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An integrated approach to model the establishment, water use and growth of new perennial pasture species

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Abstract: Perennial pastures increase the sustainability of Australian cropping systems by increasing out-of season water use, improving ground cover and helping to avoid dryland salinity. *Medicago sativa* (lucerne) is the most common perennial legume pasture and is adapted to a wide range of environments, but it does not persist well in areas with acid soils or low summer rainfall (Cocks 2001). Under these scenarios, native herbaceous perennial legumes, such as *Cullen australasicum* (Cocks 2001), and the exotic perennial pasture legume *Bituminaria bituminosa* var. *albomarginata* (common name albo-tedera) are potential alternatives to the currently limited perennial forage options. However, the growth and adaptability of these legumes to high-input Australian agricultural systems are likely to differ from currently used pasture species and their pasture potential has not been widely studied, tested or predicted. This paper describes the modelling of three aspects of the performance of these species, with the overall aim of predicting their performance across Australian agricultural areas.

First, we quantified the early performance of these legumes, including early establishment and first summer survival, at three locations in the wheatbelt of Western Australia (WA): Buntine, Merredin and Newdegate. Lucerne was used as a reference. Initial analysis showed significant variability in their early adaptability and Principal Component Logistic Regression (PCLR) modelling revealed that temperature and a number of soil parameters (moisture, pH, available sulfur, available aluminium, conductivity and organic carbon) were all important in determining the early establishment and summer survival of these legumes under field conditions.

Second, a mechanistic physiological growth model was developed to estimate the daily net photosynthesis based on light decay down the canopy (Thornley 2002). Respiration and senescence rates were incorporated in the model to estimate the daily biomass loss and thus daily net dry matter production was estimated. The influence of drought on leaf expansion and senescence was accounted for through the changes in soil water potential. Thermal time and soil water potential were used to simulate the leaf area index development under drought.

Finally, crop phenology and growth parameters measured for the two species under a diverse range of soil and climatic conditions are being used to modify the existing Agricultural Production Systems Simulator (APSIM) lucerne module to simulate *B. bituminosa* var. *albomarginata* and *C. australasicum* growth and production in APSIM.

Once the models have been validated, they will be used to predict the performance of *C. australasicum* and *B. bituminosa* var. *albomarginata* under a wide range of environmental conditions in order to identify potentially suitable regions in WA, and across the country, for further trials and eventual adoption of these perennial pasture legumes. In addition, simulations will be done to predict future performance under expected climate change scenarios.

Keywords: APSIM, lucerne, modelling, native perennial pastures

1. INTRODUCTION

Perennial pastures are important to increase the water use of Australian agricultural systems, thus reducing the likelihood of dryland salinity developing and improving system sustainability. Removal of deep-rooted native perennial vegetation and replacement with annual crops and pastures in Australian arable lands during the last century has resulted in widespread salinity, which has in turn reduced the area of land suitable for growing crops. Incorporation of perennial legume pastures has the potential to reduce or avoid salinity and brings extra benefits to farmers such as reducing nitrogen-fertiliser costs, improving soil properties, and helping with disease and weed control. *Medicago sativa* (lucerne) is currently the perennial pasture legume most widely used in the wheatbelt of Western Australia (WA). However, lucerne is not well adapted to the marginal soils and the hot dry weather frequently prevailing in this region (Cocks 2001). A native legume, *Cullen australasicum,* and an exotic legume, *Bituminaria bituminosa* var. *albomarginata* (common name albo-tedera), have been studied as potential alternatives to lucerne in this area.

Microclimatic requirements for seedling establishment are much more restrictive than the conditions necessary for the persistence of mature perennial vegetation. Furthermore, emergence and seedling survival are key processes for the establishment of a uniform plant density, and are mainly controlled by the availability of water and the microclimate near the soil surface. Low rainfall, acidic soils and hot summers, common scenarios in the WA wheatbelt, would likely have further adverse effects on the early performance of new perennial pasture legumes and these effects are highly unlikely to be the same as occur of the reasonably well-studied lucerne. Therefore, there is an urgent need to study the early germination, emergence and establishment of these potential new perennial legume species under a range of marginal field conditions, as well as evaluate the productivity of mature plants under these conditions.

Models are powerful tools to test hypotheses, synthesise knowledge, describe and understand complex systems and compare different scenarios. Plant growth modelling has become a key research activity, particularly in the fields of agriculture, forestry and environmental science (Boote *et al*. 1998; Williams *et al*. 1989). Several types of plant growth models exist, with varying degrees of complexity, depending on their end use and application. The APSIM (Agricultural Production Systems Simulator) model has been successfully adapted to model the production of lucerne in agricultural systems in WA (Robertson *et al*. 2002). However, information on basic growth characteristics and environmental responses of new perennial pasture legume species is limited and their performance under diverse environmental conditions is not known. Furthermore, no attempts have yet been made to estimate, model or predict their production under a range of environmental conditions.

In this paper we explain the establishment, phenology and growth of albo-tedera and *C. australasicum* under a range of conditions in the WA wheatbelt and use to develop three separate models. First, data on seedling emergence and survival is being used to develop empirical models to predict early survival of these species under a range of soil and climatic conditions. Second, a mechanistic physiological growth model is being developed to estimate the photosynthesis, growth and biomass production of these species. Finally, crop phenology and growth parameters measured for the two species under a diverse range of soil and climatic conditions are being used to modify the existing APSIM lucerne module to simulate albo-tedera and *C. australasicum* growth. These models will eventually be used to predict the performance of albo-tedera and *C. australasicum* at locations within WA and the southern Australian wheatbelt with varying rainfall and temperatures. Performance under various management options, such as grazing regime and planting density, will also be examined, as will performance under a range of predicted climate-change scenarios. Each of these three models will be discussed.

2. MODELS OF SEEDLING ESTABLISHMENT AND SURVIVAL

2.1 Site description

Three experimental sites representing the WA wheatbelt were used in this study. They were located at Buntine (LIEBE group long-term research site, 20 km west of Buntine), Merredin (WA Department of Agriculture and Food Research Station) and Newdegate (WA Department of Agriculture and Food Research Station, 18 km west of Newdegate town site).

2.2 Plant material, field design and management

Albo-tedera, *C. australasicum* and *Medicago sativa* (lucerne) were used. Lucerne was included as a reference. Field sites were established in a blocked design, with six row replicates, with a 1 m gap between replicates. Each replicate consisted of rows, 1 m apart, where each row was assigned to a randomly selected accession of any of the species. Furrows were prepared and seeds were placed at a uniform distance and covered with a thin layer of fine top soil. Guard rows were established with lucerne. Sites were managed to be kept weed and pest free during the study period.

2.3 Data collection and statistical analysis

Sites were visited at one-month intervals and the number of seeds that had germinated and established was counted for all the species during each visit. The time at which the highest establishment counts were observed was recorded. Counts at this stage were used for the analysis of seedling establishment and for comparison purposes. Final seedling counts were recorded towards the end of the peak summer in January. Proportion of survival was calculated as the ratio between seedling counts during the final recording and counts observed at the peak establishment. Weather data for each site for the period of study was obtained from the Bureau of Meteorology web site. Soil samples representing the top 30 cm of soil were taken between rows from all three sites at the time of seeding. Each soil sample was analysed separately to determine physical and chemical characteristics. Further data on survival counts will continue to be taken in the future and this study will continue.

Statistical analyses were carried out to determine whether soil and weather data could be used to predict establishment and survival. Since both the establishment and survival data were binomial counts, logistic-ANOVA was performed in SAS, with PROC LOGISTIC. To reduce the dimensionality of the soil and weather data and examine variability within and across sites, PCA was performed in SAS with the standardised variables using Proc PRINCOMP. The principal components were then regressed against the establishment or survival counts to find significant relationships using a stepwise principal component logistic regression (PCLR) with a LOGIT link function. Throughout this analysis, lucerne was considered as the reference.

2.4 Preliminary Results

Initial analysis of establishment and survival showed that air temperature, soil moisture and rainfall were important for the initial establishment and survival of all species. Furthermore, soil characteristics such as pH, available sulfur, available aluminium, conductivity and organic carbon were also important in determining the spring establishment and summer survival of pasture species in the WA wheatbelt. However, analysis will continue in future with the collection of more data.

3. NOTATION AND UNITS

The full description of notations used in this paper is provided in Table 1.

Table 1. Parameter and variable descriptions used in equations.

Parameter/ Variable	Description	Parameter/ Variable	Description
L	Leaf area index	P_{can}	Canopy photosynthesis
T_{mean}	Daily mean temperature	R	Whole-plant respiration rate
T_b	Base temperature	R_g	Growth respiration
SM	Soil moisture status	M	Dry mass
I_0	Irradiance level above the canopy	t	Time
I_{leaf}	Incident radiation on a leaf	k_s	Senescence rate
k	Extinction coefficient	Y_g	Growth yield
m	Leaf transmittance	k_m	Maintenance coefficient
θ	Convexity of the response	f_i	Fraction of dry matter partitioned to each organ
α	Quantum yield	S_i	Sink strength of i^{th} organ
P_{max}	Maximum photosynthetic rate	S	Sink strength of all organs

4. GROWTH SIMULATION

For the purpose of parameterising the growth simulation, plant phenology and biomass production was recorded over time. Field trials established in the WA wheatbelt, as well as plants grown in the glasshouse facility at UWA, were used for this purpose. Weather data were obtained from the website of the Bureau of Meteorology.

4.1 Leaf area development

Leaf area development of the crop as a whole, rather than that of individual leaves, is sufficient for most crop growth model purposes (Marcelis *et al*. 1998). Thus, in our approach leaf area development (leaf area index-L) is described as a function of temperature sum and plant/soil water status.

$$L = f(T_{mean} - T_b).SM \tag{1}$$

where parameters and variables are described in Table 1.

4.2 Light profile in the canopy

The equations proposed by Monsi and Saeki (1953, translated 2005) for the light incident on a horizontal plane (I) (µmol PAR m^{-2} s^{-1}) and that incident on a leaf (I_{leaf}) at a depth L (leaf area index), are used to estimate the instantaneous light interception by the canopy.

$$I(L) = I_0 e^{-kL} \tag{2}$$

$$I_{leaf}(L) = \frac{k}{1-m} I(L) = \frac{k}{1-m} I_0 e^{-kL} \tag{3}$$

where parameters and variables are described in Table 1.

4.3 Canopy photosynthesis

The non-rectangular hyperbola for the response of instantaneous leaf photosynthetic rate (Thornley 2002), P_{leaf} (µmol CO_2 m^{-2} s^{-1}) to incident light, I_{leaf}, is estimated by,

$$P_{leaf} = \frac{1}{2\theta}(\alpha I_{leaf} + P_{max} - \sqrt{[(\alpha I_{leaf} + P_{max})^2 - 4\theta\alpha I_{leaf} P_{max}]}) \tag{4}$$

where parameters and variables are described in Table 1. Canopy photosynthesis (P_{can}) is estimated by considering sun and shade leaves in the canopy based on exponential light decay down the canopy and an acclimated rectangular hyperbola as described by Thornley (2002). L will be estimated on a daily time interval. I_0 is not averaged in space or in time, but rather each single value of I_0 is used to estimate P_{can}.

Whole-plant respiration rate (R) (µmol CO_2 m^{-2} s^{-1}) can be estimated by considering growth respiration (R_g) and maintenance respiration (R_m) components (Thornley & Cannell 2000). Therefore, carbon conservation can be described as,

$$P_{can} = \frac{dM}{dt} + k_s M + R \tag{5}$$

Further, the growth respiration component is proportional to the growth rate of mass (dM/dt + k_sM) and the maintenance component is proportional to the dry mass (M). Thus mass growth rate is,

$$\frac{dM}{dt} = Y_g(P_{can} - k_m M) - k_s M \tag{6}$$

where parameters and variables are described in Table 1. The ratio of respiration to gross photosynthesis will be estimated during the growth of the plant under different water and nutrient regimes, and is used in simulation.

4.4 Dry matter partitioning

In many crops neither the source nor the transport path are dominating factors in regulating dry matter (DM) partitioning at the whole plant level and DM partitioning among plant organs is primarily regulated by the sink strengths of the organs (Marcelis 1996). Accordingly, models have been developed where the fraction of DM partitioned to each organ (f_i) is determined by the organ's sink strength (S_i), relative to the total sink strength of all organs (ΣS),

$$f_i = \frac{S_i}{\sum S} \qquad (7)$$

where parameters and variables are described in Table 1. This potential demand is quantified by the potential growth rate of the organ as described by Marcelis (1996). Finally, the dry matter available for each organ is calculated by integrating over time. The mechanistic approach we use to estimate the biomass production is summarised in Figure 1, and an example of the model output of the simulated biomass of *C. australasicum* is shown in Figure 2.

5. SIMULATION OF GROWTH AND DEVELOPMENT IN APSIM

5.1 Phenology

Phenology parameters are being derived from the field experiments as well as published studies of legumes (lucerne). Thermal time is used in the model to drive phenological development and canopy expansion. Crop phenology is divided into phases separated by stages, such as sowing to emergence, emergence to the end of juvenile face, floral initiation phase, flowering and seed setting phase. The duration of each phase is based on daily temperature and photoperiod. Parameterisation with respect to water requirements and the response of plants to soil moisture status will initially be done using the information available for lucerne and for other legume species and adjusted as necessary. Number and weight of senesced leaves will be measured and senescence rate (k_s) will be estimated.

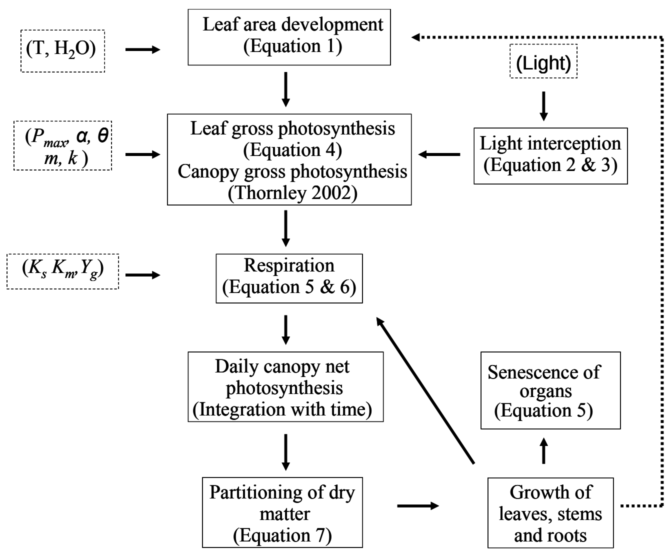

Figure 1. Generalised biomass production model overview showing how pasture growth can be simulated from canopy photosynthesis and through carbon use in respiration, under a diverse range of field conditions. Driving variables are the amount of radiation (light), temperature (T) and the soil moisture availability (H_2O), as shown in the broken line boxes. Parameters needed to explain the photosynthetic and respiration responses are also shown in the broken line boxes (italics). Solid lines indicate direct relationships and the broken line indicates an indirect relationship.

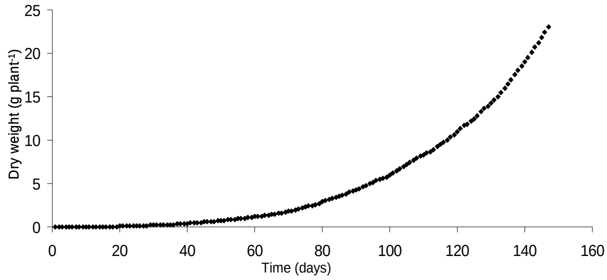

Figure 2. Simulated dry matter production of *C. australasicum* plants on a per plant basis (g) over time (days) when plants were grown under optimum environmental conditions.

5.2 Leaf area development

Glasshouse trials and data from the field sites will be used to derive functions for the size, appearance, expansion and senescence of leaves. Leaf appearance will be determined from the rate of node appearance on the main stem and the potential number of leaves per main stem node. A similar approach has been used by Robertson *et al.* (2002) to construct a general legume model in APSIM.

5.3 Biomass accumulation and partitioning

Biomass accumulation is derived through the radiation-use efficiency (RUE). RUE will be calculated from the experimental data, accounting for changes over time (with developmental stages) and any seasonal change. Daily biomass production will be partitioned to different plant parts in different ratios, depending on the crop growth phase. Biomass data from some of the experiments and field trials will be used to parameterise the model, and other data 'held back' in order to validate the simulations.

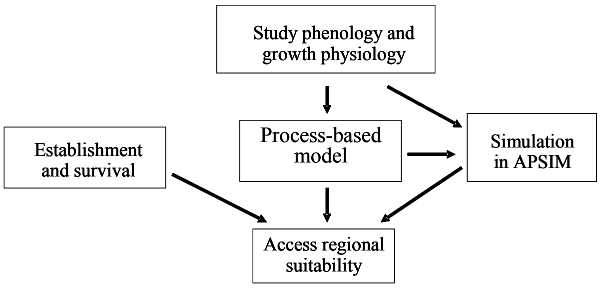

Figure 3. Generalised overview of our general approach to model the establishment, growth and development of perennial legumes and thus assess the suitability of different species for regions across the WA wheatbelt.

6. CONCLUDING REMARKS

Recent developments in soil-related problems such as salinity and predicted future changes in climate highlight the importance of new perennial pasture legumes in the WA wheatbelt. Good initial establishment and subsequent growth are important characteristics for a potential pasture species if it is to be adopted into a new system. Our preliminary modelling indicated that the establishment of albo-tedera, and *M. sativa* were affected by soil pH, available sulfur, available aluminium, conductivity and organic carbon as well as soil moisture and temperature. Future work will aim to construct a validated model of establishment and survival for the whole region. Growth of these two new legumes is promising in marginal soils in hot dry summers in the WA wheatbelt and simulations of growth under optimum conditions has been done with a physiological mechanistic model. Modifications of these growth models for simulations under adverse field scenarios are continuing, as is the adaptation of the APSIM lucerne model to represent these novel pasture legumes. Once the models have been developed and validated for the experimental sites, they will be used to predict the performance of *C. australasicum* and albo-tedera under a wide range of environmental conditions (temperature, rainfall, soil) in order to identify potentially suitable regions in WA and across the country for further trials and eventual adoption of these perennial pasture legumes. In addition, simulations will be done to predict future performance under possible climate-change scenarios. Our overall approach is summarised in Figure 3.

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