward root growth of trees was severely restricted by an impermeable soil stratum, and trees thereby forced to develop widely extending lateral roots well out into the crop or pasture zone. In this scenario, once water accumulated prior to tree establishment had been utilised, trees and annual plants would then be in direct competition for contemporary rainfall. For short-rotation forestry practices, the time scale over and extent to which either of these scenarios operates becomes highly relevant since timing of harvests would then provide management opportunities for fine tuning issues such as tree water availability and crop competition.

Many of the early studies into effectiveness of trees in reducing watertables looked at their impact on groundwater levels. These are the ultimate test of the effectiveness of trees but provide no detail of the sources used. Considering this, budgets on a tree belt basis can provide useful additional detail to groundwater studies and allow estimates to be made of the optimal number of such belts across a given area to reduce deep drainage to zero.

4.12 Pertinent site hydrological details

The Kalannie site was on a gentle slope (1.5 %) with a natural drainage line running through it as indicated in Fig. 4.1A. Trees were planted in twin-row belts (Fig. 4.1B) with intervening alleys 45–120 m wide carrying annual crops and pastures.

The soil at the site was a gradational yellow sand (Gn 2.21: Northcote, 1979) overlying a siliceous hardpan of variable thickness (0.1–2 m) and at 1–8 m depth across the general study area. Below the hardpan was a sandy clay pallid zone (R. Speed pers. comm.) in which the moderately saline regional groundwater (450–1100 mS/m) was encountered at 8.5–14 m depth below soil surface.

A perched fresh aquifer was present on the hard siliceous layer at a depth of 4.2–5.3 m but only in the vicinity of the drainage line. This was studied separately along with adjacent areas where a perched aquifer did not occur.

4.2 Aims

The aim of this part of the study was to quantify the water sources utilised by five- to seven-year-old *E. kochii* subsp. *plenissima* trees growing at a deep sand site underlain by a root-impeding hardpan at Kalannie, Western Australia. We examined water use over a 22 month period for coppiced and uncut young trees growing with or without a fresh perched aquifer.

We expected to find coppice using less water than uncut trees, and that soil moisture below uncut trees would be depleted but that they would not be accessing groundwater through the hardpan at the site. The overall objective was to reach conclusions regarding the management of short-rotation tree crops to maintain adequate water availability to trees, as well as determining the proportion of the landscape that would have been required under oil mallee belts to achieve zero net recharge over the study period.

4.3 Methods

4.3.1 Experimental design

The three locations (Sites 1, 2 & 3) at which water budgets for trees and adjacent pasture were constructed are shown in Fig. 4.1A. Soil depth to the hardpan was 5.1–5.5 m at Site 1 and 6.3–7.1 m at Site 2, 700 m upslope from Site 1. Neither site featured a perched aquifer and the thin partly fractured hardpan was permeable to water and probably penetrable by taproots of trees (R. Speed, pers. comm. and observations of the present study). Site 3, downslope on the drainage line, featured a permanent fresh aquifer (< 100 mS/m) perched on the thick, impenetrable hardpan. The aquifer was encountered at 4.2–5.3 m below soil surface.

This part of the study was carried out from November 20, 1999 to October 5, 2001, as trees aged from 5.3 to 7.2 years since planting. Water budgets were constructed at each site for (i) uncut saplings, (ii) trees coppicing after being cut 5 cm above ground level in October 1999, and (iii) pasture beyond the range of influence of tree roots.

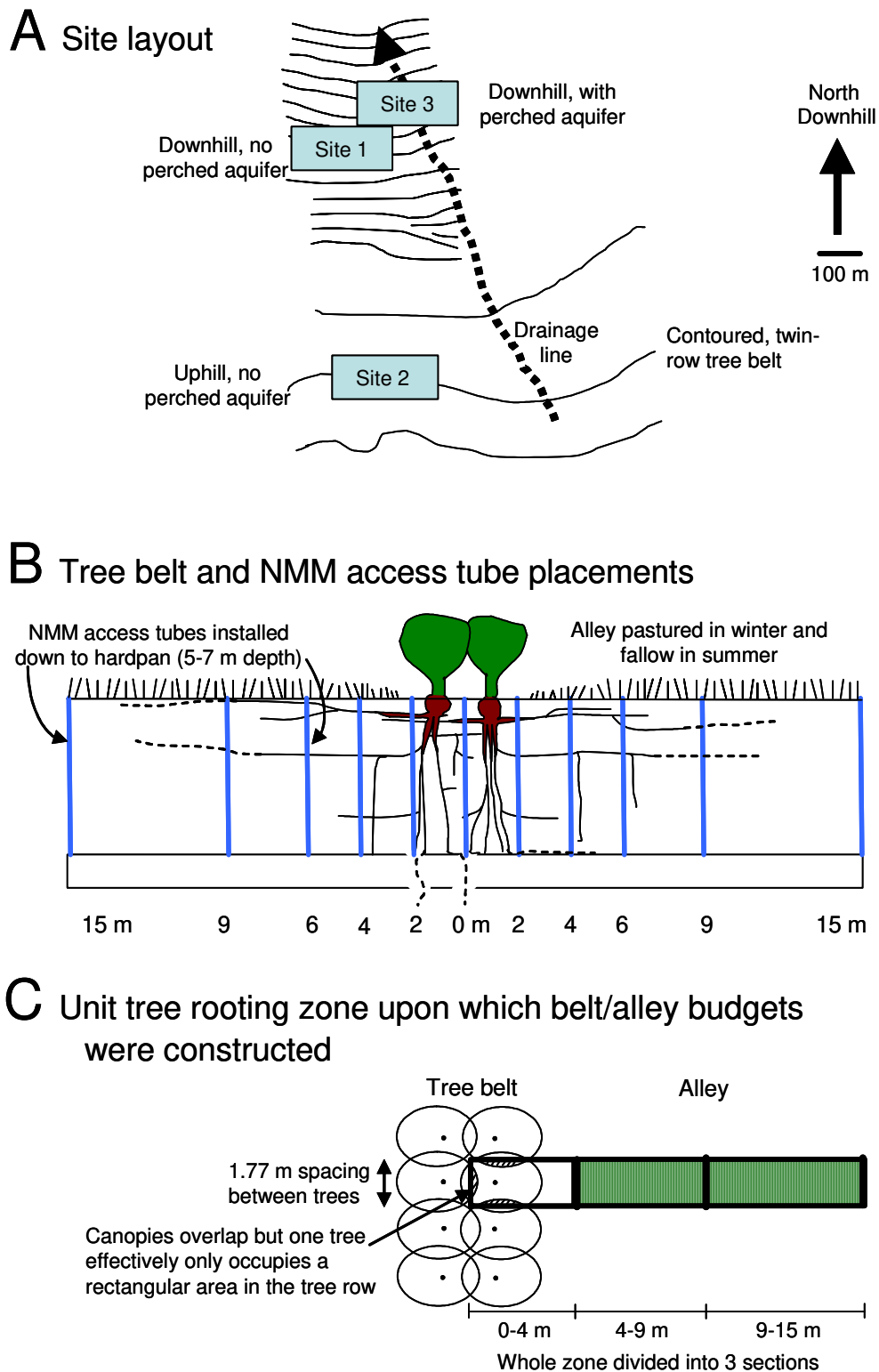


Figure 4.1 (A) Aerial view of Kalannie trial site showing tree belts on contours and areas where water budgets were constructed (Sites 1, 2 and 3). (B) Cross sectional view of tree belt showing hardpan and position of access tubes in transect for soil moisture measurement. (C) Representation of the belt/alley unit for which water budgets were constructed.

4.3.2 Construction of water budgets

Transects for budgets of water use of tree belts were constructed on a unit tree basis 1.77 m wide and extending 15 m outwards from the centre of the twin-row tree belt (0 m in Fig. 4.1C) to well beyond the maximum lateral extent of tree roots recorded at the site, and termed a ‘belt/alley budget unit’ (Fig. 4.1C). This maximum possible zone of influence of a single tree was partitioned into sections 0–4 m, 4–9 m and 9–15 m from the centre of the tree row, and inputs and outputs and changes in soil water estimated for each section separately.

Three successive 6–8 month periods (A, B & C) compared how trees sourced water when exposed to contrasting conditions of soil moisture, incident rainfall and cutting regime. Pooling data for Periods A, B & C, a picture was then obtained of the total fluxes over the whole study interval.

Each water budget was constructed using the equation

$$P - T_B - T_A - E_B - E_A - I_B - \Delta S - D = 0 \quad (1)$$

where P is rainfall, T_B and T_A represent transpiration in belt (trees) and alley (pasture) respectively, E_B and E_A are evaporation from soil surfaces of tree belt and pastured alley respectively, I_B is rain intercepted by tree canopies and subsequently evaporated directly back into the atmosphere, ΔS is the change in the measured soil store (down to the hardpan or top of the capillary fringe where the perched aquifer was present), and D is deep drainage (negative value) or deep water uptake from below the depth of study (positive value). It was assumed that any surface run-on in heavy rain events would be countered by an equal run-off of water on the downslope side of the tree belt. All terms in Equation 1 were measured experimentally except for D which was calculated by solving Equation 1 (Wallace, 1996).

4.3.3 Tree biomass and leaf area

Above-ground dry biomass and the proportions of dry shoot biomass of coppice and uncut trees consisting of leaves were obtained from the data set given in section 3. Leaf specific areas (m^2 of one-sided leaf/g dry matter) were determined on four successive occasions during the study from four uncut and coppicing trees of each site and treatment.

4.3.4 Tree transpiration (T_B)

Transpiration of uncut saplings at Sites 1, 2 & 3 was assessed by the heat pulse method (Hatton *et al.*, 1995) employing Greenspan (Warwick, Qld., Australia) SF300 split probe sensors. Four to six stems were logged at each site at any one time with installations changed on a 6–9 month basis. Two probe sets were inserted at random depths and orientations in each stem at 10–20 cm above ground level. Bases of stems were cut under water at the end of a series of measurements and shoot bases quickly transferred into a solution of 0.05 % basic fuschin. Shoots continued to transpire for 3 hours before being harvested for determination of leaf area and examination of dye distribution. Transport typically occurred through all but the central pith of the stems, with heartwood not yet formed. Incremental increases in both conductive area and leaf area over the 6–9 month logging period were then back-calculated using strong relationships with stem cross sectional area ($r^2 = 0.9$ and 0.82 respectively) which was routinely measured. Daily transpiration rates of stems were then scaled according to progressive mean tree leaf area at each site (Hatton *et al.*, 1995; Hatton and Wu, 1995).

Coppice stems were of insufficient diameter for insertion of heat pulse probes so their daily transpiration was estimated indirectly based on ratios of mean leaf areas of coppicing and uncut trees at a site, and an appropriate correction for the faster rates transpiration on a leaf area basis of coppicing than uncut trees recorded in cuvette-based investigations of gas exchange of canopies in a companion study (Wildy *et al.*, submitted-a).

4.3.5 Rainfall (P), throughfall (TF), stemflow (SF) and interception (I_B)

Rainfall (P) was measured automatically at the site. Throughfall (TF) was measured on four uncut trees at each of the three study locations by random placement of collecting troughs under tree canopies. Stemflow (SF) of the same trees was assessed by sealing a shaped aluminium cone extruding 7 cm from the bark surface on stems greater than 2 cm diameter with each collecting station 20 cm above ground level. Fractions of rain fall events intercepted and subsequently evaporated directly from tree canopies (I_B) was then determined according to the equation

$$I_B = P - TF - SF \quad (2).$$

Functions relating TF and SF to P were generated from 24 variously sized rainfall events occurring over the study period. Substituting these into Equation 2 enabled a predictive curve for I_B to be generated based on P alone. The large numbers (100–170) of small diameter stems and low stature of coppicing trees prevented direct measurements of SF and TF so predictive functions generated for uncut trees were employed when assessing I_B of coppiced trees, after taking into account the smaller relative canopy area of coppice than uncut trees.

4.3.6 Soil moisture (ΔS) assessments by neutron moisture meter (NMM)

A transect for NMM measurement was installed at each site through belts of both coppicing and uncut trees. Transects were positioned to include average-sized trees for the study belt with 100 % survival in the immediate vicinity. Access tubes were placed centrally in each transect at the mid point of the tree belt (0 m) and at 2, 4, 6, 9 and 15 m outwards in either direction (Fig. 4.1B) and data for the opposing halves were later averaged. Separate sets of four tubes were also installed well out in pasture at each of the three sites to monitor changes in soil moisture during pasture and fallow phases of untreed areas. All tubes were installed down to the hardpan (5–7 m). Neutron counts were measured at 20 cm increments over the zone 10–130 cm and then at every 40 cm on fourteen occasions during the 22 month study period. Four access tubes at each site were calibrated gravimetrically to 4 m depth at the end of the study following the procedure of Greacen (1981). Regressions of neutron counts against volumetric water contents were similar for all access tubes so broad calibration equations were generated for soil depths 0–0.2, 0.2–0.4, 0.4–0.6 and >0.6, assuming depths greater than 4 m to possess calibration characteristics similar to the soil immediately above.

4.3.7 Soil evaporation (E_A) and pasture transpiration (T_A) in untreed alleys

Soil evaporation (E_A) during summer fallows, and pasture transpiration plus soil evaporation ($T_A + E_A$) during winter months in alleys well away from trees, were calculated indirectly by comparing rainfall received over a period with the net depletion or addition of soil water in upper soil layers as assessed by NMM to 1 m during summer fallow and 1.5 m during winter when pasture was present (Gregory *et al.*, 1992; Bolger and Turner, 1999). This approach was possible throughout Periods B and C since rainfall events were small and failed to wet soil profiles deeper than 1 m. However, during the first 6 months of the study (Period A), large rain events wetted alley profiles to great depth, incurring drainage past 1.5 m depth. It was then assumed that soil evaporation rates proceeded at the maximum rate recorded at other times during the study.

Since the rainfall:NMM technique cannot separate pasture transpiration and soil evaporation (Gregory *et al.*, 1992) we distinguished these components indirectly using a transpiration ratio of 300 mL water transpired per gram of above-ground dry matter produced by pasture (see Lewis and Thurling, 1994; Bolger and Turner, 1998; Pate and Dawson, 1999). With above-ground biomass of pasture assessed at 2.5 t DM/ha in 2000 and 2.0 t DM/ha in 2001, this gave an estimated transpiration loss of 75 mm in 2000 and 60 mm in 2001. Subtracting these T_A values from $T_A + E_A$ for the two winters then indicated a mean soil evaporation value of approximately 0.2 mm/day. This value is similar to rates recorded for similar soil types and soil moisture conditions in the Western Australian wheatbelt (see Eastham *et al.*, 1999; Eastham and Gregory, 2000).

4.3.8 Pasture transpiration and soil evaporation in the alley within the zone of influence of tree roots and soil evaporation under belts (E_B)

For simplicity and uniformity between treatments we used the same suppression rate for pasture growth moving away from tree canopies in the construction of all water budgets. Due to the depth of the soil we assumed that in most cases a reduction in pasture growth would have extended one canopy height (~3 m) from the edge of the canopy (see Cleugh *et al.*, 2002; Knight *et al.*, 2002). This was also measured further along the same study belts when sown to wheat in 2000 (Simmons, 2000). Assuming a linear increase from 0 pasture growth at the canopy edge up to the full rate 3 m out from the canopy edge, we then used a stepwise function to set the first 1.5 m from canopy edge (2.5–4 m from belt centre) at 0 pasture growth and the next 1.5 m (4–5.5 m from belt centre) at the full rate. This conveniently allowed us to disregard pasture evaporation in the 0–4 m zone and use the full rate over the rest of the alley (4–15 m) as measured in the tree-free areas. E_B , over the 0–4 m section of transect, was assumed to proceed at half the rate estimated out in alleys, due to the extra shade afforded by the trees and the lower amount of rain falling on the soil in this area due to interception (see also data of Ellis *et al.*, in press). Evaporation from this comparable zone under coppice was assumed to proceed at full rate for the first two periods because of the reduced canopy cover initially and then at half the full rate in Period C as the coppice approached the canopy cover of uncut trees.

4.4 The fate of rain on sapling canopies

Tree canopies reduce effective rainfall reaching the ground because a certain fraction of the rain is retained on leaves from where it evaporates again (termed ‘interception’). A further fraction of rain runs from leaves then down branches to be channelled down stems and along roots (‘stemflow’). The remainder of the rain hitting the canopy drips through to the soil surface (‘throughfall’).

We quantified these fractions for saplings for most of the rain events during the water balance study period and generated equations for each fraction (Fig. 4.2A). The greatest proportion of rain falling in the canopy occurred as throughfall. For example, a 20 mm rainfall event would result in approximately 3 mm entering the soil as stemflow, 11 mm reaching the soil surface as throughfall and 6 mm intercepted by the canopy and evaporating directly back to the atmosphere. Thus, the effective rainfall reaching the ground is only 14 mm.

Stemflow did not occur at all with rainfall events under 1 mm. Since canopies could only hold a certain amount of water on wet leaf surfaces, larger rain events result in a lower proportion of interception than smaller rain events.

Using these equations and the sizes and times of rain events at the site over the study period (Fig. 4.2 B), the fate of rainfall events in terms of stemflow, throughfall and interception were assessed for the three Periods A, B and C for which we constructed detailed water budgets for tree belts. Data are shown in the cumulative plots of Fig. 4.2C. For Period A, when 238 mm of rain fell, including two unusually large cyclonic events, throughfall plus stemflow accounted for 74 % of the rainfall whereas in the driest period B, with only 122 mm rain mainly as very small events, only 51 % of the incident rain reached ground level. Corresponding data for Period C when 202 mm of rain fell showed throughfall and stemflow to account for 58 % of rainfall.

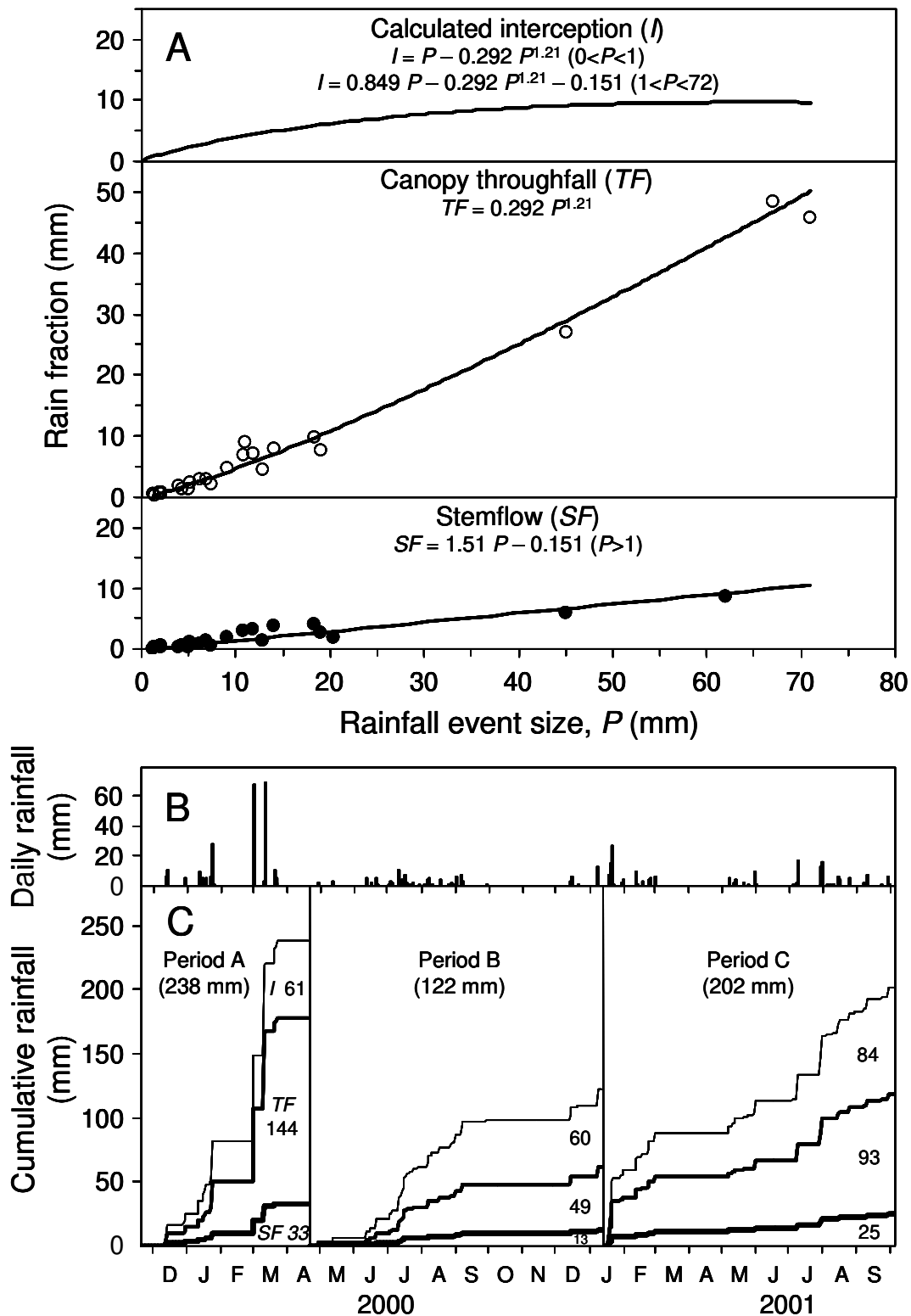


Figure 4.2 Breakdown of 24 measured rainfall events upon sapling canopies into interception, throughfall and stemflow (A) used to produce the formulae (also shown in A) which then allowed the total rainfall during the study (B) to be divided into cumulative totals of each rain fraction for the three budget periods (C).

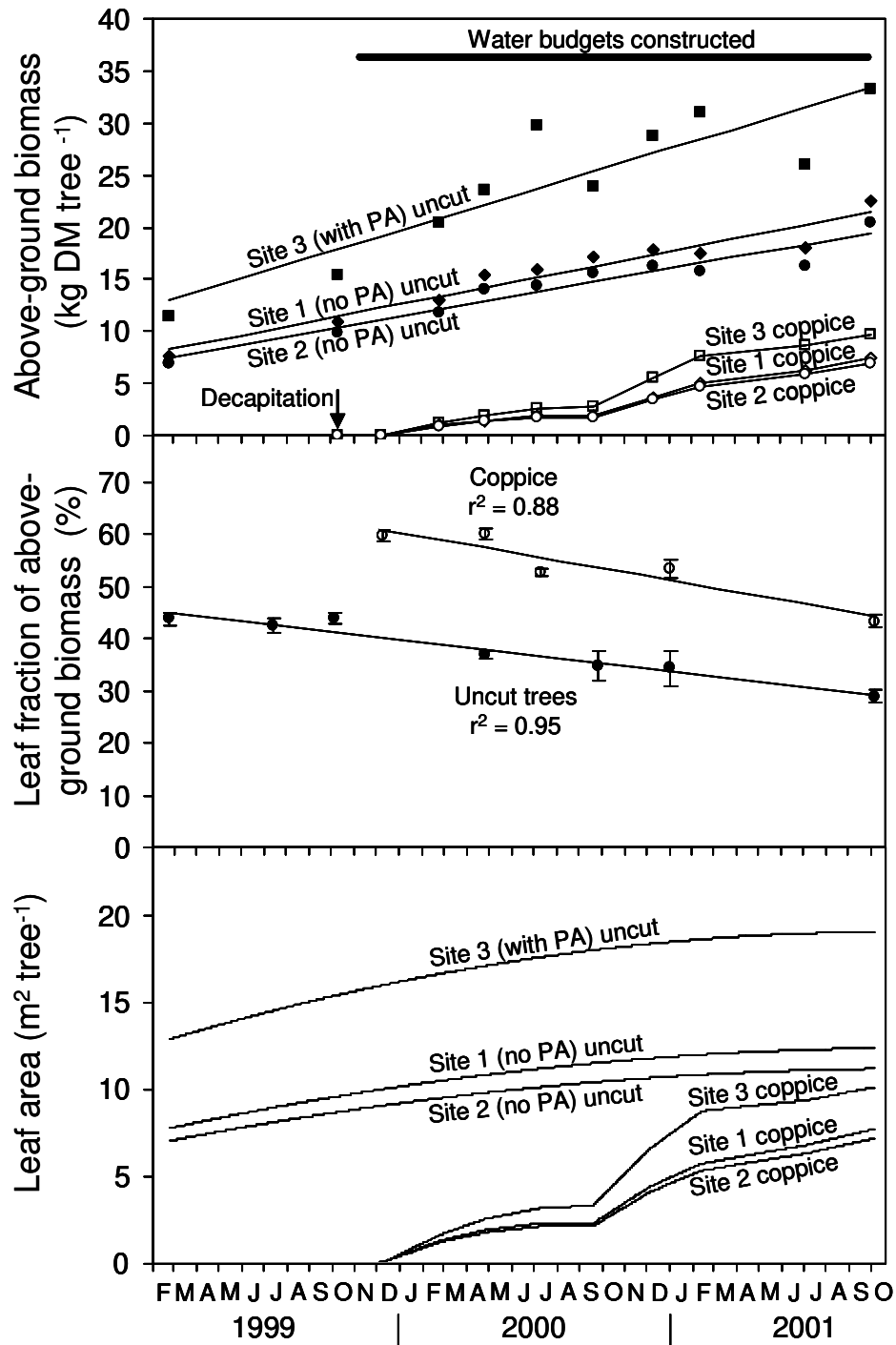


Figure 4.3 (A) Shoot biomass of uncut saplings and coppiced trees and saplings at sites where water budgets were constructed ('PA', perched aquifer), (B) leaf proportion of above-ground biomass for coppiced and uncut trees used in calculation of (C) leaf area over the study period.

4.5 Transpiration by saplings and coppice with or without a perched aquifer

We measured sapling transpiration at Sites 1 and 2 (no perched aquifer) and Site 3 (with perched aquifer) using heatpulse probes (Hatton *et al.*, 1995) and scaled them to the mean leaf area at each site (Figs. 4.3 and 4.4A). We calculated coppice transpiration at the same sites based on the ratios of mean leaf areas of coppicing and uncut trees (Fig. 4.3) and an appropriate correction for the faster rates of transpiration on a leaf area basis of coppicing than uncut trees recorded in cuvette-based investigations of gas exchange of canopies (Fig. 4.4 B&C).

Saplings at Site 3 with a perched aquifer grew approximately 50 % larger than trees without a perched aquifer (Fig. 4.3A), and accordingly also transpired more water (Fig. 4.4A), especially during summer months when temperatures were warmer. Saplings at Sites 1 and 2 without a perched aquifer showed noticeable increases in transpiration after heavy rain events towards the drier end of the study (see arrows, Fig. 4.4A).

Coppiced trees transpired at greater rates on a leaf area basis (Fig. 4.4B) but since leaf area was much lower, transpiration on a whole plant basis was lower for coppiced trees than saplings (Fig. 4.4C). However, by the end of the study period transpiration of coppiced trees had returned to approximately 60–75 % of that of saplings.

4.6 Soil water contents under tree belts and adjacent pasture

At each site and for both saplings and coppiced trees, access tubes for neutron moisture meter assessment of soil moisture were installed in the centre of each tree belt ('0 m') and then at 2, 4, 6, 9 and 15 m out in both directions from the tree row centre into the adjacent pasture (see Fig 4.1B). Access tubes were installed to the depth where the siliceous hardpan was encountered (5–7 m). A further set of tubes were installed in pasture away from the influence of tree roots.

Fig. 4.5 shows sequential changes in volumetric moisture contents of soil profiles for the various zones between successive access tubes during the study. Water contents at field capacity (FC) and the limit of plant available water (LPAW) are shown for the respective profiles. Comparisons between sites with (Site 3) and without (Sites 1 & 2) perched aquifers were complicated by different depths of soil profiles and higher percentages of clay in the soil profiles with no perched aquifer. Note that soil moisture data for Site 3 do not include the perched aquifer or the capillary fringe above this, but just the free draining soil above these zones.

At the end of the wet Period A at Site 1, water contents were greatest at 15 m from the tree row centre and least at 0–2 and 4 m, and at 6 and 9 m water contents were intermediate. Over the following dry months, water contents at 15 m decreased probably due to natural drainage of the profile, but water contents at 6 and 9 m from the tree belt centre decreased more so, indicating that trees were utilising water from these distances during this period. By the end of Period C, water contents of all tubes between 0 and 9 m were equally dry, at the limit of plant available water, while there were still significant water stores at 15 m from the tree belt centre.

Corresponding data were obtained for changes in soil water in similarly averaged transects through coppiced belts at each site using identical procedures (data not shown).

Table 4.1 summarizes all soil moisture data from uncut trees, coppice and pasture as mm equivalents of changes in soil moisture (ΔS) between beginning and end of the three study periods. Data were pooled to provide mean values for the soil zones used in the later construction of water budgets, namely 0–4 m, 4–9 m and 9–15 m.

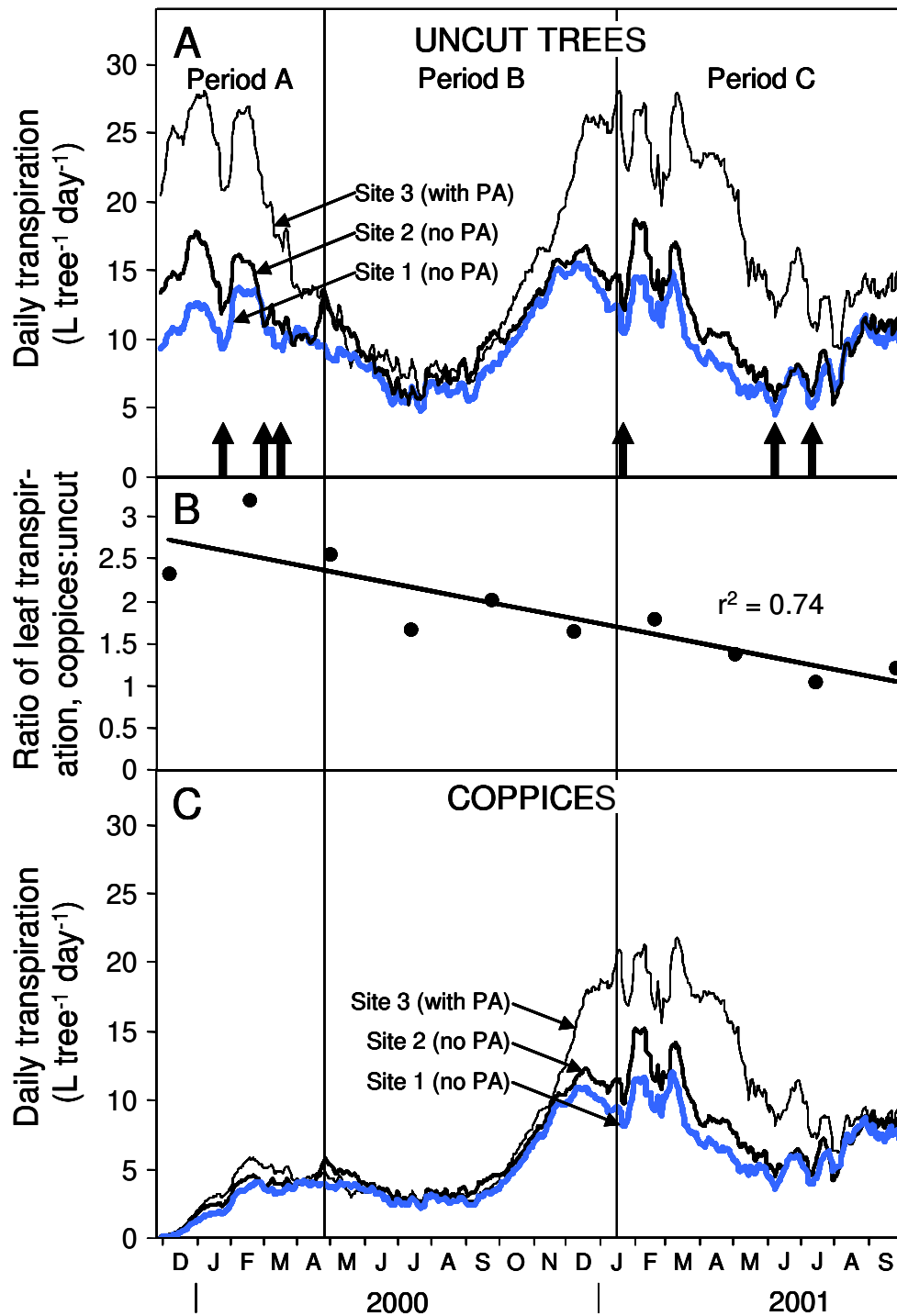


Figure 4.4 (A) Ten day moving averages of daily transpiration by uncultured saplings at the three sites where budgets were constructed ('PA', perched aquifer). Arrows denote rain events exceeding 30 mm within a three day period. (B) Ratio of leaf transpiration rates of coppice:uncultured tree measured with cuvette over whole canopies, and subsequent trendline used in the calculation of coppice transpiration. (C) Ten day moving averages of estimated daily transpiration by coppiced trees.

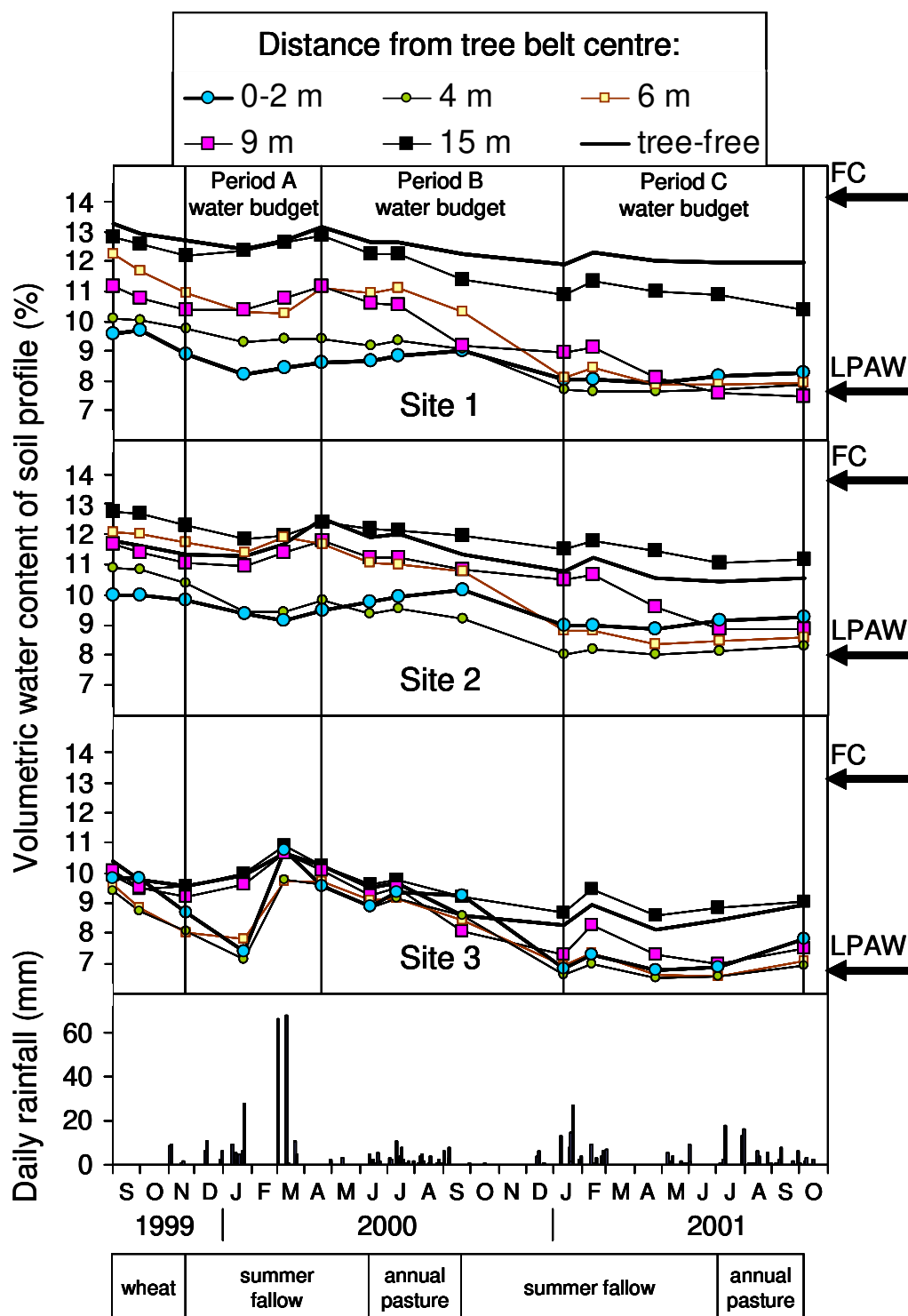


Figure 4.5 Mean volumetric soil moisture content down measured soil profiles for transects through uncut tree belts and adjacent alley under wheat, pasture or fallow at the Kalannie trial site. Each line corresponds to access tubes at varying distance from the belt centre, where 0-2 m was under tree canopy and 4, 6, 9 and 15 m were under adjacent alley. Field capacity (FC) and limit of plant available water (LPAW) are shown for each profile. Note wetting of profiles after heavy rainfall and faster drying under trees compared to alleys.

During the very wet period (A) all but the inner most zones of transects under uncut trees recorded a recharge of soil water reserves, and extents of recharge were greater for coppicing than uncut trees. Net recharge of soil profile water was less in pasture because profiles were almost fully recharged before the study began. The rainfall in Period A therefore mostly resulted in free drainage. During Periods B & C soil moisture was depleted in most zones of profiles though to a lesser extent directly under uncut trees than coppice (0–4 m zone) since profiles were already dry under uncut trees (see Fig. 4.5).

Table 4.1 Consecutive changes in unsaturated soil moisture (ΔS) over the 22 month study expressed in mm equivalents (with negative numbers indicating profile drying). Soil moisture was measured down to the hardpan (depth listed) except at Site 3, with a perched aquifer on the hardpan, where soil moisture was calculated only to the top of the capillary fringe.

	Depth of measured profile (m)	Change in soil moisture over measured profile (L)								
		Period A (238 mm)			Period B (122 mm)			Period C (202 mm)		
		0–4	4–9	9–15	0–4	4–9	9–15	0–4	4–9	9–15
Uncut trees										
Site 1	5.1	–16	14	38	–44	–128	–107	10	–26	–50
Site 2	7.1	–28	6	29	–57	–155	–79	18	–40	–69
Site 3	3.1	36	44	24	–94	–88	–67	20	6	9
Coppice										
Site 1	5.5	40	37	31	–177	–112	–80	–13	–24	–2
Site 2	6.3	46	97	96	–96	–172	–142	18	–33	–48
Site 3	3.1	19	38	28	–71	–56	–44	25	4	15
Pasture free of tree roots										
		<u>0–15</u>			<u>0–15</u>			<u>0–15</u>		
Site 1	5.3	26			–68			3		
Site 2	6.3	73			–109			–14		
Site 3	3.1	21			–61			20		

4.7 Soil evaporation and pasture transpiration

These measurements are summarized in Table 4.2 for pasture, uncut trees and coppice for the three periods of the study. All values are given in mm per day and refer arbitrarily (see Glossary for notes on mm equivalents) to the entire 15×1.77 m transects over which water budgets were constructed (see Fig 4.1C). Soil evaporation rates were lowest in Period B since only 36 mm of rain fell in the five months of fallow and winter rainfall was largely utilised by pasture.

Table 4.2 Pasture transpiration and soil evaporation rates (mm/day) used over each period for the whole 15 m wide zone used in construction of water budgets.

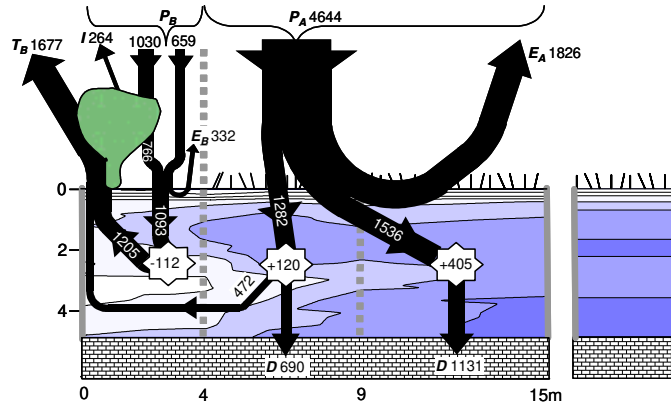
	Period A (151 days)		Period B (268 days)		Period C (266 days)	
	Pasture trans.	Soil evap.	Pasture trans.*	Soil evap.	Pasture trans.†	Soil evap.
Uncut trees	-	0.54	0.54	0.22	0.48	0.41
Coppice	-	0.62	0.54	0.25	0.48	0.41
Pasture	-	0.62	0.74	0.25	0.66	0.47

* for the 102 days when pasture was present

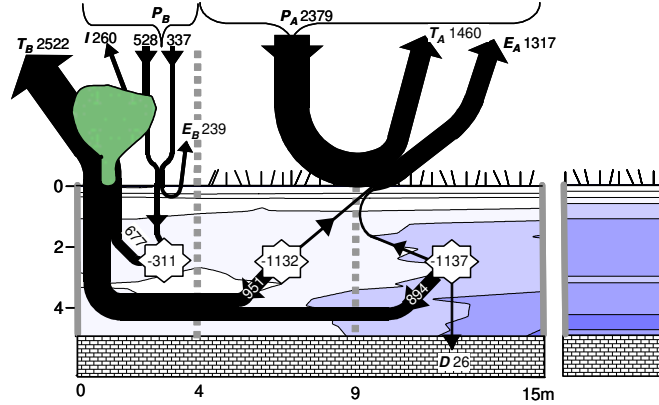
† for the 94 days when pasture was present

SITE 1 UNCUT SAPLING

Period A (238 mm rain)



Period B (122 mm rain)



Period C (202 mm)

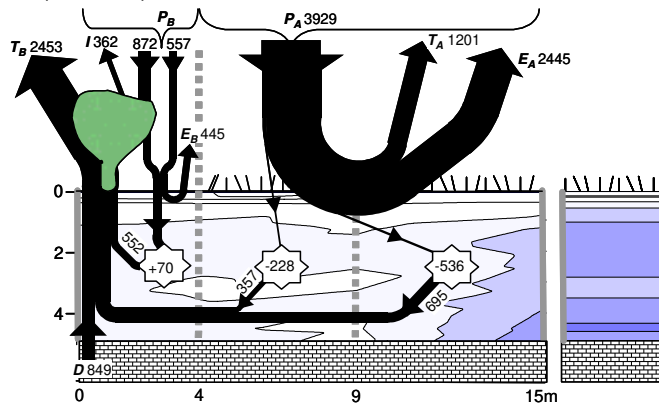


Figure 4.6 Water budgets for a single representative uncut *Eucalyptus kochii* tree in a belt next to adjacent agricultural land over three consecutive 6–8 month periods at Site 1 at Kalannie, Western Australia. Arrows represent water fluxes, lines thicknesses are drawn to scale, and all values are given in L over the 1.77 m × 15 m budget area. The three zones, 0–4 (tree belt), 4–9 and 9–15 (pastured alley) are delineated by dashed vertical lines. The hardpan is shown at the base of each cartoon and soil moisture conditions at the end of each budget period are indicated by darker (wet soil) and lighter (dry soil) shading. Soil moisture in nearby pasture free of tree roots are also shown for comparison on the right of each budget. The major fluxes are P, precipitation, T, transpiration, E, evaporation, I, interception, D, deep drainage or deep water uptake, and ΔS , change in soil moisture storage down to the hardpan (shown in stars) where subscripts B and A refer to belt and alley parts of the transect respectively.

4.8 Example of water budget construction

As detailed more fully in the Methods section, water budgets were constructed on a unit tree basis 1.77 m wide and extending 15 m outwards from the centre of the row (see Fig. 4.1C). This potential zone of influence of a tree was partitioned into sections 0–4 m, 4–9 m and 9–15 m and inputs and outputs and changes in soil water estimated for each section separately. The whole zone is termed a ‘belt/alley budget zone’.

Firstly, a fully annotated example presented below and shown in Fig. 4.6A is presented for uncut trees of Site 1 for Period A and explains the procedures used in model construction.

(i) Rainfall of 238.5 mm during the period was equivalent to 6333 L falling on the 15×1.77 m wide unit tree budget zone. Knowing the ratio of projected canopy cover to total root catchment area, 1030 L of rain would then be expected to have fallen on a tree’s canopy, a further 659 on the rest of the 0–4 m zone and the remainder (4644 L) in outer parts of the transect (4–15 m) but still within the potential range of tree roots.

(ii). Using the relationships established between rainfall event size and canopy interception (Fig. 4.2), a total 264 L from the various rainfall events incident on the canopy was evaporated directly while the remaining 766 L would have been committed to throughfall plus stemflow. With an estimated evaporation loss of 332 L from the soil surface of the 0–4 m zone of the transect, the net amount of water entering the soil and thus potentially available to trees would then be 1093 L, or 65 % of the rain on this zone.

(iii) Of the 4644 L of rain falling on the 4–15 m section of the transect, soil evaporation accounted for 1826 L while the remainder of 2818 L entered the soil profile. Of this total, 1282 L entered the 4–9 m zone and 1536 the 9–15 m zone. Note that during Period A no pasture was present since it spanned summer months (see Fig. 4.5) so pasture transpiration was not included in this period’s budget.

(iv) Tree transpiration over the study period was 1677 L (Fig 4.4A). Soil moisture data (Fig. 4.5A and Table 4.1) showed a net decrease for the 0–4 m zone down to the hardpan of 112 L through either deep drainage or tree transpiration. Given the dryness of the soil in this zone (see moisture profile in Fig. 4.5, Period A) we assumed that both the net input of rainfall (1093 L) and the decrease in soil water (112 L) were devoted exclusively to tree transpiration.

(v) The remaining 472 L needed to meet the budget for tree transpiration was then assumed to have been sourced from the next adjacent soil zone (4–9 m). With 1282 L entering this zone from rainfall less evaporation (described above), and soil moisture increasing by 120 L, then 690 L must have left the profile in deep drainage. Similarly for the 9–15 m zone, 1536 L entered the profile and the net increase in soil water was 405 L, leaving 1131 L to leave the profile in deep drainage.

(vi) In this example, all water used by trees was accounted for from measured changes in soil water in the unit tree zone, and no deep water uptake was implied. The construction procedure looks at net changes over a period and therefore assumes soil water to be used directly by trees rather than having drained below the depth of measurement and then having been taken up from depth again. In other budgets, deep water uptake was conservatively estimated only when rainfall inputs and soil water changes over the whole 15 m width were insufficient to meet the transpirational demands of trees.

(vii) All budgets were presented with line thicknesses drawn proportional to amounts of water available from, used by or transported. Measured values for tree transpiration and changes in the soil water reserve and estimates of evaporative losses from the soil and pasture transpiration can then be visually compared between treatments and time periods. At the same time, the net extent of free

drainage through profiles *versus* the extent to which trees had utilised deep water from below the hardpan or the perched aquifer can be compared.

4.9 Water budgets for saplings and coppice without a perched aquifer

4.9.1 Saplings

This comparison for Site 1 examined how water budgets changed relative to previous and current rainfall for the three consecutive periods (Fig. 4.6).

Period A commenced with substantial moisture reserves in the soil profiles and further large episodes of rainfall augmented water reserves and led to considerable deep drainage below the 4–15 m zones of the transect. Pasture was absent in this period and soil and canopy evaporation losses from the transect were 1.5 times greater than transpiration of uncut trees. Net deep drainage was equivalent to 29 % of incident rainfall across the transect. Contour profiles for NMM assessments of soil water at the end of the period showed depletion of reserves in the 0–4 m zone under trees.

The longer Period B had just over half of the rainfall of A but tree transpiration rates for the period were greater. The balance indicated negligible deep drainage and trees sourcing 73 % of their water from previously stored moisture across the 4–15 m zone since soil in the 0–4 m zone was completely dried out. Transpiration of pasture cover was a large component of the budget at this stage.

Period C incurred greater rainfall than in B. Tree transpiration was as high as in B but with greater soil evaporation and less soil water available for tree and pasture transpiration the water balance for C indicated that 28 % of the water transpired by trees had come from soil water and rainfall in the 9–15 m zone and a further 35 % from deep water within or below the hardpan.

4.9.2 Coppiced trees

Corresponding models for water use by coppiced trees at Site 1 for the Periods A, B and C are presented in Fig. 4.7. The most noticeable features are the very small transpiration loss of the young coppice (Period A) and the large increases in transpiration through Periods B and C.

As expected from low coppice transpiration and absence of pasture cover, Period A showed deep drainage losses across the whole transect equivalent to 39 % of incident rainfall. In Period B, contours of soil moisture showed substantial drying of soil under trees as transpiration of enlarging canopies of coppicing trees increased. Nevertheless deep drainage occurred from other parts of the transect profile. Period C witnessed further drying out of the profile and a small net uptake of water by roots from groundwater, despite water seemingly still available in the 9–15 m zone.

4.9.3 Notes on the usage of water within or below the hardpan

In the final 8 months of the study (Period C), 35 % (at Site 1, Fig. 5.6C) and 34 % (at Site 2, individual data not shown) of the water transpired by uncut trees was calculated to have been sourced from deep water, *D*. This refers to water below the depth of soil measurement, i.e. from within the hardpan or from the clay and/or moderately saline groundwater below the hardpan. The fact that this water was only accessed in the final 8 months of the study, after soil was dry 6.5 m from the edge of the tree canopy, suggests that this was not a preferred source for the tree due either to its depth, salinity or the low penetrability of the hardpan to roots. This is in contrast to the fresh perched aquifer which was utilised heavily and constituted 89 % of the uncut trees water use at Site 3 in Period C (individual data not shown).

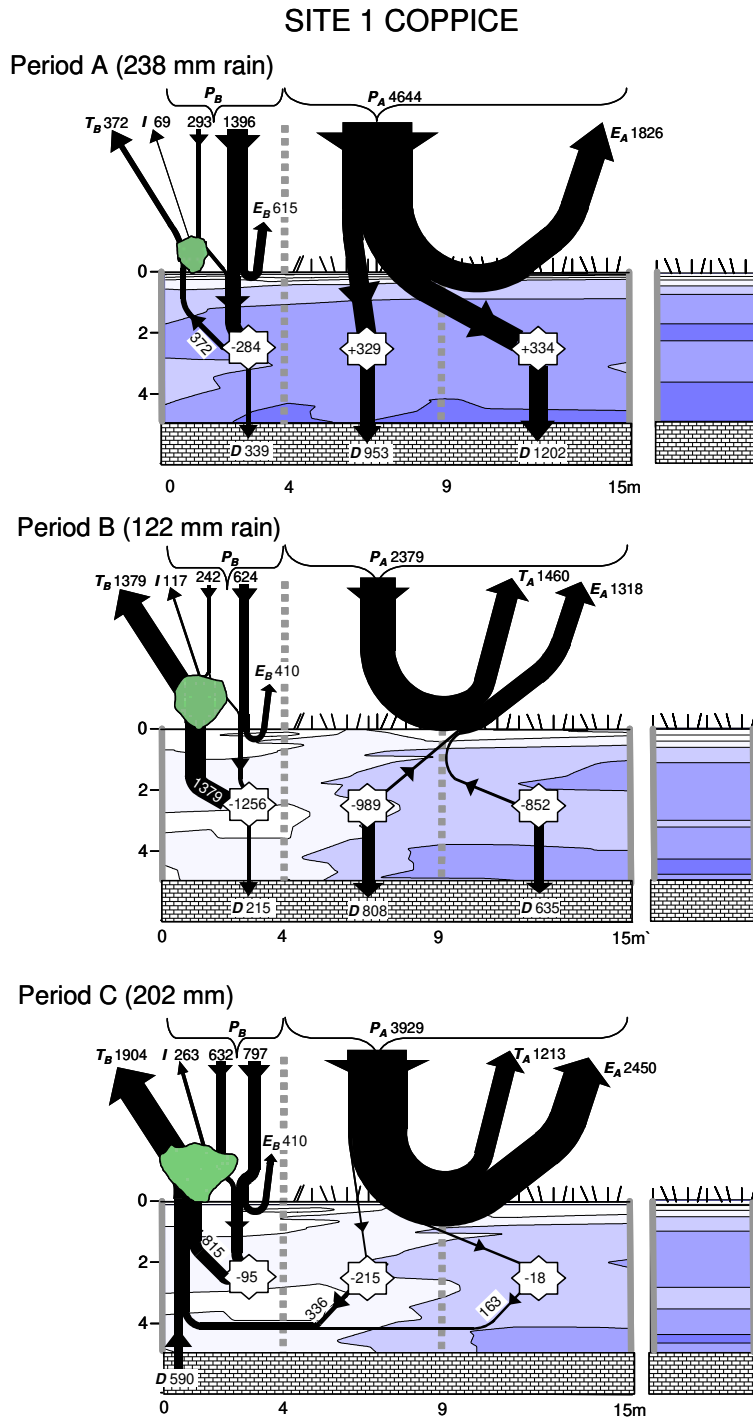


Figure 4.7 Water budgets for a single representative coppiced *Eucalyptus kochii* tree in a belt next to adjacent agricultural land over three consecutive 6–8 month periods at Site 1 (without a perched aquifer) at Kalannie, Western Australia, after being cut just prior to the beginning of Period A. See caption to Figure 4.6 for detailed descriptions of annotations.

If saturated water stores such as groundwater below a hardpan are not well utilised by trees (as in the case here for Sites 1 & 2), then transpiration rates and productivity would be expected to decrease in ensuing years as trees become more reliant on rainfall for their water. Evidence for this for Sites 1 and 2 saplings was found in transpiration rates before and after rain (see arrows in Fig. 4.3). In the first summer transpiration rates didn't increase after the indicated rainfall events because the nearby soil was still moist, but in the second summer, when soil water was becoming depleted, Site 1 & 2 uncut trees showed declining transpiration rates before the rain, followed by a noticeable increase after the rain. This was not observed for Site 3 trees transpiring freely with access to the perched aquifer.

It must be noted that the error associated with the calculation of D (net deep drainage to or uptake from water bodies below the depth of measurement, also referred to as deep water) is likely to be large since it is usually calculated as the remainder necessary to close water balances such as Equation 1 used in this study (Wallace, 1996). This therefore makes it subject to the compounded errors associated with the measurements of every other term in the equation (see Hatton *et al.*, 1995; White *et al.*, 2002). Consequently, we conservatively calculated deep water uptake by always assuming trees to use soil water directly instead of the possibility of soil water draining below the depth of measurement and being taken up again by trees. This approach does not affect the final calculation of net deep drainage over any given period but does affect conservatively the assessment of the ability of the trees to access deep water in relation to soil water.

More important, though, was a possible underestimation of uncut tree competition with pasture in the last winter of the study. We constructed all models assuming full pasture growth did not begin until 3 m out from the edge of the canopy, i.e. one canopy height. While there was no observable suppression zone next to trees, it is probable, however, that tree roots of Site 1 & 2 uncut trees were competing with pasture to a greater degree in the last season of the study judging by the comprehensive drying of soil almost to 15 m (Fig. 5.6C) and the evidence of increased transpiration of these trees following rain. If competition was occurring here at a greater rate than we assumed in the model construction, then a greater proportion of the water transpired by trees would have been accessed from contemporary rain reaching the alley topsoil (accompanied by a reduction in pasture transpiration) and the calculations of deep water uptake for Site 1 & 2 uncut trees in Period C would have been too high.

In short, we cannot prove definitively that trees without access to perched aquifers were able to access deep water through the hardpan. The lack of differentiation in $\delta^2\text{H}$ ratios at this site (e.g. see Burgess *et al.*, 2000) prohibited the use of natural isotope abundance techniques to gain further evidence in this matter (Wildy and Pate, unpublished data). However, we also determined coppice at Sites 1 and 2 to also use deep water (see Fig. 4.7C) even though there was still soil water available 6 m from the canopy edge, so we conclude that the likely scenario is that if trees were accessing deep water within or below the hardpan, this source of water was a relatively small part of the whole water budget due to the difficulty in accessing it, and was certainly only likely to be utilised after nearby soil water was depleted.

4.10 Water budgets for pasture or trees with or without a perched aquifer

4.10.1 Water budgets for the whole study period

These comparisons (Fig. 4.8) were between the adjacent downslope Sites 1 and 3 (see Fig. 4.1A), the former located well outside and the latter on top of the perched aquifer on the drainage line through the slope. Budgets for the whole 22 month period for each site are shown for pasture, coppice and uncut trees. The following points are of interest.

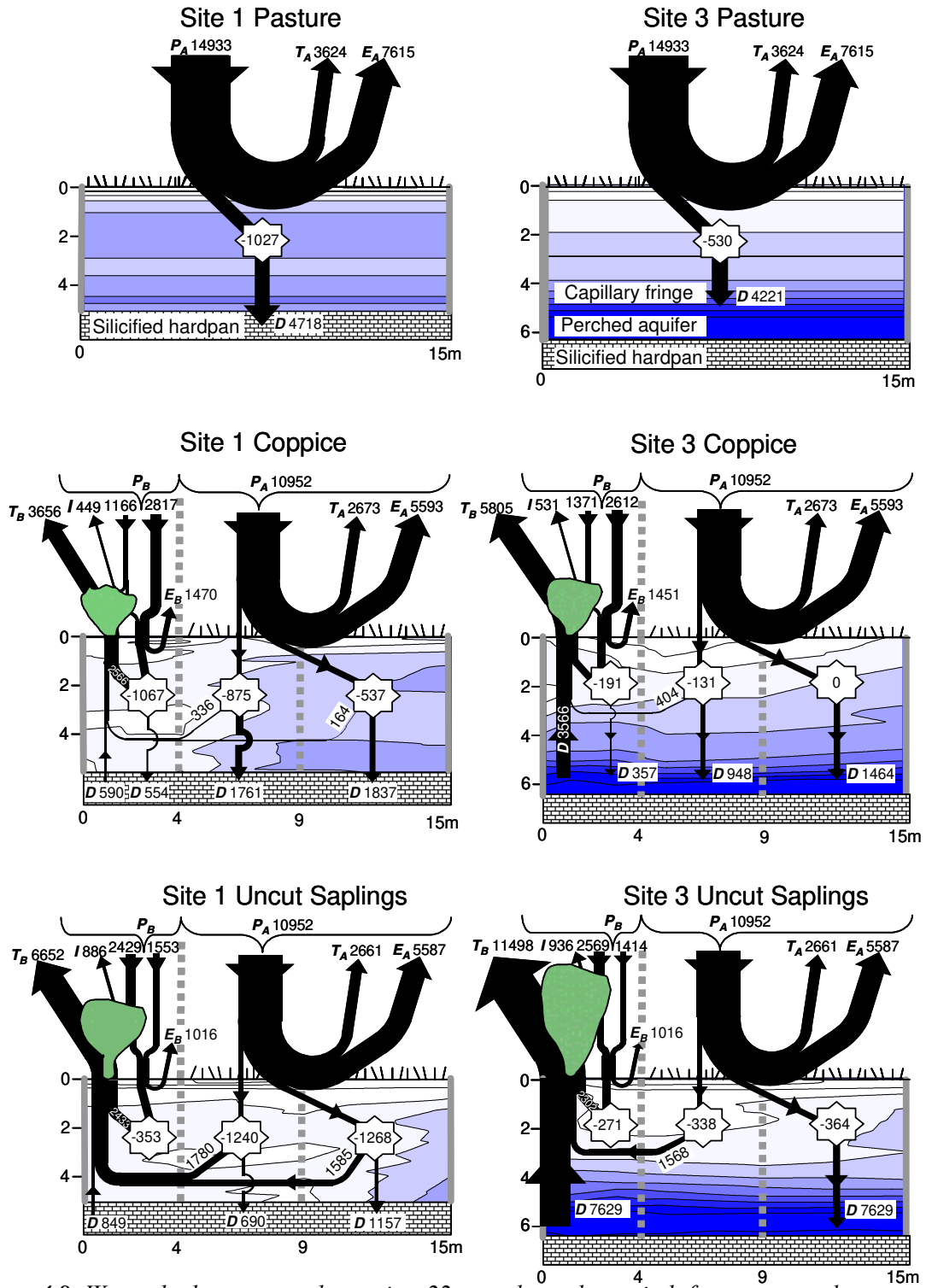


Figure 4.8 Water budgets over the entire 22 month study period for pasture alone, and for *Eucalyptus kochii* tree belt/pasture transects at Kalannie, Western Australia. Trees were either cut to ground level just prior to the beginning of the study or left to grow uncut. Budgets on left refer to Site 1 (no perched aquifer) and on right depict Site 3 (with perched aquifer, seen as dark layers in soil profile). See caption to Figure 4.6 for detailed description of annotations. Note that changes in and fluxes to and from soil moisture stores (ΔS , shown in stars) at Site 3 refer only to the soil above the capillary fringe (i.e. 0–3.1 m).

(i) Pasture areas showed the equivalent of 32 % of rainfall over the period lost to groundwater at Site 1 and 28 % lost to the perched aquifer in the case of Site 3. Pasture and soil evaporation accounted for only 75 % of total rainfall.

(ii) Coppice and adjacent pasture at Site 1 dried out the soil in all parts of the profile but did not prevent considerable deep drainage. Little of water utilised by coppiced trees at this site was accessed from deep water or soil water in the 9–15 m zone. Coppice at Site 3 regenerated more rapidly with access to free water of the perched aquifer and this led to net uptake from the aquifer in the 0–4 m zone under the trees at Site 3 and roughly equivalent losses to the aquifer in the zone 4–15 m.

(iii) Expressed in terms of net balances between rainfall and soil water (upper layers and deepwater/aquifer) coppices with access to the perched aquifer maintained hydrologic balance over the budget area, but coppices without a perched aquifer caused 134 mm to drain below the 15 m wide zone.

(iv) The presence of the aquifer promoted greatly increased growth of uncut saplings before and during the study, resulting in their transpiration over the 22 month period being almost twice that of trees at Site 1. Trees at Site 3 accordingly accessed 66 % of their water from the shallow, fresh perched aquifer (summarised in Table 5.3) whereas those at Site 1 were calculated to have acquired only 13 % of their transpired water from water below the hardpan (Table 5.3).

(v) Water balances between incident rainfall and soil/aquifer/deep water reserves showed uncut trees and pasture at Site 1 to incur a net deep drainage loss of 38 mm over the entire profile (7 % of incident rainfall), but also dried out the transect profile considerably to the extent of 108 mm (equivalent to 19 % of incident rainfall). By contrast, net water uptake from the perched aquifer by uncut trees and pasture (Site 3) was 218 mm (equivalent to 39 % of rainfall), compared to a drying of only 37 mm (equivalent to 7 % of rainfall) due to the shallowness of the soil profile down to the top of the capillary fringe.

4.10.2 Sources of water accessed by saplings in future years if left uncut

Saplings growing without a perched aquifer (Sites 1 & 2) had essentially dried the soil to the hardpan to 15 m from the centre of the tree belt. If trees were left uncut then the future sources of water available for utilising would become important and impact on future productivity and crop and pasture growth in the vicinity of the trees.

These trees were calculated to have been accessing water stores below the hardpan (see section 4.9.3). If so, this source would probably increase in relative importance and provide an unlimited source of water since the regional groundwater (moderately saline at 450–1100 mS/m) would then be accessible. However, the combination of the depth and salinity of this source, as well as possible bottlenecks to water flow in the roots penetrating the hardpan, would probably not allow rapid rates of transpiration (and thus growth) from this source alone.

Regardless of the availability of water from below the hardpan, trees would continue to exploit soil water over the extent of their rooting catchments as it was replenished by rainfall. Due to the extensive spread of roots covering 5 times the area of the aerial canopy, this would constitute a good source of water for trees under average climatic conditions. It is also likely that the lateral extent of root systems would increase further. However, this would be at the expense of productivity of the adjacent crops and pastures growing in this same zone.

Table 4.3 Total tree transpiration partitioned into individual sources of water utilised by *Eucalyptus kochii* at Kalannie, WA, over a 22 month period receiving 562 mm of rainfall. Treatments are ranked in order of decreasing total transpiration. Values are expressed in mm equivalents over the 1.77 m wide x 15 m tree/pasture budget zone (Figure 4.1C) and also as the percentage of total transpiration.

Treatment	Total tree transp.	Soil water ^a and rainfall falling on section			Deep water
		0–4 m	4–9 m	9–15 m	
Uncut saplings, Site 3	433	87 (20 %)	59 (14 %)	0 (0 %)	287 ^b (66 %)
Uncut saplings, Site 2	291	95 (33 %)	91 (31 %)	57 (20 %)	47 ^c (16 %)
Uncut saplings, Site 1	251	92 (37 %)	67 (27 %)	60 (24 %)	32 ^c (13 %)
Coppice, Site 3	218	69 (32 %)	15 (7 %)	0 (0 %)	134 ^b (61 %)
Coppice, Site 2	161	78 (48 %)	37 (23 %)	25 (16 %)	21 ^c (13 %)
Coppice, Site 1	138	97 (69 %)	13 (9 %)	6 (4 %)	22 ^c (17 %)

^a unsaturated soil moisture down to hardpan at Sites 1 & 2 or capillary fringe at Site 3

^b water from fresh perched aquifer above hardpan

^c water from within or below hardpan

4.10.3 Using harvests as a means of managing water use and competition

Cutting trees could be seen as a means of avoiding water stress in later years and the associated reductions in growth rates and increases in competition with crops and pastures. The dry soil would then act as a buffer into which new moderate rainfalls would infiltrate but not drain through. This water would then presumably act later as a water source for trees as their canopies redeveloped.

This is discussed further in the final discussion (section 5).

4.10.4 The impact of tree belts on site hydrology

Finally, an assessment can be made of the impact of the tree belts at the trial site on the hydrology of the site. In the absence of trees, recharge under pasture was on average 175 mm, or the equivalent of 33 % of the incident rainfall during the study (Table 4.4), which is typical of other values for sandy soils in the wheatbelt (Anderson *et al.*, 1998).

In contrast, uncut trees growing without a perched aquifer had the net effect of allowing only 27 mm to drain below the 15 m wide belt/alley zone we calculated the water budgets over (of which tree cover was 17 %) (Table 4.4). Uncut trees transpiring more rapidly at Site 3 had the net effect of taking up 218 mm from the perched aquifer over the 15 m wide zone.

Due to the lower transpiration of Site 1 and 2 coppice (without a perched aquifer) over the period, these belts allowed considerable drainage below them over the 15 m water budget zone (117 mm averaged over both sites). Soil water depletion occurred to a much greater extent under saplings where there was no perched aquifer (118 mm) than coppice at the same sites (88 mm) or pasture alone (44 mm).

Table 4.4 Net water fluxes (mm equivalents) over the 15 m wide zone over which water budgets were constructed (~2.5 m maximum tree canopy and 12.5 m adjacent pasture, or 17 % tree cover) compared with pasture only, over a 22 month period. Sources are indicated as negative values in the budget while sinks are positive. Soil water depletion was measured down to the hardpan at Sites 1 & 2 (5–7 m) and to the top of the capillary fringe (3.3 m) above the water table at Site 3.

	Rain -fall	Tree Transp. + Interception	Soil Evap.	Pasture Transp.	Net Soil Water Depletion	Net Deep Water Uptake (+) or Drainage (–)
Sites 1 & 2 (no perched aquifer)						
Uncut saplings	562	–304	–249	–100	118	–27
Coppice	562	–166	–266	–100	88	–117
Pasture only	562	-	–287	–136	44	–183
Site 3 (with perched aquifer)						
Uncut saplings	562	–468	–249	–100	37	218
Coppice	562	–239	–265	–100	12	30
Pasture only	562	-	–287	–136	20	–159

4.11 Estimates of tree cover required for hydrologic control

Table 4.4 showed the net recharge or uptake over the 15 m wide water budget unit (e.g. see Fig. 4.1C and Fig. 4.7). This represents the situation where 17 % of the landscape is planted to trees (a repeating unit of 2.5 m of trees, 1.5 m of uncropped bare land and 11 m of pasture. In this section, we roughly manipulate the tree or crop/pasture areas to achieve zero net recharge. The aim is to achieve hydrological balance with the minimum area of trees.

Note that an equivalent way of writing this aim would be “what spacings of tree belts across the landscape would ensure trees will not run out of water?” (Fig. 4.9). If the tree component were the main economic unit, there would still be no advantage in planting ‘too many’ trees since limited water resources would not permit increases in overall site productivity in the long term. This would represent land being wasted on trees that could otherwise have been used for cropping, and wasted money on excessive tree establishment. The following text is arbitrarily written in terms of the former view point (“how many trees are needed to stop recharge?”).

The 17 % revegetation used in these budgets was more than sufficient to halt net recharge of water to below the depth of measurement where saplings were growing with access to the perched aquifer. In this scenario, net water uptake over the whole 15 m wide belt/alley water budget unit was 218 mm (Table 4.4). A further area of leaking pasture could be incorporated while still maintaining zero recharge. Since net recharge under pasture alone at Site 3 was 159 mm then another 10.9 m of pasture could be hydrologically supported by the tree row. That is, a 2.5 m belt of 5–7 year old uncut saplings, 1.5 m of uncultivated soil adjacent to the tree row and $11 + 10.9 = 21.9$ m of pasture or crop would have had a balanced water budget. Since the budget unit repeats (see Fig. 4.10) then the total alley width would be $21.9 \times 2 = 43.8$ m for a 5 m wide twin row belt of trees (Table 4.5). This would represent 10 % tree cover. Sites with a perched fresh aquifer are the most amenable to growing tree but do not occur over the whole landscape to a great extent (Lefroy *et al.*, 2001).

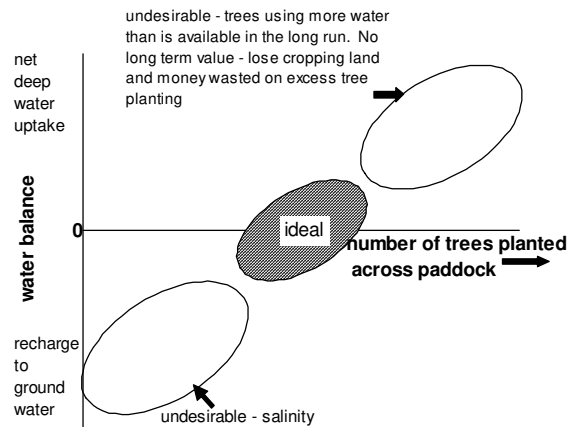


Figure 4.9 Diagram demonstrating that there is no advantage in planting more trees than are required for zero recharge. 'Not enough' is equally undesirable as 'too many'.

Coppiced trees growing with access to the perched aquifer were close to zero net water flux in the 15 m wide water budget unit, taking up 30 mm or the equivalent of 5 % of rainfall over the period. Similarly, saplings growing without access to the perched aquifer were also close to achieving hydrological control over the 15 m wide budget zone, yielding 5 % of rainfall over the period as recharge. Assuming these values close to being acceptable would indicate that the cropable alley of 11 m in the standard budget would have been supported hydrologically, giving an alley width of 22 m between repeating twin row tree belts (see Fig. 5.10 and Table 4.5).

When trees were coppiced in the absence of a perched aquifer, the 17 % revegetation used in the construction of these budgets was insufficient to stop recharge (117 mm) (Table 4.4). It is difficult to calculate the area under trees that would have been required for hydrologic balance, but considering the 166 mm tree transpiration with 17 % tree cover in the budget, it could be estimated that approximately 25 % tree cover would have been necessary for zero recharge. This would equate to a pasture width of 9.75 m in the budget area after the 1.5 m wide area bare area next to trees was taken into account, and a 19.5 m wide crop/pasture alley between repeated budget units (Table 4.5).

Leaving coppiced trees to grow for a further year (beyond the scope of this study) would have resulted in substantially more water being transpired by the tree component and the proportion of land needed under trees would have been reduced below the 25 % estimated for 0–2 year coppice.

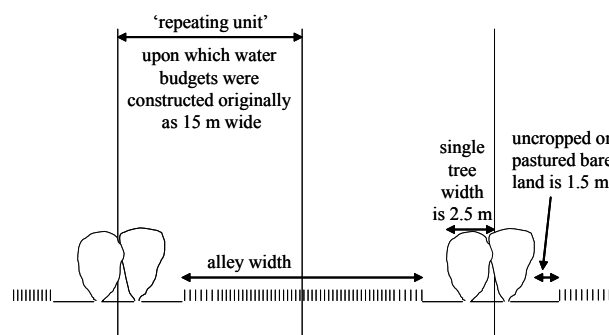


Figure 4.10 Conceptual diagram and terminology for assessing the amount of tree cover required for hydrological control. We modified the proportions of tree and crop cover of the original 15 m wide belt/alley budget units to achieve approximately zero recharge.

Table 4.5 Specifications for zero recharge in each of the tree belt situations studied in this project (sapling or coppice, with or without perched aquifer). See text for details of derivation, but essentially calculated from deep drainage or deep water uptake values given in Table 4.4. The data are expressed on a repeating unit basis (see Figs. 4.10 and 4.1C) and then the total alley width available for annual crop or pasture is shown.

Scenario	Repeating unit basis			Landscape tree cover	Total alley width available for crop or pasture
	Tree belt width	Bare land next to tree canopy	Pasture or crop width		
	(m)			(%)	(m)
With shallow, fresh perched aquifer					
5–7 year old saplings	2.5	1.5	21.9	10	43.8
0–2 year coppice	2.5	1.5	11	17	22
Without shallow, fresh perched aquifer					
5–7 year old saplings	2.5	1.5	11	17	22
0–2 year coppice	3.75	1.5	9.75	33	19.5

Note that all values refer specifically to the trees studied in this ‘case study’ and should not be generalised to other sites. They also refer specifically to young saplings (5–7 years old) or coppice 0–2 years after cutting. For example, younger, smaller trees with a lower leaf area would use less water and thus would have require a larger percentage of the landscape to achieve zero recharge.

At this site, the proportion of the landscape needed under trees in the various scenarios are in the lower end of the range reported by other researchers in recent national work on the effectiveness of trees in controlling recharge (George *et al.*, 1999; Dunin, 2002; Knight *et al.*, 2002; Stirzaker *et al.*, 2002; White *et al.*, 2002). This is partly due to the low rainfall experienced at this site (mean annual average 319 mm), allowing a large proportion of the trees water to be taken from sources other than contemporary rainfall.

The alley widths available for cropping or grazing (right hand column, Table 4.5) would be considered by most farmers to be very narrow. Except for the case of saplings growing with access to the perched aquifer, all scenarios would also involve tree root competition across the whole of the alley so crop and pasture production would be further reduced.

It would be tempting to double the width of the tree belts and thus the alley width available for cropping. Where the perched aquifer was present this may be feasible since water draining below the crops may reach the hardpan and move laterally to be intercepted by the tree belts. Where the perched aquifer was not present, though, a simple doubling of row and alley widths may be less likely to succeed since trees were primarily relying on the soil below adjacent pasture for water reserves. If belts were more than two trees in width then middle rows may simply become more water stressed. Similarly, water draining below the crop/pasture in the middle of the alley out of reach of lateral tree roots might percolate directly to the ground water, contributing to further salinity and possibly not being later accessed by trees.

Note that the following calculations used in this report are based on recharge or uptake below the budget unit and do not take into account the additional effect of soil water drying by trees compared to pasture alone. If differential soil drying was also taken into account then lesser tree belt areas than derived here would be needed. Calculations presented in the journal format (Wildy *et al.*, submitted-b) using the same raw data did take into account additional soil drying and the proportions of trees calculated for hydrological balance was accordingly lower. However, this method may in turn be an

overestimation since trees used soil water at faster rates than deep water or groundwater as discussed above.

4.12 Water-use efficiency of saplings versus coppice

Water-use efficiency (WUE) is a term describing the efficiency with which biomass is produced in terms of the amount of water transpired. Plants that produce a greater amount of biomass for a given amount of water are more water-use efficient than plants producing a lesser amount. We used the transpiration and above- and below-ground biomass data to calculate WUE for saplings and coppice at the three sites (Table 4.6).

Coppiced trees produced biomass with much greater water-use efficiency than saplings did (Table 4.6). Coppiced trees produced 80 % of the shoot biomass that saplings did, and 50 % of the root biomass, but transpired only 53 % so the overall water-use efficiency was higher for coppice (2.31 g/L) than for saplings (1.77 g/L). The details of the physiology behind this are unnecessary for the current report but have been described in a separate paper (Wildy *et al.*, submitted-a). Eastham *et al.* (1994) also found water use efficiency of coppiced mallees to be higher than that of uncut trees when based on shoot biomass alone.

Table 4.6 Calculation of water-use efficiency of dry matter production (WUE) for *Eucalyptus kochii* as uncut saplings or October-cut coppice, calculated from biomass increases and transpiration over a 22 month period at three locations across the study paddock at Kalannie, Western Australia. Means subtended by different letters are significantly different ($\alpha = 0.05$).

	Above-ground growth increment (kg DM tree ⁻¹ *)	Lignotuber growth increment (kg DM tree ⁻¹)	Root growth increment (kg DM tree ⁻¹)	Transpiration (L tree ⁻¹)	WUE (g DM L ⁻¹)
Uncut saplings					
Site 1	9.1	1.1	3.3	6650	2.03
Site 2	8.2	1.0	3.0	7700	1.58
Site 3	13.3	1.6	4.8	11500	1.71
Mean	10.2	1.2 b	3.7 b	8620 b	1.77 a
Coppice					
Site 1	7.5	0.4	1.4	3660	2.54
Site 2	7.5	0.4	1.4	4270	2.17
Site 3	9.8	0.5	2.6	5800	2.23
Mean	8.2	0.5 a	1.8 a	4580 a	2.31 b

*DM, dry matter

In summary, high water-use efficiency of coppiced trees centred not around leaf level gas exchange but appeared to be more related to the use of the preformed root system. Compared to saplings, a lesser amount of assimilates fixed during photosynthesis need to be allocated to root growth in coppiced trees so more are available for shoot growth, which in turn allows for the production of more photosynthates. Coppiced trees also produced a greater number of thinner leaves for a given carbon investment, which also leads to greater overall growth rates, as does the higher leaf:stem

biomass ratio of coppiced trees. Physiological features that promote rapid growth can also promote high water-use efficiency on a whole-plant basis (Binkley *et al.*, in press).

Coppiced trees were also less water stressed than saplings due to their lower leaf area relative to root catchment so would need to invest less photosynthates into continuous production of new exploratory roots than would saplings. Use of the preformed carbohydrate reserves in coppiced trees may also be a reason for their high WUE, but this effect would only apply in the early stages of new shoot formation.

The practice of coppicing trees on short rotations would appear to be a particularly effective means of producing woody biomass in water limited environments.

4.13 Summary of main results

This part of the study described detailed measurement of the fate of rainfall on tree belts and adjacent pasture and its subsequent usage either directly or from water previously stored in the soil profile, or from perched or deep aquifers. It compared saplings and coppiced trees, both with and without access to a perched aquifer.

- Saplings transpired more water than coppiced trees, and coppiced trees were transpiring at only 60–75 % of sapling rates two years after cutting.
- Trees used more water than rainfall. Soils dried out directly under trees more than under pasture. Soils dried more under saplings than coppice.
- When trees did not have access to a perched aquifer, saplings sourced water from adjacent crop/pasture areas up to 12.5 m from the canopy edge and down to the hardpan (5–7 m depth).
- The alley farming layout is therefore important in tree productivity in such dry environments since land adjacent to the belt provides a large proportion of the trees' water.
- It appeared that saplings without access to a perched aquifer were also accessing water from below the hardpan although there was some uncertainty associated with the method of determination for this.
- Where there was a shallow, fresh perched aquifer below the tree belts, water use by both saplings and coppice was 40–60 % higher than for similar treatments lacking a perched aquifer.
- Over the 15 m wide belt/alley budget unit consisting of a 2.5 m wide tree and 12.5 m of adjacent cleared land, saplings with access to perched aquifer had a positive water budget, with net water uptake of 218 mm, as did coppice at the same site (30 mm net uptake). Saplings without a perched aquifer allowed 27 mm recharge equivalent to 5 % of rainfall over the period over the budget area, and coppice allowed the equivalent of 21 % of rainfall as recharge.
- Manipulating the proportion of tree and crop/pasture cover showed that 10 % of the landscape under twin row 5–7 year old sapling belts with intervening alleys of 44 m would have resulted in zero recharge when a perched aquifer was present. This increased to 17 % for coppice with a perched aquifer or saplings without a perched aquifer, and in these situations the intervening alley available for crop/pasture would be 22 m. For coppice without a perched aquifer, approximately 25 % of such areas would have been needed under trees, with cultivatable widths only 19.5 m wide.
- Coppiced trees were significantly more efficient in water use in terms of the amount of dry matter produced per unit of water transpired.

5. Discussion: managing water use and productivity

The data from this case study have shown that mallees can be successfully grown in belts through paddocks in the dry conditions of the Western Australian wheatbelt. Mean annual increments (MAIs) of 5–7 t dry matter/ha/yr (tree canopy area basis) would be produced if trees are cut on 2 year intervals or greater. These are respectable figures especially considering the very low rainfall at the site. By way of comparison, native vegetation in the area grows at rates of 1–3 t DM/ha/yr, the median rate of production in forests across the world is between 6 and 10 t DM/ha/yr (Cannell, 1989), and highly productive *Eucalyptus globulus* plantations in the higher rainfall south west of Western Australia produce in the range 15–25 t DM/ha/yr.

It is likely that alternative species or genera would exist that would be more productive initially than oil mallees, since the early development of a large root system in mallees reduces the rate of leaf production, which is the ultimate driver of plant growth rates. However the extensive root system probably allows the species to access water from great distance and depth and so survive drought periods such as experienced during the last year of this study. In addition, early production of a large lignotuber enables mallees to be capable of regeneration after harvesting at relatively young ages, and also on repeated rotations of very short intervals in comparison to the tolerance of many other species.

Indeed, mallees should endure repeated harvest as long as they are on rotations of 2–3 years. Cutting on intervals of less than 2 years would jeopardise the vigour of rootstocks after a number of harvests due possibly to a starvation of photosynthates to rootstocks and a lack of new secondary root growth between each cut. There are a number of other reasons favouring rotation lengths of greater than one to two years. Firstly, yields are increased by cutting on two to three year cycles rather than one year cycles, due to the small amount of growth in the first year after cutting (the ‘penalty year’). Secondly, from the point of view of salinity control, water use will also be low if trees are cut on less than 2 year rotations. Thirdly, the economics of the harvesting process would be enhanced by allowing trees to grow larger, e.g. into the third or fourth year (R. Giles, pers. comm.).

Planting trees in belts between tree-free alleys was integral to the relatively high productivity of the trees in this study given the low rainfall environment. Indeed, saplings transpired between 2.7 and 4.5 times the amount of rain falling directly on their canopies, or 7 to 13 times the amount of water actually available for transpiration after interception and soil evaporation of incident rain was taken into account. Most water transpired by trees without access to a perched aquifer was sourced from unsaturated soil stores below the trees and beyond the tree belt in the pastured alley. By the end of the study, these trees had dried the soil to 15 m from the tree belt centre (12.5 m from the canopy edge). A full 51 % of water transpired by saplings at sites without a perched aquifer was obtained from the adjacent alley (4–15 m from the tree belt centre).

The optimal position of tree belts is on localised sites where shallow, fresh perched aquifers exist since water use and thus productivity is high (40–60 % higher in this study than for trees without a perched aquifer). Water draining from soil below adjacent crop/pastures out of the reach of tree roots can later be intercepted by trees as the water moves laterally downslope in the perched aquifer. This is an ideal situation for tree biomass production in low rainfall areas. Only approximately 10 % of these areas would have needed to be under tree cover as saplings, or 17 % under coppice from 0–2 years since cutting. Of course, such values are specific to the site and rainfall conditions experienced before and during the study. In any event, while such areas contribute disproportionately highly to further salinity, areas with perched fresh aquifers are not a major proportion of the Western Australian wheatbelt and would comprise less than 5 % of the land surface in the Western Australian wheatbelt (D. Bennett, pers. comm., Lefroy *et al.*, 2001).

In contrast, a greater proportion of the land surface of the Western Australian wheatbelt would resemble the case of the trees growing without a perched aquifer and with a root-impeding layer at depth. Here, our measurements showed that at least 17 % of such areas would have needed to be covered in twin-row belts of saplings, or about 25 % as coppice on a two year cycle, in order to have reduced recharge to zero during this study. This also involved the entire alley between belts being explored by tree roots at sometime or other during the study period when the tree component consisted of saplings. This would result in high levels of competition with crops and pastures grown in these alleys and is thus likely to be a major problem with alley farming with trees left to grow as large saplings or trees. This would be more accentuated the shallower the root-impeding layer was to become. Cutting trees may be a means by which competition could be managed, as discussed further below.

The advantages of coppicing trees in water-limited areas such as the wheatbelt rather than growing large trees include

- short return times on investment
- no re-establishment costs after harvest
- reduction of competition with crops
- higher water-use efficiency
- growth rates of uncut trees may eventually reduce due to exhaustion of water resources

If salinity control is the major goal though, coppicing trees is less desirable since it results in lower water use for the following 2 years than if the trees were left uncut. This is mainly due to the slow growth, and hence water use, in the 'penalty year' following cutting, and by the third year water use would be expected to be similar to that of uncut trees.

The cutting regime could be viewed as a water management tool at the tree grower's discretion. For example, in a drought year when competition with adjacent crops is likely to occur and similarly deep drainage of soil water to recharge groundwater bodies is likely to be minimal, then the decision could be made to cut trees. On the other hand, if a wet summer had occurred then trees could be retained for the following cropping season since they would be able to utilise the excess soil moisture and convert this into extra tree biomass.

Manipulation of harvests could also be carried out in average seasons to coincide with crop rotations, so that small coppice was present coinciding with the most valuable crop. The part of the tree cutting cycle in which trees were largest could be timed to coincide with the least valuable part of the crop/pasture rotation e.g. as pasture when sheep could also benefit from the shelter afforded by the tree belts.

Future research would extend the findings of this study to a wider range of sites and species, for example testing the water use of trees on heavy clay sites. Devising 'ready reckoners' for estimating the optimal proportion of land required under coppiced trees would be useful so that (i) recharge was adequately managed and (ii) money and arable land was not wasted on excessive tree planting that was not able to be supported in maximum growth rates at a site in the long run. Ellis *et al.* (2001) provided a very useful system for tree belts in long term equilibrium at a site. An extension of this to deal with permanently-juvenile trees as is the case of short-rotation coppice silviculture would be useful. Long-term experiments to verify the ability of rootstocks to sustain early levels of productivity after repeated harvests are also needed. It is also important to test whether other species exist which can out-perform native mallee species in survival, productivity and long-term endurance following repeated harvests on short rotations.

6. Glossary

alley farming	where the tree component in an agroforestry system is concentrated into narrow belts creating cleared alleys available for cropping or pasture
aquifer	an underground saturated water body
capillary fringe	the soil above a saturated water body (such as the perched aquifer) which remains wet as a result of capillary rise
coppice	the regrowth following shoot harvest
cut	see 'harvest'
decapitate	see 'harvest'
deep drainage	water moving below the depth of crop/pasture or tree roots to cause recharge
dry matter (DM)	biomass that has been dried at 70°C to constant weight
field capacity	the moisture content of soil when it has been fully wet and then drained to allow excess water to leave
harvest	removal of the above-ground shoots of trees to within 5 cm of ground level
interception	the fraction of rain falling on a plants foliage that is directly evaporated from the foliage during or after the rain event
lateral root	a root growing more or less horizontally, usually more prevalent nearer the surface
lignotuber	the woody swelling at the base of the shoot at ground level commonly called a mallee root, which remains after harvest and houses meristematic bud sites from which new stems arise after harvest
mean annual increment (MAI)	a measure of average yield each year over a period of time. Expressed here as tonnes of above-ground dry matter per hectare of tree belt area per year.
meristematic bud sites	the cells located just below the bark on lignotubers and lower stems which give rise to new shoots after fire or harvest
mm equivalents	relating water use in litres to an equivalent depth of water in mm (e.g. as rainfall is usually expressed). Using the example of rainfall, note that the area which it refers to does not matter when rain is expressed in mm, but if it is expressed in litres then the area needs to be specified. Conversely, if a given volume of water in litres is said to have transpired through a tree, then the mm equivalents will depend on the area for which it is calculated over. This could be just the canopy area (high mm value over small area) or the whole paddock (low mm value over a large area). For conversions, value in litres = value in mm / area in m ² . One litre is equivalent to one mm of water spread over one square metre.
penalty year	the period after harvest when coppiced trees grow slowly as a new canopy is formed (see section 3.3 for example).
perched aquifer	an aquifer formed due to water percolating through soil and ponding above a relatively impermeable layer
photosynthates	the sugars produced by the process of photosynthesis
photosynthesis	the process by which plant convert carbon dioxide from the atmosphere into utilizable sugars using light as a source of energy
recharge	water not transpired by tree or crop/pasture and not held in the soil, draining below a specified depth (here the depth to which calculations were performed – to the hardpan where a perched aquifer was not present or to the top of the capillary fringe when a perched aquifer was present). This is presumed to eventually reach the ground water and contribute to further water table rises.
repeating unit	a repeating section of an alley farm, extending from the middle of the tree belt out half way out into the alley
rootstock	the lignotuber and root system, i.e. which remains after harvest

rotation length	the time interval between successive harvests
sapling	a tree that is intact and has never had its shoots removed by harvest
silviculture	the cultivation of, or management practices employed in growing, a stand of trees (literally 'wood culture')
sinker root	a root growing more or less vertically, also known as a tap root
starch	the major carbohydrate reserve material accumulated in woody plants providing an energy source for rapid growth or regrowth after cutting when photosynthesis alone is not sufficient for a plants sugar requirements
stemflow	the fraction of rain falling on a plants foliage that is channelled down stems to the soil surface
throughfall	the fraction of rain falling on a plants foliage that reaches the ground (without being channelled down stems)
water use efficiency (WUE)	a measure of the amount of dry matter produced per unit of water transpired

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