18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009
http://mssanz.org.au/modsim09

Development and testing of a horticultural crop model within APSIM

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Abstract: Ongoing uncertainty in irrigation water supply is a problem facing many of Australia's horticultural producers, whether it is due to drought, groundwater depletion, increased water regulation or community expectation for natural resource conservation. To respond to these pressures, improved irrigation management options are required. Simulation analyses provide the ability to explore the impacts of management options under these changing conditions but to date appropriate tools have not been available for horticulture. APSIM is a component-based modelling environment that has a long history of usage in crop, pasture and forestry systems analysis. Horticultural crop models are now being included into the suite of crop models available within APSIM. APSIM-Broccoli is one such model.

APSIM-Broccoli calculates plant growth, development and water use on a daily time step. Predictions of phenological development emerge from calculations of various growth processes. For example, time to floral initiation is calculated from thermal time adjusted for accumulated vernalisation from germination or transplanting, and time to buttoning is dependant upon the thermal time required for the appearance of all leaves initiated prior to floral initiation. Photosynthesis is calculated using a light use efficiency which is affected by temperature, water and nitrogen stresses. A simple phytomer approach is used for canopy development where each successive leaf on the main stem is defined in terms of the length of its growth, lag and senescent phases. Assimilate is partitioned to individual leaves based upon daily growth rates determined by temperature-dependant leaf expansion processes. Canopy water demand is calculated using a Penman-Monteith formulation within the APSIM Micromet module (Snow and Huth, 2004). Extraction of soil moisture to satisfy this demand is calculated using the approach of Meinke et al. (1993).

Testing of the model was carried out using two datasets chosen to highlight different areas within the model. The data of Tan et al (2000) includes leaf and phenological observations for several cultivars over a broad range of sowing dates for two locations in South East Queensland. APSIM-Broccoli was able to describe observed crop responses in canopy development and floral initiation to climatic conditions. Data for Broccoli growth and water use from the Gatton Research Station (27.55°S, 152.33°E) has been used to test the capability of the model in simulating biomass production and yield across different seasonal condition and irrigation strategies.

Other horticultural crop models are currently under development. These include sweet corn, green bean, lettuce and potato. Once complete, these models will be used to explore management decisions at the field and farm level for landholders facing complex irrigation management decisions.

Keywords: *APSIM, Brassica oleracea, Irrigation*

1. INTRODUCTION

Ongoing uncertainty in irrigation water supply is a problem facing many of Australia's horticultural producers, whether it is due to drought, groundwater depletion, increased water regulation or community expectation for natural resource conservation. To respond to these pressures, improved irrigation management options are required for a range of horticultural crops and growing regions. Simulation analyses provide the ability to explore the impacts of management options under these changing conditions but to date appropriate tools have not been available for horticulture. This paper describes one of the current efforts aimed at addressing this shortcoming.

2. THE AGRICULTURAL PRODUCTION SYSTEMS SIMULATOR (APSIM)

APSIM (Keating et al., 2003) is a cropping systems modelling environment specially designed to allow a plug-in-pull-out approach for the integration of various simulation models via a common modelling protocol (Moore et al., 2007). It is a product of the Agricultural Production Systems Research Unit (APSRU). APSIM can be configured with modules suitable for the simulation of many different systems. Whilst these initially concentrated upon dryland cropping systems, APSIM's usage has broadened and now it is also being used in the study of forestry (Paydar et al 2005), agroforestry (Huth et al 2002) and pasture (Snow et al 2007) systems. Horticultural crop models are now being included into the suite of crop models available within APSIM. APSIM-Broccoli is one such model.

3. THE APSIM-BROCCOLI MODEL

3.1. Overview

The APSIM-Broccoli model operates on a daily timestep. Information on soil water and nitrogen contents are provided from the Soilwat and SoilN modules (Probert et al 1998). Management actions such as irrigation, fertiliser application, tillage, sowing and harvesting are handled by various auxiliary modules within APSIM. The plant model itself therefore focuses only on crop growth, development and resource use. Implementation was via the new APSIM Generic Plant Model (Holzworth and Huth 2009). Symbols used in the model description are defined in Table 1.

3.2. Phenological Development

The basic model of phenological development is illustrated in Figure 1. Thermal time is used to describe the rate of crop development through these growth phases. A different phenological model is applied for sown and transplanted crops. The duration of each growth phase is dependant upon several parallel processes. The duration of the juvenile phase is dependant upon accumulated vernal days (T_{min} 0°C, T_{opt} 2°C, T_{max} 15°C) as described by the vernalisation model of Robertson et al. (2002). The duration of the vegetative phase is calculated from the number of leaf primordia produced prior to floral initiation and a leaf appearance rate. The remaining growth phases have fixed thermal time durations.

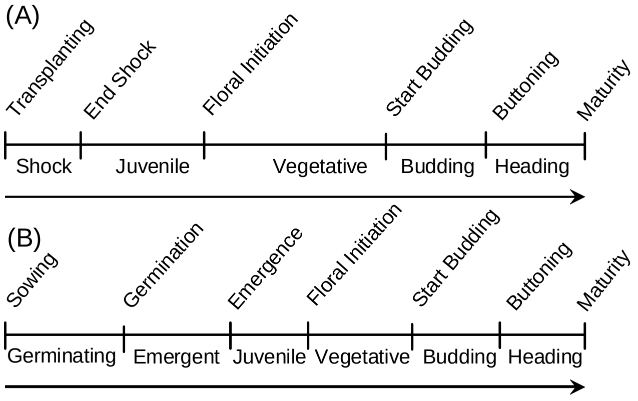

Figure 1. APSIM-Broccoli Phenological Stages and Phases for a) transplant, and b) sown crops.

3.3. Canopy Development

Canopy development is calculated using a phytomer-based approach. Leaf appearance on the main stem is calculated using a fixed leaf appearance rate, or phyllochron, expressed on a thermal time basis. Final leaf number is calculated in a similar manner using accumulated thermal time since germination, assuming three leaf primordia are present in the seed at germination. Once a leaf emerges it goes through three distinct growth, lag and senescent phases. The duration of the growth phase increases with node number on the main stem and can be equated to the number of expanding leaves observed on the plant when that particular node completes expansion. Duration of the senescent phase has been set to 200 degree days and the remaining duration of the lag phase is fitted to observations of leaf senescence.

Table **1**. Notation and Units. Symbols used in the description of the APSIM-Broccoli Model.

Symbol	Description	Units
E_t	Daily plant transpiration	mm d^{-1}
E_{t0}	Potential daily plant transpiration	mm d^{-1}
EF	Depth of the soil water extraction front	mm
EFV	Potential extraction front velocity	mm d^{-1}
i	Layer index number	-
k	Canopy light extinction coefficient	-
kl	Soil water extraction coefficient	d^{-1}
LAI	Leaf area index	m^2 m^{-2}
Q_d	Daily total shortwave radiation	MJ m^{-2} d^{-1}
T	Daily air temperature	°C
t	Time	d
U	Plant water uptake	mm
W	Plant biomass	g m^{-2}
x	Depth within the soil profile	mm
ε	Plant light use efficiency	g MJ^{-1}
θ	Volumetric soil water content	mm^3 mm^{-3}
θ_{LL}	Volumetric soil water content at the lower limit of extractable soil water	mm^3 mm^{-3}
ω_{EV}	Soil water factor for extraction front advance	-
ω_g	Water stress factor for daily growth	-

3.4. Crop Growth and Biomass Partitioning

Daily growth in plant biomass is calculated from daily intercepted shortwave radiation using a light use efficiency which is affected by various soil and climatic factors. In these analyses only temperature and water supply are assumed to be limiting although the model can account for other limitations such as inadequate nutrition. Interception of solar radiation is computed assuming an exponential decay of light within a canopy. Daily growth rate is calculated with the following:

$$\frac{dW}{dt} = \varepsilon(T, \varpi_g)(1 - e^{-k\,LAI})Q_d \qquad (1)$$

Daily biomass production is partitioned into the various plant organs (Leaf, Root, Stem, Floret) using partition fractions which change with crop growth stage. For example, Figure 2 demonstrates the changes in partitioning of growth into stem for Autumn or Spring grown Broccoli. Prior to floral initiation, 20% of above ground growth goes into stem. This increases to 50% during the vegetative phases but then decreases to 22% once Heading commences.

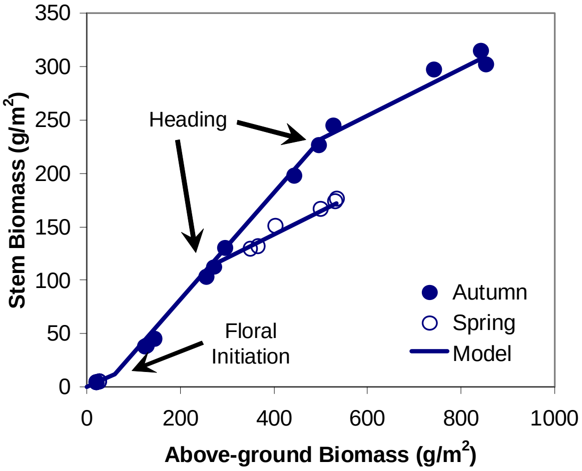

Figure 2. Partitioning of above-ground biomass into stem across growth phases for Autumn or Spring crops of Broccoli grown at Gatton in 2006 (see Section 4.2 below for experiment description)

3.5. Water Demand and Extraction

The uptake of soil water by the plants is driven by the plant demand for water from the soil, the amount of water available within the soil, and the rate at which that stored moisture becomes available to the plant as the root system develops. Plant water demand (E_{t0}) is calculated using a formulation of the Penman-Montieth equation (Snow and Huth, 2004).

The ability of the plants to meet this water demand will depend on the depth of the extraction front and the ability of the roots within that soil to extract any available moisture. The soil water balance used with APSIM (Probert et al., 1998) uses a series of soil layers to describe the vertical distribution of soil moisture. Water from each layer becomes progressively available as the extraction front progresses to greater depths. The rate of progress is calculated using a potential extraction front velocity which is discounted based upon the soil water content of that layer to capture the effect of dry soil layers on root penetration. The modifier ω_{EV} decreases from 1 at 25% of maximum plant available water content to 0 at the lower limit of plant available water.

$$\frac{dEF}{dt} = EFV \times \omega_{EV}(\theta_i) \tag{2}$$

Once the extraction front has reached a layer, potential uptake of water from that layer is described using a simple first order decay model (Passioura 1983; Meinke et al 1993) for water content above the lower limit of plant available soil water.

$$U_i = \frac{d\theta_i}{dt} \times dx_i = -kl_i(\theta_i - \theta_{ll,i}) \times dx_i \tag{3}$$

The parameter, kl, captures the effects of both soil hydraulic conductivity and root length upon root water uptake and represents the fraction of the remaining plant available soil moisture that can be taken up on a daily basis. Daily water use by the plants is then set to be equal to the minimum of water supply and demand.

$$E_t = \min(E_{t0}, \sum U) \tag{4}$$

If supply is greater than demand, uptake from each layer is scaled downward in proportion to the ratio of demand to supply. The ratio of actual transpiration (E_t) to potential transpiration (E_{t0}) is used to quantify daily plant water stress factor for plant growth (ω_g) where a value of 1 signifies no stress and 0 means absolute stress.

4. MODEL TESTING

4.1. Phenological Datasets of Tan et al (2000)

The data of Tan et al. (2000) provides a large and detailed dataset for model development and testing including timing of emergence, floral initiation, maturity and leaf appearance for three Broccoli cultivars at two locations (Gatton and Brookstead) encompassing a wide range of sowing dates.

Method

Accumulated thermal time and vernal days was calculated for each crop from germination (assumed 1 day after sowing) to floral initiation. Cardinal temperatures for vernalisation were taken from Robertson et al. (2002). Accumulated thermal time from emergence was compared with regular counts of visible leaf number. Base, optimum and maximum temperatures for development were optimised to maximise the proportion of the variation accounted for in estimates of timing of floral initiation and leaf appearance.

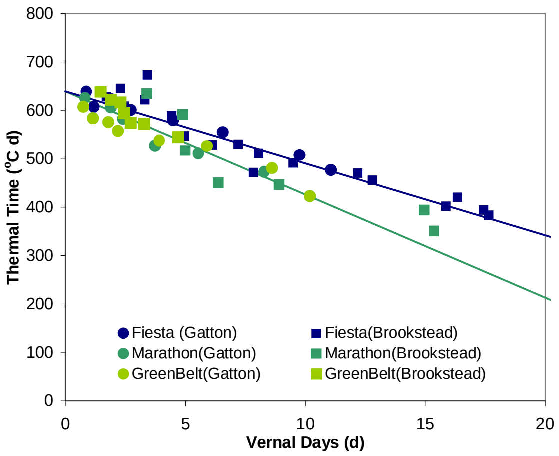

Figure 3. Change in thermal time from sowing to floral initiation as affected by accumulated vernalisation for three cultivars at Gatton and Brookstead in 1997.

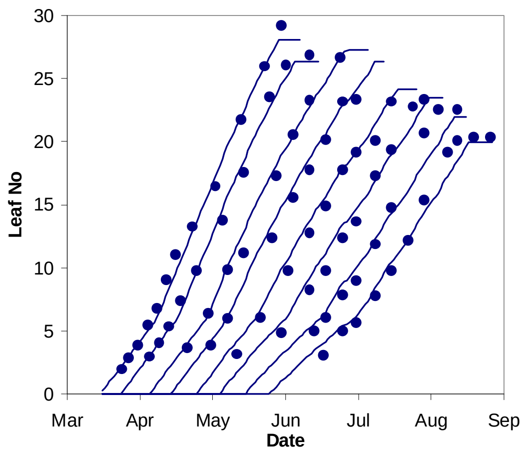

Figure 4. Observed and Predicted impact of time of sowing on leaf appearance rates and final leaf numbers for Broccoli (cv. Marathon) grown at Gatton in 1997.

Results

Figures 3 and 4 demonstrate some of the results for the proposed model. The fitted cardinal temperatures (T_{base} 5°C, T_{opt} 25°C, T_{max} 35°C) enable the model to describe both crop development and leaf appearance on a common thermal time basis. Tan et al. (2000) showed the absence of a photoperiod response in broccoli and applied a simple model with a fixed thermal time requirement for floral initiation. Both the floral initiation and final leaf number data of Tan et al (2000) indicate a likely vernalisation response in broccoli which was not available in the model used by the original authors. The incorporation of a vernalisation submodel into the overal phenological model within APSIM-broccoli explains not only the timing to key growth stages such as floral initiation, but helps to explain the variation in leaf numbers between planting dates. It also suggests that all of the cultivars may share a common thermal time requirement prior to vernalisation but may only differ in their vernalisation response (i.e. common intercept but different slope in Figure 3). Moreover, two of cultivars seem to share a common vernalisation response. These two points significantly reduce the burden of parameterisation for phenological development.

4.2. Irrigation response experiment, Gatton 2006.

Detailed data on broccoli growth and production responses to irrigation supply is required for model development and testing.

Method

An experiment was conducted at the Queensland Department of Primary Industries and Fisheries Gatton Research Station (27.55° S, 152.33° E) to study the impact of differing levels of water stress on Broccoli growth, development and yield. Two planting dates were used: 4th April 2006 and 29th June 2006. Three water regimes were established for each planting. The first provided a water non-limiting control. The second sought to induce a mild mid-season water stress condition by withholding irrigation for several weeks. The final treatment sought a severe water stress condition by withholding irrigation for a longer duration but ensuring stress was relieved before buttoning. Soil water content was monitored using a Neutron Moisture Probe. Biomass production and canopy area was measured via destructive sampling through the season. Leaf appearance and expansion of individual leaves was monitored on nine tagged plants within each treatment. Weather data was collected from the on-site meteorological station.

Parameterisation of the model for the dataset used information from various sources. Crop development was parameterised as per the analysis in section 4.1. Soil information was obtained using the techniques described in Dalgliesh and Foale (1998). Data obtained during the experiment was used to describe the changes in leaf expansion along the main stem and partitioning of growth between plant organs. Remaining parameters were either assumed to be similar to those used to simulate canola and so were set equal to values in the APSIM-canola model (Farre et al, 2002) or were taken from the work of Olesen and Grevsen (1997).

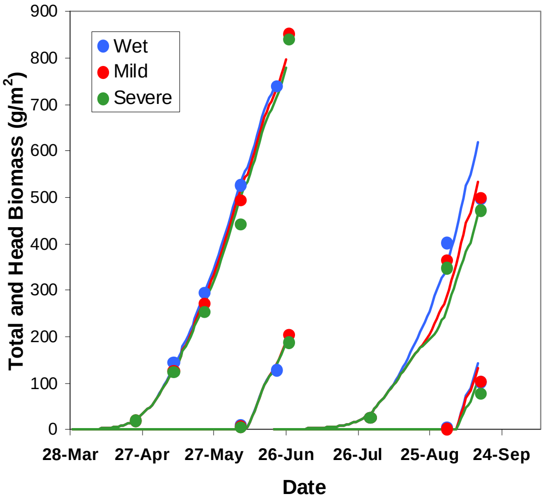

Figure 5. Observed and predicted total crop biomass and head/floret mass for three irrigation regimes and two sowing dates at Gatton in 2006.

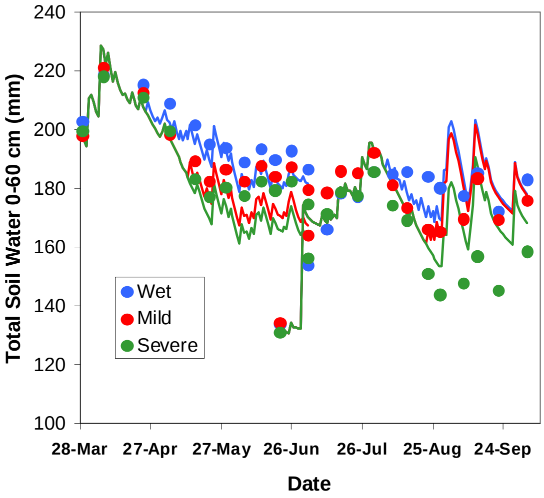

Figure 6. Observed and predicted total soil water to 60 cm depth for three irrigation regimes and two sowing dates at Gatton in 2006

Results

The model is able to adequately describe the growth of broccoli under the different irrigation and climatic conditions experienced within the experiment. Figure 5 shows that the predicted time course of crop biomass is generally well captured, apart from a slight underestimate of treatment response within the first sowing, and an overestimate of the treatment response in the second sowing date. The reasons for this are likely demonstrated in Figure 6. Water use is overestimated in the autumn sown crop and underestimated in the spring sown crop. Simple sensitivity analyses and investigation of the model output indicated that the amount of water lost to evaporation from the soil surface was an important determinant of crop growth in such a drought-sensitive crop. In these systems, planting bed design and planting geometry as well as trickle irrigation placement can impact on evaporation losses. The simple one-dimensional description of the system used in the current model may be inadequate to describe this. Similarly, trickle irrigation systems with broccoli result in a partial root system wetting as only the inner section of the bed is watered. This is likely to impact on crop water extraction and water stress levels. Figure 6 shows that the first crop stressed at higher water contents than the second crop. This is likely due to gradients across the crop bed. A simple two-dimensional spatial capability is possible in APSIM and has been used to study tree-crop interactions, including spatial variation in tree root water uptake (Huth et al., 2002). We would suggest that this should be employed in future simulations to see if this can assist in describing the changes in irrigation efficiency of these systems.

5. DISCUSSION AND CONCLUSIONS

Agricultural systems models have a long history in assisting scientists and land managers to understand their systems and the ways in which they can be managed. The incorporation of horticultural crop models into the APSIM suite of tools will enable these same benefits to be realised within the horticultural industries. Initial testing of the APSIM-Broccoli model shows promise but much more development, including a wider range of crops and management options, will be required to enable APSIM to deal with the complex horticultural systems. Complexity arises in terms of crop rotations, planting geometry and novel irrigation techniques. Many of these, as discussed above, introduce spatial considerations that cannot be captured in such a simple one-dimensional model and so, where possible, simple two-dimensional formulations are being incorporated into the model configuration.

Farmers operating within the horticultural industry also have a wide range of crops as part of their enterprise and so the number of horticultural crop models must increase to enable APSIM to be used effectively in these systems. To achieve this, models for sweet corn, green bean, lettuce and potato are currently under development as part of various efforts within APSRU and its collaborators. Once complete, these models will be used to explore management decisions at the field, farm and enterprise level for landholders facing complex irrigation management decisions.

ACKNOWLEDGMENTS

Much of this work has been supported by the "Driving better vegetable irrigation through profitable practice change" project funded by Horticultural Australia Ltd (Project VG07023).

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