A Parameter Space and Simulation Response Surface for Agroforestry Design

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Abstract: Australia is beset by enormous environmental problems caused by an hydrological imbalance that has resulted from the extensive clearing of native vegetation for agriculture. There is now a focus on redesigning our agricultural systems, returning trees to the landscape, and thereby restoring the water balance. We need agroforestry design criteria across a wide range of soil, climate, and hillslope conditions. As comprehensive field studies are not widely available we used a biophysical model (Topog_Dynamic) of a catchment with growing vegetation to simulate the growth and water balance of belts of trees across a wide range of environmental conditions. To do this in an organised way we developed a scenario modelling tool (Topog_Scenario) to combine inputs and collate outputs for over 9000 simulations. This was then used to develop response surfaces for each of a given set of simulations. This paper presents some of the response surfaces developed for a range of input conditions including different hillslope profiles, soil salinity, climate, planting position and tree belt width. The non-linearity of interactions gives some non-intuitive results, such as belts at different parts of the landscape performing relatively differently depending on which combination of soil and climate the modelling scenario uses.

Keywords: Agroforestry; Scenario; Response surface

1. INTRODUCTION

Australia is facing enormous problems of land degradation due to rising watertables, soil salinisation, erosion and soil structure decline. These have arisen from agricultural practices that have dramatically altered a delicate water balance that existed in the native vegetation systems prior to European settlement 200 years ago. There is now a concerted effort to restore deep-rooted perennial vegetation to the agricultural landscape, as a means of the restoring the water balance, and doing this in a manner which complements agricultural productivity. To facilitate this a team of scientists from CSIRO has been developing a book of design guidelines for agroforestry across southern Australia [Stirzaker et al., in press]. The design principles are based on knowledge gained over the last 20 years on tree growth and water use, however, field data on agroforestry is scant. Experiments and demonstration plantings have been undertaken, but only a few have measurements adequate to really characterise and quantify the growth potential of these systems. Moreover, it is not possible to replicate experiments in more than a few configurations and under a few field conditions, as it takes up to 20 years for the full potential of such plantings to be realised. Modelling is really the only method for generalising results from experiments to other site conditions, but we should be cognisant of the limitations of our models, and cautious about extending results beyond the calibration parameter space.

To model even a modest combination of agroforestry arrangements with a representative set of site conditions presents the problem of a huge number of simulations. The array of possible conditions of climate, slope, soil type, profile and depth, of hillslope convergence and divergence, and soil salinity and watertable conditions is virtually limitless. Add to that an array of different planting arrangements and hillslope locations and the number of required model simulations is into the many thousands; and then the results need to be assembled in some organised and analysable form.

To address this huge logistic task we developed TOPOG_Scenario [Silberstein and Vertessy, 1999], a software program that combines a range of different model combinations into a scenario batch. It sets up parameter files to run our ecohydrologic model, selects desired outputs, and compiles summaries of each model run into a few tables that can readily be imported into a graphics package for presentation and analysis.

This paper presents results from a few of the more than 9,000 simulations that were performed during this project, and discusses the implications of the number of parameter permutations for modelling in this fashion.

2. MODEL DESCRIPTION

Topog_Dynamic is a biophysical process-based distributed hydrological model, that includes algorithms to simulate plant growth and water uptake, and link these to soil moisture and salt conditions [Silberstein et al., 1999; Vertessy et al., 1996]. Unsaturated vertical flow is modelled by Richards' equation, and lateral saturated flow by Darcy's Law. Vertical solute transport is modelled by the 1-dimensional convection diffusion equation. It requires a catchment element network based on a digital elevation model (DEM), spatially distributed soil descriptions including layering within the profile, and runs on a daily time-step to climate data. Vegetation can be distributed heterogeneously across the catchment network and is described by parameters that represent the response of canopy conductance to environmental variables, and transpiration and carbon assimilation are linked through the canopy conductance. Carbon is distributed above and below ground according to site conditions, and the above ground pool to stems and leaves according to allometric relationships from available literature. The proportion of carbon assimilated below ground is set by [Landsberg and Waring, 1997] :

$$a_{roots}=(1-b)/(1+2.5x_w) \qquad (1)$$

where b is a parameter setting the minimum level of above ground partitioning, and x_w is the soil moisture-salinity stress index, defined below.

The root water uptake, and root carbon allocation are both controlled by a root zone soil-moisture-salinity stress index calculated as the average of the combined soil moisture potential and osmotic potential for each soil interval (i) within the rooting depth of the vegetation:

$$x_{wi}=\frac{\rho_i \Delta z_i \min\left(\psi_{lmax}-\psi_i+\eta\pi_i,0\right)}{\psi_{lmax} z_r} \qquad (2)$$

The total stress factor x_w is then the sum of these; and ψ_{lmax} is the maximum leaf water potential (i.e. most negative) of the plants, z_r is the maximum rooting depth, ψ_i is the soil moisture potential and π_i is the osmotic potential due to salt in the soil moisture, within each depth interval i, of thickness z_i, and ρ_i is the proportion of roots within the depth interval, and η is the salt sensitivity factor. The salt sensitivity factor is used in the model to scale the osmotic potential of the groundwater relative to soil moisture potential. Generally it is set at 1. The proportion of water extraction, and carbon allocation, assigned to each soil interval, i, is determined as x_{wi}/x_w,

Topog_Dynamic was first calibrated on a range of hillslopes with differing properties, to yield results that were consistent with field observations of tree growth rates, evapotranspiration and watertable levels. We then used the model to predict hillslope hydrologic dynamics and tree growth outside the calibration conditions. Whilst we cannot guarantee that the model is providing realistic predictions in all cases, this is the only means we have of estimating hydrologic and tree growth dynamics for a wide variety of conditions.

The simulations discussed here are for plantations grown for 30 years in belts across a hillslope. The belts had varying widths from 30 m up to 300 m, and were systematically placed at different locations on the hillslope. The hillslopes used for the simulations were 600 m long.

3. ENVIRONMENTAL PARAMETERS

There is virtually no limit to the number of combinations we could run in any scenario batch, but clearly not all possible combinations of soil, slope and climate exist in nature, and not all those which do exist are likely to be appropriate for agroforestry. For these simulations, we have chosen the following:

- Five soil profiles selected from an existing CSIRO database, as representative of widely occurring agricultural soils (see CSIRO National Soils Database);
- Five climate data files representing agricultural areas, for which we had access to long records (~20 yrs);
- Two slopes to represent relatively steep (30%) and gentle (5%) terrain, and a concave and convex hillslope with mean slope 15%;
- Three soil salinity levels were simulated: no salt, mildly saline (0.6 kg/m^3 soil, equivalent to 1,000 mg/L in saturated water content, which has an electrical conductivity (EC) of about 1.6 dS m^{-1}), and highly saline (6 kg m^{-3} soil, equivalent to saturated water content of 10,000 mg L^{-1}, and EC of about 16 dS m^{-1});
- A range of planting locations for trees across a hillslope, with varying belt widths and separations.

Table 1. Soil profiles used in the simulations for five sites listed in the CSIRO National Soil Database.

Profile type	Measurement location and code	Soil horizon and texture		K_{sat} (m/day)	Horizon thickness (m)	
					Hill top	Hill bottom
Duplex 1	Seaham (CP319)	A	Sandy loam	0.2	0.25	0.50
		B	Medium/heavy clay	0.002	0.35	1.50
Duplex 2	Billaglen (CP326)	A	Sandy clay loam	0.9	0.15	0.40
		B	Medium clay	0.009	1.00	2.00
Gradational 1	Wagga Wagga (CP331)	A	Sandy loam	1.8	0.15	0.40
		B	Sandy clay loam	0.5	0.80	8.00
Gradational 2	Alstonville (CP321)	A	Clay loam	3.2	0.20	0.20
		B	Clay loam	2.6	2.50	10.0
Duplex 3	Newholme (CP330)	A	Sandy loam	4.6	0.20	0.75
		B	Medium clay	0.002	0.60	8.00

These conditions lead to 300 parameter combinations for each planting scenario. In this paper we discuss two planting scenarios; one with five planting positions and the other with 15.

Rainfall at Coffs Harbour (NSW) is very high (1696 mm) and is summer dominated, while Geraldton (W.A.) (446 mm) has a Mediterranean climate with a strong winter dominance. Wagga Wagga (NSW) (621 mm) experiences fairly uniform rainfall throughout the year. Both Kyabram (Victoria) (445 mm) and Warrenbayne (Victoria) (871 mm) have greater monthly rainfall during the winter months.

4. RESULTS

4.1 Trees in Different Hillslope Locations

The range of responses of a modelled 30 m wide belt of trees on a 600 m long hillslope, is shown in Figure 1. Relative total evapotranspiration from the belts over 30 years of growth is shown, grouped by climate, slope, and soil profile, with no salt in the soil. The chart shows how variable performance can be and emphasises that such plantings need planning. The figure shows the results of 500 30 year simulations. Each line is made up of 5 points, each point being the total ET from the simulation of a single narrow (30 m) belt of trees on a hillside. The steeper the line, the more significant slope position will be to tree growth. The primary responses are summarised as follows:

4.1.1 Effects of rainfall

As rainfall increases, so does ET. Rainfall increases across the diagram from left to right, resulting in an increase in tree water use. Seasonal distribution of rainfall also has a major impact, as shown for Kyabram and Geraldton, that have the same annual rainfall but Kyabram has greater summer rainfall, so the trees are not subject to drought stress to the same degree. The interaction between climate variables and soil is also shown by the total ET at Warrenbayne being greater than Coffs Harbour, despite less rainfall, because of the drier atmosphere and clearer sky conditions.

4.1.2 Effects of soil depth

On deeper soils (Duplex 3, and the two Gradationals) water use and growth are greater. Deeper soil allows greater storage for longer periods, giving the trees a buffer against drought conditions, and also they are less likely to suffer waterlogging.

4.1.3 Effects of hillslope position

Moving the trees down slope gives them access to deeper soil, and to the possibility of more water flowing from upslope, hence improving growth in most cases. However, for most soils under the Geraldton climate, in which the trees are limited by rainfall, this effect is less pronounced. Excess water is only available in winter, when the trees are least able to use it, and the advantage of lower slope positions is only significant on certain soil types (the deeper more permeable Duplex 3 in our example). The other exception clearly illustrated is on the concave hillslope under the heavier rainfall climates, where growth increases as the trees are placed further downslope only until they reach a point where waterlogging severely impacts on them.

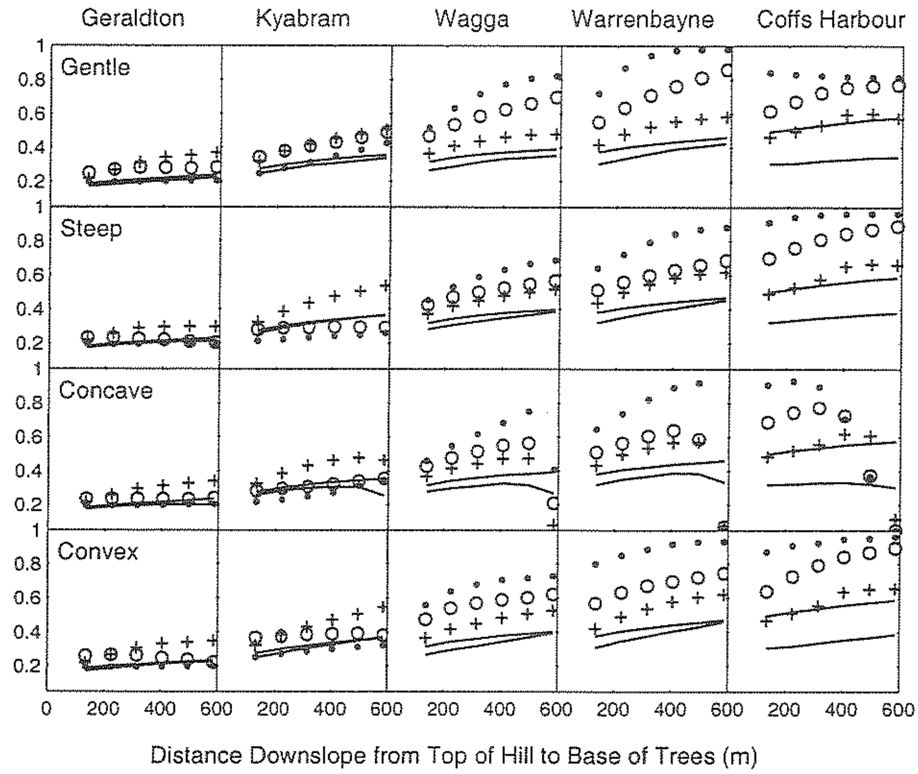

Figure 1. Modelled relative evapotranspiration (ET) from a single belt of trees located at different positions on a hillslope, in the five climate zones, and the five selected soil profiles, on gentle (5%), steep (30%) and concave and convex slopes, and with no salt in the profile. The soils are indicated as (–) Duplex 1, (-•) Duplex 2, (+) Duplex 3, (o) Gradational 1, (•) Gradational 2.

4.2 Effects of Tree Belt Width

Simulations were run for belts of varying widths, located at different places on the hillslope. These simulations were run in three batches, with the narrowest belt (30m) placed at the top, bottom or in the middle of the hillside, for each batch, respectively. The simulations were run in three batches of five runs, with each run for a belt of a different width, and the belts progressively wider from a) the bottom of the slope, b) the middle of the slope and c) the top of the slope. The widths used were 30 m, 60 m, 120 m, 240 m and 300 m, being 5%, 10%, 20%, 40% and 50% of the hillslope respectively.

The full range of responses is complicated, so we present only a selection from the full set. Figure 2 shows the total wood volume of trees in the progressively widening belts, on the gentle (0.05) slope, with the Geraldton and Kyabram climates. The envelope curve which would be formed by tracing the left hand end of each line, is the expected water use of a narrow belt of trees, placed at different locations down the hillslope (equivalent to that shown in Figure 1), and can be seen to increase as the trees are moved downslope.

The difference soils make is clearly illustrated, as is the effect of climate on the interaction between soils and the trees. For example, under the Geraldton climate with no salt, growth is suppressed on Duplex 2, relative to Duplex 3, because it is shallower and hence stores less water. It is also less permeable so more water runs off the surface and water in the soil does not run laterally to feed downslope trees. The Duplex 2 soil and Geraldton climate combination is likely to produce maximum lateral flow in winter, when the trees are least able to use it. These attributes contribute to a lesser variation in growth through each belt, because the trees on the upslope side of the belt are not receiving significantly more usable water than their downslope neighbours. The converse is true on the deeper more permeable Duplex 3. In belts planted from the bottom of the hillslope (lines) the trees on the downslope side ***lack*** water as the belt is made wider. The lower limit to growth is governed by the rainfall and is represented by the lowest point on the curve (where the curve flattens out around 6 m^3/ha/yr).

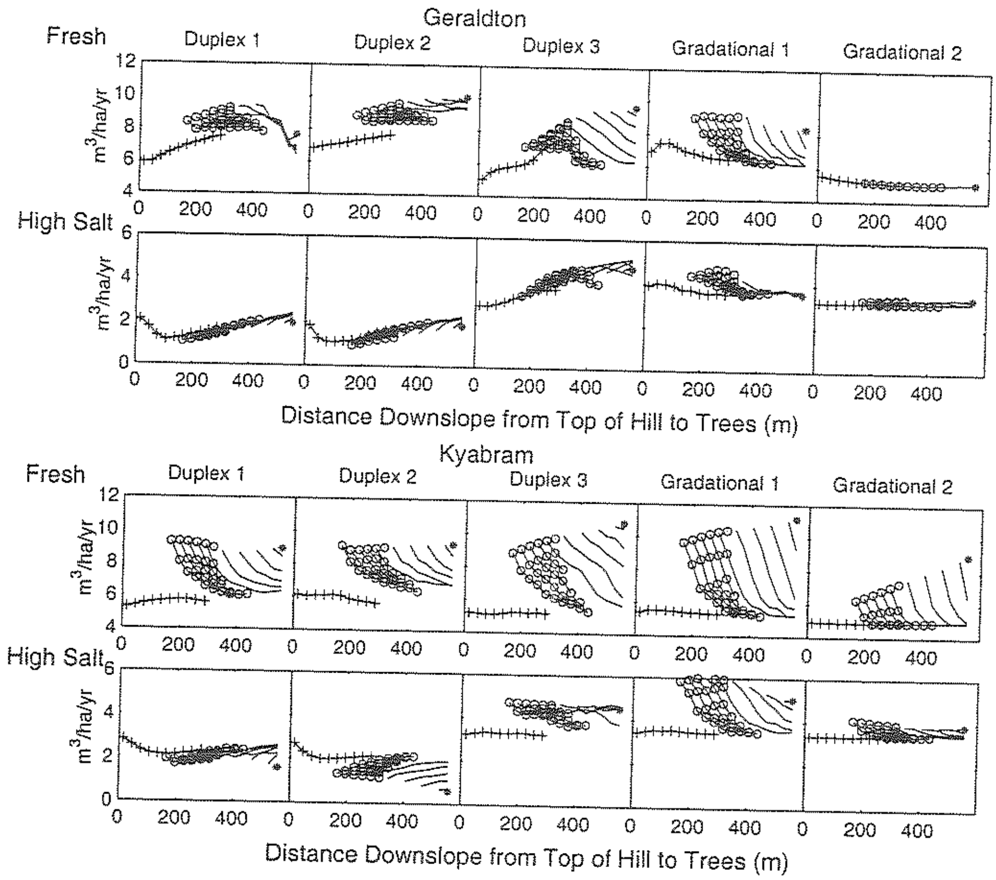

Figure 2. Stem wood growth of trees in belts of different widths and hillslope positions, on a slope of 0.05, for the Geraldton (W.A.) and Kyabram (Victoria) climates, for two soil salinities. Each line of points represents, for a single 30 year simulation, the average wood production of trees at different positions in a single belt. The projected length of the line of points onto the horizontal axis indicates the width of the belt and its location on the hillslope for that simulation. The small dots joined by a line show growth for belts planted at the base of the hillslope, with each belt extended progressively further upslope. The circles (o) joined by lines shows belts at midslope positions, and the "+" lines shows a belt extended down from the hilltop. The narrowest belt is 30 m wide and is plotted as a single point.

The belts planted from the middle of the Geraldton hillslope without salt on Duplex 3 (* lines) show the composite effects of water flowing from upslope and the deeper soil downslope. Growth peaks where the combination is optimum. This effect is not seen on Duplex 2 because there is less water flowing from upslope and it is shallower. It is also much reduced when there is high salinity in the soil.

The belts planted from the hilltop (+ line) do not gain much water from upslope, and in most cases growth reduces downslope until the soil is deep enough to make a difference. Under the Geraldton climate on Gradational 3 soil, growth is poor. This is because for this highly permeable soil, normally an advantage, under Geraldton's climate, the water is there when it is least needed, and drains below the root zone of the trees. As such they are stressed for most of the summer.

When the soil has salt in it there is less variation in growth with belt width, spacing, and position, because the trees use less of the water, so there is more water flowing down slope to the next trees. There is a relative improvement in growth downslope from having wider belts. This is because the wider belts relieve the waterlogging impact somewhat.

On saline soils with shallow perching layers (Duplex 1 and 2) there is a benefit to lower slope trees of having upslope plantings. This is especially clear under the Kyabram climate, where the wider belts grow significantly better than the narrow ones at the bottom of the slope.

5. DISCUSSION

Growth is maximised by planting trees in arrangements that use as much water as possible.

When lateral flow occurs, water capture can be maximised by planting the trees in belts far enough apart to allow a significant quantity of water to reach the watertable. However, if they are too far apart, more water may collect than the belt can use and flow past them further down slope, or in extreme cases may lead to waterlogging. The simulations in Figure 3 show that in general the trees at the upslope side of a belt grow best, as they intercept water flowing from upslope. However, for a wide belt at the top of the hill, which is more dependent on soil depth than on flow from upslope, we expect the best growth to be at the lower side. The small amount of lateral flow that is intercepted by the upslope trees and prevented from moving down slope to the other trees is compensated for by the increase in depth.

The results presented give an indication of the huge variety of responses that come from the non-linear interactions encapsulated in the model. Many of these results, while explainable *post hoc*, are not necessarily intuitive.

6. CONCLUSION

In this paper we have explored the range of responses that might be expected of an agroforestry plantation on a hillside. We showed how varied the growth may be, even with relatively simplistic representations of the natural permutations that will exist in the field. Simple assumptions of how much water may be available to trees depending on annual rainfall, or hillslope position have been shown to be misleading in many cases. Our model suggests that the many interactions and feedbacks between trees and soil through their root response to moisture and salt can lead to counter-intuitive results. Seasonal distribution of rain and evaporative demand will have a big influence on how efficient trees are at using water on the hillside, and hence on their growth. It remains to field test the simulations made here in as many combinations as possible, so that we may learn how well we are representing these interactions. There are many processes that are not represented in the model that could influence the results in the field, and coupled with the extreme variability that exists in real soils and other catchment attributes, could lead to larger differences in response than we have simulated. Our results show that even subtle differences in field conditions may lead to large differences in growth. It remains now to test these arrangements in real field trials to be undertaken over the next few years.

Our study illustrates the complexity in trying to reproduce real systems with numerical models. It also illustrates the value of complex physical models, because by evaluation of the results we see where inconsistencies in data or incomplete descriptions of nature exist. We will never be able to reproduce the full richness of nature in computer models, but by continually improving our models and testing them through as many conditions as possible we can explore the implications of our understanding. It is when our models fail to reproduce apparent observations that we learn the most from them – either about our conception of nature, or about the data we have collected to test it.

7. ACKNOWLEDGEMENTS

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