

Modelling the impact of native pastures to examine the relative effects of land use change

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Abstract: This paper describes (1) the development and validation of a native pasture model that accounts for species abundance, (2) the integration of the native pasture model into a catchment framework and (3) the likely biophysical trade-offs associated with increasing the proportion of native perennial pasture species within a pilot catchment. The rationale for developing the model was to build on the conceptualisation of contemporary pasture models and include new algorithms that better represent native grass species commonly found in temperate climate regions of Australia. The native pasture model is phenologically based and simulates both daily pasture growth and soil water dynamics. It was developed and validated against data from field experiments conducted at Wagga Wagga in NSW, Australia, for two native grass species, *Austrodanthonia* spp. (winter dominant C₃) and *Bothriochloa macra* (summer dominant C₄). The model predicted seasonal pattern and inter-annual variation of soil moisture contents and green leaf area index (GLAI) for various planting densities. There was a high correlation between the simulated and measured soil moisture contents ($r^2 = 0.81$, $p < 0.0001$ for *Austrodanthonia* spp; $r^2 = 0.73$, $p < 0.0001$ for *Bothriochloa macra*) and GLAI ($r^2 = 0.66$, $p < 0.0001$ for *Austrodanthonia* spp; $r^2 = 0.83$, $p < 0.0001$ for *Bothriochloa macra*) at actual measurement dates.

The native pasture model was integrated into a physically-based catchment modelling framework (Catchment Analysis Tool, CAT) to provide a flexible platform for simulating the environmental impacts of various pasture management options and the likely consequences of land use changes on catchment dynamics. This catchment model comprises numerous vegetation modules (including cropping, forestry and alternative pasture models) of varying complexity. An example of how the native pasture model can be used within the CAT framework is described by the application to the Bet Bet catchment which has been identified as a high salt exporting catchment within the Murray Darling Basin of Australia. The Bet Bet catchment currently yields and exports annually approximately 36,056 ML and 20,000 tonnes of salt respectively. The grazing of unimproved pastures is the dominant land use within the catchment such that economically viable options for increasing perenniality in the catchment are limited to working with the native perennial grasses already present and targeted tree planting. The study evaluated the water yield, saturated area and salt load trade-offs associated with increasing the proportion of native perennial pasture species. Scenarios considered varying proportions of summer or winter dominant native pastures across the catchment in comparison to reforestation. Results indicate that complete reforestation of the grazing area would reduce both stream flow and salt exports, by 6,299 ML yr⁻¹ and 10,486 tonnes salt yr⁻¹ respectively. Complete catchment coverage of *Bothriochloa macra* was estimated to increase stream flow by 3,987 ML yr⁻¹ as well as to reduce groundwater inflows by 1,429 ML yr⁻¹ (2,745 tonnes salt yr⁻¹). In contrast, *Austrodanthonia* spp. pasture was estimated to increase stream flow by 4,378 ML yr⁻¹ and increase salt export by 714 tonnes salt yr⁻¹. Targeted restoration of either summer or winter dominant native pastures within the steeper regions of the catchment with slopes greater than 5% (representing 11% of the catchment area) was considered. Results show that restoration of *Bothriochloa macra* in the upper catchment increased stream flow by 132 ML yr⁻¹ and reduced salt loads by 472 tonnes salt yr⁻¹, whereas restoration of *Austrodanthonia* spp. increased stream flow by 409 ML yr⁻¹ and reduced salt loads by 109 tonnes salt yr⁻¹. In contrast, reforestation in the upper catchment reduced stream flow by 5,650 ML yr⁻¹ and salt loads by 8,689 tonnes salt yr⁻¹. Overall, results suggest that increasing the proportion of summer active native perennial grasses across large parts of the catchment may be an effective salinity management option for reducing recharge and salt loads to rivers.

Integration of a validated native pasture model into the CAT framework is shown to provide the capability to simulate the long-term effects of land use changes in the landscape on catchment dynamics.

Keywords: Native pasture model, Catchment Analysis Tool (CAT), catchment yield and salt export.

1. INTRODUCTION

Australia is estimated to have approximately 190 Mha of unimproved pasture (ABS, 2008), the majority of which are grasses which are indigenous (native) to Australia. Whereas many of the introduced species that have their origins in Europe, Asia, Africa and other parts of the world are considered more nutritious and have been widely adopted and extensively used in grazing enterprises, many of the native grasses are drought resistant and require low fertiliser and management inputs (CSU, 2009). These characteristics make them suitable for inclusion into an integrated grazing system, particularly in low rainfall areas. To assess the environmental and productivity impacts of different management strategies aimed at utilising native pasture grazing systems requires the application of a biophysical catchment model. However few catchment scale biophysical models adequately describe the phenological dynamics that distinguish different pasture species.

Three one-dimensional biophysical models have been extensively used to model native pastures in Australia, namely GRASP (McKeon *et al.*, 1982), GRASSGRO (Freer *et al.*, 1997) and the SGS pasture model (Johnson, 2008). GRASP has been designed to model native pastures in tropical and sub-tropical environments of Northern Australia. Originally based on the pasture production model outlined by McKeon *et al.* (1982), GRASP is mechanistic by nature though algorithms within the model are empirically derived. It does not simulate phenological development of the sward and consequent changes in root:shoot partitioning, nor does it simulate some components of the soil water balance (such as run-on, lateral drainage or unsaturated flows in saturated soils) or animal behavioural attributes.

In contrast, GRASSGRO combines animal, soil moisture and pasture growth models with management regime to simulate pasture and animal production of grazing enterprises (Moore *et al.* 1997; Clark *et al.* 2000) at a number of locations and soil types using a daily time-step with the only input data required being daily meteorological data. The GRASSGRO decision support tool also has the capability to simulate simple grazing production systems with outputs including an economic analysis and a simple soil water balance.

The Sustainable Grazing Systems (SGS) Pasture Model was developed as part of the Sustainable Grazing Systems National Experiment for the purpose of analysing data and processes within the national experimental sites (Johnson *et al.*, 2003). The model simulates water dynamics, nutrient dynamics, herbage accumulation, animal growth and management on a daily timestep. The underlying model conceptualisation philosophy was to simplify complex processes whilst ensuring appropriate system behaviour in addition to providing the user with an interface that enables most parameters to be modified. Johnson *et al.* (2003) highlighted the need to balance complexity, realism and tractability with simple parameterisation. Whilst specific parameter profiles for some of the introduced temperate species (e.g. phalaris, annual ryegrass, perennial ryegrass) have been constructed, generic native perennial grass profiles were created for both C3 and C4 grasses.

Catchment-scale biophysical models typically use generic vegetation modules to estimate transpiration under various land-uses. For instance, SWAT (Neitsch *et al.*, 2001) adopts a heat unit approach to represent all land uses. More broad-scale catchment models (SIMHYD) typically estimate transpiration based on the FAO56 crop factor approach. In contrast, the Catchment Analysis Tool (CAT) comprises many farming systems models linked within a catchment framework with allowance for landscape connectivity and connection to a distributed, multi-layered groundwater model (Beverly *et al.* 2005). This catchment model was selected to integrate the developed native pasture sub-model as the catchment model construct facilitates incorporation of different pasture/crop/tree modules of varying complexity. It was deemed computationally efficient to undertake development of a native pasture model that incorporates concepts previously published with revision to account for plant abundance or density.

This paper describes the development of a native pasture growth model to further investigate the role of key morphological features for water use possessed by the grasses *Austrodanthonia* spp. and *Bothriochloa macra* and the embedment of this model into the CAT with application to the Bet Bet catchment.

2. THE NATIVE PASTURE MODEL

2.1. Overview

The native pasture model uses a mass balance approach to estimate soil/water/plant interactions on a daily timestep. Daily pasture growth is represented using the phenological concepts embedded in a number of contemporary dynamic biophysical pasture models (Littleboy and McKeon, 1997; Johnson *et al.*, 2003; Moore *et al.*, 1997) designed to simulate daily pasture growth and soil water dynamics. The model assumes that plant growth is based on a cycle of phenology to describe net primary production, assimilate partitioning

between root, shoot and stems, decay functions and root mobilisation processes. The allocation and transfer of biomass from immature development through to dead/litter and ultimately null, is controlled by a series of decay functions. The model is capable of simulating a series of swards that compete based on root development and intercepted light. The physiological status of the plant through these cycles is expressed through several discreet phenostages, (vernalisation, vegetative, reproductive, flowering and post-reproductive) influenced by, and incorporating, a variety of different environmental controls. Additionally, transitions between stages are governed by elapsed time or incrementing environmental variation. The phenological status influences the allocation of net primary production (NPP) throughout the system but does not control the amount of NPP produced. A full description of the model is detailed in DPI (2009).

The model was constructed to simulate a native grass experiment conducted at Wagga Wagga, NSW, whereby the C₃ grass *Austrodanthonia spp.* and the C₄ grass *Bothriochloa macra* were planted in a randomised complete block design at four planting densities (4, 9, 16 and 25 plants/m²) and monitored for changes in soil water content to a depth of 180 cm.

A tissue pooling system similar to that of the SGS model (Johnson *et al.*, 2003) was used to describe the overall biomass/energy transfer system with aboveground photosynthates passing through immature, mature, senescing and dead phases on the way to a litter pool and eventually a null pool which returns carbon to the soil. The rate at which this material passes through these pools is species specific, though increases with increasing temperature and decreasing soil moisture.

2.2. Key model enhancements

Consistent with GRASSGRO (Moore *et al.*, 1997), net primary production is a function of solar radiation and light interception, with limitations on growth based on soil moisture status, water logging and temperature. Available light is a function of green leaf area index (GLAI) which has been modified from Freer *et al.* (1997) to contain a shading function as found in Equation 1.

$$AL_j = \left(\frac{1 - \exp(-k_j GLAI_j)}{1 - \exp(-k_i GLAI_i)} \right) \cdot (1 - (Glfsshade_j)) \quad (1)$$

where AL_j is the available light for species j , k_j is the average extinction coefficient for species j , $GLAI_j$ is the green area index of a species' established or seedling plants for either species j or for the entire pasture i and $Glfsshade_j$ is the available light limitations due to shading by pasture biomass

The shading function is sigmoidal in shape and relates potential light interception to pasture biomass (Equation 2). As native pastures often retain a proportion of standing dead between seasons, it was necessary to account for this to prevent overproduction when allowed to grow tall and rank.

$$Glfsshade_j = 1 - (0.9(SIG(B_{min}, B_{max}, shdshp))) \quad (2)$$

where B_{min} is the minimum biomass levels for the pasture where shade impacts available light, B_{max} is the maximum biomass levels for the pasture above which biomass has no additional impact on available light and $shdshp$ is the curvature function for biomass and shading. The sigmoidal function is based on Freer *et al.* (1997) as defined by

$$SIG(x, a, b) = \left(1 + \exp \left(- \frac{2 (\ln(0.95) - \ln(0.05))}{b - a} \left(x - \frac{a + b}{2} \right) \right) \right)^{-1} \quad (3)$$

where x , a and b represent B_{min} , B_{max} and $shdshp$ respectively

Two options were developed to explain the relationship between actual basal area and the basal area coefficient, one mechanistic in nature, the other empirical. The mechanistic basal equation assumes a sigmoidal function exists between the minimum and maximum potential basal area. An actual basal area of 0.3 was assumed to equate to maximum potential growth thus leading to Equation 4.

$$K_{BA,j} = 1 - \exp(-12x_j)^4 \quad (4)$$

where $K_{BA,j}$ is the basal area coefficient for species j and x_j is the user defined basal area of species j .

The second basal equation was formulated from a non-linear regression analysis of daily growth during the growing season (October and November for *Austrodanthonia* spp.) to basal area for each species. User-defined parameters K_{B1} and K_{B2} were derived from this relationship for each species and incorporated into the power function in Equation 5.

$$K_{BA,j} = K_{B1,j} x_j^{K_{B2,j}} \tag{5}$$

where $K_{BA,j}$ is the basal area coefficient for species j , x_j is the user defined basal area of species j , $K_{B1,j}$ is the user defined coefficient for species j and $K_{B2,j}$ is the user defined exponent for species j .

Other key modifications include temperature and water logging growth limiting factors, various root distribution functions, fertility impacts on net primary production and phenostage growth partition ratios as reported in Southwell (2009).

2.3. Parameter estimation

Key parameters, namely specific leaf area, root distributions and basal area, were set based on the experimental data collected whereas other values were based on reported estimates from the literature (e.g. Robinson and Archer, 1988; Cook *et al.*, 1976), or else were set based on anecdotal observation. Parameters associated with processes not directly measured such as coefficients describing response curve shape were set using the non-linear parameter estimation software package PEST (Doherty, 1994). This software performed iterations comparing modelled with observed LAI and soil water data using weighted least-squares to estimate parameter values that most satisfactorily reproduce observed outcomes.

2.4. Pasture growth

The correlation coefficient (r) between all measured *GLAI* data and modelled data was 0.93 as seen in Table 1 with a corresponding regression coefficient (r^2) of 0.82. When considered with least squares regression intercept (b) and least squares regression slope (a) values close to 0 and 1 respectively, this suggests that the model predictions are reasonable when compared to observed values of *GLAI*. Overall, the root mean square error as a percentage of the mean (μ RMSE) for all data was only 12.67%, reducing to 7.67% and 8.23% at the *Bothriochloa macra* (*B*) and *Austrodanthonia* spp. (*D*) species level respectively.

2.5. Soil moisture

The relationship between soil water deficit observations and modelled estimates are summarised in Table 2. The correlation coefficient (r) for all data was calculated to be 0.91 (Table 2) with a corresponding regression coefficient (r^2) of 0.87. Correlation values decreased with decreasing density for the *Austrodanthonia* spp. treatments. This did not

Table 1: Statistics of predicted to observed green leaf area (*GLAI*) for all data, *Bothriochloa macra* (*B*) treatments, *Austrodanthonia* spp. (*D*) treatments and the two species at each of the planting densities of 4, 9, 16 and 25 plants m^{-2}

	b	a	r	r ²	RMSE
All data	0.018	0.92	0.93	0.82	0.016
B.macra (B)	0.043	0.90	0.93	0.83	0.014
Aust.spp (D)	0.002	0.84	0.93	0.66	0.005
4B	0.045	1.03	0.91	0.84	0.019
9B	0.043	0.70	0.95	0.87	0.032
16B	0.032	1.00	0.94	0.89	0.025
25B	0.031	0.11	0.95	0.83	0.035
4D	0.002	0.43	0.92	0.26	0.008
9D	0.002	0.66	0.94	0.32	0.007
16D	0.006	0.82	0.95	0.48	0.007
25D	0.038	0.75	0.95	0.68	0.015

Table 2: Statistics of predicted to observed soil water deficit (SWD) for all data, *Bothriochloa macra* (*B*) treatments, *Austrodanthonia* spp. (*D*) treatments and the two species at each of the planting densities of 4, 9, 16 and 25 plants m^{-2} .

	b	a	r	r ²	RMSE
All data	18.47	0.91	0.91	0.87	20.87
B.macra (B)	32.60	0.81	0.83	0.87	28.80
Aust.spp (D)	2.87	1.11	0.81	0.87	15.92
4B	29.32	0.95	0.92	0.84	34.86
9B	39.34	0.78	0.93	0.91	30.50
16B	20.03	0.84	0.94	0.89	22.60
25B	35.09	0.79	0.91	0.91	25.74
4D	-5.41	1.16	0.52	0.85	14.37
9D	0.68	1.24	0.57	0.89	18.43
16D	1.81	1.13	0.70	0.90	14.32
25D	13.16	0.97	0.83	0.91	16.19

occur for *Bothriochloa macra* though least squares regression intercept values (b) were further from the origin.

3. CATCHMENT MODEL

The modelling approach used the Catchment Analysis Tool (CAT) framework (Beverly *et al.*, 2005; DPI, 2009) to assess the on-site and off-site impacts of various vegetation restoration strategies to reduce catchment salt exports. This model uses a combination of a suite of farming system models linked within a catchment framework with allowance for landscape connectivity. The farm-scale models range in complexity from a simple crop factor approach to phenologically based crop, pasture and forest growth modules and account for position in the landscape (topography, soil type, aspect and slope), climate, land use and land management and simulate water balance, nutrient transport and production on a daily time step. A common water balance, erosion, nutrient, carbon and soil evaporation module is used by all the available crop-growth models. The CAT has also been developed to link with the fully distributed multi-layer groundwater model MODFLOW (McDonald and Harbaugh, 1988) to account for groundwater dynamics and provide a whole-of-catchment water balance whereby recharge estimates from the farming system models are explicitly incorporated into the groundwater model.

4. THE BET BET CATCHMENT APPLICATION

4.1. Model application objectives

The integration of the native pasture model into the catchment framework was evaluated by application to the Bet Bet catchment which is located in North Central Victoria, Australia (Figure 1). The Bet Bet catchment covers approximately 64,432 ha and is predominantly used for grazing (71%) with 19% being treed and the remaining 10% being categorised as towns, roads and water bodies and horticulture. A major objective of this study was to assess the potential consequence of future land-use options on the catchment hydrology and salt balance. Six scenarios were carried out using the CAT framework utilising the native pasture model to examine (a) the impact of applying the native pasture model on estimates of catchment hydrology compared to previous hydrologic estimates derived using a simple pasture model, and (b) the impact of changing from a predominantly C3 pasture to a C4 pasture. Six scenarios were considered, namely: (1) current land use with pasture being represented by an unimproved pasture; (2) current land use with C3 native pasture replacing all previous pastures; (3) current land use with C4 native pasture replacing all previous pastures; (4) restoring C3 native pasture on land classes of greater than 5% slope in the upper Bet Bet creek study area; (5) restoring C4 native pasture on land classes of greater than 5% slope in the upper Bet Bet creek study area; (6) replacement of all grazed pasture with trees across all land classes. Simulated depth to watertable, stream yield, and change in salt loads were compiled for each scenario.

4.2. Calibration of the Bet Bet model

The linked surface water/groundwater Bet Bet catchment model was calibrated based on matching streamflow, salt loads and groundwater hydrograph data for the period 1974-2000. Streamflow results were also compared to the Loddon REALM Model (SKM 2004). The mean annual results derived using the CAT for baseflow and streamflow were 17 mm/yr and 55 mm/yr respectively compared to REALM estimates of

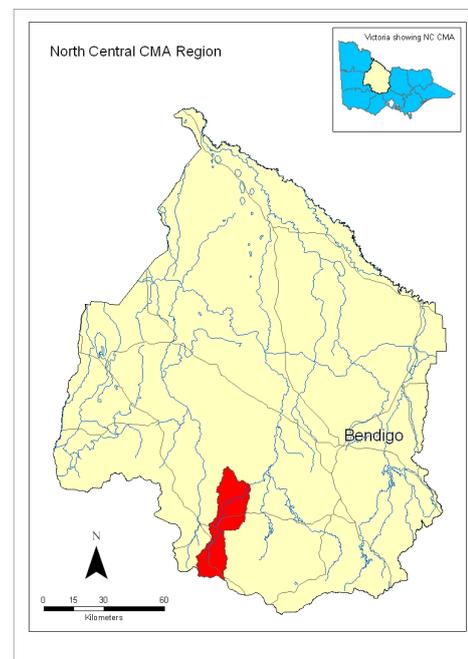


Figure 1. Location of the Bet Bet catchment within the North Central Catchment Management Area of Victoria, Australia

13 mm/yr and 57 mm/yr. A coefficient of determination of 0.71 was derived based on comparing monthly observed versus predicted streamflow with a Nash-Sutcliffe Index (NSI) (Nash and Sutcliffe, 1970) of 0.74.

A multi-layered distributed MODFLOW groundwater model had previously been developed (Beverly *et al.*, 2008) for the Bet Bet catchment and calibrated for the period 1974 to 2000 inclusive using groundwater bore hydrograph datasets and mapped discharged site information. This model was used in the current study to estimate the potentiometric surface and groundwater discharges under various land-use scenarios. The calibrated groundwater model estimated an area of 16,200 ha to be subject to high watertables less than 1.5 metres from surface which was in agreement with the groundwater discharge based on aerial photographs of 15,500 ha.

Table 3: Mean annual water balance components (mm/yr) for each scenario considered. Also summarized are the corresponding saturated areas and changes in stream flow and salt export relative to current practice.

Scenario	1 Current practice	2 B. macra	3 Austrod.	4 B. macra on slopes >5%	5 Austrod. on slopes >5%	6 Tree with fixed canopy
Water Balance (mm/year):						
Rainfall	557.2	557.2	557.2	557.2	557.2	557.2
Soil evaporation	188.1	175.1	149.7	186.7	183.5	203.9
Transpiration	298.8	315.4	327.1	301.2	302.6	330.4
Evapotranspiration	486.9	490.5	476.8	487.9	486.0	534.4
Quick flow	22.1	28.4	29.0	22.3	22.7	12.1
Recharge	47.5	38.9	51.7	46.3	47.8	12.5
Saturated area (ha)						
<2.0 m	5,368	4,181	5,612	5,070	5,149	1,755
<1.0 m	733	515	785	689	718	155
<0.1 m	186	106	197	167	176	37
Changes relative to Scenario 1.						
Recharge (%)	0	-18.0	9.0	-2.4	0.7	-73.8
Stream flow* (ML/year)	0	3,987	4,378	132	409	-6,299
Salt output (t/year)	0	-2,745	714	-472	-109	-10,486

* Stream flow calculated as the sum of quick flow and base flow as defined from the groundwater model

4.3. Scenario results

The key mean annual water balance components for each of the six scenarios considered are summarised in Table 3. These results are based on 1957 to 2005 modelled daily estimates. Also summarised are the associated long term changes in areas associated with various shallow depth-to-watertables. Scenarios 2 (Bothriochloa pasture replacing existing unimproved pasture throughout the catchment) and 6 (reafforestation) were found to have the greatest impact on groundwater dynamics in the Bet Bet catchment, reducing recharge by 18% and 74% respectively (Table 3) relative to Scenario 1 (current practice with unimproved pasture). As a consequence, less groundwater base flow was predicted to occur, reducing salt output from the catchment by 2,745 and 10,486 tonnes annually (Scenarios 2 and 6 respectively). Annual stream flow was also reduced in Scenario 6 by 6,299 ML yr⁻¹; however, due to greater quick flow in Scenario 2, stream flow increased by 3,987 ML yr⁻¹. Scenario 3 (Austrodanthonia pasture) increased recharge (9%), stream flow (4,378 ML yr⁻¹) and salt output (714 tonnes salt yr⁻¹) relative to Scenario 1.

5. DISCUSSION AND CONCLUSIONS

The developed native pasture model has been shown capable of estimating differences in soil water deficit and green leaf area index for summer and winter dominant growth native pastures. Integration of this model into the CAT catchment modelling framework provides the capability to simulate the long-term effects of

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land use changes in the landscape, such as pasture/crop/woodland conversions, on catchment dynamics. The results have shown the potential benefit of a highly summer dominant pasture on catchment hydrology with differences between the two native species evident, suggesting that increasing the proportion of summer active native perennial grasses across large parts of the catchment may be an effective salinity management option for reducing recharge and salt loads to rivers whilst enhancing water quality.

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