Predicting the Water Use and Growth of Plantations on Hillslopes: The Impact of Planting Design

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Abstract: This paper presents the results of an investigation involving the calibration and testing of an ecohydrologic model, TOPOG-Dynamic. We describe how the model was used to simulate the water use and growth of different plantation designs sited on a hill-slope where lateral flow of water is significant. Model results were compared to measured leaf area index, wood volume, and pasture and plantation transpiration. The model performed well giving confidence in the model parameterisation. Following calibration the model was used to simulate how water use and growth of the belt plantation could behave in the future. Wood volume predictions from this simulation compared well to those measured and modelled in other studies. Modelling exercises supported findings from field investigations that growth at the upper edge of the tree belt was enhanced as a result of the run-on of water from upslope areas. A new plantation design, covering the same area as the belt plantation, but consisting of four narrow strips of trees rather than one wide strip was also simulated. This four strip design was aimed at utilising run-on from up-slope and inter-strip areas. The simulations showed that plantation growth and water use were enhanced in the strip planting. The strip planting produced 9% more wood, and transpired 23% more water than the belt plantation. The scenario modelling technique used shows potential as a means for developing guidelines for agroforestry design.

Keywords: Scenario modelling; Plantation; Water balance; Carbon Balance; Agroforestry; Topog_Dynamic

1. INTRODUCTION

Land degradation resulting from rising watertables is a major issue in many parts of Australia. This problem has resulted from the replacement of deep rooted, high water-use, native species with shallow rooted crops and pastures that use much less water. Remediation and prevention of the land degradation problems associated with high watertables (i.e. land salinisation and waterlogging) is necessary to prevent further productivity losses.

The establishment of small plantations strategically located on farms, commonly referred to as agroforestry, appears to show potential as a means of reversing trends in rising watertables. The benefits of establishing agroforestry systems are two-fold; firstly, water balance benefits can be achieved through enhanced evapotranspiration (ET), and secondly, trees can become a new source of income through the timber produced.

The key to successful incorporation of trees into farming systems lies in the ability to locate trees in the best possible position in the landscape in order to derive the optimum environmental benefits and growth. With this objective, many different planting strategies in different hill-slope locations have been trialed in Australia [e.g. Bari and Schofield, 1992; Marshall et al., 1997]. In previous field investigations [McJannet et al., 2000; McJannet and Vertessy, 2001] we reported on the performance and behaviour of an agroforestry system in the Warrenbayne area of Victoria, which was designed to intercept water moving through the landscape from the upper slopes to foot-slope discharge areas. In these field investigations the importance of plantation edge effects and the run-on of water from up-slope areas into the upper edge of the plantation were identified as important contributors to plantation productivity and survival.

The establishment, and monitoring of agroforestry designs is an expensive and time consuming process. Hence, the ability to predict the relative performance of different plantation designs on a hill-slope is highly desirable. We have developed a modelling approach that enables us to simulate the performance of agroforestry designs under different conditions, or scenarios.

This paper presents the calibration, testing, and use of the TOPOG-Dynamic modelling framework. Two applications of the model are presented. Firstly, the growth and water use of the existing plantation was simulated over a 30 year period. Secondly, the model was used to analyse the effects of different plantation design on water balance and plantation growth.

2. MODEL DESCRIPTION

TOPOG-Dynamic is a physically based ecohydrological model that simulates the three-dimensional water and solute dynamics within a catchment (as a set of coupled one-dimensional and two-dimensional equations) on a daily time-step, and couples these to plant growth and carbon allocation [Silberstein et al., 1999] (Figure 2). This model is a development of an earlier version called TOPOG-IRM [Vertessy et al., 1996; Dawes et al., 1997].

TOPOG-Dynamic uses Richards' equation for vertical soil moisture flow, which is solved using a finite difference scheme on a vertically distributed soil, and Darcy's Law for lateral saturated flow. The surface energy balance is based on the Penman-Monteith model [Monteith and Unsworth, 1990] which drives transpiration for up to two canopy surfaces and evaporation at the soil surface. Radiation transmission through the canopy follows the Beer-Lambert Law, and the ambient vapour pressure deficit of the understorey and soil surface are modified using an adaptation of the technique of Grantz and Meiner [1990] as described by Vertessy et al. [1996]. Soil water extraction by the roots is distributed through the multi-layered soil and represented as a sink term at each of the soil depth nodes.

The plant growth module in TOPOG-Dynamic and its predecessors has been described in detail by other authors, however, this version of the model is different from those previously used [Vertessy et al., 1996; Dawes et al. 1997; Silberstein et al., 1999] in that it includes new procedures for allocating carbon to stems and leaves. The new version employs concepts from the 3-PG forest productivity model of Landsberg and Waring [1997]. The 3-PG model uses simple allometric relationships to estimate the partitioning of carbon into stems and leaves. These allometric ratios, which are widely available for many species and locations and are relatively easy to measure, can be used to constrain tree growth patterns [Landsberg and Waring, 1997]. The allometric ratios are determined in the model using the mass of foliage and the mass of stem (including bark and branches). The allometric relationship used to describe the partitioning between the mass of foliage and stems takes the following form:

$$W_i = a_i B^{n_i} \tag{1}$$

Where W is the total mass of the tree and I denotes any component part.

In earlier versions of TOPOG-Dynamic carbon partitioning above ground between stems and leaves was assumed to be 50% to each. This has been updated with the adoption of the partitioning logic of Landsberg and Waring [1997]. The proportion of carbon assimilated (a_{roots}) below ground is determined as follows:

$$a_{roots}=(1-b)/(1+2.5x_w) \tag{2}$$

where b is a parameter setting the minimum level of above ground partitioning and x_w is the "soil moisture-salinity stress" factor.

The allocation of above ground carbon to stems and leaves is determined using allometric relationships which are usually determined on an operational basis by foresters. The proportion attributed to stems (p_{stem})is given by:

$$p_{stem}=1/(1+A_{stem}W^{N_s}) \tag{3}$$

where A_{stem} and N_s are the allometric parameters determined from forest measurements, and W is the average stem mass in the stand.

Incorporation of 3-PG allometric relationships into TOPOG-Dynamic allows carbon to be allocated to stems and leaves in a more appropriate manner for different species.

All of these processes are calculated in each element in a mesh that represents the terrain. The elements are bounded above and below by contours, and aligned along flow trajectories down the slope.

3. FIELD INVESTIGATIONS

3.1 Site Description

Field measurements were conducted in a belt plantation in the Warrenbayne area of Victoria.

This plantation is sited on a hill-slope approximately 600 m long. Upper slopes have gradients of approximately 20% while at lower slopes it is approximately 5%. The soils are approximately 10 m thick beneath the plantation with thinner deposits up-slope and thicker down-slope. The mean annual rainfall for this are is 860 mm, however, year to year variability in rainfall is pronounced and drought periods are not uncommon. A more detailed description of the site is given by McJannet et al., [2000].

Soil distribution and depth over the hill-slope was determined through the drilling of a transect of bore holes from the hill-top to the foot-slope. The basic soil profile consisted of a 1 m thick A horizon overlying a thick B horizon of colluvial material, varying between 1 and 10 m thickness.

3.2 Field Measurements

An automatic weather station was used to measure temperature, humidity, solar radiation and rainfall. The leaf area index (LAI) of the canopy was measured periodically using an LAI-2000 Plant Canopy Analyser.

Plantation transpiration was measured using sap flow loggers and pasture transpiration was measured using a Bowen Ratio system [McJannet et al., 2000].

The wood volume of the plantation was determined on six occasions during the first five years of plantation establishment.

4. MODEL PARAMETERS

The model was set up with a mesh of 722 elements generated from a digital elevation model (DEM) and covering 9.1 ha of the hillslope. Average element size was 126 m^2. Soil profiles and vegetation were distributed across the element network so that spatial variability in these components could be represented.

Vegetation within the plantation area of the hill-slope was represented as a two layer system, with an overstorey of trees and an understorey of pasture. The remainder of the hill-slope was covered by pasture only. The parameters used to define the physiological and energy balance properties of the two vegetation types are based on field measurements and published values from the literature.

Calibration was carried out by manually adjusting the calibration parameters to best fit measured LAI and estimated ET and wood volume accumulation.

5. MODEL TESTING

5.1 Growth Parameters

Observed and LAI and wood volume compared well for the first five years of plantation establishment (Figure 1), giving confidence in the ability of TOPOG-Dynamic to predict the growth of trees.

5.2 Transpiration

The agreement between observed and simulated plantation transpiration was reasonable for the 30 day calibration period. The average transpiration rate measured was 2.01 mm d^{-1} while the average simulated transpiration rate was 2.38 mm d^{-1}.

The agreement between observed and predicted pasture transpiration rates was also good. Average daily pasture ET was measured as 0.5 mm d^{-1} for the calibration period, while the predicted pasture ET rate was 0.44 mm d^{-1}.

6. SIMULATED GROWTH AND WATER BALANCE

6.1 Growth Performance

Results from a 30 year simulation of leaf area index development for five selected elements within the plantation is shown in Figure 1A. After the first five years of simulation, the initial increasing trend in plantation LAI slowed, and LAI levelled out at an average of 3.3. Plantation LAI varied depending on different climatic conditions peaking at slightly greater than 4 during wet conditions and dropping to as low as 2.2 during droughts.

The average wood volume from selected elements over the 30 year period is shown in Figure 1B. Also shown are measured [Stackpole et al., 1999; Harper et al., 1999; Morris, 1999], and modelled [Morris, 1999] wood volumes for other *E. globulus* plantations. This comparison gives confidence in the ability of TOPOG-Dynamic to estimate reasonable wood volumes for the Warrenbayne plantation.

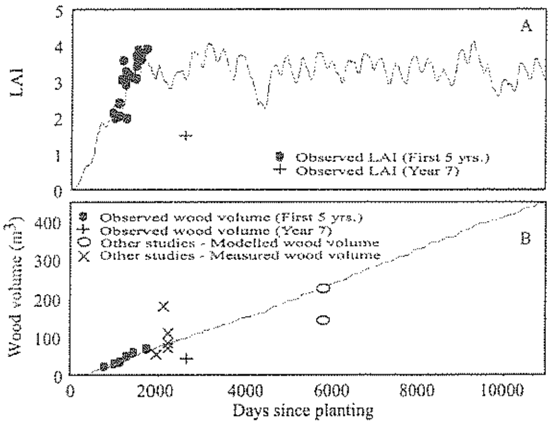

Figure 1. Observed and simulated LAI (A) and wood volume (B).

Figure 1 shows observed LAI and wood volume for the plantation for the five year calibration period, with recently (Year 7) observed LAI and wood volume, that are much lower than predicted. The reason for this is that the synthetic climate file and the real climate data for this period are quite different. In reality the plantation experienced two years of drought around year 7, whereas the synthetic climate data, which is recycled historic data, had more rainfall. However, although TOPOG-Dynamic can simulate decline in live wood in a stand, it is unable to simulate individual tree mortality as a result of drought stress. Consequently, the effect of such an extreme drought would probably not be adequately simulated, even with the correct climate.

The spatial pattern of average annual ET for all elements of the plantation after the 30 year rotation is shown in Figure 2A. A clear characteristic of this figure is the large difference between ET of the pasture and plantation. Also of importance is the pattern of average annual ET found within the plantation. All of the elements at the upper edge of the plantation have used considerably more water than those at the bottom edge. This a result of run-on of moisture from up-slope pasture areas.

Cumulative wood volume production for all elements after the 30 year rotation is shown in Figure 2B. As with ET, tree growth was greatest at the upslope edge of the plantation where water supply was supplemented by run-on. The average total wood volume for the plantation at the end of the 30 year rotation was 430 m^3 ha^{-1}.

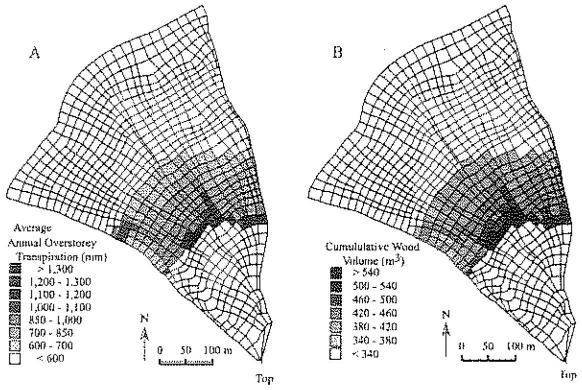

Figure 2. Average annual ET (A) and Wood Volume (B) after a 30 year simulation with belt planting.

7. SCENARIO ANALYSIS

7.1 Plantation Design

Field measurements revealed the importance of the run-on process to plantation transpiration and growth [McJannet and Vertessy 2001] and were also simulated for the current plantation layout.

To take full advantage of the increased water use and productivity found at the upper edge of the plantation, a new plantation design based on the utilisation of the run-on effect was proposed. This design was made up of four narrow strips of plantation which are positioned across the hill-slope. These strips are about 30 m wide and are separated by a width of about 60 m. The strips cover the same area of the hill-slope as the wide belt .

Using the same topographic network, soil profiles, climate data and vegetation parameters developed for the growth and water balance of the Warrenbayne plantation, we then simulated the productivity of the strip planting design.

7.2 Scenario Modelling Results

The advantage to the strip plantations of run-on from up-slope and inter-strip areas is shown by Figure 3A. The upper edge of all of the plantation strips has higher ET than the lower edge, with many elements using an average of 1300 mm y^{-1} over the 30 year period. As with the tree belt simulation, some areas of the strip planting configuration have very low ET as a result of waterlogging induced by topographic focussing and water table perching in the lower slopes.

The spatial pattern of wood volume after 30 years growth in each of the plantation strips is shown in Figure 3B. The impact of run-on on plantation growth is clearly illustrated in this figure. The upper edges of all four of the plantation strips show elevated wood production, usually in the 500 to 540 m^3 ha^{-1} range.

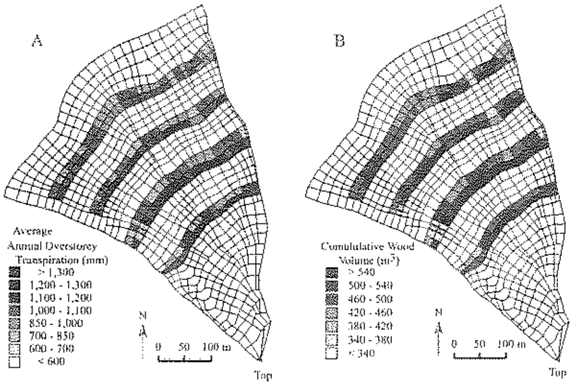

Figure 3. Average annual ET (A) and Wood Volume (B) after a 30 year simulation with strip plantations.

7.3 Comparison of Plantation Designs

Figure 4A shows a comparison of the average annual transpiration for each five year interval of plantation establishment for the wide belt and narrow strips. The transpiration of the strip plantation was greater than that of the belt configuration. During the first ten years of simulation, transpiration of the belt plantation was greater than that of the strips but this is reversed for the remainder of the 30 year simulation. Average annual transpiration for the 30 years simulation was 1190 mm for the strips plantation and 970 mm for the belt plantation. After 30 years of growth, the strip planting configuration had transpired 23% more water than the belt configuration.

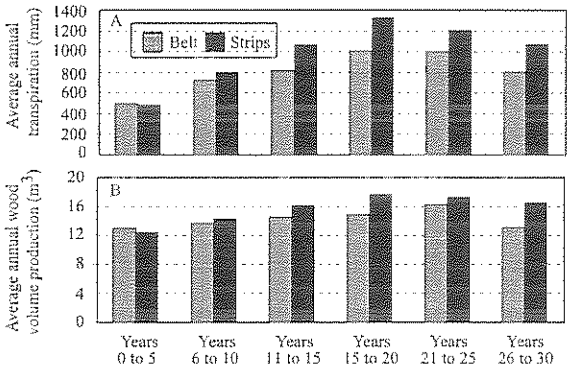

Figure 4. Average annual transpiration (A) and wood production (B) for each 5 year interval.

The total wood production for each five year interval of plantation growth shows a similar pattern to average annual transpiration (Figure 4B). Average annual wood production for the strips plantation was 15.7 m^3 compared to 14.3 m^3 for the belt planting configuration. At the end of the 30 year period the strips had produced 472 m^3 of wood compared to 428 m^3 for the belt configuration, a difference of 9%.

8. DISCUSSION AND CONCLUSIONS

Testing of TOPOG-Dynamic predictions gave us confidence in the model parameterisation and the model's ability to predict water balance and growth performance of a plantation. We got reasonable agreement between observed and predicted values of plantation LAI and wood volume, pasture and plantation transpiration.

With confidence in the model's predictive capabilities we then simulated the growth of the belt plantation at the Warrenbayne site over a 30 year period and demonstrated that the wood volumes predicted were comparable to other modelled and measured values in the literature for *E. Globulus* plantations.

It is acknowledged that one of the weaknesses of TOPOG-Dynamic is its inability to simulate the death of individual trees due to drought or water-logging stresses. This, with the fact that we did not have access to climate data through the drought period, resulted in large differences between predicted and observed wood volume and LAI values in the plantation at year 7. However, the strength of the modelling lies in its potential to predict relative differences in growth and water consumption for different plantation designs. Future developments of TOPOG-Dynamic will include routines for inducing individual tree mortality and stand thinning during drought or waterlogging for extended periods.

A scenario modelling exercise was undertaken to test the belief that the productivity of plantations could be enhanced by utilising the run-on of moisture from upslope areas. We simulated a strip planting consisting of four narrow strips that covered the same area of the hill-slope as the belt planting configuration.

The results of the strip planting scenario showed that the run-on effect could be used to enhance plantation productivity and water use.

We conclude that hill-slope plantations should be designed take full advantage of run-on in situations where lateral flows of water on the hillslope are significant. This will be the case on steep hillslopes underlain by deep and permeable soils, or where surface runoff is common. run-on from up-slope areas as a means of supplementing rainfall and thus enhance water use and wood production.

Our investigation has provided a unique insight into the behaviour of plantations on hill-slopes. Most studies of agroforestry systems involve measurements on small plots within larger plantations, whereas our investigation has looked at the behaviour of a plantation in relation to its position in the landscape. This has enabled the affect of lateral processes on plantation behaviour to be assessed.

The simple scenario modelling approach which we have utilised in this investigation shows potential as a powerful predictive tool for agroforestry design. Further development and application of this approach will be the subject of a subsequent paper.

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