CSIRO PUBLISHING

Australian Journal of Experimental Agriculture, 2007, **47**, 992–999 www.publish.csiro.au/journals/ajea

Using APSIM-soiltemp to simulate soil temperature in the podding zone of peanut

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Abstract. Measurement or accurate simulation of soil temperature is important for improved understanding and management of peanuts (*Arachis hypogaea* L.), due to their geocarpic habit. A module of the Agricultural Production Systems Simulator Model (APSIM), APSIM-soiltemp, which uses input of ambient temperature, rainfall and solar radiation in conjunction with other APSIM modules, was evaluated for its ability to simulate surface 5 cm soil temperature in 35 peanut on-farm trials conducted between 2001 and 2005 in the Burnett region (25°36′S to 26°41′S, 151°39′E to 151°53′E). Soil temperature simulated by the APSIM-soiltemp module, from 30 days after sowing until maturity, closely matched the measured values ($R^2 \geq 0.80$) in the first three seasons (2001–04). However, a slightly poorer relationship ($R^2 = 0.55$) between the observed and the simulated temperatures was observed in 2004–05, when the crop was severely water stressed. Nevertheless, over all the four seasons, which were characterised by a range of ambient temperature, leaf area index, radiation and soil water, each of which was found to have significant effects on soil temperature, a close 1 : 1 relationship ($R^2 = 0.85$) between measured and simulated soil temperatures was observed. Therefore, the pod zone soil temperature simulated by the module can be generally relied on in place of measured input of soil temperature in APSIM applications, such as quantifying climatic risk of aflatoxin accumulation.

Additional keyword: modelling.

Introduction

Soil temperature can directly affect crop yield by a range of physiological processes. It can also have indirect effects on soil nutrient availability and host–pathogen relationships. For example, in peanuts (*Arachis hypogaea* L.), soil temperature has been reported to affect pod formation, rates of pod growth and development (Leong and Ong 1983; Golombek and Johansen 1997; Vara Prasad *et al*. 2000), nitrogen fixation (Kishinevsky *et al*. 1992) and susceptibility to *Aspergillus flavus* (Hill *et al*. 1983), a fungi that produces harmful aflatoxins. Hence, accurate measurement or simulation of soil temperature could significantly improve our understanding and management of the crop. For example, a decision support system, 'AFLOMAN', which uses input of soil temperature to monitor preharvest climatic risk of aflatoxin production in peanut kernels has been recently developed and applied to the Australian peanut industry (Wright *et al*. 2005). The use of this decision support system is currently limited to growers who can directly measure soil temperature. However, it could be extended to more growers if soil temperature in the pod zone (~5 cm) could also be accurately simulated using crop models.

Soil temperature is influenced by solar radiation, air temperature, site topography, soil water content, texture and the presence of leaf canopy and litter. Several crop simulation models currently have the ability to empirically simulate soil temperature (Williams *et al*. 1984; Probert *et al*. 1998; Jones *et al*. 2003). These models, however, do not account for crop canopy cover and hence can overestimate soil temperature under some situations. The crop canopy limits the flux of radiative heat transfer from the atmosphere into the soil during the day, and upward emission of long-wave thermal radiation from the soil into the atmosphere during the night. Recognising that several empirical soil temperature models were not able to account for the effect of canopy cover, Paul *et al*. (2004) developed a new empirical model for estimating soil temperature in temperate forests, called 'Soil Temperature Under Forest' (STUF). The model of Paul *et al*. (2004), which uses concepts outlined by Campbell (1985), requires the input of daily average temperature, leaf area index (LAI) and litter mass. However, it is not a process-based model and operates independently of changes in soil water. A process-based soil temperature model developed earlier by Luo *et al*. (1992) accounts for canopy development and soil water in conjunction with an alfalfa (*Medicago sativa* subsp. *sativa*) growth model. The model was reported to work well in simulating soil temperature for irrigated alfalfa crops. However, little is known about its performance with other crops, such as peanuts grown under rainfed cropping conditions, where crop cover and soil water vary widely in response to the stage of development and

10.1071/EA06137 0816-1089/07/080992

seasonal conditions. More recently, a module to simulate soil temperature, called APSIM-soiltemp, was added to the Agricultural Production Systems Simulator Model (APSIM; Keating *et al*. 2003) suite of modules (APSRU 2005). APSIM also has another module, APSIM-peanut, which can simulate leaf area development, yield and crop water use by peanuts under different climatic regimes and cropping systems (Hammer *et al*. 1995; Robertson *et al*. 2002). It may be possible to link the APSIM-peanut module to the APSIM-soiltemp module, to provide additional inputs for more accurate prediction of the effects of changes in canopy development and soil water on soil temperature. However, this possibility has not yet been tested.

The objective of this study was therefore to evaluate the effectiveness of the APSIM-soiltemp module linked with the APSIM-peanut module to simulate soil temperature in the podding zone of rainfed peanut crops, as well as to examine its potential application in quantifying climatic risk of aflatoxin contamination in peanuts.

Materials and methods

APSIM-peanut module

The APSIM-peanut module is part of the generic legume family of APSIM modules that uses radiation, ambient temperature, and rainfall on a daily time step to simulate peanut development, growth and yield (Robertson *et al*. 2002).

APSIM-soiltemp module

The APSIM-soiltemp (APSRU 2005) simulates daily soil temperature using a numerical energy-balance algorithm described by Campbell (1985). The module works according to the principles of energy balance and transfer of soil heat, as modified by a growing crop. The main input in the module is ambient air temperature, which is obtained from the APSIM-met module. The module obtains input of soil layer depth, volumetric water content, bulk density, potential and actual evaporation from the APSIM-soil water module. The effects of soil surface cover from residues and leaf canopies are estimated from the heat flow differences between the potential and actual evaporation. A user is required to give the input of boundary layer conductance and clay content applicable for the soil. The boundary layer conductance varies from 0–100 J/s.m.K and, for the Red Ferrosol of the farms used in this study, a conductance value of 15 was found to be appropriate. The clay content specified for the soil was 60%. The module uses soil evaporation derived from the APSIM soil water module (which is in turn modified by canopy and residue cover) to account for the evaporative loss of energy (J/s.m^2) from the soil surface and the incident net radiation (J/s.m^2) as a part of the upper boundary condition. The average annual temperature, daily input of minimum and maximum temperatures, radiation (for simulation of potential and actual evapotranspiration by the soil water module) and rainfall inputs were derived from the APSIM-met module.

Measurement and simulation of soil temperature

All measurements of soil temperature were made in rainfed peanut crops in farmers' fields in the Burnett district (25°36′S to 26°41′S, 151°39′E to 151°53′E) of south-eastern Queensland during the 2001–02, 2002–03, 2003–04 and 2004–05 growing seasons (October–May). In total, there were 10 fields in 2001–02, 16 in 2002–03, five in 2003–04 and four in 2004–05. The soils of the farms were categorised as Red Ferrosols (i.e. deep red clay loam or oxisols with ~60% clay content; Soil Survey Staff 1975), with a plant available water holding capacity of ~140 mm to a depth of 1.8 m. After appropriate land preparation, all fields were machine-sown with seed of one of the peanut cultivars given in Table 1. Sowing dates varied from 21 October to 24 November in 2001–02, from 12 November to 7 January in 2002–03, from 29 October to 16 November in 2003–04, and from 16 November to 18 November in 2004–05. The inter-row spacing was 90 cm, and intraplant spacing was ~11 cm, giving a population of ~10 plants/m^2. Crops were protected from pests and diseases throughout the season following recommended plant protection measures.

To measure soil temperature in each farm, a precalibrated 15 cm long temperature sensing probe (Tinytag Hasting Dataloggers, Australia) was buried at a depth of 5 cm, just adjacent to a row of peanuts. An electrical lead connected the probe to a Tinytag datalogger housed in a well-ventilated white plastic enclosure fixed at a height of 1 m above the soil surface. The datalogger also logged the enclosure temperature, which was used as the ambient temperature input to run the model. Soil and ambient temperatures were logged at 1-min intervals and automatically integrated on an hourly basis, before being downloaded periodically into a laptop computer. The daily maximum and minimum temperatures were obtained from the 24 hourly readings for a day. Rainfall was also recorded in the paddock. Radiation data was obtained from the 'SILO' website (www.nrw.qld.gov.au/silo/, verified 29 May 2007). In 2003–04 and 2004–05, ambient temperature was not recorded up to the first 50 days, and was also obtained from the 'SILO' website. Management variables (such as cultivar, plant population, sowing date, starting soil water) specified in the management module are shown in Table 1.

The APSIM-soiltemp module (version 4) was run to simulate soil temperature along with APSIM-peanut and other modules, via APSIM's plug-in and plug-out capability and using weather input for each farm. All measured and simulated soil temperature data were compared using a regression approach. The relationship of soil temperature with weather variables (ambient temperature and radiation), fractional available soil water (FASW) and LAI was examined from their partial regression plots using DataDesk 6.1 software (Data Description Inc., Ithaca, NY). The method reports the relationship between y and x_j variables after the linear effects of the other x-variables have been removed from both.

Results and discussion

Changes in soil and ambient temperatures and leaf area and soil water during the seasons

The range of measured soil and ambient temperatures varied from ~15 to 35°C (Fig. 1). For this range of temperatures, simulated soil temperature was close to measured soil temperature throughout the first three peanut growing seasons, except in 2001–02 and 2002–03 at the start of the season

Table 1. Agronomic details of different on-farm trials conducted in Kingaroy and Coalstoun Lakes regions from 2001 to 2005

Farm no.	Sowing date	Harvest or maturity date	Cultivar	Sowing depth (mm)	No. of plants/m^2	Starting water[A]	Nearest MET station
1	21 Oct. 2001	11 Apr. 2002	Streeton	50	10	2/3	Kingaroy
2	22 Nov. 2001	26 Apr. 2002	VB97	50	10	2/3	Kingaroy
3	31 Oct. 2001	4 Apr. 2002	VB97	50	10	2/3	Kingaroy
4	1 Nov. 2001	26 Apr. 2002	Streeton	50	10	2/3	Kingaroy
5	31 Oct. 2001	21 Mar. 2002	VB97	50	10	2/3	Kingaroy
6	24 Nov. 2001	17 Apr. 2002	Streeton	50	10	2/3	Kingaroy
7	20 Nov. 2001	17 Apr. 2002	Streeton	50	10	2/3	C. Lakes
8	20 Nov. 2001	17 Apr. 2002	Streeton	50	10	2/3	C. Lakes
9	30 Oct. 2001	21 Mar. 2002	VB97	50	10	2/3	Kingaroy
10	23 Nov. 2001	18 Apr. 2002	VB97	50	10	2/3	Kingaroy
11	10 Dec. 2002	12 Apr. 2003	Streeton	50	10	2/3	C. Lakes
12	10 Dec. 2002	16 May 2003	Streeton	50	10	2/3	C. Lakes
13	31 Oct. 2002	30 Jan. 2003	NC7	50	10	2/3	Kingaroy
14	30 Oct. 2002	27 May 2003	Florunner	50	10	2/3	Kingaroy
15	28 Dec. 2002	26 May 2003	Streeton	50	10	2/3	Kingaroy
16	31 Dec. 2002	27 May 2003	Streeton	50	10	2/3	Kingaroy
17	29 Oct. 2002	31 Dec. 2003	VB97	50	10	2/3	Kingaroy
18	31 Dec. 2002	27 May 2003	VB97	50	10	2/3	Kingaroy
19	30 Dec. 2002	25 May 2003	VB97	50	10	2/3	Kingaroy
20	3 Nov. 2002	13 May 2003	Florunner	50	10	2/3	C. Lakes
21	21 Nov. 2002	21 Apr. 2003	Streeton	50	10	2/3	C. Lakes
22	2 Nov. 2002	5 Apr. 2003	Streeton	50	10	2/3	C. Lakes
23	20 Nov. 2002	21 Apr. 2003	Streeton	50	10	2/3	C. Lakes
24	28 Dec. 2002	22 May 2003	VB97	50	10	2/3	Kingaroy
25	31 Dec. 2002	25 May 2003	Streeton	50	10	2/3	Kingaroy
26	31 Dec. 2002	15 May 2003	Streeton	50	10	2/3	Kingaroy
27	16 Nov. 2003	28 Mar. 2004	Streeton	50	10	1/2	C. Lakes
28	5 Nov. 2003	17 Mar. 2004	Streeton	50	10	1/3	C. Lakes
29	29 Oct. 2003	25 Mar. 2004	VB97	50	10	1/3	Kingaroy
30	4 Nov. 2003	30 Apr. 2004	Florunner	50	10	1/2	Kingaroy
31	31 Oct. 2003	21 Mar. 2004	VB97	50	10	1/3	Kingaroy
32	18 Nov. 2004	29 Apr. 2005	Streeton	50	10	2/3	C. Lakes
33	16 Nov. 2004	2 May 2005	Florunner	50	10	2/3	Kingaroy
34	18 Nov. 2004	2 May 2005	Streeton	50	10	1/10	Kingaroy
35	16 Nov. 2004	2 May 2005	VB97	50	10	2/3	Kingaroy

[A] Presented as a fraction of the full volume.

(Fig. 1). As measurement of soil temperature commenced at least 1 month later in 2003–04 and 2004–05, this initial discrepancy could not be ascertained in these seasons. The discrepancy in the measured and simulated temperatures during the first few weeks of the previous (2001–02 and 2002–03) two seasons may have occurred because the APSIM-soiltemp module used the average annual ambient temperature to initialise the simulation. Also, the starting soil water (which was assumed to be around 50–66% level) may have either overestimated or underestimated the actual soil water and could have also affected the simulation in the early stages. Starting the simulation 10–15 days before the start of growing season, or initialising simulations using actual soil temperatures, would therefore improve estimation of soil temperature in the early stages of crop growth. Indeed, in the 2003–04 season, when simulation of temperature started from sowing but measurement of soil temperature started at 4–5 weeks after the sowing, such a discrepancy was not observed. On these low water holding capacity Red Ferrosols soils, estimates of starting water have fewer implications on temperature simulation in the later stages of crop growth, as crop performance is determined more by the current rainfall. The average in season rainfall was 350 mm in 2001–02, 295 mm in 2002–03, 430 mm in 2003–04 and 250 mm in 2004–05.

The mean ambient temperature was up to 8°C lower than the measured or simulated soil temperature (Fig. 1). Under a growing crop, spatial and temporal changes in canopy development and soil wetness may differentially influence soil temperature at different stages of crop growth, whereas these effects would only have a relatively small effect on ambient temperature. Therefore, differences between soil and ambient temperatures seem to have occurred due to dynamic changes in leaf canopy development and soil water. As the APSIM-peanut module has been found to satisfactorily simulate peanut LAI and water use (Hammer *et al*. 1995; Robertson *et al*. 2002), simulated values of these output variables are presented in Fig. 1. In the 2003–04 season, when LAI was higher than in other seasons, soil temperature tended to be similar to ambient temperature for most of the growing season from about a month after sowing; much larger discrepancies were observed in the other seasons. This may be because greater amounts of radiation may have reached the soil surface in seasons with smaller crop LAIs, thus permitting greater heating of the soil (Fig. 1). These inconsistent differences mean that ambient temperature may be a less useful surrogate measure for soil temperature. The linking of the APSIM-peanut module with the APSIM-soiltemp module allows these dynamic changes in crop development to be accounted for, for the more accurate simulation of soil temperature.

The regression analysis of measured and simulated soil temperature data over all years, from 30 days after sowing, showed there was accurate simulation of soil temperature in the 2001–02, 2002–03 and 2003–04 seasons, with the intercept passing close to the origin (Fig. 2). The R^2 of the relationship between the measured and simulated temperatures was ≥0.80 and the slope close to a 1 : 1 line for the 2001–02, 2002–03 and 2003–04 seasons.

The relationship of measured and simulated soil temperatures in the 2004–05 season was, however, comparatively weaker (R^2 = 0.55), with a significant intercept suggesting that the module was under predicting soil temperature (Fig. 2). While the overall low R^2 in 2004–05 could be partly attributed to the narrower range of sowing dates used, it could also be hypothesised that the observed under prediction of soil temperature could be associated with paraheliotropic leaf movements (i.e. the folding and movement of leaves parallel to sun rays), which is known to occur in peanuts in response to protracted drought (Isoda *et al*. 1996). This effect would mean the APSIM-soiltemp module may slightly under predict soil temperature in very low rainfall years, when leaves undergo paraheliotropic movement. Such movements essentially reduce the light extinction coefficient ‘*k*’ (Matthews *et al*. 1988; Chapman *et al*. 1993). Ridao *et al*. (1996) observed a significant positive relationship between *k* and soil water levels in faba bean (*Vicia faba* L.) and attributed it to paraheliotropic movement of leaves at lower soil water levels, whereas no such relationship was observed in semileafless peas (*Pisum sativum* L.) not showing such movements. Although light interception was not measured in the crops monitored in the present study, visual observations indicated that more light was penetrating through

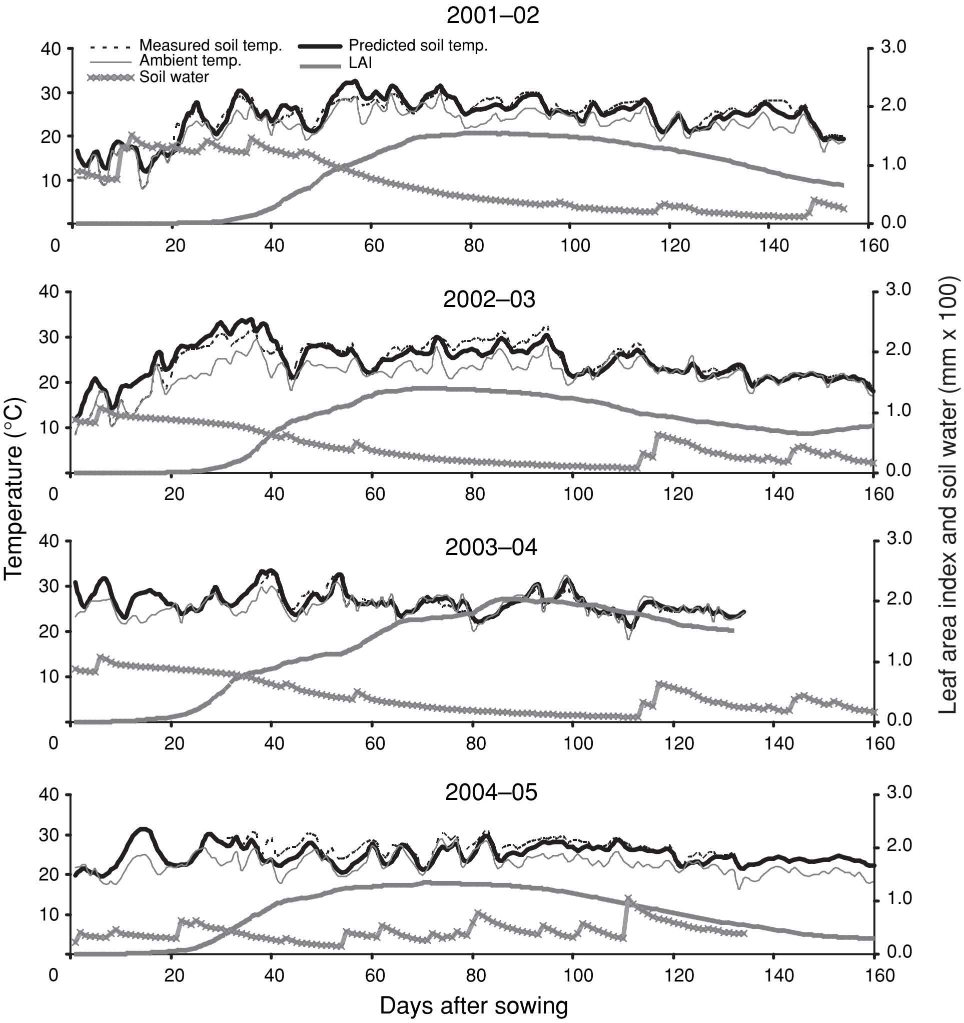

Fig. 1. Dynamics of measured and APSIM-soiltemp simulated soil temperatures, ambient temperature, leaf area index and available soil water in four typical peanut farms in the South Burnett during the 2001–05 seasons.

canopies in rainfed crops in 2004–05, in comparison to adjacent unstressed crops with similar leaf area. This suggests that *k* would have been substantially reduced by drought. Indeed, during sensitivity testing of the model, we showed that arbitrarily reducing *k* from 0.40 to 0.15 at very low levels of FASW to mimic the paraheliotropic response, significantly reduced the intercept for the 2004–05 season data (Fig. 2). Importantly, this change in the model did not greatly affect the slope and intercept in the other (higher rainfall) seasons (data not shown). In the APSIM-peanut module, the relationship between water stress and extinction coefficient in peanut has yet to be parameterised (Robertson *et al*. 2002). Determination of the relationship between crop extinction coefficient and soil water status, and its incorporation into the APSIM-peanut module, could therefore greatly improve the accuracy of simulation of soil temperature for severely stressed peanut crops.

Even without modifying the extinction coefficient, the root mean square deviations were generally ~6% of the average soil temperature, indicating an acceptable range of errors in different seasons (Table 2). Over all four seasons, the relationship between measured and simulated soil temperatures produced a near perfect 1 : 1 fit without any significant intercept [$y = 0.057(\pm\ 0.1593) + 0.992(\pm\ 0.0064)\ (P < 0.01) \times x$; $R^2 = 0.85$]. The performance of the APSIM-soiltemp module compared very favourably with that developed by Paul *et al*. (2004). However, unlike the empirical model of Paul *et al*. (2004), which required calibration of at least eight parameters using a large number of location specific datasets to account for leaf and litter cover, the APSIM-soiltemp module only required calibration of the boundary layer conductance. More importantly, the APSIM-soiltemp module could easily be linked with other APSIM modules, such as APSIM-peanut, to concurrently use model generated output from other modules as input parameters.

Factors affecting soil temperature under a peanut crop

The correlations derived using the pooled data across all four seasons showed that soil temperature was significantly correlated with daily ambient temperature ($r = 0.854$, $n = 4125$), radiation (r = 0.539), and LAI (–0.456). However, as dimensions of a multiple regression equation, ambient

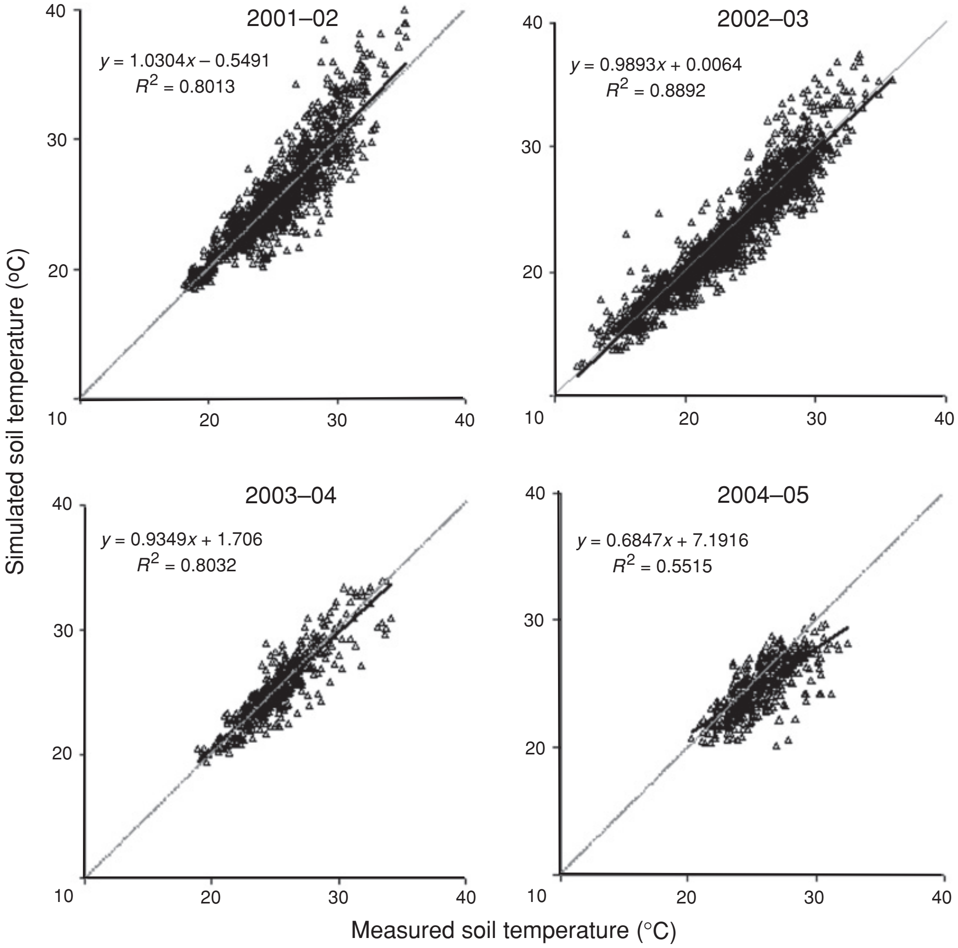

Fig. 2. Linear relationships between measured and APSIM-soiltemp simulated soil temperatures from 30 days (or later in some trials) after sowing for 10 farms in the 2001–02 season, 16 farms in 2002–03 season, five farms in 2003–04 season and four farms in 2004–05 season. The solid line represents the regression line and the dotted line represents the slope line.

Table 2. Root mean square deviations (RMSD) of the relationships between measured and APSIM-soiltemp module simulated soil temperatures

Values in parentheses are RMSD as a percentage of mean soil temperature

Season	RMSD
2001–02	1.68 (6.6)
2002–03	1.42 (6.2)
2003–04	1.26 (5.0)
2004–05	1.39 (5.4)

temperature, radiation, LAI and FASW, all contributed significantly to the observed variation in soil temperature, thus highlighting their role in modulating soil temperature. The partial regression of residuals of each of these dimensions against residuals of soil temperature (which removes the linear effects of the other dimensions in the multiple regression equation) indicated that, of the 83.1% total variation in soil temperature accounted for in the multiple regression equation, 73% was contributed by ambient temperature, 7% by LAI, 1.9% by radiation and 1.2% by FASW. While higher ambient temperatures and radiation increased soil temperature, higher LAI and FASW reduced it (Fig. 3). While FASW may not directly contribute to reduced soil temperature once the surface layer is dry, it may indirectly contribute by keeping leaves horizontally aligned to the soil surface. Under non stressed conditions (FASW > 0.5), the horizontally oriented (diaheliotropic) leaf area would tend to reduce day time soil temperatures by insulating the soil surface, as well as increasing evapotranspiration. However, fuller canopy coverage may also hinder soil cooling during the night by limiting the upward emission of long-wave thermal radiation from the soil into the atmosphere. However, peanut leaves tend to orient vertically during the night and may not insulate the soil as effectively as during the daytime, thus permitting some dissipation of heat from the soil into the atmosphere. These factors will contribute to their role in keeping the soil cooler under harsh tropical and subtropical conditions.

Applications of soil temperature model

Vara Prasad *et al*. (2000) suggested that maintaining soil temperature in the optimum range was critical to maximising flower production, proportion of pegs converting to pods and overall pod growth rates. Since higher LAI and FASW may assist in lowering soil temperature, this opens up the possibility of maximising pod yield by manipulating the pod zone soil temperature via management of LAI and FASW. Indeed, Davidson and Williams (2002) were able to achieve more

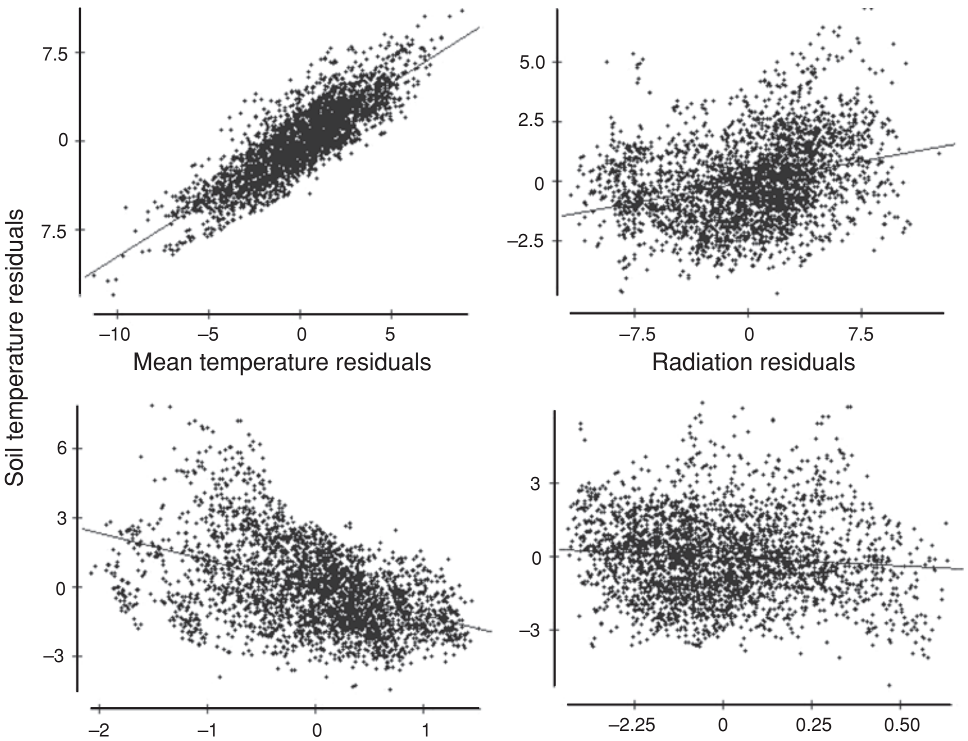

Fig. 3. Relationships of residuals of partial regression coefficients of mean ambient temperature, radiation, leaf area index (LAI) and fractional available soil water (FASW) with APSIM-soiltemp simulated soil temperature. The solid line represents the regression line. The multiple regression equation, $y = 3.442 + (0.947 \times \text{ambient temperature}) + (0.099 \times \text{radiation}) - (1.473 \times \text{LAI}) - 1.596\ (\text{FASW})$, explained 83.1% of the total variation to which 73% was contributed by ambient temperature, 7% by LAI, 1.9% by radiation and 1.2% by FASW. All values were significant at $P = 0.01$.

synchronous pod set and higher yield by maintaining maximum soil temperature in the optimal range of 26.7–27.8°C and minimum daily temperatures in the range of 21.2–23.4°C, via a computer based expert irrigation system ('Irrigator-Pro'). This system uses measured daily soil temperature to simulate a stress index required for a range of applications, including irrigation scheduling and pest and disease management. The APSIM-soiltemp module, validated in the present study, offers the possibility of improving the management of peanuts in similar expert or decision support systems, by providing accurate inputs of simulated soil temperature.

In the past, a suggestion has been made that soil temperature, instead of air temperature, should be used in the computation of thermal time for peanuts. This is because the main temperature 'sensor' of the peanut plant lies near the base of the plant meristem and this, being in proximity to the soil, could be more influenced by soil temperature than air temperature (Leong and Ong 1983). If maturity prediction via soil temperature input is proven to be more accurate than use of ambient temperature input, as suggested by Leong and Ong (1983), then the model prediction of soil temperatures could provide a simple method for improved maturity prediction in peanuts. However, this would require recalibration of the thermal time targets for the crop, which are currently based on air temperature.

Another immediate application for the APSIM-soiltemp module is in conjunction with the APSIM peanut module, where soil temperature is a key input for the in-season monitoring of aflatoxin risk, which is calculated within a decision support system called AFLOMAN (Rachaputi *et al*. 2004; Wright *et al*. 2005). In this system, an aflatoxin risk index (ARI) is calculated based on soil temperature and FASW values during the pod filling stage. Based on the results presented in this paper, it is clear that simulated soil temperatures could be effectively used to calculate accurate estimates of ARI, via inputs of ambient temperature and radiation. Given that the ARI increases substantially at lower levels of FASW, it will also be important to eventually include the relationship between crop extinction coefficient and soil water status in the ASPIM-peanut module, to improve the accuracy of simulation of soil temperature for severely stressed peanut crops.

Conclusions

Ambient temperature was found to be a major factor influencing soil temperature across different farms. However, our results demonstrated that dynamic changes in the peanut canopy also make a substantial contribution to the change in soil temperature, independently of ambient temperature. The APSIM-soiltemp module was able to simulate the pod zone soil temperature (surface 5 cm) with a high level of accuracy over a wide range of soil temperature, from ~30 days after sowing. This soil temperature model is far superior to other empirical based models, mainly because it is able to account for variations and influences of crop canopy cover. The model can provide reliable estimates of soil temperature for use in applications where it is currently required as a measured input. Although not yet tested in other crops, we believe the APSIM-soiltemp module may have wider application in other crops, provided the necessary validation work is conducted.

Acknowledgements

The authors thank all the peanut growers in the Burnett region of south-east Queensland who allowed measurements of soil temperature in their fields. Financial support from the Grains Research and Development Corporation (GRDC) under projects DAQ543 and DAQ 00070, the Australian Centre for International Agricultural Research (ACIAR) under project PHT 97/017, and the Peanut Co. of Australia (PCA) is gratefully acknowledged.

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Manuscript received 4 April 2006, accepted 2 March 2007