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Alley farming for improved water management and nutrient cycling

**A report for the
RIRDC / L&W Australia / FWPRDC / MDBC
Joint Venture Agroforestry Program**

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Foreword

The management of water in Australia's cropping landscapes is one of the major challenges facing rural industries over the coming century. With dryland salinity predicted to affect some 15 million hectares of cleared farmland over the next fifty to one hundred years, it is imperative we find cropping systems capable of making full use of Australia's low and unreliable rainfall.

Agroforestry systems have long been advocated as one approach to improve water management. This report describes research into the water use and yield trade-offs involved in alley farming systems where trees are mixed with crops and pastures. While this report deals specifically with alley cropping systems on sandplain soils, the principles involved and the research methods used are applicable to measuring the trade-offs between water use and crop yield in other environments.

This study will assist landholders and catchment managers in deciding when and where alley farming is appropriate, and adds to our understanding of the place of agroforestry systems in the agricultural landscape.

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This report, a new addition to RIRDC's diverse range of over 1500 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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Abbreviations

B value	the $\delta^{15}\text{N}$ value obtained from nodulated plants raised in the absence of mineral nitrogen (see $\delta^{15}\text{N}$ below)
DM	dry matter
DSE	dry sheep equivalent
dS/m	deci-Siemens per metre (a measure of salinity based on electrical conductivity)
EDM	edible dry matter
E_0	potential evapotranspiration (in this study, based on Penman-Monteith evapotranspiration)
NMM	neutron moisture meter (for manual measurement of soil water content)
TDR	time domain reflectometry (for continuous measurement of soil water content)
$\delta^{13}\text{C}$	ratio of carbon stable isotope (^{13}C : ^{12}C) in a sample relative to that in a universal standard, measured in parts per thousand (‰)
δD	ratio of deuterium (stable isotope of hydrogen) to hydrogen (D:H) in a sample relative to that in a universal standard, measured in parts per thousand (‰)
$\delta^{15}\text{N}$	ratio of nitrogen stable isotope (^{15}N : ^{14}N) in a sample relative to that in a universal standard, measured in parts per thousand (‰)
%Ndfa	% nitrogen derived from the atmosphere

Executive Summary

Introducing trees into farming systems has been advocated as a means of improving water and nutrient management in agricultural landscapes. The objectives of this project were to measure

- 1) the extent to which trees in an alley cropping configuration intercepted water and nutrients leaching below the root zone of adjacent crops
- 2) the amount of water taken up by the trees and the proportion taken up from soil and groundwater sources
- 3) the extent of competition for water between trees and crops
- 4) the effect of trees in an alley cropping systems on farm profit.

To address these questions, the growth, water use and nitrogen fixation of four-year-old tagasaste (*Chamaecytisus proliferus* Link) trees in alley cropping and plantation layouts and crop yields in the alley system were assessed over three years. The site at Moora, 150 km north of Perth, Western Australia was on a deep infertile sandy soil typical of the sandplain soil found along the western and southern margins of the Western Australian cropping zone. These soils also share characteristics with soils in the lower south east of South Australia and the Eyre Peninsula. Tagasaste has already achieved a significant level of adoption in these areas with an estimated 100,000 ha established, primarily for stock feed. A key question addressed in this research was to determine the potential role that a well adapted tree such as tagasaste could have in managing water in cropping systems.

Key findings

Water use: Despite a five-fold higher tree density in the plantation plots and higher soil water content in alley plots, tree growth and water use on a per tree basis were closely similar in the two layouts. Transpiration in plantation plots was also very similar in the second and third years of regrowth after cutting (850 and 870 mm respectively in 1997 and 1998). This represented 0.54 and 0.63 of potential evapotranspiration (E_0) and occurred despite a two-fold increase in total tree biomass over those two years. This surprising lack of difference between two quite different tree layouts was attributed to the increasing proportion of woody biomass over time in this fast growing species, the increased age of leaves and internal shading of leaves and the high levels of leaf fall in the plantation plots in response to the long dry summer. Interception by tree canopies in the plantation plots accounted for 38% of rainfall in 1998, being estimated to be 140 mm, giving total tree water use of 975 mm for that year. In short, the water use of trees in this environment was found to be energy limited in winter and water limited in summer.

Soil water vs ground water uptake: Deuterium analysis of water sources showed that trees at both densities drew on soil water for 90% of their transpiration in the first winter and 50% in the second, switching progressively to near total dependence on a perched fresh aquifer at 5 m depth each summer and early autumn. Seasonal changes in carbon isotope composition of new shoot tips indicated that by the third summer, plantation trees were less stressed than alley trees suggesting heavier dependence on groundwater. Evidence was found that tagasaste trees practice hydraulic lift, bringing groundwater to near-surface soil layers in summer and autumn. They also demonstrated an ability to respond rapidly to irrigation and summer rainfall by increasing transpiration rates two to three-fold, equalling potential rates of evapotranspiration

Deep drainage: Recharge to the perched water table (ie., deep drainage below the crop roots) was estimated to be 193 mm under sole crop (52% of rainfall) and 154 mm under alley crop (42% of rainfall) in the third year of the experiment. When uptake of groundwater by trees was included, net drainage under alley cropping reduced to 32 mm or 9% of annual rainfall.

Lateral influence of trees: Soil water uptake by trees in alley cropping was found to extend 2, 4 and 8 m laterally from the tree rows in their first, second and third years of regrowth respectively. Lateral extension of tree roots in alleys without crop was no greater than in alleys with crop, despite the absence of competition, lack of disturbance of surface tree roots and the fact the soil profile 8 m from the tree rows was never less than half full in alleys without crop.

Crop yield and profitability: The yield of lupins was 23% higher in alley crop than sole crop in the first year of the study while that of oats was 8% lower in the second year and lupins 32% lower in the third. The implications of this 30m alley system for farm profit under a lupin wheat rotation based on the first and second years results was that compared to sole crop, it would not break even until year seven. For older trees with greater lateral root extension and higher competition as seen in year three, the breakeven period would be likely to extend even further.

Nitrogen fixation and uptake from soil: In terms of the potential of tagasaste trees in alley cropping to address nitrogen pollution, both alley and plantation trees were found to derive 83% of their nitrogen from the atmosphere. Inputs of fixed nitrogen to standing biomass and leaf litter were estimated to be 83 kg/ha/yr for alley and 390 kg/ha/yr for plantation trees over the first two years of regrowth. In their second year of regrowth after cutting, the plantation tagasaste trees fixed a massive 587 kg N/ha, at the top of the range reported in the literature for any woody legume. While this large input of N would have great potential benefit if cut for fodder, it has potentially negative implications in terms of nitrate pollution of aquifers, soil acidification, and also suggests that there would not be significant interception of nitrogen leached from the crops in a tagasaste alley system.

Conclusion: It was concluded that for water management, plantations would be a more appropriate strategy for than alley cropping, given that trees in alley cropping used no more water than trees in plantation, reduced crop yield by an average 20% over the second and third years and relied heavily on the presence of a shallow fresh aquifer, a very localized phenomenon at catchment scale. It was estimated that 24% of a catchment of this type would need to be established to tagasaste plantations cut and grazed on an 18-month rotation and 20% if trees remained uncut to manage water tables.

1 Background - tagasaste in Australian farming systems

1.1. Introduction

Tagasaste (*Chamaecytisus proliferus* [L. fil.] Link subsp. *proliferus* var. *palmensis* [H. Christ] A Hansen and Sunding) (Fabaceae:Genisteae) is an evergreen tree legume endemic to the Canary Islands (27° 50'–29° N; 13–18° E) . Reaching 4 to 5 metres under favourable conditions, it is closely allied to the brooms and gorses. Attention was drawn to its economic potential for livestock production by Dr. Victor Perez who described its very localized occurrence at an elevation of 1000 m on loose volcanic scoria and ash on the island of La Palma, (Perez 1865 quoted in Anon 1893). Noticing that local farmers had collected seed from these wild populations and were cultivating the trees as a source of fodder for domestic animals, he introduced it into cultivation on the island of Tenerife and described its merits as a fodder tree.

Francisco-Ortega *et al.* (1990, 1991, 1993) have described seven morphological forms of *C. proliferus* endemic to the Canary Islands, known variously as tagasaste, white tagasaste and escobon (Spanish for broom). Only one of the morphological forms described by Perez as originating from La Palma is readily eaten by stock. Mendez (1993) reported that some 5 000 ha of this form was under cultivation throughout the archipelago.

Tagasaste was introduced to Australia in 1879 when seed was sent from the Royal Botanic Gardens, Kew to the Botanic Gardens in Sydney and Adelaide. It is now reported as naturalized in Australia, New Zealand, South Africa, Java, Hawaii and California, but only cultivated for stock feed in Australia and New Zealand (Francisco-Ortega *et al.* 1990). It is believed to have been introduced to Western Australia by settlers from South Australia (Snook 1986) and was soon adopted as a reliable source of protein for poultry production during the period of feed shortage during summer and autumn. Long before its broadacre use as fodder for sheep and cattle, tagasaste was a common sight planted around homesteads for this purpose.

Early reports indicated a marked difference of opinion between the Director of the Adelaide Botanic Gardens and a botanist from the New South Wales Department of Agriculture as to value of tagasaste (Schomburgk in Anon 1891, Turner in Anon 1891):

‘The tagasaste has found a most suitable and congenial climate in South Australia, flourishing alike in wet and dry seasons. I have frequently drawn attention to the value of this plant in my reports of previous years, and during that time have distributed seeds for cultivation. It seems to me that in matters of this kind, both the pastorists and agriculturalists have hitherto shown a most remarkable degree of apathy. Considering that the most severe drought does not affect it at all, it would be advisable for every farmer to plant every spare corner of his land with tagasaste’.

Dr. Schomburgk, Adelaide Botanic Gardens, 1888

‘A Canary Island shrub called tagasaste is now occupying much attention in some quarters, which experience will eventually prove to have been misdirected. I have observed this shrub for a number of years, having raised from seed some of the first plants ever seen in Australia. I have a shrub now under my charge which is about 15 feet high, but I can firmly assert that an old man saltbush would at the same age have produced about twice the amount of a superior fodder, and would grow in even more adverse circumstances of drought and heat’.

Mr. Frederick Turner, Department of Agriculture NSW, 1889

These accounts remain a fairly accurate reflection of the regard in which this plant is currently held in the western and eastern parts of the continent, reflecting differences in geology and climate. The early history of tagasaste in Australia featured several enthusiastic champions of its wider use, notably

Schomburgk (cited in Anon 1893), Maiden (1915), and Snook (1952, 1961) but lack of sound empirical data and practical difficulties associated with its use meant that it was not until the late 1980s that large-scale adoption began.

Since that time, interest has developed in the broader integration of tagasaste into dryland farming systems for salinity management, wind erosion control and soil amelioration. The successful development of such multi-purpose agroforestry systems requires a deeper understanding of the plant than has been necessary to date for its development as a fodder crop. Its growth pattern, water use, adaptation to heat and water stress and interactions with crops and pastures are currently poorly understood. This chapter reviews the current state of knowledge on tagasaste as background to subsequent chapters on the water use, growth, nitrogen inputs and energy use efficiency of tagasaste alley cropping and plantation systems.

1.2. Plant growth and edible dry matter production

Early reports from South Australia indicated that the trees grew better in sandy soil than heavier ground, reached their mature height of 4.6 m within three years, and were best established at a density of 2.5 to 3.5 m apart i.e. 800-1600 trees/ha (Schomburgk quoted in Anon 1891). It was also noted that the cut branches were readily eaten by sheep and cattle and that the trees could be cut two to three times over summer after which they rapidly refoliated.

The first measurements of dry matter (DM) production were reported by Snook (1952, 1961) from a small experimental plot on deep sands at Perth, Western Australia (annual rainfall 875 mm). Edible dry matter (EDM) production for three-year-old trees cut once a year was 16 kg/tree although the density was not reported. Snook (1986) later extrapolated this to suggest that a yield of 11.2 t EDM/ha was possible assuming a density of 700 trees/ha. Subsequent measurements of tagasaste EDM are summarised in Table 1.1, together with levels of conventional herbaceous pasture production reported for the same locations.

The data of Table 1.1 show that tagasaste only represented a clear advantage over conventional pastures on deep sands. The relationship between annual rainfall and tagasaste production across the five sites ($r^2 = 0.70$) is 6.1 kg EDM/ha per mm of annual rainfall. Annual pasture production in the wheatbelt of Western Australia by comparison is within the range of 10 to 25 kg/ha/mm of growing season rainfall, based on experimental data across all soil types (MA Ewing unpublished data). While one relationship is based on growing season rainfall and one annual rainfall, direct comparison is not possible. However, it is apparent that tagasaste production is at or below the bottom of the range for annual pastures. This helps to explain why it is only on the deep infertile sands in Western Australia and South Australia that interest in tagasaste for animal production has been maintained.

Four studies have examined the influence of plant density on tagasaste DM production. Milthorpe and Dann (1991) in New South Wales and Wiley and Maughan (1993) in Western Australia both found that production from mature trees (>3 years old) receiving annual rainfall in the range 420-450 mm/yr peaked at a density of approximately 800 trees/ha. At 640 mm annual rainfall, Milthorpe and Dann (1991) found production peaked at 8000 trees/ha while at 1100 mm/yr, McGowan and Matthews (1992) measured peak production at a density of 20 000 trees/ha. McGowan and Matthews (1992) also clearly demonstrated the summer active growth pattern of tagasaste with winter, spring, summer and autumn growth accounting for 9, 32, 46 and 13% of annual production, respectively.

Table 1.1. Edible dry matter production from three-year-old tagasaste trees and dry matter production of herbaceous pastures from five sites in southern Australia.

Rain (mm/yr)	Soil type	Tagasaste EDM (t/ha/yr)	Herbaceous pasture DM (t/ha/yr)	Ratio tag/pasture (EDM/DM)	Source and location
350	Deep sand	3.2 ^a	2.5 ^b	1.3	Eastham <i>et al.</i> (1993), Wongan Hills WA
420	Red-brown earth	1.1	2.3	0.5	Milthorpe and Dann (1991), Condobolin NSW
450	Deep sand	3.0	0.8	3.8	Oldham <i>et al.</i> (1991), New Norcia WA
640	Podsol	2.0	4.0	0.5	Milthorpe and Dann (1991), Yass NSW
1100	Red gradational	7.9	10.0	0.8	McGowan and Matthews (1992), Ellinbank Vic.

^a based on reported fresh weight assuming 35% DM of which 55% is edible

^b based on 10 kg/mm of growing season rainfall (MA Ewing pers. comm.)

Studies of feed quality (Snook 1961, Borrens and Poppi 1990, Oldham *et al.* 1994) suggested that tagasaste contained sufficient protein (14-27%) and energy measured as *in vitro* DM digestibility (65 - 80%) to maintain high animal growth rates throughout the year. However, reports of EDM yield and *in vitro* nutritional value were apparently insufficient to inspire confidence in this novel forage system, even on deep sands. Snook (1986) attributed the very limited adoption of tagasaste to poor establishment due to hardseededness, predation by rabbits, the impracticality of the cut-and-carry fodder system, damage to trees through over-grazing and set stocking and 'lack of courage' on the part of land owners. It was not until large-scale animal production experiments in the late 1980s demonstrated the practicality of *in situ* grazing and the profitability of tagasaste that significant adoption began.

1.3. Animal production and grazing management

Schomburgk (in Anon 1891) reported that when fed to cattle, each 40 kg of tagasaste fodder produced 1 kg of flesh (*sic*). Assuming 'flesh' refers to the dressed weight of an animal, and the tagasaste feed is expressed in terms of edible fresh weight, this conversion rate is strikingly similar to that reported by Oldham *et al.* (1991, 1993). The latter reported that 3000 kg EDM/ha (approximately 7500 kg/ha of edible fresh weight) could produce 350 kg/ha/yr live weight (approximately 175 kg/ha dressed weight), giving a conversion rate of 43:1 compared to 40:1 in the case of Schomburgk.

While the cut-and-carry system did not suit the extensive nature of animal production, direct grazing was also found to be impractical as trees out grew the reach of browsing animals and were often killed through bark stripping (Snook 1986). The development of pruning machinery in the 1980s saw the first studies of performance of animals grazing mechanically cut hedgerows. The expectation was that tagasaste could be used to maintain body weight and wool growth rates year round.

Oldham and Moore (1988) demonstrated that production of 3000 kg EDM/ha/yr was sufficient to maintain the body weight of young sheep at a stocking rate of 30 dry sheep equivalent (DSE) per hectare over 100 days, the approximate length of the annual autumn feed shortage. This represented an eight-fold increase in year round carrying capacity for these deep sands. This system gave the trees a nine month period of recovery from cutting and grazing and hence prevented damage from prolonged exposure to grazing. Based on these levels of production, Oldham *et al.* (1991) suggested that planting 10% of the typical Western Australian sheep/wheat farm to tagasaste would substitute for grain and

other supplementary feeding. Assuming a 20-year plantation life, this represents a return to investment of 20% (Mattinson and Oldham 1989). While increases in clean fleece weight of 25-30% were also demonstrated in young sheep (Oldham *et al.* 1991), associated changes in fibre diameter meant there was no consistent commercial advantage.

Research shifted to cattle production following a sharp downturn in wool prices in 1990. Early work suggested that liveweight gains of 0.6 kg/head/day were possible over summer (Oldham *et al.* 1994). Later work has indicated that cattle continuously grazing tagasaste required grain supplements to maintain these growth rates over summer (Costa *et al.* 1995, Tudor *et al.* 1995).

Continuous grazing of tagasaste with cattle proved to be a breakthrough. The resulting low, compact hedgerows had a high leaf to stem ratio, were subject to far less damage than when grazed with sheep and did not require frequent cutting. In the five years following the outcome of the first grazing experiments, an estimated 50 000 ha was planted in Western Australia (Maughan and Wiley 1994) and 1000 ha in south eastern South Australia and north western Victoria (R Peake personal communication). By 1999, an estimated 100 000 ha had been established in Western Australia (G Tudor personal communication).

Growth rates of sheep and cattle grazing tagasaste are still considered to be lower than would be expected from its nutritional composition (Tudor *et al.* 1995). Several feeding experiments with sheep (McGowan and Matthews 1987, Borrens and Poppi 1990) and cattle (Brammar and McGowan 1990) have shown lower production from tagasaste than alternative feeds. Lower levels of intake and poor rumen function (Edwards *et al.* 1995) and poor mineral nutrition of animals grazing tagasaste (Costa *et al.* 1994, McGowan *et al.* 1995, Edwards and Allen 1998) lead to research on secondary compounds in tagasaste. The phenolic group was the initial focus of attention (Fortune and Bailey 1993, Thye 1996) but results have been inconclusive. Research is also underway examining the feasibility of developing weeping or dwarf cultivars from naturally occurring forms in order to overcome any requirement for cutting (Barton and Hamblin 1999).

1.4. Multipurpose agroforestry systems

Dann and Trimmer (1986) suggested tagasaste deserved attention as a multipurpose agroforestry species as it produces fast growing shelterbelts and fixes atmospheric nitrogen in addition to producing fodder. Snook (1986) and McGowan (1991) describe its multipurpose use sixty years ago when double-fenced hedgerows were used as paddock boundaries, windbreaks and fodder reserves.

In the early 1990s, landholders in Western Australia and the lower south east of South Australia began experimenting with alley cropping systems where crops are cultivated between wide spaced rows of trees (Lefroy and Scott 1994, Stirzaker and Lefroy 1997). This is generally practiced to control wind erosion but it is also commonly assumed that there will be beneficial effects on crop and pasture yields through microclimatic effects and that paddock scale water use will increase, reducing deep drainage. Tagasaste and *Acacia saligna* are the most commonly used species on deep sands.

The expectation of benefits for crop yield was originally based on an international review of the effects of windbreaks on crops (Kort 1988) and work indicating improvement in pasture production in the lee of windbreaks in western Victoria (Bird 1991). Grain yield in one commercial tagasaste-lupin alley cropping system however was found to be 20% lower than the open paddock yield, most likely due to the increased frost damage observed in the more sheltered alleys (Lefroy and Melvin 1996). A three year study involving a range of crops at four sites across Australia has shown no significant benefit to crop yield from the presence of shelterbelts (Carberry *et al.* in press).

Growing awareness of the scale of the salinity problem has renewed interest in the integration of trees into farming systems to increase water use, particularly in areas where no herbaceous perennial options exist. Sandplain soils over 1m in depth suited to tagasaste constitute some 20% of the cropping zone (Carder and Grasby 1986) with an estimated 20% of this area overlying fresh aquifers (George 1992).

To estimate the proportion of land required under perennial vegetation to manage water tables, it is necessary to know the amount of water that is currently in excess of crop and pasture water use and the water use of trees. Several studies have attempted to measure the water use of tagasaste trees. Using the ventilated chamber technique (Engel 1986, R Engel and PR Scott cited in Raper 1998) estimated tagasaste water use on a duplex soil in a 500 mm rainfall zone to be 408 mm/yr, (0.27 pan evaporation). Eastham *et al.* (1993) used water balance to estimate the water use of three-year-old trees at 562 mm/yr in a 350 mm/yr rainfall zone (0.20 pan evaporation), and reported that tree biomass declined in subsequent years as soil water reserves that had accumulated under annual cropping became depleted. Speed *et al.* (1993) monitored the effectiveness of revegetating an entire small catchment with tagasaste, reporting that while the local perched aquifer dried up, the deeper regional system continued to rise at approximately 0.2 m/year, highlighting the importance of the scale of revegetation required.

Studies that are restricted to measuring total tree water use, however, provide no information on the proportional uptake of soil and groundwater by the tree where this is accessible. Neither do they provide information on the lateral and vertical extent of the trees' capture zone, or the extent to which trees compete with annual plants for available soil water. Such information is necessary to determine whether spaced agroforestry systems represent any advantage over dense, segregated tree planting in terms of water use per unit area occupied by tree canopies. Where the water use of spaced trees is higher than dense plantings, they can be used to de-water the agricultural landscape with minimal displacement of agricultural production. There is also the question of the impact of grazing and harvest of multipurpose systems on leaf area and tree water use.

Some hydrologic modeling has suggested that vegetation planted diffusely across the landscape is more likely to impact on the large scale processes responsible for rising water tables and salinity than dense, segregated plantings even though the total area under trees may be similar (Raper and de Broekert 1996, Clarke *et al.* 1998). However, these studies involved assumptions about temporal and spatial patterns of tree water uptake and the impact of trees on crops and pastures for which there is no empirical support.

In short, there is a lack of sound empirical evidence for the economic and environmental benefits of highly integrated agroforestry systems such as alley cropping. Adoption of tagasaste for animal production did not take place until its economic advantage over conventional feeds had been well established, despite the presence of enthusiastic advocates for its wider use for almost one hundred years. In a similar way, landholders are unlikely to adopt alley cropping or other spaced agroforestry systems until there is evidence of economic and environmental benefit to the landholder, despite encouragement from government agencies in search of strategies for salinity management (eg. Western Australian Government 1996).

The expectation that there will be benefits to the landholder and the landscape from the close integration of trees and crops is often based on the assumption that as trees are deeper rooted than crops, competition for resources will be minimal. Some studies of integrated agroforestry systems, however, have found crops to be deeper rooted than the trees, resulting in a high degree of competition (Dupraz *et al.* 1998). Studies of alley cropping in Africa have shown that in water limiting environments, competition between trees and crops for water increases the risk of crop failure compared to monocultures (Ong 1995), particularly when fast growing tree legumes like *Leucaena leucocephala* are used. As a result, the adoption of alley cropping in the semi-arid tropics has been low, despite twenty years of extension effort based on putative benefits to soil fertility and crop yield.

The implication is that where trees are closely integrated with crops, advantages over the production of crops in monoculture are only likely to occur if there is complementary use of limiting resources. Complementarity between trees and crops is potentially based on spatial, temporal and functional differences in patterns of resource acquisition (Ong *et al.* 1996). In other words, differences in root architecture, phenology and specialised means of resource uptake, such as nitrogen fixation, proteoid roots and hydraulic lift.

Where trees are the only biological option to increase catchment scale water use, the key decisions that have to be made are what proportion of the landscape requires planting and whether this should be in the form of segregated blocks or integrated agroforestry systems. The basis for this decision will be whether integrated systems involve a larger gain in production over segregated systems, or a smaller loss. To assess the long-term sustainability as well as shorter-term commercial viability of such multi-species systems, their impact needs to be assessed by some measure of resource use efficiency as well as conventional economic terms. Such farming systems need to be tested at an appropriate scale, and the underlying biological processes understood if effective integrated systems are to be applied across a range of environments.

1.5. Outline of this report

Chapter 2 Agroforestry for water management. This chapter begins with an examination of the features likely to govern the effectiveness and profitability of agroforestry systems designed to manage rising water tables. A framework for Australian conditions is then presented that considers the interactions between trees, crops and their below ground environment and how these interactions are likely to influence water use, crop yield and profitability. The application of this framework is then illustrated using data on tree water use, crop yield and projected crop gross margins from a three-year field study where trees had access to a shallow fresh water table, amongst the most favourable conditions likely to be encountered. The discussion is then broadened to encompass soil, relief and groundwater conditions more typical of the southern Australian cropping zone. The relative merits of segregating, integrating and rotating trees with crops are then explored.

Chapter 3 Growth and water use of tagasaste. The growth and water use of tagasaste trees in alley and plantation layouts are compared. The morphological, phenological and physiological characteristics of mesophytic (soft-leaved) trees such as tagasaste that enable them to adapt to the severe semi-arid climate of the southern Australian cropping zone are then discussed. Features discussed are i) root architecture and nodulation, ii) growth, transpiration and water use efficiency, iii) relative dependence on soil and groundwater, iv) water stress and response to summer drought, and v) response to episodic recharge of the soil profile over summer and evidence for hydraulic lift.

Chapter 4 Water balance of a tagasaste alley cropping system. This chapter presents data on the components of the water balance for the alley crop and sole crop treatments. Data are presented on the extent to which tree rows 30m apart intercepted water draining below inter-cropped lupins in the third year of the experiment. The aim of this component of the experiment was to measure i) the amount of water used by alley trees, ii) the proportion that came from soil and groundwater, and iii) the impact of trees on deep drainage. The concept of a no-drainage/no-yield ratio is introduced as a way of quantifying the trade-off between crop yield and water management in an agroforestry system. This is the ratio of the lateral influence of the trees on reducing deep drainage to zero to their lateral influence on reducing crop yield to zero. Where this ratio is greater than 1, i.e., where the influence of trees on drainage is greater than their influence on yield, it suggests alley cropping would be a more appropriate strategy for water management than plantations.

Chapter 5 Nitrogen fixation by tagasaste trees in alley and plantation layouts. This chapter describes the use of ^{15}N natural abundance technique to quantify the nitrogen inputs by tagasaste trees in alley cropping and plantation systems. Of interest here is the potential of trees to take up nitrogen that is leached below the root zone of annual crops. The high levels of nitrogen fixation measured in this experiment suggest that tagasaste is unlikely to play a significant role in the uptake of soil nitrates and in fact may present problems of its own in terms of nitrate pollution and acidification.

Chapter 6 Synthesis and conclusions. This chapter reviews the findings of the previous chapters and examines their implications for the role of agroforestry in cropping systems in southern Australia.

2 Agroforestry for water management in the cropping zone of southern Australia

2.1. Introduction

This chapter investigates the degree of intervention required to manage rising water tables through the reintroduction of trees into an agricultural landscape and the impact this is likely to have on crop yield and profitability.

2.2. Determinants of water use in a tree-crop system

The tree-crop system represented in Figure 2.1 can be regarded as the smallest repeating unit in an agroforestry landscape. To be acceptable to farmers we must be able to demonstrate its profitability. To be creditable to hydrologists we must quantify the average drainage through the tree-crop unit. Profitability can be summarised by the expression given by Lefroy and Scott (1994) as

$$\text{Net benefit} = T - Y1 + (Y3 - Y2)$$

where T is the value of the tree products, Y1 is the value of crop/pasture displaced, Y2 is the value of crop/pasture lost due to competition with trees and Y3 is the value of increased crop/pasture or stock yield due to shelter, reduced waterlogging, falling water tables or other effects of the trees.

Reducing drainage to an acceptable value will require a certain area under trees and the distribution of tree roots into part of the crop root zone (S2) and the zone immediately below it (S3). Factors that increase water capture will in most cases decrease productivity, necessitating a delicate balance between these two management objectives.

Crop water use

Central to the argument of reintroducing trees is the fact that the agricultural landscape leaks more water than the pre-existing vegetation. Quantification has been notoriously difficult because drainage is normally calculated as the difference between evapotranspiration and rainfall and contains the errors inherent in both these measurements. In a review of the literature, George *et al.* (1997) report at least a 100-fold increase in deep drainage following clearing in the lower rainfall areas, from <0.1 mm/yr to >10 mm/yr. Peck and Hurlle (1973) used catchment scale chloride balance to estimate rates of recharge since clearing in the 500-1000 mm annual rainfall zone of south western Australia. Their estimate of recharge in seven cleared catchments ranged from 23 to 430 mm/yr (3% and 38% of rainfall respectively) with a mean of 10% of annual rainfall. Values at the high end of this range have been reported for deep sands at Moora (mean annual rainfall 462 mm), the site that is the focus for this study. Combining continuous measurement of soil water and a model using 80 years of historical weather data, Asseng *et al.* (1998) report the median drainage below the root zone of annual crops at Moora to be 140 mm/yr or 30% of annual rainfall.

Attempts to increase evapotranspiration by manipulating winter-growing crops and pastures are limited by three characteristics of the southern Australian environment. Firstly, there is the asynchrony between the seasonal patterns of temperature and rainfall, resulting in a surplus of water over the winter months. Secondly, many of the crop-growing soils have a low water holding capacity or subsoils hostile to root growth with the result that annual rainfall can not reliably be stored within the rooting depth of annual plants. Thirdly, the high variability in rainfall amount and distribution results in occasional large episodic events outside the winter growing season for which there is no effective avenue of transpiration in the agricultural landscape. The argument that increasing the yield of annual crops will result in significant increases in evapotranspiration and a subsequent decrease in deep drainage has been challenged by studies showing that increases in crop transpiration are largely achieved at the expense of soil evaporation, not drainage, with little change in total evapotranspiration (eg. Smith *et al.* 1998).

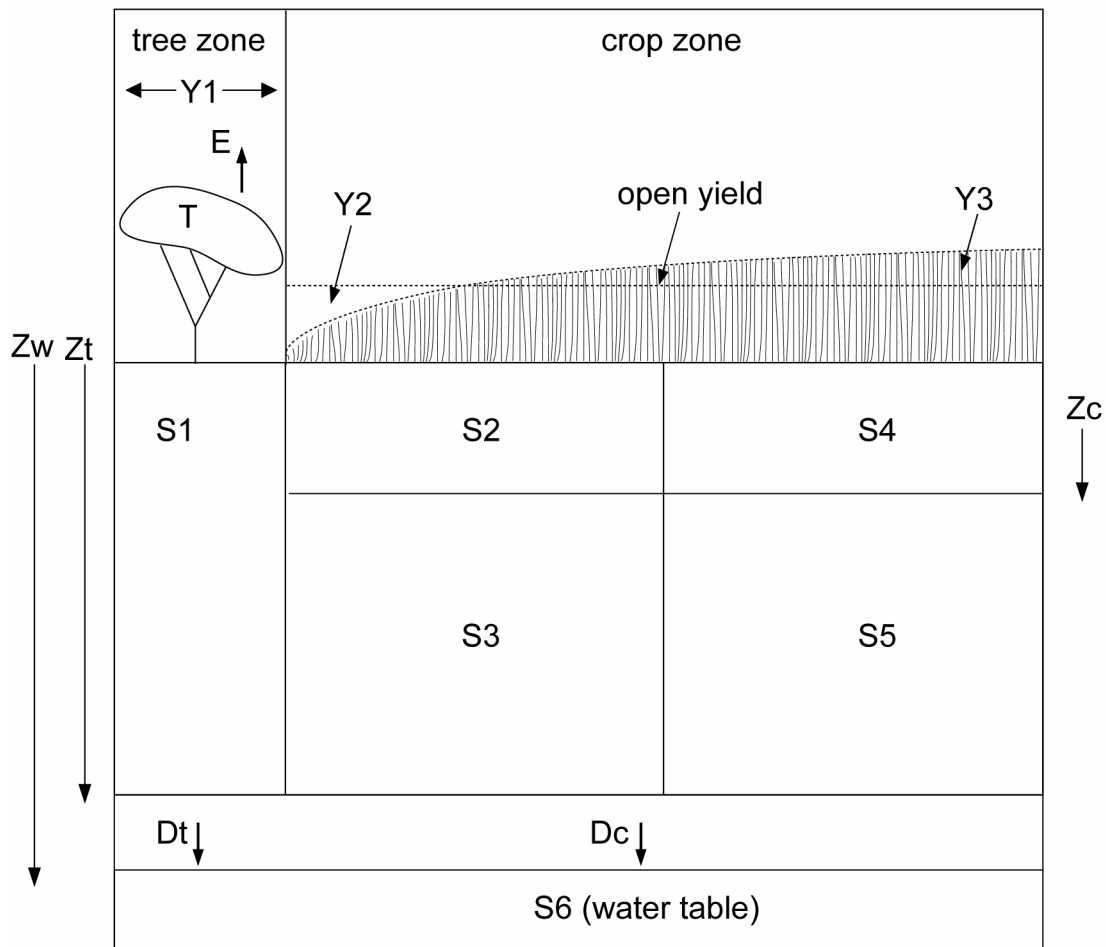


Figure 2.1. The interactions between trees, crops and their below ground environment in a simultaneous agroforestry system. The variables that determine the effectiveness of water management are crop rooting depth (Z_c), tree rooting depth (Z_t), depth to water table (Z_w), size of the soil zones occupied by tree roots (S1, S2, S3) and crop roots (S2, S4) and neither (S5), the transmissivity and salinity of the saturated zone (S6), tree water use (E), and drainage (Dt, Dc). The variables that determine profitability are the value of crop displaced by trees (Y1), direct value of tree products (T), yield foregone in the competition zone (Y2) and yield increase due to shelter effects outside the competition zone (Y3).

Tree water use

Drainage under native vegetation in lower rainfall zones of southern Australia was negligible because, over the long term, leaf area index adjusted to match rainfall (see Hatton and Nulsen, 1999). In the <600 mm rainfall zone, it is reasonable to assume that water use of trees in native vegetation is constrained by rainfall and not by the trees' physiological capacity to use water. However, in a spaced agroforestry system where water is left unused by crops, it is the area of land that tree roots can explore, and not rainfall, that has a greater bearing on tree water use. Theoretically, tree water use would then be limited by the energy absorbed by the canopy, and could be several times higher than annual rainfall on a projected canopy area basis. If this is the case, it may be possible to mimic the water balance of the natural system using a fraction of the land under trees with a high leaf area index and the rest under crops. Stewart (1984) used this approach to calculate the percentage of land area required under trees (A) to prevent water table rise:

$$A = (R - E_{\text{crop}}) / (E_{\text{tree}} - E_{\text{crop}})$$

where R is the annual rainfall and E_{crop} and E_{tree} are the annual average water use of crops and trees respectively.

Even with tree water use at only 50% of pan evaporation, the above equation gives cause for optimism. For example, if annual rainfall is 500 mm, annual crop evapotranspiration 400 mm and trees could potentially use 1200 mm, then the proportion of a catchment which must be reforested to eliminate drainage is 12%. This would seem an achievable objective.

Experience suggests, however, that the above example is flawed on two counts. Firstly, although rates of tree water over 1200 mm/yr have been reported over short periods for irrigated plantations and sites over shallow water tables (Myers *et al.* 1996, Marshall *et al.* 1998), they seem to be the exception. Annual water use of less than 1000 mm is the norm (Raper 1998), even when trees have apparent access to water stored either laterally or deep in the subsoil. A second more serious flaw is the assumption that trees could access and transpire all the water unused by crops. This would require absolute complementarity between tree and crop water use, a most unlikely scenario that is dealt with in the next section.

Unsaturated soil stores (S1, S2, S3, S4, S5)

The store of water under the tree canopy (S1) is determined by the rooting depth of the tree and the water holding capacity of the soil. For mature jarrah trees (*Eucalyptus marginata*) in this region, rooting depth may be 15 to 20 m (Kimber 1974). However, it is the rooting pattern beyond the tree canopy that is critical to the success of agroforestry. The ideal root morphology of species introduced for water management would be a low root length density in the topsoil with extensive lateral distribution below the rooting zone of annual plants. This would minimise competition with crops, act as a safety net for leaching nutrients and provide a buffer against recharge. Such a strategy is, however, at odds with the characteristics of the below-ground environment of this region. Endemic and well-adapted introduced summer-active trees on sandplain soils exhibit a dimorphic structure suited to a water uptake pattern of retrieval following winter drainage rather than interception at the time of rainfall. The extensive lateral roots are probably more important for the capture of nutrients, rather than water (Pate *et al.* 1984, Dawson and Pate 1996, Pate and Bell 1999) and this would explain why they tend to be confined to the topsoil.

There is little information on the dimensions of soil store S2. Zohar (1985) reported that roots from a *Eucalyptus* windbreak spread 20 m into an adjacent cotton field in the top 0.8 m of soil, resulting in considerable competition. Least information of all exists for soil store S3, the zone critical to the success of agroforestry, as this is where trees are never in competition with crops. Data from Eastham *et al.* (1990) suggest that trees at low densities develop shallower rooting patterns. This presents a challenge for agroforestry that relies heavily on spatial complementarity between spaced tree and crop roots.

The essential factor in exploiting the unsaturated soil stores is the presence and density of tree roots in a particular zone. Unsaturated soil transmits water so slowly that water as little as 1 m from the edge of the root zone is unavailable to the tree. Stirzaker *et al.* (1999) describe a capture zone beyond the tree root zone where deep drainage can be controlled without competition with crops. The capture zone operates when rain moves through a wet crop root zone (S4) adjacent to a dry tree root zone (S3). Water that has moved through the crop root zone is pulled sideways towards the dry tree root zone under the influence of capillary forces at the same time as it moves downwards under the influence of gravity. However, the capture zone does not operate over a distance of more than 3 m from the extremity of the tree root zone and would not, in most cases, increase the ability of trees to capture significant additional water in an agroforestry context.

In summary, drainage from S1 will be negligible in the <600 mm rainfall zone, except on coarse sandy soils. We may expect drainage to be low from S3, where tree roots can capture water from both the topsoil and subsoil. Drainage from S5 would be higher than S3 (as S5 contains no tree roots). Some competition will be inevitable in zone S2, but this could be minimised by selecting for maximum

temporal complementarity between tree and crop (Ong *et al.* 1996, Ong and Leakey 1999). Questions that remain to be answered include: 1) what root length densities are required in each zone to manage recharge? 2) what degree of variation in root architecture can be found in well adapted tree species? 3) is root pruning effective in limiting competition?

Saturated soil store (S6)

The saturated zone is a potentially important store of water, particularly as the area of land where water tables are within range of tree roots is increasing. When trees take up water from the water table or the capillary fringe above the saturated zone, water will be replaced laterally at a rate proportional to the saturated hydraulic conductivity of the soil and the gradient generated by the localised drop in water table beneath the tree. Because the saturated conductivity of soil is orders of magnitude greater than the unsaturated conductivity, the influence of the tree on the water table level can be seen over a considerable horizontal distance. With reference to Figure 2.1, if the roots in S1 reach the water table, the tree can access water that has drained below S3 and S5 via the saturated zone. Thus, unlike the unsaturated case above, trees can potentially protect a large area outside the physical extent of their own roots. For example, a belt of trees drawing on a water table can use all the water that drains through the crop root zone for a distance of 30 m beyond the physical extent of their roots in a clay soil and 400 m in sand. These distances can be calculated using estimates of the saturated conductivity of the soil, the depth of the saturated layer, the rooting depth of the trees and the annual drainage (Stirzaker *et al.* 1999).

The ability to switch rapidly between alternative water sources, such as near surface soil water and groundwater, is an important adaptation to difficult environments, which has been reported in several endemic tree species (Thorburn *et al.* 1995, Mensforth and Walker 1996, Dawson and Pate 1996). However, the ability of trees to use water from the saturated zone is severely limited by salinity. When trees use water from the water table, salts dissolved in the groundwater will concentrate in the root zone of the trees, because roots exclude almost all the salt at the root surface during transpiration. Even if salt tolerant vegetation is used, the faster that groundwater is used, the faster the salt levels will build up in the soil.

If the groundwater is already moderately saline (>5 dS/m), then the maximum salinity in the capillary fringe at which trees use minimal water is reached within a couple of years or less (Thorburn *et al.* 1995, Stirzaker *et al.* 1999). Under such circumstances trees will use less than 0.5 mm/d from the water table and their impact on groundwater levels will be small (George *et al.* 1998, Smith *et al.* 1998). In fact planting trees or fodder shrubs in saline discharge areas, whilst making best use of the land, cannot provide a cure for the problem of salinity unless mechanisms exist for flushing away salts that have accumulated in the soil profile.

Tree-crop interactions

When the tree and the crop are both drawing on limited resources from the same pool they are in competition. The skill in agroforestry design is to minimise the competition and maximise the complementarity between the two species. Complementarity occurs in a tree-crop mixture when the mixture 1) uses a greater fraction of a limiting resource and/or 2) either component makes more effective use of a limiting resource than sole crops (Ong and Black 1994, Cannell *et al.* 1996). Examples of greater resource capture include trees extracting water unavailable to crops by virtue of spatial complementarity or temporal complementarity (using off-season water). Examples of more efficient resource use include the greater water use efficiency in the 'quiet zone' in the lee of the windbreak (Frota *et al.* 1987), and the greater water use efficiency of certain C_3 plants growing in light shade. Greater efficiency of resource use may also occur through functional complementarity, eg. using nitrogen fixing trees and trees with proteoid roots capable of extracting phosphorus from low P soils.

In the early phase of agroforestry research, it was assumed that complementarity of resource capture between trees and crops would largely offset the competition (Ong and Leakey 1999). This has not proved to be the general case in low to medium rainfall zones. Research has since suggested that

competition is more likely to be encountered than complementarity, often because tree roots occupy the same soil zone as crops. This has been shown to occur as a result of physical and chemical barriers to root penetration (Ong 1996), as a consequence of pruning regimes which can lead to a higher proportion of superficial roots (van Noordwijk and Purnomosidhi 1995) and where soil structure is such that annual rainfall can readily be stored within the top metre or two of the profile (Dupraz *et al.* 1995, 1998).

The net effect of mixing trees with crops is more likely to depend on the relative value of the tree and the crop than on the interactions between them. While positive effects at a distance may compensate for competition close to the tree, this has not been the experience with a wider range of crops over a range of sites and seasons in south western Australia. Data comparing mean crop yield in the lee of windbreaks and in the open for six crops over five years at a range of sites showed a small positive effect of shelter outside the competition zone, but no significant change when the total arable area was considered (R Sudmeyer, unpubl. data). This lends support to van Noordwijk's (1996) assertion that agroforestry systems are only viable if the direct values of tree and crop per unit area occupied are similar unless there is strong complementarity of resource use. If a tree is of lower value than the crop, it must pass significant resources on to the crop to warrant its inclusion. The onus is therefore on finding tree crops with higher annual returns than grain given the higher cost of establishment and the lag time before returns.

2.3. Water use and productivity of tagasaste alley cropping

This section presents the first 18 months data from a case study of a simultaneous agroforestry system on a deep sand in south western Australia where trees have access to a shallow fresh water table. This represents the ideal case in terms of tree water use.

The site at Moora (lat. 30° 45'; long. 116° 40'), 150 km north of Perth, originally supported a woodland community dominated by *Banksia prionotes*, described by Pate and Bell (1999). This site is typical of the sandplain regions of southern Australia that remained uncleared for agriculture until the 1950s and 60s when trace element technology enabled crop and pasture production on these very infertile soils. Following a one-off application of copper, zinc and molybdenum, these sandplain soils were typically sown to annual pastures dominated by the naturalised sandplain lupin *Lupinus cosentinii* and top-dressed each year with phosphate fertilizer. The very high level of nitrate recorded in the perched water table at this site (13 ppm N) is probably the result of 30 years of fixation and leaching in these legume-dominated pastures. Development of the sweet lupin grain crop *L. angustifolius* in the 1970s saw the rapid adoption of continuous lupin/cereal rotation as a viable cropping option (Gladstones 1982, Marsh 1995).

Rising water tables, herbicide resistance, wind erosion and subsoil acidity have since raised doubts about the sustainability of annual crop and pasture systems on these soils. As described earlier, median annual drainage for this site has been estimated to be 140 mm/yr (Asseng *et al.* 1998). Given that the objective is to prevent further rise in a water table, the question is what density and arrangement of trees would be required, and what would be the consequence for agriculture?

An 8 ha experimental site was established in 1992 to compare the water use and productivity of alley cropping with sole tree and sole crop treatments (see Figure 2.2). Trees in the plantation (sole tree) and alley plots were direct seeded in 1992 in rows orientated north-south. Spacing between trees in a row ranged from 0.6-0.7 m with the spacing between rows being 6m in plantations (giving a density of 2300 trees/ha), and 30 m in alley plots (giving a density of 550 trees/ha). There were two alley treatments, alley crop and alley fallow. In the latter, a chemical fallow was maintained between tree rows to enable measurement of tree water uptake in the absence of crop competition and disturbance of surface roots. All treatments were replicated twice in plots 50 m by 160 m (0.8 ha).

From 1992 to 1996, the trees were grazed by sheep and cattle at high stocking rates each autumn as part of an animal production experiment. In May 1996 when the present study began, the previously

uncut trees were mechanically pruned from 3 m to 0.6 m to mimic the regime commonly used in commercially managed stands of tagasaste. Grain lupins (*Lupinus angustifolius* var. Gungurru) were sown in alley crop plots on June 20 1996, followed by oats (*Avena sativa* var. Toodyay) on June 8 1997 and *L. angustifolius* var. Merrit on May 6 1998. Annual applications of 13 kg/ha of phosphate were made to all plots each autumn.

The very low fertility and water holding capacity of the soil can be seen from the data in Table 2.1. Field capacity and wilting point were based on the maximum and minimum water contents recorded in the field, the later being mean values for the driest holes at the driest time of year (center of tree rows in autumn, $n=6$). Since clearing 34 years ago, a fresh (<1 dS/m) perched water table developed over a clay layer at approximately 10 m depth. Depth to the water table was monitored monthly at eleven wells distributed across the site. For the duration of the experiment it was approximately 5 m below the surface. Annual rainfall was 445, 431 and 376 in 1996, 1997 and 1998 respectively, compared with the long term average of 462 mm.

The soil characteristics and very low relief at this site mean that the water balance is essentially a vertical exchange, and for the purposes of this study it is assumed there is no runoff and no lateral water movement above the saturated zone. The aim of the experiment was to quantify the variables described in the previous section. Soil water content was measured to a depth of 3.7 m in sole tree and sole crop treatments using a neutron probe and TDR. Replicated transects of PVC neutron probe access tubes were also positioned at 0, 1, 2, 4, 8 and 15m either side of the tree rows in the alley treatments. The neutron probe was calibrated gravimetrically and the counts converted to volumetric water content using separate regression equations for 0-20cm, 20-80cm, 80-140cm and 140-370cm depths of the soil profile. The r^2 values for these equations were 0.72, 0.96, 0.97, and 0.95 respectively.

Transpiration by the tagasaste was measured by fitting stems with heat pulse sapflow sensors (Hatton *et al.* 1990) once they reached sufficient size (>10 mm diameter) in December 1996. These were moved to fresh stems on a six-monthly rotation. Flux per unit area conductive wood was then scaled up to plot level transpiration using data from four-monthly surveys of stem size distribution and conductive wood area per unit land. Data from an on-site weather station was used to calculate Penman-Montieth evapotranspiration, hereafter referred to as (E_0). A more complete description of the methods is given in Chapter 3 (p 28), prior to the description of growth and water use of the trees in their second and third years of coppice re-growth. This chapter specifically examines the water use potential of multipurpose systems where tagasaste trees are cut and grazed on a one to two year rotation for fodder production.

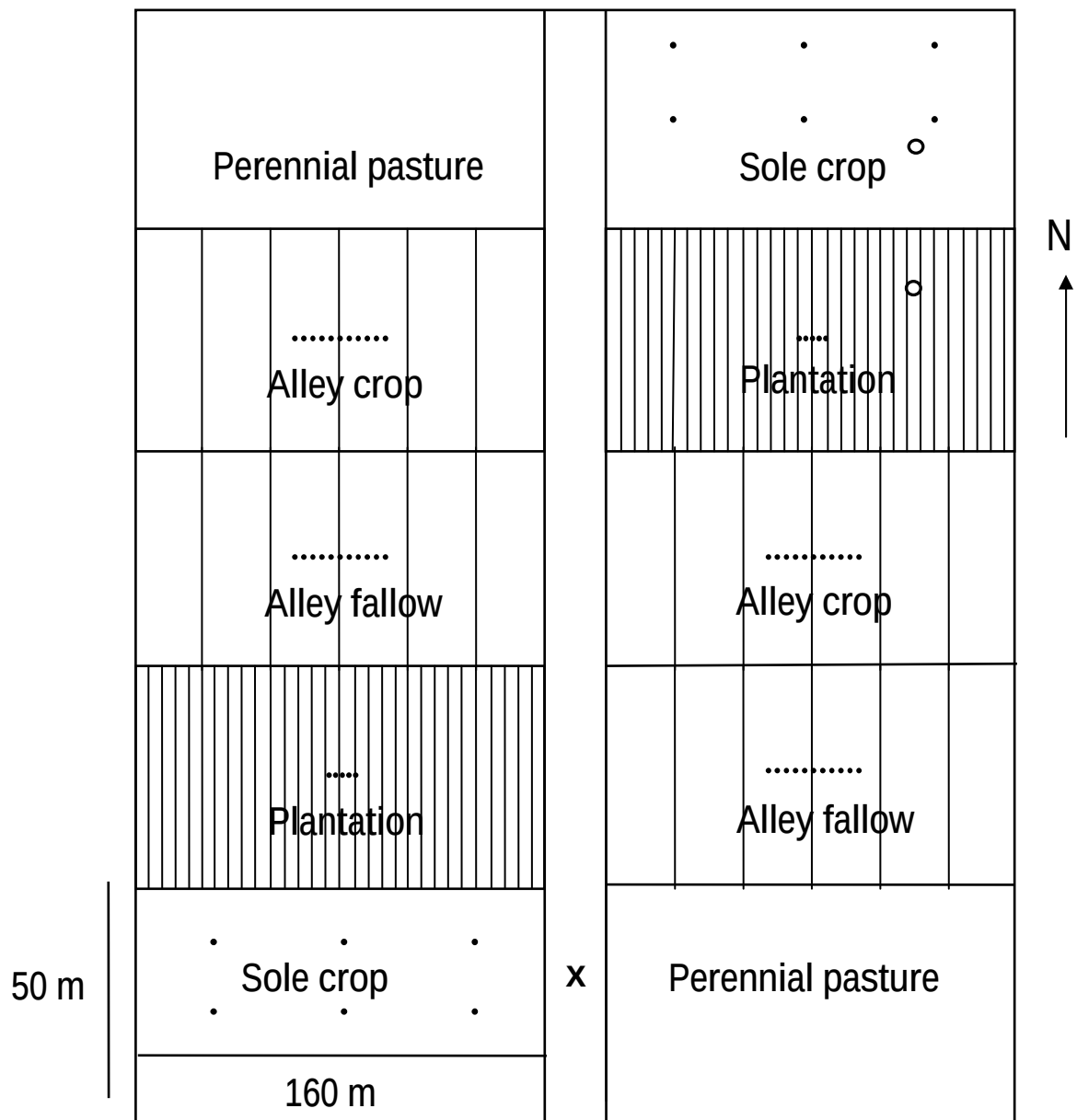


Figure 2.2. Site layout showing design and location of treatments and the position of the transects of neutron moisture meter access tubes (.....), TDR probes (o) and weather station (x).

Table 2.1. Description of the soil profile at the alley cropping experimental site.

	A ₁ Horizon	A ₂ Horizon	B Horizon
Depth (mm)	0-100	100-300	300-10 000
Colour and texture	grey sand	pale grey sand	yellow sand
Bulk density	1.55	1.61	1.61
Water content at field capacity (% v/v)	10	10	10
Water content at wilting point (% v/v)	3	3	3
Saturated hydraulic conductivity (mm/h) ¹	300	300	300
pH (in 0.01 M CaCl ₂)	5.2	4.8	4.8 - 5.4
Organic carbon (C%)	0.50		
Phosphorus (ppm)	13	8	2
Nitrogen (ppm NO ₃)	7	2.5	<1
Potassium (exch., soil)	0.03	0.03	0.02

¹ Keith Smettem, University of Western Australia, personal communication

Crop water use

The time series in Figure 2.3 commenced in July 1996 following a very wet opening to the winter season, when the measured profile depth of 3.7 m was close to the upper drained limit in each treatment (220 mm). By the end of the lupin growing season (November 1996), available water content had been drawn down to about 100 mm. Between April 1997 (break-of-season rains) and August 1997, the soil profile under the oat crop progressively filled, with about 120 mm left in the profile at harvest in December. These changes in soil water content under the sole crops illustrate a pattern typical of annual plants in this environment. The profile fills from the break of season until mid to late winter followed by rapid draw down over spring when there is sufficient leaf area and radiant energy for significant transpiration.

There is little change over summer and autumn when the land is fallow. Lupins extracted water from a depth of up to 3.5 m in 1996 although the season terminated before they had exploited all the available water between depths of 2 and 3.5 m (Figure 2.4a). This illustrates the difficulty in defining the dimensions of zones S2 and S4 in Figure 2.1. The oat crop did not use water below 2.2 m in the 1997 season.

Tree water use

At the end of the first growing season (November 1996), the soil profile to 3.7 m in the sole tree and alley crop treatments contained 75 mm (29% full) and 90 mm (37% full) respectively, compared to 115 mm (47% full) under the sole crop (Figure 2.3). The tagasaste had been heavily pruned to a height of 0.6 m in May 1996, but was not pruned before the next rainy season. After this time, the soil profile below 0.75 m in the sole tree treatment did not refill because of the greater leaf area. There was a marked slowing down of water extraction by the tagasaste after October 1996 coinciding with the emptying of the profile and the increasingly warm weather.

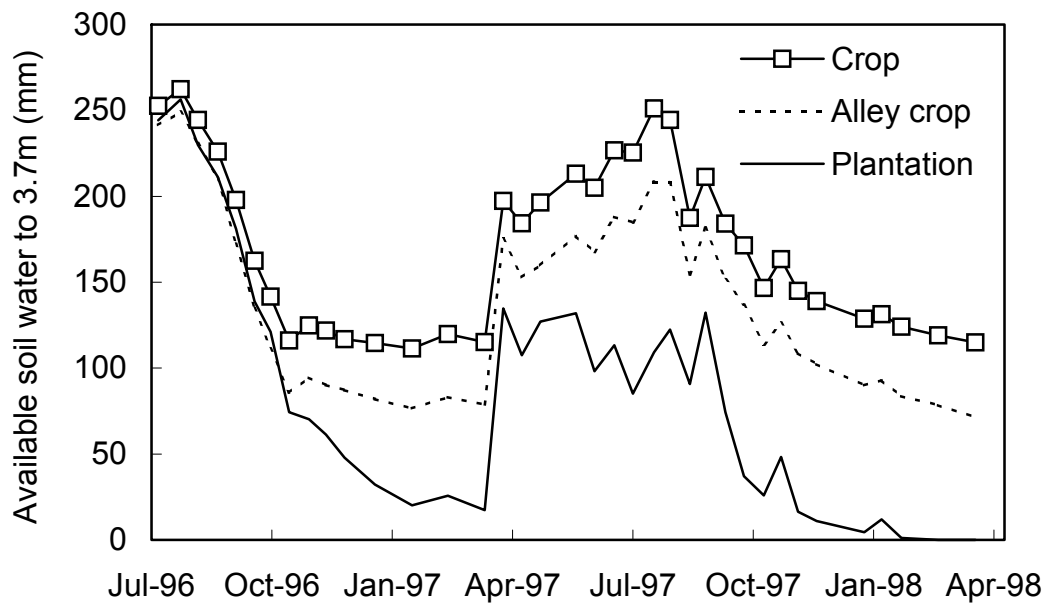


Figure 2.3. Change in available soil water content under crop, alley crop and tagasaste plantation at Moora, Western Australia, from July 1996 to April 1998.

Figure 2.4 shows soil water content under sole crop, plantation and alley crop treatments for April 2 1997, at the driest time of the year. The residual water in the upper layers of the crop (Figure 2.4a) and alley crop treatments (Figure 2.4b) was a consequence of isolated storms in late summer. The most striking feature of Figure 2.3b is the restricted lateral extraction of water by alley cropped tagasaste trees. Soil water extraction is confined to a zone within 4 m either side of the tree rows which provides an estimate of the width of soil zone S3 for the first year's growth. From Figure 2.4b it is evident that the 20 mm buffer of dry soil in the alley crop compared to the sole crop treatment (Figure 2.4) was confined to a very narrow zone immediately under the trees.

Tagasaste transpiration was remarkably similar throughout 1997 (Figure 2.5) with a mean daily water use of 2 mm/d ranging from a low of 1.5 mm/d in winter to a high of 2.5 mm/d in summer. Despite the fact there was fresh groundwater in a highly transmissive aquifer available at a depth of 5 m, the tagasaste did not achieve better than 0.40 of E_0 over summer months and 0.48 of potential for the year. Total transpiration over 12 months from January 1997 (ie. from 6 to 18 months after cutting) was measured at 749 mm.

Assuming for the moment a further 150 mm as soil evaporation and canopy interception, total evapotranspiration would be in the order of 900 mm/yr. (A more detailed water balance for the alley crop and sole crop treatments in the third year of re-growth is described in Chapter 4). This estimate can be used to construct a simple replacement series between sole crop with evapotranspiration of 320 mm/yr (rainfall of 460 mm/yr less median deep drainage of 140 mm/yr) and sole tree using 900 mm/yr. This indicates 24% tree cover at the catchment scale would be required to prevent further water table rise (Figure 2.6). This assumes that all trees have access to a perched fresh water table, there are no positive or negative interactions between trees and crops in terms of water use, and trees are cut on an 18-month rotation.

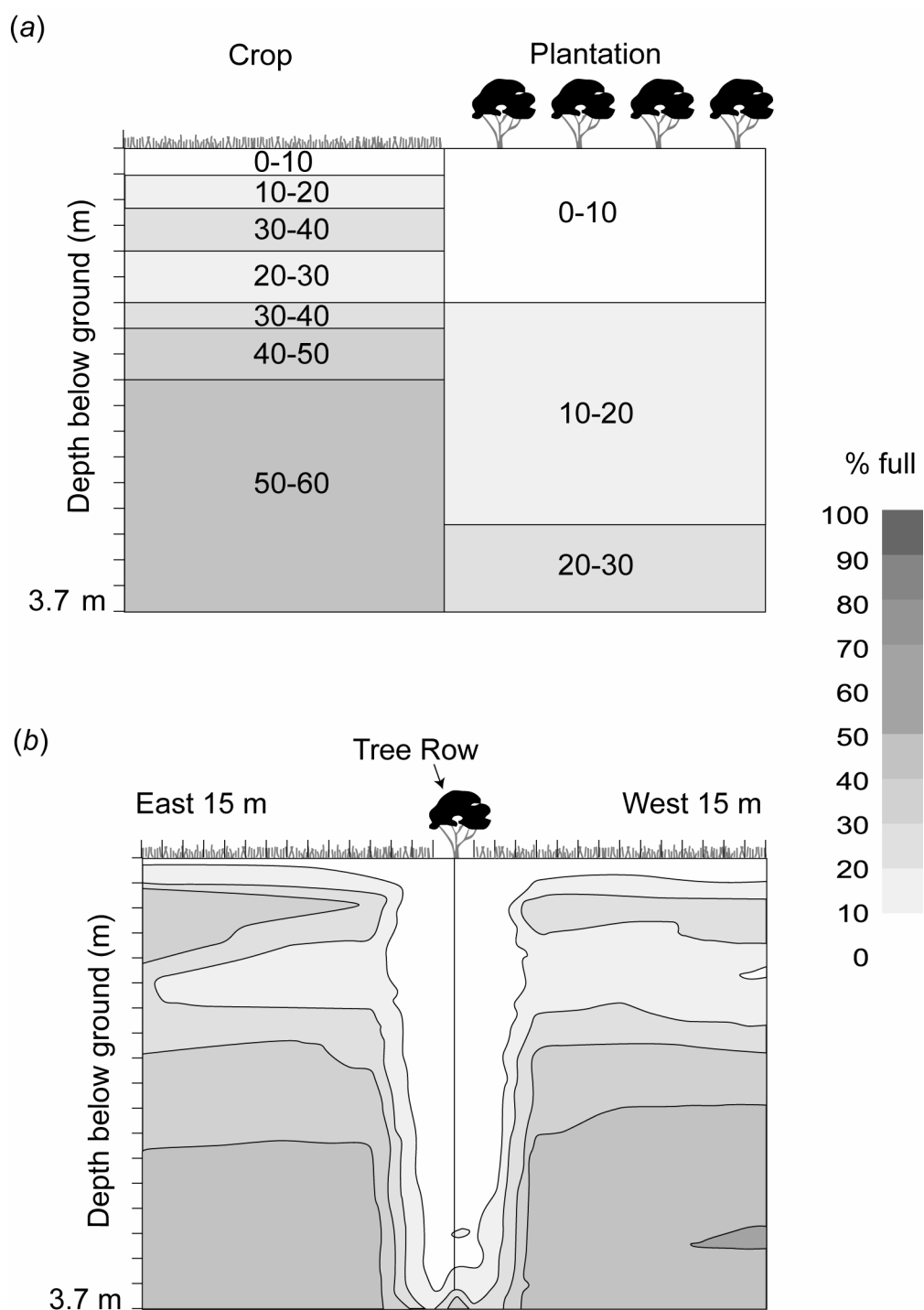


Figure 2.4. Soil water content (a) under crop (left, mean of 12 access tube readings) and plantation (right, mean of 4 access tube readings) at Moora, Western Australia, on April 2 1997; (b) measured in a transect across alley crop plots on April 2 1997 showing the narrow zone of soil water extraction by rows of tagasaste trees. Water content expressed as % full for soil profile to a depth of 3.7 m (mean of two transects).

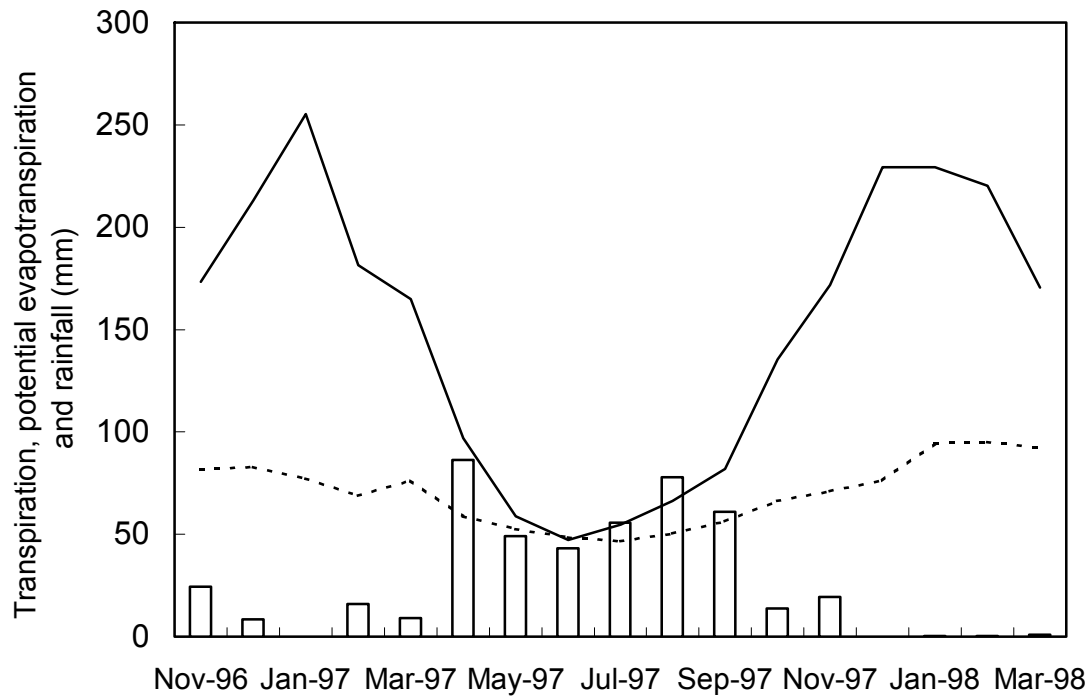


Figure 2.5. Transpiration by tagasaste plantation (---), potential evapotranspiration (—) and rainfall (columns) at Moora, Western Australia.

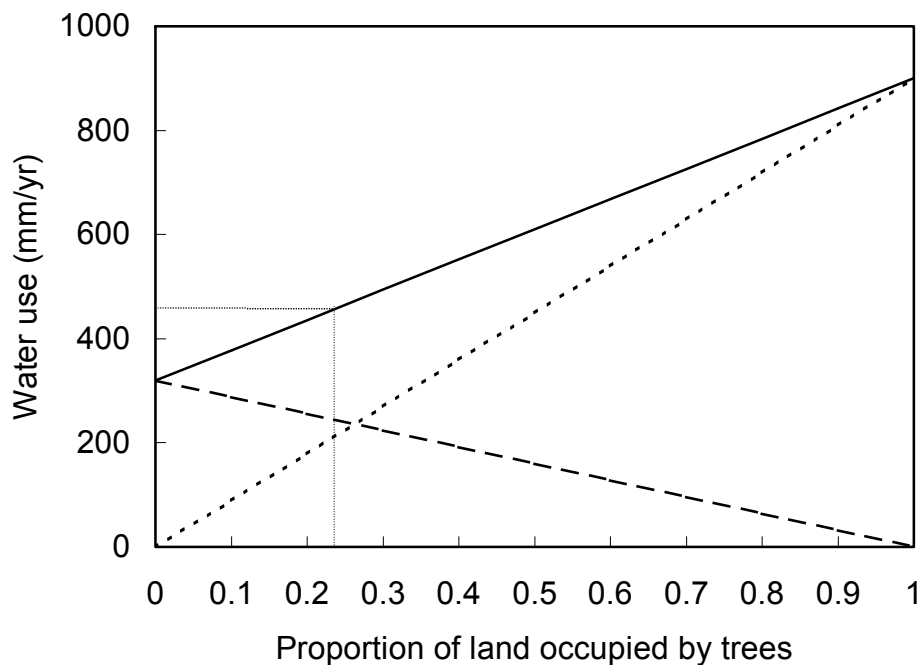


Figure 2.6. A replacement series involving sole crop (—) with evapotranspiration of 320 mm/yr (rainfall less median deep drainage) and plantation (---) with evapotranspiration of 900 mm/yr, showing that alley cropping (the combination of the two) would require 24% tree cover at the catchment scale to account for annual rainfall of 460 mm/yr and prevent further water table rise.

Tree-crop interactions

Tree-crop interactions can be viewed from two perspectives – the effect of the trees on the crop, and the effect of the crop on the trees. The impact of the trees on crop yield was measured by harvesting continuous transects across the 30 m alleys with a 1.8 m wide mechanical harvester and comparing that to the yield from a similar area in the sole crop plots (Figure 2.7). A positive response to shelter was measured in lupins. There was a 29% increase in grain yield over the arable area compared to the sole crop treatment and a 23% increase over the total land area, ie. including the arable land displaced by trees (Figure 2.7a). The shelter effect was detected only in grain yield, with no significant difference in biomass between alley and sole crop plots measured at three stages during the vegetative phase. A pot experiment using soil taken in a transect across an alley showed no significant differences in plant growth or grain yield of lupins along the transect, suggesting the yield response in the field was due to above-ground rather than below-ground influence of the tree roots on soil conditions such as nutrient availability or organic matter. The yield of oats in 1997 was 8% lower than sole crop while the yield of lupins in 1998 was 32% lower than sole crop (Figure 2.7b).

Assuming that the grain yields in 1996 and 1997 are typical of alley cropping with trees cut on a two-year rotation, and that wider tree belts would have similar effects on crop yield as single rows, then increasing tree belts from 10% to 24% to meet the water use objective would result in a 3% drop in lupin yield and a 22% drop in the yield of oats over the total land area under alley cropping compared with sole crop. In a lupin/cereal rotation, the cereal phase is generally the more profitable with the legume being important as a source of residual nitrogen and as a disease break. This situation would therefore be unacceptable unless the tree has a commercial product of similar or higher value than the displaced crop and its harvest does not compromise the water use or shelter roles of the tree.

Where the proportion of land under trees required for water management is low, or where shelter is the primary consideration, these yield data suggest there may be medium to long term benefits from the response of the legume phase to shelter that could justify adoption (Figure 2.8). However, the initial cost of establishment and the lag between planting and yield response inevitably means a period of forgone income, in this case 7 years. The amount of forgone income can be regarded as a measure of the willingness to pay for water management on the part of landholders and/or the degree of investment required by society for such an approach to become commercially attractive.

The effect of the crop on the trees was minimal. We might expect tagasaste trees surrounded by annual crops to extract more water than those in plantation, but no difference in transpiration rate was detected. This suggests that in the first 18 months of regrowth, tagasaste does not have the rooting architecture of an ideal agroforestry tree (Figure 2.4b). It may also explain why so little competition was observed in the crop zone adjacent to the trees in the first two years (Figures 2.7a, b).

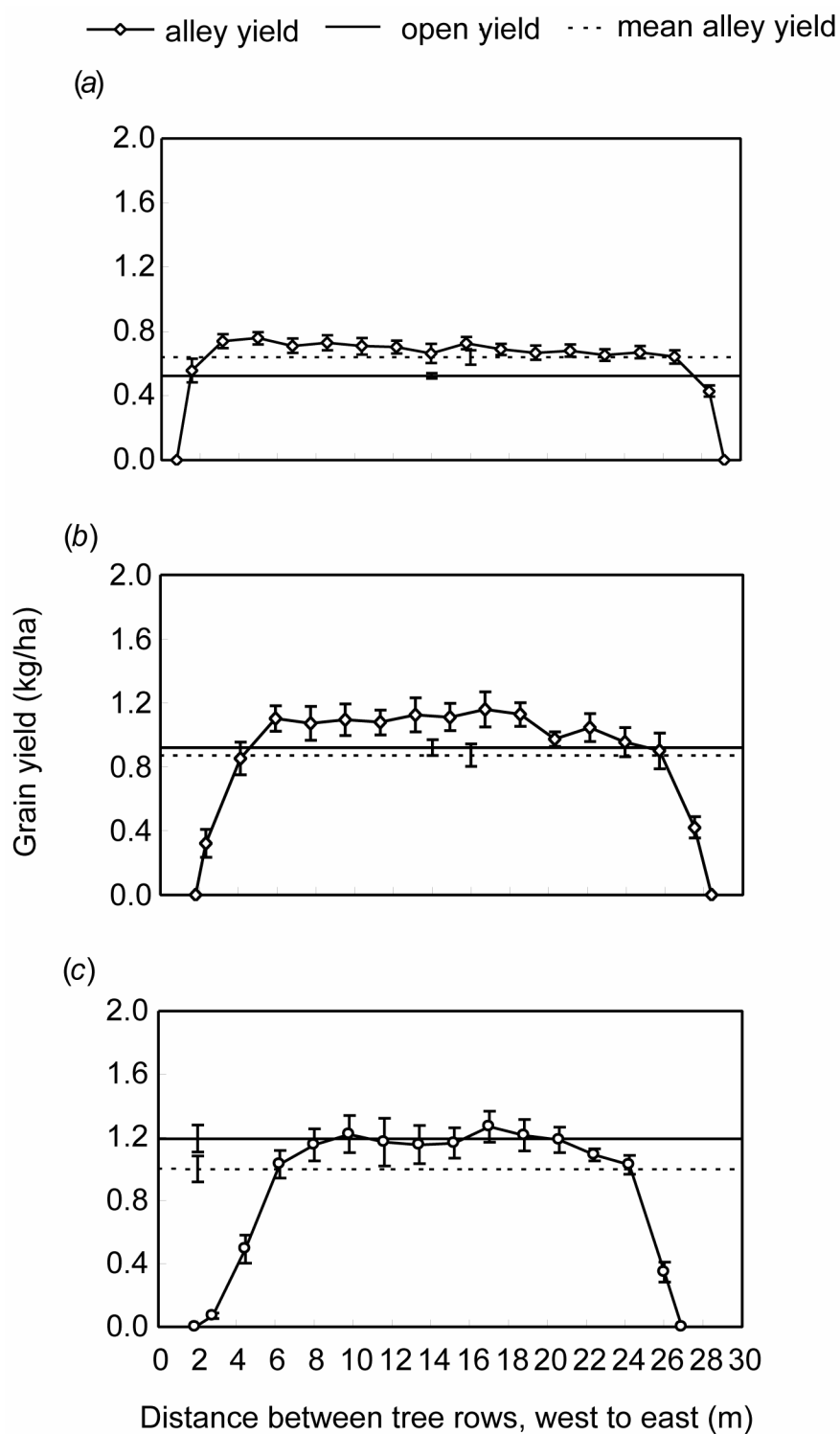


Figure 2.7. Grain yield of (a) lupins 1996, (b) oats 1997 and (c) lupins 1998 harvested in 1.8 m widths in a continuous transect across 30 m wide alleys ($n=5$) at Moora, Western Australia.

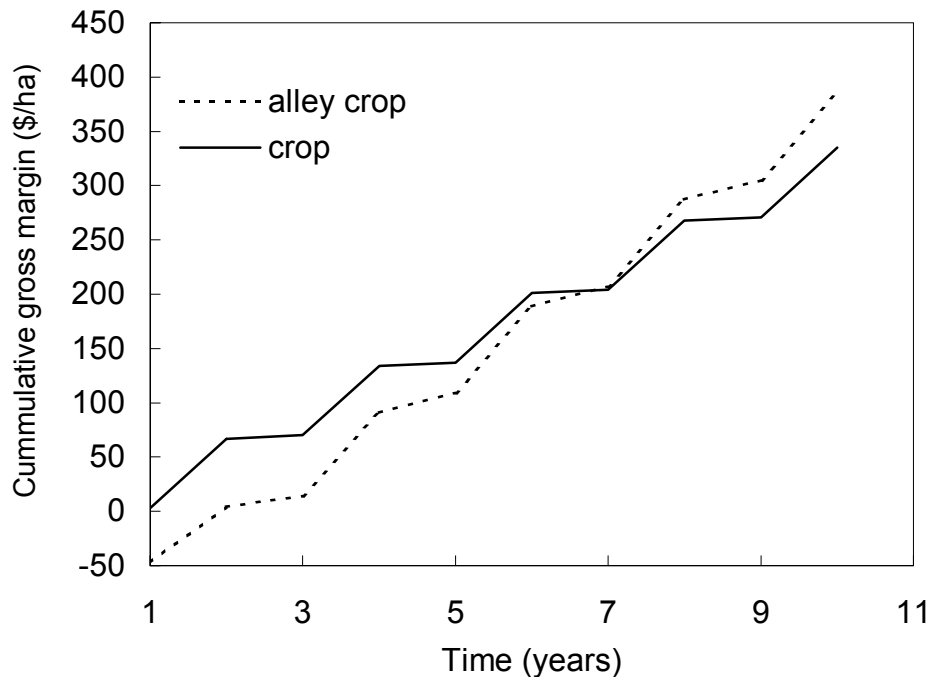


Figure 2.8. Cumulative gross margin for a lupin cereal rotation under conventional and alley cropping based on data collected at Moora, Western Australia. Assumes a 20% yield increase due to shelter effects in the lupin phase and a 5% yield increase due to shelter effects in the cereal phase. Establishment assumes direct seeded trees occupying 10% of arable area, reaching a mature height in year 5. The area between sole crop and alley crop gross margins shows the opportunity cost (from years 1 to 7) and profit (year 7 on).

2.4. Implications for agriculture

In many parts of the world, woodland and forest have been converted to grassland without suffering the hydrologic consequences that have been experienced so rapidly after the introduction of agriculture in southern Australia. The great age and low hydraulic gradient of this landscape combined with the asynchrony between rainfall and radiant energy that typifies a semi-arid Mediterranean-type climate are the fundamental reasons. Rehabilitation strategies based on winter active plants are demand limited, ie. limited by low potential evaporation at the time of major recharge events. If we are to address the problem of saline water tables there will have to be large-scale introduction of deep-rooted perennial vegetation into the agricultural landscape. There are potentially three ways to do this, namely to segregate, to integrate or rotate perennial vegetation with conventional agriculture (van Noordwijk *et al.* 1997).

To segregate trees and crops

Segregation involves growing and managing each species separately. Modern agriculture is based on monocultures precisely tuned to be productive when subsidised by inputs of fossil fuel energy. The most appropriate strategy may be to manage the best land to be as productive as possible, and to set other land aside for environmental services (van Noordwijk and Ong 1999). In the context of the salinity problem, a proportion of the land could be put under conventional forestry to reduce drainage, with the remainder under conventional crop and pasture monocultures. There are three problems to this approach. Firstly, it is difficult to identify areas in a catchment where there is sufficient lateral movement for excess water to move from cropping land to blocks of trees. Though there are some examples of strategically placed plantations intercepting groundwater (eg. George *et al.* 1997), it is more likely that trees in plantations will have to survive on annual rainfall once they have mined the water left behind by annual crops or pastures. Secondly, hydrologists in Australia continue to revise upwards the area that needs to be revegetated as more data becomes available, to the point where

annual agriculture may only be viable on just 20% of the land (Schofield *et al.* 1989, Hatton and Nulsen 1999). Thirdly, many regions where dryland salinity is a problem do not have sufficient rain to sustain profitable commercial forestry.

One example where segregation does have merit is if trees can access relatively fresh water tables over transmissive aquifers, as in the case study above. With drainage under crops averaging 140 mm/yr, tagasaste was able to extract approximately 440 mm/yr from the water table (900 mm evapotranspiration less 460 mm mean annual rainfall). Thus each hectare of tagasaste could protect some three hectares of arable land. Using this example, the area of a catchment which needs to be revegetated to prevent drainage is presented in Table 2.2. The proportion of trees and crops was arrived at by allocating all the area with access to a fresh saturated zone to plantations of tagasaste, and then assigning three times that area to annual crops or pastures and the remaining area required for water use to 'dryland' plantation and trees in alley cropping (as windbreaks with trees occupying 10% of the arable area). The outcome is that for every 5% decrease in the area of land that is overlying a saturated zone below the 25% reforestation target, the area required under trees rises by 15%. However, this relies on the unrealistic assumption that all deep drainage will reach a perched aquifer within reach of tree roots.

Moreover, the area of land having a saturated zone within reach of trees in any given catchment is difficult to estimate without extensive drilling. Experience suggests that only a small proportion of aquifers in the cropping zone are likely to be both fresh and within the rooting depth of trees. George (1992) estimated from a drilling program in the eastern wheatbelt (annual rainfall 300-350 mm/yr) that at most 20% of the sandplain soil units had an underlying shallow saturated zone that was relatively fresh (2-10 dS/m). Sandplain constitutes about 20% of soils in the crop-growing region (Carder and Grasby 1986) and the occurrence of relatively fresh water tables is rare on other soil types.

Table 2.2. The influence of the extent of the saturated zone within reach of trees on the proportion of a catchment requiring revegetation for evapotranspiration to equal rainfall. Assumes annual deep drainage is 140 mm, annual average rainfall is 460 mm, crop water use is 320 mm, plantations over a fresh water table use 900 mm and plantations without access to a fresh water table are in equilibrium with rainfall.

Extent of saturated zone (%)	Plantations + WT (%)	Annual crops & pastures (%)	Trees in alley cropping (%)	Plantations - WT (%)	Total revegetation (%)
2	2	6	1	91	94
5	5	15	2	78	85
10	10	30	3	57	70
15	15	45	5	35	55
20	20	60	6	14	40
25	25	75	0	0	25

To integrate trees and crop

Alley cropping is an example of integration, where the domain of the tree overlaps with that of the crop so that trees and crops share or compete for the same resources. The pivotal question here is when is it better to integrate than to segregate. The rationale for growing crops and trees simultaneously is that it increases the chance of capturing all available resources. How this increase in total resource capture is partitioned between the two species will determine the productivity and economic viability of the integrated system.

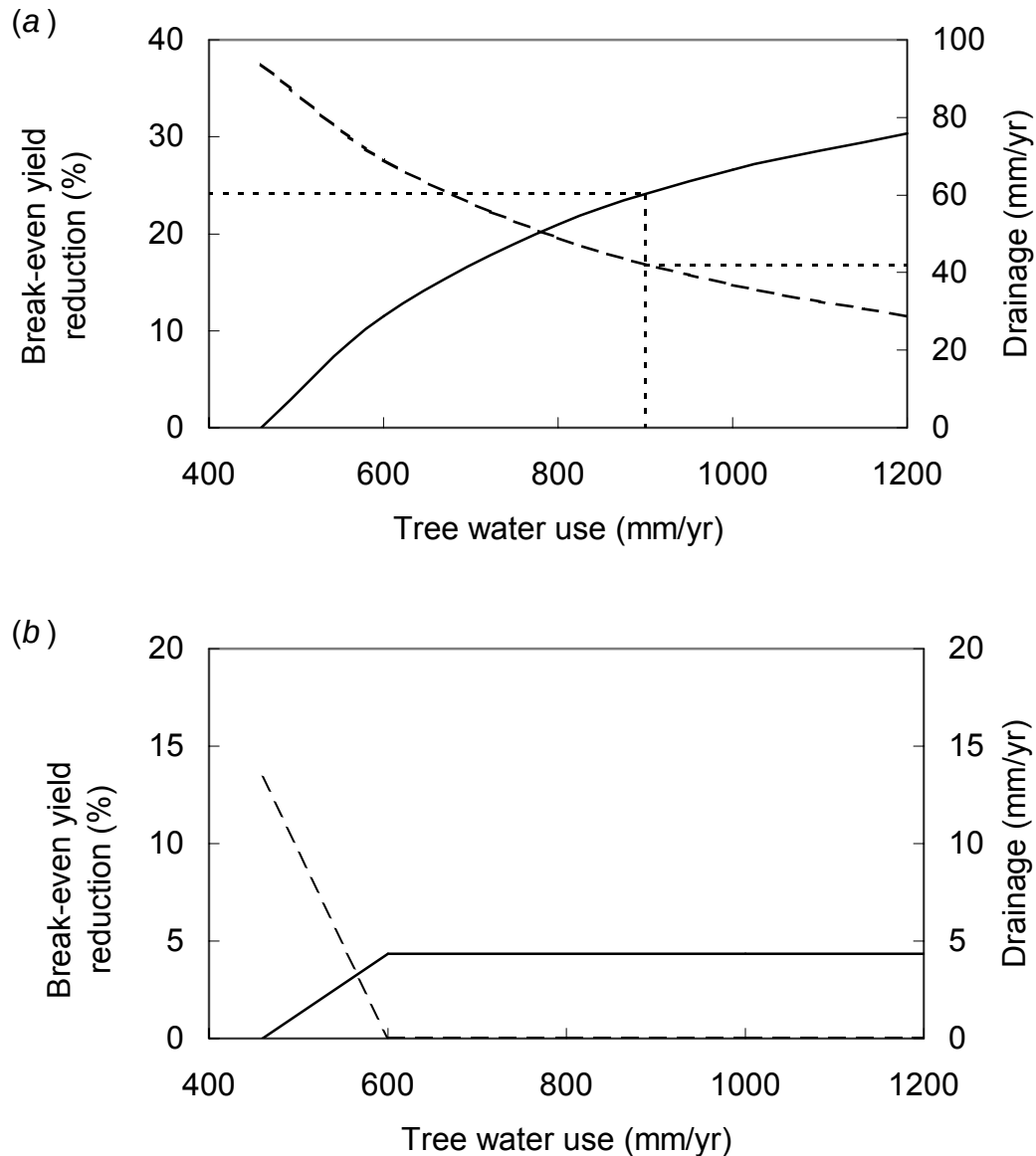


Figure 2.9. The break-even yield reduction (—) and drainage (----) as a function of the water use of the trees integrated with crops when drainage below the crops is (a) 140 mm/yr and (b) 20 mm/yr.

A framework for deciding whether to segregate or integrate is illustrated in Figure 2.9 for the Moora region (annual rainfall and crop water use 460 and 320 mm/yr respectively). For the purpose of this example it is assumed the tree component cannot access a water table. The following assumptions are made to examine the most favourable possible outcome for integration:

1. In the segregated case (plantation) the projected area of the tree canopy and root zones are the same, so that tree water use is equal to rainfall.
2. In the integrated case (alley farming) the trees are spread out such that their roots explore the entire area under cropping.
3. Annual rainfall can be contained within the depth of the soil profile occupied by tree roots (ie. the entire area of the catchment).
4. There is a linear relationship between the amount of water a crop uses and its productivity.

The trees integrated with crops will have access to water unused by the crop and will, based on the second assumption, use more water than trees in plantation. If integrated trees use more water per unit

projected canopy area than segregated trees, it follows that a lower proportion of reforested land will achieve a given total tree water use. This leaves a greater area of land for crops. However, crop growth will be reduced in the integrated case because of competition from trees. Thus there is a trade-off in the integrated case between a greater area of cropped land and tree-crop competition. The following steps need to be taken to evaluate the trade-offs between greater area under crop, tree-crop competition and deep drainage:

1. Estimate the total excess water in the catchment when it is entirely planted to crops.
2. Estimate the discharge capacity of the catchment.
3. Calculate the area under crop that produces recharge equal to the discharge capacity and plant the remainder of the catchment to trees.
4. Estimate/measure the annual water use of a line of trees planted in cropping land.
5. Calculate the area of land that should be planted to lines of trees so that rainfall minus the sum of tree water use and crop water use is equal to the discharge capacity of the catchment.

For the Moora example above, average drainage is assumed to be 140 mm/yr. To reduce this figure to around 40 mm/yr (ie. by about 70%) we would need to put about 70% of the catchment under plantations of trees. However if we measured that a belt of trees in cropping land without access to a water table was able to use 900 mm/yr, we could achieve the same objective by having 17% of the catchment planted to tree belts. Figure 2.9a illustrates the fact that as tree water use increases, drainage decreases and the amount of competition that can be tolerated in alleys increases. It indicates the yield loss that can be tolerated and the drainage when trees use a nominal 33% of the water in a catchment at intensities ranging from 460mm to 1200mm (ie. from plantations occupying 33% to belts occupying 13% of the area). The break-even yield reduction is the percentage reduction in crop yield that can be tolerated in the alley-cropped case. For a tree water use of 900 mm/yr, the break-even yield reduction is 24%. At this break-even yield reduction, the total yield in the alley crop system would equal that when trees and crops were segregated. The break-even yield reduction arises because the cropping area has increased from 30% (segregated case) to 67% (integrated case). The above proportions reflect the extent of tree planting needed in the segregated and integrated cases respectively to keep drainage at 40 mm/yr.

The above example shows that there may be scope for integration when the drainage is as high as occurs on the sandplain. However, it is more common in the cropping belt for drainage to be around 20 mm/yr, and at these lower values the case for integration is much weaker. Once the trees use more than 600 mm/yr there is no further excess water and additional water used by trees is directly at the expense of the crop. This gives a maximum break-even yield reduction of less than 5%, which would be difficult to achieve in most circumstances (Figure 2.9b). It must be noted that the above examples describe the ideal case for integration where the trees capture all the water that would have drained below crops. The tree in this study (tagasaste) did not fit the assumption of wide and deep lateral-rooting. Moreover the use of annual tree and crop water estimates can lead to wrong conclusions. The area of trees integrated into cropping land may be just right in an average year to soak up the water unused by crops. In a dry year there will be no excess water and the trees will always be in competition; in a wet year the area under trees will be too low to have an impact. These problems are not as severe in the segregated case, where trees will not compete in dry years and can respond by using more water in wet years. If it is essential to halt deep drainage in catchments exporting large amounts of salt, but with relatively low drainage, it may be better to think in terms of alley forestry than alley cropping, ie. wide belts of trees separated by fallow land. Trees growing in areas with insufficient rainfall to produce a commercial product could become a commercial proposition with access to water from wide, uncropped alleys. Alley forestry would be a less risky proposition than alley cropping and would be more effective in unusually wet years.

As described above, a certain amount of tree-crop integration is acceptable to farmers. In many cases it is driven by the value of the tree fodder and the protection trees afford to crops during extreme weather events. Although alley cropping in Australia is carried out with much greater tree-crop separation than normally seen in the tropics, the observation by Sanchez (1995) is pertinent: 'alley cropping is like playing with fire, because it has strongly positive and strongly negative interactions

and thus requires precise fine tuning in every situation'. It remains to be seen whether we in Australia can find tree species of sufficiently high commercial value and manage to integrate them with crops with the appropriate degree of finesse to satisfy both productivity and water balance objectives.

To rotate crops with herbaceous perennials

Increasing awareness by agronomists of the scale of the salinity problem has fuelled a resurgence of interest in rotating lucerne with dryland crops (Ridley *et al.* 1998, Dunin *et al.* 1999). Lucerne has proved itself as a valuable plant in conventional rotations, and farmers with the skill to manage lucerne in dryland environments have found it to be both profitable and effective in de-watering subsoils. However, the requirements of lucerne are exacting and it will be very hard pressed to survive in areas with acidic or heavy clay subsoils.

Gardner (1944) identified the relative absence of herbaceous plants as a defining feature of the flora of south western Australia. This is unlike the situation in eastern Australia where extensive areas of grassland were, and still are, to be found (Moore, 1970). Early European explorers in the south west noted areas of grassland managed by aborigines with fire for hunting and ease of movement. These were, with some very minor exceptions, the grassy understorey of woodland vegetation, rather than grasslands in their own right (Hallam, 1979). The life form analysis presented by Pate and Bell (1999) for the Banksia woodlands illustrates the characteristic dominance of woody over herbaceous perennial species. The relative absence of herbaceous perennial plants in the original vegetation does not rule out the possibility of developing well-adapted cultivars of lucerne-like plants, but it does suggest that successful adaptation of this life form to a wide range of habitats in this region presents a significant challenge. The need for roots capable of penetrating physically and chemically inhospitable subsoils and the difficulty of maintaining mesophytic foliage through hot dry summers are two challenges to the development of well-adapted herbaceous perennials. The persistence of limited plantings of drought tolerant summer active perennial grasses such as *Chloris gayana*, *Erharta calycina* and *Eragrostis curvula*, (all from southern Africa) in the southern and western part of the region does provide some grounds for optimism. For those reasons it may be more promising to explore the potential of very short rotation forestry (Harper *et al.* 1999).

The challenge for agroforestry

The foregoing discussion highlights problems with segregation, integration and rotation of perennial plants as strategies for water management. It would seem that deep-rooted, summer active vegetation needs to be widely dispersed across the landscape in a manner similar to that in the original woodland. This prognosis is not new. Over 90 years ago, the Government Analyst advising a wheatbelt farmer how to prevent wells and soaks becoming saline, suggested it would require replanting trees in a manner 'practically co-extensive with the original forest' (Mann 1907). The expectation that small localised plantings of high water use trees could manage recharge and limit the displacement of conventional agriculture is unrealistic, being limited by the area of land overlying a fresh saturated zone within reach of tree roots, the slow rate of lateral water movement through soil and the conservative rates of water use of trees. As Hatton and Nulsen (1999) point out, little short of geological rejuvenation will alter this situation.

Those factors within our influence that could lead to more concentrated revegetation and less displacement of agriculture include identifying and mapping shallow fresh water tables, using earthworks to divert surface water as concentrated recharge within the root zone of trees (McFarlane and Cox 1990) and using geological structures as indicators of improved soil water availability (Farrington and Salama 1996, Clarke *et al.* 1998). The biological options include selection of tree species with root architecture and functional characteristics complementary to annual plants. Chapter 3 specifically examines the question of the root architecture and water uptake of tagasaste as the trees in the experiment described above grew into their second and third seasons, while Chapter 4 examines the trade-off between drainage management and crop yield reduction in three-year-old re-growth.

However, these questions are likely to be secondary to the challenge of developing new tree crops that could commercially drive even a small degree of displacement of grain agriculture. Progress towards

the development of viable tree crops in this region (Bartle *et al.* 1996) and high seed yielding herbaceous perennials in the Great Plains of Kansas (Jackson and Jackson 1999) indicates that domesticating perennial species is a decades long process with a high degree of uncertainty. The low rates of biomass accumulation of semi-arid woody species (eg. Pate and Bell 1999) accentuate this challenge.

Whether water management involves integrating, segregating or rotating trees with crops, the transition from an exclusively annual-based agriculture to one with a significant component of woody perennials inevitably involves a lag between establishment and first returns to the landholder (eg. Figure 2.8). This problem was recognised over 24 centuries ago, when the Athenian politician Peisistratus established low interest loans to farmers forced by severe soil erosion to make a transition from grain agriculture to the cultivation of vines and olives (Claiborne 1970). Similar intervention by government or industry will be equally important if such a transition is to occur in southern Australia.

In the sense used by Jackson (1999), this is a region with low ecological amplitude. Unlike the young post-glacial soils of the Middle East and Europe from which grain agriculture evolved, it appears we cannot stray far from the original vegetative structure without paying a penalty. Whether viable functional mimics of that original vegetation can be developed, herbaceous or woody, remains to be seen.

3 Growth, water use efficiency and adaptive features of tagasaste

3.1. Introduction

In this part of the study we set out to identify the morphological, phenological and physiological characteristics that enable a soft-leaved species such as tagasaste to adapt to the severe semi-arid Mediterranean climate zone of south western Australia. To do this we studied a range of adaptive features of trees established in plantations and in a wide-spaced alley cropping format, namely (1) root architecture and nodulation, (2) growth, transpiration and water use efficiency, (3) relative dependence on soil and groundwater, (4) water stress and response to summer drought, and (5) response to episodic recharge of the soil profile over summer.

3.2. Materials and methods

The experimental site and treatments are described in Chapter 2 (section 2.3).

Dry matter accumulation

Growth rate was measured by harvesting 16 trees (8 from plantation and 4 from each alley treatment) each month from August 1996 to July 1998 and then at three-monthly intervals until April 1999. Shoot biomass above the pruned height of 0.6 m was weighed fresh in the field and a representative sub-sample from each tree weighed and then oven dried to enable calculation of coppice dry matter production. Shoot:root dry weight ratio was estimated by mechanical excavation of four trees in March 1997. Two trees cut the previous May and two left uncut were harvested and the soil within a 0.5 by 2 m area of each stump sieved exhaustively to a depth of 4 m to retrieve root biomass. To account for secondary thickening in the above-ground stump, estimates of coppice:stump dry weight ratios were made in March 1997 and April 1999 by harvesting trees at ground level and comparing weights above and below the cutting height of 0.6 m. Regular harvests of coppice dry matter were then converted to total plant dry matter using mean shoot:root and coppice:stump ratios. As no difference was detected in the growth rates of alley crop and alley fallow trees, data from these treatments were pooled and are referred to hereafter as 'alley' treatment.

Tree transpiration and potential evapotranspiration

Transpiration was measured using sapflow sensors (Hatton *et al.* 1990) fitted to tagasaste stems, moved to a fresh set of stems on a six-monthly rotation. Six stems of varying size were logged using Greenspan SF300 sensors in plantation from January 1997 to January 1998, and in alley crop from January 1997 to February 1999. An additional 24 stems were logged with sensors using the heat ratio method (Burgess *et al.* 1998) in plantation from May 1998 to April 1999, and in alley crop from May 1998 to December 1998. Flux per stem was scaled up to plot level transpiration using data from four-monthly surveys of stem size distribution (10 trees per treatment) and measurements of conductive wood area made after immersing freshly cut stems in a 0.05% solution of basic fuchsin for a two-hour period of transpiration. Rainfall, air temperature, wind speed, solar radiation and relative humidity were measured using an on-site automatic weather station (Campbell Weather Watch 2000) and these parameters used to calculate Penman-Monteith potential evapotranspiration (Campbell 1977, Monteith and Unsworth 1990), referred to hereafter as E_0 .

Transpiration ratio measurements in field and glasshouse

Young tagasaste trees were grown in either 10 L pots or 1.5 m high, 250 L polyvinyl chloride columns of soil collected from the Moora site to compare their transpiration ratios (water use per unit accumulated dry matter) with those of field-grown trees. Water use of 28 pot-grown six-month-old trees was monitored over the period August to October 1997 by daily weighing and addition of water to compensate for transpiration loss. Pots were mulched with polyethylene beads to limit evaporation losses and water loss from four similarly mulched control pots without trees subtracted from mean

cumulative water use of pots with trees at the end of each experiment. Dry matter accumulation was calculated by subtracting the dry weight of 24 matched seedlings harvested at the commencement of the experiment from the dry matter of experimental plants at the conclusion.

Water use of 24 column grown trees was monitored by recording the volume of water that had to be progressively added to restore field capacity. Four control columns without trees were used to correct for evaporation losses. Rainfall received at the soil surface during experiments conducted outdoors was measured with gauges in each column and canopy runoff recorded using stem flow collectors. To examine the effects on tree growth and water use efficiency of water being freely available throughout the column as opposed to solely as sub-surface water, sets of 12 columns were randomly assigned to each of two treatments. One set was maintained at full soil water status by watering from above and the other set watered via a slotted access tube to maintain a water table at constant height in the gravel fill at the base of the column.

Soil water content in the field

Soil water content was measured with neutron probes at 20 cm intervals to a depth of 3.7 m from July 1996 to December 1998 at two-week intervals in winter and monthly over summer. Six access tubes were located in each sole crop plot, five in each plantation plot (at 0, 1.5 and 3 m either side of tree rows) and eleven in each alley crop and alley fallow plot (along transects at 0, 1, 2, 4, 8 and 15 m either side of tree rows), giving a total of 78 access tubes. Neutron probes were calibrated in the field and separate calibration equations were used for 0-20, 20-80, 80-140 and >140 cm depth intervals to convert neutron counts to volumetric water content.

Assemblies of time domain reflectometry (TDR) probes were installed in one plantation and one sole crop plot on April 27 1997. Four metre deep wells were excavated (mid-way between tree rows in plantation) and lined with 1.5 m diameter concrete pipe. Ports were cut through the concrete liner on the undisturbed side of the well, equidistant between tree rows in the case of plantation. Probes were then inserted horizontally at depths of 20, 65, 150, 225, 290 and 350 cm after excavating 60 cm of soil and pushing the 40 cm wave guides into the undisturbed sand. Three additional probes were also installed in the plantation plot to measure rainfall interception. Two probes with 40 cm wave guides were located mid way between tree rows to measure through-flow, one vertically and one obliquely over the depth 0-20 cm, and one 40 cm probe installed adjacent to a tree trunk to measure stem flow. A probe with 40 cm wave guides was also installed obliquely over the depth 0-20 cm in the sole crop plot. Measurement at hourly intervals commenced on September 17 1997 and continued until December 1998.

Relative dependence of trees on soil and groundwater

Differences in deuterium:hydrogen (D:H) natural abundance isotope signals between tagasaste xylem sap, groundwater and the xylem sap of annual plants (as representative of soil water) were used in a mixing model to estimate the relative amounts of soil and groundwater used by the tagasaste. Deep mechanical excavations showed that some tagasaste roots reached the water table, branching and terminating at the capillary fringe at between 4 and 5 m. Xylem sap from the last 30 cm of these sinker roots was found to conform closely ($\pm 1.5\%$) in its D:H value to that of groundwater collected from wells within 20 m of the excavations.

Xylem sap was collected by mild vacuum extraction of segments of non-transpiring stems to obtain reference sources of xylem mobile water (Dawson and Pate 1996). Sap samples were collected monthly from ten shoot segments in each of two replicated alley crop and alley fallow plots between June 1996 and April 1998. Groundwater samples were collected synchronously from the 11 wells at the site. Samples of stem bleeding xylem sap of relatively shallow-rooted annual weed species were collected monthly during the winter growing season.

Two annual weed species, wild radish (*Rhaphanus raphanistrum*) and wild turnip (*Brassica tournefortii*) were found to exude large volumes (up to 10 ml/hr.plant) which permitted samples to collect rapidly in narrow tubes attached to the stem, thereby minimising D:H changes due to

evaporation in the tube. Excavation showed that the roots of the weed species extended to between 1.5 and 2 m within the first two months of growth, exploiting the same mid to upper soil zone in which most non-sinker roots of tagasaste were located. As the annual species did not establish until the first rains of autumn (April/May) and had senesced by late November, application of the mixing model was restricted to the seven to eight month wet season.

Water from groundwater and xylem sap samples were extracted by cryogenic vacuum distillation (Erhlinger and Osmond 1989) and D:H values estimated by converting the constituent hydrogen and deuterium to gaseous form and analysing for isotope abundance using a high precision mass spectrometer (VG Isogas SIRA 10), as described by Dawson (1993) and Dawson and Pate (1996).

Carbon stable isotope ($\delta^{13}\text{C}$) analysis of new shoot growth

New shoot growth was harvested each month for $\delta^{13}\text{C}$ analysis. Actively growing 3-10 cm lengths of apical growth were selected from random positions in the canopy of 30 trees from each of the six rows in the alley plots and from every sixth row of the 30 rows in the plantation plots. By tagging newly expanded portions of shoots in each interval of the study, it became evident that coppice branches grew virtually continuously and that a new segment of shoot apical growth of 3-10 cm length was produced each month. In this manner it was possible to follow seasonal changes in $\delta^{13}\text{C}$ signals of the photosynthetically fixed carbon which had been incorporated into new shoot DM during each sampling interval, and thereby compare the relative degrees of water stress experienced by the trees from each plot and treatment over the study period.

3.3. Results and discussion

Adaptive features of tagasaste evident in the field

- Coppice shoot characteristics

The four-year-old trees in all plots resprouted rapidly and prolifically from the stumps after being cut back to 0.6 m above ground level in May 1996. Over the next 3 years of the study, coppicing shoots exhibited an essentially open ended pattern of shoot growth with no evidence of producing resting buds during periods of stress. Terminal flowering on a few large branches of some trees occurred in the second spring after cutting (1997) and virtually all trees flowered and set seed the following spring. However, vegetative growth continued at a high rate throughout, largely due to outgrowth of axillary shoots on main branches which had flowered or where apices had been damaged.

Pronounced wilting of leaves was encountered during early afternoons of unusually hot days from November through to April. When only mildly affected, restoration of turgidity occurred quickly the following evening, but sequences of several days of relatively severe wilting triggered leaf shedding of older foliage, well in advance of normal senescence. General senescence and shedding of foliage first occurred from lower regions of coppice shoots in autumn 1997 and premature abscission of still green foliage occurred frequently during heat stress in summers and autumns over the next two years. Death of emergent shoot tips on canopy faces exposed to hot winds was also observed on days of very high temperature ($>40^\circ\text{C}$) and low humidity. Production of new axillary shoots restored leaf area following onset of rain and colder conditions the following autumn. Leafiness of canopies was visibly more pronounced in winter, spring and early summer than during peak water stress in late summer and early autumn. Rates of shoot extension were notably greater in spring and early summer than in other times of the year.

- Root morphology

Young trees quickly developed a distinctly dimorphic root architecture consisting of radially extending superficial laterals and deeply penetrating sinker roots (see Pate and Dixon 1996, Pate *et al.* 1998, Pate and Bell 1999 for other species sharing this habit). This occurred whether plants had been established from seed in pots or large columns, transplanted as bare rooted seedlings or direct sown in the field.

Mechanical excavations extending to the water table at 5 m showed that virtually all major sinker roots of trees five to seven years old had already reached the water table. Each sinker root descended directly downward without major branching in the final 2 m, and then branched repeatedly on reaching the capillary fringe above the water table, providing multiple access to a large area of the saturated zone.

The lateral component of the root system comprises a number of roots arising from upper parts of the root stock that extend rapidly outwards for at least 15 m in five-year-old alley trees. Other laterals originate at lower levels, essentially as horizontally extended outgrowths from descending tap roots. As a further complication, secondary or minor tap roots may descend from laterals at 1-2 m out from the point of attachment to the main root stock.

Seasonal growth of fine feeding roots typically develop from the perennating portions of all superficial lateral roots, following wetting of the top 60 cm of the soil profile by autumn rain or aseasonal rainfall in summer. These roots typically persist and continue to grow and branch through winter until late spring, but then senesce once the upper soil dries out. Lateral roots are also present, albeit in lesser amounts, in the moist cooler soil zone at 0.5-1.5 m deep. These deeper roots apparently remain alive and functionally active through summer.

Excavations to 60 cm depth along metre wide transects between alley and plantation tree rows in winter enabled variations in lateral fine root biomass to be assessed with distance out from tree rows. In the alley plot, a thin veneer of roots at low near uniform density ramified across the 30 m distance between tree rows, indicating the capacity of a tree to extend its sphere of influence at least to the middle of an alley. In the closely spaced plantation, trees made a much greater investment of roots per metre within the 6 m space between tree rows. The result was that similar amounts of total root biomass were retrieved by sieving soil from five 0.3 m³ pits spaced evenly along the two transects (89.6 g in the alley and 78.2 g in the plantation).

- Nodulation of root systems

The clusters of fine roots produced each autumn on shallow lateral roots developed many small unbranched nodules. These nodules and the rootlets on which they were borne persisted only for the winter and spring following the autumn of their inception. Most sinker roots excavated in winter and summer were encircled by closely grouped elongated branched nodules, typically concentrated in the 2.5 to 3.5 m depth zone of the soil profile with some occurring as close as 1 m from the surface. Their lobed appearance and the haemoglobin pigmentation of their younger regions strongly suggested the nodules to be perennial (as reported for other woody legumes, Pate 1961, Pate 1977, Pate and Unkovich 1999) and therefore probably active in N fixation throughout the year.

- Proportional growth of roots and shoots

Dry weight ratios of shoot:root were estimated for trees grown in pots and soil columns, and coppiced and uncut trees excavated at the field site one year after cutting had occurred. Ratios for young trees grown in pots lay within the range 1.1 to 1.3 while those of 1-1½ year-old trees grown in tall columns in the range 1.2 to 2.7. The ratios of cut and uncut trees excavated in the field were 2.5 and 2.9 respectively. This similarity indicated how rapidly tagasaste restores the balance between its above- and below-ground biomass following removal of most of the shoot.

Dry matter accumulation and transpiration

Comparisons of tree growth and transpiration were made for the two-year period April 1997 to April 1999, ie. over the second and third full years regrowth after the trees were cut. Data for dry matter gain are shown in Figure 3.1a, using lines of best fit to construct generalised growth curves for alley (alley crop and alley fallow) and plantation plots. Similar patterns of growth were evident for all trees at the site, but with slower growth of alley trees during the cropping season of 1997. Thereafter through 1998 to the last harvest in April 1999, growth of alley trees tracked closely that of plantation trees.

Plantation and alley treatments showed essentially no differences in transpiration per tree per day throughout the study (Figure 3.1b). During 1997, rates fell slightly from April to mid winter, consistent with onset of cool conditions, and then rose progressively during spring until December. Rates then declined sharply over the period January to May 1998, possibly reflecting heat stress and reduction in soil water reserves. Leaf shedding was minimal during this period since most foliage was less than 12 months old. Comparison of data from Greenspan heat pulse units and gauges using the heat ratio method (see April 1998 onwards Figure 3.1b) indicated the latter showed consistently higher values. Nevertheless, only slight differences were recorded for alley and plantation trees, transpiration rates of both increasing progressively from mid winter 1998 through to the end of the year.

Somewhat surprisingly, water loss per tree per day during 1998 was not appreciably greater on a month-by-month basis than in 1997 (Figure 3.1b), despite total tree dry matter being two-fold higher. More conservative stomatal control would be expected in canopies containing high proportions of leaves entering their second year and experiencing progressively increased shading of foliage within and between trees. Considerable shedding of older foliage occurred in late summer of 1998 in both alley and plantation trees. This amounted to 14% of above-ground biomass in 1998 (see Chapter 5).

As no difference was detected between water use of alley and plantation trees, sapflow data recorded with Greenspan gauges was pooled for trees at both densities. Expressing this as plantation transpiration on a plot area basis (mm/d) enabled comparison with daily E_0 (Figure 3.1c). The resulting data shows that trees performed at near potential rates when unstressed in the cooler months but cut back progressively on loss in the mid summers 1998 and 1999 to levels of only 30% and 34% of potential respectively. Total transpiration by trees in the plantation plot over the period April 1997 to March 1998 was 849 mm (0.55 of E_0) and 870 mm between April 1998 and March 1999 (0.63 of E_0).

The site was subject to a large (138 mm) cyclonic rainfall event between March 19 and 21 1999, representing the highest recorded rainfall for that month in 100 years of records. The response of E_0 and tree transpiration to this event can be seen in Figure 3.1b and c and will be discussed later.

Rainfall interception by tree canopies

Interception by tree canopies was estimated from the difference between the change in soil water content immediately before and after each rainfall event measured with TDR probes, and the daily rainfall recorded by the weather station in one of the plantation plots over 1998. Two vertical 40 cm probes, one between rows measuring through flow only and one adjacent to a trunk measuring through flow plus stem flow, gave interception estimates of 72% and 75% respectively over the entire season. These were considered to be overestimates as the probe head would have shielded the probes, particularly during small events. The oblique probe situated between the rows and measuring to 20 cm depth was therefore used to calculate interception (Table 3.1) given that it would have been more sensitive to smaller rainfall events and the mid row position appeared to be representative of the plantation as a whole. As TDR readings were made hourly, the maximum water content could be recorded before redistribution took the wetting front below the depth of the probes. This method could not be used for large rainfall events (>20 mm) as water moved below the probes before the end of the rainfall event. For the 4 events where rainfall was >20 mm (out of the total of 111 events for the year), interception was assumed to be 2.9 mm, the average recorded for events between 10 and 20 mm.

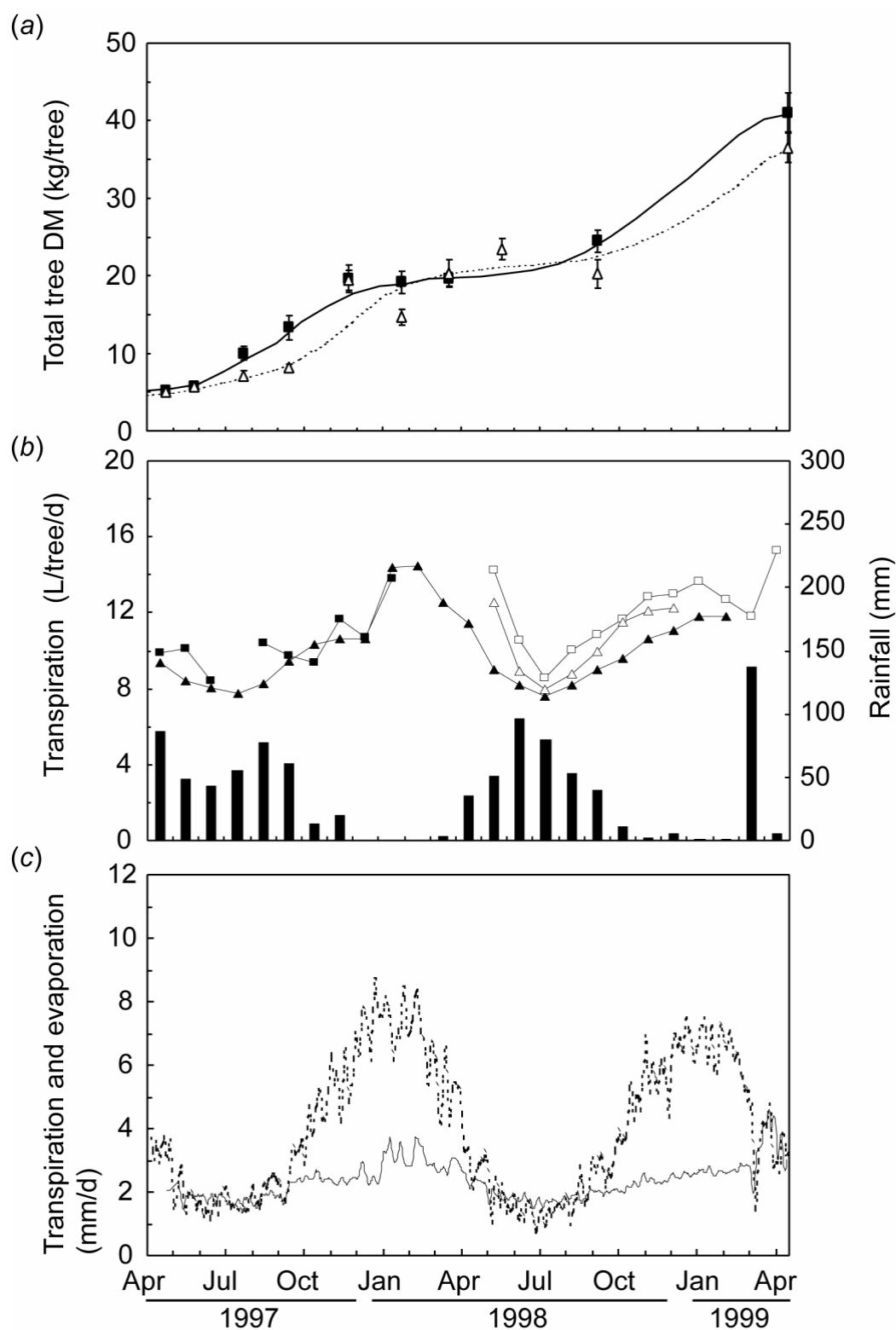


Figure 3.1. Growth and transpiration of tagasaste trees at Moora, Western Australia, from April 1997 to April 1999. (a) total dry matter production of plantation (■, —) and alley (△, ---) trees; (b) rainfall and tree transpiration measured with heat pulse sapflow gauges (plantation ■, alley crop ▲) and heat ratio sapflow gauges (plantation □, alley crop △); (c) transpiration of tagasaste trees in plantation on a whole plot basis (—) and E_0 (---).

The resulting estimate of 38% of annual rainfall evaporating directly from the tree canopies (Table 3.1) is higher than reported interception rates of 10 to 20% for eucalypt forest (Dunin *et al.* 1988, Feller 1981). However, higher canopy storage capacity has been reported for exotic species (conifers) than eucalypts in Australia (Ashton 1980). Interception rates of this order have also been reported from studies of conifers in Britain (Gash *et al.* 1980), beech (*Nothofagus sp.*) in New Zealand (Rowe 1983) and a short term study of jarrah (*Eucalyptus marginata*) in south western Australia (Sharma 1984). The fact that a large proportion of the rainfall occurred in small events in 1998 is likely to have contributed to the high figure in this study, as would the higher E_0 experienced at Moora than in the above studies.

Table 3.1. Rainfall interception by tree canopies in a tagasaste (*Chamaecytisus proliferus*) plantation plot at Moora, Western Australia. Numbers in brackets indicate events outside the range of measurement using TDR probes to 20 cm which were assumed to be 2.9 mm each.

Rainfall event class (mm)	Number of events	Amount (mm)	Interception (mm)	Interception (% of rainfall)
0-2.0	61	42.0	36.0	86
2.1-5.0	19	65.4	50.8	78
5.1-10.0	10	65.2	30.6	47
10.1-20.0	7	92.8	11.0	12
>20.1	4	105.6	(11.6)	(11)
Total	101	371	140	38

With this estimate of interception it is now possible to estimate total evapotranspiration for the plantation as 975 mm (835 mm transpiration for the calendar year 1999 plus 140 mm interception). Using the replacement series discussed in Chapter 2, the area required under three-year-old trees to prevent further water table rise becomes 20%, compared to 24% for younger trees (see Figure 2.5).

Whole plant transpiration ratios of containerized and field grown trees

Table 3.2 records dry matter increments and transpiration loss for containerized and field grown trees. Despite differences in tree age, location and season of study, the transpiration ratios recorded lay within a relatively narrow range (186 to 366 L/kg). Pot- and column-grown trees studied in the glasshouse, subject to lower wind speed and higher humidity than outdoors, showed lower ratios season for season (186-293 L/kg) than did trees grown outside (314-366 L/kg). Trees grown outdoors in columns from spring 1997 to autumn 1998 showed no difference in water use efficiency when watered to field capacity from above than when watered from below via an artificial water table (see Table 3.2). The mean value for trees at the field site over two years averaged for all seasons (247 L/kg), was close to the middle of the range for container-grown trees across all ages and growing conditions.

Relationship between soil water status and dependence of trees on groundwater

Soil water data from the transects of neutron probe access tubes was integrated in alley fallow, alley crop and plantation treatments by converting to volumetric water content and summing across the plots to provide a comparison of seasonal changes in total available water in the top 370 cm of the soil profile. Available soil water was defined as total soil water content minus the lowest water content recorded in the driest profile at the site (see Table 2.1).

The analysis (Figure 3.2a) showed all treatments were equally close to maximum storage of plant available water in mid-August 1996 after effective recharge by mid-winter rains following cutting of trees in May. By harvest of the lupin crop in early December 1996, available soil water in alley crop

plots had been reduced to 36% of its winter maximum compared to lesser reductions in alley fallow (64%) and sole crop (46%, data not shown). Greatest reduction in soil water occurred in plantation plots where the December value was 20% of peak winter storage.

The winter rains of 1997 recharged all plots but to a lower extent in plantation (~120 mm) than in alleys (~180 mm) (see Figure 3.2a). By harvest of the oat crop in December 1997, available soil water had been reduced to essentially zero in plantation compared to approximately 100 mm in alley plots. Sole crop plots (not shown) at that stage showed 137 mm of residual water.

The winter rains of the 1998 season rapidly refilled the soil profile to maxima in August of 200 mm in the alley plots but only 90 mm in the plantation. By harvest of the lupins in December 1998, these reserves had been reduced to zero in the plantation, 53 mm in the alley crop, 90 mm in alley fallow and to 74 mm in sole crop (not shown).

Seasonal changes in dependence of alley and plantation trees on groundwater is shown in Figure 3.2b. Winter values for 1996 and 1997 were based on deuterium:hydrogen (D:H) analysis of tagasaste xylem sap, groundwater and annual reference plants (solid lines, Figure 3.2b) (The stable hydrogen isotope ratios (δD) on which this was based are shown in Figure 4.6a). Summer values for 1996/97 and 1997/98 were based on soil water depletion over rain-free periods (dotted lines, Figure 3.2b). From April to December 1998, xylem sap samples were not available. However, as interception had been estimated from TDR data, relative dependence of trees on soil and groundwater was inferred from sapflow measurements of tree transpiration and water balance, calculated as:

$$T_{\text{soil}} + E = \Delta S + P - I$$

where T_{soil} is tree transpiration from the unsaturated zone, E is evaporation from the soil surface, ΔS is change in stored soil water, P is rainfall and I is interception. Evaporation was not independently measured in this study, however an estimate of the extent of evaporation from the soil surface in the plantation was possible during winter 1997 when transpiration measured by sapflow gauges was found to account for 79% and 82% of soil water depletion respectively for two rain-free periods.

The overall trend apparent in Figure 3.2b was greater dependence on soil water in winter than summer, rapid switching to groundwater in early summer and to soil water with the break of season rains, and greater dependence on groundwater in all treatments over time. Comparisons between plantation and alley treatments were not possible beyond April 1998 due to absence of D:H data and lack of soil evaporation measurement in alley treatments to enable water balance estimates.

Table 3.2. Transpiration ratios (litres of water transpired per kilogram of total dry matter produced) for tagasaste trees growing under glasshouse and field conditions. Containerized plants were grown at Perth and field plants at Moora, Western Australia.

Growing conditions	Period (days)	DM increment	Water use	Transpiration ratio (L/kg)
In glasshouse				
(i) 10 L pots				
Aug - Oct 1997	50	5.02 g	933 ml	186
Oct - Nov 1997	43	4.85 g	1423 ml	293
(ii) 250 L columns (1.5 x 0.4 m)				
Feb 1997 - May 1998	85	108 g	24.6 L	228
Outside in 250 L columns				
Aug - Nov 1997	90	122 g	44.6 L	366
Aug - Apr 1998	133	739 g	232 L	314
Aug - Apr 1998 ^a	133	144 g	46.1 L	320
In situ (Moora)				
Apr - Apr 1999	760	31.9 kg	7895 L	247

^a watered from below via artificial water table

Carbon isotope discrimination values as indices of water stress

Data for $\delta^{13}\text{C}$ of newly formed shoot tip dry matter collected progressively from the three treatments (Figure 3.2c) showed seasonal fluctuations of the order of 3-5‰ between least stressed mid winter values (-28.5‰ up to -27.3‰) and peak stress late summer/autumn values (-25.5‰ to -23‰). According to the generally accepted interpretation of $\delta^{13}\text{C}$ data implicit in the studies of Farquhar and colleagues (Farquhar and Richards 1984, Farquhar *et al.* 1989), the more negative winter values denote relatively high ratios of CO_2 concentration from inside to outside of leaves, reflecting relatively open stomates, low instantaneous water use efficiency and transpiration close to potential rates (see Figure 3.2c). Conversely, the less negative $\delta^{13}\text{C}$ values for dry matter laid down in summer and autumn would indicate tight stomatal control, high water use efficiency, and as shown in Figure 3.1c, tree water losses well below potential evaporation rates.

A number of subtle differences between treatments over the course of the study emerge from the data shown in Figure 3.2a-c.

- (I) *June to December 1996.* During this period, coppice shoots were relatively small but growing rapidly. As expected of their lesser draw down of soil water reserves, alley fallow trees showed $\delta^{13}\text{C}$ values more negative (less stressed) than in trees of alley crop or plantation. This applied especially during spring and summer when alley fallow $\delta^{13}\text{C}$ values were up to 3‰ below those of other treatments.
- (II) *December 1996 to April 1997.* During this period, available soil water in alley fallow remained higher than in alley crop and higher again than in plantation, but trees in all treatments switched to equally heavy dependence on groundwater. This suggested that much of the remaining soil water in the alley treatments was beyond the lateral range of tree rows. Closely similar peak $\delta^{13}\text{C}$ values were achieved by trees in all treatments just before the onset of autumn rains, indicating uniformly high levels of water stress.
- (III) *April to December 1997.* Soil water was rapidly recharged in May and alley fallow and alley crop treatments retained higher soil water reserves through to September. Rates of decline in soil water from their respective plateau values were then slower in alleys than in the denser plantation

(Figure 3.2a). These differences were accompanied by heavier dependence on groundwater in plantation (Figure 3.2b), but surprisingly the $\delta^{13}\text{C}$ values in plantation trees indicated less stress than in alley trees.

- (IV) *December 1997 to April 1998*. The plantation plots continued to show significantly more negative (less stressed) $\delta^{13}\text{C}$ values throughout this period despite their soil water resource being virtually depleted. This suggests that plantation trees, being forced into proportionally greater dependence on groundwater throughout the previous 6 months, responded by improving their access to groundwater through root development to a greater extent than did alley trees at lower density.
- (V) *April to December 1998*. Data for proportional dependence on groundwater were unfortunately available only for plantation trees. However, $\delta^{13}\text{C}$ values of plantation trees indicated less stress than in alley trees, implying better general access to water than in alley trees. This difference was quickly reduced in spring with the onset of warmer weather, when $\delta^{13}\text{C}$ values for dry matter for all treatments became closely similar. $\delta^{13}\text{C}$ signals indicated lower levels of stress in all treatments over this compared to earlier summers, as indicated by maxima falling from -23‰ in 1996 to -24‰ in 1997 and -25‰ in 1998. This can be regarded as further evidence that all trees progressively improved their access to groundwater with age and were therefore able to exercise less restrictive control on water loss than was evident earlier in the coppicing cycle.

More loss of foliage occurred in the third summer than the previous two. As shown earlier (Figure 3.1b), this resulted in very small increases in transpiration per tree between the summers of 1997 and 1998. Relatively unstressed $\delta^{13}\text{C}$ signals typical of all treatments in the last year of the study presumably reflected improved access to the water table, combined with an ability to reduce leaf area to less limiting levels.

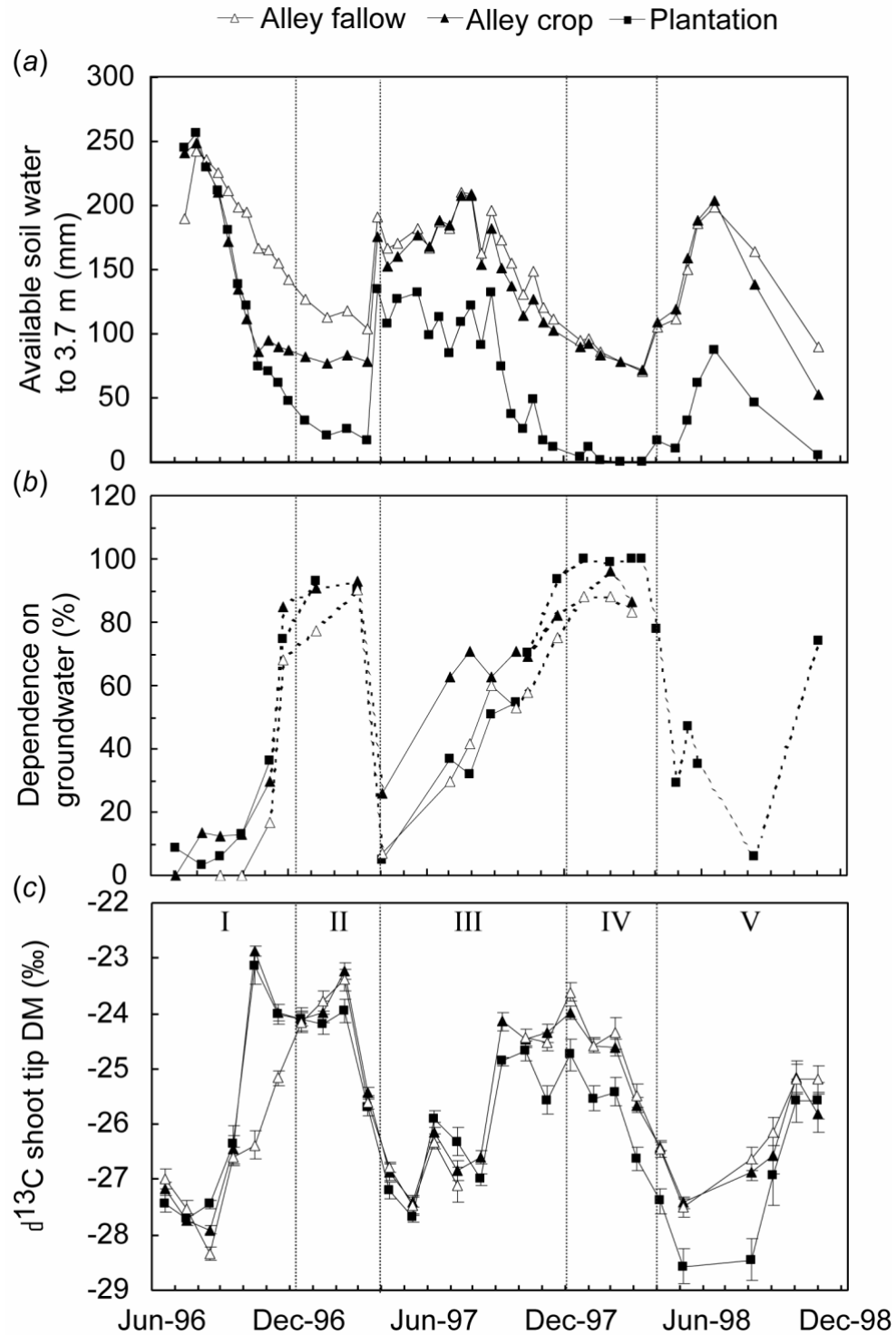


Figure 3.2. Change in soil water content, dependence of tagasaste trees on groundwater and $\delta^{13}\text{C}$ of shoot tip dry matter in plantation (■), alley crop (▲) and alley fallow (△) treatments at Moora, Western Australia. (a) soil water content measured every 14 days during the crop growing season and monthly over summer from July 1996 to July 1998, and at anthesis and harvest in 1998; (b) proportional dependence on groundwater derived from deuterium:hydrogen analysis of tagasaste xylem sap, groundwater and annual reference plants in winter (—) and soil water depletion over rain free periods in summer (---); (c) monthly $\delta^{13}\text{C}$ of shoot tip dry matter.

Response of trees to irrigation and summer rainfall

Tagasaste did not respond to small rainfall events in summer. Following a 16.6 mm rainfall event on November 12 1998, soil water extraction increased from 0.2 mm/d before the rain to 1.7 mm/d immediately afterwards, but this had a negligible effect on transpiration (Figure 3.3). This suggests the trees were facultative in their use of soil and groundwater, switching to greater reliance on soil water but not breaking out of their conservative water use mode as indicated by the low E_t/E_0 ratio.

When a more significant change in soil water content occurred, a different pattern of tree water use emerged. On March 9 1999, 200 mm of flood irrigation was applied to four plantation trees logged with sapflow gauges in order to examine the effect of restoration of soil water status on tree transpiration rate. Time courses of transpiration and E_0 before, during and after the irrigation event are shown in Figure 3.4. Available soil water above 360 cm was essentially zero at the time of the irrigation and tree transpiration was occurring at 3 mm/d. Trees responded immediately to the added water by elevating their transpiration to 7 mm/d, representing the only time outside mid-winter when tree transpiration reached potential rates. A second irrigation, also of 200 mm, was applied on March 16 and this again prompted an immediate response in transpiration, which then closely tracked E_0 until the end of April.

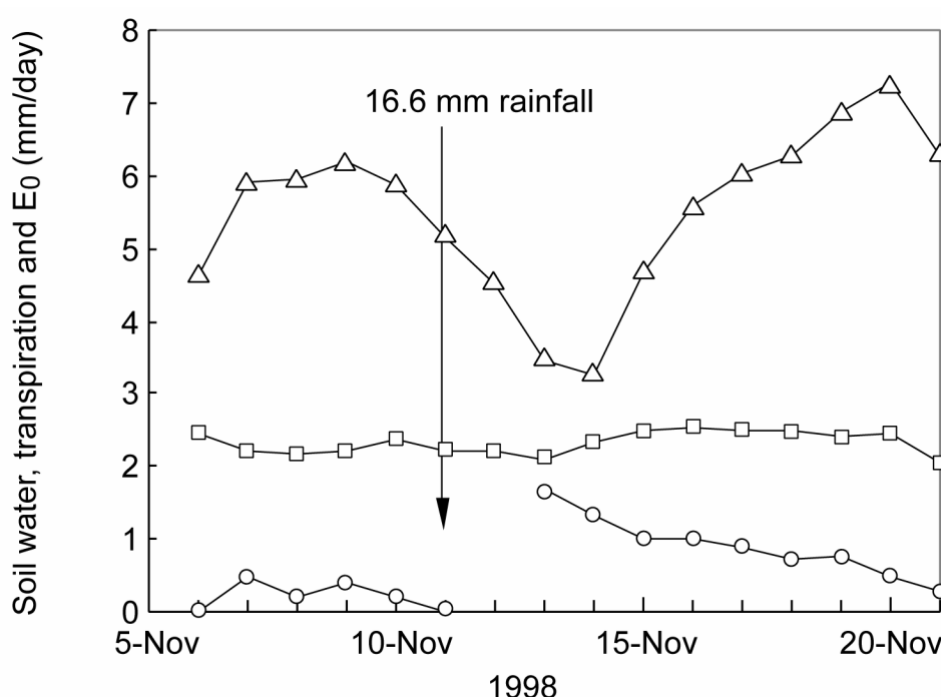


Figure 3.3. Change in soil water content (○), tree transpiration (□) and E_0 (△) before and after a late spring rainfall showing facultative use of soil water by tagasaste trees at Moora, Western Australia.

Five days after the irrigation experiment, a decaying tropical cyclone resulted in 138 mm of rainfall at the site over 3 days (March 21 to 24). Sapflow gauges installed in trees away from the above mentioned irrigated area recorded transpiration rates below 3 mm/d prior to the rain, equivalent to 60% of E_0 (Figure 3.4). Transpiration fell to 1 mm/d during the actual rainfall event then rose slowly over the next 10 days and continued at high levels for the next month or so with occasional daily peaks of 6 to 7 mm/d. Transpiration remained close to E_0 over the remainder of March and April.

Following the two irrigations and the rainfall event, the tagasaste rapidly dried down the soil profile, with extraction fastest at 20 cm and 65 cm, and then fairly uniformly to a depth of 350 cm. By April 30, 39 days after the rain, water content at all depths was 4.5%. This means that either tagasaste roots grew quickly over the entire depth or were already present and alive prior to the rain. The latter case seems unlikely given that the profile from 1 to 4 m had been dry for the previous 15 months. One

possible explanation is that roots were present and kept alive by hydraulic lift, discussed further below.

Taken together with earlier comparisons of potential evaporation and transpiration (Figure 3.1c), the data of Figure 3.4 strongly suggests that availability of soil water is the principal regulatory agent limiting tree transpiration during summer and early autumn, despite access to a fresh water table. When soil water status is restored by irrigation or stochastic large rainfall events, previously tight stomatal regulation of tree water loss is immediately relaxed resulting in near maximum possible evaporative losses from transpiring foliage. This capacity to respond opportunistically may be viewed as an important element in adaptation of tagasaste to the highly variable Mediterranean climate of south western Australia.

Measurements were made of $\delta^{13}\text{C}$ values of new shoot tip DM laid down by plantation trees prior to and after restoration of soil water deficit by irrigation and cyclonic rainfall. Prior to the irrigation and cyclone, the mean $\delta^{13}\text{C}$ was -26.8 ± 0.19 , ie. close to those obtained for bulk samples of plantation plots (see Figure 3.3). When irrigated trees were sampled at the end of April, the $\delta^{13}\text{C}$ signal had fallen to -28.4 ± 0.08 , while trees subject to rainfall only gave values of -27.9 ± 0.14 . In both cases, the significant lowering of $\delta^{13}\text{C}$ signals after restoration of soil water status was assumed to be symptomatic of lower water stress in foliage supplying the carbon used in shoot growth.

Evidence for hydraulic lift by tagasaste roots

The first evidence that hydraulic lift might have been occurring in tagasaste came from the discovery during early morning excavations in February and March 1997 of moist zones at 30-60 cm depth in an otherwise very dry soil profile at the base of both alley and plantation trees. These moist zones contained apparently healthy feeding roots, extended up to 75 cm out from the trunk bases of the trees, and were surrounded on all sides by powder dry soil typical of the upper profile at that time of year. Runoff of dew and rain were discounted since all observations were made during long rain-free periods and were preceded by dew-free nights. Roots within the moist zones bore turgid haemoglobin-pigmented nodules, whereas fine roots and nodules in adjacent dry zones of soil had long since senesced and their remains desiccated.

Further substantiation came from measurements of soil water status in plantation plots using both NMM and TDR. The time series of contour maps of soil water content derived from NMM data shown in Figure 3.5 depict a typical sequence of events from wetting of the profile in winter 1997 through to the next major recharge in autumn 1998. By early summer the profile between the 6 m spaced tree rows was very dry except for a distinct band of soil in the zone 50-80 cm below the surface. This zone remained moist and well demarcated from drier zones above and below throughout the ensuing four months (December 1997 to April 1998). Such prolonged and significant retention of moisture in such a specific zone is most likely to result from hydraulic lift, or at least from recharge of water in fine lateral roots biomass through intake of tap root derived water, as has been described occurring in *Banksia prionotes* in a similar deep sand environment (Dawson and Pate 1996).

TDR measurements of soil water content under plantation trees over the summer of 1997/87 and 1998/99 provided further evidence of hydraulic lift (Figure 3.6). Large diurnal fluctuations in soil water content were detected by the probes located horizontally at 65 and 150 cm depth while lesser, random variations with no diurnal periodicity were detected by the probe at 225 cm (Figure 3.6). The possibility that the diurnal change in water content was an artifact of the diurnal temperature pattern in upper soil layers was discounted by comparison with probes in the crop treatment at the same depths.

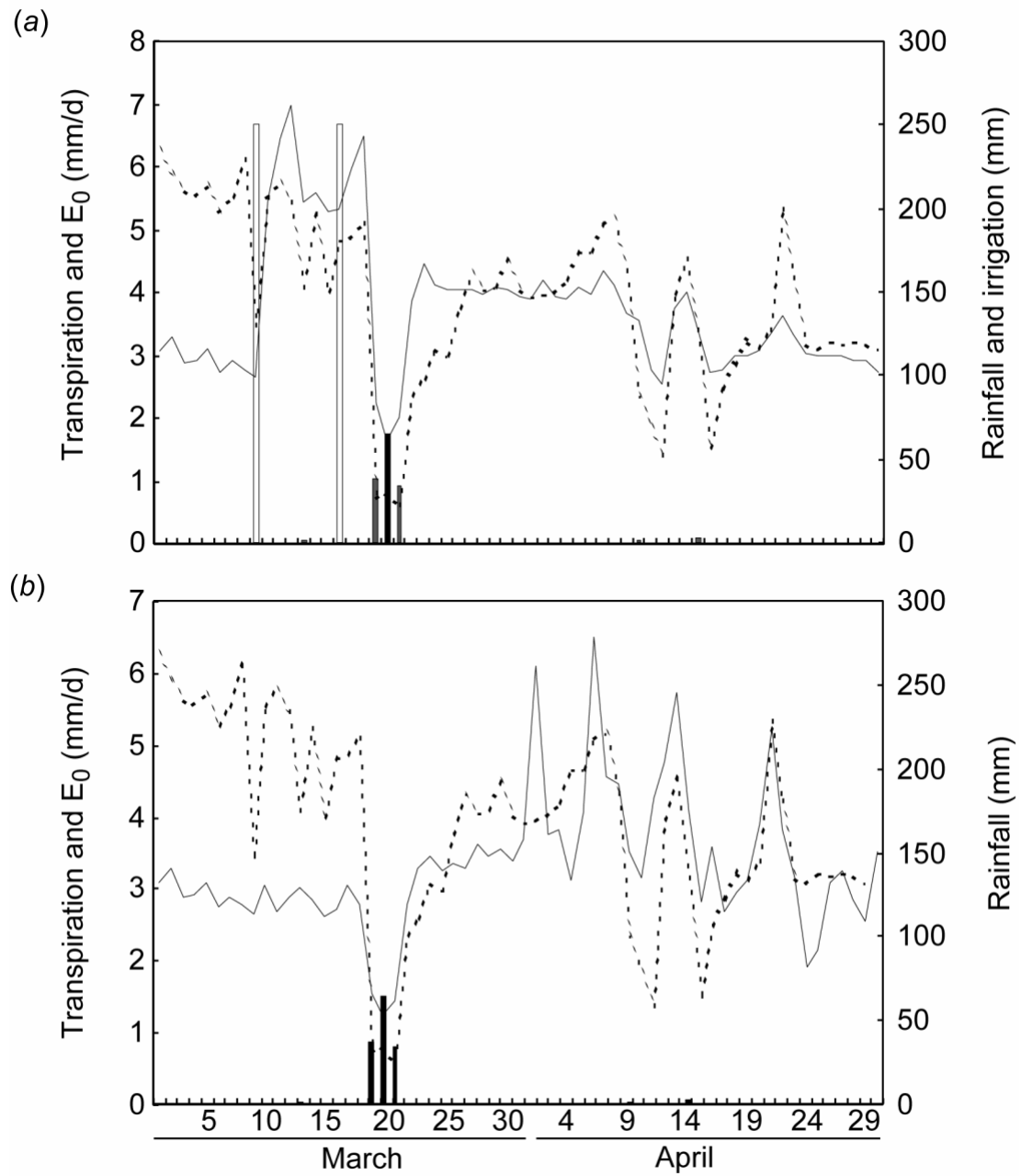


Figure 3.4. E_0 and tree transpiration following rainfall and irrigation from March 1 1999 to April 30 1999 at Moora, Western Australia. (a) E_0 (---) and transpiration (—) of plantation tagasaste trees receiving irrigation (open columns) and summer rainfall (filled columns); (b) E_0 (---) and transpiration (—) of unirrigated plantation tagasaste trees subject to summer rainfall only (filled columns).

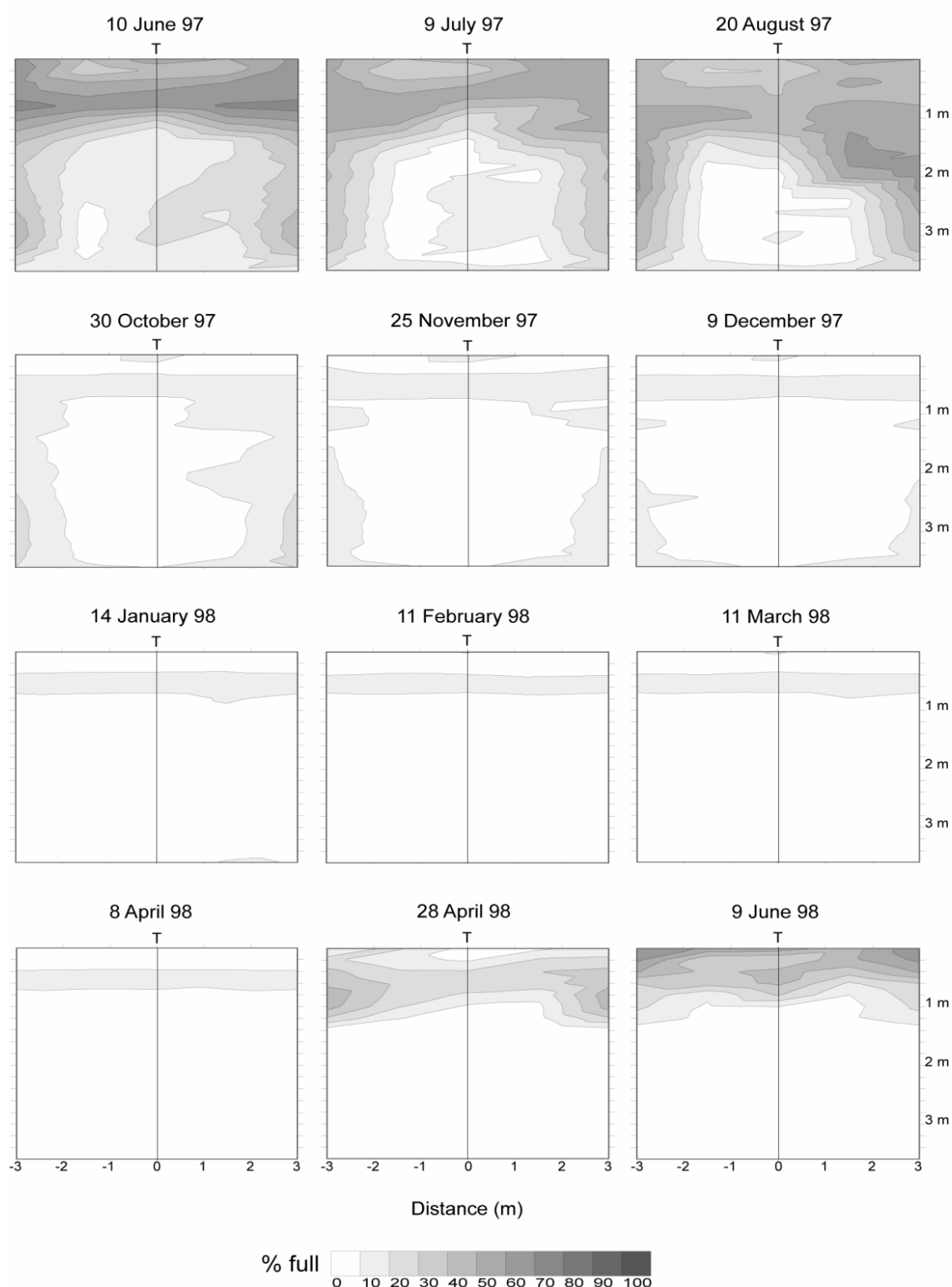


Figure 3.5. Spatial distribution of soil water in plantation plots from June 1997 to June 1998 showing band of moist soil in summer between 50 and 90 cm deep in the profile suggesting hydraulic lift. Water content is plotted as a percentage of the highest value recorded during the study with an interval of 10%. Raw data was recorded with neutron probes across two replicated transects (3, 1.5, 1.5, and 3 m either side of tree rows (T)) at 19 depth intervals per hole (20 cm intervals from 10 cm to 370 cm).

The maximum water content was found to occur between 6 and 9 am and the minimum close to 5 pm (Figure 3.6a). This is consistent with the patterns of diurnally reversing xylem flow obtained using sapflow gauges and dye injection in a study of the endemic tree species *Banksia prionotes* in remnant vegetation adjacent to the tagasaste site (Burgess *et al.* in press).

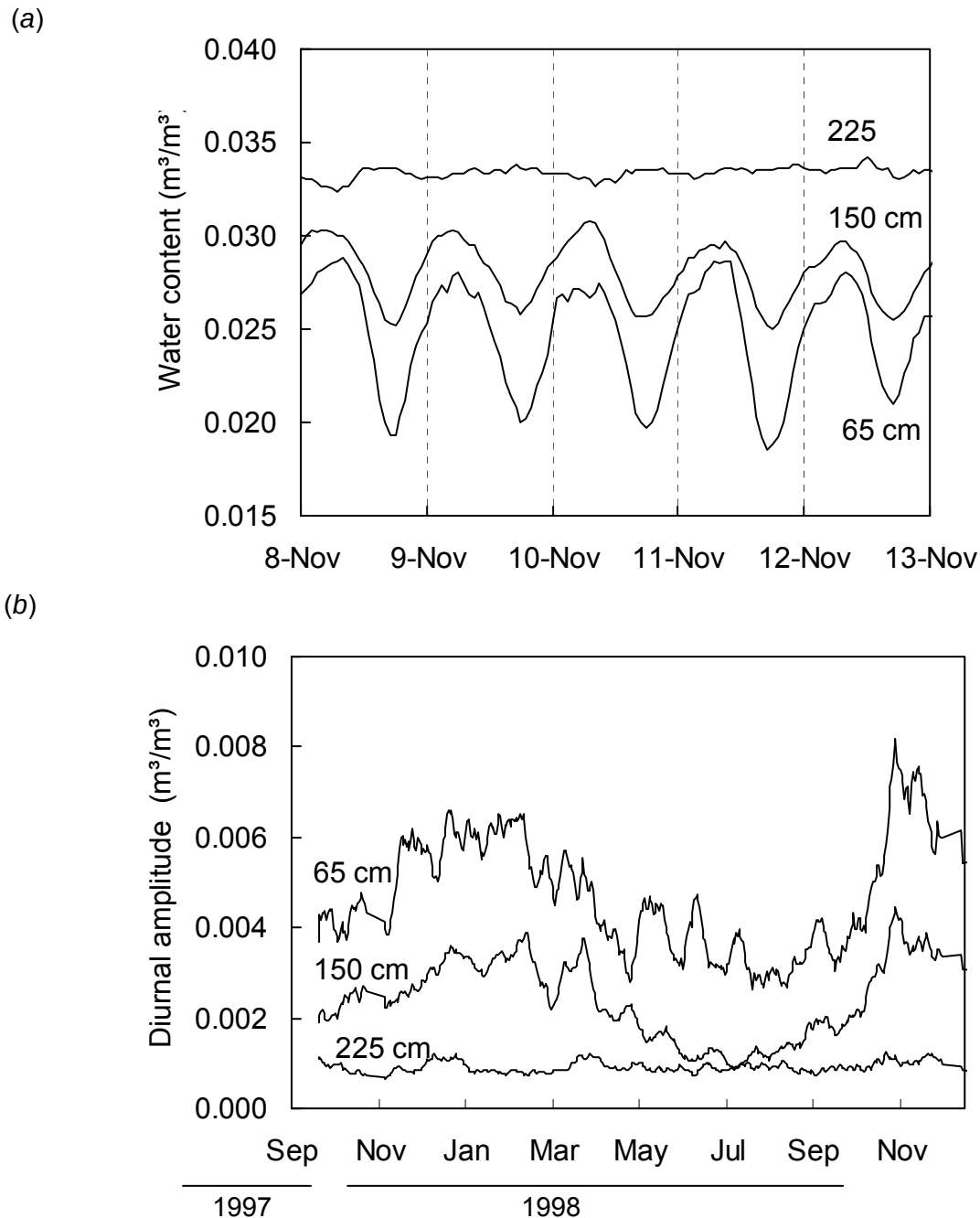


Figure 3.6. Changes in soil water content measured with TDR probes suggesting hydraulic lift by tagasaste trees (a) diurnal change in water content shown as a six point moving average of hourly TDR data recorded over a five day period at 65, 150 and 225 cm depths in November 1997, (b) daily amplitude of diurnal change in water content plotted as a ten day moving average showing lowest amplitude in winter and highest in summer. (Amplitude of 0.001 in volumetric water content at 225 cm was not diurnal fluctuation but random error between measurements).

The amplitude of the diurnal change in soil water content gives some indication of the amount of water lifted each night. If we assume for instance that the amplitude at 150 cm shown in Figure 3.6b was representative of hydraulic lift occurring between 50 and 150 cm, then the amount of water lifted in summer was approximately 3 mm/d ($1000 \text{ mm} \times 0.003 \text{ mm}^3/\text{mm}^3$), similar to total sapflow measurements of tree transpiration.

Further evidence for hydraulic lift came from excavation of roots to a depth of 1 m mid row in the plantation in December 1999 (Figure 3.7). While the root dry matter retrieved decreased rapidly with depth, root water content indicated that roots below about 60 cm were alive, while those near the surface were dead. Given the low soil water content at this time, hydraulic lift is the most likely means by which these roots remained alive. At the time of this excavation, it was discovered that the TDR probe at 65 cm in the plantation plot had been inserted into soil disturbed in the process of excavating the well, and that the root biomass surrounding this probe was 2 to 3 times as great as that found elsewhere in the plantation at this depth. The data for water content at 65 cm in Figure 3.6b therefore probably show an uncharacteristically high level of hydraulic lift than that occurring in the plantation as a whole.

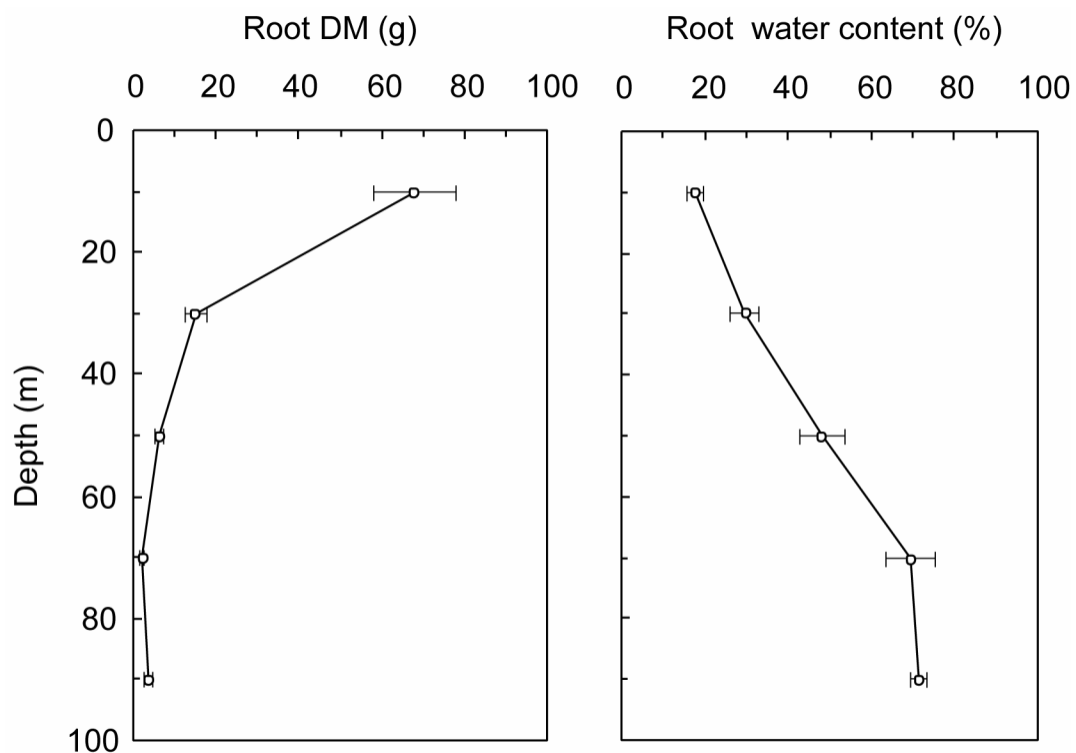


Figure 3.7. Dry weight and water content of roots sieved from $5.4 \times 10^2 \text{ cm}^3$ of soil at 10, 30, 50, 70 and 90 cm depth intervals mid way between rows of tagasaste trees in a plantation plot in December 1999 ($n=6$) showing the proportion of live roots increasing with depth.

3.4. Conclusion

The structural, morphological and physiological features of tagasaste were studied in order to appreciate more fully how this mesophytic tree adapts to the harsh Mediterranean climate of south western Australia. Such understanding might assist the identification and selection of further exotic tree species well adapted to meet the environmental goal of increasing water use and managing salinity in medium to low rainfall agricultural landscapes.

Distinctive features of tagasaste that emerged from this study were (i) a strongly dimorphic root system, (ii) an open ended pattern of growth, with the associated characteristics of heat stress-induced leaf shedding and rapid response to aseasonal rainfall, (iii) ability to use large amounts of groundwater, and (iv) possible hydraulic lift of groundwater to upper soil layers to maintain roots alive and ready to respond to rainfall.

The dimorphic root system enables the plant to access soil and groundwater at depth with its clusters of deep sinker roots, while also foraging at least 15 m laterally for water and nutrients with its shallow surface roots. This root architecture is a feature shared with summer active woody species from this region (Pate and Dixon 1996, Pate *et al.* 1998, Pate and Bell 1999) and other parts of Australia (Zohar 1985).

The fact that no difference was detected between growth rates and water use of trees at alley and plantation densities was surprising, given that available soil water was consistently higher in alley plots. One possible explanation is that the root architecture of the tree is insufficiently plastic to utilise soil water stored below 60 cm at distances of more than a few metres laterally from trees, while simultaneously investing heavily in root biomass at the capillary fringe of the water table. To resolve this question it would be necessary to compare the patterns of soil water extraction of trees without access to a water table at wide and narrow spacings.

The use of $\delta^{13}\text{C}$ as an indicator of water stress suggested that trees in all treatments, regardless of plant density or competition with annual crops, experienced progressively less water stress each summer over the three-year period of coppice regrowth. The finding that trees in plantation plots displayed significantly less stress (more negative $\delta^{13}\text{C}$) over the last summer than trees in the two alley treatments implied that trees forced by depleted soil water reserves to invest more root biomass at the capillary fringe eventually became better protected against summer water stress than those more reliant on water from the unsaturated zone.

The essentially open-ended pattern of shoot growth typical of tagasaste distinguishes it from most indigenous woody species, which initiate resting buds and enter a period of dormancy when soil water reserves are depleted in late summer or early autumn (Bell and Stephens 1984, Pate and Bell 1999). By contrast tagasaste responded to severe conditions of water and heat stress by dramatically reducing its leaf area through shedding along with much tighter stomatal control than evident under less stressed conditions.

Surprisingly, water use per tree in the third year of the study was only marginally greater than in the second, despite a two-fold increase in plant biomass. This was most likely due to the higher proportion of wood to foliage with age, more conservative stomatal control exerted by canopies containing a higher proportion of older, shaded leaves (with consequently less effective rates of gas exchange), and the increased occurrence of leaf shedding with age during times of heat and water stress. In addition, measurements of transpiration ratios of container and field grown trees indicated that tagasaste has a marked capacity to fine-tune its use of water to suit circumstances across a wide range of ages and growing conditions. The range of water use efficiencies observed (186-320 L/kg) fell within the range measured for other tree species studied in this environment (Pate and Dawson 1999).

The response of trees to irrigation in summer, involving an instantaneous relaxation of stomatal control and elevation of transpiration rates up to and exceeding Penman-Montieth potential rates, strongly suggested that low availability of soil water, rather than high temperatures and vapour pressure deficits in summer, was the primary limitation to tree transpiration. This was also supported by the experiment with column-grown trees in which both dry matter increment and water use of trees growing in dry soil above an artificial water table at 1 m were one fifth of trees watered from above. The ability of tagasaste to take up water from the capillary fringe therefore appears to be limited not

by depth to groundwater, summer dormancy or atmospheric conditions but by some intrinsic characteristic of this species.

Our observations of hydraulic lift (or at least hydraulic recharge of upper lateral roots with water derived from tap roots) is an adaptation that tagasaste appears to share with deep-rooted endemic trees such as *Banksia prionotes* growing in similar environments (see Dawson and Pate 1996). While the evidence presented here for hydraulic lift in tagasaste is not fully conclusive, if it occurred widely and consistently it would offer this species the means to maintain the functional integrity of fine roots and N₂ fixing root nodules for several months a year when soil is critically dry.

Two aspects of this study are relevant to the challenge of revegetation in the drier cropping areas. Firstly, the courses of tree transpiration and potential evapotranspiration over the study period illustrated that water use in this environment is energy limited in winter and water limited in summer. As a result, tagasaste exhibited a relatively small annual variation in transpiration compared to potential rates, ranging from 1 mm/d in winter to 3 mm/d in summer with an annual average 0.6 of potential. This value is at the upper end of the range reported by Raper (1998) in a review of tree water use in Mediterranean environments of southern Australia. In terms of groundwater use in summer, the 3 mm/d recorded for tagasaste in summer was twice as high as those reported by Thorburn (1996) in a review of water use by trees on shallow water tables. This climatic constraint to tree water use suggests that the strategy of preferentially locating trees in parts of the landscape with high water availability in summer (eg. Farrington and Salama 1996, Clarke *et al.* 1998, Hatton and Nulsen 1999) has more relevance to catchment scale water management than the search for so called high water use tree species. Secondly, it is apparent that exotic mesophytes such as tagasaste can be as well suited to this environment as endemic woody sclerophytes, indicating the search for suitable species need not be limited to the latter group of plants.

Summary

- Dry matter (DM) accumulation and transpiration were closely similar at alley and plantation densities despite higher soil water contents in alley plots. Transpiration at plantation density amounted to 0.55 and 0.63 of Penman-Montieth potential evapotranspiration (E_0) in the second and third years of regrowth after cutting, respectively.
- Mean water use efficiency over the three years was 247 L/kg DM, compared with values in the range 186-320 L/kg for younger pot and column grown trees. Neutron moisture meter (NMM) assays of soil moisture and deuterium:hydrogen ratios of groundwater and xylem water of tagasaste and annual weeds showed that trees became increasingly dependent on groundwater over time and had the capacity to switch rapidly between soil and groundwater sources.
- Seasonal changes in carbon isotope composition of new shoot tip dry matter indicated plantation trees became less stressed by the third summer as they adapted to heavy dependence on groundwater. In the third season's regrowth, NMM profiles and time domain reflectometry (TDR) assays indicated there was no deep drainage at plantation density, and that trees were hydraulically lifting groundwater to near surface soil in the dry season.
- Additional adaptive features of importance to this environment included heat stress induced leaf shedding, development of perennial root nodules on lower parts of tap roots, and an ability to respond in summer to artificial irrigation or aseasonal rainfall by rapidly increasing transpiration two- to three-fold to values equalling E_0 .

4 The water balance of a tagasaste alley cropping system

4.1. Introduction

Alley cropping is the practice of growing crops in the alleys between spaced rows of trees or shrubs. Spaced agroforestry systems such as alley cropping and parkland agroforestry have been advocated as a means of increasing water use in the agricultural landscape of southern Australia and therefore contributing to the management of dryland salinity (Lefroy *et al.* 1993, Lefroy and Scott 1994). An estimated 10 000 ha of alley cropping had been adopted in Australia, commonly on the assumption of benefits from reduced wind erosion, increased water use and improved crop and animal productivity through changed microclimate (Stirzaker and Lefroy 1997). However there are few empirical studies in Australia that quantify these effects (Bird 1992, Nuberg *et al.* in press, Sudmeyer *et al.* in press). In particular, questions remain about the relative impact of spaced trees on crop yield and water balance at field and catchment scale.

Sanchez (1995) identifies the aim of agroforestry as using trees to capture resources unused by crops without compromising crop yield. For such perfect complementarity to exist where agroforestry is used for water management, deep-rooted summer-active trees would need to capture all the drainage below shallow-rooted winter-active annual crops without depressing yield. On the other hand, perfect competition would occur if trees capture water entirely at the expense of the crop and drainage remains unaffected. For agroforestry to be an effective and economically viable option for water management, it is necessary to know where a particular tree-crop combination falls between these two extremes.

In practical terms this means quantifying the following features of a tree-crop system:

1. the size of the soil zones occupied by tree and crop roots
2. the amount of deep drainage occurring under sole crop
3. the water use of spaced trees
4. the yield of crops with and without the presence of tree belts.

From these, the proportion of the landscape under trees and the spacing between tree rows required to meet a particular drainage reduction target can be determined.

This chapter concentrates on components of the water balance in the alley crop and sole crop treatments at the site described in Chapter 2 (p 12) in the third cropping season when instrumentation enabled measurement of the components of the water balance. The aims of the experiment were to determine i) the amount of water used by alley trees, ii) the proportion that came from soil and groundwater, and iii) the impact of trees on deep drainage.

Given the difficulty of accounting for the fate of rainfall in mixed plant communities, four different approaches were combined in this study in order to answer the above questions. Neutron moisture meters provided replicated measurements of soil water status at regular intervals and a means of measuring the spatial distribution of water across the agroforestry treatments. TDR was used for fine scale continuous measurement of the water status of the highly transmissive soil in the two extreme treatments, tree plantation and annual crop. Sapflow gauges were used to measure tree transpiration and assist in partitioning soil water loss between transpiration and drainage. Stable isotope analyses were used to partition tree water use between soil and groundwater sources.

4.2. Materials and methods

The experimental site and treatments are described in Chapter 2 (p 12). The methods used are described in Chapter 3 (p 28).

4.3. Results

Conceptual model of tree-crop interactions

The conceptual approach used in quantifying the interactions between trees and crops is shown in Figure 4.1. The soil profile is divided into zones (S1-7) on the basis of the presence of tree roots, crop roots, both or neither. This is based on the conceptual model presented in Chapter 2 (Figure 2.1) with modifications made to more accurately reflect the root architecture of tagasaste described in the previous chapter. Complete quantification of all transfers occurring within and between the soil zones in Figure 4.1 was not possible as there was insufficient instrumentation to measure drainage and crop evapotranspiration across the tree-crop interface. Emphasis was placed instead on measuring tree water uptake from soil and groundwater in the alley crop treatment and drainage in the sole crop treatment, and from this information, inferring drainage in the alley crop treatment.

Seasonal conditions and crop yields

Rainfall, grain yield in sole crop and alley crop and the area occupied by tree canopies over the three years is shown in Table 4.1. Following cutting on May 26 1996, the trees continued to grow over the following two and a half years with the canopy width reaching 6 m by harvest in 1998, meaning the trees occupied 20% of the total land area in the alley treatments (tree rows 30 m apart). The long term average rainfall recorded for Moora is 462 mm.

Alley crop yields in Table 4.1 are calculated on a whole plot basis, including the area of land occupied by trees. When only the arable land in alley crop plots is considered, yield in alley crop was 29% higher than in sole crop in 1996, 4% higher in 1997 and 19% lower in 1998. The increase in the first year was observed in grain yield but not in above-ground biomass. Less flower and pod abortion was observed in alley crop than sole crop plots in late spring of that year, possibly due to the shelter effect of the 2 m high trees. In 1997, yield loss was due to displacement of arable land by the trees, not to competition, while in 1998 yield loss was due to both displacement and competition.

Table 4.1. Rainfall, area under trees and grain yield in sole crop and alley crop 1996-1998.

Year	Crop	Rainfall (mm)	Area occupied by trees (%)	Grain yield (t/ha)		Influence of trees on yield (%)
				alley crop ^a	sole crop	
1996	Lupins	445	8	0.52	0.64	+23*
1997	Oats	431	14	0.92	0.85	-8
1998	Lupins	376	20	1.19	0.81	-32*

^a includes the area occupied by trees

* differences significant at $P = 0.05$

Rainfall distribution over the three seasons and the corresponding change in soil water content in sole crop plots are shown in Figure 4.2 to give an indication of the situation that exists under conventional farming practice. In each season, a rise in the perched water table occurred in the month after stored soil water store reached its maximum. The water table fell 24 cm during the study period following three years of below average rainfall. This contrasts to the general long term average rise of 20 cm/yr reported by Speed *et al.* (1993) for this region. Given the highly transmissive nature of the aquifer and the large size of the topographic catchment, the response observed in the water table would have been a whole-catchment phenomenon, with the trees in the 8 ha experimental plot having no discernible influence on the saturated zone.

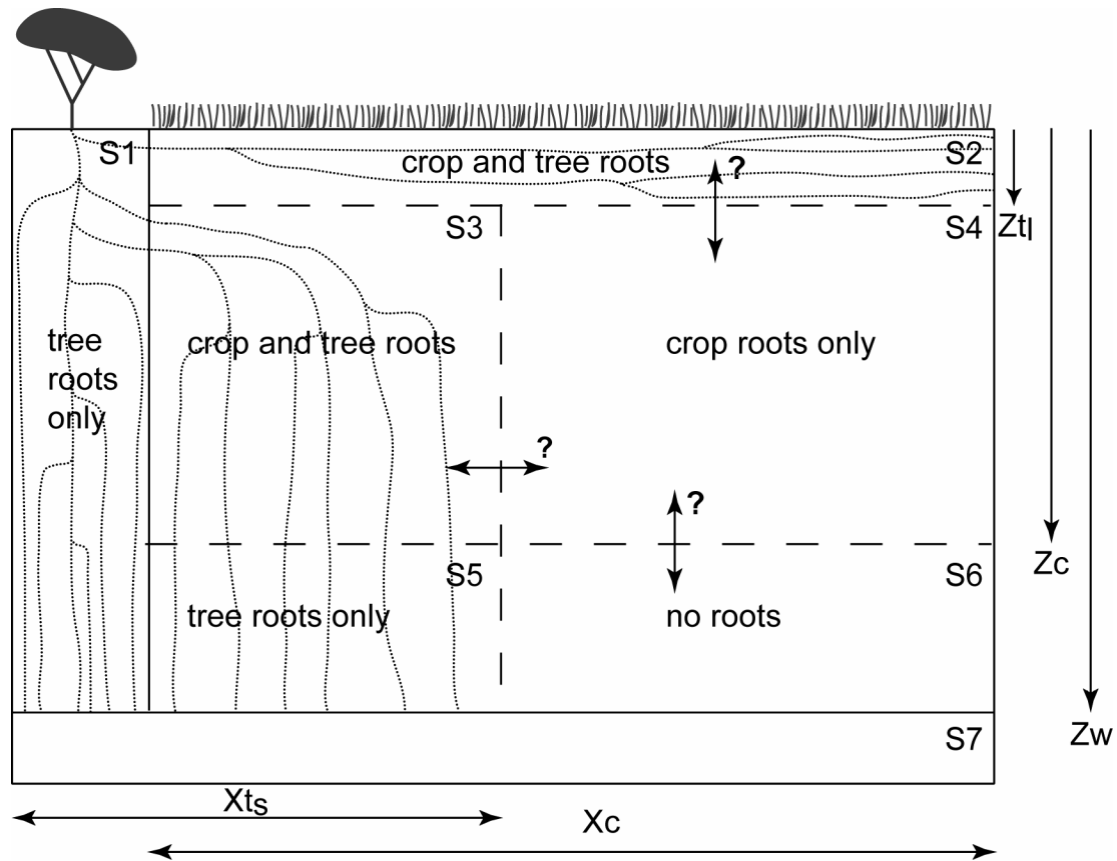


Figure 4.1. Schematic representation of the interaction between trees and crops in an alley cropping system with the below ground environment divided into zones (S1-S6) occupied by trees and crop roots. Critical dimensions are depth of crop roots (Z_c), depth to water table (Z_w), depth to which lateral roots extend (Z_{tl}), width of crop zone (X_c) and lateral extent of tree sinker roots (X_{ts}). Lateral water movement above the saturated zone and runoff are assumed to be negligible. The saturated zone is S7.

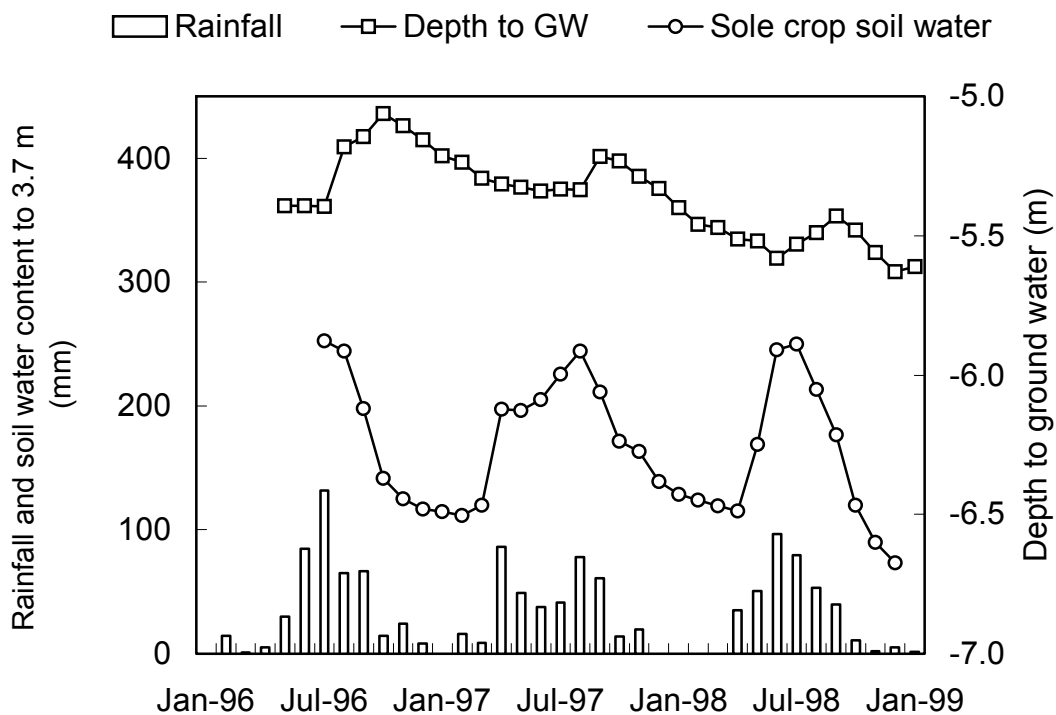


Figure 4.2. Rainfall (columns), depth to groundwater ($\square$) and monthly soil water content under sole crop treatment as an indication of conventional practice in the region ($\circ$).

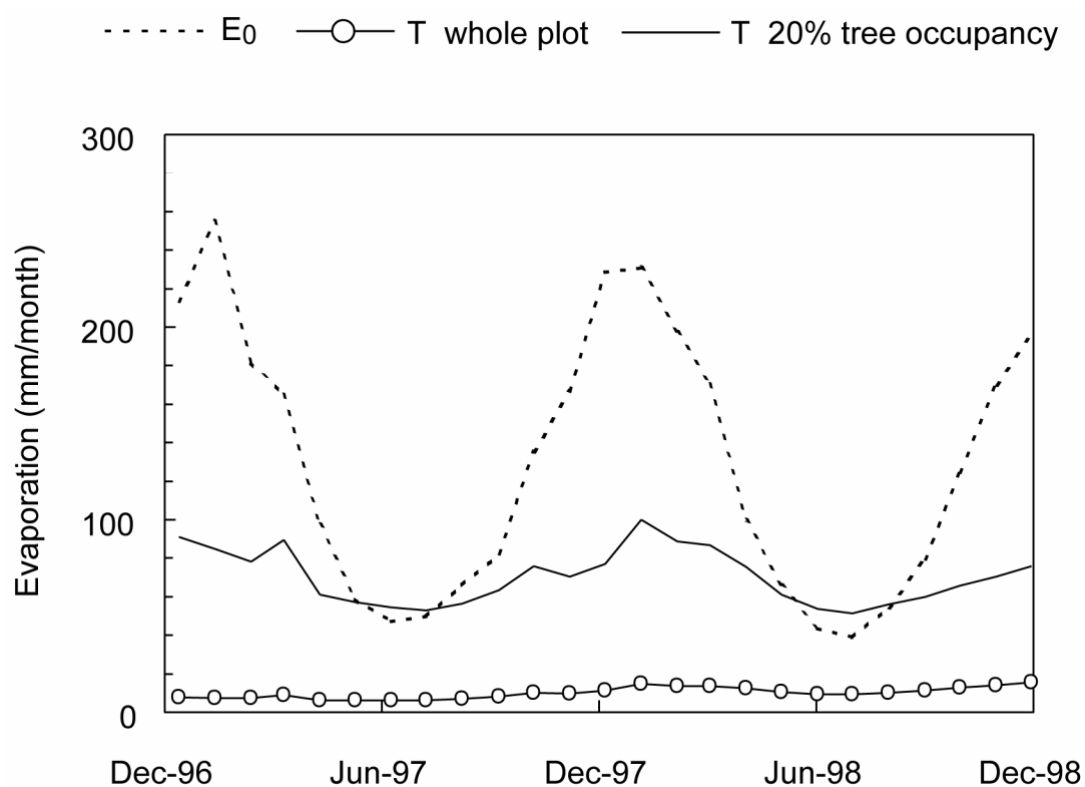


Figure 4.3. Penman-Monteith potential evapotranspiration (E₀, ---) and tagasaste transpiration (T) over the 20% of land occupied by trees in alley cropping at maturity (—) and on a total plot area basis (○).

Total tree water use

Seasonal fluctuations in tree transpiration and E_0 are compared in Figure 4.3. Transpiration in millimetres per month is expressed on the basis of the 20% of land occupied by trees in alley cropping at the end of the study (6 m wide tree belts spaced 30 m apart) and over the whole plot basis including the cropped area. Annual tree transpiration on a whole plot basis was 170 mm in 1997 and 167 mm in 1998. When expressed in terms of the 20% occupied by tree canopies, transpiration loss was 0.54 of E_0 in 1997 and 0.57 in 1998.

Tree water uptake from the unsaturated zone

Following cutting of the trees in May 1996, the soil profiles in all treatments had filled equally by late winter with integrated data from neutron probe readings across the plots showing that average soil water content to 3.7 m reached maxima in late August of between 285 and 300 mm. By harvest of the 1996 lupin crop, total soil water content had been reduced to 45% of its winter maximum in alley crop, 55% of that in the sole crop and 70% in alley fallow. As shown in Figure 4.4, these changes in soil water content were not distributed evenly across the alley plots but confined to a narrow zone immediately below the tree rows (Figure 4.4). From these data it is possible to estimate the vertical and lateral extent of tree roots.

The lateral domain of the tree appeared to have extended out to about 2 m by crop harvest on December 3 1996 (Figure 4.4a, k), increasing to 4 m over the following summer (Figure 4.4b, l). Little change occurred over the subsequent cropping season between April and December 1997. Then over the second summer, the lateral domain of the tree root systems appeared to extend to a maximum of approximately 8 m (Figure 4.4d, n). Comparing the distribution of soil water in alley crop (Figure 4.4a-e) with alley fallow (Figure 4.4k-o) shows that the lateral extent of water extraction by tree roots differed little between these two treatments, despite the absence of crop competition and physical damage to tree roots from cultivation in alley fallow. The extending lateral influence of the trees over the course of the study is also evident from data showing available soil water between 290 and 370 cm along a transect from the tree row to the centre of the alleys (Figure 4.5). In 1996 and 1997, the change in soil water content below 290 cm would have been due solely to the trees while in 1998, the deeper rooted lupin crop would have influenced the data of Figure 4.5.

Partitioning tree water use between soil and groundwater sources

Two approaches were used to partition tree water uptake between soil and groundwater. Over summer, tree water uptake was estimated from neutron probe measurements of soil water depletion in alley crop plots over rain-free periods. In winter 1996 and 1997, differences in the deuterium:hydrogen (D:H) ratios of groundwater, tree xylem sap and the xylem sap of annual herbaceous plants (as indicators of soil water D:H ratios) was used to calculate the proportion of tree transpiration derived from each source.

Soil water depletion in summer

The first step in using the water balance approach was to establish the boundaries of the soil zones shown in Figure 4.1 to determine how much of the soil water depletion from each plot over rain-free periods could reasonably be attributed to tree uptake. The outer boundary of S3 and S5 (lateral extent of water extraction by trees) was taken to extend from 2 to 4 m over the first summer (Figure 4.4a, b) and from 4 to 8 m over the second (Figure 4.4c, d). The outer boundary of S1 was the distance from the centre of the tree row to the crop edge at harvest, 0.8 m over the first summer and 1.7 m over the second. The lower boundary of S2 was set at 60 cm, based on excavations in May and July 1997 which revealed lateral tagasaste roots extended to that depth across the 30 m alley between tree rows (as described in Chapter 3).

Water loss from each zone was calculated volumetrically from NMM data, summed, and then converted to millimetres on a whole plot basis. The theoretical upper limit of soil water uptake by trees would be the sum of soil water depletion from all soil zones containing tree roots (S1, S2, S3 and S5). However, water loss from S2 was very similar to loss from the top 60 cm in sole crop plots for all periods examined, indicating this loss could equally be attributed to soil evaporation. The

estimate of soil water extraction by trees was therefore taken to be the sum of S1, S3 and S5 plus that part of S2 within limit of the bulk of the trees roots (ie. the outer boundary of S3 and S5). These values for tree water uptake from soil and total tree transpiration measured by sapflow gauges are shown in Table 4.2 for the 13 rain-free summer periods over the course of the study.

Table 4.2. Soil water uptake by tagasaste trees in alley cropping derived from neutron probe measurements of change in soil water content over rain-free periods in summer.

Period Start	Finish	Days	Total tree water use ^a (mm)	Soil depletion ^a (mm)	Tree water uptake from soil (%)
22-Oct-96	5-Nov-96	14	6.7	3.3	48
3-Dec-96	17-Dec-96	14	8.4	1.3	15
17-Dec-96	9-Jan-97	23	14.1	1.9	13
9-Jan-97	6-Feb-97	28	14.9	1.4	10
5-Mar-97	2-Apr-97	28	15.6	1.1	7
16-Apr-97	30-Apr-97	14	5.7	4.2	74
15-Oct-97	30-Oct-97	15	7.5	2.7	36
30-Oct-97	12-Nov-97	13	6.1	1.9	31
25-Nov-97	9-Dec-97	14	6.8	1.1	16
9-Dec-97	14-Jan-98	36	20.1	4.0	20
14-Jan-98	27-Jan-98	13	8.6	1.0	12
11-Feb-98	11-Mar-98	28	17.5	2.2	13
11-Mar-98	08-Apr-98	28	15.8	2.1	13

^a expressed on a whole plot basis where tree canopies occupied 7-20% of land area over the course of the study and tree roots, extending from 2m to 8m laterally from tree rows, occupied approximately 12-50%.

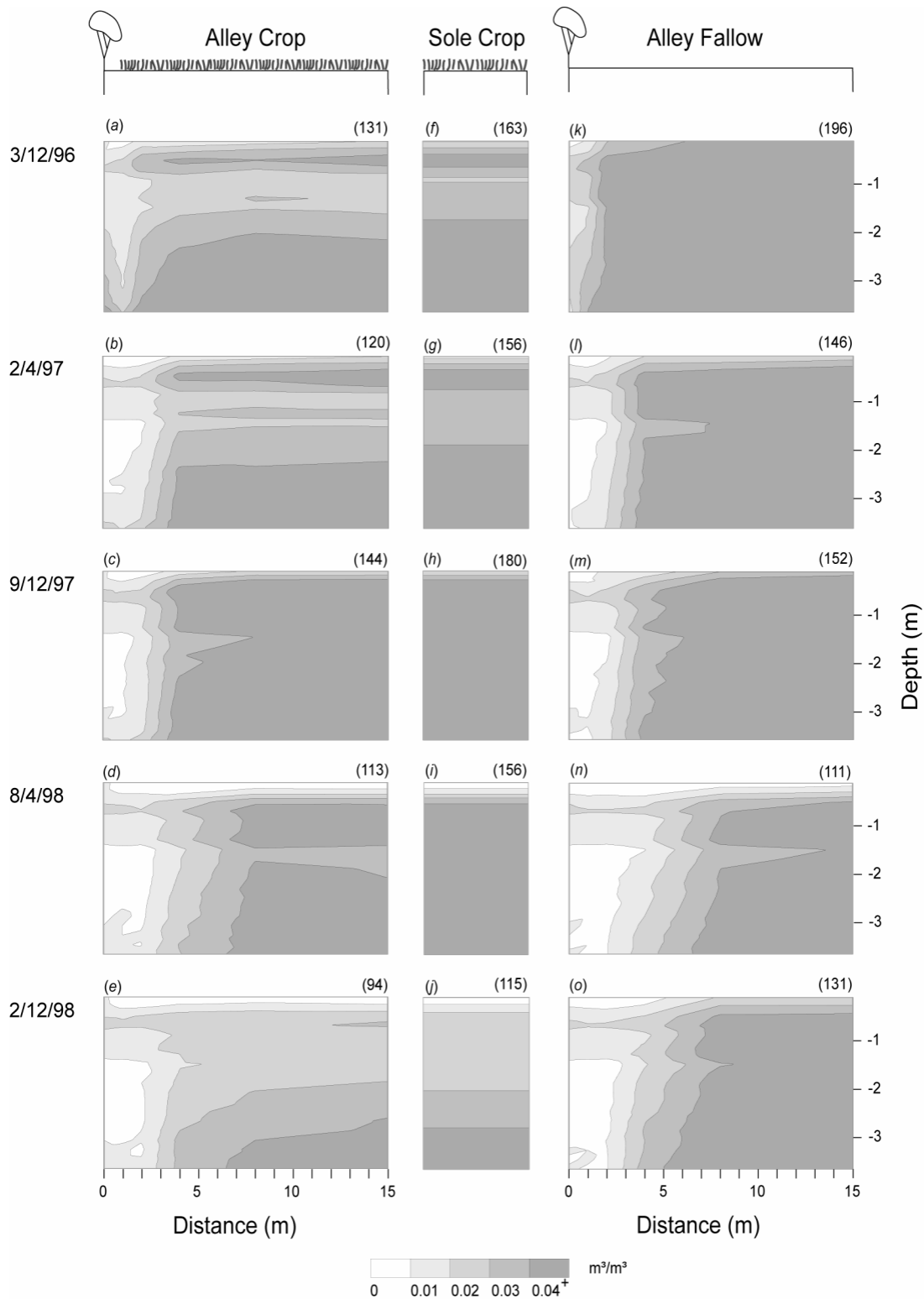


Figure 4.4. Soil water content under alley crop (left), crop (centre) and alley fallow treatments (right) at harvest (December) and just prior to the break of season rains (April) from December 1996 to December 1998. Soil water content in alley crop and alley fallow are mean values ($n=4$) of neutron probe measurements made at 19 depth intervals per hole (20 cm intervals from 10 cm to 370 cm) in 6 access tubes (0, 1, 2, 4, 8 and 15 m from the tree rows) plotted at a contour interval of 0.01 m³/m³. Soil water content in crop treatment is the mean of 12 access tubes. Numbers in brackets are total soil water content (mm) integrated across each treatment.

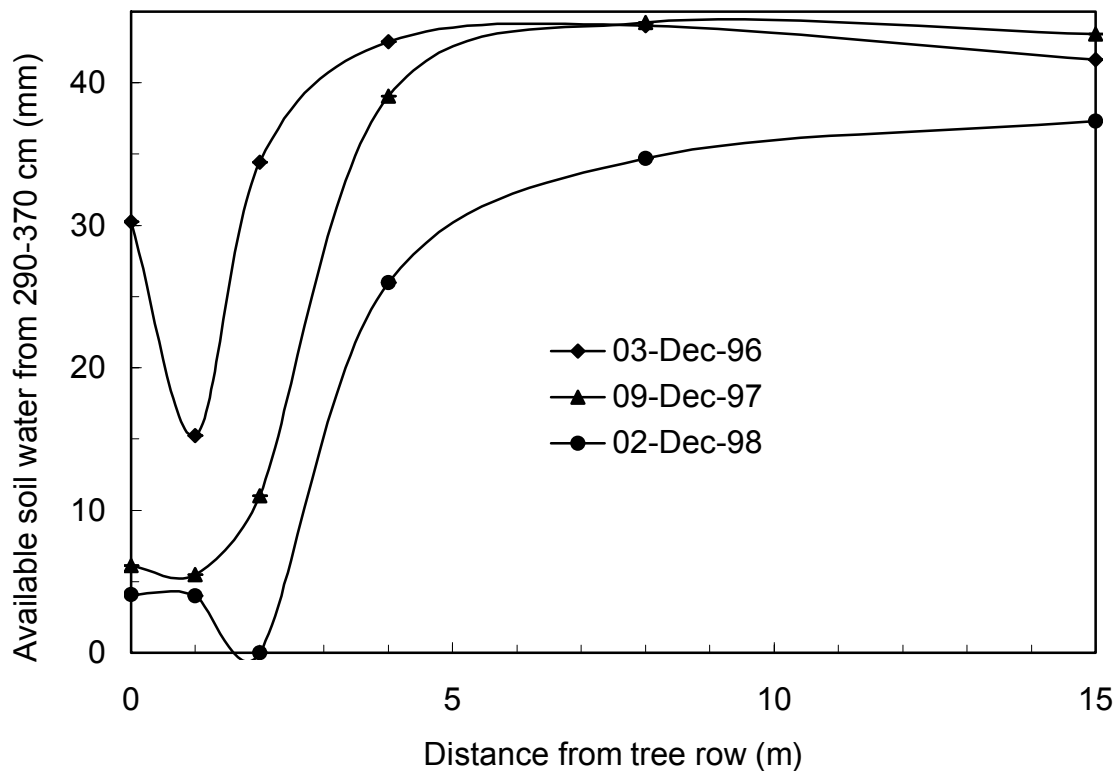


Figure 4.5. Available soil water content below the crop root zone in alley crop plots at Moora, WA at crop harvest in 1996, 1997 and 1998 showing the extending lateral influence of tree roots.

Deuterium mixing model

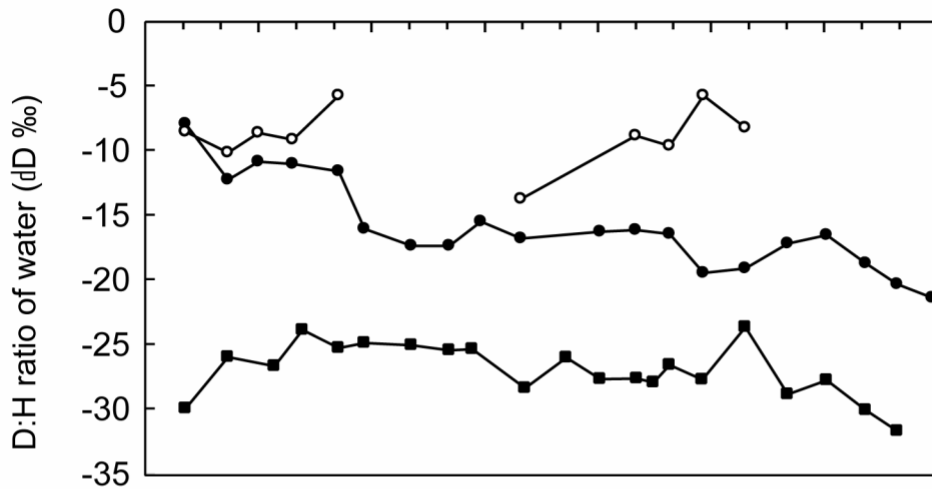
The deuterium:hydrogen ratios (δD of water ‰) for the various sources used in the mixing model are shown in Figure 4.6a. This indicates clear discrimination between values for annual plant xylem sap (ie. soil water) and groundwater. Dawson and Pate (1996) and Farrington *et al.* (1996) have shown that the high degree of discrimination between soil and groundwater commonly seen in this environment is due to the fact that the major contributors to groundwater recharge are large rainfall events occurring in late winter (and therefore likely to move rapidly through the soil profile) that tend to have very negative δD values. The values for tagasaste were similar to those for annual plants at the beginning of the experiment, soon after the trees were cut, and became more negative over the course of the experiment.

The deuterium data for winter 1996 and 1997 were combined with the soil water extraction by trees estimated from water balance (Table 4.2) to derive a seasonal profile of relative dependence of alley crop trees on soil water from July 1996 to March 1998 (Figure 4.6b). Good correlation between the two methods can be seen in April and October 1997, occasions when the presence of shallow-rooted annual plants necessary for the deuterium method coincided with periods without rainfall.

The combined data sets show declining dependence on soil water during the course of each winter, higher dependence on soil water in the first than second winter (86% and 54% respectively) and rapid switching from soil to groundwater in late spring 1996 and back to soil water following an episodic rainfall event in April 1997. The actual amounts of water used by the trees from soil and groundwater sources during and between each crop growing season are shown in Table 4.3.

(a)

—●— Alley crop xylem sap —○— Annual plant xylem sap —■— Groundwater



(b)

—■— deuterium method —□— summer soil water depletion

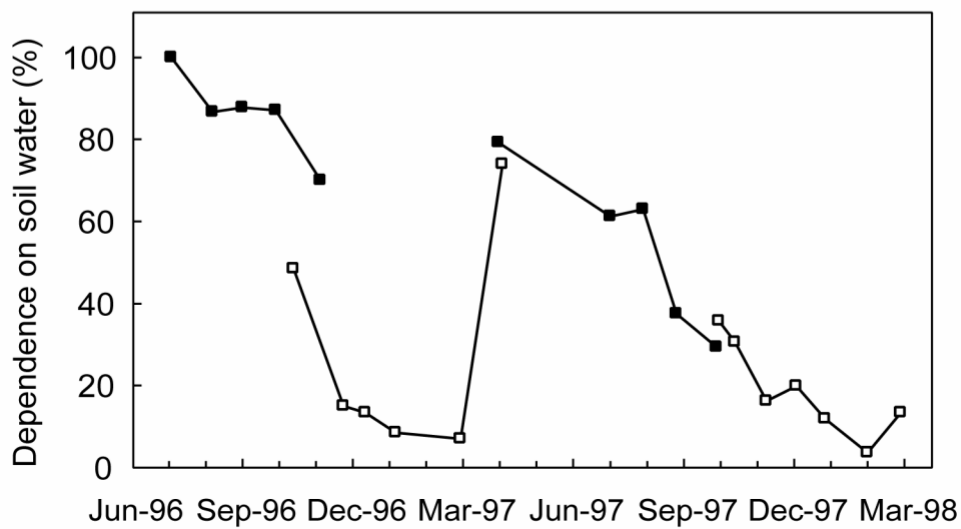


Figure 4.6. (a) Stable isotope ratios (δD of water ‰) for tagasaste xylem sap (●), groundwater (□) and annual plants as reference values for soil water (○); (b) Dependence of tagasaste trees on soil water from August 1996 to April 1998 using two methods; a mixing model based on deuterium:hydrogen ratios of xylem sap, groundwater and annual plants (■) and water balance calculated over periods without significant rain (□).

Table 4.3. Tree transpiration (T_{tree}) in alley crop derived from soil and groundwater (GW) on a seasonal basis from June 1996 to December 1998. The proportion of soil water transpired in winter was determined from deuterium:hydrogen ratios of tree xylem sap, annual plant xylem sap and groundwater and in summer from water balance over rain-free periods. Values for winter 1998 (in brackets) are estimates assuming a similar relationship between soil water dependence and rainfall distribution as observed in 1997. Seasons are based on harvest and sowing dates.

Season	Days	Rain (mm)	T_{tree} total (mm)	T_{tree} from soil (mm)	T_{tree} from GW (mm)	T_{tree} from GW (%)
Winter 1996 (20 Jun - 3 Dec)	166	354	38	29	9	24
Summer 96/97 (4 Dec - 7 Jun)	85	183	93	20	73	79
Winter 1997 (8 Jun - 9 Dec)	84	248	77	33	44	56
Summer 97/98 (9 Dec - 5 May)	46	38	84	9	75	89
Winter 1998 (6 May - 2 Dec)	210	332	83	(36)	(47)	(57)

Rooting depths of the sole crop

Neutron probe data suggested the maximum rooting depth of the 1996 lupin crop was 290 cm while that of the 1997 oat crop was 170 cm and the 1998 lupin crop 350 cm. Hourly TDR measurements provided more detailed insight into the rooting dynamics of the latter two crops (Figure 4.7). This data needs to be interpreted with care because the change in water content with time is dependent on the rate water arrives from the layer above, drains to the layer below and is extracted by roots. Nevertheless the data shows that the rooting front of the oat crop in 1997 definitely reached 150 cm, probably 230 cm, but not 360 cm.

The change in water content at 230 and 360 cm between September and November 1997 was very similar to that observed during a later fallow period in autumn 1999, which showed similar rates of loss at these water contents in the absence of a crop (data not shown). For the 1998 lupin crop, it appears that the loss of water at 150 cm between June 18 and August 20 was predominantly through drainage, but that the accelerated loss after August 20 (see arrow in Figure 4.7) was a consequence of roots reaching this depth. A similar argument suggests that appreciable root extraction at 230 cm occurred around September 15 and at 360 cm commenced after October 4, with drainage predominating prior to this.

The lupin crop clearly extracted more water from the 230 cm and 360 cm depths than the oat crop, dropping the water content to the lower limit for this soil. At the end of the season the lupin crop had extracted 66 mm more water than the oat crop from the 150–360 cm zone.

Estimated drainage from TDR

Drainage is very difficult to estimate from water content data, even with appropriate data on the relationship between hydraulic conductivity and water content, particularly in this transmissive soil where wetting fronts move quickly through the profile. For the purpose of this study, the hourly TDR data was used to provide an estimate of drainage in one location of the field from the end of the 1997 oat crop to the end of the 1998 lupin crop.

Between harvest of the oat crop (December 9 1997) and the opening rains of the following season (April 16 1998), the loss of water from the profile was 34 mm. As this was from below 150 cm, it was

assumed to be all drainage. However, as vapour transfer to the surface may have occurred over this period, this estimate would have to be considered a maximum value. The wetting front reached 20 cm with the opening season rains and 75 cm by May 21 (data not shown) by which time rainfall for the season was 63 mm. By June 12, the wetting front had reached 150 cm and 230 cm after a total of 153 mm (Figure 4.7). The water content at 360 cm increased from 0.06 to 0.09 m³/m³ on June 18 and from 0.09 to 0.1 m³/m³ on July 10. Thus it can be assumed that drainage continued at a low rate until June 18, increased slightly until July 10, and occurred rapidly after this date.

The period of enhanced drainage beyond 360 cm continued until the time that the rooting front reached this depth, which was approximately October 4. Drainage between July 10 and October 4 can be estimated by assuming that evapotranspiration would be at close to E_0 at this time of the season (1-3 mm/d), since the leaf area was developing rapidly. The decrease in water store between these dates was 185 mm, rainfall was 121 mm, and E_0 was 175 mm giving a drainage residual of 131 mm. Given that crop transpiration would not always occur at potential rates, the drainage estimate for this period would have to be considered a minimum value. From October 4 until harvest on December 2, during which time the profile was drier than at any time during the previous oat crop, it can be assumed that drainage was <0.1 mm/d contributing a further 5 mm.

It is now possible to estimate drainage below 360 cm from the end of the oat crop to the end of the following lupin crop by considering drainage as having occurred in 4 distinct phases:

1. Over the summer/autumn period between harvest of the oat crop on December 9 1997 and the opening season rains on April 16 1998, 34 mm was lost (0.27 mm/d), almost all of which was from below 150 cm.
2. From the opening rains on April 16 until the rapid drainage occurred after July 10 we assume drainage continued at a similar rate as above giving a further 23 mm (85 days at 0.27 mm/d).
3. For the period July 10 to October 4 when the majority of the drainage occurred, 131 mm was lost assuming that crop water use was close to E_0 .
4. From October 4 until harvest on December 2, when the profile was drier than at any other time, we assume a further 5 mm of drainage (<0.1 mm/d).

Cumulative drainage can therefore be estimated to be the sum of the above, 193 mm.

Estimating drainage in alley crop

The components of the water balance for sole crop and alley crop for the period when drainage could be estimated from TDR (from harvest of the oat crop in December 1997 to harvest of the following lupin crop in December 1998) are shown in Table 4.4. For the sole crop, E_{crop} was estimated by difference from total rainfall, drainage, and the change in soil water storage over the period as measured by neutron probe:

$$E_{\text{crop}} = P - D - \Delta S$$

For alley crop, drainage was estimated by difference using the following equation:

$$D = P - E_{\text{crop}} - T_{\text{soil}} - T_{\text{gw}} - I - \Delta S$$

In the alley crop, E_{crop} was assumed to be 194 mm, the same as sole crop over the arable area (ie. 80% of that in sole crop on the basis that no difference was detected in above-ground crop biomass at anthesis and harvest between sole crop and alley crop). Water use by the trees from the soil (T_{soil}) was 45 mm and water use by the trees from the groundwater (T_{gw}) was 122 mm (Table 4.3). Interception (I) was measured by TDR in the plantation treatment with a closed canopy to be 140 mm or 38% of rainfall (see Chapter 3). In the alley crop treatment, interception was therefore assumed to be 20% of this (28 mm) on the basis of tree density and canopy cover. Table 4.4 shows the estimated drainage when groundwater uptake is excluded (to examine the case if groundwater was too deep or salty to be used), and when the measured groundwater uptake is included.

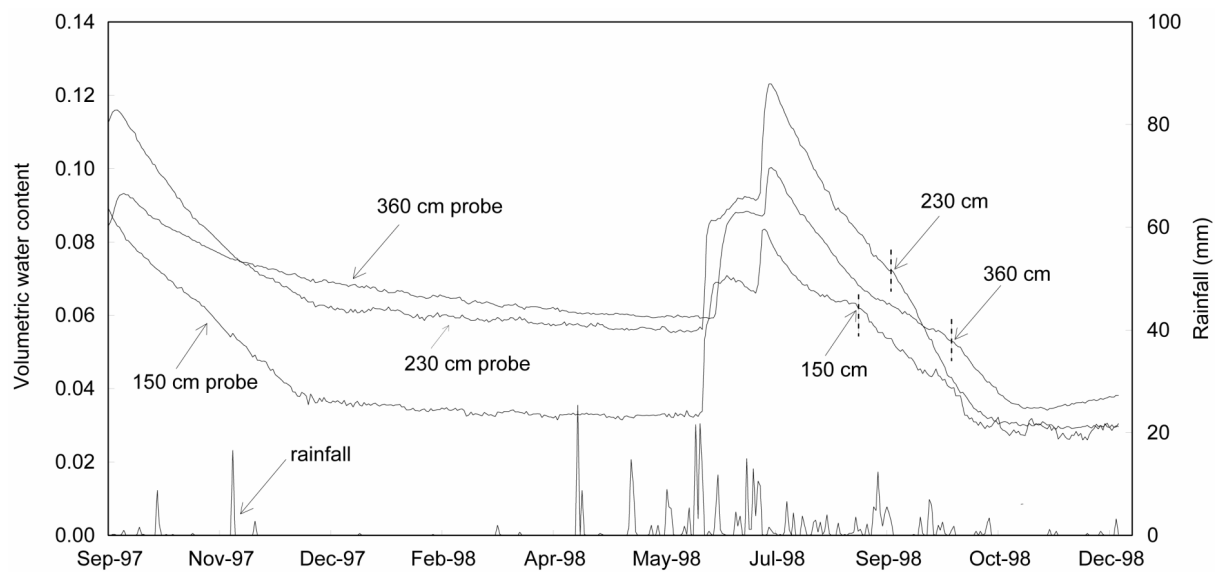


Figure 4.7. Daily average TDR traces from probes located 150, 230 and 360 cm deep in the lupin crop from September 1997 to December 1998. Vertical dotted lines denote time of increased water loss, presumably when the crop roots reached the indicated depths.

This approach indicates that 6 m wide belts of tagasaste, spaced 30 m apart, reduced seasonal drainage from 52% of rainfall under a sole crop to 42%. If groundwater uptake by trees occurring predominantly in the summer months is included, drainage over the whole year is reduced to 9% of rainfall.

The general validity of these estimates can be examined by application of a second method. The very low soil water contents measured throughout the year out to 2 m either side of the tree rows suggested that drainage would have been minimal in this zone. We also know that the tagasaste had almost no influence on soil water content between 8 and 15 m from the tree rows (Figure 4.4). Between 2 and 8 m from the tree row, both soil water uptake by trees and drainage occurred. Drainage can then be approximated by assuming it was zero over the first 2 m of the alley, the same as the sole crop between 8 and 15 m (193 mm/yr) and half that in sole crop over the 2-8 m zone. This gives a seasonal drainage estimate of 129 mm and an annual drainage estimate of 7 mm, somewhat less than that calculated by the water balance method.

Table 4.4. Components of the water balance for a) sole crop and b) alley crop from December 9 1997 to December 2 1998 (358 days). E_{crop} is crop evapotranspiration, D is drainage, ΔS is the change in soil water content, T_{soil} is tree transpiration from the unsaturated zone, T_{gw} is the tree transpiration from groundwater and I is rainfall interception by the tree canopy.

a)

Rain	E_{crop}	D	ΔS	$D/Rain$
371	243	193	-65	0.52

b)

Method	Rain	E_{crop}	ΔS	T_{soil}	T_{gw}	I	D	$D/Rain$
Excluding T_{gw}	371	194	-50	45	0	28	154	0.42
Including T_{gw}	371	194	-50	45	122	28	32	0.09

4.4. Discussion

This study was undertaken to assess the effectiveness of adding spaced rows of trees to an annual cropping system to reduce the amount of deep drainage in a situation where trees had access to a permanent fresh water table. In the final year of the study when the trees occupied 20% of the land area, estimated drainage was reduced from 193 mm/yr to 32 mm/yr. This occurred in a year when drainage was higher than the long term value of 140 mm/yr reported by modeling studies (Asseng *et al.* 1998).

The purpose of adding trees to cropping systems for salinity management is not to reduce drainage to zero in a single paddock, but to bring the average recharge from a catchment closer to the discharge capacity of that catchment. It is possible to compare the effectiveness of an integrated tree-crop system such as alley cropping with that of separate monocultures of crops and trees in reaching this target. Stirzaker *et al.* (2000) have quantified the complementarity that exists in a tree-crop system designed for water management with the no-drainage:no-yield ratio, the ratio of the area over which drainage is reduced to zero to the area over which yield is reduced to zero. It reflects the balance between the amount of land protected by trees against drainage (Ellis *et al.* 1999) and the net effect of trees on crop yield (Lefroy and Scott 1994). If this ratio is greater than one, there are advantages in mixing trees and crops; if less than one the balance between recharge control and productivity would be best achieved through monocultures of trees and crops, as discussed in Chapter 2. For instance, we know that drainage under the plantation treatment was zero (Chapter 3). Therefore, if we put 20% of the land under plantations, drainage would be reduced by 20% and yield by 20% (displacement) giving a no-drainage:no-yield ratio of one.

For the last year of the alley crop experiment, yield was reduced by 32%. This can be attributed to displacement of crops by trees (20%) and the effects of tree-crop interactions (12%). If we ignore the access these trees had to groundwater, drainage was reduced by 20% in the tree crop mixture giving a no-drainage:no-yield ratio of 0.6, indicating there is no advantage in using the mixture. When we include the access to groundwater the ratio becomes 2.5 (a 32% yield decrease and a 83% decrease in drainage). The tree-crop mixture therefore has a proportionally greater effect on reducing drainage than on reducing yield (Figure 4.8).

However, when we move from paddock to catchment scale, this last case becomes unrealistic as it assumes all alley trees would have access to a fresh aquifer over the 20% of a catchment required under trees to prevent further water table rise at this level of water use (Chapter 3). Plantations would be the only practical strategy for making effective use of localised, perched aquifers and the highly transmissive nature of the aquifer in this case would mean that trees could access groundwater draining below crops hundreds of metres away. In addition, the total length of the tree-crop interface, and therefore the amount of competition, would be lower with plantations.

Alley cropping would be an appropriate strategy where there were less transmissive aquifers underlying a large proportion of a catchment. A more closely integrated tree-crop system would then be necessary to ensure that trees retained access to groundwater. Alley cropping would also be appropriate on highly transmissive sands if the root architecture of tagasaste trees were sufficiently flexible that in the absence of a fresh water table, trees exploited a wider zone of unsaturated soil than was evident in this study and maintained the rates of transpiration measured here. However, if evapotranspiration of spaced trees in the absence of a water table was less than that measured in this experiment, the best strategy would be to strategically locate dense stands of trees over shallow fresh water tables. The limiting factor would then be the proportion of a catchment where trees had access to shallow fresh water tables in order to meet the recharge reduction target, as shown in Table 2.2.

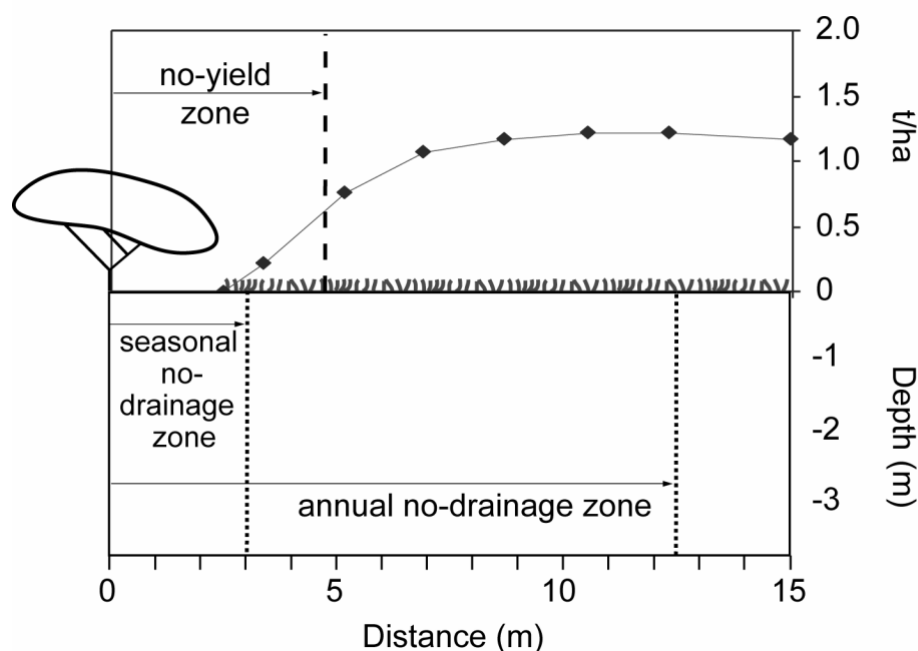


Figure 4.8. The no-yield area:no-drainage area ratio, a binary representation of the above- and below-ground influence of trees. Where the ratio is small, ie. the no-drainage zone is larger than the no-yield zone, integrated tree crop systems are more effective than segregated systems (plantations) at optimising water management and crop yield. Yield data from Lefroy and Stirzaker (1999).

A surprising finding was that the lateral extension of tree roots in the alley fallow treatment was no greater than in alley crop. This was despite the absence of crop competition, the lack of disturbance of lateral roots through cultivation and the fact the soil profile 8 m from the tree rows was never less than half full. One possible explanation is that once the trees had commenced investing heavily in roots at the capillary fringe, they lacked the plasticity to increase their capacity to scavenge laterally for water. While the high quality of the groundwater in this study enabled us to measure rates of tree water use at the upper end of the range for this environment, it is atypical of southern Australia generally and limits our ability to extrapolate the data widely.

The average 16% reduction in crop yield in the alley treatment over three years compared with sole crop contrasts with the neutral to positive influence of windbreaks on crop yield reported in an international review by Kort (1988). Recent Australian studies have reported little if any benefit to crop production from windbreaks (Carberry *et al.* in press, Sudmeyer *et al.* in press). While any yield loss might be offset in economic terms by harvesting tagasaste biomass as a valuable source of autumn fodder, this would reduce transpiration rates and consequently increase the total area required under trees from the 20% estimated for three year old regrowth to the estimate of 24% for younger regrowth (Chapter 2).

Drainage in sole crop in 1998 was particularly high due to rainfall distribution, with 47% occurring in June and July when evaporative demand was lowest. This drainage estimate of 52% of annual rainfall was higher than the long term estimate of 30% for this region (Asseng *et al.* 1998) and 38% for similar transmissive sands in the higher rainfall zone (Peck and Hurlle 1973). By comparison, studies across a wider range of soil types in the cropping zone of southern Australia (250-500 mm/yr) suggest deep drainage to be generally <20% of annual rainfall (Hatton and Nulsen 1999, Walker *et al.* 1999).

The trade-off between grain yield and the environmental benefit of trees seen in this study has parallels with alley cropping in other parts of the world. In the tropics alley cropping has been promoted as a means of increasing soil fertility and controlling erosion (Kang *et al.* 1992). The trade-

off is between water and nutrients, with prunings from fast growing tree legumes being used as soil mulch with anticipated benefit to soil fertility and crop yields. Ong (1996) however, concluded in a review of alley cropping in Africa that the general experience was increased risk of crop failure due to competition for water, particularly in the lower rainfall sub-tropics (<1000 mm). Ong and Leakey (1999) suggest that alley cropping in the sub-tropics with fast growing trees is analogous to highly competitive, early stage succession in savannah ecosystems. The complementarity of resource use between trees and grasses, anticipated in much of the agroforestry literature and described in studies of sub-tropical savannahs, is likely to be a feature of later rather than earlier stages of succession. They conclude that where crop production is water-limited, the best strategy is to segregate trees from crops rather than integrate them, targeting landscape niches where unused resources accumulate. In other words, assume that competition dominates in young agroforestry systems and apply nitrogen fertilizer rather than tree mulch.

Research in southern Europe has also challenged the assumption that complementarity of resource use between trees and herbaceous plants will be the norm as a result of vertical stratification of their root systems. Adding high value spaced trees to fodder crops in Southern France was seen as a means of making more efficient use of water and nutrients and diversifying farm income. Water balance studies however showed that the herbaceous components (*Onobrychis sativa* L. and *Festuca arundinacea*) had greater rooting depth than the tree (*Prunus avium* L.) and reduced both water use and growth of trees compared to those in monoculture (Dupraz *et al.* 1995, 1998).

In Australia the choice is stark and of a very different nature; increase leaf area in agricultural landscapes on a permanent basis and live with some degree of trade-off or accept increasing levels of salinity (Hatton and Nulsen 1999, Walker *et al.* 1999). That implies understanding, and where possible reducing, the yield penalties at the tree-crop interface. This study highlights the importance of knowing the extent to which tree root architecture varies within and between species. Further research identifying the water capture zone of trees with and without access to fresh water tables would contribute to the more effective use of agroforestry systems for water management.

Summary

- Components of the water balance of a tagasaste alley cropping system were measured to assess the extent to which tree rows 30 m apart, with access to a fresh perched water table at 5 m depth, were able to capture deep drainage from an inter-cropped cereal/legume rotation in their third year of regrowth after cutting.
- Neutron probe data showed that the four-year-old trees, cut back to 0.6 m high at the beginning of the experiment, developed lateral roots extending 2, 4 and 8 m laterally from the tree rows in their first, second and third years of coppice regrowth respectively.
- Combining data from soil water depletion in summer and deuterium:hydrogen ratios of groundwater, xylem sap of trees and herbaceous plants, it was shown that tagasaste trees drew on soil water for 90% of their transpiration in the first winter and 50% in the second, while switching to near total dependence on groundwater each summer.
- Tree water use on a whole plot basis was 170 mm in 1997 (68% from groundwater) compared with 167 mm in 1998 (73% from groundwater). Recharge to the perched water table was estimated to be 193 mm under sole crop in 1998 (52% of rainfall), reducing to 32 mm when uptake of groundwater by the tree was included.
- The concept of a no-yield:no-drainage ratio is used to quantify the trade-off between crop yield and recharge prevention in agroforestry.
- Based on the amount and spatial pattern of water uptake by trees in their third year of regrowth, it is concluded that plantations would be a more appropriate strategy than dispersed planting such as alley cropping at this site, the same conclusion as was reached for trees in their first year of regrowth.

5 Nitrogen fixation by tagasaste trees in alley and plantation layouts

5.1. Introduction

The annual legumes lupin (*Lupinus angustifolius* L. and *L. cosentinii* L.) and subterranean clover (*Trifolium subterraneum* L.) continue to rank of great importance on acidic sandy soils in rotation with cereal crops across a wide area of south western Australia. While considerable inputs of fixed nitrogen are generated by these legume components (Unkovich *et al.* 1997), the recent work of Anderson *et al.* (1998a, 1998b) has shown that inefficient usage of nitrogen resources may result in appreciable leaching of nitrate, mostly resulting from mineralisation of legume residues. This, combined with incomplete usage of rainfall by annual based crop:pasture systems can lead to progressive elevation of water tables and nitrate pollution of aquifers within a region (Pate and Bell 1999).

The tree legume, tagasaste (*Chamaecytisus proliferus* Link) is being grown increasingly on deep sands of Western Australia, where it currently plays an important role across some 100 000 ha of farmland as a supplementary source of stock feed during autumn (G Tudor pers. comm.). There is therefore considerable interest in whether introduction of this deep-rooted legume at wide spaced alley or dense plantation components of ecosystems within the region, might fulfill the dual role of ameliorating hydrological imbalance while concurrently providing economically important inputs of biologically fixed nitrogen.

In this chapter we first test applicability of the ^{15}N natural abundance technique for assessing proportional dependence of tagasaste on symbiotically fixed N using a series of pot trials on nodulated young trees. Satisfied that the technique was likely to produce reliable results, we employed it to monitor nitrogen fixation performances of coppicing alley- and plantation-format tagasaste growing on deep sand at Moora, Western Australia.

5.2. Materials and methods

Glasshouse studies

The first stage of the study was conducted in pots in a naturally lit, heated glasshouse in Perth, Western Australia to assess the extent of stable N isotope fractionation within effectively nodulated tagasaste when young trees were fixing N in presence or absence of a defined source of inorganic N. It was thus hoped to determine how best to apply the technique to estimate symbiotic nitrogen fixation of the species under field conditions.

Plastic pots of 10 L capacity containing heat-sterilised nutrient-free silica sand were each sown with five tagasaste seeds in autumn (April 1997) and thinned on emergence to three seedlings per pot. Seeds were inoculated at sowing with a commercial peat inoculum containing a *Bradyrhizobium* strain (CC1502, Bio-Care Technology Pty Ltd, Somersby NSW) specifically recommended for tagasaste. Seedlings were watered twice weekly with either a N-free nutrient solution or a similar quantity of the same base nutrient solution containing 1, 5 or 10 mM NO_3^- . The volume of nutrient solution added on each occasion was sufficient to flush out previously applied nutrients, thereby preventing build-up of unused salts in the rooting medium. Each nitrate treatment involved three replicate pots, while six replicate pots were set up for the minus N treatment to permit an additional harvest four months after conclusion of the nitrate feeding trial.

The $\delta^{15}\text{N}$ of the N of the supplied nitrate (3.45‰) was selected as being roughly similar to that shown in a preliminary study of soil mineral N components, ($\delta^{15}\text{N}$ 3.1 to 4.5‰), at the field study site. Young trees from all NO_3^- -treated plants and half of the minus N pots were harvested in late August 1997, 145 days after sowing (DAS). The remaining minus N pot cultures were harvested in December 1997 (269 DAS) to allow $\delta^{15}\text{N}$ values to be assessed for the various components of older taller trees. Each

harvested plant was separated into stems, leaves, roots and live (haemoglobin pigmented and presumably fixing) nodules, and each component bulked on a per pot basis. Fallen leaves were also collected at the second harvest of the minus N pots. All plant components were oven dried to constant weight at 70°C, weighed and then ground in a Retsch ball mill to pass a 0.8 mm mesh prior to analysis for total N and $\delta^{15}\text{N}$.

Field studies at Moora

A description of the site and treatments are given in Chapter 2 (p 12). Harvests of above-ground biomass of the trees were made on a monthly basis in the first year and on a three-monthly basis thereafter to assess rates of growth and nitrogen accumulation. On each occasion all coppice regrowth on four randomly selected trees from each plot was cut back to the initial prune height of 0.6 m. Fresh weight of new coppice material was recorded immediately in the field, appropriately sized representative subsamples selected and weighed, and the resulting material taken back to the laboratory for drying and determination of fresh weight:dry weight ratio. Coppice dry matter (DM) yields per tree were thus determined for each treatment. For the purposes of this study, data for alley crop and alley fallow plots were pooled and referred to hereafter as 'alley' treatment. Dry biomass was then fed through a chipper before being further subsampled and fine-ground to await analysis for total N and $\delta^{15}\text{N}$.

In addition to sampling whole coppice shoots, new shoot growth was harvested each month. A single actively-growing 3-10 cm apical region of a coppice shoot was selected from random positions in the canopy of each of 30 plants from each of the six rows in an alley plot, or from each of six randomly selected rows of the 30 row plantation plots. By tagging the youngest one-third expanded leaf on a series of reference shoots at one time of sampling it was possible to determine how much new growth had occurred by the next sampling, and thereby indicate what length of shoot tip needed to be harvested to include only this new extension growth. Since coppice shoots grew virtually continuously over the study period, the monthly harvests of apices were regarded as progressively assessing the newly acquired and mobilised N allocated to shoot growth over specific periods.

At the end of this study (May 1998) total accumulation of N by trees of alley and plantation during the two-year period of coppice regeneration was assessed. It was assumed that the mean shoot:root biomass dry weight ratio of 2.7, recorded in the middle of the study period (see Chapter 3) for a series of exhaustively excavated trees from the same plots, applied to both the initial and final harvest times of the present study. Knowing also the DM ratio of coppice regrowth to parent lower trunk biomass at final harvest, increments in total DM per tree were estimated. Using values for %N in DM of coppice shoot, stump and roots, it was possible to assess distribution of incremental N between these parts on a per tree basis.

Tagasaste leaf litter was collected from the alley treatments at final harvest, using a series of 1 m² quadrats randomly placed beneath tree canopies and extending to the outer limits (2.3-2.8 m) to which litter had accumulated. Comparable collections of litter in plantation tree rows were taken from the middle of a tree row to the mid-regions between the adjacent rows of trees. Using information on tree planting density in rows of a treatment, current accumulation of litter biomass was estimated on both a metre row or per tree basis. Using values for %N in litter DM, total amounts of N in accumulated litter were assessed on a hectare basis.

Measurement of symbiotic nitrogen fixation in pot studies and field grown plants using the ^{15}N natural abundance technique

Measurement of nitrogen fixation closely followed the methods described recently by Unkovich *et al.* (1994, 1997). Plant dependence on nitrogen fixation (%Ndfa) was estimated by comparing the $\delta^{15}\text{N}$ values of plant material sampled from the N₂-fixing legume with that of either the fed source mineral N (pot NO₃-application study), or selected non-leguminous reference plants (field studies) whose $\delta^{15}\text{N}$ signals were assumed to match those expected of tagasaste if it were relying solely on soil N. In both cases allowance had to be made for any isotope fractionation occurring during the N₂ fixation process,

or as fixed N subsequently exchanged between plant parts. Extent of such fractionation was assessed using $\delta^{15}\text{N}$ values obtained from nodulated pot cultured plants raised in absence of combined N. Relevant $\delta^{15}\text{N}$ values are referred to hereafter as 'B' values for the various plant parts whose %Ndfa was being assessed.

Thus for pot grown plants,

$$\% \text{Ndfa} = \frac{\delta^{15}\text{N of fed NO}_3 - \delta^{15}\text{N of selected part of NO}_3\text{-grown tagasaste}}{\delta^{15}\text{N of fed NO}_3 - \text{B value of matching plant part of fully symbiotic tagasaste}} \times 100$$

and, for field grown plants,

$$\% \text{Ndfa} = \frac{\delta^{15}\text{N of shoot of reference non-legumes} - \delta^{15}\text{N of shoots of tagasaste}}{\delta^{15}\text{N of shoots of reference non-legumes} - \text{B value of tagasaste shoot (pot study)}} \times 100$$

In the field studies of tagasaste N_2 fixation, $\delta^{15}\text{N}$ values for shoots of the oldest (269 DAS) pot grown fully symbiotic tagasaste (1.5 m tall) were used as B values, while reference plants used to sample pools of available soil N comprised a range of common annual weed species, principally capeweed (*Arctotheca calendula* L.), wild radish (*Raphanus raphanistrum* L.) and mustard (*Brassica tournefortii*). The 0-3 m deep-rooting profiles of these species matched closely those typical of lateral feeding roots of tagasaste. The above-mentioned weed species were sporadically present in all but the sprayed out parts of the study block, but were available as sufficiently large individuals only during the winter and spring seasons (June-November).

Samples of nitrate-rich groundwater (6-13 mg/L $\text{NO}_3\text{-N}$; see Pate and Bell 1999) were collected from bores in the plots and subjected to ^{15}N assay. Shoot material was sampled from two reference species known to have root systems sufficiently deep to tap nitrate-enriched groundwater. One of these, the phraeatophytic tree *Eucalyptus todtiana*, was growing in close proximity to the study plots while the other species, the native herbaceous perennial *Ptilotus polystachyus*, was sparsely distributed across the plots. An earlier study (Pate *et al.* 1993) had shown the latter species to be nitrophilous and therefore likely to be subsisting mostly on nitrate in soil and groundwater. Since this species was summer active in its growth, it provided vital reference non-legume plant biomass for the November to April period when annual weeds were not available. In certain regions of the plot large mature plants of *P. polystachyus* had established stands of seedlings in close vicinity, thereby making it possible to compare the $\delta^{15}\text{N}$ signals of juveniles, whose roots had not yet penetrated below 1.5 m, to those of large parent plants with tap root systems penetrating to the water table.

$\delta^{15}\text{N}$ values and corresponding measurements of %N in dry matter samples were conducted using an ANCA system (Europa Instruments), incorporating a CHN analyser and high precision mass spectrometer (VG Isogas SIRA 9). Analytical procedures and estimates of likely errors of measurement were as detailed in the recent publications of Unkovich *et al.* (1994, 1997).

Having derived %Ndfa estimates based on total coppice N, balance sheets were constructed for progressive symbiotic nitrogen fixation and uptake of soil N by tagasaste over the study period, using data on a per tree or hectare basis for coppice biomass total N plant, and on litter deposited under trees of the alley and plantation plots of the trial.

5.3. Results

Glasshouse studies of N isotope fractionation in symbiotically-dependent and nitrate-fed young trees

$\delta^{15}\text{N}$ values for shoots, leaves, stems, roots and nodules, and whole plants grown with or without nitrate and harvested at 145 DAS are shown in Figure 5.1. Comparable data for the later harvest (269 DAS) of symbiotically-reliant plants are given in Table 5.1b. Plants dependent solely on fixed N_2 showed relatively little net fractionation (± 0.5 to 0.9%) of their total plant N against atmospheric N_2

($\delta^{15}\text{N} = 0\text{‰}$), but substantial retention of the heavy isotope in their nodules (7.2‰ at 145 DAS). Less marked isotopic fractionation was then evident as N released from nodules became partitioned between stem (negative values of -1.3 to -1.7‰), leaves and roots (both parts with slightly positive $\delta^{15}\text{N}$ values). A similar order of ranking of $\delta^{15}\text{N}$ values for plant parts was also evident for the three nitrate treatments (Figure 5.1), but this was overridden by a general tendency towards more positive $\delta^{15}\text{N}$ values as nitrate supply was increased and trees incorporated increasing amounts of the enriched nitrate source ($\delta^{15}\text{N} = 3.45\text{‰}$).

The values in Figure 5.1 were then used to derive a set of %Ndfa values (see Table 5.1a) for the component N fractions of the various parts of the young trees harvested from each nitrate treatment. Resulting data for whole plant N showed a substantial decrease in proportional dependence on N_2 fixation (85% down to 37%) as the nitrate supply increased. Similar trends were recorded for the %Ndfa values of shoots and leaves. However, regardless of concentration of nitrate supplied, shoots ranked greatest, nodulated roots least and leaves intermediate in dependence on fixation, indicating that fixed N was preferentially allocated to above-ground parts whereas nitrate-N was sequestered especially by roots.

Growth and N accumulation in coppicing alley and plantation plots

Variations in amounts of coppice DM per tree were large between and within plots of alley and plantation treatments at each time of sampling (see Figure 5.2a), so only general courses of coppice growth are indicated, using curves of best fit. Combining this information with %N in DM of corresponding coppice biomass samples (Figure 5.2b), cumulative N yields in coppice biomass of alley and plantation trees were derived (Figure 5.2c). The data indicated relatively slow coppice growth and N accumulation in the first eight or so months as trees recovered from cutting, followed by a rapid escalation of growth which resulted in an almost four-fold increase in accumulated DM and N over the second season of growth. Apart from a short lived tendency for dry matter and N to accumulate at a faster rate in plantations than alleys during winter and spring of the second season (1997), the two planting formats showed remarkably similar overall patterns of growth and N acquisition (Figure 5.2c).

There was a general trend for coppice biomass to be richer in N (3 to 4.5% N in DM) in the first season after cutting (Figure 5.2b), as expected from progressive accumulation of woody material as coppice stems became secondarily thickened and shed N rich foliage. There was also a tendency in both plantation and alleys for N concentration in coppice DM to be particularly low during late summer and autumn (1996/7 and 1997/8), coincident with stress-induced leaf fall. Conversely %N increased sharply from the onset of rains in May through winter to the following August/September when coppices were at peak leafiness and presumably capable of assimilating more than sufficient N to maintain their current growth.

Summer stress in the last season of the study (January to April 1998) resulted in particularly severe leaf shedding, especially in dense canopies of the plantation treatment. This was reflected in negligible increases, or even decreases, in coppice DM and total N over this period (see Figure 5.2c).

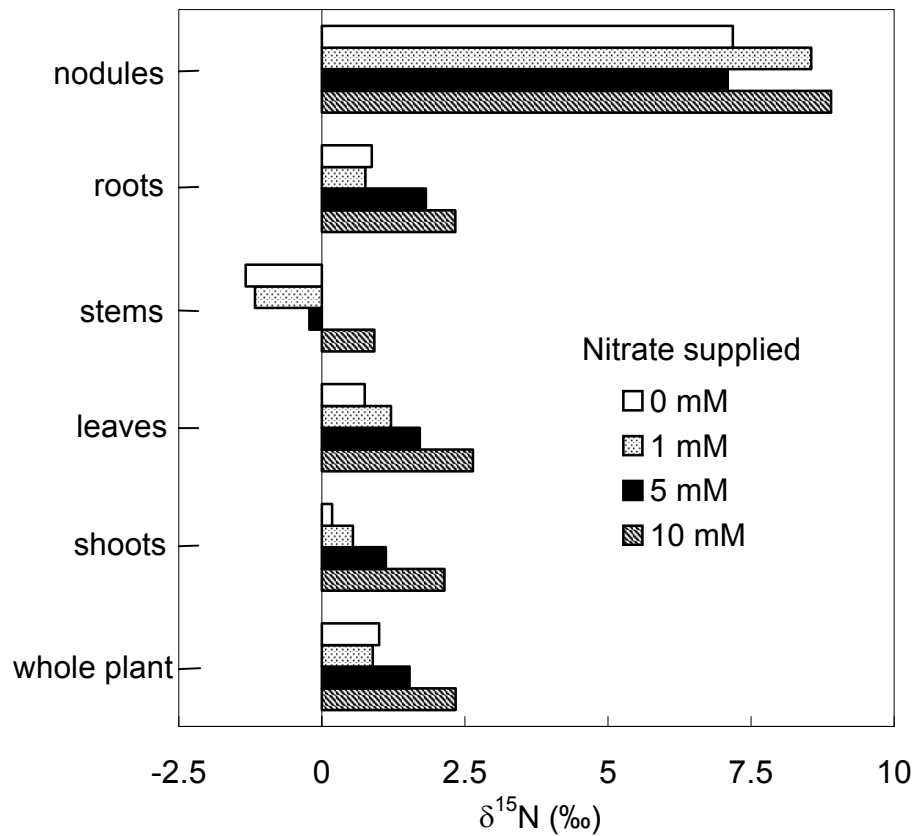


Figure 5.1. $\delta^{15}\text{N}$ values of the total N of dry matter of whole plant and component parts of young trees of tagasaste (*Chamaecytisus proliferus*) raised in sand culture in a glasshouse in Perth, Western Australia. All trees were effectively nodulated with a bacterial partner recommended for the species. The four treatments involved zero nitrate (fully symbiotic) and three constantly maintained levels of nitrate. Harvests at 145 days after sowing with three replicate pots (3 trees/pot) for each treatment. %Ndfa values derived from the values are shown in Table 5.1.

Table 5.1. Use of the ^{15}N natural abundance technique to assess proportional dependence on N_2 fixation (%Ndfa) of effectively nodulated tagasaste grown in pot cultures fed with a range of constantly maintained levels of nitrate

- (a) Estimates of %Ndfa in leaves, shoots, nodulated roots or whole plants of pot cultured tagasaste fed 0, 1, 5 and 10 mM KNO_3 and harvested at 145 days after sowing (DAS).

Applied nitrate	%Ndfa ^b			
mM KNO_3 ^a	Leaves	Shoots	Nodulated roots	Whole plant
0	100 (1.2)	100 (2.0)	100 (10.5)	100 (3.7)
1	83 (1.3)	89 (1.5)	64 (7.8)	85 (1.9)
5	64 (3.3)	71 (3.6)	36 (4.1)	63 (3.5)
10	30 (8.5)	40 (5.1)	25 (2.5)	37 (3.2)

^a $\delta^{15}\text{N}$ of applied nitrate was 3.45‰.

^b Assessments based on the $\delta^{15}\text{N}$ values for biomass total N given in Figure 5.1. Values in parentheses denote standard errors.

- (b) $\delta^{15}\text{N}$ values of dry matter total N of symbiotically N dependent tagasaste grown in minus N glasshouse sand culture and harvested 269 DAS^a.

	$\delta^{15}\text{N}$ (‰) ^b	s.e.
Whole plant	-0.47	0.04
Shoot	-0.48	0.06
Leaves	0.53	0.10
Stem	-1.67	0.20
Nodulated roots	-0.53	0.20
Fallen leaves	0.07	0.10

^a These values are used as B values when assessing %Ndfa of field grown tagasaste.

^b Comparable values for an earlier harvest (145 DAS) are shown in Figure 5.1.

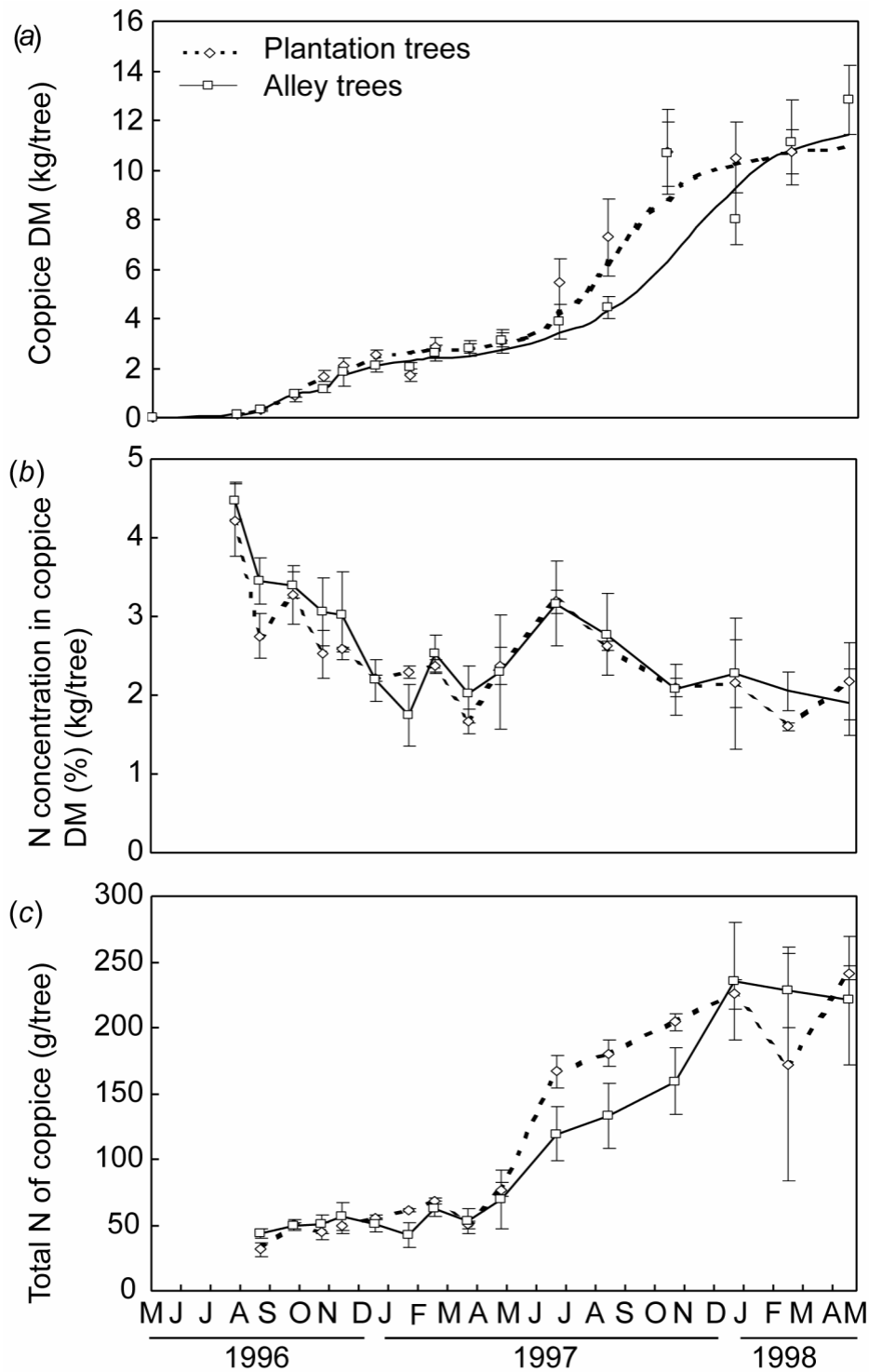


Figure 5.2. Assessments of (a) cumulative gain of coppice dry matter (from Lefroy, Pate and Stirzaker, submitted); (b) N concentrations in dry matter; (c) cumulative increases in total N of coppice regrowth of tagasaste trees over a two year period after an initial cut (May 1996) when four years old. Note much faster growth and N gain in the second than the first season after cutting. Alley trees with annual crop or fallow between tree rows were at a density of 550 trees/ha, those in plantation format at 2330 trees/ha. The study site on a property near Moora, Western Australia, was on deep sands overlying non-saline groundwater at 5 m depth.

$\delta^{15}\text{N}$ signals of agrosystem components and derivation of %Nd_fa for whole coppice and new shoot tip growth of alley and plantation tagasaste

Figure 5.3 summarizes data for $\delta^{15}\text{N}$ values of coppice total N of alley and plantation tagasaste, shoot total N of reference plants and corresponding %Nd_fa values for trees of all treatments and planting formats for the two years of study. Data sets for whole coppice DM (Figure 5.3a) and coppice tip growth (Figure 5.3b) showed relatively small changes in $\delta^{15}\text{N}$ of coppice N between harvest times, but a slightly narrower and more negative range of values for whole coppice shoot N (-0.4 to 0.9‰) than for corresponding shoot tip N samples (0.7 to 2.1).

Because of the sporadic distribution of reference species within and between plots, $\delta^{15}\text{N}$ values for reference plant collections made across the study site were pooled for each time of sampling regardless of species concerned and location of collection. This common set of reference plant values was used for deriving the %Nd_fa values given for whole coppice and coppice shoot tips in Figure 5.3a and b. When deriving %Nd_fa values for whole coppice N, the B value of -0.48‰ (Table 5.1a) obtained for 269 day old shoots of the symbiotically-dependent pot grown plants was used, whereas when making similar estimates for shoot tip biomass, the B value of 0.53‰ obtained for leaf material of the same pot cultured plants was employed.

The span of $\delta^{15}\text{N}$ values for reference species (Figure 5.3) tended to be broader (2.2 to 5.1‰) than for tagasaste but was still sufficiently positive relative to that of the tagasaste to obtain meaningful values for %Nd_fa of simultaneously sampled tagasaste biomass. $\delta^{15}\text{N}$ values for mature deep-rooted individuals of the perennial *Ptilotus* (range 2.9 to 5.1‰) were not appreciably different from those of shallower-rooted annual weeds (range 2.4 to 4.7‰). $\delta^{15}\text{N}$ values for seedling *Ptilotus* whose roots had penetrated to only 1.5 m, were also indistinguishable from those of adjacent adult plants with roots extending to at least 3.5 m depth. Values for groundwater nitrate (range 2.5 to 4.8‰), lower tap root xylem sap N of tagasaste (2.8 to 3.3‰), and summer shoot growth of *Eucalyptus tottiana* (3.7 to 4.0‰) also lay within the same range as that displayed collectively by the samples of *Ptilotus* and annual shallow-rooted weeds. These data collectively suggested that the predominantly nitrate-related $\delta^{15}\text{N}$ signals recorded for groundwater and tagasaste sinker root xylem sap were not appreciably different from those displayed by the various non- N_2 fixing reference plants. We therefore felt confident when using the pooled data reference plant $\delta^{15}\text{N}$ data for annual weeds and *Ptilotus* shown in Figure 5.3a and b when making assessments of %Nd_fa of plantation and alley trees. Furthermore, because of the close similarity in $\delta^{15}\text{N}$ values of alley and plantation treatments, the mean values for these for each time of sampling were used to derive the %Nd_fa values shown in Figure 5.3a and b. The values thus denote overall performance of all trees at the site in terms of dependence of whole coppice or shoot tip growth on fixed N.

The mean values for %Nd_fa alluded to above, indicated uniformly high (78-89%) dependence of whole coppice growth on fixed as opposed to soil N (Figure 5.3a). The partner set of values for new shoot tip growth (Figure 5.3b) were more variable (range from 52 to 86%), with evidence of lower overall dependence on fixed N (66%) than was exhibited by whole coppice biomass (82%).

Time courses of accumulation of N from fixation and soil into coppice biomass of alley and plantation trees

This analysis (Figure 5.4) combined information on cumulative N build up in coppice growth of alley and plantation trees (Figure 5.2c) and corresponding %Nd_fa data for the intervals of the study period as recorded for the two treatments. Resulting data are plotted separately in terms of accumulation of soil-derived and fixed N by coppice growth of alley (Figure 5.4a) and plantation (Figure 5.4b).

(a) Whole coppice DM

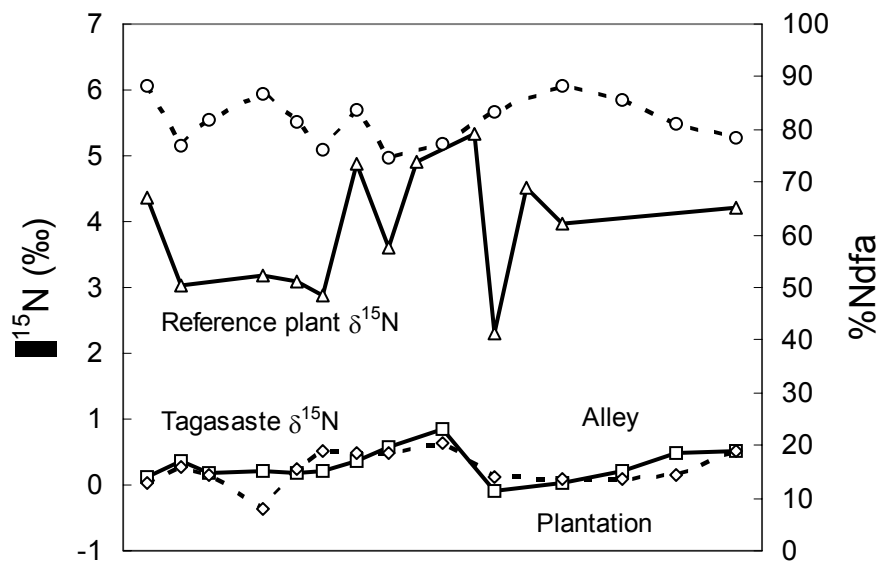
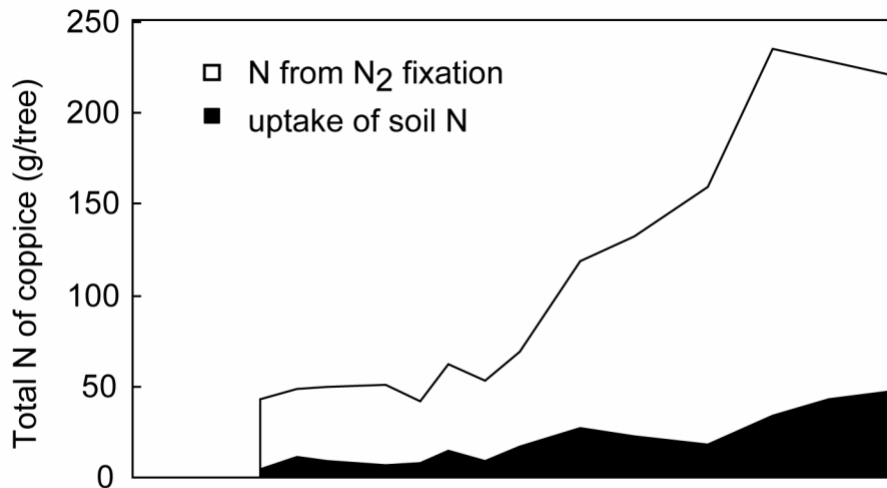


Figure 5.3. $\delta^{15}\text{N}$ values for total N of (a) whole coppice dry matter; (b) new leafy shoot growth dry matter sampled sequentially from coppice regrowth of trees of tagasaste after a first (May 1996) cut when four years old. Data are given for trees in alley (550 trees/ha) and plantation (2300 trees/ha) formats at Moora, Western Australia. Mean $\delta^{15}\text{N}$ values are shown in (a) and (b) for non-legume reference plant (annual weeds and the deep rooted perennial *Ptilotus polystachyus*) shoot biomass collected across the study site, and these pooled values used when deriving the sets of mean %Ndfa values given for plantation and alley trees in (a) and (b).

Total amounts of N at final harvests of alley and plantation were closely similar (approximately 230g N/tree), with the bulk of this derived from fixation. However, there was evidence of accumulation of N by coppice growth in plantation plots somewhat in advance of that of alley plots during winter/spring of 1997. Competition with the crop for water and nutrients during spring may well have delayed growth and N accumulation of alley crop trees relative to those of the plantations. Based on the cumulative N at final harvest shown for total coppice N in Figure 5.4, mean %Ndfa for trees across all plantation and alley plots was rated as 83%.

(a) Alley plots



(b) Plantation plots

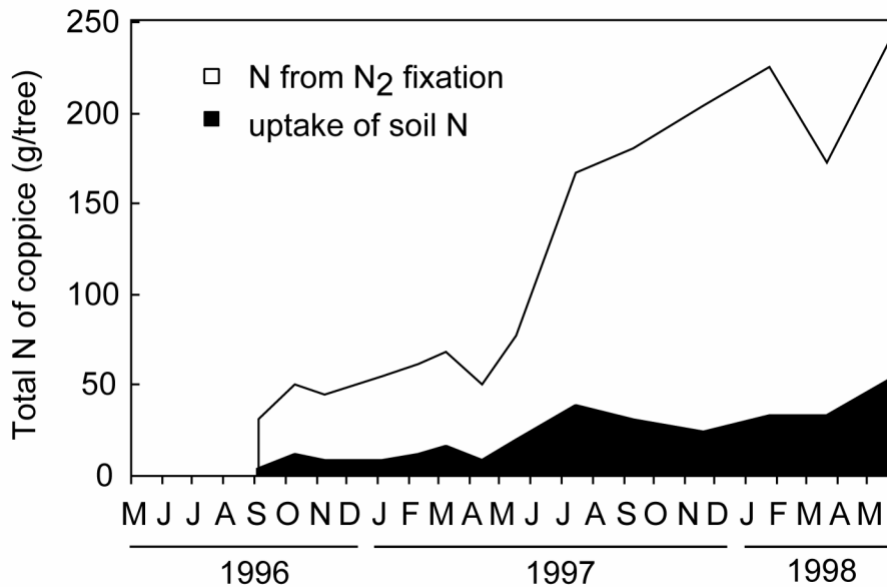


Figure 5.4. Progressive accumulation of total N in coppice regrowth of (a) alley-grown and (b) plantation-grown tagasaste trees over a two-year period of recovery from a first cut (May 1996) when trees were four years old. Data derived from Figures 5.2 and 5.3, with values for %Nd_{fa} of alley and plantation plots used to distinguish proportions of N derived from fixation and uptake of combined N of soil or groundwater. The data of this figure are used to compare rates of N accumulation in winter, spring, summer and autumn seasons of study, as summarized in Table 5.2. Study site on deep sand overlying non-saline groundwater at 5 m depth at Moora, Western Australia.

5.4. Discussion

The pot culture studies on tagasaste described in the first part of this chapter served the principal purpose of testing the applicability of the ¹⁵N natural abundance technique in assessing proportional dependence of the species on fixed N. Using a defined nitrate supply ($\delta^{15}\text{N}$ of 3.45‰) as alternative N source to nodulated young trees, $\delta^{15}\text{N}$ signals of the total N of whole plant biomass and of specific parts of the trees were measured when reliant solely on fixed N or when exposed to a range of constantly maintained nitrate concentrations in the rooting medium. Using B values obtained for fully symbiotic plants, %Nd_{fa} values were derived for each component part of the trees which had been

supplied with nitrate. The study showed minimal isotopic fractionation during the actual fixation process, judging from the closeness between the $\delta^{15}\text{N}$ value for whole plant N of zero nitrate treatments and that of atmospheric N_2 . However, appreciable fractionation occurred during subsequent partitioning of the fixed N, with nodules highly enriched, leaves and roots slightly enriched and stems somewhat depleted in ^{15}N . These findings, taken with evidence of similar orders of ranking of $\delta^{15}\text{N}$ values for component parts of the nitrate-treated plants and a general increase in $\delta^{15}\text{N}$ values as these treated plants were exposed to increasing concentrations of nitrate, indicated that the technique offered promise as a means of measuring N_2 fixation inputs under field conditions. Successful application would then be possible only if the sources of inorganic N available to tagasaste from soil or groundwater carried a $\delta^{15}\text{N}$ signal sufficiently and reproducibly different from that of atmosphere N_2 to allow %Nd_{fa} to be assessed with sufficient reliability (see Unkovich *et al.* 1994). It appeared that these conditions were met at Moora, but as indicated from our trial pot study, it was still necessary to apply appropriately selected B values derived from the pot study when using $\delta^{15}\text{N}$ data from field analyses to determine %Nd_{fa}.

Application of the technique at our study site required access to suitable reference source materials (see Pate *et al.* 1994) to monitor $\delta^{15}\text{N}$ values of the plant available mineral N in the rooting environment of the tagasaste. Here we used shoot biomass N of shallow-rooted annual herbaceous weed species to monitor $\delta^{15}\text{N}$ values of plant available soil N in the top 2m of the soil profile, and shoot biomass N of deep-rooted perennials, xylem sap N obtained from the non-nodulated lowermost regions of tap roots of tagasaste trees, and groundwater itself to monitor $\delta^{15}\text{N}$ values of the inorganic N available to deeply penetrating roots of tagasaste and reference *Ptilotus* plants from lower parts of the soil profile or from groundwater. The finding of broadly similar $\delta^{15}\text{N}$ values, mostly within the range 3 to 4.5‰ for the above sample sources, encouraged us to believe that the technique would give valid measurements of %Nd_{fa} if we were to recourse simply to data on reference plant shoot N. When making such assessments we matched B values for whole shoot of the late-harvest of pot cultured, fully symbiotic tagasaste trees against $\delta^{15}\text{N}$ values of tagasaste whole coppice shoot N, and B values for leaves of the same pot cultured plants for assessing %Nd_{fa} of the N of the sequentially collected leafy shoot tips of the alley and plantation trees.

Using the above protocols, we hoped to overcome the various difficulties and possible sources of error known to apply to studies of biological fixation by tree or shrub legumes using the ^{15}N natural abundance or isotope dilution techniques (eg. see discussions of Shearer *et al.* 1983, Shearer and Kohl 1986, Domenach *et al.* 1989, Peoples *et al.* 1991, Danso *et al.* 1992, Ovalle *et al.* 1996, Peoples *et al.* 1996).

Rates of N accretion by alley and plantation trees are shown in Table 5.2. These values were derived from (a) amounts of total N in regrowth biomass at the end of the two years of coppicing (item 1, Table 5.2, derived from Figure 5.4), and (b) estimates of increments in N contents of parent lower trunk material below the coppice shoots (item 2, Table 5.2) and N of root biomass (item 3), as derived from ratios of dry matter and total N in shoot to root, and the DM ratio of coppice regrowth to parent lower trunks (JS Pate, unpublished data). Totals for the above three items amounted to 306 g N and 339 g N per tree for alley and plantation respectively. With 550 trees/ha in the alley configuration, and 2300/ha in plantation spacing, these values would translate to 168 kg N/ha in total tree biomass of the alley treatments and 780 kg N/ha of the plantations over the two years of study.

The dense, 3 cm deep carpet of mostly decomposed litter accumulating under the tagasaste trees was composed principally of fallen foliage from the trees, but also contained some seeds and fine twig material. Concentrations of N in this litter were relatively high (1.5-2.0% N in DM) and, with litter densities in the range of 18-25 kg DM/tree, amounts of litter N accumulated under each tree turned out to be surprisingly large (item 4 Table 5.2), namely 179 g N/tree (98 kg N/ha) for alley and 192 g N/tree (447 kg N/ha) for plantation. Assuming that this litter had accumulated at a constant rate over the six years of tree growth and that mineralisation of N of litter had been negligible, one third of

the above amounts, namely 33 and 149 kg N/ha respectively, would have been expected to have been returned as litter to the ecosystem during the two year study period.

Table 5.2. Net N balances of alley- and plantation-spaced tagasaste trees over a two year period of coppice regrowth following cutting of virgin trees when four years old (Moora, Western Australia June 1996-June 1998)

Quantity (g total N/tree)	Alley trees	Plantation trees
1. Coppice shoot regrowth ^a (2 year study period)	221	242
2. Lower stem increment ^b (2 year study period)	18.4	19.4
3. Root biomass increment ^b (2 year study period)	67	78
4. Accumulated litter ^c (6 years of trees growth)	179	192

^a Values derived from Figure 5.2c.

^b Based on shoot to root dry weight ratios of uncut four-year-old trees and coppicing trees 18 months after cutting, dry weight ratios of coppice regrowth to basal biomass of parent lower trunks (Lefroy, Pate and Stirzaker, submitted) and %N in dry matter of these components.

^c Assessed by sampling across the full litter fall area of trees of alley and plantation, measuring litter dry weights and %N in dry matter, and estimating cumulative litter fall in terms of g N per metre of tree row and on a per tree basis.

The above tree-derived N inputs can be converted to annual rates of fixation using the above-mentioned mean %Nd_{fa} value of 83% for plantation and alleys suggested from the data on whole coppice N shown in Figure 5.4. The total N increment of 201 kg N/ha as living biomass plus litter fall associated with two years of coppicing of alleys then equates to a mean fixation input of 83 kg N/ha/yr whereas trees at plantation spacing would be expected to be fixing at a rate of 390 kg N fixed/ha/yr. However, these estimates are rated as conservative since it is most likely that rates of litter fall would have increased as trees aged and one would have expected substantial losses of N during leaching of decomposing litter. Furthermore, the analysis failed to take into account turnover of N in seasonal formation and senescence of nodule and root biomass, an item already known to be of considerable magnitude in the cycling of fixed N in herbaceous crop and pasture legumes (see literature cited by Unkovich *et al.* 1997) and in shrub legumes such as *Leucaena leucocephala* (see van Kessel *et al.* 1994).

The only other detailed study of N₂ fixation in tagasaste of which we are aware is that of Ovalle *et al.* (1996) who compared biomass accumulation, %Nd_{fa} and inputs of fixed N of this introduced species and three Chilean tree legumes. Biomass production over a two-year period from sowing was shown to be much greater in tagasaste than in the native legumes, for which a mean %Nd_{fa} value of 86% was recorded and a fixation yield equivalent to 49 g N/tree/yr. While it is clearly unwise to compare performances of the young uncut trees used in the above study directly against our own data on coppicing of much larger and older trees, both studies suggest high levels of symbiotic competency in the species under the field conditions tested. Ovalle *et al.* (1996) have also reported finding nodules at considerable depth (below 2 m) as well as on the upper feeding roots of field-grown tagasaste (see Chapter 3). We view the perennial character of the former class of nodule as a means of allowing fixation to continue through summer when most nodules on upper lateral roots have senesced.

It is of interest to compare the values for annual inputs of fixed N made by alley and plantation trees of tagasaste at Moora with those recorded for nitrogen-fixing trees of other agro-ecosystems. The review of Danso *et al.* (1992) is particularly relevant in summarizing data for %Nd_{fa} and fixation inputs for a

range of tree/shrub species other than tagasaste. The values quoted are 45-65%Nd_{fa} and fixation inputs of 304-548 kg N/ha/yr for various studies on *Leucaena leucocephala*, 11-18% and 43-102 kg N/ha/yr for *Sesbania sesban*, 35-45% and 505-581 kg N/ha/yr for *S. rostrata*, 72% and 108 kg N/ha/yr for *Gliricidia sepium*, 60% and 94 kg N/ha/yr for *Albizia lebbeck*, and 39-76% and 43-60 kg N/ha/yr for the *Frankia*-based symbiosis of the non-legume tree *Casuarina equisetifolia*.

While the above estimates derive mostly from radically different planting designs, management practices, tree ages, densities and climate conditions than in the present investigation, our values of 83%Nd_{fa} and 390 kg N/ha/yr for plantation-grown tagasaste rank high amongst the species listed. Moreover, the trees in our two-year study were severely compromised by cutting of shoots at the beginning of the study period, so it would be more appropriate to use data for second year of coppice growth after cutting (see data for May 1997 to May 1998, Figure 5.2c) to denote maximum fixation performance of the species at the site. Increases of 150-170 g N per tree shown for this second year, commuted at 83%Nd_{fa} and expressed in terms of annual accretion of living biomass plus litter fall of N, would then equate to 587 kg N/ha/yr for the plantation treatment - a value at the very top of the ranges reported for other N₂ fixing species alluded to above. We would regard this value of 587 kg N/ha/yr to be close to the potentially maximum achievable by plantation-grown tagasaste in Western Australia, since the mild winters and high levels of solar radiation experienced, combined with continued access to non-limiting supplies of non-saline groundwater at the study site, would provide ideal circumstances for peak productivity and symbiotic performance in the species.

Finally, it should be pointed out that while the present study shows marked benefit from tagasaste in terms of inputs of fixed N into forage biomass of agricultural ecosystems, its limited dependence on nitrate from soil and groundwater, combined with possible additions of mineralized N from decomposition of tagasaste litter, would indicate a potentially negative impact in terms of pollution of aquifers with nitrate. The extent to which this occurs compared to that already occurring through use of annual legume species has still to be evaluated.

Summary

- ¹⁵N natural abundance assessments of N₂ fixation of tagasaste in alley (550 trees/ha) and plantation (2300 trees/ha) formats were undertaken at a study site at Moora over a two-year period of shoot regrowth (coppicing) after pruning four-year-old trees.
- Cumulative N yields and %Nd_{fa} values were similar for trees at alley and plantation densities, with much less coppice N accumulation in the first than second year after cutting.
- Mean dependence on atmospheric nitrogen for all trees at the site was 83%. Scaled to a plot area, inputs of fixed N into current biomass plus fallen litter over the two years of coppicing were estimated as 83 kg N/ha/yr for the alley and 390 kg N/ha/yr for the plantation system. In the second year after cutting, the plantation tagasaste fixed 587 kg N/ha, probably close to the maximum achievable in this environment. Data are discussed in relation to previous studies on nitrogen dynamics of shrub legumes in agroforestry systems.

6 Synthesis and conclusions

The primary purpose of this study was to assess whether two novel agroforestry systems, tagasaste alley cropping and tagasaste in plantation, represented any improvement over conventional cropping in terms of water and nitrogen management on sandplain soils. This section reviews the findings and examines their implications for the role of agroforestry in this environment.

6.1. Water use

The most significant finding was that trees at wide spacing, with a potentially larger volume of soil from which to take up water, did not use more water than trees in dense plantations. This is contrary to expectations based on the edge effect observed with dense stands of many tree species where growth of the outer row(s) is enhanced through better access to resources. This finding removed any advantage in the use of spaced tagasaste trees over plantation in terms of water use per unit area of canopy.

This finding may have been influenced by the presence of highly transmissive sand overlying a shallow fresh water table. One possibility is that the root architecture of tagasaste is not sufficiently plastic to make use of soil water stored below 60 cm at distances of more than a few metres laterally from trees once it has begun investing heavily in root biomass at the capillary fringe to a water table. To resolve this question it would be necessary to compare the patterns of soil water extraction of trees without access to a water table at wide and narrow spacings (eg Smith *et al.* 1997).

While groundwater use by tagasaste in summer of 3 mm/d was high compared to other studies of trees on shallow water tables (Thorburn 1996), the annual variation in transpiration was small relative to potential evapotranspiration. Whereas potential ranged from 1 mm/d in winter to 9 mm/d in summer, transpiration of tagasaste trees ranged from 1 to 3 mm/d with an average 0.6 of potential. This was a clear illustration that plant water use in this environment is energy limited in winter and water limited in summer.

The response of trees to summer irrigation, with transpiration rates elevated up to and exceeding Penman-Montieth potential, supported the conclusion that availability of soil water rather than atmospheric conditions was the primary limitation to transpiration during summer and autumn. The column experiment (in which water use of trees growing in dry soil above an artificial water table at a depth of 1 m was one fifth of those watered from above) suggested that it was not depth to groundwater that was significant, but some other aspect of plant water uptake.

In the third year of the study when the water balance was estimated for the alley crop treatment, trees reduced deep drainage by 20%. When groundwater uptake by trees was included, the trees effectively accounted for 83% of deep drainage. While this gives the impression that alley cropping would be a very effective strategy for water management, it relies on the unreasonable assumption that access to shallow fresh aquifers would apply to spaced trees over an entire catchment.

In summary, three reasons emerged to indicate that plantations would be a more appropriate strategy for water management than alley cropping in this environment.

1. Trees in alley crop used no more water than densely planted tagasaste, providing no advantage for alley cropping in terms of the area of arable land displaced by trees per mm of water transpired (Chapter 3).
2. Tree water use at the level measured in this study is possible only where trees have access to shallow fresh water tables, and the best use of such localized phenomena would be blocks of trees (Chapters 2 and 4).

3. The mean effect of alley trees on grain yield over the last two years of the study (-20%) was greater than that due to crop displacement alone (-17%), indicating competition between trees and crops (Chapter 2).

The third reason does not rule out alley cropping entirely. If, in the absence of points 1 and 2 above, the effect of the trees on reducing drainage was proportionally greater than the effect on reducing crop yield, or the value of tree products compensated for the loss of crop, alley cropping would be an appropriate choice.

Table 6.1. The fate of rainfall (371mm) under sole crop, alley crop and plantation systems at Moora from 9 December 1997 to 2 December 1998.

Component of the water balance	The fate of rainfall (mm)		
	Sole Crop	Alley Crop	Plantation
Crop transpiration	234	194	
Tree transpiration (from soil)		45	236
Tree transpiration (from water table)		122	599
Interception		28	140
Change in soil water store	-65	-50	0
Drainage	193	154 (32) ^a	0

^a Net accession to groundwater after deducting uptake by trees.

6.2. Nitrogen cycling

The implications of the nitrogen study of the two agroforestry systems (Chapter 5) are less clear than is the case with water use. On the one hand, there are considerable potential benefits for animal production from the large inputs of fixed nitrogen into forage biomass (averaging 83 kg/ha in alleys and 384 kg/ha in plantation over three years). On the other hand, the limited dependence of tagasaste on nitrate in soil and groundwater, combined with the likely additions of mineralized nitrogen to the system from decomposed leaf litter and cycling through animals, indicated a potentially negative impact in terms of nitrate pollution of groundwater. The extent to which this occurs compared to that due to the use of annual legumes has yet to be determined. The 587 kg N/ha fixed by plantations in their second year is much greater than to be expected from annual legumes in the region. This was possible only because of the perennial nature of the species and the permanent access to a fresh water table, which enabled trees to use the equivalent of twice rainfall and maintain growth and fixation at such high rates.

6.3. Profitability

The adoption of innovations in farming systems depends to a great extent on the short term economic implications for the landholder, regardless of environmental benefits. Profitability was examined by comparing grain yield in alley crop with sole crop (Chapter 2)

In terms of grain yield, alley cropping showed a 23% yield advantage over sole crop in the first year, an 8% penalty in the second and a 32% penalty in the third. While caution should be exercised in drawing any conclusions from three years results in a region with a highly variable climate, the implications of these findings are worth briefly examining.

The positive influence of the trees in the first year, when lateral extension of deeper roots was limited to 2 m and the potential for below-ground competition low, might suggest a strategy of alley cropping with annual tree pruning. However, the yield increase in alleys in the first year could equally reflect a particular combination of seasonal conditions that resulted in minimal competition for water (late spring rain) and a positive response to shelter (hot dry winds during lupin flowering).

If the first year's yield results could be replicated over a range of seasonal conditions, there would be reason to recommend alley cropping with annual tree pruning as more economically attractive than sole cropping. However, the water management role of the trees would be compromised compared to that of older trees. Such a strategy might be considered where wind erosion control was a higher priority than water management. The weakness with that strategy would be that trees cut in autumn when fodder is in greatest demand would leave land vulnerable when wind erosion hazard is highest and the maximum distance between rows with a peak height of two metres would be 20 m (Kort 1988).

In the gross margin analysis, if an annual cutting cycle is assumed in order to maximise returns from the trees, a commercial value placed on the tree fodder and yield penalties are assumed to be due to displacement only, the result is a gross margin 45% higher than sole crop. If on the other hand trees remained uncut and ungrazed in order to maximise water use and erosion protection, or if yield penalties in the order of 30% were experienced as in the third year of this study, sole crop would be the more profitable option than alley crop.

6.4. Implications for alley cropping

In terms of water use and profitability, tagasaste plantations proved to be a more appropriate land use system than alley cropping. In terms of nitrogen inputs and their long term consequences however, the situation is equivocal and would require a study of the fate of nitrate returned to the soil through leaf fall and animal cycling in grazed plantations compared to nitrate leaching in the other two systems.

While alley cropping did not emerge as an appropriate strategy for water management in this case, this study did suggest it would have an advantage over both sole cropping and plantations in the following situations:

1. Where deep drainage is high and tree root architecture is such that the Drainage: Yield ratio is low, ie. where the tree has extensive lateral roots that can access water below the crop root zone.
2. Where the value of tree products is sufficiently high to cancel out the effects of displacement and competition with annual crops.

6.5. Implications for agroforestry

Two aspects of this study are relevant to the general question of how best to introduce trees into the drier cropping areas for water management. Firstly, the pattern of tagasaste water use highlighted the fact that tree transpiration in this environment tends to be energy limited in winter and water limited in summer. The implication is that the strategy of locating trees in parts of the landscape with high water availability in summer is more relevant to water management than the search for so called high water use tree species. Secondly, adaptive features of tagasaste identified in this study (hydraulic lift, perennial nitrogen fixing nodules and heat-stress induced leaf shedding) indicate that exotic mesophytic (soft-leaved) trees can adapt well to the harsh Mediterranean-type environments of southern Australia, and the search for suitable agroforestry species need not be limited to endemic sclerophytic (tough-leaved) species.

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