A Simple Method for Hillslope Agroforestry Design

R.P. Silberstein[a,b], **R.A. Vertessy**[b,c] **and T.J. Hatton**[a,b]

[a]*CSIRO, Land and Water, Floreat Laboratories, Private Bag No. 5, P.O. Wembley WA 6913, Australia*
(Richard.Silberstein@clw.csiro.au)
[b]*Cooperative Research Centre for Catchment Hydrology*
[c]*CSIRO, Land and Water, Black Mountain, Canberra, ACT, 2601, Australia*

Abstract: This paper addresses the problem of designing belts of trees on a hillslope, strategically placed to intercept water flowing from upslope preventing it reaching the problem areas characterised by waterlogging and salinity. In a companion paper to this, the huge range of possibilities for agroforestry plantings is discussed. A sophisticated biophysical model was used to predict growth and water balance over a range of edaphic conditions. However, the response surfaces generated are complicated and difficult to interpret. In this paper we present a simple spreadsheet model (HillBelt) that calculates the location and width of tree belts on a hillslope, given estimated soil and climatic conditions. The model is deceptively simple, because it implicitly encapsulates an enormous body of knowledge in the selection of appropriate parameters for a given situation. The guiding principle is that maximising growth requires maximising water use by the trees. We present simple rules for estimating how much water may be available for trees to use, and where and how wide tree belts should be to optimise this. The assumptions and caveats of the method are discussed.

Keywords: Agroforestry; Spreadsheet model; Water balance

1. INTRODUCTION

The state of Australia's environment has received considerable attention in recent times, with particular focus on the havoc of rising watertables and salinity in agricultural areas. These problems have arisen because in clearing for agriculture, we upset a delicate hydrological balance. Agricultural crops and pastures use less water than the native vegetation, and every wet season a small amount of water recharges the groundwater system, that would not have previously. The result is rising watertables, waterlogging and salinity in areas that were once some of our best agricultural land [Schofield et al., 1988]. There is now a major focus on returning trees to the landscape in ways that complement existing agricultural enterprises [Prinsley et al., 1990; Schofield, 1992]. The intention is to productively use water that might otherwise flow to areas where it causes waterlogging or salinity. However, land managers lack the necessary tools to do this in a systematic and effective way.

This paper explores the design of tree belts on pastured hillslopes to intercept surface and shallow subsurface flows from upslope, with the primary objective of achieving groundwater control (Figure 1). The aim is to maximise the effectiveness of the tree belts by placement at the best location on the hillside, and at the optimum inter-belt spacing, and belt width. The capture of this water can increase tree growth and help lower local watertables, thereby relieving waterlogging and salinity problems at the base of the slope. Such an agroforestry design is applicable only to local groundwater systems [Coram, 1998].

The growth of tree belts will depend on a large range of factors, including climate, soil profile and depth, occurrence of waterlogging and salinity, and competition from other trees and agriculture around them. Because field data are only available from a few sites, our recourse was to run thousands of simulations with a detailed biophysical model to predict the water use and growth of tree plantations over the wide range of conditions [Silberstein et al., 2001]. The analysis of these simulations was very complicated and a simpler approach is required for field application.

We present an approach for the day to day design process of agroforestry plantations. We reduce the complicated analysis, and detailed hydrological and biophysical knowledge required into a simple spreadsheet, that is founded on the fundamental principle that maximum growth of trees will come from maximum water use by them. We have called the model "HillBelt". The model assumes that we can represent the system in a steady state with respect to available water and water use of trees. This work is included in a new book on guidelines for agroforestry, to be published in 2001 [Stirzaker, et al., in press].

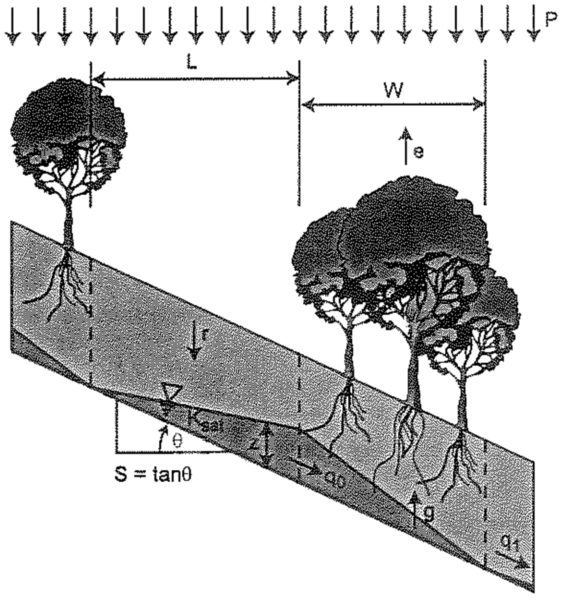

Figure 1. The conceptual model used in **HillBelt**, of lateral subsurface water flow being captured by trees on a hillslope. P = rainfall; L = inter-belt spacing, which is the distance covered in annual pasture or crop up the slope to the divide or to another tree belt; W = belt width; r = the leakage below the root zone of these areas (all of which is considered to reach the watertable); e = total evapotranspiration of the tree belt; q_o = the flow into the root zone of the tree belt; z is the depth of flow into the trees; q_1 = the water flowing past the trees; g = the uptake from the watertable by trees; K_{sat} = the saturated hydraulic conductivity of the soil; and Δ = the slope.

2. METHODOLOGY

2.1 General Principles

The design of agroforestry plantations depends on a few fundamental guiding principles:

- there is a strong, positive relationship between annual rainfall and tree growth, particularly in the 400–1,000 mm annual rainfall zones;
- the growth of trees will be higher if they have access to a source of fresh water additional to rainfall;
- the production per unit area of trees planted is greater if they are planted in belts rather than large blocks, because the opportunity to capture water from outside the plantation is increased.

The full potential of tree belts on a hillside can only be realised if:

- there is some excess water to capture;
- there is sufficient slope and the soil is permeable enough for lateral flow to occur;
- the lateral flow is shallow enough that the tree roots can reach it.

The success of tree belt plantings on hillslopes depends on climate (rainfall amount and timing, potential evaporation), hillslope geometry (slope, curvature, profile, length), and soil properties (depth, water-holding capacity, saturated hydraulic conductivity). Any salt in the water will reduce tree water uptake and growth, so belts will work best where the shallow groundwater is fresh or where leaching events occur often enough to prevent salt accumulating in the root zone.

Pastures rarely use all the rain that falls on them, particularly on wetter sites. Figure 2 gives a guide to the proportion of annual rainfall used through evapotranspiration (ET) by pastures in south-eastern Australia. The actual rate of ET may be higher if the pastures are improved, or lower if the pastures are heavily grazed or degraded. The wetter the site, the more excess water is likely to be available.

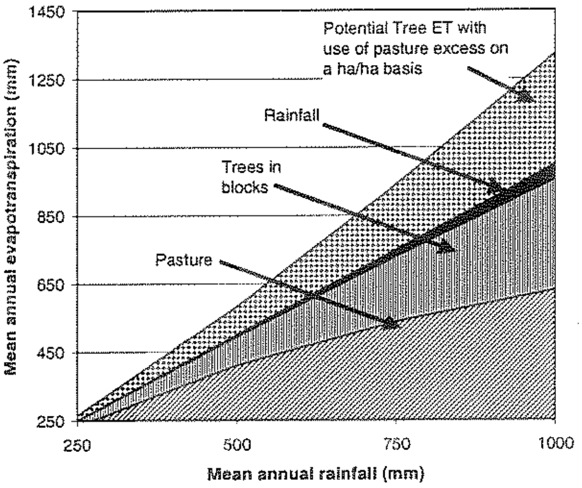

Figure 2. Mean annual ET from pasture, trees in blocks and trees in belts, as a function of average annual rainfall in south-eastern Australia. In principle, the difference between the "tree" line and the "pasture" line is the water that could be available for use by trees.

3. *HillBelt* AGROFORESTRY DESIGN

The fundamental design parameters for a belt of trees in a paddock on a hillside are the quantity of water available for use by the trees, how quickly it can run to them, and how much water they use. In Figure 1 the available water flowing from the pastured area of length L is $L \times r$. The amount of water used by a width W of trees is $W \times g$, and the slope (Δ) and the hydraulic conductivity (K_{sat}) of the soil control the rate of supply of groundwater flowing laterally to the trees.

3.1 Estimating the Available Water

The rate of lateral flow on a hillslope depends on its slope and the hydraulic conductivity of the soil. In Figure 3, if the hillslope sits in the white (best) or shaded (intermediate) zones there is a good chance that some lateral subsurface flow will occur. However, it should be noted that if the local watertable is very deep or persists for only short periods of time then the opportunities for tree belts to capture lateral subsurface flows from upslope areas are limited. If hillslope conditions fit in the dark zone of Figure 3, tree belts are unlikely to capture any subsurface flow from upslope. However, if the soil hydraulic conductivity is particularly low at the surface (as is common in degraded grazing areas), there is a chance that tree belts will still capture some surface runoff during rainfall events. For this to occur, either the surface soil hydraulic conductivity under the tree belts must be appreciably higher than that in the pastured areas, or the surface roughness within the tree belts – perhaps caused by logs or constructed banks – must be great enough to pond significant amounts of runoff.

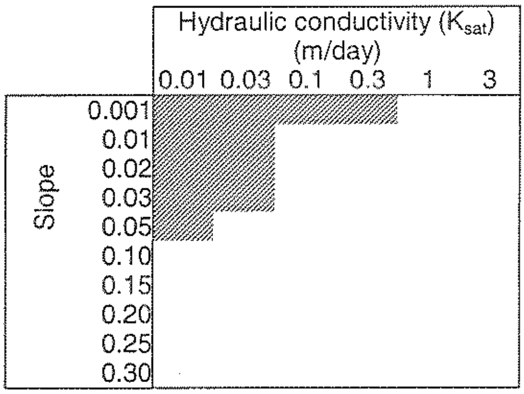

Figure 3. The effect of slope and the saturated hydraulic conductivity of soil in determining the lateral sub-surface flow of water on hillslopes. (dark = insignificant lateral movement, shading = some lateral movement, white = significant lateral movement.)

3.2 Inter-belt Spacing and Belt Width

Inter-belt spacing and belt width are related: the wider the inter-belt spacing, the more water that can be captured and hence the wider the tree belts can be made. The right balance of belt widths and spacings will ensure that all the water will be used by the trees and enough will be available to maximise their growth. If belts are wider than necessary to use up the water conveyed from upslope, trees on the down slope side of the belt will not benefit from lateral flows, and have reduced growth.

Referring to Figure 1, for a tree belt to use all the water conveyed to it from upslope, ***Lr*** must equal ***Wg***. Similarly, the ratio of belt width to inter-belt spacing must equal the ratio of recharge to groundwater uptake. In other words:

W/L must equal r/g

The rate of supply of groundwater per unit length of tree belt (along the contour) is represented by q_o and is dependent on the K_{sat} of the soil, the slope and the tolerable saturation thickness. It is given by:

$$q_o = \Delta\, K_{sat}\, z$$

For the trees to use all the water supplied to them, q_o must equal ***Wg***. The flow past the trees, q_1, would then be zero. The discharge capacity of a catchment or hillslope is the minimum value on the hillslope of the product [$\Delta\, K_{sat}\, z$].

On a given hillslope, it is desirable to maintain the depth to saturation at greater than some minimum amount. This depth will determine a critical saturated depth of water flowing laterally, which we denote z_c. For non-waterlogged steady state conditions, we require that the supply (recharge from the inter-belt area) be no more than the discharge capacity of the hillslope. In other words:

Lr should not be greater than $\Delta K_{sat} z_c$

If the inflow ***Lr*** is greater than $\Delta K_{sat} z_c$ then the perched watertable will rise, leading to waterlogging.

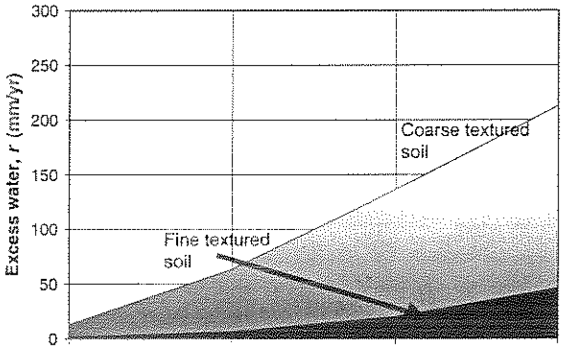

Figure 4. A guide to estimating excess water, ***r***, running from pastures or crop land for sites with different soil textures and average annual rainfalls. The lighter area denotes the range for sand and the darker area for finer textured soil profiles. These curves are derived from data collated from many studies and presented by [Petheram et al., 2000].

In these calculations we assume that all the available water can be delivered to and used by the trees. We implicitly account for overland flow to the trees and for any subsurface leakage penetrating beyond the perching horizon which is therefore not available to the trees. The seasonality and timing of rainfall events, the quantity of rain and the inter-storm period all affect water availability to the trees and the occurrence of waterlogging.

3.3 Getting the Design Parameters Right

Clearly the key to good design of an agroforestry system is getting the belt width (W) and inter-belt spacing (L) right. The most important site characteristics affecting these are (see Figure 1):

- the soil saturated hydraulic conductivity (K_{sat});
- slope (Δ);
- the tolerable saturation thickness of the groundwater (z);
- the inter-belt area 'excess water' (r), see Figure 4 caption; and
- the groundwater uptake rate of the trees (g).

3.4 Estimating values for site parameters

In making these calculations it is assumed values for the various parameters can be obtained. Note that if there is significant variation in slope and soil type along the hillslope, it may be necessary to break the hill into segments and estimate discrete values of K_{sat} and Δ for each segment.

Saturated hydraulic conductivity: To measure this accurately requires expert knowledge and special apparatus, but a rough estimate can be made if the soil texture is known: K_{sat} can be approximated at 1 m/day for sand, 0.1m/day for loam and 0.01m/day for clay.

Slope: This is calculated as hillslope vertical rise per lateral distance. Hence, if a hillslope rises 20 m over a lateral distance of 200 m, then $\Delta = 20/200 = 0.1 = 10\%$.

Tolerable saturation thickness of the groundwater: This is an estimate of the maximum saturation thickness tolerable at the down slope edge of the inter-belt region (i.e. where a tree belt starts). If, for example, a perching layer at this point is 4 m below the ground surface and the trees would suffer waterlogging stress if the groundwater reached within 1 m of the ground surface, then the value of z at this location would be 3 m.

The inter-belt area 'excess water': this is a combination of the annual depth of water that leaks beyond the pasture root zone and joins the shallow groundwater system supplying the root zone of the tree belt, and any overland flow that leaves the pastured area and reaches the capture zone of the tree roots. It is very difficult to measure or model this due to climatic dynamics and the inherent variability of field conditions. As an estimate, r can be taken to be equal to 10–15% of annual rainfall for sand, 5–10% for loam and 1–5% for clay profiles under pasture. For any given soil texture, if rainfall is summer-dominant and/or the soils are deep, recharge rates should plot towards the lower end of the range shown in Figure 4, and towards the higher end if rainfall is winter-dominant and/or the soils are shallow.

Water use by trees: For the design calculation, we require a realistic estimate of how much the trees will use at the site, rather than what they would use if it was available in limitless supply. This is difficult to estimate and requires expert knowledge, but sapflow measurements are now common in water balance studies, and can be made relatively easily. In south-west W.A. it is likely to be around 150 mm-250 mm per year. It would be more if the water was available in summer, but generally surplus water is only available during winter when the trees can not make great use of it. In northern Victoria it may be more, as summer rainfall is more likely. In these estimations W is taken to be the planted width of trees, assumed to be close enough to use all the water that falls within the belt. Also, we have not taken explicit account of the fact that trees can send roots laterally into pastured areas to capture water. This ability means that the effective W may be greater than the notional width of a planted belt. It is important to note that the total water used by the trees, Wg, is taken on a per planted area basis for calculation of the water balance of the whole hillslope.

4. WORKED EXAMPLES

The purpose of our design is to maximise watertable control with the minimum area planted to trees. Thus, we want to match the groundwater recharge rate to the discharge capacity of the hillslope. If the recharge rate is higher than that, the watertable will rise; if it is lower, the watertable will fall.

4.1 Example 1, East Belka, W. A.

For a hillslope with characteristics similar to those at East Belka in south-western Australia: average annual rainfall = 330 mm, distributed mainly over six months of the year; $\Delta = 3\%$; $K_{sat} = 0.3$ m/day; $z = 1.5$ m; $r = 10–40$ mm/yr; and $g = 50–100$ mm/yr.

Table 1 provides upper and lower estimates of the inter-belt spacing and belt width needed to match recharge to the discharge capacity of the hillslope.

Table 1. Results from HillBelt used to calculate the inter-belt spacing and width of tree belts required to maintain optimal water control on a hillslope in south-western Western Australia.

K (m/day)	No. of Wet months	z=critical depth of saturation (m)
0.3	6	1.5

Slope (%)	*L* = inter-belt spacing (m)						*W* = belt width (m)				
	r = inter-belt excess water (mm/yr)						*g* = groundwater uptake by belt (mm/yr)				
	10	20	**40**	60	100		**50**	75	**100**	150	200
2	164	82	41	27	16		33	25	16	11	8
3	**246**	123	**62**	41	25		**49**	37	**25**	16	12
5	411	205	103	68	41		82	62	41	27	21
10	821	411	205	137	82		164	123	82	55	41

How far apart can the belts be and still avoid waterlogging?

How wide should the belts be to use up this water?

Table 2. Results from HillBelt used to calculate the inter-belt spacing and width of tree belts required to maintain optimal water control on a hillslope in north-eastern Victoria.

K (m/day)	No. of Wet months	z=critical depth of saturation (m)
0.1	6	1.0

Slope (%)	*L* = inter-belt spacing (m)						*W* = belt width (m)				
	r = inter-belt excess water (mm/yr)						*g* = groundwater uptake by belt (mm/yr)				
	20	40	60	100	200		100	150	200	250	300
5	91	46	30	18	9		18	12	9	7	6
10	183	91	61	37	18		37	24	18	15	12
20	365	183	122	73	37		73	49	37	29	24
30	548	274	183	110	55		110	73	55	44	37

Depending on whether r = 10 or 40 mm/yr, the inter-belt spacing should be no greater than 246 and 62 m respectively if z is not to be exceeded. The minimum belt width required to use the lateral inflows at this site would be 25 and 49 m when g is 50 and 100 mm/yr respectively.

4.2 Example 2, Warrenbayne, Victoria

At Warrenbayne in north-eastern Victoria the characteristics are: average annual rainfall = 870 mm, distributed relatively evenly throughout the year, so 12 wet months; Δ=20%; K_{sat}=0.1 m/day; z=1.0 m; r=60–100 mm/yr; and g =100–200 mm/yr.

Table 2 provides upper and lower estimates of the inter-belt spacing and belt width needed to match recharge to the discharge capacity of the hillslope. For r values of 60 and 100 mm/yr, the inter-belt spacing should be 122 m and 73 m, respectively. The minimum belt widths required to use the lateral inflows at this site are 73 and 37 m if g = 100 and 200 mm/yr, respectively.

These two examples illustrate the different planting strategies needed at sites with different characteristics. The East Belka site has little excess water, low slope and high K_{sat} while the Warrenbayne site has much more water, a steeper slope and low K_{sat}. The result is that significantly different proportions of the slope need to be planted to trees for recharge control.

Some further generalisations can be made:

- the greater the pasture leakage, the closer the belts should be;
- the greater the groundwater uptake, the narrower the belts may be;
- the steeper the slope, the further apart the belts can be (with accompanying increasing width);
- the shorter the wet/winter period, the closer the tree belts should be. This is because the

same amount of water may be perched in the soil but concentrated in a shorter period, so the saturation thickness is greater.

5. DISCUSSION

There is uncertainty in all of the input parameters, particularly r and g; this needs to be remembered when the designs are being developed. The inter-belt spacing calculated above is the maximum we advise, while the calculated belt width is the minimum required to accompany that spacing. Planting narrower belts closer together can be expected to give more effective water use and better growth for the same planted area because of the edge effect discussed earlier. The key to watertable control is to maintain the W/L ratio to ensure maximum water usage; therefore, the proportion of the whole hillslope planted to trees should be $W/(L+W)$.

Growth near the edges of tree belts is enhanced, because those trees get access to water not available to the trees at the inside of the belt. Water flowing laterally will penetrate different distances into the belt on different occasions. For example, the flow may penetrate further during intense rainfall events or in winter when the trees are using less water. The simple steady state model used in this paper does not, and cannot, account for this. To compensate, we have built in an allowance by choosing values for r and g that express how much water *is*, rather than how much *could be*, available and used. Our calculations also ignore the influence of salt which is concentrated as the trees withdraw water from the soil, reducing tree water uptake and growth.

6. CONCLUSIONS

Addressing Australia's salinity and land degradation problems requires more than planting trees, but the problems have arisen because we cleared too many trees. The solutions, and there will be many, will require an increased presence of trees and other perennial vegetation in agricultural landscapes. Land managers need help to design agroforestry plantings that will be sustainable and effective. The possible permutations available for tree plantings in any one location are endless, and very complicated to analyse in detail. However, in this paper we have presented fundamental principles, of potential water availability, and water use by trees on a hillslope that can be used to make relatively simple calculations, to make this process tractable by many people. This is condensed to a simple spreadsheet model that can be used easily in the field. However, it is essential that the user is cognisant of the diverse range of field conditions that can affect how the design principles should be applied at any specific location. We recognise the value of detailed modelling and analysis of the complicated systems we seek to manage, however scientists need to have regard to the use of our knowledge for the common good. To facilitate this it is essential we condense knowledge into readily accessible formats for daily application; to this end we have derived the spreadsheet described. Copies of the spreadsheet are available from the authors or JVAP.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Coram, J., (Ed). *National Classification of Catchments*, Water and Salinity Issues in Agroforestry No. 3. Rural Industries Research and Development Corporation, 1998.

Petheram, C., L. Zhang, G.R. Walker, and R. Grayson, *Towards a Framework for Predicting Impacts of Land-Use on Recharge: A Review of Recharge Studies in Australia*. Technical Report 28/00. CSIRO Land and Water, 2000.

Prinsley, R.T., M. Stocking, J. Bojo, and N. Abel, Agroforestry for Sustainable Production. Economic Implications, London, UK: Commonwealth Science Council, 1990.

Schofield, N. J., Tree planting for dryland salinity control in Australia, *Agroforestry Systems*, 20:201-23, 1992.

Schofield, N.J., J.R. Ruprecht, and I.C. Loh, *The Impact of Agricultural Development on the Salinity of Surface Water Resources of South-West Western Australia*. Report No. WS27. Water Authority of Western Australia, 1988.

Silberstein, R.P., R.A. Vertessy, and D.Mc Jannet, A parameter space and simulation response surface for agroforestry design, In *Proceedings of MODSIM 2001 Congress*. The Australian National University, The Modelling and Simulation Society of Australia and New Zealand Inc., 2001.

Stirzaker, R.J., Vertessy, R.A. and Sarre, A., *Trees, Water and Salt: An Australian guide to using trees for healthy catchments and productive farms*, Rural Industries R & D Corporation, Kingston, ACT, Australia, in press.