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Agroforestry for water management in the cropping zone of southern Australia

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Abstract. Agroforestry has been advocated as a means of managing excess water that has accumulated in the agricultural landscape of southern Australia since clearing of native vegetation. This article examines the feasibility and profitability of agroforestry systems designed to manage rising, saline watertables. A framework for Australian conditions is described that considers the interactions between trees, crops and their below ground environment and how they influence water use, crop yield and profitability. Data is presented from a study of a commercial scale agroforestry system under ideal conditions where trees have access to a shallow fresh water table. The discussion is then broadened to encompass soil, relief and ground water conditions more typical of the southern Australian cropping zone. The relative merits of segregating, integrating and rotating trees with crops are then examined. It is concluded that, in most cases, trees would need to be widely dispersed over a significant proportion of the landscape to manage deep drainage and salinity. Agroforestry is therefore only likely to be an effective solution to water management where trees can compete directly on commercial terms with conventional agriculture. Given the generally low rates of biomass accumulation in semi-arid woody species, this presents a significant challenge for agroforestry in the cropping zone of southern Australia.

1. Introduction

Converting the woodland, forest and heath communities of southern Australia to exotic annual grasslands of crops and pastures has severely disrupted the hydrologic cycle. The deep-rooted summer active component of the native vegetation draws on sub-soil and sometimes groundwater reserves recharged over winter. By contrast, rainfall unused by annual shallow-rooted agricultural crops and pastures accumulates in the landscape and manifests as seasonal waterlogging and rising water tables. The most dramatic consequence is that ancient stores of salt in the subsoil are carried up into the active root zone by rising watertables (Hatton and Nulsen, this volume). This article investigates the degree of intervention required if we are to manage this process through the re-introduction of trees into an agricultural landscape.

Clearing of native vegetation has proceeded largely unchallenged over most of this century due to the commitment by government and the community to expansion of agricultural development (Lines, 1991) despite early appreciation of the hydrologic changes involved (Despessis, 1902; Western Australian Government, 1917; Wood, 1924) and despite warnings of the consequences

(Burvill, 1947). The new hydrology of cleared landscapes is associated with degrading processes in addition to salinity. Soil erosion, acidity and soil structural decline, combined with pollution of groundwater and eutrophication of surface waters, are all related to changes in the way water moves through the landscape (McFarlane et al., 1993). Management of water is therefore a key element in any strategy to improve agricultural sustainability in this region. Recent predictions that salinity will affect about 30% of cleared land in south western Australia by the time a new hydraulic equilibrium is reached some time next century, (Ferdowsian et al., 1996; George et al., 1997), are driving government and farmers to find alternative systems of land use.

Four articles in this volume examine the question of designing sustainable land use systems in southern Australia from first principles using the processes occurring in pre-existing plant communities as models for theoretical agricultural mimics (Hatton and Nulsen; Pate and Bell; Hobbs and O’Connor; and Dunnin et al.). All pay particular attention to the capture and redistribution of water and all conclude that a significantly higher year-round leaf area is required for water management than could ever be found in farming systems based solely on annual plants.

A pragmatic way to achieve this objective is to evaluate farming systems that already include economically valuable perennial species in the hope that these profit-driven systems will have hydrologic side-effects of the required magnitude. The recent practice of alley cropping is an example. Alley cropping, or hedgerow intercropping, evolved as an attempt to reduce soil erosion and increase soil fertility on sloping soils in the tropics (Kang et al., 1990). A similar novel cropping system, though on a much broader scale, has been developed in southern Australia by farmers attempting to manage rising water tables and wind erosion. Trees are also planted to provide additional sources of income through their timber (*Eucalyptus* and *Pinus* spp.) or fodder value (Acacia spp. and tagasaste [*Chamaecytisus proliferus* Link, var. *palmensis*]) and typically occupy 5 to 25% of arable land (Lefroy et al., 1993). In terms of water management, the hope has been that at this density and arrangement, the trees will be able to capture and transpire sufficient water to account for the amount of excess water currently leaching below the root zone of annuals.

The alley cropping experience represents an opportunity to empirically test the effectiveness of a form of intervention that has already passed the critical tests of acceptability and practicality in the eyes of some landholders (see Pannell, this volume). The question remains whether it is capable of achieving the ecological objective of water management in its commercially acceptable form. The next section describes a theoretical framework for evaluating the trade-offs between water management and agricultural productivity of a tree-crop system. Part three describes an experiment comparing the water use and productivity of conventional cropping and a tagasaste alley cropping system on a deep infertile sand in south western Australia. The implications for agriculture are discussed in the final section.

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

The tree-crop system represented in Figure 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

Net benefit = T – Y1 + (Y3 – Y2)

where T = 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 watertables 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 (S4). Factors that increase water capture

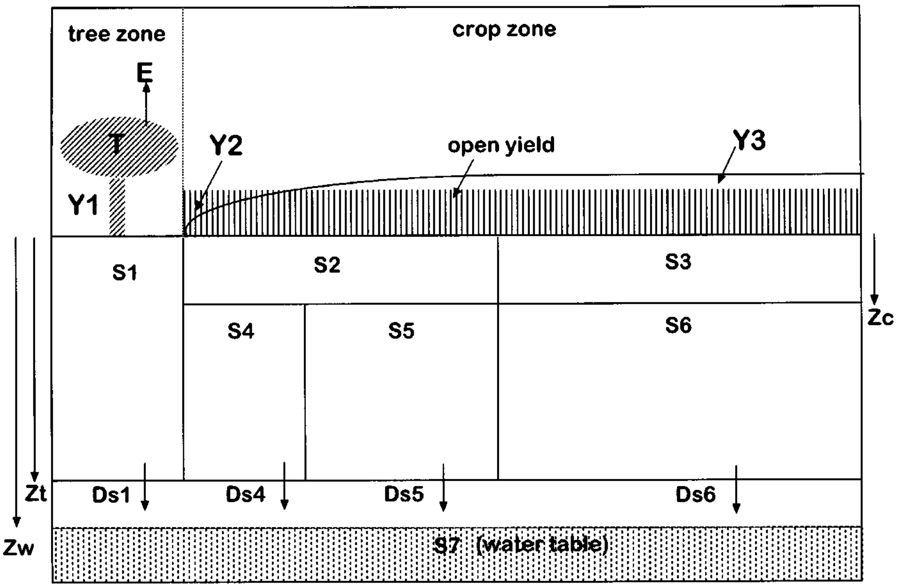

Figure 1. The interactions between trees, crops and their below ground environment in a simultaneous agroforestry system. The variables that determine the effectiveness of water management are crop rooting depth (Zc), tree rooting depth (Zt), depth to water table (Zw), size of the soil zones occupied by tree roots (S1, 2 and 4) and crop roots (S2 and 3), the transmissivity and salinity of the saturated zone (S7), tree water use (E), and drainage (Ds). 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).

will, in most cases decrease productivity, necessitating a delicate balance between these two management objectives.

2.1. *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 hundred fold increase in deep drainage following clearing in the lower rainfall areas; from < 0.1 mm yr^{-1} to > 10 mm yr^{-1}. Peck and Hurle (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^{-1} (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 (rainfall 460 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 y^{-1} or 30% of annual rainfall.

Attempts to increase evapotranspiration by manipulating crops and pastures are limited by three characteristics of the southern Australian environment. Firstly there is the asynchrony between 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, so annual rainfall can rarely 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 largely countered by studies showing that increases in crop transpiration are achieved at the expense of soil evaporation, not drainage, with little change in total evapotranspiration (e.g. Smith et al., 1998).

2.2. *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, this volume). 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:

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

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 y^{-1} have been reported over short periods for irrigated plantations and sites over shallow watertables (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.

2.3. *Unsaturated soil stores (S1, S2, S3)*

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 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, this volume) 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 S4, the zone critical to the success of agroforestry as this is where trees are never in competition with crops. Data from Eastham and Rose (1990) suggest that trees at low densities develop shallower rooting patterns. This presents a challenge for agroforestry, which 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 falls onto a wet crop root zone (S2) adjacent to a dry tree root zone (S4). 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 S4, where tree roots can capture water from both the topsoil and subsoil. Drainage from S5 would be higher than S4 (as S5 contains no tree roots) but lower than from S6, as there are no tree roots in the topsoil zone immediately above S6. Some competition will be inevitable in zone S2, but this could be minimised by selecting for maximum temporal complementarity between tree and crop (see Ong and Leakey, this volume). 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 and 3) the effectiveness of root pruning in limiting competition in S2.

2.4. *Saturated soil store (S7)*

The saturated zone is a potentially important store of water, particularly as the area of land where watertables are within range of tree roots is increasing. When trees take up water from the watertable 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. The saturated conductivity of soil is orders of magnitude greater than the unsaturated conductivity so the influence of the tree on the watertable level could be seen over a considerable horizontal distance. With reference to Figure 1, if the roots in S1 reached the watertable, the tree could access water that drained below S5 and S6 via the saturated zone. Thus, unlike the unsaturated case above, trees could potentially protect a large area outside the physical extent of their own roots. For example, a belt of trees drawing on a watertable could 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 a 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 rapidly switch between alternative water sources such as near surface soil water and groundwater is an important adaptation to difficult environments observed in endemic tree species (Thorburn et al., 1995; Mensforth and Walker, 1996; Dawson and Pate, 1996) and tagasaste (Pate and Dawson, this volume). However the ability of trees to use water from the saturated zone is severely limited by salinity. When trees use water from the watertable, 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 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^{-1} from the watertable 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.

2.5. *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). Examples of greater resource capture include trees extracting water unavailable to crops by virtue of spatial complementarity (deeper rooting habit) 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, e.g. using nitrogen fixing trees and trees with proteoid roots capable to extract 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, this volume). 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., 1997; Dupraz et al., 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. While competition close to the tree may be compensated for by positive effects at a distance, such as from shelter as in the tagasaste alley cropping experiment below, 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 pers. comm.). 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.

3. Water use and productivity of tagasaste alley cropping

This section presents 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 kilometres north of Perth, originally supported a woodland community dominated by *Banksia prionotes*, described by Pate and Bell (this volume). This site is typical of the sandplain regions of southern Australia that remained uncleared for agriculture until the 1950's and 60's 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 thirty years of fixation and leaching in these legume-dominated pastures. Development of the sweet lupin grain crop *L. angustifolius* in the 1970's saw the rapid adoption of continuous lupin/cereal rotation as a viable cropping option (Gladstones, 1982; Marsh, 1997).

Rising water tables, herbicide resistance, wind erosion and sub-soil acidity have since raised doubts about the sustainability of annual crop and pasture systems on these soils. As described earlier, median annual drainage is about 140 mm y^{-1} in this 460 mm rainfall environment. If our 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 a tree/crop mixture with sole tree and sole crop treatments. The tree/crop mixture was a single row of the fodder tree tagasaste planted at 1 m spacing in rows 30 m apart giving a tree density of approximately 550 ha^{-1}, a design based on a commercial alley cropping system (Lefroy and Melvin, 1996). Tagasaste was introduced to Australia from the Canary Islands last century and is grown primarily in dense plantations where it is mechanically pruned to provide fodder for sheep and cattle. In the sole tree (plantation) treatment, tagasaste was planted at 1 m spacing in rows 6 m apart (2330 trees ha^{-1}). Trees were direct seeded in rows orientated north/south using a commercial tree planter and cut back from 2 m to 0.6 m high in May 1996 when measurement began. Grain lupins (*Lupinus angustifolius* var. Gungurru) were sown in the sole crop and alley crop plots in June 1996 followed by oats (*Avena sativa* var. Toodyay) in 1997. Each treatment was replicated twice in plots 50 m by 160 m.

The very low fertility and water holding capacity of the soil can be seen from the data in Table 1. Since clearing 34 years ago, a fresh (< 1 dS m^{-1}) perched water table has developed lying over a clay layer at approximately 10 m depth. For the duration of experiment it was approximately 5 m below the surface. 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 neutron probe access tubes were also positioned across the tree rows between the centres of adjacent alleys. Transpiration by the tagasaste was estimated by fitting stems with heat pulse sapflow sensors (Hatton et al., 1990), moved to fresh stems on a three monthly rotation. Flux per unit area conductive wood

Table 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 F.C. (% v/v)	12	12	12
Water content at W.P. (% v/v)	3	3	3
Sat. hydraulic. cond. (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

was then scaled up to plot level transpiration using data from three monthly surveys of stem size distribution and conductive wood area per unit land.

3.1. *Crop water use*

The time series in Figure 2 commences in July 1996, following a very wet opening to the winter season, when the measured profile depth of 3.7 m was

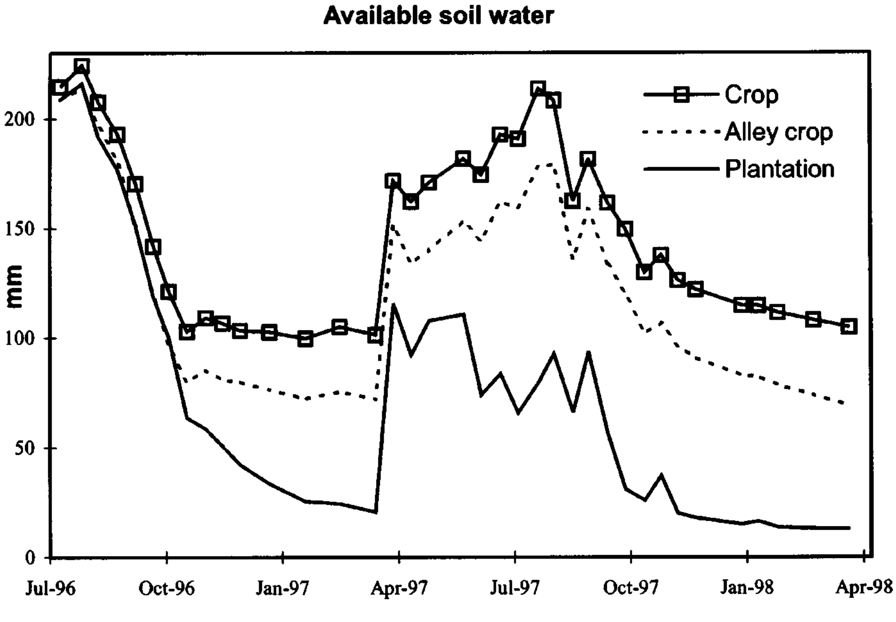

Figure 2. Change in available soil water content under crop, alley crop and tagasaste plantation at Moora, Western Australia, from July 1996 to April 1998.

at 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 102 mm. Between April 97 (break-of-season rains) and August, the soil profile under the oat crop progressively filled, with about 120 mm left in the profile at harvest. 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 although the season terminated before they had exploited all the available water between depths of 2 and 3.5 m (Figure 3a). This illustrates the difficulty in defining the dimensions of the zone S2 and S3 of Figure 1. The oat crop did not use water below 2.2 m in the 1997 season.

3.2. *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 64 mm (29% full) and 80 mm (37% full) respectively, compared to 102 mm (47% full) under the sole crop (Figure 2). The tagasaste had been heavily pruned to a height of 0.6 m in April 96, but was not pruned before the next rainy season. After this time, the soil profile in the sole tree treatment did not refill below 0.75 m 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 hotter weather. A comparison of deuterium/hydrogen ratios of groundwater, xylem sap of shallow rooted annuals (as an indicator of soil water) and xylem sap from tagasaste stems indicated that the tagasaste went through a sudden change in its relative dependence on groundwater and soil water (Pate and Dawson, this volume). Between November and December each year it switched from a 20% dependence on groundwater to 60% dependence. During this same period, wilting and desiccation of young tagasaste shoot tips was observed indicated that this mesophytic shrub, adapted to a more humid maritime environment, was experiencing heat stress. This was associated with a sharp increase in delta ^{13}C ratios of shoot tip samples over the same period (Pate and Dawson, this volume), suggesting increased periods of stomatal closure.

Figure 3 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 3a) and alley crop treatments (Figure 3b) was a consequence of isolated storms in later summer. The most striking feature of Figure 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. From Figure 3b it is evident that the apparent

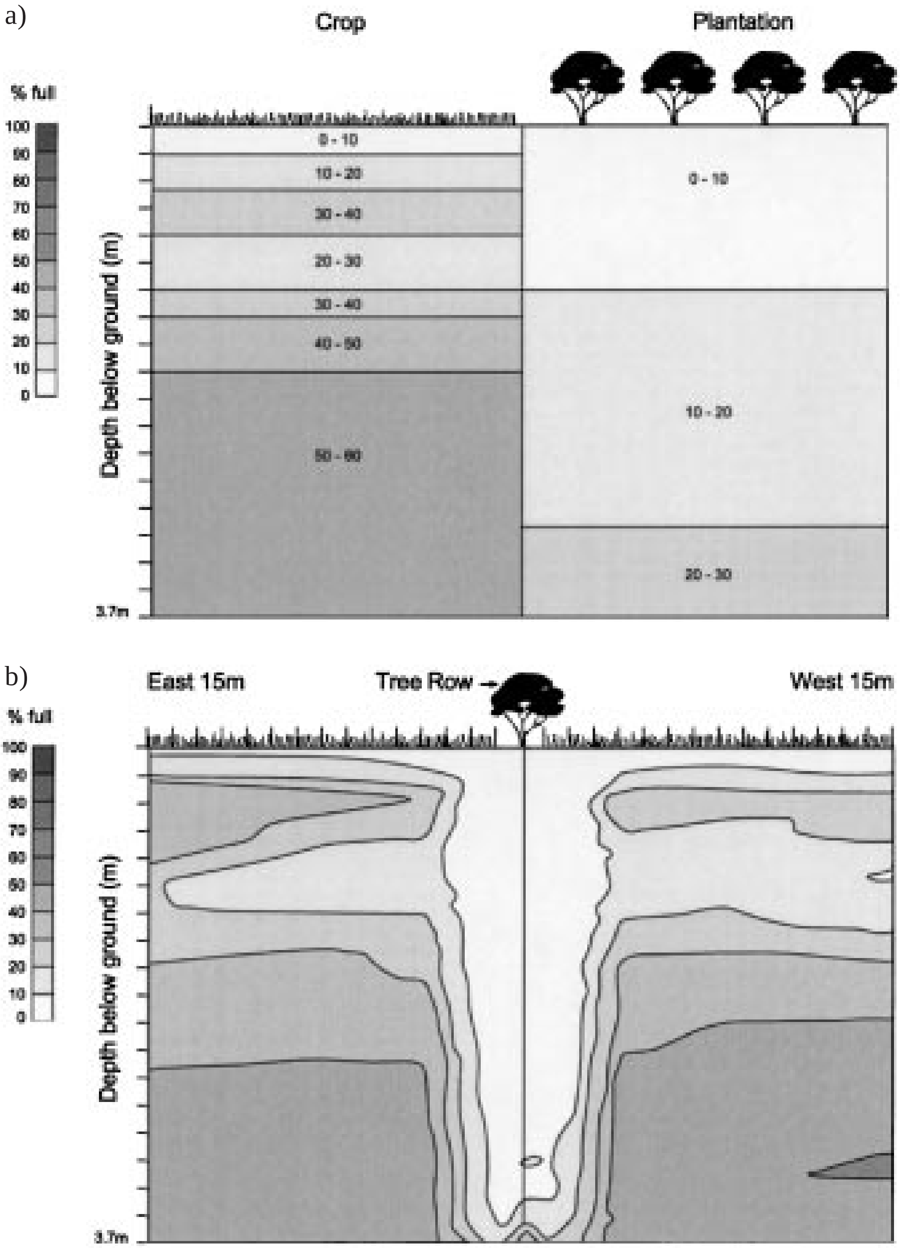

Figure 3. a). Soil water content under crop (left, mean of 12 access tube readings) and plantation (right, mean of four access tube readings) at Moora, Western Australia, on April 2, 1997. Water content expressed as % full for soil profile to a depth of 3.7 m. b). Soil water content measured in a transect 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).

20 mm buffer of dry soil under the alley crop compared to the sole crop treatment (Figure 2) was confined to a narrow zone immediately under the trees.

Tagasaste transpiration, as measured by sap flow, was remarkably similar throughout the year (Figure 4) with a mean daily water use of 2 mm d^{-1} ranging from a low of 1.5 mm d^{-1} in winter to a high of 2.5 mm d^{-1} in summer. Despite the fact there was fresh groundwater in a transmissive aquifer available at a depth of 5 m, the tagasaste did not achieve better than 40% of potential rates over the three summer months and 48% of potential for the year. Total transpiration over 12 months from January 1997 was measured at 749 mm. Allowing for a further 150 mm as soil evaporation (estimated from changes in soil water content in the top 20 cm) and canopy interception (measured with transects of rain gauges), total evapotranspiration was in the order of 900 mm y^{-1}. Assuming for the moment no positive or negative interaction between trees and crops, a simple replacement series between sole crop with evapotranspiration of 320 mm y^{-1} (rainfall of 460 mm y^{-1} less median deep drainage of 140 mm y^{-1}) and sole tree using 900 mm y^{-1} indicates 24% tree cover at the catchment scale would be required to prevent further water table rise (Figure 5). This assumes that all trees would have access to a perched fresh water table.

3.3. *Tree-crop interactions*

Tree-crop interactions can be viewed from two perspectives – the effect the trees have on the crop, and the effect the crop has on the trees The impact of

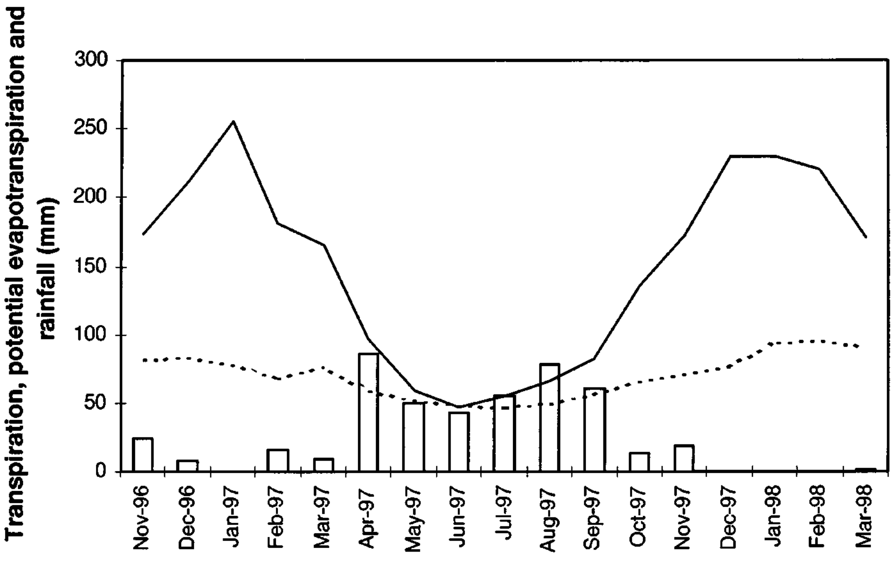

Figure 4. Transpiration by tagasaste plantation (dashed line), potential evapotranspiration (solid line) and rainfall (columns) at Moora, Western Australia.

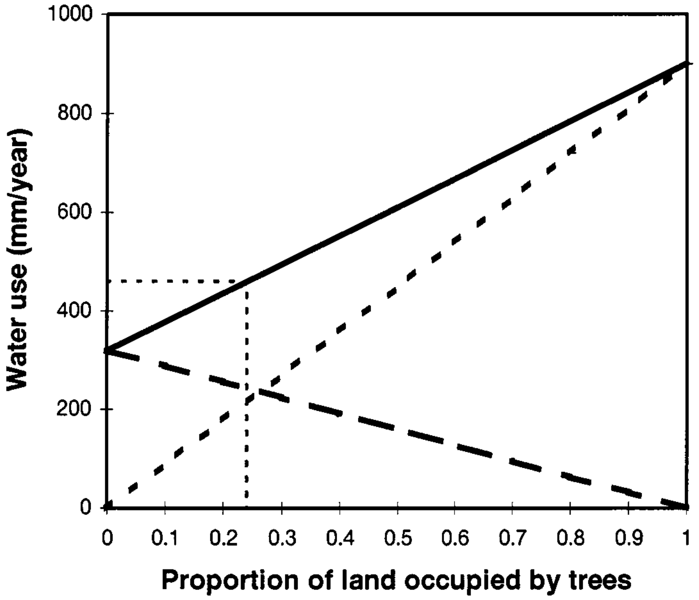

Figure 5. A replacement series involving sole crop (dashed line) with evapotranspiration of 320 mm per year (rainfall less median deep drainage) and plantation (dotted line) using 900 mm per year showing that 24% tree cover at the catchment scale would be required to account for annual rainfall of 460 mm y^{-1} and prevent further water table rise.

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 6). A positive response to shelter was measured in lupins in 1996. There was a 29% increase in grain yield over the arable area compared to the sole crop treatment and a 22% increase over the total land area, i.e. including the arable land displaced by trees (Figure 6a). 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 suggesting the yield response in the field was due to above-ground rather than below-ground influence of the trees. The yield of oats was 4% higher per unit arable land under alley cropping but not significantly different over the total area (Figure 6b). Thus the legume and cereal crops responded differently to shelter, as reported by others (Kort, 1984; Bicknell, 1991). In 1998 lupin yield was significantly lower in alleys.

Assuming yield effects similar to 1996 and 1997, and that wider tree belts would have similar effects on crop yield as single rows, increasing the area of land under trees from the present 10% to 24% (to fit the water use objective established above) would result in a 3% drop in lupin yield and a 22%

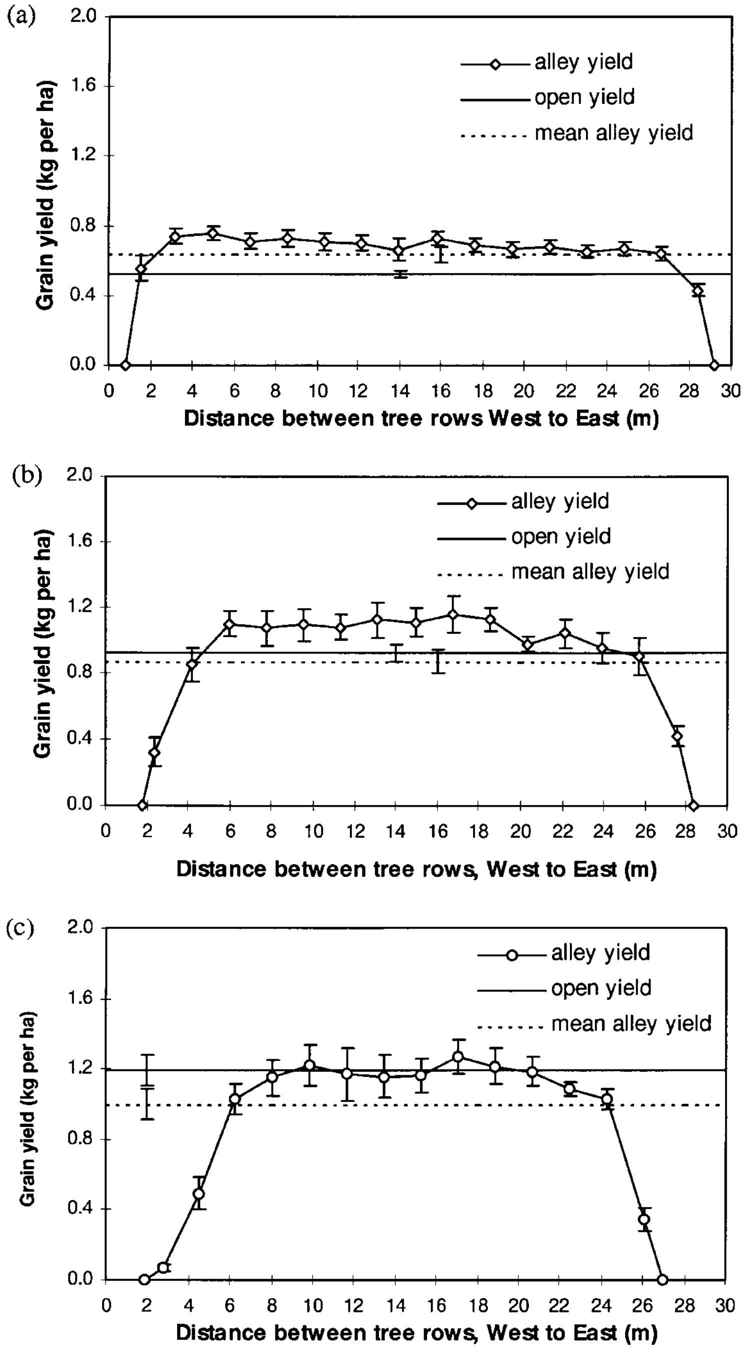

Figure 6. Yield of lupins 1996 (a), and oats 1997 (b) and lupins 1998 (c) measured in 1.8 m widths in a continuous transect across 30 m wide alleys (*n* = 5) at Moora, Western Australia.

drop in the yield of oats over the total land area under alley cropping compared to 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 required under trees for water management is low, or where shelter is the primary design criteria, yield data for the first two years suggest there may be medium to long term benefits from the response of the legume phase to shelter that could justify adoption (Figure 7). However, the initial cost of establishment and the lag between planting and yield response inevitably means a period of forgone income, in this case seven 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 intervention 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 is further evidence that tagasaste does not have the rooting pattern of an ideal agroforestry tree (Figure 3b). It may also explain why so little competition was observed in the crop zone adjacent to the trees in the first two years.

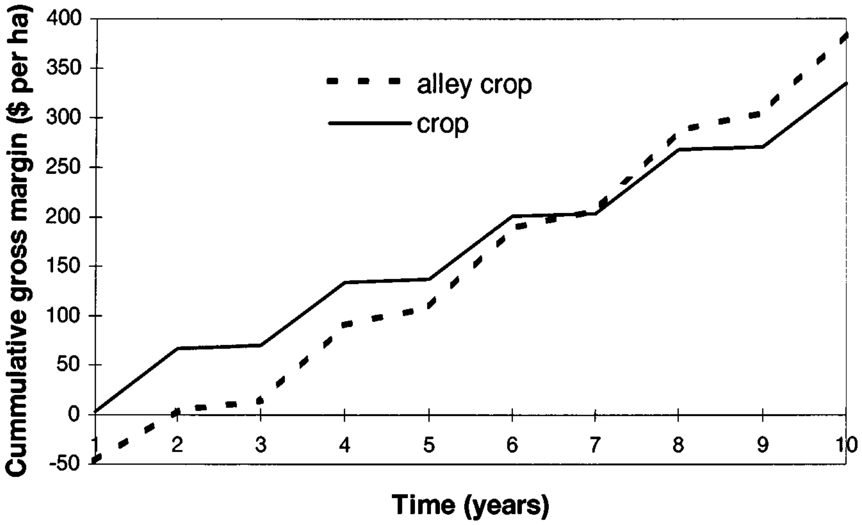

Figure 7. Cumulative gross margin for a lupin cereal rotation under conventional and alley cropping based on data collected at Moora, Western Australia. Assumes a twenty percent yield increase due to shelter effects in the lupin phase and a five percent yield increase due to shelter effects in the cereal phase. Establishment assumes direct seeded trees occupying ten percent of arable area, reaching a mature height in year five.

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 in southern Australia so rapidly after the introduction of agriculture. 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 watertables 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).

4.1. *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. It may be best to continue to manage the best land to be as productive as possible in this way, and to set other land aside for environmental services (van Noordwijk, this volume). 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. First, it is difficult to identify areas in a catchment where there is sufficient lateral movement so that excess water can move from cropping land to blocks of trees. Though there are some examples of strategically placed plantations intercepting groundwater (e.g. 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. Second, 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 (Miller et al., 1981; Schofield et al., 1989; Hatton and Nulsen, this volume). Third, 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 watertables over transmissive aquifers, as in the case study above. With drainage under crops averaged 140 mm y^{-1}, tagasaste was able to extract 420 mm y^{-1} from the watertable. 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. The proportion of trees and crops was arrived at by allo-

Table 2. The extent of the saturated zone and its effect on the proportion of a catchment requiring revegetation for catchment evapotranspiration to equal rainfall. Assumes annual median deep drainage is 140 mm, annual average rainfall is 460 mm, crop water use is 320 mm, plantations over a water table use 900 mm and plantations without access to a water table are in equilibrium with rainfall.

Extent of saturated zone (%)	Plantations + WT (%)	Annual crops and 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

cating all the area with access to the saturated zone to plantations of tagasaste and then assigning three times that area to annual crops or pastures and the remainder to ‘dryland’ plantation and trees in alley cropping (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 a 25% reforestation target, the area required under trees rises by 15%. However the assumption that all deep drainage will reach a perched aquifer is not realistic. The fact that regional groundwater systems are rising in the order of 0.2 m y^{-1} in the Moora region (R. Speed, pers. comm.) and are not responding to localised revegetation that has dried up perched systems (R. Speed et al., 1993), indicates that some recharge is bypassing these perched aquifers. 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 y^{-1}) 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 watertables is rare on other soil types.

4.2. *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.

A simple framework for deciding whether to segregate or integrate is illustrated in Figure 8 for the Moora region (annual rainfall and crop water use 460 and 320 mm y^{-1} respectively). For the purpose of this example it is assumed the tree component cannot access a watertable. 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.

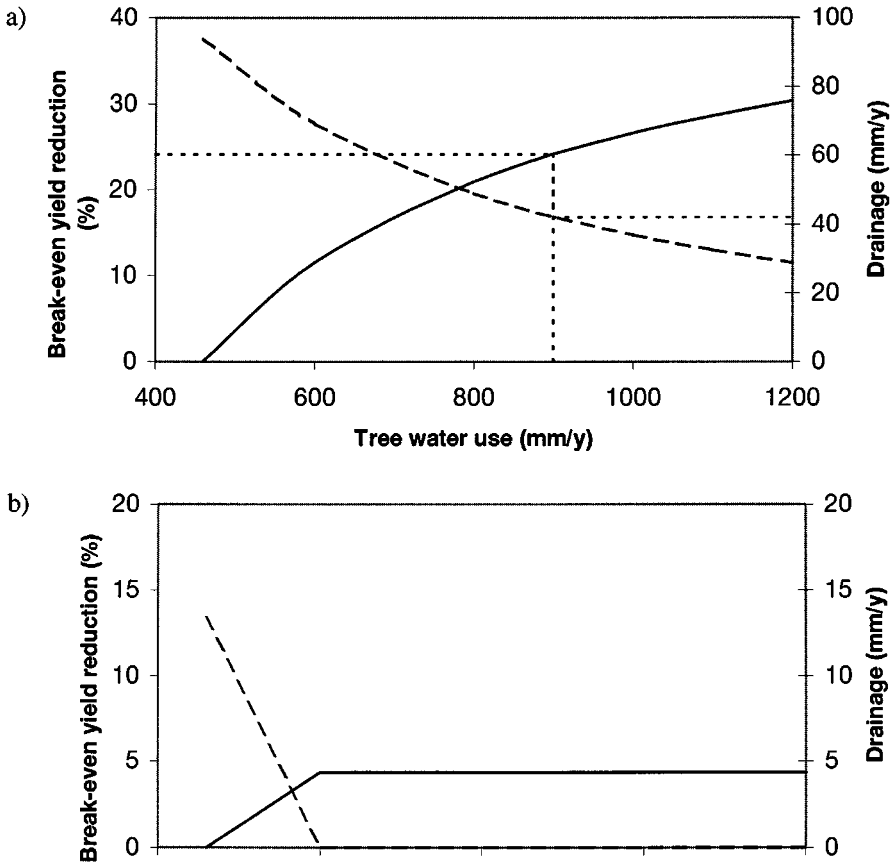

Figure 8. The break even yield reduction (solid line) and drainage (dashed line) as a function of the water use of the trees integrated with crops when drainage below the crops is a) 140 mm per year and b) 20 mm per year.

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 assumption 2, 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 the sum of tree water use and crop water use is equal the discharge capacity of the catchment.

For the Moora example above, we calculate average drainage as 140 mm y^{-1}. If we wanted to reduce this figure to around 40 mm y^{-1} (i.e. 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 was able to use 900 mm y^{-1}, we could achieve the same objective by having 33% of the catchment planted to tree belts. Figure 8a illustrates the effect of putting 33% of the catchment under tree belts on break even yield reduction and drainage. 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 y^{-1}, 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 y^{-1}.

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 y^{-1}, and at these lower values the case for integration is much weaker. Once the trees use more than 600 mm y^{-1} 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 8b).

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 is 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 average drainage is relatively low, 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 uncropped alleys. Alley forestry would be a less risky proposition than alley cropping and would be more effective in unusually wet years.

It should be remembered, as described in section 1 and 2, that 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.

4.3. *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., this volume). Lucerne has proven 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 much of cropping zone of southern Australian where there are 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). While 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 not grasslands in their own right (Hallam, 1979). The life form analysis presented by Pate and Bell (this volume) also 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 the 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 sub-soils 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. It may be better to think in terms of very short rotation forestry.

4.4. *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 (this volume) 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. These 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 (Jackson, 1985) indicate 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 (e.g. Pate and Bell, this volume), 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 (e.g. Figure 7). 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.

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.

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