Agricultural and Forest Meteorology 180 (2013) 182–193

Contents lists available at SciVerse ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Estimation of solar radiation based on air temperature and application with the DSSAT v4.5 peanut and rice simulation models in Thailand

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ARTICLE INFO

Article history:
Received 7 March 2013
Received in revised form 2 June 2013
Accepted 19 June 2013

Keywords:
Modified Bristow–Campbell model
Estimation coefficient
RMSE
RMSEn
CSM-CERES-rice model
CSM-CROPGRO-peanut model

ABSTRACT

Estimation of solar radiation (SRAD) from daily air temperature by the modified Bristow–Campbell (B–C) model requires three empirical coefficients that are area specific. Previous estimates of these coefficients for Thailand were based on limited data without any evaluation. Accurate estimation of solar radiation has become more important with the wider application of environmental models. The objective of this study was to calibrate and evaluate the coefficients for Thailand with a broader range of data. Meteorological data from 2008 to 2011 were obtained from eight weather stations, three in the North (Chiang Mai, Chiang Rai and Nakhon Sawan), two in the Northeast (Khon Kaen and Ubon Ratchathani), one in the Central (Lop Buri) and two in the South (Chumporn and Surat Thani). Data for 2010 for all locations except Chiang Rai were used for calibration of the coefficients and the remaining data were used as independent data sets for evaluation. The coefficient of determination (R^2), root mean square error (RMSE) and normalized root mean square error (RMSEn) were used as indicators of the agreement between the observed and the calculated SRAD. The results showed that the calibration was acceptable ($R^2 = 0.56$, RMSE = 3.07 MJ m^{-2} d^{-1} and RMSEn = 17.5%). The derived values are $a = 0.63$, $b = 1.89$ and $c = 1.54$. These new coefficients performed well during evaluation with the 13 independent data sets from the eight locations for all four regions, with the R^2, RMSE and RMSEn values in the range of 0.39–0.70, 2.42–3.79 MJ m^{-2} d^{-1} and 14.0–21.7%, respectively. In addition, simulations using estimated SRAD from the derived values provided high R^2 values for peanut and rice yield and total dry matter. These new coefficient values can be used to estimate solar radiation from air temperature data for all locations in Thailand and similar environments in Southeast Asia.

1. Introduction

Solar radiation at the earth's surface is one of the most vital meteorological factors determining agricultural productivity as it is used by crops for transpiration and photosynthesis (Reddy and Ranjan, 2003). Solar radiation data are, thus, important for research in agriculture, ecology, hydrology, meteorology, and soil physics, and specifically in crop modeling (Hunt et al., 1998; Ball et al., 2004; Chen et al., 2011). Such data, however, are not readily available from many meteorological stations across the globe compared to other meteorological data due largely to the high cost of data collection, the requirement for expensive equipment and the difficulty in sensor calibration (Almorox and Hontoria, 2004; Menges et al., 2006; Bakirci, 2007; Robaa, 2009; Fodor and Mika, 2011). This situation has been reported for many countries, including Italy (Bindi and Miglietta, 1991), Canada (Hunt et al., 1998), Australia (Liu and Scott, 2001), Turkey (Bakirci, 2009), USA (Mahmood and Hubbard, 2002) and Thailand (Jintrawet et al., 2002). Lack of adequate observations on solar radiation can be a problem for studies of land-surface processes and is a major limitation in the application of crop growth simulation models (Thornton and Running, 1999; Liu and Scott, 2001). To overcome this problem, indirect estimation of solar radiation from related parameters is required.

Several techniques have been developed to estimate solar radiation using various climatic parameters such as sunshine duration (Ampratwum and Dorvlo, 1999; Rivington et al., 2005; Yorukoglu

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http://dx.doi.org/10.1016/j.agrformet.2013.06.015

and Celik, 2006), temperature (Bindi and Miglietta, 1991; Hunt et al., 1998; Thornton and Running, 1999; Goodin et al., 1999; Liu and Scott, 2001; Mahmood and Hubbard, 2002; Rivington et al., 2005; Rehman and Mohandes, 2008), relative humidity (Thornton and Running, 1999; Rehman and Mohandes, 2008), precipitation (Bindi and Miglietta, 1991; Hunt et al., 1998; Thornton and Running, 1999; Liu and Scott, 2001), and precipitation and temperature combined (Garcia y Garcia and Hoogenboom, 2005; Garcia y Garcia et al., 2008). In addition, new observation technologies using satellite data have also become prominent (White et al., 2008, 2011), but they have not been extensively evaluated for tropical regions where crops are normally grown during the rainy season, causing interference with clouds.

Among the numerous calculation methods, the sunshine and temperature based models are widely used for estimating solar radiation (Liu et al., 2009). Although the sunshine based method is generally accurate (Iziomon and Mayer, 2002; Podestá et al., 2004; Trnka et al.,2005), its use is rather limited due to the lack of sunshine duration data (Liu et al., 2009). On the other hand, air temperature data are normally available for most meteorological stations. Thus, temperature-based models are most commonly used for the estimation of solar radiation. One of the models that has been developed for estimating solar radiation based on the relationship between atmospheric transmittance and the daily range of the air temperature is the original Bristow–Campbell (B–C) model (Bristow and Campbell, 1984). This model is rather simple, requiring two readily available types of data, i.e. latitude and daily air temperature (Goodin et al., 1999). It has been used widely by researchers for computing daily solar radiation values (Hunt et al., 1998; Thornton and Running, 1999; Goodin et al., 1999; Meza and Varas, 2000; Mahmood and Hubbard, 2002; Podestá et al., 2004; Trnka et al., 2005 Menges et al., 2006; Liu et al., 2009; Chen et al., 2011).

The original B–C model was developed for SRAD estimation based on the availability of meteorological surface data. It exploits the relationship between diurnal air temperature range and irradiance load to estimate the daily flux of incoming solar radiation (Goodin et al., 1999). Three empirical coefficients, i.e. *a*, *b*, and *c*, are required by the original B–C model to determine the transmissivity coefficient which is used to estimate solar radiation. These coefficients are calculated from air temperature and solar radiation data and, thus, must be derived at the sites where both air temperature and solar radiation data are available (Goodin et al., 1999). However, the values of these three coefficients are site specific, as solar radiation varies depending on the latitude of the area, including local atmospheric conditions. For an accurate and precise estimation of solar radiation, these coefficients need to be derived specifically for the area in which they will be used in the modified B–C model (Goodin et al., 1999). So far this has only been done for a limited number of regions, e.g. Kansas, USA (Goodin et al., 1999), Australia (Liu and Scott, 2001) and China (Liu et al., 2009).

Jintrawet et al. (2002) estimated the values of the coefficients of the original B–C model, and incorporated them into a simple software program named "WeaData 1.0" for estimating the solar radiation from maximum and minimum temperature for Thailand. The software is intended for use in agricultural research and applications of crop simulation models in Thailand and Southeast Asia. The coefficients derived by Jintrawet et al. (2002), however, still have some drawbacks. Firstly, they were calibrated using data from only two locations, i.e. Chiang Mai (in the North) and Khon Kaen (in the Northeast), which do not represent the full range of weather conditions in Thailand. Secondly, the derived coefficients were never evaluated with an independent data set, particularly from different locations for the same region. There is, thus, a need to derive new values of these coefficients from a wider range of temperature and solar radiation data for more accurate estimates,

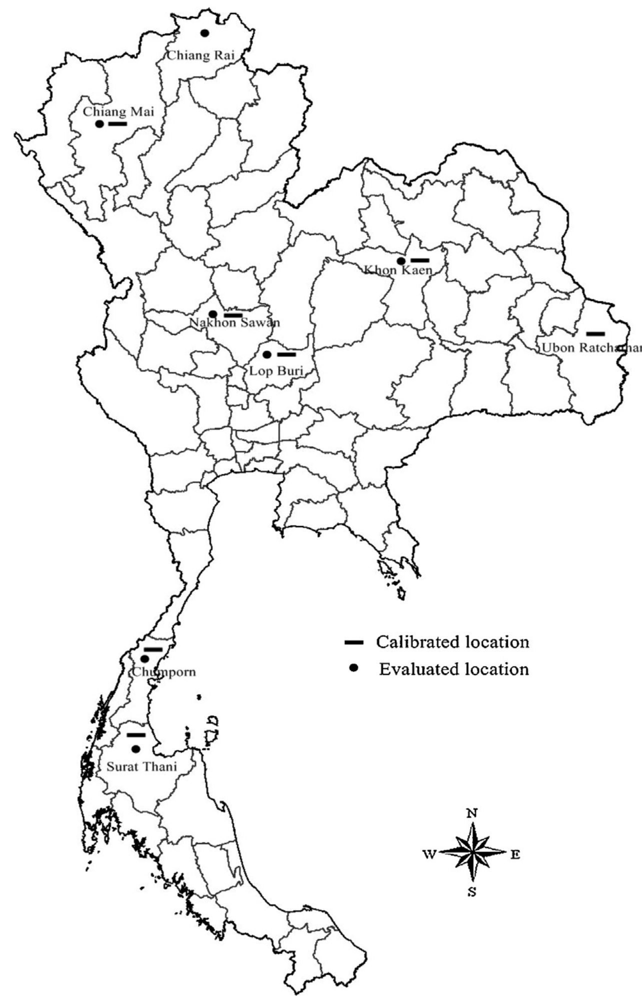

Fig. 1. The locations used for calibration and evaluation of the coefficients.

and the generated solar radiation data from the derived coefficients need to be evaluated with independent data sets that cover a reasonable range of locations in Thailand. The objective of this study was to recalibrate and evaluate the three empirical coefficients, i.e. *a*, *b*, and *c* of the modified B–C model for calculating solar radiation in Thailand from air temperature data and to determine the impact on simulated peanut and rice yield.

2. Materials and methods

2.1. Meteorological data

The meteorological data used in this study included daily solar radiation, daily air temperature and latitude. They were obtained from eight weather stations, including three in the North (Chiang Mai, Chiang Rai and Nakhon Sawan), two in the Northeast (Khon Kaen and Ubon Ratchathani), one in the Central (Lop Buri) and two in the South (Chumporn and Surat Thani) (Fig. 1). The latitude, longitude, elevation and period of recorded data for each location are presented in Table 1.

2.2. Formulae

The original Bristow and Campbell (1984) model (hereafter denoted as the original B–C model) and the modified Bristow and Campbell (Goodin et al., 1999) model (hereafter denoted as the modified B–C model) were used to estimate solar radiation

Table 1
Sources of the meteorological data that were used in this study.

Location	Latitude (N)	Longitude (E)	Elevation (m)	Recorded data[a]
Chiang Mai	18°90′	99°02′	304	2008–2010
Chiang Rai	19°94′	99°85′	394	2008–2009
Nakhon Sawan	15°67′	100°13′	34	2008–2010
Khon Kaen	16°78′	102°95′	210	2008–2010
Ubon Ratchathani	15°25′	105°02′	131	2010
Lop Buri	15°27′	101°19′	10	2008–2010
Chumporn	10°40′	99°18′	3	2009–2010
Surat Thani	9°13′	99°15′	10	2009–2011

[a] Data record starts on 1 January of the first year and ends on 31 December of the final year for daily solar radiation and daily maximum and minimum temperature.

(hereafter denoted as SRAD) from air temperature. Both original and modified B–C models calculate SRAD by estimating the daily transmissivity coefficient (T_t) which is defined as

$$T_t = \frac{R_s}{Q_o}$$

Where T_t is the average transmissivity of the atmosphere during one day, R_s is the daily solar radiation at the earth's surface (MJ m^{-2} d^{-1}), and Q_o is the daily solar radiation at the top of the atmosphere (MJ m^{-2} d^{-1}). Q_o is determined as a function of site latitude using the equation of Allen et al. (1998):

$$Q_o = \frac{24(60)}{\pi} S_0 d_r (h_s \sin\phi \sin\delta + \cos\phi \cos\delta \sin h_s)$$

where S_0 is the solar constant (0.0820 MJ m^{-2} min^{-1}), d_r is the inverse relative distance Earth-Sun (measured in radians), h_s is the half day length (measured in radians), ϕ is the latitude of the location of interest and δ is the solar declination (measured in radians).

In the modified B–C model, the transmissivity coefficient is estimated from the daily air temperature range (ΔT_j) using an exponential equation as follows (Goodin et al., 1999):

$$T_t = a\left[1 - \exp\left(-b\frac{\Delta T^c}{Q_o}\right)\right]$$

$$\Delta T_{(j)} = TMAX_{(j)} - \frac{TMIN_{(j)} + TMIN_{(J+1)}}{2}$$

where a, b, and c are empirical coefficients, $TMAX$ is daily maximum temperature (°C), $TMIN$ is daily minimum temperature (°C), and j is the day of the year.

2.3. Calibration and evaluation of a–b–c coefficients

The observed solar radiation and air temperatures data for the year 2010 from seven locations in Thailand, i.e. Chiang Mai, Nakhon Sawan, Lop Buri, Khon Kaen, Ubon Ratchathani, Chumporn and Surat Thani provinces (Fig. 1), were combined into one set of data and used for calibration of the three empirical coefficients of the modified B–C model. The default values of the coefficients, i.e. a = 0.63, b = 1.94 and c = 1.53, that were included in the WeaData 1.0 program (Jintrawet et al., 2002) were used as the initial values to calibrate the new set of coefficients. The first step of the calibration was determining the value of the a coefficient as the best upper bound value of the transmissivity coefficient values (T_t). This was done by assessing the value of the a coefficient as the asymptotic between transmittance (T_t) for higher ΔT (clear day) temperature amplitude.

The next step, we developed the expression:

$$\begin{aligned} u &= 1 - \left(\frac{Tr}{a}\right) = \exp[-b(\Delta T^c)] \rightarrow \ln u = -b\Delta T^c \rightarrow v = \ln(-\ln u) \\ &= \ln(b) + c\ln\Delta T \end{aligned}$$

This leads to a linear relationship between v and $\ln\Delta T$, which was fitted by a least-square method for the b and c coefficients. For all three coefficients, the parameters that were used to determine the goodness of fit between the observed and the simulated values of solar radiation were the coefficient of determination (R^2) from regression analysis, the root mean square error (RMSE) (Wallach and Goffinet, 1987) and the normalized root mean square error (RMSEn) (Loague and Green, 1991). The highest value of R^2 and the lowest value of RMSE and %RMSEn were used to indicate the best fit between the calculated values of solar radiation and their corresponding observed values.

The root mean square error (RMSE) and the normalized root mean square error (RMSEn) were computed using the following equation:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i-1}^{n}(P_i - O_i)^2}{n}}$$

where n is the number of observations, P_i is the calculated value for the ith measurement and O_i is the observed value for the ith measurement.

$$\mathrm{RMSEn} = \frac{\mathrm{RMSE} \times 100}{\bar{O}}$$

where RMSE is the root mean square error and $\bar{O}$ is the mean of the observed values.

The derived coefficients a, b and c obtained from calibration were then used to evaluate the generated solar radiation data with the corresponding independent data set. For each location, the daily data for air temperature for a particular year were used to calculate the daily solar radiation for that same year; the calculated data were then compared with the corresponding observed data, and their goodness of fit was determined. The data that were used for the evaluation included solar radiation for 2008 from five locations, i.e. Chiang Mai, Chiang Rai, Nakhon Sawan, Khon Kaen and Lop Buri, solar radiation data for 2009 from seven locations, including Chiang Mai, Chiang Rai, Nakhon Sawan, Khon Kaen, Lop Buri, Chumporn and Surat Thani, and solar radiation data for 2011 from Surat Thani. The accuracy of the coefficients was determined by the goodness of fit between the calculated values of solar radiation with their corresponding observed values, as indicated by the values of R^2, RMSE and RMSEn.

2.4. Model simulation with new coefficients

We used the new estimated SRAD values to simulate peanut and rice data sets in Thailand using the DSSAT Cropping System Model Version 4.5 (Hoogenboom et al., 2010). Observed and calculated solar radiation data, using the new coefficients, were used as weather input data to simulate yield and total dry matter of 17 peanut lines (Suriharn et al., 2007). Peanut was simulated for the early rainy season with a planting date of May 5th for the 2008 and 2009 cropping seasons using a 20 cm × 50 cm plant spacing.

The simulation of rice covered seven non-photoperiod sensitive varieties (Somchit, 2012) planted in 2008 cropping season in five locations (Chiang Rai, Chiang Mai, Nakhon Sawan and Lop Buri) and 2009 cropping season in seven locations (Chiang Rai, Chiang Mai, Nakhon Sawan, Lop Buri, Chumporn and Surat Thani). Rice yield and total dry matter was simulated, using the new coefficients, using transplanting method on January 19 of 2008 and 2009, with three 25 day old seedlings using 3 plants per hill at a 25 cm × 25 cm plant spacing. In addition, a rice experimental data set included with DSSAT v4.5, i.e., the 1985 rice experiment, was used to simulate with the new coefficients. The 1985 rice experiment was conducted in 1985

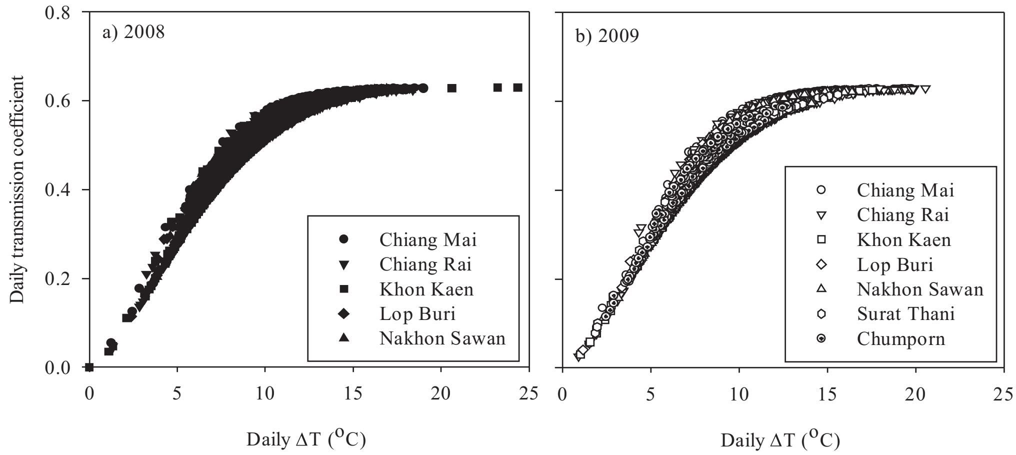

Fig. 2. Relationships of daily ΔT and transmissivity coefficient using the new coefficients.

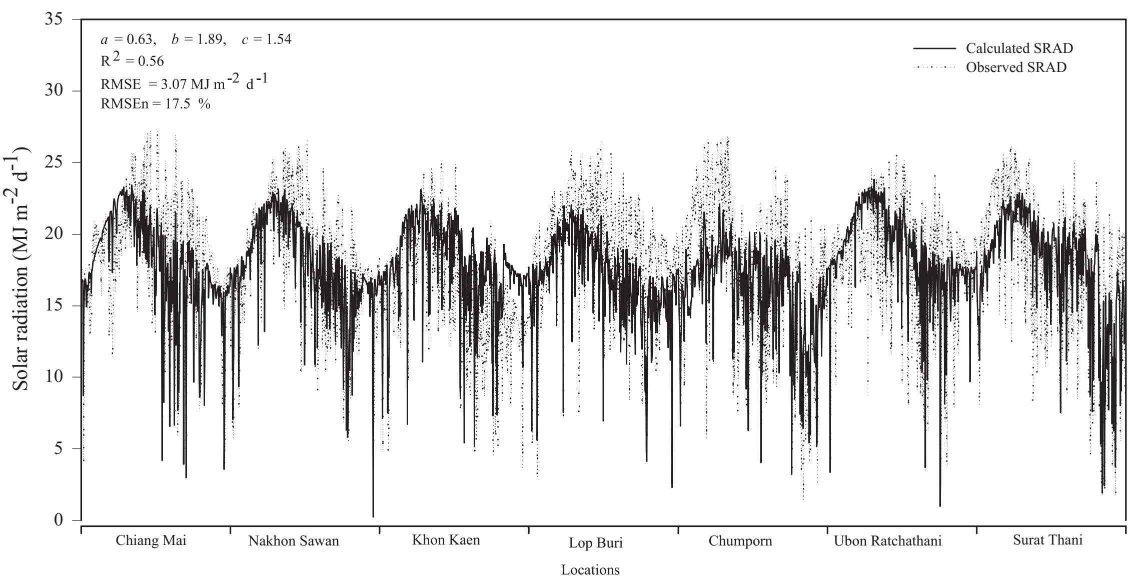

Fig. 3. Comparison between 2010 observed (dotted) and the calculated SRAD (solid) for the calibration of the coefficients.

Table 2
Coefficient of determination (R^2), root mean square error (RMSE) and normalized root mean square error (RMSEn) for the evaluation of the old coefficients of Jintrawet et al. (2002) and the new coefficients derived in this study against 13 independent data sets.

Dataset	Location	Year	Old coefficients for Chiang Mai[a]			Old coefficients for Khon Kaen[b]			New coefficients[c]		
			R^2	RMSE (MJ m^{-2} d^{-1})	RMSEn (%)	R^2	RMSE (MJ m^{-2} d^{-1})	RMSEn (%)	R^2	RMSE (MJ m^{-2} d^{-1})	RMSEn (%)
1	Chiang Mai	2008	0.12	17.10	95.9	0.12	16.40	91.9	0.62	2.50	14.0
2	Chiang Mai	2009	0.04	17.41	96.8	0.04	16.66	92.7	0.56	2.81	15.7
3	Chiang Rai	2008	0.12	16.03	97.2	0.13	15.33	93.0	0.63	2.85	17.3
4	Chiang Rai	2009	0.02	16.55	96.9	0.02	15.74	92.2	0.55	3.08	18.1
5	Nakhon Sawan	2008	0.06	17.58	98.3	0.07	16.95	94.8	0.62	2.51	14.1
6	Nakhon Sawan	2009	0.08	17.16	97.9	0.09	16.54	94.3	0.56	2.61	14.9
7	Lop Buri	2008	0.13	18.26	98.2	0.14	17.77	95.6	0.55	3.40	18.3
8	Lop Buri	2009	0.09	17.81	96.9	0.10	17.30	94.1	0.41	3.27	17.8
9	Khon Kaen	2008	0.05	16.90	98.5	0.06	16.31	95.1	0.39	3.25	19.0
10	Khon Kaen	2009	0.09	16.88	98.0	0.09	15.61	90.6	0.60	2.42	14.0
11	Surat Thani	2009	0.54	17.49	98.8	0.55	16.90	95.5	0.58	2.87	16.2
12	Surat Thani	2011	0.62	17.04	101.4	0.63	16.59	98.7	0.70	2.86	17.0
13	Chumporn	2009	0.39	17.67	101.2	0.39	17.28	99.0	0.51	3.79	21.7
Mean			0.18	17.22	98.2	0.19	16.57	94.4	0.56	2.94	16.8

[a] Old coefficients for Chiang Mai: $a = 0.65$, $b = 0.004$ and $c = 2.4$.
[b] Old coefficients for Khon Kaen: $a = 0.62$, $b = 0.008$ and $c = 2.4$.
[c] New coefficients: $a = 0.63$, $b = 1.89$ and $c = 1.54$.

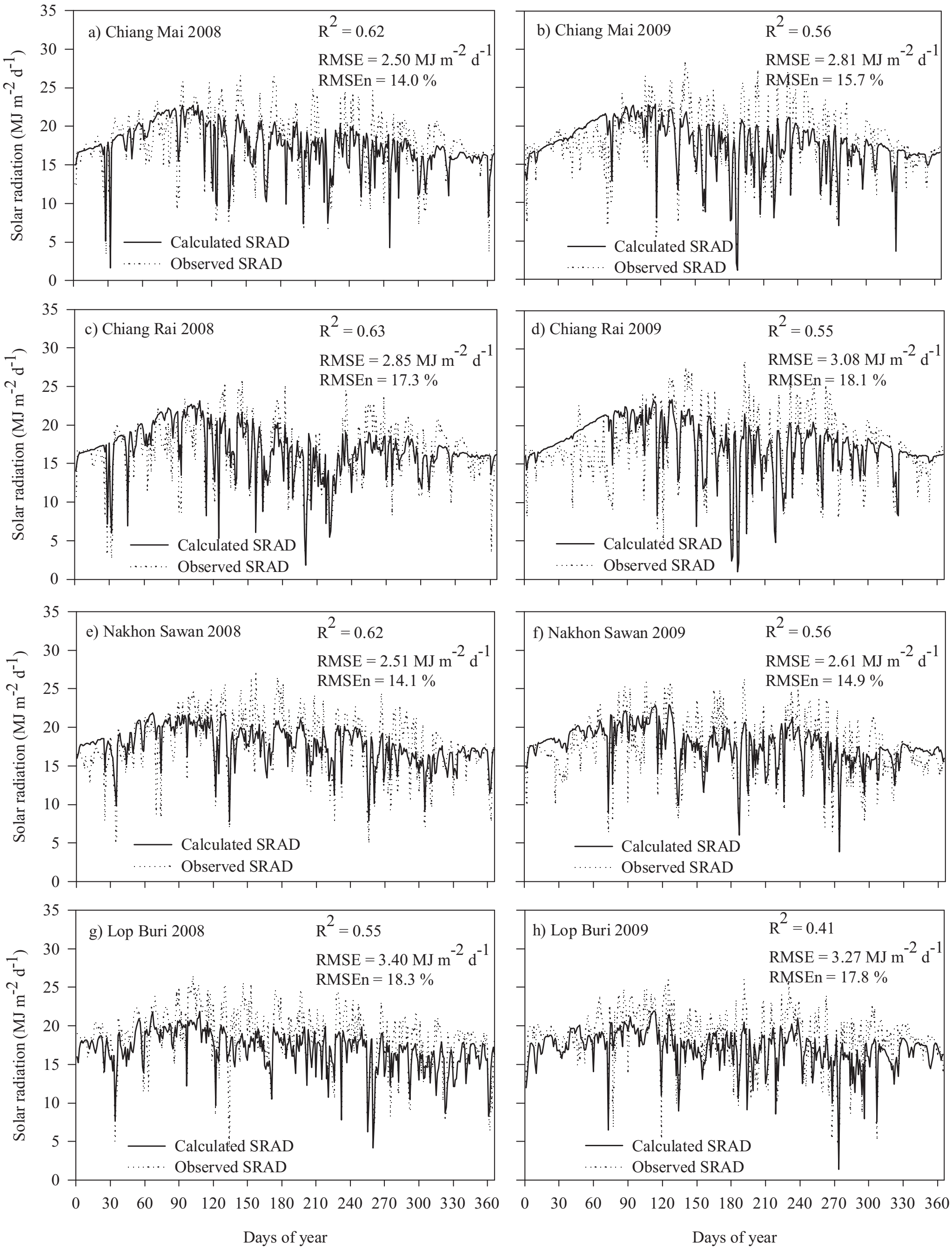

Fig. 4. Comparison between observed (dotted) and the calculated SRAD (solid) for the validation of the coefficients with independent data from four provinces in the North and the Central Regions.

at the Suphanburi Rice Research Center using non-glutinous and non-photoperiod sensitive rice variety RD 23 (Jintrawet, 1991). The taxonomy of the soil of the experimental site is a fine, mixed, non-acid, isohyperthermic, aeric tropaquepts. Six nitrogen rates consisting of 0, 38, 75, 112, 150, and 188 kg N/ha replicated four times, were arranged in a Randomized Complete Block Design. The fertilizer was equally split and applied at the time of transplanting and about 30 days after transplanting. Urea (46% nitrogen) was used as the nitrogen source. The experiment was transplanted on September 3, 1985, using 25 days old seedlings at three plants per hill at a 25 cm × 25 cm plant spacing.

To determine the accuracy of model simulation with estimated and observed SRAD, we compared simulated anthesis date, physiological maturity date, total dry matter and yield of both peanut and rice experimental data sets with the observed data using a 1:1 line graph and indicated their agreements by the values of R^2, RMSE and d-statistic. The d-statistic (d-stat) or 'index of agreement' value (Willmott, 1982) was computed using the following equation:

$$d\text{-stat} = 1 - \left[\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{\sum_{i=1}^{N}[|P_i'| + |O_i'|]^2} \right]$$

where N is the number of observations, P_i is the calculated value for the ith measurement and O_i is the observed value for the ith measurement. The d-stat value of a 'good' model should approach unity.

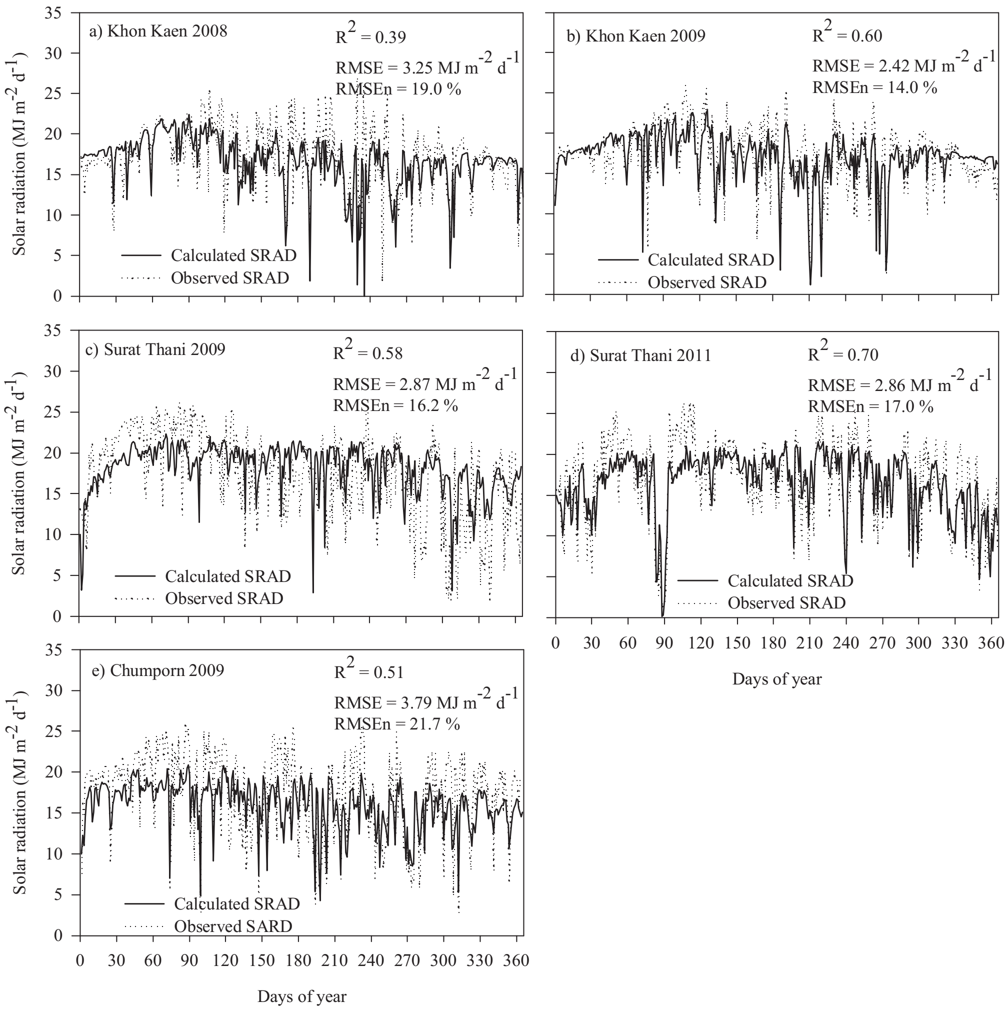

Fig. 5. Comparison between observed (dotted) and the calculated SRAD (solid) for the evaluation of the coefficients with independent data from one province in the Northeast and two provinces in the South.

3. Results

3.1. The new coefficients

The best values for the new *a*, *b* and *c* coefficients for the modified B–C model that were derived from the calibration are 0.63, 1.89 and 1.54, respectively, as compared to the old coefficients of 0.64, 0.006, and 2.4 for the original B–C model, respectively. Fig. 2 shows the relationships of the daily temperature differences and daily transmissivity (T_t), which suggests that all of the seven weather stations used in our study show a similar seasonal variation, but not quite the day-to-day oscillations. The calculated daily solar

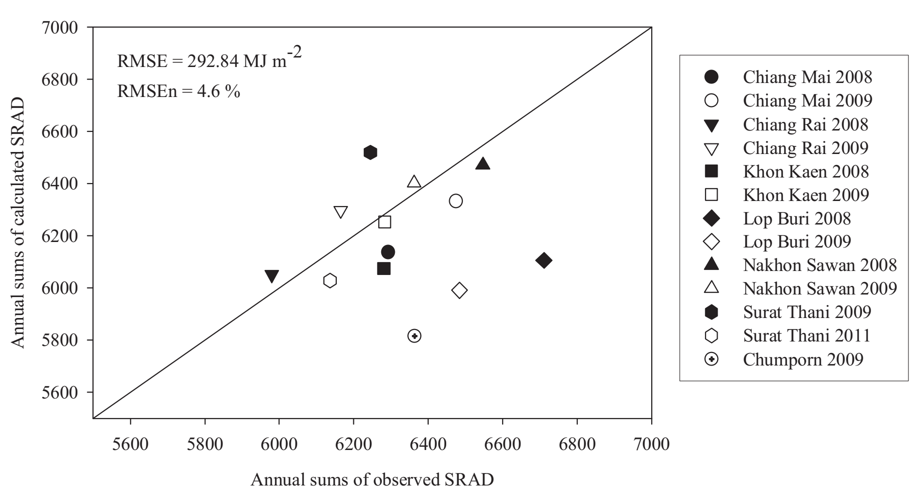

Fig. 6. Comparison of observed solar radiation (SRAD) and calculated solar radiation using new coefficients for seven locations in Thailand.

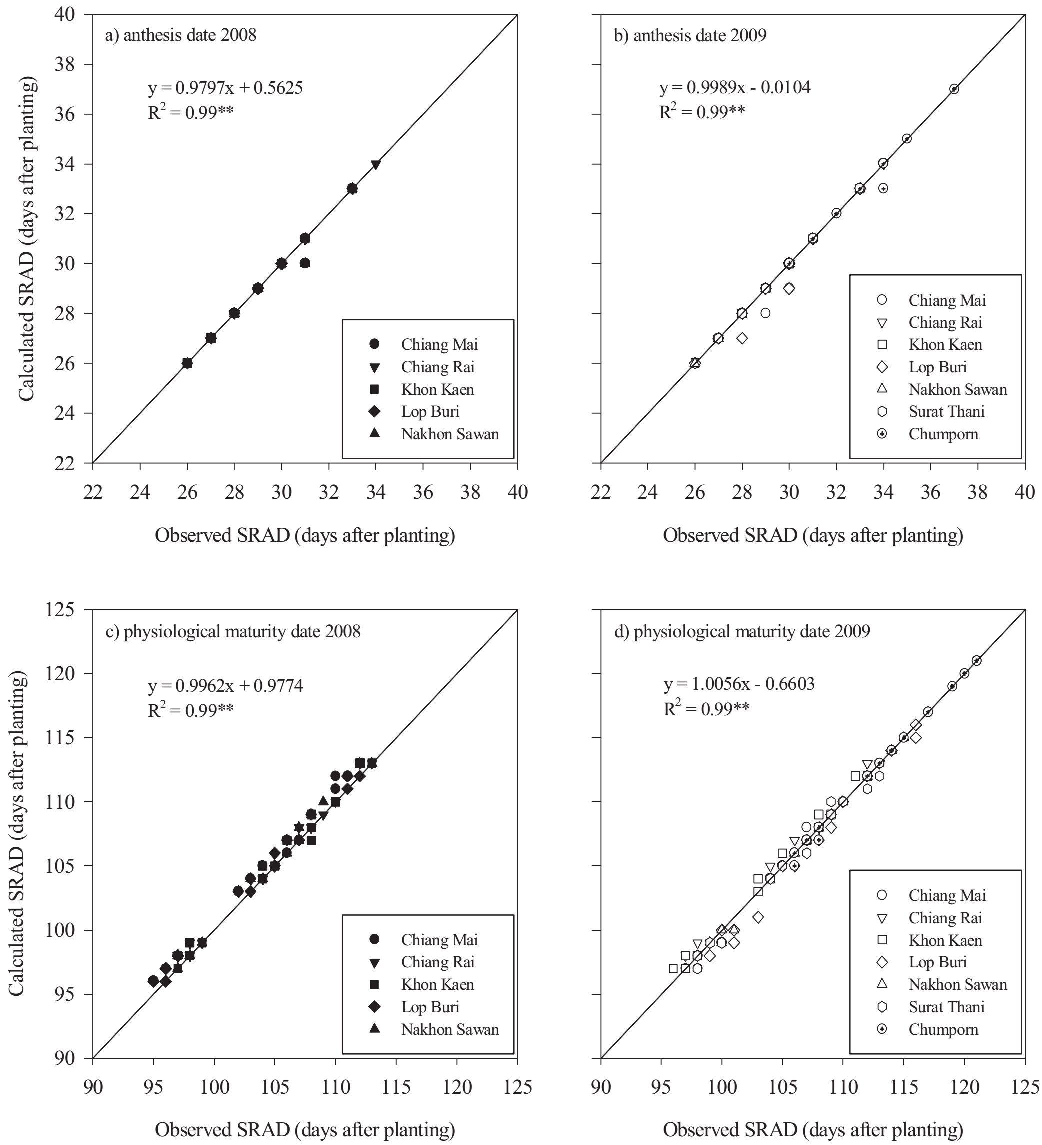

Fig. 7. Anthesis date simulated with calculated versus observed SRAD for 2008 (a) and 2009 (b) and physiological maturity date simulated with calculated versus observed SRAD for 2008 (c) and 2009 (d) of 17 peanut lines (** indicates highly significant at 0.01% probability).

radiation for the seven locations in 2010 using these coefficient values agreed reasonably well with the corresponding observed values that were used for the calibration (Fig. 3), with the values for R^2, RMSE and RMSEn being 0.56, 3.07 MJ m^{-2} d^{-1} and 17.5%, respectively. This indicated that the calibration method yields better results. The values of the new coefficients differed considerably from those of Jintrawet et al. (2002), which were a = 0.65, b = 0.004 and c = 2.4 for Chiang Mai and a = 0.62, b = 0.008 and c = 2.4for Khon Kaen, especially the b and c coefficients were different. It is interesting to note that the coefficients of the study conducted by Jintrawet et al. (2002) closely followed those published in the original B–C model paper, which were obtained for mid-latitude sites in western United States.

Results of the evaluation of the new set of coefficients against 13 independent solar radiation data sets are presented in Table 2 and compared with the old sets of coefficients for Chiang Mai and Khon Kaen of Jintrawet et al. (2002). The solar radiation data that were used for evaluation included those for 2008 from five locations

Table 3
Observed and simulated top weight (TW) (kg/ha), coefficient of determination (R^2), root mean square error (RMSE) and d-statistic for the evaluation of the old coefficients of Jintrawet et al. (2002) and the new coefficients derived in this study using the 1985 rice experimental data.

Nitrogen rate	Observed TW	Simulated TW		R^2		RMSE		d-Statistic	
		Old	New	Old	New	Old	New	Old	New
0 kg N/ha	2723	2386	2320	0.990	0.991	525.9	608.7	0.989	0.985
38 kg N/ha	3447	3509	3400	0.979	0.981	528.9	469.0	0.994	0.995
75 kg N/ha	3778	4350	4219	0.981	0.983	1072.5	887.6	0.982	0.987
113 kg N/ha	5687	5972	5746	0.925	0.930	1425.9	1268.6	0.977	0.981
150 kg N/ha	5921	5972	6346	0.923	0.928	1388.6	1295.6	0.979	0.981
188 kg N/ha	6365	5972	6346	0.872	0.879	1861.7	1860.2	0.964	0.963

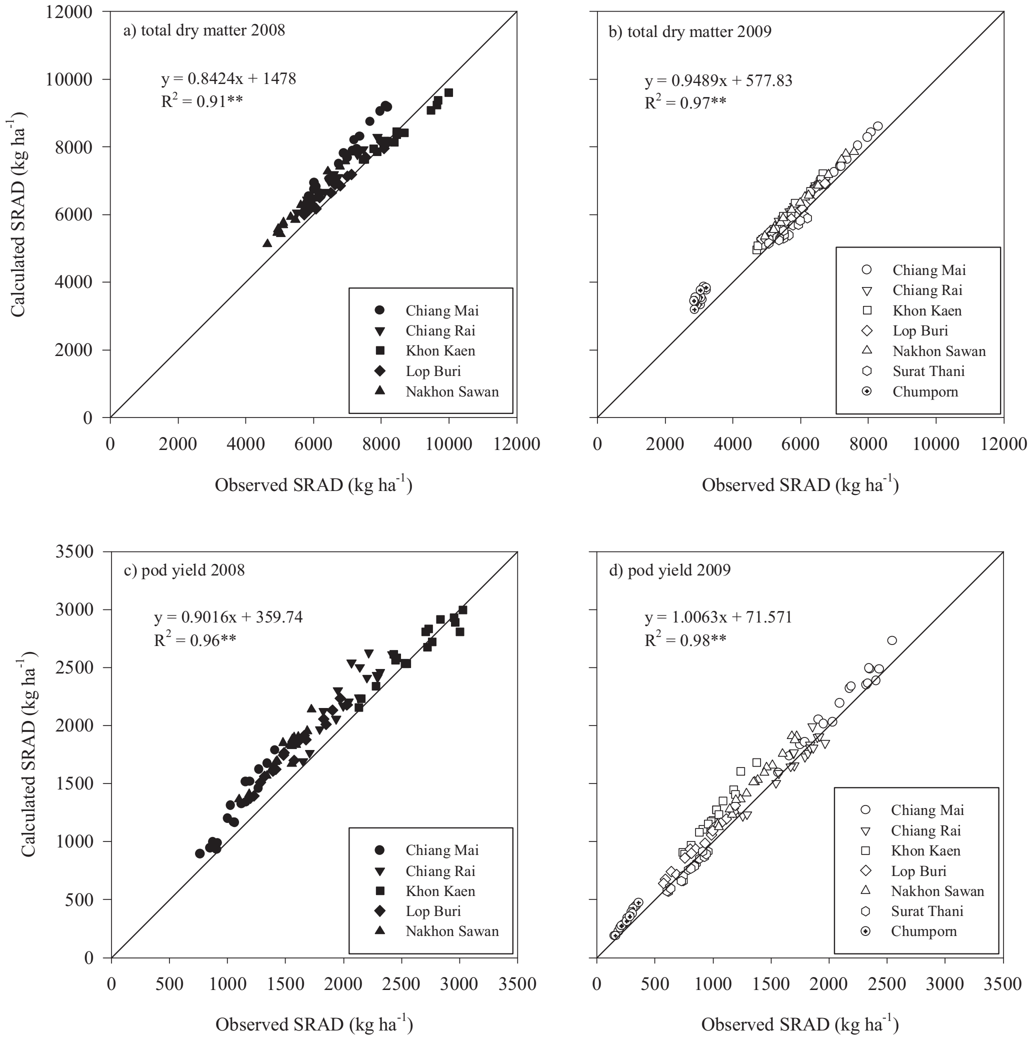

Fig. 8. Total dry matter simulated with calculated versus observed SRAD for 2008 (a) and 2009 (b) and yield simulated with calculated versus observed SRAD for 2008 (c) and 2009 (d) for 17 peanut lines (** indicates highly significant at 0.01% probability).

(Chiang Mai, Chiang Rai, Nakhon Sawan, Khon Kaen and Lop Buri), for 2009 from seven locations (Chiang Mai, Chiang Rai, Nakhon Sawan, Khon Kaen, Lop Buri, Chumporn and Surat Thani) and for 2011 from Surat Thani. The results showed that the new set of coefficients provided estimates for solar radiation that were much closer to the corresponding observed values than those derived from the two old sets of coefficients, as shown by much higher values for R^2 and substantially lower values for RMSE and RMSEn for the evaluation data (Table 2). The new set of coefficients resulted in R^2 values in the range of 0.39–0.70 with a mean of 0.56, compared to 0.02–0.62 with a mean of 0.18 for the old set of coefficients for Chiang Mai and 0.02–0.63 with a mean of 0.19 for the old set of coefficients for Khon Kaen. It is to be noted that coefficients of determination are better but not optimal. The RMSE values obtained from the new set of coefficients varied between 2.42 and 3.79 MJ m^{-2} d^{-1} with a mean of 2.94 MJ m^{-2} d^{-1}, substantially lower than 16.03–18.26 MJ m^{-2} d^{-1} with a mean of 17.22 MJ m^{-2} d^{-1} that were obtained from the old set of coefficients for Chiang Mai and 15.33–17.77 MJ m^{-2} d^{-1} with a mean of 16.57 MJ m^{-2} d^{-1} that were obtained from the old set of coefficients for Khon Kaen. Similarly, the values of RMSEn for the new set of coefficients ranged from 14.0–21.7% with a mean of 16.8% were much lower than 95.9–101.4% and 90.6–99.0% with a mean of 98.2% and 94.4% that were obtained from the old sets of coefficients for Chiang Mai and Khon Kaen, respectively. These results indicated that the new set of coefficients was much better than the old set in the estimation of solar radiation from temperature data.

Results of the evaluation of the new set of coefficients with SRAD data from the two provinces in the North (Chiang Mai and Chiang Rai) and two provinces in the Central Region (Nakhon Sawan and Lop Buri) for 2008 and 2009 are shown in Fig. 4, while results of the evaluation with the observed data from Khon Kaen province in the Northeast for 2008 and 2009, from Surat Thani province in the South for 2009 and 2011, and from Chumporn province also in the South for 2009 are presented in Fig. 5. The graphs showed a good agreement between the estimated and the observed SRAD values for all 13 data sets, as indicated by reasonably high R^2 and low RMSE and RMSEn. Except for Lop Buri in 2009 and Khon Kaen in 2008 for which R^2 was somewhat low (0.39–0.41), the R^2 values for the other 11 data sets were reasonably high, ranging from 0.51 to 0.70. Also, the RMSE and RMSEn values were low for all 13 data sets, with RMSE values ranging from 2.42 to 3.79 MJ m^{-2} d^{-1}, and RMSEn varying in 14.0–21.7% range. These results indicated that the new values for the B–C model could generate daily SRAD data for different locations in Thailand at a reasonably high level of accuracy. We compared the annual sums of daily calculated solar radiation,

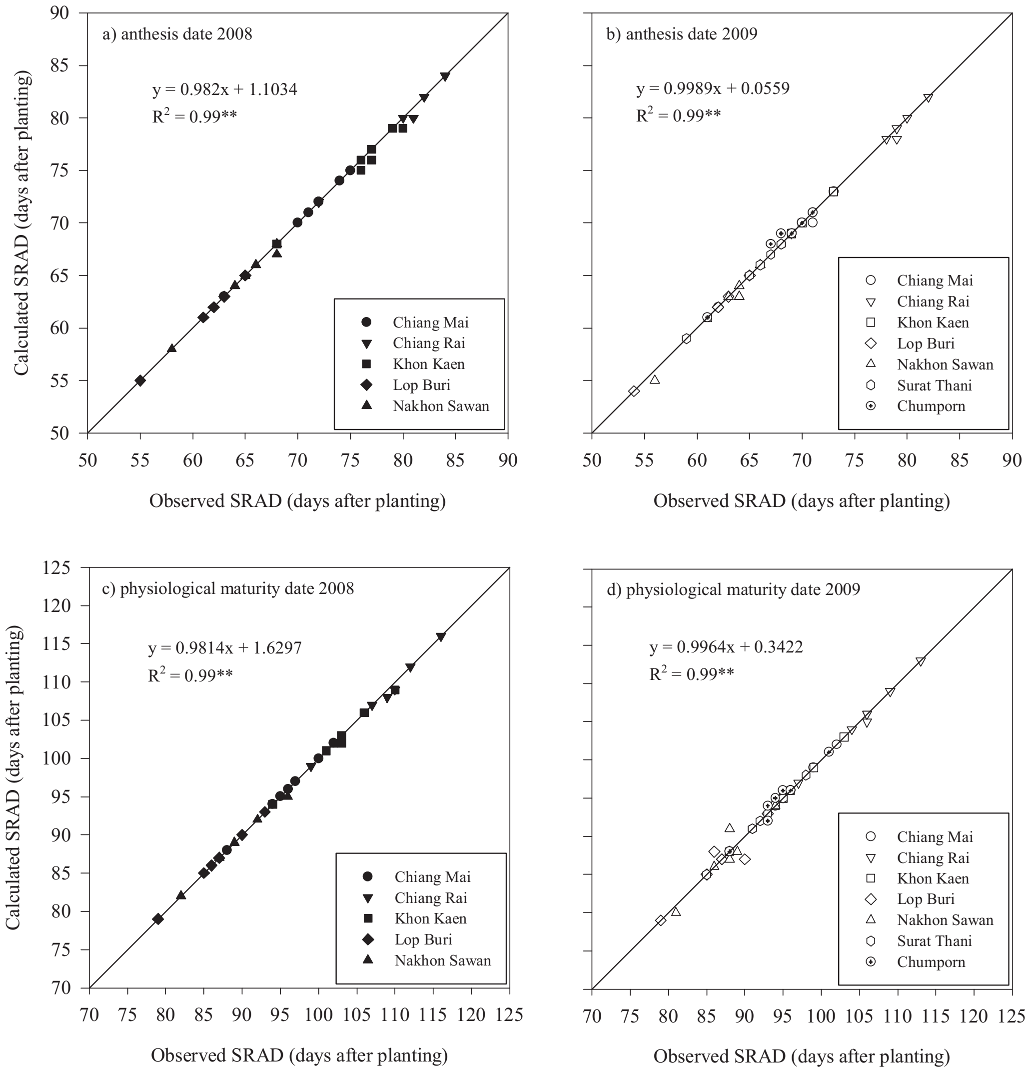

Fig. 9. Anthesis date simulated with the calculated versus observed SRAD for 2008 (a) and 2009 (b) and physiological maturity date simulated with calculated versus observed SRAD for 2008 (c) and 2009 (d) for 7 non-photoperiod sensitive rice varieties (** indicates highly significant at 0.01% probability).

using the new coefficients, with observed solar radiation (Fig. 6) and found that it is underestimated, however with a relatively low RMSEn.

3.2. Model simulation using the new coefficients

3.2.1. Peanut

The results of the anthesis and physiological maturity dates simulated by calculated and observed SRAD indicated that the coefficient of determination (R^2) for anthesis date was reasonably high at 0.99 for both 2008 and 2009. Physiological maturity dates simulated by calculated SRAD also showed good agreement with the values simulated by observed SRAD with a R^2 of 0.99 for both years (Fig. 7). One would expect this as in most cases phenology is not directly affected by solar radiation, except indirectly through drought stress.

The simulation for total dry matter and pod yield of peanut indicated that the results from the year 2009 showed a better agreement compared to 2008. Comparison between the data simulated by calculated and observed SRAD for 2008 showed values of R^2 of 0.91 and 0.96 for total dry matter and pod yield, respectively. While the values of R^2 for 2009 were 0.97 and 0.98 for total dry matter and pod yield, respectively (Fig. 8).

3.2.2. Rice

The results of anthesis and physiological maturity dates simulated by the calculated and observed SRAD for 2008 and 2009 are shown in Fig. 9. The results indicated that the anthesis and physiological maturity dates simulated by calculated SRAD showed very good agreement with the values simulated with the observed SRAD, with a R^2 of 0.99 for both years.

Total dry matter and grain yield of rice simulated with the calculated and observed SRAD had a lower agreement than peanut (Fig. 10). The result indicated that total dry matter simulated for 2009 (R^2 = 0.83) had a better agreement than for 2008 (R^2 = 0.62). Similarly, simulated rice grain yield for 2009 had a higher R^2 value (0.82) than for 2008 (R^2 = 0.54).

Simulations of the 1985 rice experiment showed a high accuracy for top weight for all six nitrogen application rates for both estimated and observed SRAD. The result indicated that simulated top weight levels with the new coefficients had an average R^2, RMSE and *d*-statistic values of 0.95; 1.103; and 0.98, respectively (Table 3).

4. Discussion

The underlying hypothesis of this view was that the previous estimates for the coefficients of the original B–C model by Jintrawet

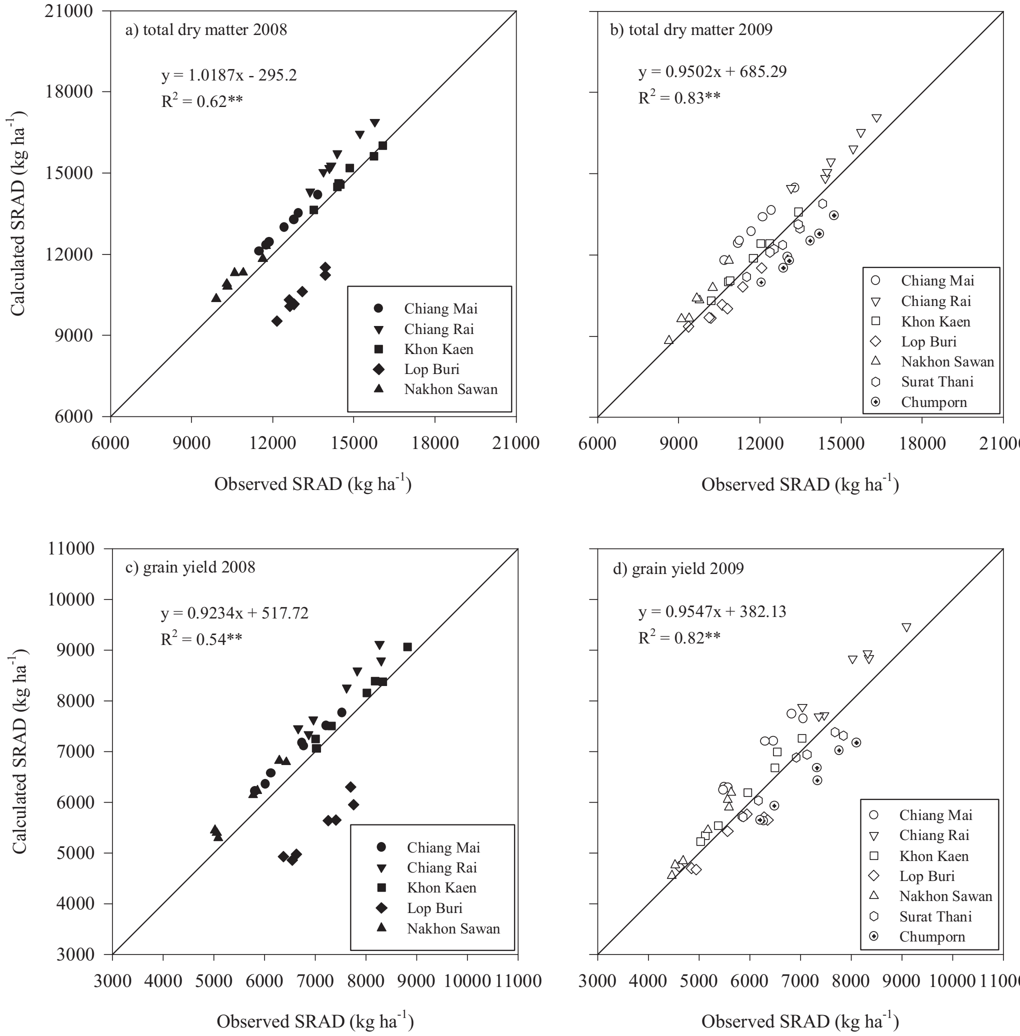

Fig. 10. Total dry matter simulated with the calculated versus observed SRAD for 2008 (a) and 2009 (b) and yield simulated with the calculated versus observed SRAD for 2008 (c) and 2009 (d) for 7 non-photoperiod sensitive rice varieties (** indicates highly significant at 0.01% probability).

et al. (2002) for calculating solar radiation in Thailand from air temperature data were not sufficiently accurate as they were derived from data from only two locations and also had not been evaluated with independent data sets. The goal of this study was to derive new values of these coefficients for the modified B–C model, from a broader range of observed data in Thailand and also to establish the creditability of these estimates for application of crop growth simulation models. To derive these coefficients, the observed solar radiation and air temperature data for 2010 from seven locations spread over four different regions of Thailand were used for calibration. The results showed that the calibration was successful. The calculated values for daily solar radiation agreed well with the corresponding observed values from which the coefficients were derived, as indicated by an acceptable value of R^2 and low values for RMSE and RMSEn (Fig. 2).

As expected, the new estimates for coefficients were greatly superior to the old estimates of Jintrawet et al. (2002) in providing calculated daily solar radiation data that were much closer to the corresponding observed data than the old estimates for all the 13 independent data sets that were used for the evaluation. This could be seen by the higher values of R^2 and lower values of RMSE and RMSEn for the new set of coefficients than for the old sets (Table 2). The evaluation of the new values of the three coefficients with the 13 independent data sets resulted in R^2 values that ranged from 0.39 to 0.70, RMSE values that ranged from 2.42 to 3.79 MJ m^{-2} d^{-1}, and RMSEn values that ranged from 14.0 to 21.7%. These are comparable with the values of RMSE obtained by Goodin et al. (1999) for evaluation of the coefficients with data from 10 test sites in Kansas which ranged from 2.0 to 6.2 MJ m^{-2} d^{-1}, with percentage error ranging from 26 to 47%. Thus, the new values of the coefficients are considered acceptably accurate in estimating solar radiation for the tropical environment over Thailand from air temperature data.

Although there are some differences in the values of R^2, RMSE and RMSEn among locations for the evaluation of the new estimates of the coefficients, these differences are rather small and have a similar magnitude as the variation of these parameters between years within a location (Table 2). This indicates that the new values of the three coefficients can provide calculated values for daily solar radiation for the locations that were evaluated at more or less equal accuracy. As these locations are scattered in all four regions of the country, these new estimates, thus, can be used in calculating solar radiation from air temperature data for all locations in Thailand and regions in southeast Asia that have a similar tropical climate. This is in line with the finding of Goodin et al. (1999) whose calibrated coefficients for a site at Manhattan could be used to estimate solar radiation at 10 different sites across the state of Kansas, and the accuracy of results approached that of the calibration sites itself. They pointed out that latitudinal deviation between the calibration site and the model test sites may play a slight role in the accuracy of the solar radiation estimate, suggesting that either overall climatic setting is not critical in determining the coefficient values or that climate does not vary sufficiently throughout Kansas to greatly affect accuracy. The same explanation can also be given for several of the applications of the estimates that were derived in this study. McVicar and Jupp (1999) also successfully developed coefficients for the modified B–C model that are suitable for large agricultural areas in Australia and China.

Model simulations using calculated SRAD data generated by new coefficients for peanut and rice experimental data sets in Thailand confirm the accuracy of the new coefficients for the modified B–C model. This new set of coefficients provides an opportunity for further testing with other crop simulation models, i.e. cassava and sugarcane, that are important in the region. As Thailand is one of the world leading producers and exporters of rice, cassava, sugarcane, and other agricultural commodities, daily solar radiation data are needed as an important input for crop simulation models for risk assessment and management under the changing economic and environmental conditions. The modified B–C model and the new coefficients are relatively easy to implement with high accuracy and require only daily air temperature data set. The data set is readily available from the website managed by Thailand Meteorological Department, currently monitoring and recording some 89 weather stations throughout the country (http://www.aws-observation.tmd.go.th/web/main/index.asp). Sixty five stations are located in the northern, northeastern, central and eastern regions where rice, cassava, and sugarcane are the major economic crops. In addition, 24 stations are located in the southern region where rubber and oil palm are grown predominantly. The "WeaData 1.0" program allows users to estimate SRAD for a given weather station from maximum and minimum temperatures and export the calculated SRAD into weather data file compatible with all DSSAT v4.5 crop simulation models. Together the new coefficients and the "WeaData 1.0" program will allow users to manage associated risk in decision making to manage limited agricultural resources such as irrigation water, chemical and organic fertilizers, with simulation models for economically important crops in Thailand and southeast Asia, including rice, cassava, and sugarcane.

5. Conclusion

A new estimation was conducted for the *a*, *b*, and *c* coefficients of the modified B–C model for calculating the SRAD for Thailand from daily maximum and minimum temperatures. The new values for the *a*, *b* and *c* coefficient of the modified B–C model are 0.63, 1.89 and 1.54, respectively. To facilitate the calculation, these new coefficient values could be used with the WeaData 1.0 program developed by Jintrawet et al. (2002) for estimating the solar radiation based on the modified B–C model. These new coefficients performed well in the evaluation with 13 independent data sets from eight locations in all four regions of the country at comparable accuracy. Model simulations using calculated SRAD on peanut and rice data sets also yield high accuracy. Therefore, these new coefficients can be used for estimating daily solar radiation from air temperature for tropical environments in Thailand and Southeast Asia.

Acknowledgements

The support of the Thai Meteorological Department, Silapakorn University and the Khon Kaen Field Crop Research Center for providing meteorological data that were used in this study is gratefully acknowledged.

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