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An index for quantifying the trade-off between drainage and productivity in tree–crop mixtures

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Abstract

The introduction of deep-rooted perennial species into catchments dominated by annual crops and pastures forms part of the strategy for managing dryland salinity in south Australia. This paper provides a methodology for determining whether it is better to mix trees and crops (agroforestry), or segregate them into plantations and monocrops, when attempting to achieve specified drainage and productivity targets. We introduce an index that quantifies the complementarity or competition for resources between the trees and crops. Data required to calculate this index include crop yield with distance from the tree belt and leaf area of the tree belt compared to the leaf area of a native stand. The method allows for a simple assessment of the most promising tree/crop mixtures. Such an assessment is needed because of the wide range of possible tree–crop–soil–climate combinations and the hydrological complexity of the tree/crop interface. Examples are given which make cases for either separating or mixing trees and crops. We predict that the success of a tree/crop mixture becomes less likely with declining crop season rainfall and increasing seasonal variability and more likely when the tree products have a direct economic benefit.

Keywords: Competition; Complementarity; Re-charge; Salinity; Tree belts

1. Introduction

Belts of trees in pasture and cropping land provide shelter and improve the amenity and nature conservation value of the farm. In south Australia, there is the additional objective of reducing drainage below the root zone of crops and pastures to address rising water tables leading to water logging and dryland salinity. Mixing trees and crops is likely to lead to greater total resource capture due to the differing phenology and root architecture

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of the two components, but the critical question is how water is partitioned between tree and crop. Trees in belts are likely to grow faster and have a greater impact on drainage than their counterparts in a plantation because of the extra resources available in the neighbouring cropped area. However, the trees compete with crops for light, water and nutrients.

There have been many attempts to work out whether, for a particular objective, it is better to mix species or to keep them separate. The land equivalent ratio (Willey, 1979) is the ratio of the area under sole crops to the area under mixed cropping that gives the same total yield, and is applicable where species are all grown for their productive value. In other cases only one species is grown for its productive value with the role of the second species being to provide a better growing environment for the crop. Ong (1996) introduced the tree crop interaction equation to quantify the consequences of mixing species, where trees were introduced to control erosion and to provide nutrients to crops by return of their prunings. van Noordwijk et al. (1997) examined the question of integrating or segregating species and land-use systems where there are dual objectives of agricultural productivity and conservation. Stirzaker et al. (1999), and Lefroy and Stirzaker (1999) examined the conditions under which trees would be best integrated, segregated or rotated with crops to minimise drainage, and hence secondary salinity in south Australia. This paper builds upon the latter, and presents a method for quantifying the degree of complementarity or competition that exists when trees and crops are mixed to meet both a drainage and productivity target. If we can demonstrate complementarity, drainage and productivity targets would be best met by tree/crop mixtures. If competition dominates, it would be better for trees to remain in plantations.

2. Theory

We assume that drainage under crops is uniform and that the water use of a complete tree canopy approximates annual rainfall for the medium and low rainfall areas of south Australia (<800 mm annual rainfall).

Annual drainage, D, in a cropped landscape is equal to:

$$D = P - E_{\mathrm{crop}} \tag{1}$$

where P is equal to annual rainfall and E_{crop} is the annual evapotranspiration from cropped land.

Drainage in a landscape partially occupied by trees, D_{t}, is:

$$D_{\mathrm{t}} = P - [aE_{\mathrm{tree}} + (1-a)E_{\mathrm{crop}}] \tag{2}$$

where a is the proportion of the land covered by trees and $E_{\mathrm{tree}} = P$ where trees are in plantations $E_{\mathrm{tree}} > P$ in the case of tree belts.

Combining Eqs. (1) and (2), the relative drainage under a landscape occupied by a belt of trees is:

$$\frac{D_{\mathrm{t}}}{D} = \frac{P - [aE_{\mathrm{tree}} + (1-a)E_{\mathrm{crop}}]}{P - E_{\mathrm{crop}}} \tag{3}$$

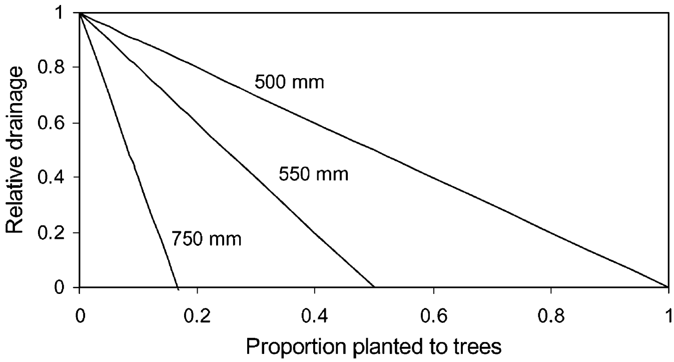

Fig. 1. The relative drainage as a function of the proportion of a catchment planted to trees when trees use 500, 550, and 750 mm per year (for annual rainfall = 500 mm per year, and annual water use of cropping = 450 mm per year; relative drainage in cleared state = 1).

which can be simplified to:

$$\frac{D_t}{D} = 1 - \frac{a(E_{\text{tree}} - E_{\text{crop}})}{P - E_{\text{crop}}} \tag{4}$$

Eq. (4) shows that for any drainage reduction target D_t/D, the required area under trees decreases as evapotranspiration from the tree belt, E_{tree}, increases. The example in Fig. 1 shows the relationship between the proportion of land planted to tree belts and the relative drainage calculated by Eq. (4) for a case where annual rainfall is 500 mm per year and annual water use under cropping is 450 mm per year. If we wanted to cut drainage by half ($D_t/D = 0.5$) and planted trees in a plantation arrangement, we would need to plant half the area to trees. However, if the tree belts used 550 or 750 mm of water, the respective proportion under trees would only need to be 0.25 and 0.08. Clearly the consumption of water in excess of rainfall by tree belts has a large effect on reducing the area of land that needs to be planted to trees.

Fig. 1 assumes that all the water used by the trees in excess of rainfall was water unused by the crop. This is the case of total complementarity of resource use. Total competition is also possible, where the extra water used by the tree is completely at the expense of the crop and that drainage remains unchanged. To make a case for tree belts, we must be able to demonstrate that the complementarity of resource use, outweighs the competition.

To demonstrate complementarity it must be quantified, and the objective of this paper is to find the simplest and most robust method of doing so. Walker and Dowling (1991) summarise the competition between a tree and the surrounding understorey by means of an 'intensity–domain' diagram (Fig. 2). The vertical axis represents the intensity of the tree as a sink for resources while the horizontal axis represents the zone occupied by the tree. In the simplest case we can assume that the tree has exclusive access to resources in the zone occupied by its own canopy. If the soil beneath the canopy cannot supply resources at a sufficient rate, then the tree will seek resources from its domain in the crop, i.e. the distance into the crop permeated by tree roots. Whereas the domain may be

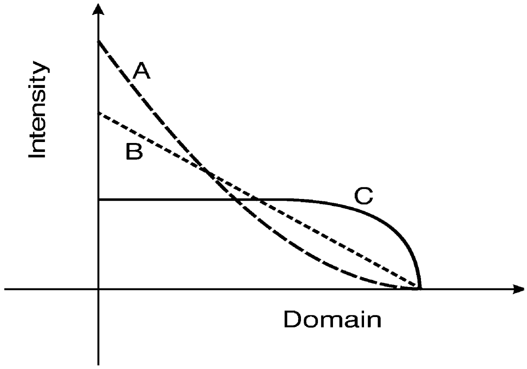

Fig. 2. The intensity (amount) of water demanded by a tree as a function of the distance from the tree (domain). Example A shows the intensity of water extraction highest next to the tree and falling exponentially with distance. Example B shows a linear decline and example C shows a constant intensity with distance from the tree belt (redrawn from Walker and Dowling, 1991).

relatively easy to quantify (the extent of the root system), the intensity within the domain is not, and will fluctuate at short time scales through the year. Example A in Fig. 2 shows the intensity of resource extraction to be highest next to the tree and falling exponentially with distance out into the crop zone. Example B shows a linear decline with distance and example C shows a constant intensity with distance from the tree belt. For belts of trees we expect examples A or B, but if the domains of two belts exhibiting B-type domains overlap we may expect to find a more constant intensity between the belts as in example C.

An intensity–domain diagram can be constructed from empirical data or predicted from a tree/crop model such as WaNuLCas (van Noordwijk and Lusiana, 1997). Prediction requires knowledge of the root length density of the tree and the distribution of water and nutrients with depth and distance from the trunk. The rooting pattern of the crop and how the two species with different growth patterns and root length densities compete for limited resources would also need to be known. Unfortunately this type of information is difficult to obtain.

We therefore use empirical data to derive a complementarity index as shown in Fig. 3. The effect of the tree on the crop is simplified to the distance over which there is no yield (the no-yield zone) and the distance over which the tree has no impact on the crop. Similarly there is an area close to the tree where there would be essentially no drainage beyond which drainage is considered to be unaffected by the tree. This we refer to as the no-drainage zone. This is not to say that the effects are limited to these regions but that they are binary representation of waning influence of the tree with distance from the stem. The ratio between these distances gives a measure of the complementarity of tree/crop systems.

3. The no-yield zone

Fig. 4 gives examples of yield with distance from tree belts for crops (Nuberg et al., 2001), pasture (Bird et al., 2001) and crops where tree roots are pruned to manage

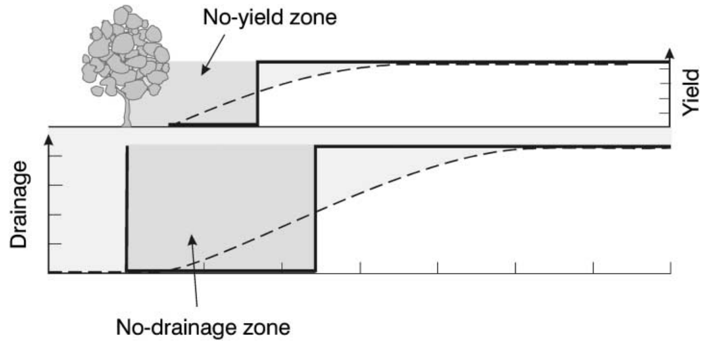

Fig. 3. The no-yield and no-drainage zones linked to a tree belt. Yield and drainage are zero at the base of the tree and increase with distance from the belt to levels characteristic of a sole crop. This is reduced to a step function to facilitate easy comparison of the magnitude of above- and below-ground effects.

competition (Sudmeyer et al., 2001) at three locations in south Australia. The yield of crops is seen to be reduced over a distance of 30–40 m from the belt (Fig. 4a). Wheat and canola yields can be summarised by ascribing a no-yield zone of between 15 and 25 m from the tree belt and 'open paddock' yield beyond this point (see also Woodall and Ward, 2002). In the case of a ryegrass/clover pasture in an average and wetter than average year, yield reduction was not as severe as for crops, with a no-yield zone less than 5 m (Fig. 4b). Root pruning can be seen to successfully limit the lateral extent and intensity of competition such that the no-yield zone decreases from around 12 to 6 m (Fig. 4c) (see also Woodall and Ward, 2002; Ong et al., 2002). However, the residual effect of root pruning on a lupin crop sown the following year was found to be considerably less, suggesting that tree roots had either reinfiltrated the crop zone adventitiously from the trunk base or by re-growth from existing roots below the pruned layer. The latter would render subsequent root pruning ineffective.

4. The no-drainage zone

Whereas the no-yield zone can be quantified empirically, the no-drainage zone presents a much greater challenge. As modelling and measurement of drainage is fraught with difficulty in pure stands of crops or trees and near impossible across a tree/crop interface, we use tree leaf area index (LAI) as a surrogate for water use, and hence drainage, using the method of Ellis et al. (1999, 2001). This method has been tested across six sites over a range of climates from 300 to 700 mm mean average annual rainfall. In one example, in the Mallee zone of south Australia, the LAI of a 10 m wide belt of *Eucalyptus dumosa* was 2.5, four times that of adjacent native woodland. Ellis et al. (2001) therefore estimated that the tree belt used most of the water equivalent to an area four times the area occupied by the crown, that is within 40 m of the trunk. If we consider one side of the tree belt, the no-drainage zone would be 20 m from the trunk or 15 m from the edge of the canopy. This does not mean that roots only extended 20 m, but that an equivalent width of 20 m was protected from drainage as shown in Fig. 3.

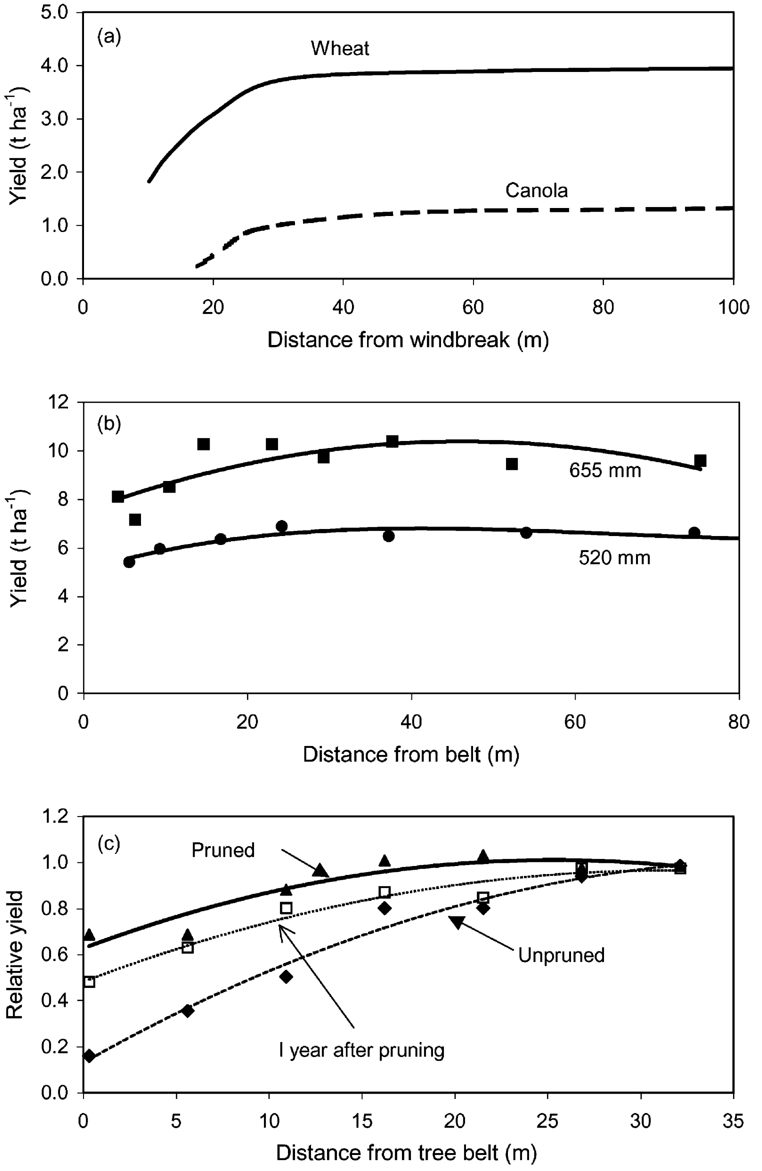

Fig. 4. (a) The yield of wheat and canola with distance from a 9 m high row of Aleppo pine (*Pinus halepensis*) windbreak at Roseworthy, SA (redrawn from Nuberg et al., 2001); (b) the cumulative annual yield of a ryegrass/ subclover pasture with distance from a 4 to 5 m high tree belt comprised of *Eucalyptus*, *Casuarina* and *Acacia* species with 520 and 655 mm of annual rainfall at a site near Hamilton, Vic., Australia (redrawn from Bird et al., 2001) and (c) the relative yield of barley with distance from a root pruned and control section of a 10 m tall maritime pine (*P. pinaster*) tree belt at a site near Esperance, WA. The graph also shows the relative yield of lupins, planted in the pruned section the following year (redrawn from Sudmeyer et al., 2001).

Table 1
The expected LAI of native tree vegetation calculated from rainfall and pan evaporation using the relationship in Ellis et al. (1999)

Location	Rainfall (mm per year)	Pan evaporation (mm per year)	Native LAI
Mildura, Vic.	293	2142	0.4
Moree, NSW	576	1978	0.8
Wagga Wagga, NSW	572	1718	1.0
Albany, WA	815	1417	1.7

Table 2
The predicted dimensions of the no-drainage zone as a function of the tree belt LAI at four locations[a]

Belt LAI	No re-charge zone (m)			
	Mildura, Vic.	Moree, NSW	Wagga Wagga, NSW	Albany, WA
0.5	6	3	3	1
1	13	6	5	3
2	25	12	10	6
3	38	18	16	9

[a] The belt of trees was assumed to be 10 m wide and the no-drainage zone is measured from the centre of the belt. A no-drainage zone >5 m extends beyond the edge of the tree canopy into the crop.

If there is no remnant vegetation for comparison it can be estimated, at least for *Eucalyptus* spp., as $2.9P/E_0$ where P is annual rainfall and E_0 is annual pan evaporation (Ellis et al., 1999). The expected LAIs of native vegetation for Mildura, Moree, Wagga Wagga and Albany are listed in Table 1, using the above formula. If we consider tree belts at each of these locations to have LAIs of 0.5, 1, 2 or 3, we can make a rough prediction about the amount of water these trees are using and therefore the dimensions of the no-drainage zone (Table 2). This is calculated as the LAI of the belt divided by LAI of a native community multiplied by the width of the belt. We have used a belt width of 10 m, which must be divided by 2 because we are only considering one edge of the tree belt. Thus, a no-drainage zone greater than 5 m means that the no-drainage zone extends beyond the edge of the tree canopy. If the LAI of the tree belt is below that of the native community, the trees are either immature, the wrong species or suffering from disease, insect attack or pesticide damage.

5. Complementarity index

We can now calculate a complementarity index as the no-drainage zone divided by the no-yield zone. For a plantation we assume the index is 1 because there is no drainage under the plantation and complete displacement of crop. If, for tree belts, the index is greater than 1 then belts of trees are a better option for achieving a drainage target than separate areas of crops and trees. Two field examples are given below.

Experiments from Esperance, western Australia showed that there was an average of 32% yield loss over three consecutive seasons in the 30 m closest to the tree belt (Sudmeyer et al., 2001; Hall et al., 2001). This equates to a no-yield zone of just 9.6 m (30×0.32). Added to this distance is half the tree belt width (9 m) to give a no-yield area of 18.6 m. Drainage over the same 3 years was decreased by 93% at 25 m from the tree belt and reached open paddock levels at 75 m (no measurements were made between 25 and 75 m). If we make the conservative assumption that tree roots had no significant influence beyond 25 m, then the no-drainage zone would be 23 m (25×0.93) plus the half width of the tree belt giving 32 m. The complementarity index is $32/18.6 = 1.7$. Since the index is greater than 1 we therefore conclude that mixing trees and crops in this situation would be a better option than separating them, when attempting to achieve a given drainage target.

A second example comes from a tagasaste (*Chamaecytisus proliferus*) alley crop experiment grown on a deep sand in Western Australia (Lefroy et al., 2001). The alleys were 30 m wide, with grain crops grown between. The no-yield zone was 5 m but the no-drainage zone was only 3 m giving a complementarity index of 0.6. In this case the index is less than 1, and since competition dominates, it would seem better to put trees in plantations that in alleys. The situation above was complicated by the presence of a fresh water table 5 m below the surface, so that although the tagasaste had a small no-drainage area, it did use water from the water table over summer. However, both the plantation and alley arrangements used groundwater, so the trade-off between drainage and yield would be best satisfied by plantations.

6. Value of tree products

Land managers need to be able to assess the financial gains and losses associated with a belt of trees as shown in Fig. 5. Experience to date suggests that the yield gains through shelter (Y_2) are similar to or less than the losses through competition (Y_1) (Sudmeyer et al., 2001). Thus, the net benefit comes down to the value of the tree product against the value of displaced crop or pasture. In the medium to low rainfall belt of south Australia there is

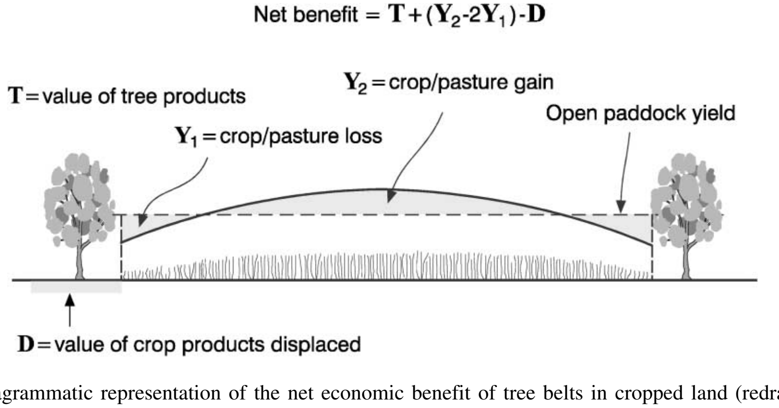

Fig. 5. Diagrammatic representation of the net economic benefit of tree belts in cropped land (redrawn from Lefroy and Scott, 1994).

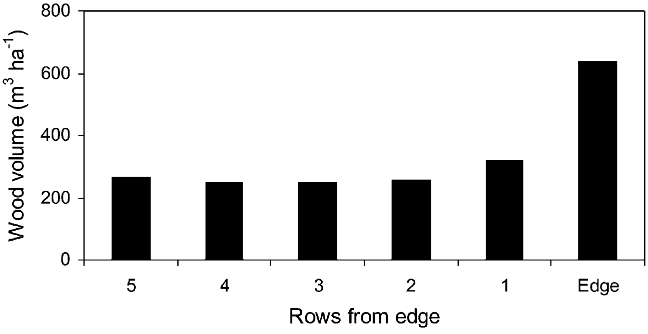

Fig. 6. The productivity of individual tree rows of a *E. globulus* plantation from the edge row to five rows in from the edge (redrawn from Albertsen et al., 2000).

currently very limited opportunity to grow tree products of similar value to crops. Thus, we can calculate the cost of achieving a given re-charge target using the equation in Fig. 5. However, the extra resources available to spaced trees may improve their productivity to the point that the net benefit becomes positive. In this case the complementarity index is irrelevant, the planting of belts can be justified on simple economic grounds.

Albertsen et al. (2000) give an example of how belts of trees could be more profitable than plantations. They found the edge rows of *E. globulus* plantations had on average double the productivity of inner rows (Fig. 6). An economic analysis, which included the extra cost of managing and harvesting edge trees and the loss of pasture along the edge, has shown that alley cropping can be the most profitable option. In areas where the site quality for trees was high, plantations were the best option. Where the site quality for trees was low, grazing was the best option. However, modelling suggests a range of sites in the middle, where enhanced edge growth made the combination of trees and pasture more profitable than either on their own. The enhanced value of the edge tree more than compensated for the no-yield zone in the pasture. Rather than a no-yield zone, we should think in terms of a no-return zone, which takes into account the productivity and value of both components. This would establish the cost of achieving a given drainage target.

Thus, the final decision on mixing trees with crops rests on two factors. If the net benefit is positive then belts are the best option on economic grounds. If the net benefit is negative and complementarity index less than 1, then re-charge control comes at least cost with the trees in plantation arrangement. When the net benefit is negative and the index exceeds 1, re-charge reduction is achieved at least cost by belts of trees.

7. Discussion

This paper started with the question, “when is it better to put trees into belts rather than plantations to reach a given drainage target?” Since spaced trees can use more water than their counterparts in a plantation, fewer trees are needed to reach the same drainage target and more land can remain in agriculture. Spaced trees may also be more productive. Our concept of the ‘complementarity index’, calculated as the no-drainage zone divided by

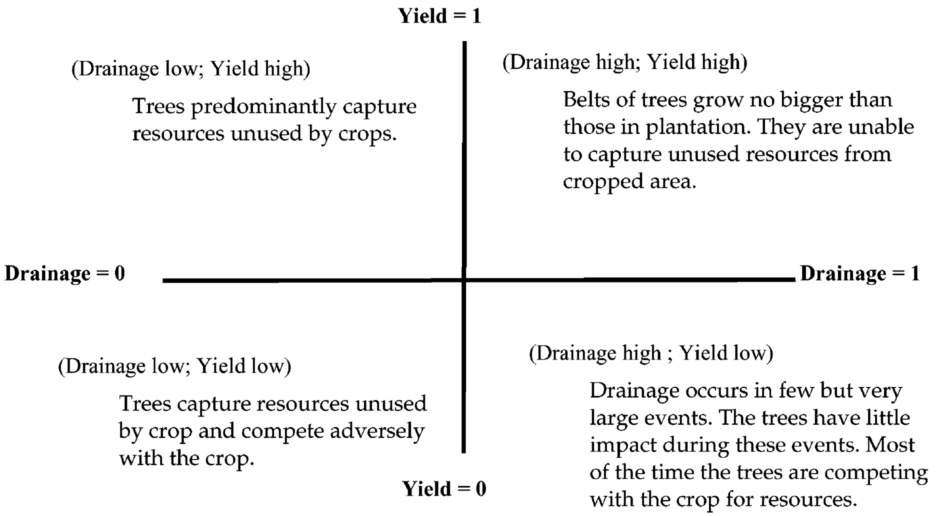

Fig. 7. The theoretical outcomes in drainage and yield for tree/crop mixtures.

the no-yield zone, determines whether this potential can be effectively captured in real situations.

There are four possible outcomes for a tree/crop mixture shown by the four quadrants in Fig. 7. The win–win situation occurs when trees use resources unused by the crop (top left quadrant, Fig. 7). Crop yield remains high, drainage is reduced and each tree receives more water than it would have in a plantation. The opposite quadrant (bottom right) portrays the lose–lose scenario. In the majority of years, the crop requires all the available water, so any water used by the tree inevitably reduces crop yield. However, drainage occurs only during infrequent large events in winter when soil profiles are full.

If yield remains high but drainage is not greatly affected (top right quadrant, Fig. 7), either the tree leaf area is too low or the root system is confined to the crown area. The most likely scenario is shown in the bottom right quadrant where both yield and drainage are reduced. In this case the complementarity index quantifies the trade-off between drainage and yield reduction and can be used to decide whether a particular drainage target could best be met by belts or plantations.

Annual variability in rainfall presents the greatest challenge to integrating trees with crops. If we know the long-term average drainage below crops, and the potential of the trees to use this water, we can work out the area of trees needed to cope with an average year. The problem is that average years under most Australian conditions are interspersed with years of above and below average rainfall. In wetter than average years there will be more water than the tree/crop mixture can cope with and drainage is likely to be high. Conversely, in dry years where resources of water and mobilised nutrients are scarce, the tree, by virtue of its perennial root infrastructure, is likely to be a stronger competitor for water than the crop (Ong et al., 1999).

Tree–crop mixtures present a trade-off between more land under crop than plantations but potentially lower average yields per hectare through competition. In water-limited

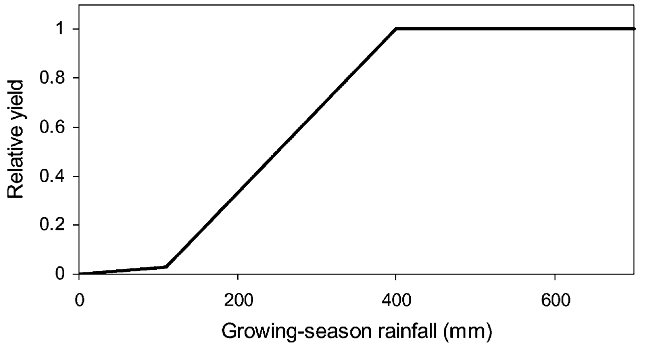

Fig. 8. A simplified relationship between growing season rainfall and yield.

environments, competition is likely to dominate that trade-off. Fig. 8 shows a simplified relationship between crop yield and growing season rainfall with a lower threshold, below which the crop produces no grain, and an upper threshold above which yield no longer responds to an increasing supply of water. At the lower rainfall end of the scale, the combination of a dry season and tree competition could push the cropped area within the tree rooting zone below the lower threshold, possibly leading to no yield at all. Mixing trees and crops therefore becomes more difficult as the rainfall approaches the lower yield threshold for crops and as the season-to-season variability increases. In this case the best way to reach the drainage target may be to think in terms of alley forestry rather than alley cropping, that is wide belts of trees with fallow areas between. Spaced belts may at least give marketable tree products from drier regions, and cropping could be opportunistic-based depending on the stored water at sowing time and/or the amount of rain at the start of the growing season.

The lesson from the above is that spaced agroforestry is more likely to be successful in wetter regions. It is also likely that pastures would be more tolerant of competition from trees than grain crops in such an environment, where late spring rain is important for grain filling in crops but often occurs after peak dry matter production of winter pastures. In fact trees may be more compatible with pasture than crops as different pasture species, exhibiting different patterns of growth, spread the period when competition can be tolerated. The implications are important as pasture dominates over cropping in the wetter areas of south Australia. More data from a wider range of experimental sites is required to test this hypothesis.

Drawbacks of the complementarity index method include the assumptions involved when estimating the no-drainage zone from leaf area, and the need to measure yield loss over several seasons. The main advantage of the method is that hydrological processes that are hard to measure, such as lateral movement of water above impermeable layers or uptake of groundwater by trees, are implicitly taken into account in the measurement of yield and leaf area. Given the wide range of crop–tree–soil–climate combinations and the hydrological complexity of the tree/crop interface, the method should allow for relatively simple assessment of the most promising tree–crop combinations.

8. Conclusions

Mixing crops with trees has the potential for drainage to be lowered using a smaller area under trees than would be required if the trees were in a conventional plantation design. We therefore conclude that, where it can be shown that the LAI of tree belts in agricultural land is substantially greater than that in native stands, and the no-yield area is modest in comparison, mixing trees and crops is a good option. In this situation, the drainage target will be met with the smallest possible displacement of traditional agricultural land. However, a successful mix of trees and crops becomes more difficult with declining cropping season rainfall and increasing seasonal variability. Every effort must be made to choose and manage trees species for a direct economic benefit. Tree products that may not be economic when planted in a plantation design, may become so when planted in belts. In such cases, the no-yield area is offset by the value of harvested tree products.

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