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Where to plant trees on cropping land for control of dryland salinity: some approximate solutions

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Abstract

The paper gives simple rules and analytical expressions to optimise the number and location of trees required to control rising watertables on relatively flat cropping or pasture land. The approach gives the flexibility needed when key parameters, such as annual drainage or subsoil conductivity, are either hard to measure or subject to large natural variability. We provide design criteria for a revegetation strategy that balances recharge control with tree/crop competition, based on the depth and quality of the groundwater and saturated hydraulic conductivity of the soil. Where watertables are below the crop and tree root zones, a wide distribution of scattered trees across the landscape is required to intercept water not used by agricultural plants. If trees can access water from the watertable, they can induce substantial horizontal movement of water. In this situation, belts of trees with alleys between them is the design which minimises tree/crop competition and is most compatible with cropping machinery. Tree belts can be spaced more than 100 m apart for most cases when the saturated conductivity of the subsoil exceeds 5 mm day^{-1}, but wide spacing between tree belts require the tree belts themselves to be correspondingly wide. However, the problem of salt build up in the capillary fringe above a watertable means that the salinity of the groundwater needs to be relatively low (less than 5 dS m^{-1}), or uptake rate from the watertable low (less than 200 mm year^{-1}), unless the root zone is leached once or twice a decade. The planting of tree belts to manage perched watertables will be of limited value unless slope exceeds 5°.

Keywords: Agroforestry; Trees; Salinity; Hydrology; Drainage

1. Introduction

Long term average water use by annual crops and pastures in Australia is less than the native vegetation they replaced because of their shallower rooting depth and seasonal

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growth pattern. Average drainage below the crop root zone in wetter regions of Australia (>750 mm year^{-1}) has increased from <5 mm year^{-1} to >20 mm year^{-1} following clearing; in drier regions drainage has increased from <0.1 mm year^{-1} to >10 mm year^{-1}, with high variability between years (reviewed by George et al., 1997). Watertables rise when more water percolates below the root zone and reaches a groundwater body than can be discharged to streams. The above rates of deep drainage following clearing are manifested in watertable rises up to 2.6 m year^{-1} in wetter regions and up to 0.5 m year^{-1} in drier regions. When salts are stored in the subsoil, they are carried into the crop root zone by rising watertables, with dire consequences for agriculture. All Australian States are to some degree affected, the worst case being Western Australia where 1.8 million ha of land are seriously salt affected, with the area expected to double in the next 25 years (Schofield, 1992; George et al., 1997).

Management options for dryland salinity on cropping land include improved agronomy to increase crop water use, introduction of perennial pastures into rotations, engineering solutions to manage excess surface or ground water and the introduction of trees. There have been many attempts to control watertables using trees, with successful outcomes in certain hydrogeological settings when trees have been planted at sufficient densities in strategic locations of the landscape (Bell et al., 1990; Bari and Schofield, 1992; Greenwood et al., 1992; Farrington and Salama, 1996; George et al., 1997). Trees must also be planted in arrangements that minimise competition for water with crops, for it is common for crops to experience water deficits even in years when drainage occurs.

Decisions on the number and distribution of trees required to manage rising watertables need to be addressed at regional, catchment and paddock scales. At the regional scale, some knowledge of the hydrogeology of a catchment is necessary to resolve questions on how regional and local aquifers interface and where salt is stored in the landscape (eg. Evans and Kellett, 1989). At the local catchment scale, there can be optimal locations for plantations in midslope or convergent zones where fresh water flows from upslope areas. There may also be features in the landscape such as dykes, changes in slope or soil type, that give plantations access to groundwater before it gets either too deep or too salty to be useful (Farrington and Salama, 1996). At paddock scale, we assume that hydrogeological features are relatively homogeneous and concentrate on the hydrological benefit we may expect from trees set against their competitiveness with crops (Ong et al., 1996).

This paper gives approximate solutions for tree density and distribution when the aim is to control rising watertables by planting trees on relatively flat cropping or pasture lands. We focus on plantings of belts, strips and scattered trees. While we recognise that returning substantial portions of catchments to plantations may also be a viable option, it is beyond the scope of this paper because much of the cropping and pasture land of Australia lies in a rainfall zone considered too low for economic plantation forestry. We consider three scenarios:

1. When the watertable is below the rooting depth of crops and trees.
2. When the watertable is within the rooting depth of the tree but not the crop.
3. When a perched or seasonal watertable is within the rooting depth of the crop and tree.

Trees and crops compete for water, nutrients and light, although here we deal with water only. For each of the above cases we need to balance the competition between trees and crops (or pastures) with the requirement that trees transpire the water unused by crops. Competition is at a minimum when the length of the tree/crop interface is low (Young, 1987), i.e. large isolated blocks of trees are less competitive with crops than the same area of trees spread out into narrow strips. Hence, the critical issue in balancing deep drainage control with competition is to understand the degree to which water moves vertically and horizontally in the three cases described above. Where there is substantial horizontal movement, water can move from the crop zone to the tree zone, thus minimising competition.

2. Theory

2.1. Case 1 – The watertable is below the depth of crop and tree roots

Here we consider only unsaturated flow in homogeneous soils, where the water table is well below the tree root system, but rising because rainfall exceeds evapotranspiration and discharge to streams. For the purposes of this analysis, a cropped paddock containing scattered trees is characterised by areas where there are only tree roots (under the crown), only crop roots, and a zone occupied by both tree roots and crop roots (Fig. 1). From an environmental perspective, we would want the tree roots to cover the entire area so that deep drainage would be minimised. From an agricultural perspective, we would want to minimise the competition between the tree and crop.

Fig. 1 shows a fringe area beyond the tree root zone which we call the capture zone. The capture zone contains crop roots but not tree roots. Trees can get very little water from the capture zone, even when their own root zone is dry, because unsaturated soil transmits water extremely slowly over such distances. However during rain, when the capture zone is above the upper drained limit, water moving through the capture zone will be pulled sideways by the dry slab of soil occupied by tree roots. Thus the capture zone

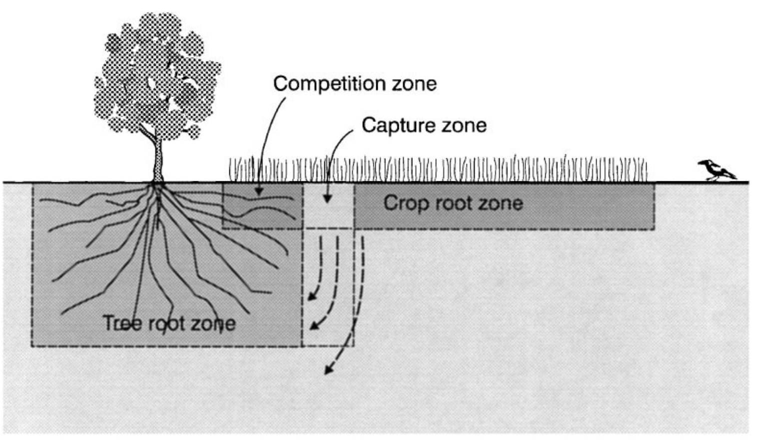

Fig. 1. Schematic diagram showing the tree and crop root zones, and the competition and capture zones.

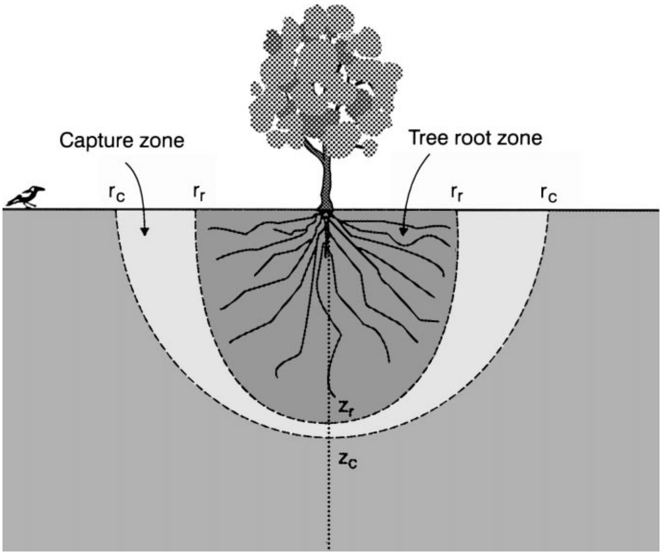

Fig. 2. Schematic diagram showing the extent of the tree root zone and capture zone having radii of r_r, and r_c at the surface.

represents a potential area where deep drainage can be controlled without competition with crops.

Consider an isolated tree in the absence of a crop where all the roots of the tree are confined within a zone having a width at the surface of r_r and a depth of z_r (Fig. 2). If the tree root zone is relatively dry, but the soil outside the tree zone is wet and draining, the water will flow sideways towards the root zone under the influence of capillary forces, at the same time as it moves downwards under the influence of gravity. The dimensions of the capture zone are determined by the balance between capillary and gravitational forces, and can be calculated using the analytical solution given in the Appendix.

2.2. Case 2 – The watertable is within the rooting depth of the tree but not the crop

Here we consider the case in which a rising watertable is within the range of tree roots but has not come to within the maximum rooting depth of crops. 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 watertable beneath the tree. The saturated conductivity of soil is orders of magnitude greater than the unsaturated conductivity, so unlike the case above, the influence of the tree on the watertable level could be seen over a considerable horizontal distance. Strips of trees with wide alleys between them would be the design most compatible with cropping. Farmers would ideally want the alleys between the trees as wide as possible for ease of machinery use and to minimise competition effects.

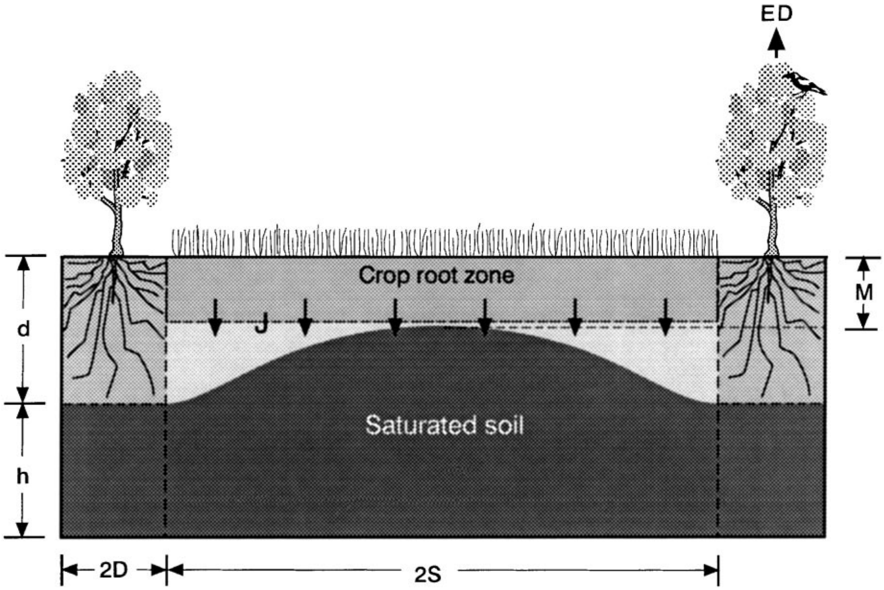

Fig. 3. Schematic diagram showing the shape of the saturated zone between lines of trees on flat land. Symbols are described in Table 1 and in the text.

Calculation of the maximum spacing of parallel belts of trees can be treated as being analogous to the spacing of ditch drains. If we want to hold the watertable just below the crop root zone at the mid point between the belts of trees, the spacing between tree belts can be calculated using Dupuit–Forchheimer drainage theory as shown schematically in Fig. 3 (Kirkham, 1967). The maximum half-spacing, S, between tree rows that will satisfy this flux is given by:

$$S = \left(\frac{K}{J}(d - M)[(d - M) + 2h]\right)^{1/2} \tag{1}$$

where K is the saturated conductivity of the soil, J the annual drainage below the crops, d the depth to the watertable below the trees, M the depth of the watertable at the midpoint between the tree belts and h the height of the watertable above some impermeable layer. In traditional drainage theory, d is the depth of the drain, which can be considered to be an infinite line sink. In our case the strength of the sink is dictated by the amount of water the trees can extract from the watertable multiplied by the width of the tree belt.

2.3. Case 3 – Seasonal watertable is within the rooting depth of the crop and tree

Cropping does not take place in areas with continuously high watertables, but perched watertables are common on texture contrast soils during the winter. In the case of a perched watertable, the maximum difference in height of the watertable between the tree belt and cropped field ($d - M$) is constrained by the depth of the top soil, i.e. when the

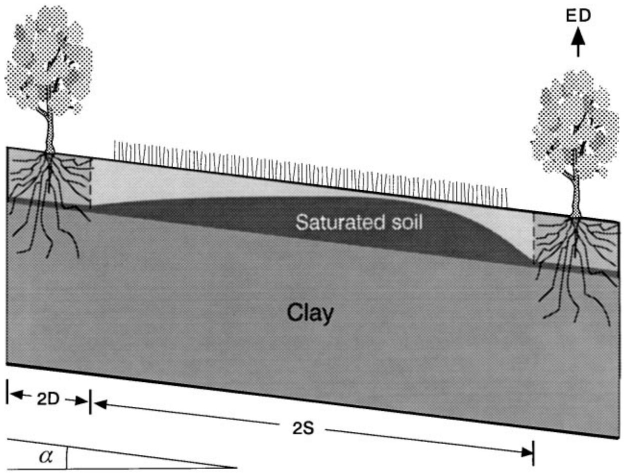

Fig. 4. Schematic diagram showing the shape of the perched watertable between lines of trees on sloping land. Symbols are described in Table 1 and in the text.

perched watertable breaks out at the surface. Similarly, h, the depth of the saturated zone through which water can move to the trees, tends towards zero as $d - M$ increases. Thus the ability of the trees to induce lateral movement, based on Eq. (1), will be minimal.

With $d - M$ and h constrained by the depth of the top soil, slope becomes a major factor in the spacing between tree belts. On sloping land, the highest point of the perched watertable is displaced downslope from the midpoint (Fig. 4). The spacing between belts of trees on a slope is more complex than the case for flat land above and can be approximated using the drain spacing theory of Wooding and Chapman (1996) as detailed in the Appendix (Eq. (A.2)).

2.4. Salt accumulation in the root zone

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. This is not a problem for perched systems, which tend to be fresh, but can be a serious problem when the groundwater is even moderately saline. The time it takes for the capillary fringe above the watertable to reach the maximum salinity after which the tree can no longer extract water is approximated by:

$$t_{\mathrm{m}} = \frac{l\bar{\theta}}{E}\left(\frac{C_{\mathrm{m}}}{C_{\mathrm{o}}} - 1\right) \tag{2}$$

where t_{m} is the time in years to reach the maximum concentration, l the height of the capillary fringe above the watertable where salt can be stored, E the water use of the tree from the watertable (mm year^{-1}), $\bar{\theta}$ the average water content of the fringe, C_{m} the maximum salt concentration (dS m^{-1}), and C_{o} the salt concentration in the groundwater (dS $^{-1}$) (see Appendix for derivation). The equation is based on the assumptions that all

Table 1
Explanation of abbreviations used in the text

Symbol	Explanation	Dimensions
S	Half spacing between two belts of trees	m
D	Half width of the belt of trees	m
K	Saturated conductivity of the soil	mm day^{-1}
J	Annual drainage below the crops	mm year^{-1}
J'	Excess of rainfall over evapotranspiration (for perched system)	mm month^{-1}
d	Depth to the watertable below the trees	m
M	Depth of the watertable at the midpoint between the tree belts	m
h	Height of the watertable above some impermeable layer	m
l	Height of the capillary fringe above the watertable	m
E	Annual water use of the trees from the watertable	mm year^{-1}
α	Is the angle of the slope to the horizontal	degrees
C_m	The maximum salt concentration in the capillary fringe	dS m^{-1}
C_0	Salt concentration in the groundwater	dS m^{-1}

the salt is stored in the capillary fringe and that there are no mechanisms occurring which move salt out of the capillary fringe, such as leaching or diffusion. This approach is a simplification of the one used by Thorburn et al. (1995), in that the rate of extraction and height of the fringe above the watertable are assumed constant with time.

A summary of symbols used and their explanation is given in Table 1.

3. Results

3.1. Case 1 – The watertable is below the depth of crop and trees roots

In order to use Eq. (A.1) in the Appendix, we assume that there is a constant flux (light rain) on the soil surface. If the tree does not take up any water, and there is no soil evaporation, water will be continuously moving through the soil to a notional deep watertable, and the water content of all zones will be uniformly wet, θ_{wet}. Under a low transpiration rate, the region of significantly reduced water content may be restricted to a small volume of the root system near the trunk, and some water will flow through the root system to the deep watertable. As the transpiration rate increases, the zone of reduced water content will become larger, and there may be competition between trees and crops. If we assume that the tree root zone is an infinite sink, and removes all the water arriving at the soil surface within r_r of Fig. 2, and so remains completely dry, θ_{dry}, we can calculate the dimensions of the capture zone. It is this extreme case we wish to investigate, since it gives the maximum influence that a tree can have beyond the physical region occupied by its own roots, i.e. the area of the paddock over which a tree could potentially reduce drainage without competing with crops.

The absolute maximum width of the capture zone depends on the depth of the tree roots and texture of the soil. The property of the soil which determines the size of the capture zone is the capillary length scale. The capillary length, l, is approximately the

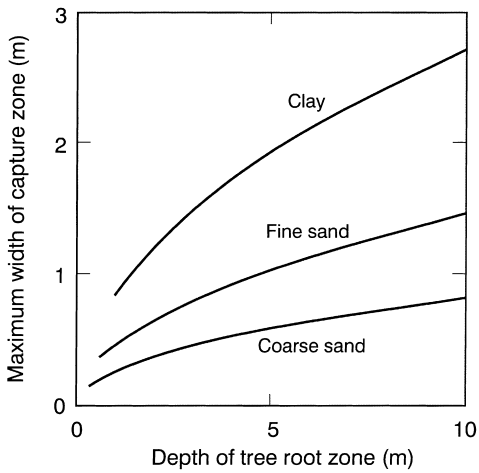

Fig. 5. Maximum width of the capture zone as a function of tree root zone depth and soil texture.

average distance that water will rise in soil until the capillary force is balanced by the gravitational force. In a coarse sand, l has a value of around 0.1 m and the capture zone would be less than 1 m wide. Clay soils have a value l of 1 m or more (White and Sully, 1987), and the capture zone could extend almost 3 m beyond the physical limit of the tree roots (Fig. 5).

3.2. Case 2 - The watertable is within the rooting depth of the tree but not the crop

Fig. 6 shows the half spacing between belts of trees as a function of soil type, drainage below the crop roots, and the rooting depth of the trees. Saturated hydraulic conductivities for a deep sand (1000 mm day^{-1}), well structured (250 mm day^{-1}), moderately structured (5 mm day^{-1}) and poorly structured (1 mm day^{-1}) subsoils were taken from Greacen and Williams (1983) and Geeves et al. (1995). These values correspond to vertical measurements; we may expect vertical conductivities to be higher than lateral conductivities because of cracks and biopores (unless there are sand lenses with high lateral transmissivity) and thus we have selected K values at the low end of the range to produce conservative estimates of belt spacing. M is set at the maximum rooting depth of the crop, since it is our ultimate objective to halt the watertable at this level, and for the purposes of Fig. 6 we have set M at 2 m. The value of d is the depth that the tree can lower the watertable to, and so $(d - M)$ represents the hydraulic head between the tree belt and the centre of the cropped alley. We consider a maximum value of d as the bottom of the root zone of mature trees. Maximum tree rooting depth of 2.5, 3 and 6 m were chosen, giving the difference in hydraulic head $(d - M)$ between the centre of the cropped field and the tree line of 0.5, 1 and 4 m, respectively.

The distance between tree belts increases as the saturated conductivity of the subsoil increases and annual drainage below the crop root zone decreases. For example, the half

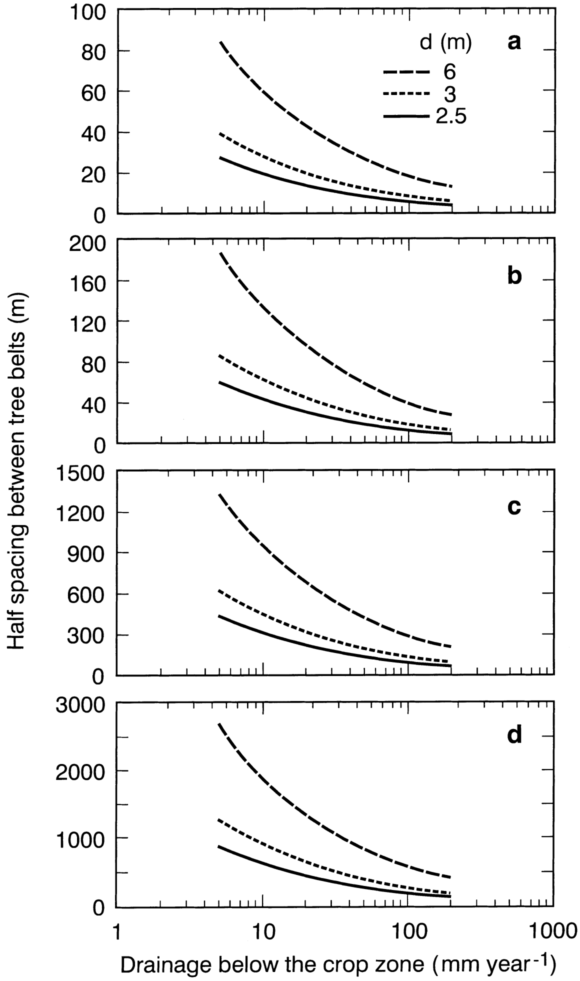

Fig. 6. Maximum half spacing between belts of trees required to stabilise the watertable at a minimum of 2 m below the soil surface. Half spacing is given as a function of annual deep drainage below a crop, when the belt of trees has caused a local drop in the watertable, *d*, to 2.5, 3 and 6 m below the soil surface for (a) poorly structured subsoil $K_{sat} = 1$ mm day^{-1}, (b) moderately structured subsoil $K_{sat} = 5$ mm day^{-1}, (c) well structured subsoil $K_{sat} = 250$ mm day^{-1}, (d) deep sand $K_{sat} = 1000$ mm day^{-1}. The depth of the saturated layer, *h*, is 10 m.

spacing between tree belts is 12 m for a poorly structured subsoil, 28 m for a moderately structured subsoil, 196 m for a well structured subsoil and 392 m for a deep sand when $h = 10$ m, $d = 3$ m, and $J = 50$ mm year^{-1} (Fig. 6(a)–(d)). The importance of the depth of the saturated layer, *h*, which represents the plane through which water can move from the cropped zone to the tree belt, it shown in Fig. 7 for K_{sat} of 1 and 5 mm day^{-1}, $J = 50$ mm year^{-1} and $d = 3$ m. The potential distance between tree belts increases rapidly up to approximately $h = 10$, and more slowly thereafter.

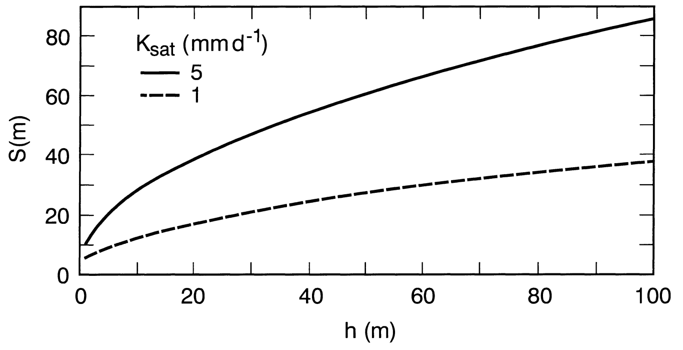

Fig. 7. Effect of depth of the saturated zone, *h*, on half spacing of tree belts, *S*, for subsoil saturated conductivities of 1 mm day^{-1} and 5 mm day^{-1}. Annual drainage, *J*, was set at 50 mm year^{-1} and tree rooting depth, *d* at 3 m.

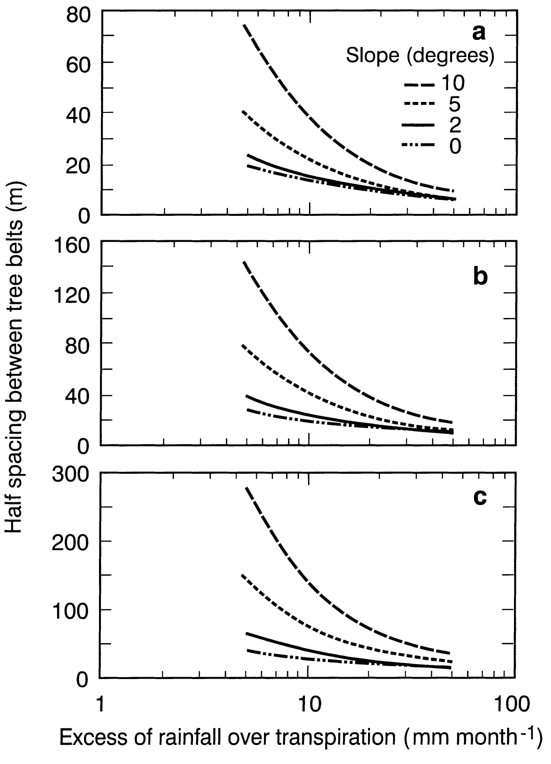

Fig. 8. Maximum half spacing between lines of trees required to stabilise a perched watertable as a function of excess monthly rainfall, at slopes of 0 degrees, 2 degrees, 5 degrees and 10 degrees for (a) silty clay loam top soil $K_{sat} = 250$ mm day^{-1}, (b) Sandy loam $K_{sat} = 500$ mm day^{-1}, (c) sand $K_{sat} = 1000$ mm day^{-1}.

3.3. Case 3 – Seasonal watertable is within the rooting depth of the crop and tree

For the case of a seasonally perched watertable, the drainage term J' is considered to be rainfall minus evapotranspiration minus leakage through the slowly permeable B horizon, calculated on a monthly basis. This represents the excess water which would have drained below the root zone if the B horizon were sufficiently permeable. In the case of a perched watertable, water moves laterally through the A horizon and saturated conductivity values of 1000, 500 and 250 mm day^{-1} were chosen as characteristic of the wheat belt, representing sandy, sandy loam and fine sandy clay loam A horizons (Geeves et al., 1995). The results clearly show that the tree belt spacing would have to be much closer in the perched watertable situation where h is low, and the value of $d - M$ is restricted by the depth of the A horizon (Fig. 8). Moreover, the effect of slope is only really significant once it reaches around 5°. A 10° slope increases the distance between tree belts considerably, but would normally be considered too steep for cropping.

3.4. Salt accumulation in the root zone

There is a dilemma associated with tree water use from the watertable. Unless there is some process to remove salt, the concentration of salt in the tree root zone will reduce, and finally halt uptake, from the groundwater. The time constant, t_m, calculated from Eq. (2), gives the approximate time that it would take for the capillary fringe to reach the maximum salinity. Hence, we can obtain the frequency of flushing events that would be

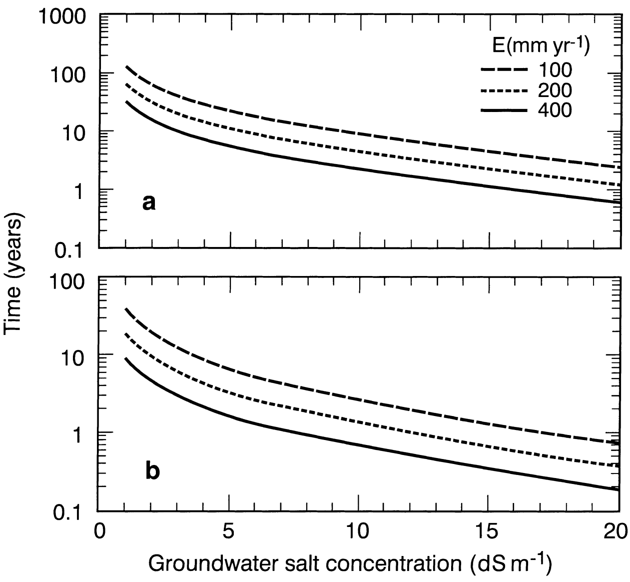

Fig. 9. The time in years to reach a salt concentration of 40 dS m^{-1} in the tree root zone as a function of groundwater salinity when the trees are using 100 mm year^{-1}, 200 mm year^{-1}, or 400 mm year^{-1} of water from a capillary fringe of height (a) 1 m and (b) 0.3 m.

required to allow a tree to continue to draw water from the watertable. In some cases the salt content in the capillary fringe may be reduced by seasonal oscillations in the height of the watertable. In other cases a period of well above average rainfall would flush the capillary fringe.

Examples of the time constant as a function of groundwater salt concentration, water use from the watertable and depth of the capillary fringe are shown in Fig. 9. In these examples the maximum salt concentration was taken as 40 dS m^{-1} and the water content of the fringe was 0.4 cm cm^{-3}. If we consider that a period of above average rainfall would flush the fringe once every 5 years, then the highest groundwater salt concentration would be 17, 11 and 6 dS m^{-1} for annual extractions of 100, 200 or 400 mm water $year^{-1}$, respectively from a 1 m high capillary fringe. If the fringe was 0.3 m high, as in the case of lighter textured soils, or salt accumulated only in the upper portion of a larger capillary fringe, then the highest groundwater salt concentration would be 7, 4 and 2 dS m^{-1} for annual extractions of 100, 200 or 400 mm $year^{-1}$ of groundwater, respectively.

4. Discussion

The output of the analytical expressions establishes the importance of tree–watertable interactions for a revegetation strategy at paddock scale. Where a rising watertable is still below the maximum rooting depth of trees, the trees would need to be scattered widely over the paddock so that they could intercept water before it passed below their roots. Where trees can access the groundwater, spacings of hundreds of metres between tree belts are possible, except for subsoils of low conductivity. Wide spacing between tree belts gives the most favourable balance between control of deep drainage and tree/crop competition. The planting of tree belts to manage shallow perched watertables on cropping land is likely to be of limited value. Whereas perched water will be of low salinity, deeper groundwater will often contain salt that will accumulate in the tree root zone and restrict its availability to trees.

Eucalypt roots have been found up to 20 m from the trunk of individual trees (Zohar, 1985), and thus outer edges of the root circles of adjacent trees could be contiguous at a density of less than six trees ha^{-1}. Although a near network of roots at the surface could be established over an entire field at relatively low tree densities, the roots would need to be deep to cope with the stochastic nature of rainfall and to avoid excessive competition with crops. Many tree species have a dimorphic root system with a relatively high density of roots in the topsoil (for capture of nutrients) from which a sparser network of sinker roots develop (Dodd et al., 1984; Dawson and Pate, 1996). Given the higher density of tree roots in the topsoil, and the propensity for trees and crops to preferentially dry the soil profile from the top down (Gardner, 1991), it is likely that trees and crops will be in competition for water.

Competition can be modified if the trees and crops have temporal complementarity in their demand for water. For example, most crops in Western Australia are not planted till after the autumn break and sowing is often followed by a period when rainfall exceeds evapotranspiration. Competition is not likely to occur until the evapotranspiration exceeds rainfall in spring or early summer. Thus potential competition may only be of concern for 2 months of the year. This is not so in eastern Australia where many crops depend on stored water carried over from one season to the next. Trees depleting the store of soil water over summer are likely to affect the following crops. Competition by trees may be offset by their capacity to improve the microclimate of the crops and pastures (Kort, 1988) or the physical conditions of the soil (Joffre and Rambal, 1988). If the trees are managed for timber, and the value of wood per unit of water transpired is similar to that of the crop, competition is no longer an issue.

The role of the capture zone in extending the influence of the tree can be significant when there are a large number of trees or shrubs with deep roots but restricted lateral spread of roots. For example, if we want to cover one-half of a field with tree roots and the tree root radius is 5 m, we would require 64 trees ha^{-1}. However, to cover the same area with tree roots when the root radius is 20 m we would require only four trees ha^{-1}. Now if each of the 64 trees with 5 m root radii had a capture zone of 2 m extending beyond the physical extent of their roots, then the area from which they could potentially protect the field from deep drainage increases from 50% to 98% of the field. This compares with an increase in the protected area from 50% to 64% in the case of four trees with large lateral spread. However, the length of the interface between the tree and crop, which is a measure of tree/crop competition, increases from 500 to 2000 m when moving from the four large trees to the 64 small trees. It must be noted that the capture zone will only be operative when the trees have substantially dried their root zones to considerable depth, and therefore will not be effective during extended wet periods. Moreover, the radius of the extraction pattern at depth would be much lower than that at the surface for dimorphic root systems.

In the second case, where trees could access the watertable, wide spacings of tree belts are possible, except in the case of soil with very low conductivity. If we consider the minimum spacing between tree belts in a cropping situation to be 40 m, this condition could be satisfied for drainage values less than 100 mm $year^{-1}$ for soils with a saturated conductivity greater than 5 mm day^{-1}, for $d - M = 1$ m and $h = 10$. In fact for the well structured clay subsoils and deep sands, the alleys between tree belts could be 400 m or more wide. Whereas, wide spacings between trees belts are good for minimising competition, correspondingly wide belts of trees are needed to keep the watertable just below the root zone of the crop. For the level of the watertable in the centre of the cropped alley to remain constant, the input of water to the watertable J from the cropped field must be balanced by the output which is due to transpiration from belts of trees:

$$JS = ED$$

where E is the annual water use by trees from the watertable (assuming the trees use all the incident rain so that there is no recharge within the tree belt) and D the half-width of the tree belt (Fig. 3). The half-width of tree belt is thus given by:

$$D = JS/E$$

Thorburn (1996) reviewed studies of water uptake by trees from slightly saline (5 dS m^{-1}) to very saline (50 dS m^{-1}) watertables and recorded maximum annual uptake rates of 440 mm $year^{-1}$. If we take this value as an upper limit, then the width of a tree belt would need to be 45 m for a belt spacing of 400 m and annual drainage of 0.05 m year^{-1}. It is tempting to see this example as an ideal solution to the problem of sustainable cropping, with large areas of land protected by belts of trees wide enough to be managed as conventional plantations. However, the problem of salt accumulation means that this strategy may be limited to regions with moderate to low groundwater salinity. Once tree water use from the groundwater drops to below 100 mm year^{-1}, tree belt widths would become unreasonably large for cropping or pasture based farming systems.

It is more difficult to satisfy the criterion for a minimum spacing between tree belts of 40 m in the case of a seasonally perched watertable within the tree and crop root zones. If rainfall exceeds evapotranspiration by 40 mm month^{-1}, then only the sandy topsoil ($K_{sat} = 1000$ mm day^{-1}) with slopes exceeding 5° would allow a 40 m wide cropped alley. A more important issue is the problem of maintaining the gradient between the tree belt and cropped part of the paddock. The depletion in the A horizon underneath the tree belt is low compared to the potential amount of water arriving from the cropped part of the field. Although the trees would have a much higher leaf area than the crops in mid winter, their water use would be limited by radiant energy. In a perched watertable situation, where the surface soils of the cropped land is wet, both treed and cropped areas are likely to be losing water at the maximum potential rate. However, it is possible that the B horizon may be more permeable under the tree belt than the cropped area because of preferential pathways made by tree roots. If this were so the B horizon beneath the trees would act as an additional storage for water which could be exploited during the summer.

Published experimental information to support the output of the analytical models described above is scarce. Kienzle and Schulze (1992) also used a Dupuit–Forchheimer approach to model the depression in groundwater below trees, and found a good fit between observed and simulated watertable fluctuations around a Eucalypt plantation in Northern Zululand, South Africa. Heuperman (1995) reported that a plantation on a clay soil in the Kyabram region of Victoria dropped the local watertable to 5 m, when the watertable depth in the surrounding irrigated pastures was 1 m. The drawdown effect of the plantation could be observed up to a distance of 40–90 m from the plantation edge, consistent with results for a low permeable clay soil such as in Fig. 6(a). In an experiment with 30 m wide cropped alleys between 2 m wide belts of tagasaste on a deep sand (Lefroy and Stirzaker, 1997), the tagasaste used water from a watertable 5 m below the surface, but there was no local drawdown in the watertable level under the tree line. This is what would be expected for a narrow tree belt on a soil with high saturated conductivity.

There is less experimental data to support or refute the calculations on capture zone dimension (Fig. 5) or the efficacy of trees in the presence of perched watertables. Data from a lucerne/vegetable alley cropping experiment of Stirzaker (1996) showed the importance of the capture zone in managing recharge in an irrigated situation. Lateral growth of lucerne roots was minimal, but the subsoil beneath alley cropped vegetable rows (0.6–1.8 m) contained 20–65 mm less water than subsoils beneath a monocrop of vegetables, even after heavy rainfall events sufficient to saturate the subsoils. Presumably the water draining below the vegetable roots was drawn sideways under the influence of the dry subsoil beneath the lucerne. In Esperance, Western Australia, a perched watertable was about 20 cm lower at 8 m from a tree line compared to the open paddock for 4 months during winter (David Hall, personal communication, 1997).

Despite the lack of experimental information at this stage, analytical expressions are useful for quickly assessing a number of different tree planting designs, particularly where input data are either hard to get or extremely variable. For example, Greenwood et al. (1992) found that saturated conductivities at their site varied by over three orders of magnitude over short distances. With such uncertainty surrounding key parameters, our approach to designing tree density and location needs to be suitably flexible. The long time steps (months/years) used in our calculations are also valid, as annual drainage is extremely variable between years but the width of the tree belt is fixed for the rotation time of the plantation.

5. Conclusion

The critical issue in balancing deep drainage with competition is to understand the degree to which water moves vertically and horizontally in the zone of soil accessible to tree roots. Where watertables are below tree roots, a wide distribution of trees across the landscape is required. This may be acceptable on pasture lands, but not on high productivity cropping lands, unless the trees have an economic value to offset the effects of competition. Trees using water from the watertable can induce substantial horizontal movement of water, so competition can be minimised. However, the problem of salt build up in the tree root zone means that the salinity of the ground water needs to be low, or uptake rate for the watertable low, unless there are frequent flushing events. The planting of tree belts to manage perched watertables in unlikely to be of much value unless slope exceeds 5°. We emphasise that information on regional and catchment scale hydrologic processes is vital before planning a local revegetation strategy, as the benefits of paddock scale plantings can be overwhelmed by these larger scale effects.

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Appendix

A.1. Case 1 – The watertable is below the depth of crop and tree roots

We assume that water is applied at a steady uniform rate to the horizontal soil surface at $z = 0$, and flows downwards through the soil, with x, y and z Cartesian coordinates, and that z is measured positive downwards. Some of the water is taken up by the plant–root system, and the rest drains downwards to the watertable. We assume that the root system and the flow are axisymmetric, so that the soil water content θ is a function only of depth

z and radial coordinate r,

$$\theta = \theta(r, z), \ r^2 = x^2 + y^2$$

We assume a homogeneous 'Gardner soil' in which the unsaturated hydraulic conductivity $K(\psi)$ has an exponential dependence on moisture potential ψ, and used a scaled Kirchhoff potential Θ, which is a monotonic function of soil water content θ. The Kirchhoff potential method is used as a mathematical simplification of Darcy's law (Gardner, 1958). For a 'Gardner soil', the soil water flow equation is linear, and so analytical solutions can be found for many important flow systems. For a real soil with a more general dependence of unsaturated hydraulic conductivity on moisture potential, these analytical solutions give reasonable approximations for the distribution of the Kirchhoff potential. The analytical solutions are expressed in terms of a characteristic capillary length parameter which is used to scale the physical dimensions. For a given soil type, the capillary length l is defined by:

$$l = (1/K_s) \int_{-\infty}^{0} K(\psi) \mathrm{d}\psi$$

where K_s is the saturated hydraulic conductivity of the soil, $K_s = K(0)$.

The sink strength is expressed in terms of the radius r_c of the catchment area on the soil surface. The analytical solutions for the scaled Kirchhoff potential Θ and the scaled stream function F are given in Eq. (A.1). The stream function is the path that a drop of water will follow under the forces of gravity and capillarity.

$$\Theta(r, z) = 1 - \frac{r_c^2}{4l^2} \left[\frac{2l}{\rho} \exp\left(\frac{z - \rho}{2l}\right) - \exp\left(\frac{z}{l}\right) E_1\left(\frac{z + \rho}{2l}\right) \right] \tag{A.1}$$

$$F(r, z) = \frac{r^2}{r_c^2} + \frac{z}{\rho} \exp\left(\frac{z - \rho}{2l}\right)$$

where

$$p^2 = r^2 + z^2 = x^2 + y^2 + z^2,$$

and

$$E_1(w) \equiv \int_w^{\infty} (1/u) \exp(-u) \mathrm{d}u$$

is the exponential integral function (Gautschi and Cahill, 1965). From the form of the above formulae, it is evident that Θ and F can be considered as functions of the scaled distances $Z = z/l$ and $R = r/l$ and the scaled catchment radius $R_c = r_c/l$.

By definition, lines on which $\Theta(R,Z)$ is constant are also lines on which water content θ is constant. The contour $\Theta = 0$ corresponds to the water content $\theta = \theta_0$, and is the boundary of the (completely dry) root zone. The root zone is defined as the region in which Θ is negative. This contour meets the soil surface at $r = r_c$.

By definition, all the water applied to the surface on the circular area $r \leq r_c$ flows into the sink, and all the water applied outside this radius flows down to the watertable. The flow lines through the soil are contours of the stream function $F(r,z)$, which has been scaled so that the streamline starting on the surface at $r = r_c$ corresponds to the contour $F = 1$. The catchment zone is the region in which $F < 1$, which is on the upper side of the boundary. The dividing streamline approaches a stagnation point on the axis $r = 0$ at $z = z_c$, and splits into two, since $F = 1$ everywhere on the axis. For different values of the parameter R_c, we generate a family of catchment zones of different sizes and shapes. As the scaled catchment radius R_c increases, so does the scaled catchment depth $Z_c = z_c/l$, and the catchment volume increases. At the soil surface, the width of the capture zone is $r_c - r_r$.

A.2. Case 3 – Seasonal watertable is within the rotting depth of the crop and tree

The spacing between belts of trees on a slope can be found using the drain spacing theory of Wooding and Chapman (1996) when $\lambda < 1$ and is:

$$S = \frac{2(d-M) \mid 1+\kappa - H_m/X_m \mid^{(1+\kappa)/2\kappa}}{A(1-p)\lambda \tan\alpha \mid 1-\kappa - H_m/X_m \mid^{(1-\kappa)/2\kappa}} \tag{A.2}$$

where the symbols will be defined below.

h_m is the maximum height of the watertable above the impermeable base, α the angle of the slope to the horizontal, p the ratio of the excess water, J', (define as excess of rainfall over evapotranspiration) to the saturated hydraulic conductivity of the soil and is given by:

$$p = \frac{J}{K}$$

λ is a parameter defined as:

$$\lambda = \frac{4p}{(1-p)^2 \tan^2\alpha}$$

κ is a parameter defined as:

$$\kappa = \sqrt{1-\lambda}$$

H_m is the non-dimensional maximum head and defined as:

$$H_m = \frac{d-M}{(1-p)S\tan\alpha}$$

X_m is the non-dimensional distance at which H_m occurs and is defined as:

$$X_m = \frac{x_m}{2S}$$

A is a scaling parameter dependent on the scale of the system and can be determined using

$$A = \frac{\mid 1+\kappa \mid^{(1+\kappa)/2x}}{\mid 1-\kappa \mid^{(1-\kappa)/2x}}$$

Eq. (A.1) is only valid where all the water below a belt of trees moves to the next tree belt downslope.

A.3. Time to salt out the root zone

A tree using water from the watertable as in Fig. 3 will import salt into the capillary fringe above the watertable. C_o is the initial concentration of salt in the capillary fringe, l, and the average water content of the fringe, $\bar{\theta}$. If the half-width of the tree belt is D, then the amount of salt initially present in the capillary fringe A_i is:

$$A_i = lDC_o\bar{\theta} \tag{A.3}$$

For a given water use rate from the watertable, E, the amount of salt imported into the capillary fringe with time, $A(t)$ is:

$$A(t) = tEDC_o + A_i \tag{A.4}$$

where t is time. The concentration of salt in the capillary fringe with time, $C(t)$ is then:

$$C(t) = \frac{A(t)}{lD\bar{\theta}} \tag{A.5}$$

The time taken for the capillary fringe to reach a maximum salt concentration, t_m, can be found by substituting Eq. (A.4) into Eq. (A.5) and solving for t at t_m to give:

$$t_m = \frac{l\bar{\theta}}{E}\left(\frac{C_m}{C_o} - 1\right) \tag{A.6}$$

where C_m is the maximum salt concentration at which the tree can extract no further water.

References

Bari, M.A., Schofield, N.J., 1992. Lowering of a shallow, saline watertable by extensive eucalypt reforestation. J. Hydrol. 133, 273–291.

Bell, R.W., Schofield, N.J., Bari, M.A., 1990. Groundwater response to reforestation in the Darling Range of Western Australia. J. Hydrol. 115, 297–317.

Dawson, T.E., Pate, J.S., 1996. Seasonal water uptake and movement in root systems of Australian phraeatophytic plants of dimorphic root morphology: A stable isotope investigation. Oecology 107, 13–20.

Dodd, J., Heddle, E.M., Pate, J.S., Dixon, K.W., 1984. Rooting patterns of sandplain plants and their functional significance. In: Pate, J.S., Beard, J.S. (Eds.), Kwongan: Plant Life of The Sandplain: Biology of a South-west Australian Shrubland Ecosystem. University of Western Australia Press, Nedlands, WA, pp. 146–177.

Evans, W.R., Kellett, J.R., 1989. The hydrogeology of the Murray Basin, southeastern Australia. Bur. Miner. Resour. J. Aust. Goel. Geophys. 11, 147–166.

Farrington, P., Salama, R.B., 1996. Controlling dryland salinity by planting trees in the best hydrogeological setting. Land Degrad. Develop. 7, 183–204.

Gardner, W.R., 1958. Some steady-state solutions of the unsaturated moisture flow equation with application to evaporation from a watertable. Soil Sci. 85, 228–232.

Gardner, W.R., 1991. Modeling water uptake by roots. Irrig. Sci. 12, 109–114.

Gautschi, W., Cahill, W.F., 1965. Exponential integral and related functions. In: Abramowitz, M., Stegun, I.A. (Eds.), Handbook of Mathematical Functions. Dover, New York, pp. 227–251.

Geeves, G.W., Cresswell, H.P., Murphy, B.W., Gessler, P.E., Chartres, C.J., Little, I.P., Bowman, G.M., 1995. The physical, chemical and morphological properties of soils in the wheat-belt of southern NSW and northern Victoria. NSW Department of Conservation and Land management/CSIRO Aust. Division of soils Occasional report, p. 178.

George, R.J., McFarlane, D.J., Nulsen, R.A., 1997. Salinity threatens the viability of agriculture and ecosystems in Western Australia. Hydrogeol. J. 5, 6–21.

Greacen, E.L., Williams, J., 1983. Physical properties and water relations. In: Soils: An Australian Viewpoint, CSIRO Division of Soils, CSIRO/Academic Press, London, pp. 499–530.

Greenwood, E.A.N., Milligan, A., Biddiscombe, E.F., Rogers, A.L., Beresford, J.D., Watson, G.D., Wright, K.D., 1992. Hydrologic and salinity changes associated with tree plantations in a saline agricultural catchment in southwestern Australia. Agric. Water Manage. 22, 307–323.

Heuperman, A.F., 1995. Salt and water dynamics beneath a tree plantation growing on a shallow watertable. Department of Agriculture, Energy and Minerals Victoria, Institute of Sustainable Irrigated Agriculture, Tatura, p. 61.

Joffre, R., Rambal, S., 1988. Soil water improvement by trees in the rangelands of southern Spain. Ecological Plant. 9, 405–422.

Kienzle, S.W., Schulze, R.E., 1992. A simulation model to assess the effect of afforestation on ground-water resources in deep sandy soils. Water SA 18, 265–272.

Kirkham, D., 1967. Explanation of paradoxes in Dupuit–Forchheimer seepage theory. Water Resour. Res. 3, 609–622.

Kort, J., 1988. Benefits of windbreaks to field and forage crops. Agric. Ecos. Env. 22/23, 165–190.

Lefroy, E.C., Stirzaker, R.J., 1997. Design criteria for alley cropping in Southern Australia. In: Agroforestry for sustainable land-use – fundamental research and modelling, Montpellier, France, pp. 311–314.

Ong, C.K., Black, C.R., Marshall, F.M., Corlett, J.E., 1996. Principles of resource capture and utilization of light and water. In: Ong, C.K., Huxley, P. (Eds.), Tree–crop interactions: A physiological approach. CAB International, Wallingford, UK, pp. 73–158.

Schofield, N.J., 1992. Tree planting for dryland salinity control in Australia. Agrofor. Syst. 20, 1–23.

Stirzaker R.J., 1996. Lucerne/vegetable alley cropping to reduce leaching. Proc. of the 8th Australian Agronomy conference, The Australian Society of Agronomy, Victoria, pp. 522–525.

Thorburn, P.J., Walker, G.R., Jolly, I.D., 1995. Uptake of saline groundwater by plants: An analytical model for semi-arid and arid areas. Plant and Soil 175, 1–11.

Thorburn, P.J., 1996. Can shallow water tables be controlled by the revegetation of saline lands? Aust. J. Soil and Water Conserve. 9, 45–50.

Wooding, R.A., Chapman, T.G., 1996. Groundwater flow over a sloping impermeable layer: Application of the Dupuit–Forchheimer assumption. J. Geophys. Res. 71, 2895–2902.

White, I., Sully, M.J., 1987. Macroscopic and microscopic capillary length and time scales from field infiltration. Water Resour. Res. 23, 1514–1522.

Young, A., 1987. The environmental basis of Agroforestry. In: Reifsnyder, W.E., Darnhofer, T.O. (Eds.), Meteorology and Agroforestry, ICRAF, Nairobi, 29–48.

Zohar, Y., 1985. Root distribution of a eucalypt shelterbelt. For. Ecol. Manage. 12, 305–307.