Simulating perennial crops with the APSIM plant module – a study with lucerne

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Abstract

The use of perennial crops such as lucerne (*Medicago sativa* L.) is an option for improving future sustainability of agricultural systems. The planning of future adaptive agricultural strategies can be investigated through computer simulation exercises that account for the complex interactions of systems components such as climate, soil and crop management. Currently, most crop simulation models, including APSIM-lucerne, use algorithms and parameters developed for annual crops. For perennials, such as lucerne, it is necessary to quantify plant responses to a wider range of environmental conditions which occur throughout an entire growth season. More importantly, the seasonality of biomass in perennial organs of reserve (crowns and roots in lucerne) must be captured by the model. We developed a modified version of APSIM-lucerne plant module ($\text{APSIM}_{\text{mod}}$) in which total radiation use efficiency ($\text{RUE}_{\text{total}}$), the partitioning of biomass to perennial organs (p_{per}) and respiration of perennial organs (rm) were considered. These changes improved the model's ability to simulate the seasonal dynamics of shoots (RMSD = 18% mean), leaf area index (RMSD = 28% mean). The simulation of the seasonality of perennial organs of reserve (roots and crowns) improved considerably from a RMSD of 1507 kg/ha (32% of mean) to 811 kg/ha (16% of mean). These concepts can be applied to other perennial species and cultivars for which the physiological model parameters are available.

Key Words

Crop modelling, APSIM, root biomass, dry matter partitioning, lucerne, root respiration.

Introduction

Crop simulation models have developed into valuable research tools to explore adaptive options for agriculture, including adaptation to climate change (Betts 2005). Commonly, models are used to compare alternative strategies for food and fodder production considering a set of plausible production scenarios.

Quantitative knowledge on physiological plant responses to the environment and to different management practices is necessary for sensible model performance. Currently, most crop simulation models use algorithms and parameters developed to predict the growth and development of annual crop-types. However, perennial crops are also an important source of agricultural outputs with relatively lower environmental risks. To better simulate the growth of perennial crops, models must capture the changes in biomass of perennial reserve organs in response to the wide range of environmental conditions experienced by plants throughout the entire year. For example, in lucerne (*Medicago sativa* L.), crowns and roots serve as a seasonal reservoir of carbohydrates and nitrogen critical for shoot growth and stand persistence (Teixeira et al. 2007).

Lucerne is a perennial capable of fixing atmospheric nitrogen symbiotically and retrieving water from deep in the soil profile through an extensive root system. This makes it suitable as an adaptive alternative for achieving high quality forage production, with low nitrogen fertilizer inputs, in regions prone to drought owing to climate change. To better simulate lucerne above-ground yield, the allocation and consumption of biomass in perennial organs must be accurately simulated. Often, modellers adapt parameters developed for annual-crops to account for seasonality of reserve organs in perennials. For example, the Agricultural Production Systems Simulator (APSIM; Keating et al. 2003) simulates the seasonality of lucerne yield by changing the value of radiation use efficiency for shoot production (RUE_{shoot}) in autumn and spring (Robertson et al. 2002).

Recently, the explicit simulation of lucerne perennial organs (crowns and roots) was developed for a simple crop model (Teixeira et al. 2009). The rationale was to use radiation use efficiency for total plant biomass production (RUE_{total}) and explicitly simulate partitioning of dry mater to roots (p_{root}) and respiration of biomass in perennial organs. It is not clear if this approach can be incorporated in more complex system models such as APSIM-lucerne to broaden their ability to simulate perennial organs. In this study, the feasibility of extending the capabilities of APSIM to capture the dynamics of perennial organs in lucerne is tested. This was done by including new algorithms to account for RUE_{total}, p_{root} and root respiration, and comparing model simulations with two years of measured field-data.

Methods

Data for model development validation

Observed data were taken from a 2-year field experiment at Lincoln University, New Zealand (43?38'S, 172?28'E) from June 2002 to December 2004 (Teixeira et al. 2007). In brief, perennial organ data comprised crown plus root biomass to 300 mm depth. Shoot biomass and leaf area index (LAI) data were also available and used to evaluate how changes in the modelling of perennial organs affected yield and canopy development. All samples were collected at ~7–10 day intervals during 14 regrowth grazing cycles of 'Grasslands Kaituna' lucerne crops grazed by sheep at ~42 day intervals. Crops received best management practices for irrigation, fertilizer and pest and disease control. Crop management was previously detailed in Teixeira et al. (2007).

Model testing and development

The seasonal dynamics of perennial organs were compared with simulations of the 'original' APSIM-lucerne plant module in version 7.2 ($APSIM_{orig}$) (Robertson et al. 2002) and a modified version ($APSIM_{mod}$) that included new algorithms to account for perennial organ dynamics (Teixeira *et al.* 2009). In this modified framework, total plant biomass assimilation was calculated daily as the product of intercepted light and RUE_{total} (Teixeira et al. 2008). Light interception increases exponentially with leaf area index (LAI) expansion (Gosse *et al.* 1984). The $APSIM_{mod}$ version used leaf area expansion rate (LAER) as a driver of LAI expansion (Figure 1a) to ensure canopy development was independent of carbon assimilation (Tardieu et al. 1999). Thermal-time accumulation is the main driver of canopy expansion in this model (Gosse et al. 1982). Total plant radiation use efficiency (RUE_{total}) was assumed to respond to air temperature (Brown et al. 2006) as depicted in Figure 1b. To explicitly account for the biomass flow into perennial organs, the fractional partitioning of biomass to perennial organs (p_{per}) (Teixeira et al. 2008) was empirically related to photoperiod (Figure 1c). The respiration of biomass in perennial organs was calculated using a daily rate of root maintenance respiration (rm_{per}) by relating the seasonal coefficients estimated for lucerne (Teixeira et al. 2009) to photoperiod (Figure 1d). Model performance was evaluated by comparing observed and simulated values of the root mean squared deviation (RMSD) and the coefficient of determination (R^2) (Kobayashi and Salam 2000). The software ModelMaker v. 4.0 (Cherwell Scientific Publishing, Ltd, UK) was used to prototype the new algorithms before inclusion into the main source code in $APSIM_{mod}$.

Figure 1. Main functions included in the original APSIM-lucerne to simulate the dynamics of biomass in lucerne perennial organs of reserve (crowns and roots).

Results and discussion

The simulations using $\text{APSIM}_{\text{mod}}$ improved model accuracy for predicting shoot biomass and leaf area index development (Table 1). The root mean squared deviation (RMSD) declined by 35 percent units and the coefficient of determination (R^2) increased by 14 percent units for the simulation of shoot yield. This indicates that the absolute partitioning of biomass to shoots in $\text{APSIM}_{\text{mod}}$ (*i.e.* the product of intercepted light, $\text{RUE}_{\text{total}}$ and 1-p_{root}) were more accurately portrayed when seasonal partitioning coefficients were used.

Table 1. Root mean squared deviation (RMSD) between observed data (lucerne shoot dry matter and leaf area index) and simulations using APSIM-lucerne in its original ($\text{APSIM}_{\text{orig}}$) and modified ($\text{APSIM}_{\text{mod}}$) versions.

	Shoot dry matter		Leaf area index	
	$\text{APSIM}_{\text{orig}}$	$\text{APSIM}_{\text{mod}}$	$\text{APSIM}_{\text{orig}}$	$\text{APSIM}_{\text{mod}}$
RMSD (absolute unit)	1.10 t/ha	0.30 t/ha	1.25 m^2/m^2	0.87 m^2/m^2
RMSD (% mean)	53	18	54	28

R^2 (%)	81	95	66	82

Perennial organs

The accuracy of simulations of biomass in perennial organs (crowns and roots) also improved in $\text{APSIM}_{\text{mod}}$ (Figure 2). The RMSD decreased from 1507 kg/ha (32% mean) in $\text{APSIM}_{\text{orig}}$ to 811 kg/ha (16% mean) in $\text{APSIM}_{\text{mod}}$. Interestingly, simulations in both APSIM versions captured the annual fluctuation in perennial organ biomass. This indicates that seasonality is largely driven by differences in carbon assimilation rates (i.e. canopy photosynthesis) through the year. However, the simulation using $\text{APSIM}_{\text{orig}}$ showed a systematic offset to observed data. At the time of the first sampling date (August 2003), the $\text{APSIM}_{\text{orig}}$ simulation underestimated perennial biomass by more than 3000 kg/ha. In contrast, the simulation with $\text{APSIM}_{\text{mod}}$ was able to accurately simulate observed data at the first sampling and correctly tracked the following seasonality of perennial biomass.

Figure 2. Measured and simulated perennial biomass (crown plus root) in lucerne crops using APSIM-lucerne in its original ($\text{APSIM}_{\text{orig}}$) and modified ($\text{APSIM}_{\text{mod}}$) plant module versions.

Given the scarcity of time-course datasets with measurements of below-ground biomass, the model was tested against data used to derive part of the model's relationships and parameters. Therefore, this study cannot be considered a definitive validation of the model because the data is not independent. Nevertheless, this provides a test to show that the concepts of total RUE, explicit partition of biomass to below-ground organs and maintenance respiration of these organs can be implemented into APSIM-plant to reproduce observed patterns of perennial biomass.

Conclusion

The seasonality of perennial organs could be simulated by including algorithms that account for total biomass accumulation, partitioning and respiration in APSIM-plant module. Specifically, the main changes necessary were the use of: (i) leaf area expansion rate (LAER) to drive LAI expansion by thermal-time accumulation, (ii) whole plant biomass assimilation via RUE_{total}, (iii) partitioning coefficients that differ with photoperiod, and finally (iv) to account for the seasonal respiration of biomass in perennial organs. This framework could be extended to other lucerne cultivars and perennial crop species after validation with independent experimental data.

Acknowledgements

Funding was from FRST programme “Land Use Change and Intensification” (C02X0812).

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