Global Theme on Agroecosystems

Report no. 45

Quantifying Yield Gaps and Abiotic Stresses in Rainfed Production Systems of Thailand

The University of Georgia

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Abstract

Quantifying potential yield and yield gap of crops for various growing conditions could provide valuable information for designing strategic crop management plans to increase crop yields. The farmers in the Phu Pha Man district of Khon Kaen province of Thailand commonly grow soybean and peanut under both rain-fed and irrigated conditions and cultivate maize under rain-fed conditions. The farmers' long-term average yields in the district are 1360 kg ha^{-1} for soybean, 1480 kg ha^{-1} for peanut and 2810 kg ha^{-1} for maize. The simulation results, using CSM-CROPGRO models for soybean, peanut and maize, showed that for the Phu Pha Man district, the yield potential of soybean ranged from 1130 to 3700 kg ha^{-1}, maize ranged from 1370 to 7460 kg ha^{-1} and peanut ranged from 630 to 3880 kg ha^{-1} under rain-fed conditions. For the fully irrigated conditions in the dry season, the yield potential of soybean ranged from 1870 to 3150 kg ha^{-1} and peanut ranged from 1840 to 3010 kg ha^{-1}. The yields were generally higher for early planting dates than for later plantings. These results indicated that farmers' yields under rain-fed conditions in the Phu Pha Man district can be more than doubled with improved management practices.

Yield gap analysis for Tad Fa watershed in Phu Pha Man district of Khon Kaen showed that under soil water and nitrogen nonlimiting conditions, the yield potential of soybean ranged from 2810 to 3630 kg ha^{-1} and for maize, it ranged from 4360 to 6130 kg ha^{-1}. The yield reductions from the yield potential caused by water and nitrogen limitations ranged from 12% to 48% for soybean and 29% to 83% for maize. Low rates of nitrogen application and pests and diseases were the main factors causing yield gaps of soybean and maize in the Phu Pha Man district. Regional analysis of peanut yields showed that northeastern region of Thailand is more productive area for rain-fed conditions, whereas northern region is more suitable to produce peanut under well-irrigated conditions during the dry season.

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Executive Summary

Quantifying yield and identifying yield gaps for various growing conditions could provide valuable information for designing strategic crop management plans to increase yield for soybean, peanut and maize in Thailand and other countries in South East Asia. However, this process is time consuming and expensive, as it may involve many years of experimental data collection. Dynamic crop simulation models provide an alternative option to determine yield for a range of growing conditions and crop management scenarios. The objectives of this study were:

- to evaluate the capability of the cropping system model (CSM) for simulating yield of the main crops in Thailand under local conditions;
- to estimate the potential yield for soybean, peanut and maize for the major agricultural production areas of Thailand; and
- to quantify the yield gaps for a range of growing conditions in Phu Pha Man district.

In order to accomplish these objectives, this research project was organized into four different components.

The first part of project was the calibration of the cultivar coefficients for two soybean cultivars, i.e., CM 60 and SJ 5. The data that were used to derive the genetic coefficients were obtained from two soybean experiments, which were conducted in 1991 at Chiang Mai University, Thailand and in 2003 at Khon Kaen University, Thailand. The results showed that the derived cultivar coefficients provided simulated values of various development and growth parameters that were in good agreement with their corresponding observed values for almost all parameters. This suggested that the cultivar coefficients for these two soybean cultivars were sufficiently accurate for future applications.

The second part was the evaluation of the CSM-CROPGRO-Soybean, CSM-CERES-Maize and CSM-CROPGRO-Peanut models. The CSM-CROPGRO-Soybean was evaluated with data from two soybean experiments that were conducted in 1994 and 2002 at Chiang Mai University and from four farmers' soybean fields in 1999 and 2000 of the Phu Pha Man district. The CSM-CERES-Maize model was evaluated with observed data that were collected in two farmers' maize fields in 2001 of the Phu Pha Man district. The CSM-CROPGRO-Peanut model was evaluated with data from an experiment that was conducted in 2002 and 2003 at Khon Kaen University. The results from this analysis showed a good agreement between simulated and observed data, and demonstrated the potential of the models to simulate growth and yield for local environments in Thailand.

The third part of the research consisted of using a combination of the crop models and GIS to simulate soybean, peanut and maize yield for the Phu Pha Man district. Growth, development and yield for two soybean cultivars, i.e., CM 60 and SJ 5, one maize cultivar, i.e., CP-DK 888 and two peanut cultivars, i.e., Tainan 9 and KK 60-3, were simulated for two planting dates during the rainy season and one planting date during the dry season using 32 years of historical weather data (1972-2003) and 22 soil series. The results showed that the soybean cultivar CM 60 had a higher yield potential yield than the soybean cultivar SJ 5 for all planting dates and the peanut cultivar KK 60-3 had a higher yield potential yield than the cultivar Tainan 9 for all planting dates. For the two planting dates during the rainy season, the potential yield for soybean, maize and peanut were generally higher for the June 15 planting date than for the August 15 planting date.

A regional yield analysis for the major peanut production regions in Thailand, consisting of 10 provinces located in the northern and northeastern region, was also conducted using a crop growth model linked to a GIS. Yields of KK 60-3 and Tainan 9 cultivars were simulated for two planting dates during the rainy season and one planting date during the dry season using six years of historical weather data, e.g., 1997 to 2002 and the data for all soil series for all 10 provinces. The spatial yield analysis was conducted by developing thematic maps with the GIS. The results provided the information that a lower temperature during early development in the dry season delayed flower initiation and extended maturity. More rainfall for the May 15 planting date contributed to higher simulated seed yield for both Tainan 9 and KK 60-3 compared to the August 15 planting date. The northeastern region was identified as a more productive area for rain-fed conditions and the northern area was more suitable to produce peanut under well-irrigated conditions during the dry season.

The fourth part of this study consisted of yield gap analysis for soybean and maize in the Tad Fa watershed. Long-term simulations were conducted in order to determine the reduction in soybean and maize yield due to water and nitrogen limitations for the Tad Fa watershed. The first set of simulations were conducted with the water and nitrogen balances "turned off", to estimate the climatic yield potential for seven different planting dates during the rainy season. Then, the reduction in yield due to water and nitrogen limitations were simulated with the water and nitrogen balances "turned on." The results indicated that the yield reduction of soybean caused by water and nitrogen limitations ranged from 12% to 48% of the climatic potential yield. Increasing the amount of N fertilizer decreased the percentages of yield reduction slightly for all planting dates. The June 15 planting date was more appropriate for soybean production for the Tad Fa watershed when compared to the other planting dates. An analysis for maize in the Tad Fa watershed indicated that yield reduction in maize caused by water and nitrogen limitations ranged from 29% to 83% of the climatic potential yield. One or more applications of nitrogen fertilizer caused a significant increase in yield for all the planting dates. Overall, the July 25 planting date was more suitable for maize production for the Tad Fa watershed when compared to the other planting dates.

In the final part of this study, a yield gap analysis was conducted between observed and simulated soybean and maize yields for the entire district of Phu Pha Man. The observed values for soybean yield for both the rainy and dry season planting dates and for maize yield for the rainy season were obtained from the Office of Agricultural Economics of Thailand, for the period of 10 years, i.e., 1993-2002. The CSM-CROPGRO-Soybean and the CSM-CERES-Maize models were run for the same years and for all seven soil series of Phu Pha Man, using the commercial cultivars, i.e., CM 60 and SJ 5 for soybean and CP-DK 888 for maize and the general crop management recommendations for this production area. The results indicated that insufficient N fertilizer and crop diseases were the factors that contributed to the small differences between observed and simulated yield value.

1. Introduction

The farmers in the Phu Pha Man district, Khon Kaen, Thailand, commonly cultivate soybean and peanut under both rain-fed and irrigated conditions and cultivate maize under rain-fed conditions. Records from the Office of Agricultural Economics of Thailand indicate that the mean soybean, peanut and maize yield over the past 10 years (1994-2003) for this production area were normally lower than expected yield, e.g., 1360 kg ha^{-1} for soybean, 1480 kg ha^{-1} for peanut and 2810 kg ha^{-1} for maize. There are several factors that influence soybean, peanut and maize yield, including the local cultivars and varieties that are used, pests and diseases, weather conditions, soil fertility, management practices, e.g., planting date, plant population and wheather irrigation and fertilizers are applied or not. Quantifying the yield and yield gap for various growing conditions would provide valuable information for designing strategic plans to increase soybean, peanut and maize yield for this production area. However, this process is time consuming and expensive as it could involve many years of experimental data collection.

In recent years, several dynamic crop simulation models have been developed as information technology tools to support strategic decision-making in research, crop production and land planning (Hoogenboom et al. 1992; Penning de Vries et al. 1993; Hoogenboom et al. 2004). These crop models can be used to evaluate agricultural production risk as a function of climatic variability, to assess regional crop yield potential across a wide range of environmental conditions and to determine suitable planting dates and other management factors for increasing crop yield (Egli and Bruening 1992; Meinke et al. 1993; Aggarwal and Kalra 1994; Meinke and Hammer 1995; White et al. 1995; Hunt et al. 1996; Chapman et al. 2000). For soybean, peanut and maize models, the process-oriented Cropping System Model (CSM)-CROPGRO-Soybean, CSM-CROPGRO-Peanut and CSM-CERES-Maize models have been developed to simulate vegetative and reproductive development, growth and yield as a function of crop characteristics, climatic factors, soil characteristics and crop managements. These models are part of suite of crop growth models that encompass the Decision Support System for Agrotechnology Transfer (DSSAT) (Hoogenboom et al. 2004).

The CSM and other models associated with DSSAT have been evaluated across a wide range of soil and climate conditions and are being used for various applications in the temperate regions. There is, however, limited evidence of their evaluation and application in tropical regions such as Thailand. It is, therefore, appropriate that the CSM-CROPGRO-Soybean, CSM-CROPGRO-Peanut and CSM-CERES-Maize models be evaluated to establish their credibility. Once they have been evaluated with local data, they can be used as decision support tools, especially for quantifying yield under various growing conditions and in identifying the yield gap for Phu Pha Man district. The objectives of this study were:

1. to evaluate the capability of the CSM-CROPGRO-Soybean, CSM-CROPGRO-Peanut and CSM-CERES-Maize in simulating yield under local conditions in Thailand,
2. to estimate potential yield for soybean, peanut and maize for the major agricultural production areas; and
3. to quantify yield and to identify the yield gaps for various growing conditions and management scenarios in Phu Pha Man district.

2. Background: Tad Fa Watershed, Khon Kaen

The Tad Fa watershed is part of the large basin of the River Chi, which is about 150 km northwest of Khon Kaen province (Fig. 1). The topography of the Tad Fa watershed consists of medium to high slopes. The information collected during the soil surveys from 2000 to 2003 has shown that there are about five different soil series in the Tad Fa watershed. In general, soil texture of these soils is mostly silty clay loam (Fig. 1; Table 1). The deforestation and agricultural practices in the region cause serious problems, such as soil erosion and deterioration of soil fertility in many areas. Land use is mostly comprised of field crops, horticulture and vegetables. The cropping systems under rain-fed condition include maize on the high land and medium slopes and upland rice on the lower slope. The fruit trees and vegetables are usually grown close to supplementary water resource on the lower slopes. Legumes and cereals are normally rotated with maize.

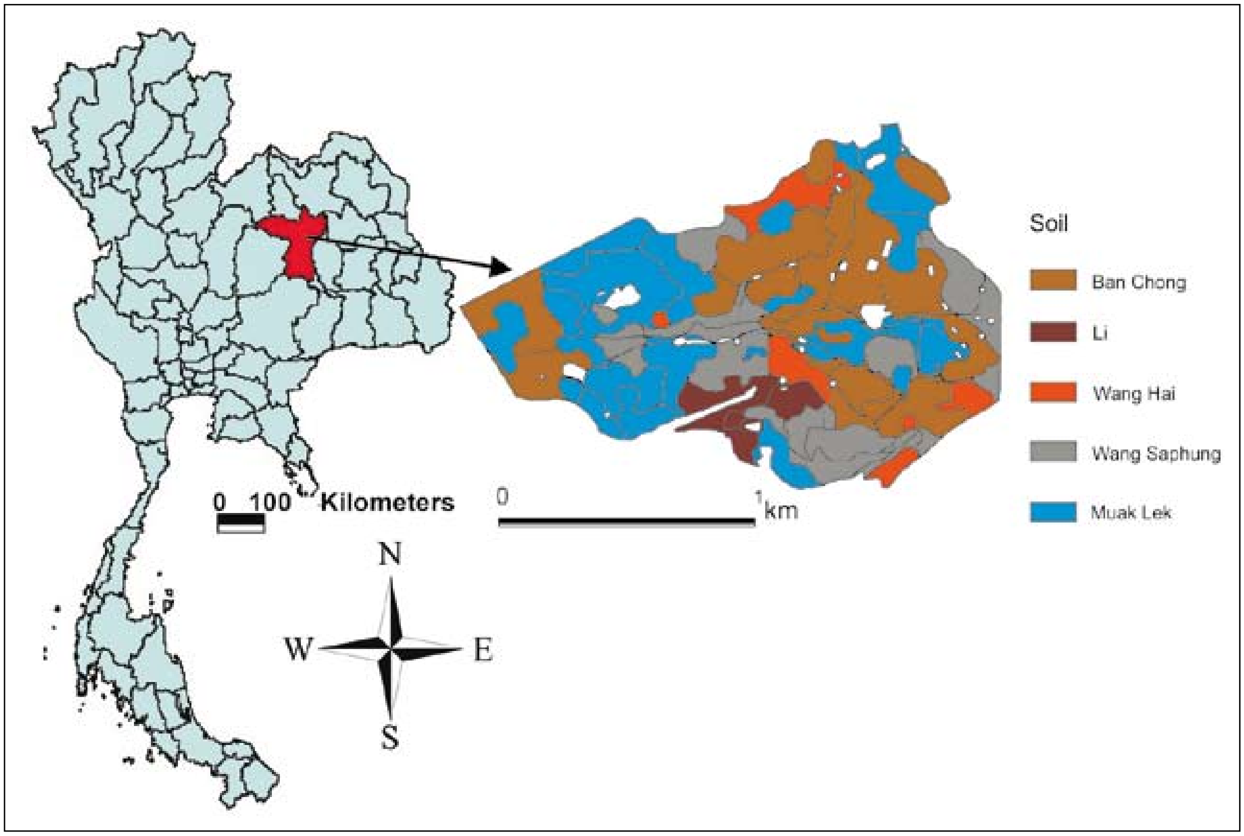

Figure 1. The Tad Fa study area in Phu Pha Man district, Khon Kaen province.

Table 1. Soil series of Tad Fa study area, Phu Pha Man district, Khon Kaen.

Soil series	Soil description	Soil depth (cm)
Ban Chong (Bg)	Fine, kaolinitic, iso Typic (Kandic) Paleustults	130
Li (Li)	Clayey-skeletal, mixed, semiact, shallow, iso Ultic Haplustalfs	57
Wang Hai (Wi)	Fine, mixed, iso Oxyaquic (Ultic) Paleustalfs	120
Wang Saphung (Ws)	Fine, mixed, active, iso Typic Haplustalfs	80
Muak Lek (Ml)	Clayey-skeletal, mixed, semiact, iso, shallow Ultic Haplustalfs	133

The historical weather data for a 32 year record period (1972-2003) indicate that annual rainfall of Phu Pha Man is about 1226 mm. A large amount of rain is observed from May to October (Fig. 2) and peaks in September (248 mm). With respect to the temperature regime, the area is part of the tropical zone and the mean minimum and maximum temperatures are 22.1 and 32.8 °C, respectively. The temperature is high from March to May and peaks in April (36.4 °C for maximum temperature and 24.9 °C for minimum temperature). The mean daily solar radiation in this area is 16.8 MJ m^{-2}. High values for solar radiation are found during May to September and peaks in May at 21.3 MJ m^{-2} day^{-1}.

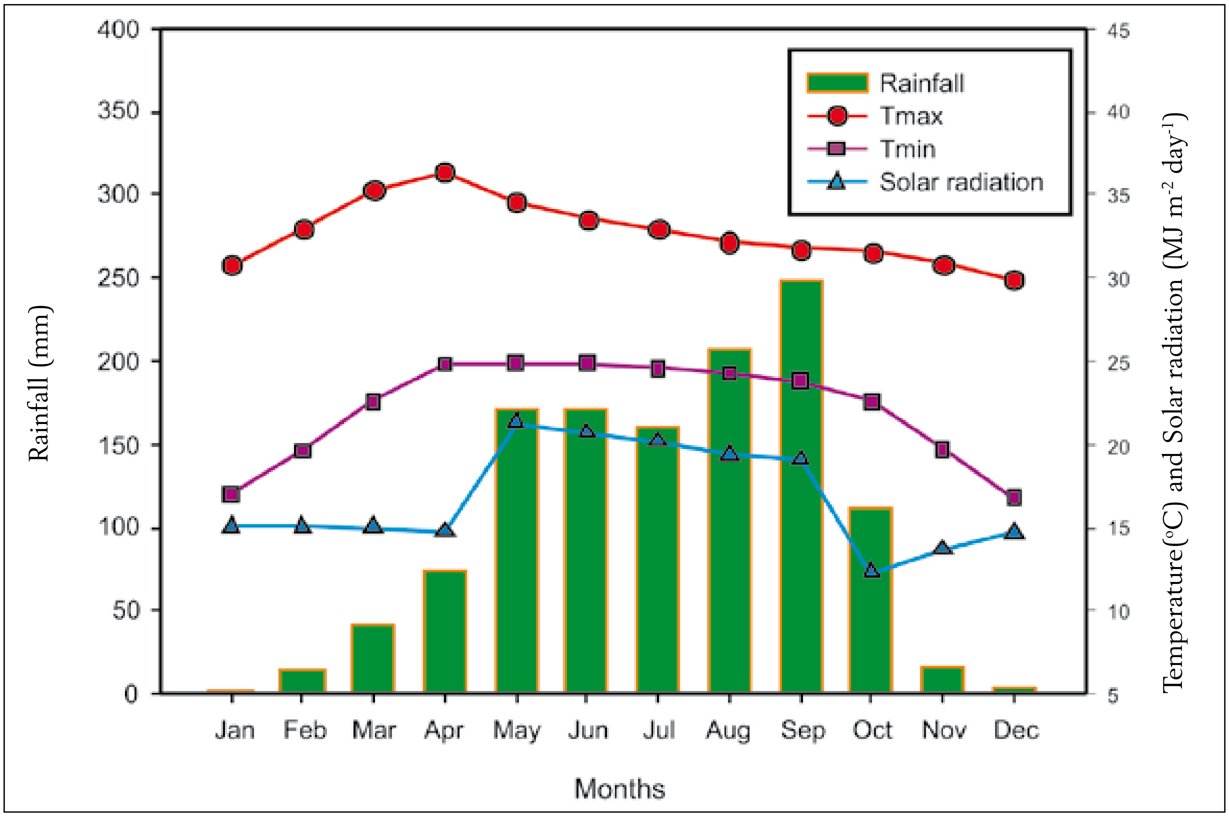

Figure 2. Mean monthly total rainfall (mm), maximum and minimum temperatures (°C) and solar radiation (MJ m^{-2} day^{-1}) for 32 years of historical weather (1972-2003) for the Tad Fa watershed.

3. Model Calibration

Introduction

The Cropping System Model (CSM) model has been developed to simulate vegetative and reproductive development, growth and yield as functions of crop characteristics, climatic factors, soil characteristics and crop managements (Jones et al. 2003). The CSM model and its associate crop modules encompass the Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.0 (Hoogenboom et al. 2004). The models have been evaluated for a wide range of soil and climate conditions and are being used as an information technology tool to support strategic decision making in research, production, land use and policy.

The inputs required to run the CSM model include information on soil and weather conditions, crop management practices and cultivar specific genetic coefficients. The information for cultivar specific genetic coefficients is normally not readily available for certain local cultivars. In the first step, therefore, a model calibration was conducted to determine the cultivar coefficients for certain soybean cultivars that are normally grown in Thailand, e.g., SJ 5 and CM 60.

Methodology

For model calibration, experimental data were obtained from two soybean experiments for the cultivars CM 60 and SJ 5. The first experiment was conducted from November 1991 to March 1992 at Chiang Mai University, Thailand and the second experiment was conducted from October 2003 to January 2004 at Khon Kaen University, Thailand. Plant densities were 20 plants m^{-2} for the first experiment and 10 plant m^{-2} for the second experiment. Data collection followed the protocol of experimental procedures for model evaluation as described in IBSNAT (1988) and Hoogenboom et al. (1999). The data that were collected included plant growth and development, crop management, daily weather conditions and soil property characteristics.

The plant development data that were measured included the dates on which 50% of the plants in a plot reached the critical developmental stages: R1 (plant with first flower), R3 (plant with a pod 2.0 cm long), R5 (when seed growth begins in at least one pod), R7 (plant with one pod yellowing). The dates of these stages were obtained by daily observations of all plants in the plot. Growth data were collected from eight individual plants at 24 different times during growing season for the first experiment. For the second experiment, plant growth data were collected from five plants at 15, 30, 45, 65, 75 days after planting. Measurements that were taken for each growth analysis sample included the dry weight of different plant components, i.e., stem, leaf, pod and total above ground biomass, leaf area index (LAI) and specific leaf area (SLA). In addition, pod yield and total above ground biomass were also collected at final harvest for both experiments.

Soil properties were collected prior to planting and included bulk density, soil texture, soil moisture, organic matter, pH, nitrate (NO_3-) and (NH_4+) concentrations and exchangeable P and K. Daily weather data, i.e., minimum and maximum temperatures, rainfall and solar radiation, were obtained from a nearby weather station. Crop management details included planting date, row and plant spacing, plant density and dates and rates of fertilizer, irrigation, herbicide and pesticide applications.

The soil parameters were calculated for the entire profile and for each soil layer with the soil data retrieval program of DSSAT (Tsuji et al. 1994), using the soil sample data. The parameters that were obtained for each soil layer were of saturated water content, drained upper limit of soil water content and lower limit of plant-extractable water. The soil surface parameters that were determined include soil surface reflectance, evaporation limit, drainage rate, runoff curve number and mineralization factor. Soil fertility factor was determined for the whole profile.

The CSM-CROPGRO-Soybean model requires 15 genetic coefficients (Table 2) that describe development and growth characteristics of soybean cultivars. To determine the genetic coefficients of CM 60 and SJ 5 cultivars, the data set collected was used as inputs in the standard format of DSSAT Version 4.0. The genetic coefficients of individual cultivar were determined by iteration of model simulation against the experimental data, following the procedures described by Hoogenboom et al. (1999). The existing genetic coefficients from the maturity groups (MG) IX were used as a starting point to calibrate both the cultivars CM 60 and SJ 5. During the first step, simulated annealing was used to solve for the critical short day length (CSDL) and photoperiod sensitivity (PPSEN) for fitting the observed flowering date. The coefficients for the durations of emergence to flowering (EMFL), flowering to beginning pod (FLSH), flowering to beginning seed (FLSD) and beginning seed to physiological maturity (SDPM) were adjusted to match the crop's life cycle for the simulated and observed data. The value for maximum leaf photosynthesis rate (LFMAX) was modified to obtain a good agreement between the simulated and observed dry matter accumulation.

The difference between simulated and observed leaf growth was minimized based on the specific leaf area (SLAVR), time to cessation of leaf expansion (FLLF) and maximum size of full leaf (SIZLF). The maximum fraction of the daily growth that is partitioned to the seeds and shells (XFRT), duration of pod addition (PODUR), seed filling duration for an individual pod cohort (SFDUR), average number of seeds per pod (SDPDV) and maximum weight per seed (WTPSD) were also adjusted for fitting observed pod and seed weights.

Table 2. Cultivar coefficients for the two local soybean cultivars.

Definition	Variable	Unit	Cultivar name	
			CM 60	SJ 5
1. Critical short day length below which reproductive development progresses with no day length effect	CSDL	Hour	12.50	11.90
2. Slope of the relative response of development to photoperiod with time	PPSEN	1 per hour	0.34	0.34
3. Time between plant emergence and flower appearance (R1)	EMFL	Photothermal day	23.0	23.0
4. Time between first flower and first peg (R2)	FLSH	Photothermal day	5.0	7.0
5. Time between first flower and first seed (R5)	FLSD	Photothermal day	10.0	11.0
6. Time between first seed (R5) and physiological maturity (R7)	SDPM	Photothermal day	34.0	31.0
7. Time between first flower (R1) and end of leaf expansion	FLLF	Photothermal day	35.0	35.0
8. Seed filling duration for pod cohort at standard growth conditions	SFDUR	Photothermal day	25.0	25.0
9. Time required for cultivar to reach final pod load under optimal	PODUR	Photothermal day	20.0	17.0
10. Maximum leaf photosynthesis rate at 30°C, 350 vpm CO_2 and high light	LFMAX	$CO_2\,m^{-2}\,s^{-1}$	1.70	1.70
11. Specific leaf area of cultivar under standard growth conditions	SLAVR	$cm^2\,g^{-1}$	280.0	280.0
12. Maximum size of full leaf (three leaflets)	SIZLF	cm^2	250.0	250.0
13. Maximum fraction of daily growth that is partitioned to seed + shell	XFRT	Unitless	0.90	0.90
14. Maximum weight per seed	WTPSD	g	0.19	0.26
15. Average seed per pod under standard growing conditions	SDPDV	Numbers per pod	1.90	1.96

The accuracy of the procedure, used to estimate the genetic coefficients, was determined by comparing the simulated values for the development and growth characteristics with their corresponding observed values and by calculating the values for root mean square error (RMSE) (Wallach and Goffinet 1987) as well as the index of agreement (*d* value) (Wilmott 1982). The values of RMSE and *d* indicate the degree of agreement between the predicted values with their corresponding observed values and a low RMSE value and a *d* value approaching unity are desirable. The RMSE was computed using the following equation:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \qquad [1]$$

where n is number of observation, P_i is the predicted value for the ith measurement and O_i is the observed value for the ith measurement. The index of agreement was computed using the following equation:

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}\left(|P_i'| + |O_i'|\right)^2} \right], 0 \leq d \leq 1 \qquad [2]$$

where n = number of observation, P_i = predicted value for the ith measurement, O_i = observed value for the ith measurement, $\bar{O}$ = the overall mean of observed values, $P'_i = P_i - \bar{O}$ and $O'_i = O_i - \bar{O}$. The derived cultivar coefficients of the individual lines were compared to determine whether the model was sensitive enough to capture the differences among the soybean cultivars.

Results and Discussion

The estimates of the cultivar coefficients related to vegetative and reproductive growth for the cultivars CM 60 and SJ 5 are presented in Table 2. To assess the accuracy of the cultivar coefficients derived from model calibration, the simulated values for four of the most critical developmental stages of the cultivars CM 60 and SJ 5 for the two different planting dates were compared with the corresponding observed values. A close agreement between observed and simulated values was obtained for all four developmental stages. The model predicted the first flowering date within two days of the observed value for both cultivars and predicted first pod and first seed dates within three days for the cultivar CM 60 and within one day for the cultivar SJ 5. The predicted physiological maturity dates for both cultivars were also within one day of the observed physiological maturity dates.

The simulated and observed values for dry weights of total biomass and pod biomass were in good agreement at the different growth stages for both soybean cultivars in two different planting dates (Fig. 3). Based on the values for RMSE and d, it was also assessed that the model predicted dry weights for total biomass, pods, stems and leaves quite well at different growth stages. The RMSE and d values for crop biomass and pod, stem and leaf weight of the two soybean cultivars for the two different planting dates ranged from 116 to 398 kg ha^{-1} and from 0.98 to 1.00 for crop biomass; from 73 to 736 kg ha^{-1} and from 0.93 to 1.00 for pod weight; from 98 to 447 kg ha^{-1} and from 0.80 to 0.99 for stem weight; and from 120 to 300 kg ha^{-1} and from 0.88 to 0.99 for leaf weight (Table 3). Predictions of LAI at the different growth stages were also quite good for the two soybean cultivars for the two planting dates. The RMSE values for this character ranged from 0.23 to 0.68 cm^2 cm^{-2} and the d values ranged from 0.85 to 0.99 (Table 3). The predictions of SLA were fair for the two soybean cultivars for the two planting dates. The RMSE values for this character ranged from 34 to 65 cm^2 g^{-1} and the d values ranged from 0.62 to 0.84 (Table 3). The differences between simulated and observed values for dry weight of crop biomass, pod and seed at harvest maturity date varied from 0.63 to 27.31% for total crop biomass, from 9.35% to 16.48% for pod mass and from 19% to 45% for total seed mass. Some of these large differences could be due to poor plant stand and other biotic and abiotic stresses that are normally not captured by growth analysis samples.

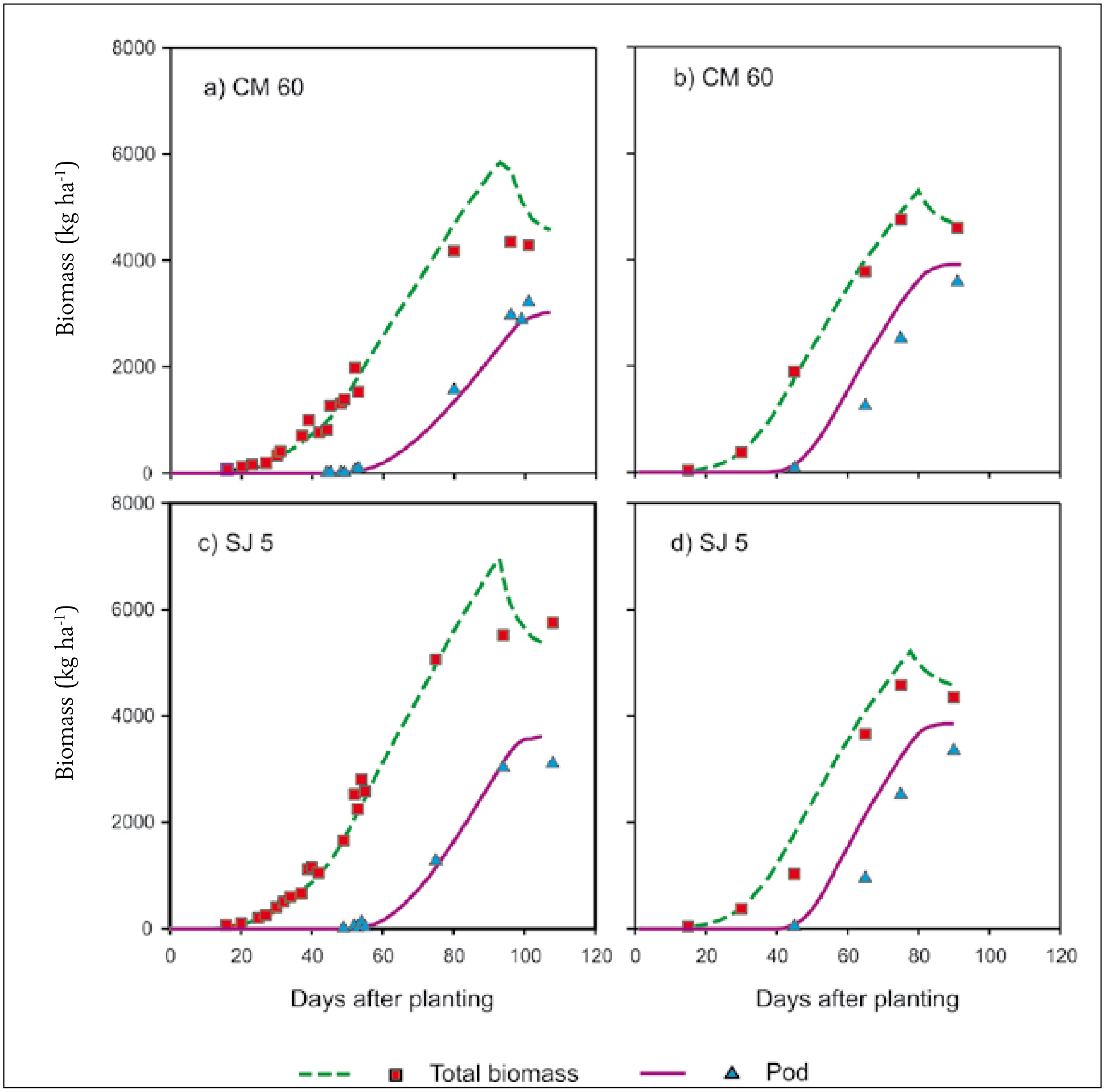

Figure 3. Simulated (lines) and observed (symbols) values for total biomass and pod weight for CM 60 and SJ 5 in 1991 (a, c) and 2003 (b, d).

Table 3. Root mean square error (RMSE) and the value for the d-Statistic for CM 60 and SJ 5 for the two different planting dates.

Planting date	Crop characteristic	CM 60		SJ 5	
		RMSE (kg ha^{-1})	*d*-Stat	RMSE (kg ha^{-1})	*d*-Stat
15 November 1991	Crop	391.48	0.98	323.59	0.99
	Pod	155.35	1.00	72.65	1.00
	Stem	447.09	0.80	215.59	0.97
	Leaf	162.56	0.95	120.30	0.99
	LAI	0.68 [a]	0.85	0.23 [a]	0.99
	SLA	65.07 [b]	0.64	35.48 [b]	0.84
20 October 2003	Crop	116.09	1.00	398.42	0.99
	Pod	580.20	0.96	735.92	0.93
	Stem	98.05	0.99	189.46	0.98
	Leaf	300.05	0.88	196.52	0.94
	LAI	0.61 [a]	0.90	0.65 [a]	0.89
	SLA	34.41 [b]	0.79	50.28 [b]	0.62

[a] Unit: cm^2 cm^{-2}; [b] Unit:cm^2 g^{-1}

4. Model Evaluation

Introduction

The CSM-CROPGRO-Soybean, the CSM-CROPGRO-Peanut and the CSM-CERES-Maize models have been developed as information technology tools to support strategic decision- making for research, crop production and land use planning (Jones et al. 2003). In order to use these models for local applications, an evaluation of these models should first be conducted to establish their credibility. Therefore, an evaluation of the CSM-CROPGRO-Soybean, the CSM-CROPGRO-Peanut and the CSM-CERES-Maize models was conducted with experimental data collected in Thailand. The data that were available included crop management, soil and weather data of the target environments and local cultivar coefficients. The determination of the cultivar coefficients for the CSM-CROPGRO-Soybean was discussed in the previous chapter.

Evaluation of CSM-CROPGRO-Soybean Model

Methodology

An evaluation of the CSM-CROPGRO-Soybean model was performed with data sets from two soybean experiments. The first experiment was conducted from January to April 1994 at Chiang Mai University, Thailand, for cultivar SJ 5. This was an experiment that included several different nitrogen fertilizer treatments. For model evaluation, no-nitrogen fertilizer treatment was selected, as soybean normally fixes nitrogen as a grain legume. The second experiment was conducted from August to December 2002 for the cultivar CM 60 with two planting date treatments, i.e., 2 August and 14 September 2002, at the experimental research station of the Multiple Cropping Center of Chiang Mai University, Thailand (Nguyen et al. 2003). Plant densities were 24 plants m^{-2} for the first experiment and 30 plant m^{-2} for the second experiment. These two experiments were well managed to avoid stresses from pests and diseases, water and nutrients. The experimental data that are required for model evaluation were collected in the same manner as the data collected for model calibration. The data included plant growth and development, soil surface and profile characteristics, local weather conditions and crop management.

In addition, the data sets from eight different farmer's practices were also used to evaluate the CSM-CROPGRO-Soybean model. These on-farm data sets all included the soybean cultivar SJ 5, which was grown under different planting dates and plant densities with and without a nitrogen fertilizer application during the rainy season of 1999 and 2000 in the Phu Pha Man district, Thailand.

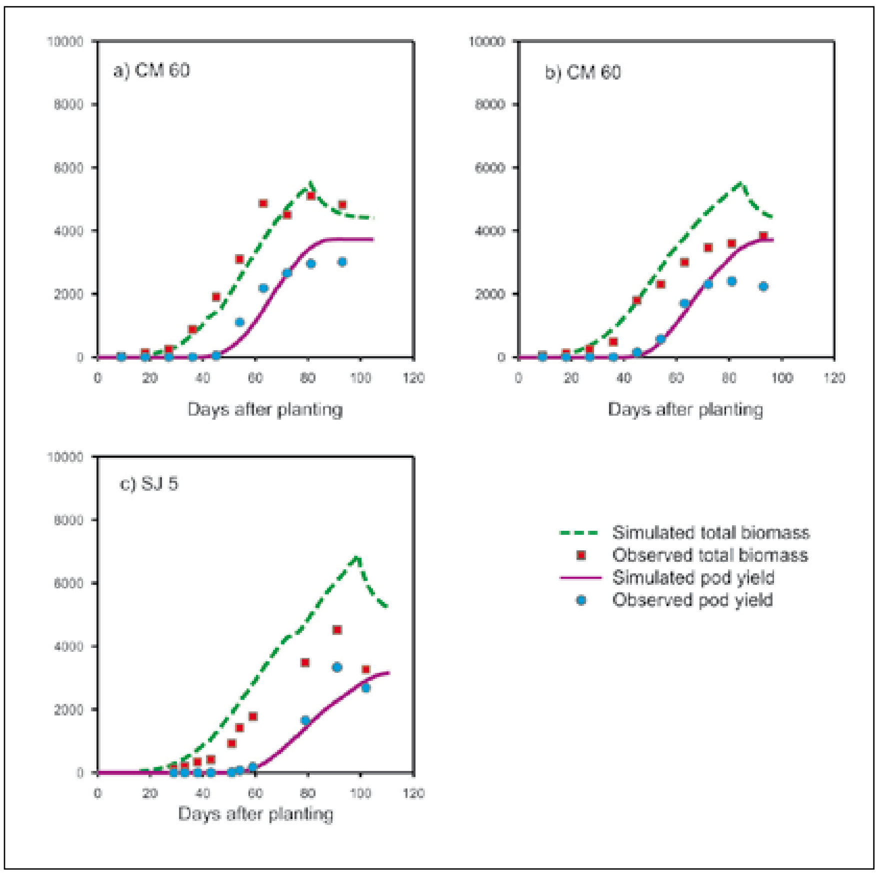

Figure 4. Simulated (lines) and observed (symbols) values for total biomass and pod weights for CM 60 in 2 August 2002 (a), 14 September 2002 (b) and for SJ 5 in 1994 (c).

Results and Discussion

The results for the CSM-CROPGRO-Soybean model evaluation with the experimental data sets in dry season of 1994 and late-rainy season of 2002 indicated that observed and simulated values for CM 60 and SJ 5 for the flowering and first pod dates were in good agreement, as the differences between simulated and observed were within three days. The differences between simulated and observed values for the first seed and physiological maturity dates were within 4 and 14 days, respectively. The simulated and observed data for pod and total crop biomass for the cultivars CM 60 and SJ 5 are depicted in Figure 4. The simulated values for dry weights of CM 60 cultivar for the August 2, 2002 planting date agreed reasonably well with the observed values. In addition, the simulated values for pod and total crop weights for CM 60 for the September 14, 2004 planting date seemed to be in good agreement with the observed values, although in general it was underestimated. In the case of the simulation of growth for the cultivar SJ 5 for the no-nitrogen-fertilizer application, the model appeared to overestimate growth of total crop weight; whereas it seemed to agree quite well with observed pod growth. The statistical evaluation of agreements between observed and simulated values for growth of pod and total crop weights using the values for RMSE and the d-Statistic indicated good agreements. The values of RMSE and *d* for total crop weight ranged from 474 to1228 kg ha^{-1} and from 0.89 to 0.99, respectively and pod weight ranged from 453 to 693 kg ha^{-1} and from 0.90 to 0.97, respectively. The differences between simulated and observed values for dry weight of crop biomass and pod at harvest maturity date ranged from 26% to 57% and from 18% to 66% of the observed values, respectively.

The model evaluation using the observed data sets from four farmers' soybean fields in 1999 and 2000 indicated that the model overestimated for some growing conditions and underestimated for the others (Table 4). However, the differences between observed and simulated seed yields were not considerably large for most growing conditions, as they were within 32% of the observed values, except for the July planting dates for both years. In most cases, it was rather difficult to accurately predict conditions in farmers' fields, due to lack of sufficient model input data, especially local weather data and soil surface and profile information.

Evaluation of CSM-CERES-Maize Model

Methodology

The CSM-CERES-Maize model was evaluated with the data observed from four different farmers' practices. These data sets were recorded for the cultivar CP-DK 888, which was grown under different planting dates and plant densities with and without nitrogen fertilizer application during the rainy season in 2001 in the Phu Pha Man district, Thailand.

Since the cultivar coefficients for the cultivar CP-DK 888 were not readily available in the database of the model, the published values for a similar growth and development cultivar, i.e., NS1 (Boonpradup 2000) were used. The cultivar coefficients for the CSM-CERES-Maize model are:

- thermal time from seedling emergence to the end of the juvenile phase (P1=364.0 degree days);
- the amount of time that development is delayed when crop is grown in a photoperiod shorter than the optimum (P2=0.6 days $hour^{-1}$);
- thermal time from silking to physiological maturity (P5=840.0 degree days);
- the maximum possible number of kernels per plant (G2=713.3);
- the kernel filling rate during the linear grain filling stage (G3=6.66 mg day^{-1});
- the interval in thermal time between successive leaf tip appearances (PHINT=38.9 degree days).

Results and Discussions

The results indicated that the model overestimated yield of some of the experiments and underestimated yields of others (Table 4). However, the simulated yields were quite close to the observed yield as indicated by small differences between observed and simulated seed yields: in all cases, the differences were within 24% of observed value. Thus, a good match between observed and simulated values was found for all four growing conditions.

Table 4. Observed and simulated yield for soybean and maize and the corresponding yield differences.

Planting date	Fertilizer ($kg\ N\ ha^{-1}$)	Plant population ($plants\ m^{-2}$)	Observed yield ($kg\ ha^{-1}$)	Simulated yield ($kg\ ha^{-1}$)	Difference [a] (%)
			Soybean (Cultivar SJ 5)		
18 Jul 1999	0	33	1151	1164	1.1
30 Jul 1999	15	20	1515	1556	2.7
23 Jul 1999	0	30	436	718	64.7
3 Aug 1999	15	18	918	678	-26.1
7 Aug 2000	0	24	603	769	-7.5
5 Aug 2000	20	14	938	730	-22.2
23 Jul 2000	0	16	806	1268	57.3
3 Aug 2000	20	16	1338	912	- 31.8
			Maize (Cultivar CP-DK 888)		
12 May 2001	0	4	1059	1316	24.3
	25	4	2494	2856	14.5
23 May 2001	0	9	2028	2280	12.4
	21	8	2920	2733	-6.4

[a] (Observed yield – Simulated yield) x 100/Observed yield.

Evaluation of CSM-CROPGRO-Peanut Model

Methodology

The CSM-CROPGRO-Peanut model was evaluated with the data sets from an experiment conducted for one small-seeded Spanish type (KK 5) and two large-seeded Virginia type (KK 60-3 and KKU 72-1) peanut cultivars for three different planting dates: June 9, 2002 (2002 rainy season), December 15, 2002 (2003 dry season) and May 8, 2003 (2003 rainy season), at Khon Kaen University, Thailand. The experimental data that were collected were those that were required for model simulation. These included plant growth and development, soil surface and profile characteristics, local weather conditions and crop management. Simulations were conducted for all three planting dates using the cultivar coefficients that were determined by Banterng et al. (2004). A comparison was also made between the observed and simulated results similar to the earlier comparisons.

Results and Discussions

The results showed a good agreement between the simulated and observed days to first flowering for the 2002 and 2003 rainy seasons, but differences as high as six days were observed for the 2003 dry season (Table 5). The model predicted days to first pod quite well for the dry season, but not so well for the rainy seasons. Predictions of days to first seed were good for some cultivars and fair for the others. Predictions of days to maturity showed rather large differences from observed data for all seasons (Table 5).

Good agreements between simulated and observed values for total biomass, stem and pod weight at the different growth stages of the three peanut cultivars were obtained for both the 2002 rainy and 2003 dry seasons (Fig. 5). Similar results were found for KK 60-3 in the 2003 rainy season (data not shown). The values for RMSE and the d-statistic ranged from 532 to 1331 kg ha^{-1} and 0.95 to 0.99 for

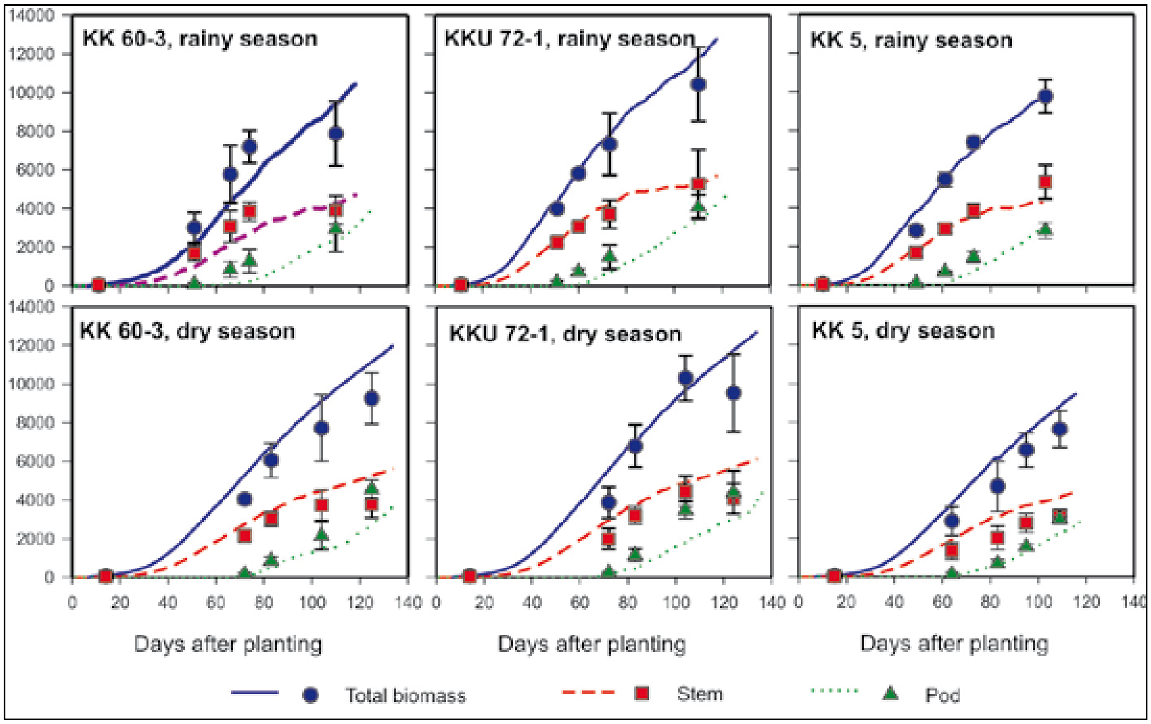

Figure 5. Simulated (lines) and observed (symbols) values for total biomass, stem and pod weights for three peanut cultivars grown during 2002 rainy and 2003 dry seasons.

total biomass, respectively, from 197 to 894 kg ha^{-1} and 0.91 to 1.00 for stem weight, respectively, and from 390 to 1072 kg ha^{-1} and 0.74 to 0.96 for pod weight, respectively. The discrepancies between the simulated and observed values for biomass could be due to the biotic and other stresses that were not accounted for by the model. In addition, pod weight for peanuts has to be determined through digging up of the plants, which is also somewhat difficult under farmers' field conditions.

Table 5. Simulated (S) observed (O) days after planting to first flowering, first pod, first seed and maturity for peanut cultivars.

Cultivar	First flowering		First pod		First seed		Maturity	
	S	O	S	O	S	O	S	O
				2002 Rainy season				
KK 60-3	28	28	48	43	56	51	119	110
KKU 72-1	28	28	48	43	54	51	118	110
KK 5	28	26	44	40	55	49	102	107
				2003 Dry season				
KK 60-3	35	41	59	60	66	71	134	126
KKU 72-1	34	40	59	60	65	71	134	125
KK 5	35	31	55	56	66	65	116	110
				2003 Rainy season				
KK 60-3	28	27	48	42	56	53	119	111

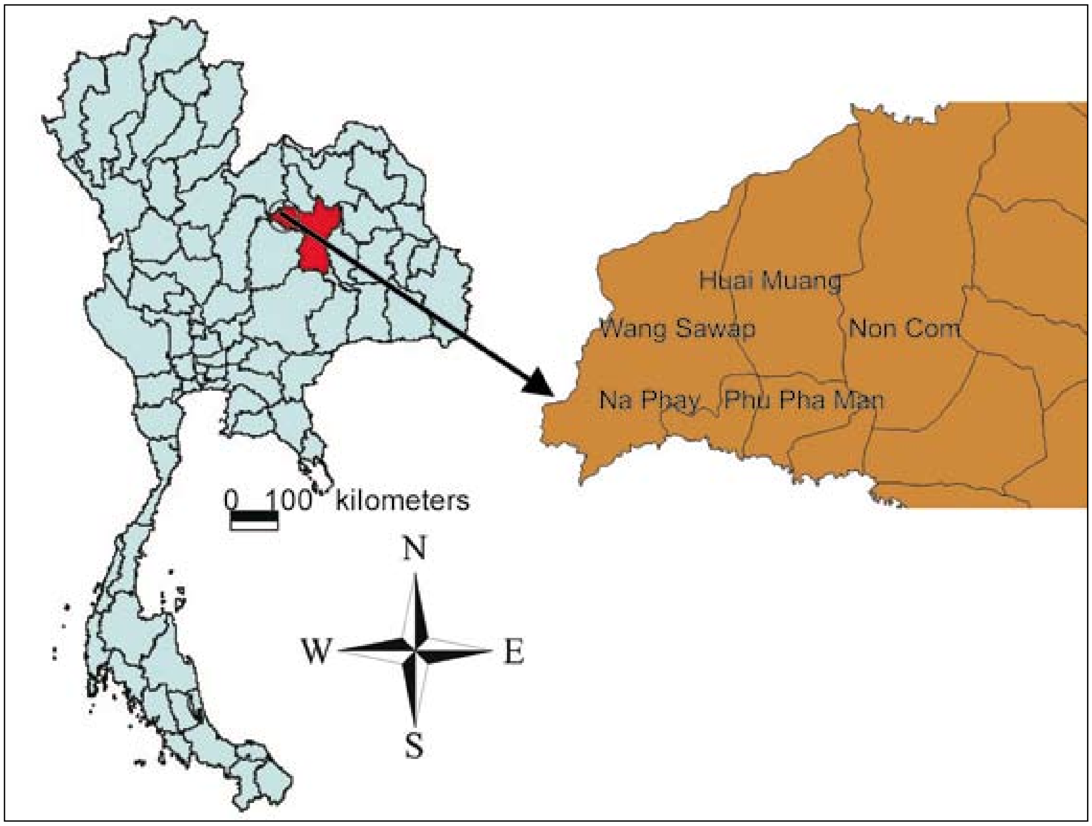

Figure 6. Study area in Phu Pha Man, Khon Kaen province.

5. Spatial Yield Simulation

Introduction

An analytical tool for evaluating soybean, peanut and maize yield in major agricultural production areas can provide valuable information for land use decision-making. The three models that were discussed in the previous chapters, e.g., CSM-CROPGRO-Soybean, CSM-CROPGRO-Peanut and CSM-CERES models, have been used extensively for these types of applications (Hoogenboom et al. 2004). When coupled with a suitable GIS to handle spatial characteristics of soil and weather data, the models can also be used for a spatial evaluation of soybean, peanut and maize yield for various production regions.

Simulating Soybean, Peanut and Maize Yields at the Sub-district Scale in Thailand

Methodology

Several programs have been developed to link the crop models with GIS. One of the most widely used GIS-Crop model linkages is AEGIS/WIN, which is also part of the DSSAT system (Engel et al. 1997; Hoogenboom et al. 1999). In this study, AEGIS/WIN was used to determine potential production for soybean, maize and peanut for five sub-districts of the Phu Pha Man district. These sub-districts were Wang Sawap, Phu Pha Man, Huai Muang, Na Phay and Non Com (Fig. 6). The inputs required for the model to be able to simulate soybean, maize and peanut yields for these five sub-districts include local soil and weather conditions, the cultivar coefficients for the local cultivars and local crop management scenarios (Hoogenboom et al. 2004).

Soil surface and profile data, including 22 soil series were obtained from the Department of Land Development, Thailand (Fig. 7; Table 6). Historical weather data for 32 years, i.e., 1972 to 2003, were obtained from the Thai Meteorological Department. Different scenarios for crop management were defined. A rain-fed condition was specified for two planting dates in the rainy season, e.g., 15 June and August and full irrigation was applied for the dry season planting date, e.g., 15 December. Plant density was set at a rate of 30 plants m^{-2} for soybean and peanut and at a rate of five plants m^{-2} for maize. No nitrogen stress was defined for all planting dates. Commercial cultivars were used in this study, which included cultivars CM 60 and SJ 5 for soybean, hybrid CP-DK 888 for maize and cultivars Tainan 9 and KK 60-3 for peanut. Soybean, maize and peanut growth, development and yield were simulated for 32 years for four sub-districts in Phu Pha Man and thematic maps for yield and other agronomic variables were generated with the GIS.

Table 6. Soil series of Phu Pha Man, Khon Kaen.

Soil series	Soil description
Ban Mi (Bm)	Very-fine, smectitic, isohyperthermic Ustic Epiaquer
Chum Phae (Cpa)	Fine-kaolinitic, iso Aeric Plinthic Paleaquults
Chatturat (Ct)	Fine-mixed, active, iso Typic Haplustalfs
Dan Khun Thot (Dk)	Isohyperthermic, coated Ustic Quartzipsamments
Dan Sai (Ds)	Fine-loamy, kaolinitic, iso Typic Kandiustults
Hin Son (Hs)	LithicI Haplustalfs
Khemarat (Kmr)	Fine-loamy, kaolinitic, iso Plinthaquic Paleustults
Kong (Kng)	Fine-loamy, siliceous, isohyperthermic Oxic Paleustults
Khao Suan Kwang (Ksk)	Fine-loamy, siliceous, subactive, iso Typic Paleustul
Lop Buri (Lb)	Very-fine, smectitic, iso Typic Haplusterts
Lat Ya (Ly)	Fine-loamy, siliceous, iso Kanhaplic Haplustults
Nong Khung (Nkg)	Fine-mixed, active, iso Aeric Endoaqualfs
Phon (Pho)	Fine-loamy, kaolinitic, iso Plinthaquic Paleustults
Phon Ngam (Png)	Fine-loamy, mixed, semiactive, iso Typic Haplustalfs
Phu Pha Man (Ppm)	Very-fine, kaolinitic, iso Rhodic Kandiustults
Sa Keao (Ska)	Loamy-skeletal, kaolinitic, iso Typic (Plinthic) Paleu
Si Thon (St)	Clay-loamy, mixed, subact, nonacid, iso Fluvaquentic Emdoaque
Ta Khli (Tk)	Loamy-skeletal, carbonatic, isohyperthermic, Entic Haplustalfs
That Phanom (Tp)	Fine-silty, mixed, semiactive, iso Ultic Haplustalfs
Tha Yang (Ty)	Loamy-skeletal, siliceous, iso Kanhaplic Haplustults
Wang Hai (Wi)	Fine-mixed, iso Oxyaquic (Ultic) Paleustalfs
Wang Nam Khiew (Wk)	Fine-loamy, mixed, semiact, iso Typic Haplustalfs

Results and Discussions

The results showed that yield potential for soybean ranged from 1130 to 3700 kg ha^{-1}, maize ranged from 1370 to 7460 kg ha^{-1} and peanut ranged from 630 to 3880 kg ha^{-1} under rain-fed conditions. For fully irrigated conditions in the dry season, yield potential for soybean ranged from 1870 to 3150 kg ha^{-1} and peanut ranged from 1840 to 3010 kg ha^{-1}.

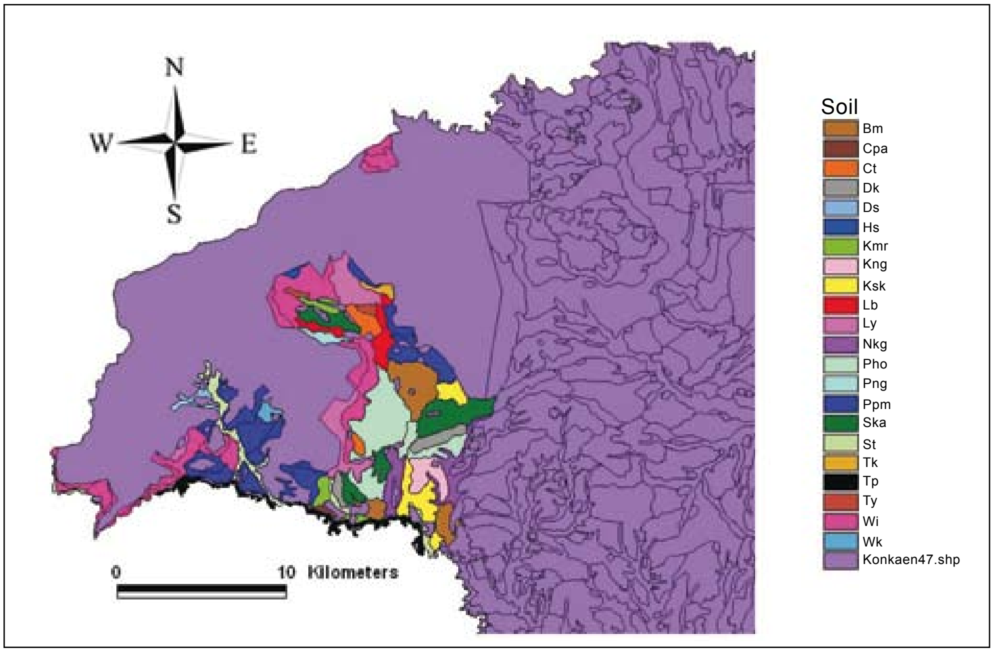

Figure 7. Soil map for Phu Pha Man, Khon Kaen province.

When comparing the performance of the two cultivars, the soybean cultivar CM 60 gave a higher yield potential than cultivar SJ 5 for all planting dates (Figs. 8 and 9). For peanut, cultivar KK 60-3 had a higher yield potential than cultivar Tainan 9 (Figs. 10 and 11) for all planting dates.

When comparing two planting dates during the rainy season, potential yield for soybean, maize and peanut for the June 15 planting date was generally higher than that for the August 15 planting date (Figs. 8, 9, 10, 11 and 12). This indicated that an early planting date of June 15 was expected to be a more productive planting date for rain-fed conditions than a later planting date. The higher yield for the June 15 planting date could be attributed to a higher rainfall and solar radiation during growing season compared to August 15 planting date.

Simulating Regional Peanut Yield of the Major Peanut Production Regions in Thailand

Methodology

The program AEGIS/Win, which is a linkage between the CSM-CROPGRO-Peanut model and the GIS ArcView (Engel et al. 1997; Hoogenboom et al. 1999), was used for regional yield analysis of the major peanut production areas, consisting of 10 provinces located in the northern and northeastern region of Thailand (Fig. 13). The inputs required for the spatial application of the model include local soil and weather conditions, cultivar specific coefficients and crop management regimes (Hoogenboom et al. 2004).

The soil map and soil properties data for these provinces were obtained from the Department of Land Development. The climatic data for 21 weather stations were obtained from the Meteorological Department. The weather data included six years, e.g., 1997-2002, of historical records. A Theissen polygon was generated to delineate the area of each weather station associated with each of production areas (Fig. 14). The scenarios for crop management were defined as follows: rain-fed conditions were used for two planting dates during the rainy season, e.g., May 15 and August 15 and full irrigation was applied for the dry season planting date, December 15. A row spacing of 0.5 m and a plant spacing of 0.2 m with two plants per hill were used. No-nitrogen stress was also set for all planting dates. Two commercial peanut cultivars from Thailand, e.g., Tainan 9, a small-seeded Spanish type and KK 60-3, a

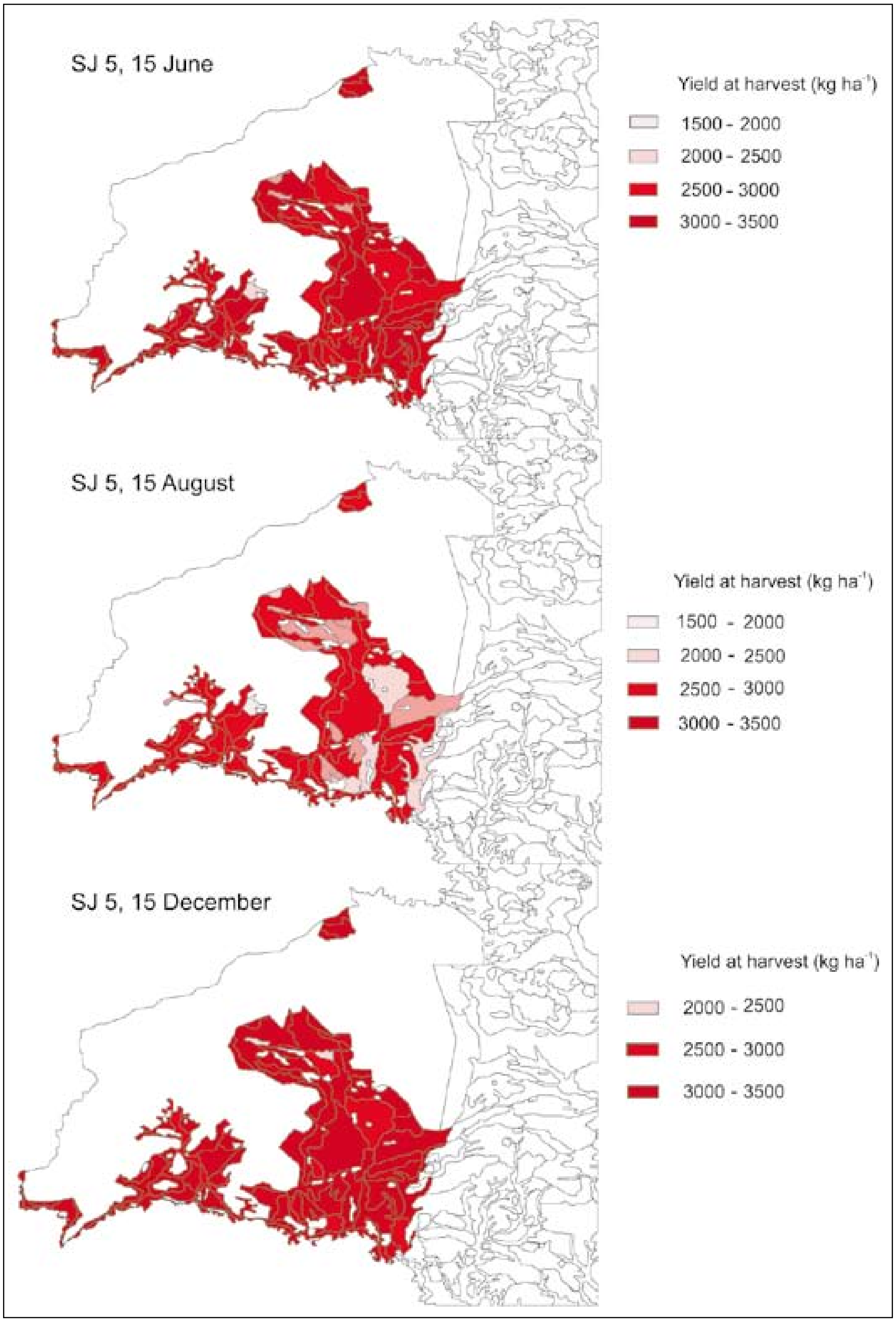

Figure 8. Spatial variation of average soybean yield (kg ha^{-1}) for cultivar SJ 5 for three different planting dates.

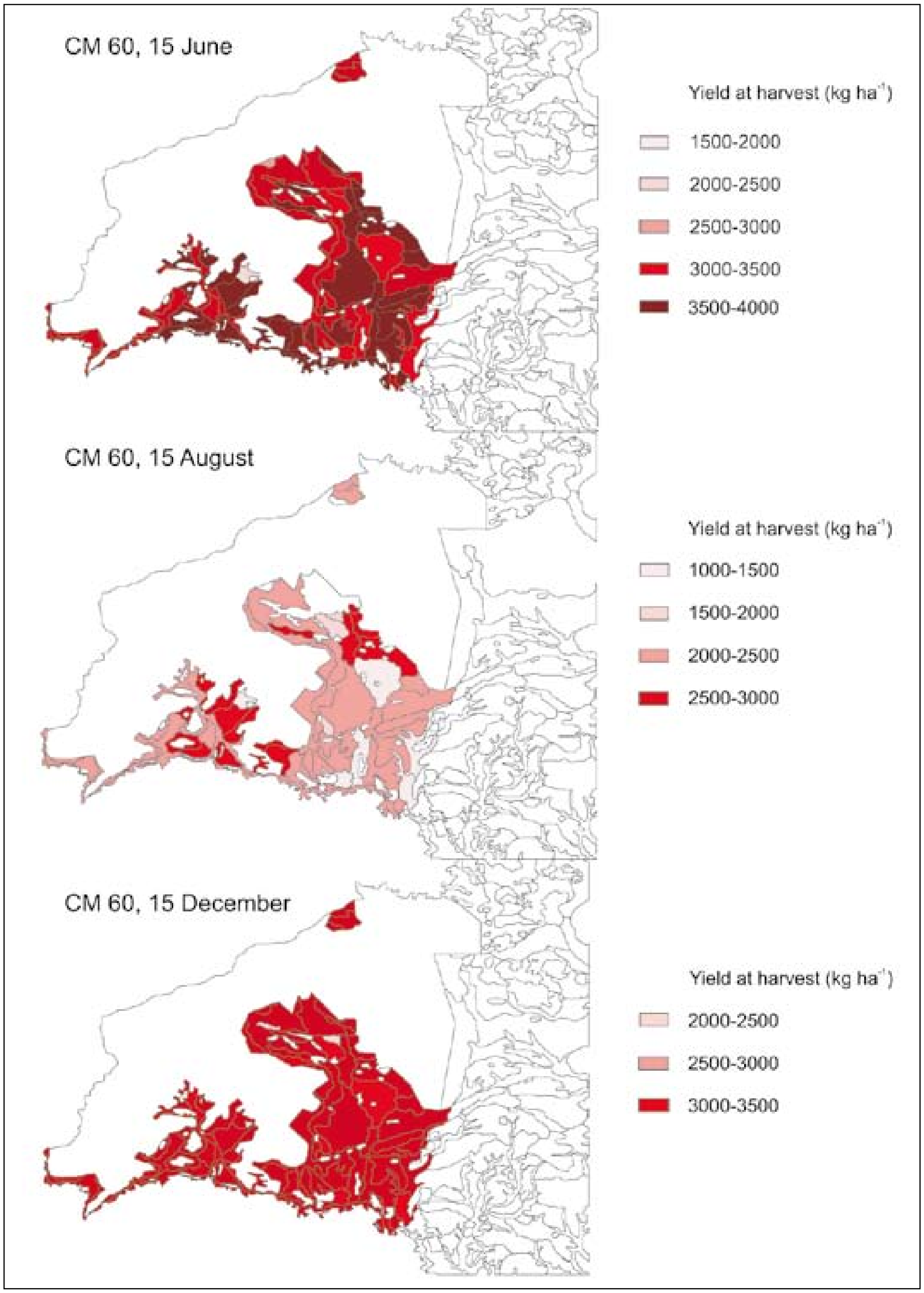

Figure 9. Spatial variation of average soybean yield (kg ha^{-1}) for cultivar CM 60 for three different planting dates.

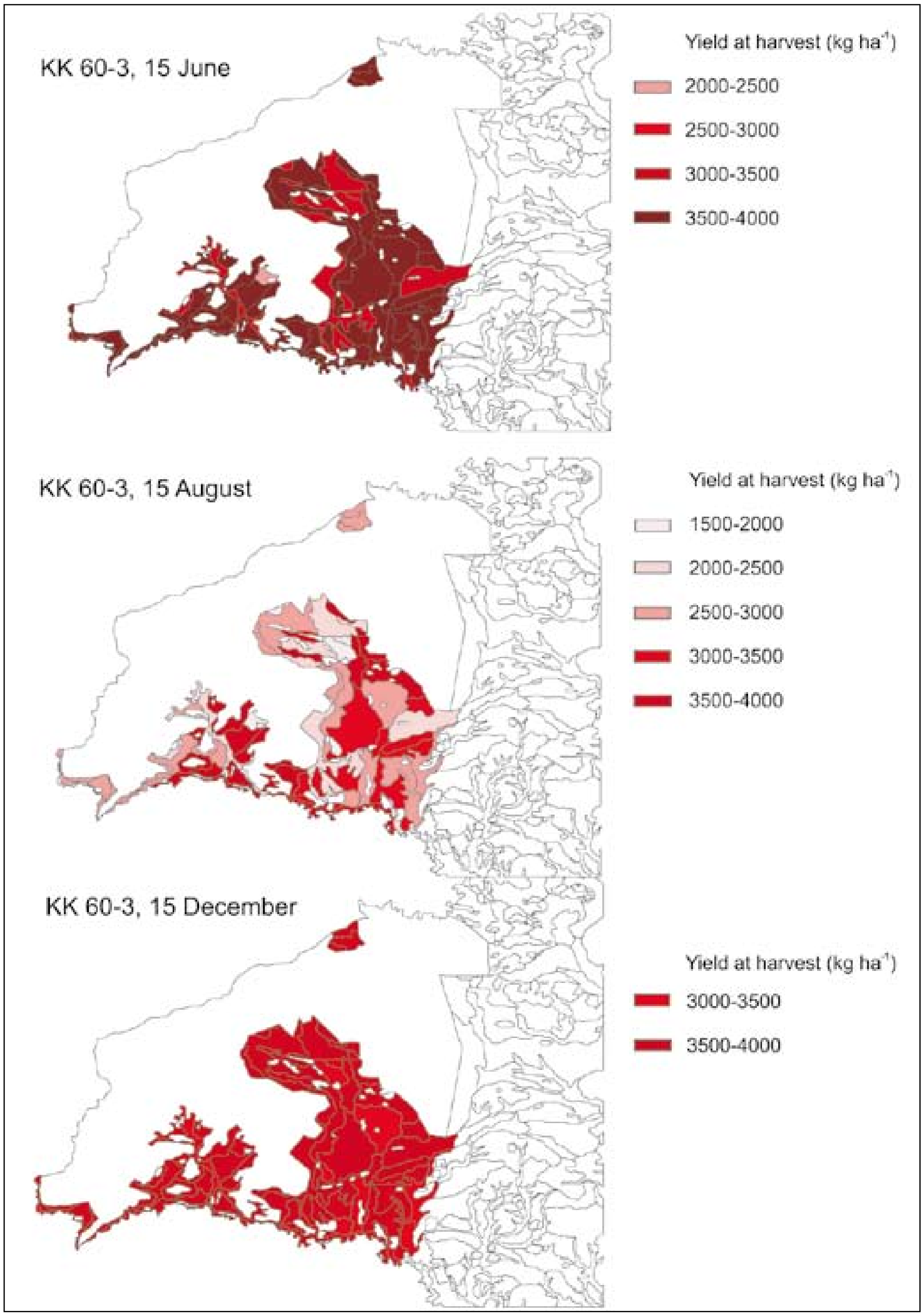

Figure 10. Spatial variation of average peanut yield (kg ha^{-1}) for cultivar KK 60-3 for three different planting dates.

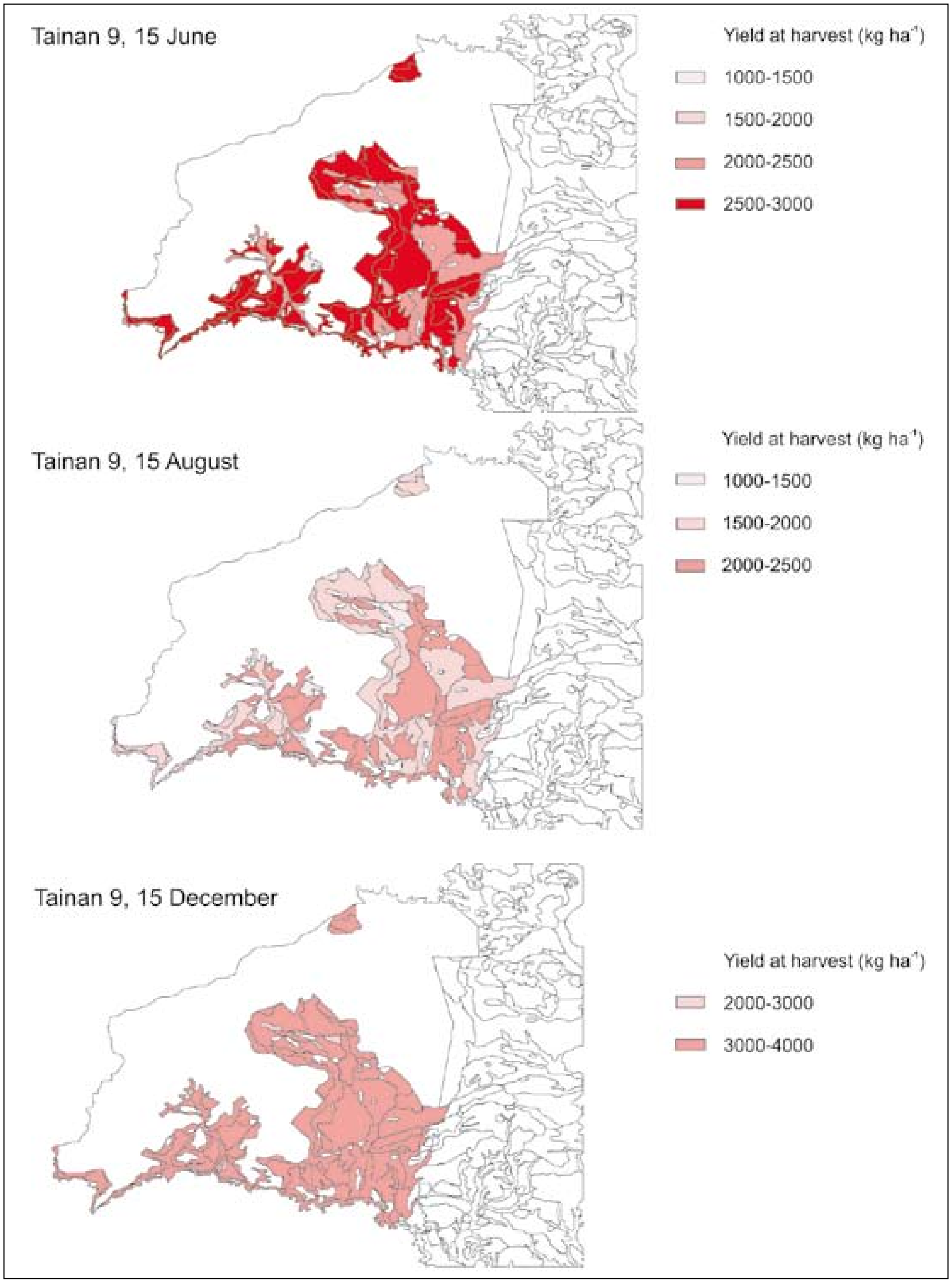

Figure 11. Spatial variation of average peanut yield (kg ha^{-1}) for cultivar Tainan 9 for three different planting dates.

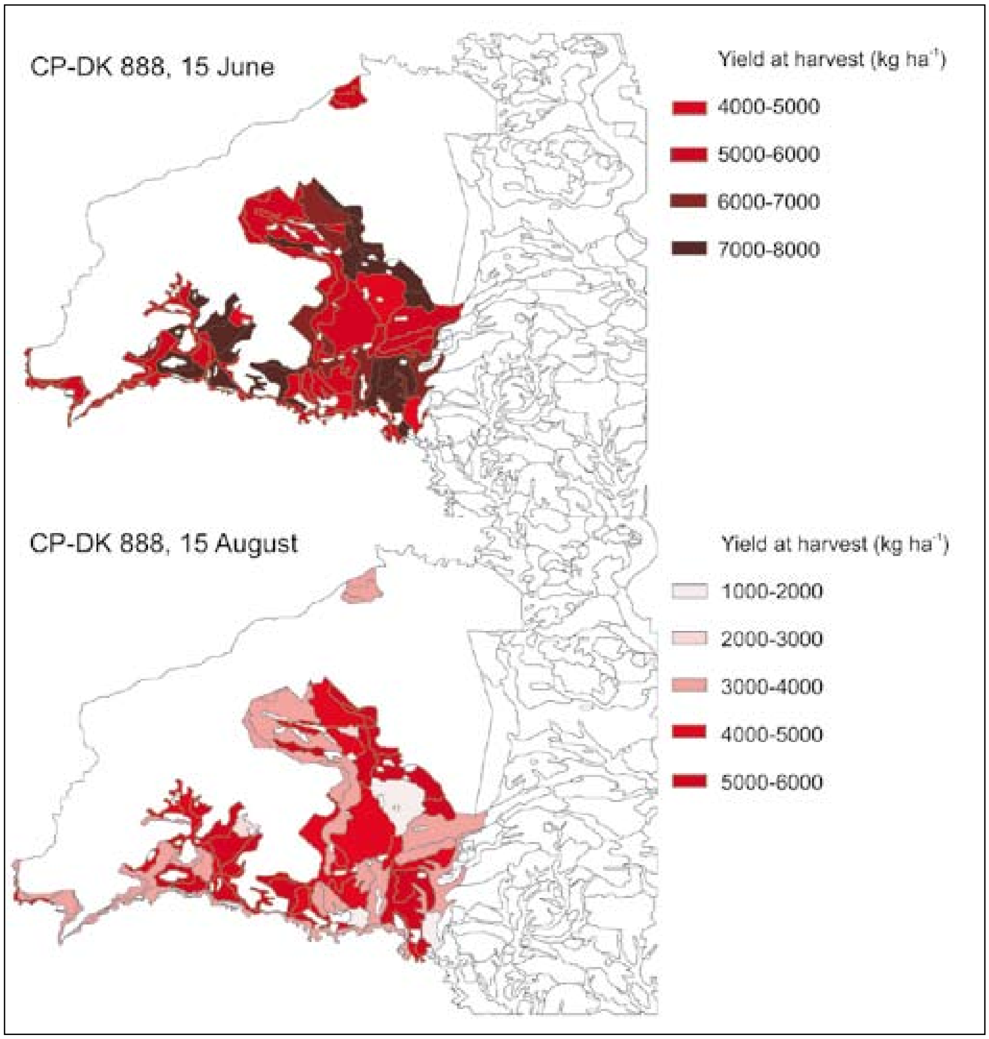

Figure 12. Spatial variation of average maize yield (kg ha^{-1}) for cultivar CP-DK 888 for two different planting dates

large-seeded Virginia type, were used for this study. The cultivar coefficients were obtained from a study conducted by Banterng et al. (2004). Peanut yield was simulated for the major peanut production areas and a regional yield analysis was conducted using thematic maps developed with the GIS.

Results and Discussions

The results indicated that the duration from planting to flowering and from planting to harvesting were about the same for the two planting dates during the rainy season. However, these durations were longer for the planting date during the dry season (Table 7). The long duration for the dry season was mainly due to cooler temperature during the first 60 days after planting, which averaged 24.6°C, compared to 27.9-28.8°C for the two planting dates during the rainy season.

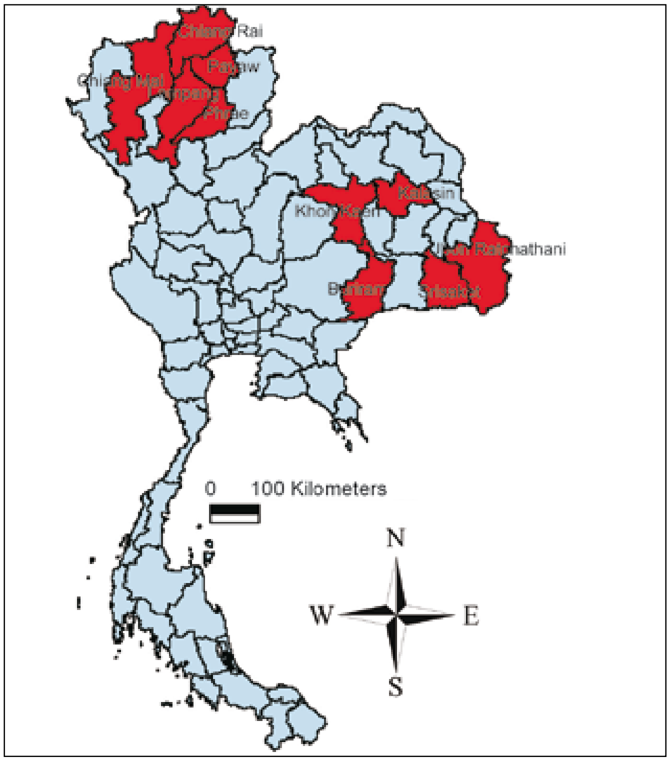

Figure 13. Map of Thailand, with study areas shown in red.

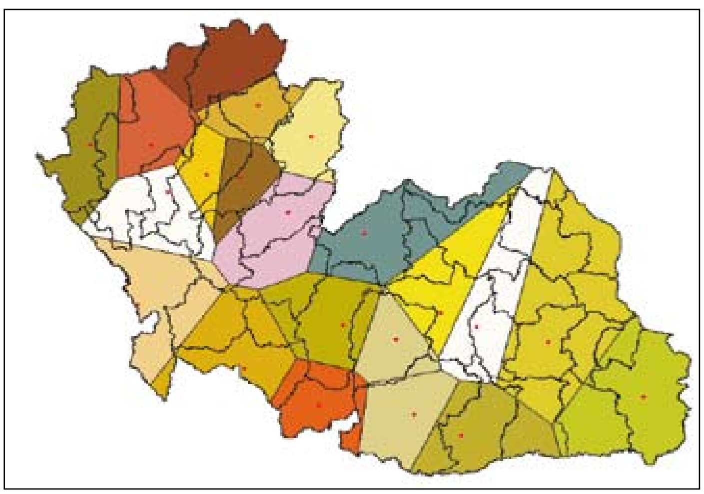

Figure 14. Thiessen polygons for each weather station.

Table 7. Total rainfall (mm) during the growing season, means for days from planting to flowering and harvest maturity (DAP) and means for simulated seed yield (kg ha^{-1}) for the peanut cultivars Tainan 9 and KK 60-3 for three different planting dates for 1997-2002.

Planting date	Irrigation	Rainfall (mm)	Flowering date (DAP)	Harvesting date (DAP)	Yield (kg ha^{-1})
			Tainan 9		
May, 15	Rain-fed	650	29	104	2450
August, 15	Rain-fed	513	29	106	2120
December, 15	Irrigated	-	37	123	2590
			KK 60-3		
May, 15	Rain-fed	784	28	119	4220
August, 15	Rain-fed	518	28	120	3110
December, 15	Irrigated	-	36	139	4210

The means of the simulated seed yield for the different planting dates and cultivars in each province were calculated and identified as different yield productivity zones on the map. Based on the simulated results for rain-fed conditions, the May 15 planting date had the highest simulated seed yield for KK 60-3 (Table 7). In addition, the northeastern region was identified as a more productive area than the northern region (Fig. 15). Similar results were found for Tainan 9 (Table 7; Fig. 15). The highest average simulated seed yield, i.e., 2910 kg ha^{-1} for Tainan 9 and 4830 kg ha^{-1} for KK 60-3, were found for the province of Ubon Ratchathani. The higher simulated seed yield for the May 15 planting date could be attributed to a higher total rainfall during the growing season compared to the August 15 planting date. For fully irrigated conditions during the dry season, the northern region was categorized as a more productive area than the northeastern region for both cultivars (Fig. 15). The province of Chiang Rai had the highest average simulated seed yield, i.e., 3000 kg ha^{-1} for Tainan 9 and 4810 kg ha^{-1} for KK 60-3 for irrigated conditions during the dry season.

6. Yield Gap Analysis

Introduction

Many factors influence crop growth, development and final yield. These include the cultivar that is commonly used by local farmers, pest and disease pressure, local weather conditions, soil fertility, crop management practices, e.g., planting date, plant population and inputs, especially irrigation and fertilizer. Quantifying the yield gaps and identifying the yield-limiting factors for various growing conditions would provide valuable information for designing strategic plans to improve crop yield for local conditions. However, this process is time consuming and expensive as it may involve many years of experimental data collection. The crop models that were discussed in the previous chapters (Jones et al. 2003; Hoogenboom et al. 2004) can also be applied to identify yield-limiting factors and quantify the yield gap between potential yield, attainable yield and actual yield for various growing conditions.

Yield Gap Analysis for Tad Fa Watershed, Phu Pha Man, Thailand

Methodology

Long-term simulations were conducted in order to determine the reduction in soybean and maize yields due to water and nitrogen limitations for the Tad Fa watershed in Phu Pha Man, northeastern Thailand. The CSM-CROPGRO-Soybean and CSM-CERES-Maize models were run for soybean cultivars SJ 5 and CM 60 and the maize cultivar CP-DK 888, with 32 years of historical weather data, e.g., 1972 to 2003 and for all

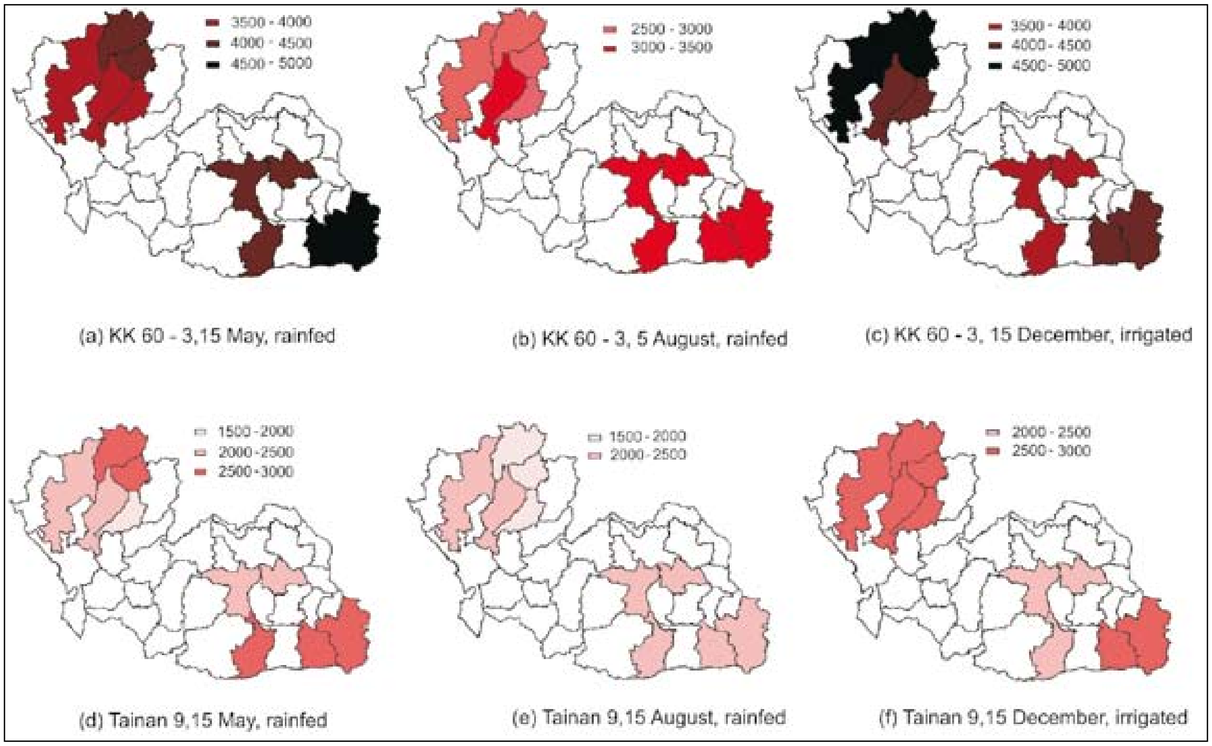

Figure 15. Spatial variation of average seed yield (kg ha^{-1}) for peanut varieties KK 60-3 and Tainan 9 for three different planting dates during the dry and rainy season.

five soil series of the Tad Fa watershed (Table 8). Different crop management scenarios were identified that represented common management practices in the watershed. A rain-fed condition was specified for seven planting dates during the rainy season, i.e., May 15 and 30, June 15 and 30, July 15 and 30 and August 15, for both soybean and maize. A plant population of 40 plants m^{-2} was used for soybean and 5 plants m^{-2} for maize. Nitrogen fertilizer applications were defined as 10, 20 and 30 kg N ha^{-1} for soybean and 30, 50 and 70 kg N ha^{-1} for maize. The model simulations were first conducted with the soil, water and nitrogen balances "turned off" to estimate yield potential due to solar radiation, temperature and photoperiod only. These yields are equivalent to obtaining yield under no-stress conditions. Then, growth limitations due to water and nitrogen stress were simulated with the simulation of the soil, water and nitrogen balances"turned on".

Results and Discussions

Yield potential for soybean, limited only by temperature and solar radiation and no-water and nutrient stress, ranged from 2810 to 3630 kg ha^{-1} for the seven planting dates (Table 9). The highest yield potential was found for the June 30 planting date. For water and nitrogen limiting conditions, soybean yield for the seven different planting dates and three different amounts of N fertilizer applications ranged from 1630 to 3030 kg ha^{-1} (Table 9). The highest mean seed yield was found for the June 15 planting date. This was due to a large amount of rainfall during the growing season, a moderate temperature and a moderate level of solar radiation. A large amount of rainfall and high solar radiation for the May 15 and 30 planting dates induced vegetative growth at the expense of reproductive growth, resulting in a lower yield compared to the other planting dates. The yield reduction of soybean caused by water and nitrogen limitations ranged from 12% to 48% of yield potential (Table 9). Increasing the amount of N fertilizer increased yield slightly for all planting dates. It has been found that applying some starter fertilizer at planting enhances overall soybean growth and ultimately leads to a higher yield.

The maize analysis for climatic yield potential, with soil water and nitrogen non-limiting, indicated that yield potential ranged from 4360 to 6130 kg ha^{-1} (Table 10). The highest yield potential was found for the July 15 planting date. For the simulation for water and nitrogen limiting situation, the results indicated that the mean simulated seed yield for the seven different planting dates and three different amounts of N fertilizer applications varied from 1050 to 4380 kg ha^{-1} (Table 10). The highest values for final yield were found for the June 15 and 30 and the July 15 planting dates, due to high amounts of rainfall during the growing season and moderate values of temperature and solar radiation (Table 10). The reduction in maize yield due to water and nitrogen limitations ranged from 29% to 83% of potential yield (Table 10). Applying additional nitrogen fertilizer reduced most of reduction in yield for all planting dates. This indicated that the application of nitrogen fertilizer was important to increase maize yield for these three planting dates.

Table 8. Soil characterization of the local soil series in the watershed; drained upper limit (DUL), lower limit of plant available water (LL), bulk density (SBDM) and percentage of clay (SLCL) and silt (SLSI) used for the crop model simulation.

Soil series	Soil depth (cm)	DUL (cm^3 cm^{-3})	LL (cm^3 cm^{-3})	SBDM (g cm^{-3})	SLCL (%)	SLSI (%)
Ban Chong (Bg)	17	0.308	0.188	1.53	34.8	25.1
	50	0.327	0.220	1.53	46.4	20.4
	65	0.327	0.220	1.53	46.4	20.4
	96	0.401	0.287	1.54	56.8	14.2
	130	0.378	0.263	1.51	52.9	21.0
Li (Li)	11	0.341	0.211	1.41	40.8	50.0
	27	0.329	0.204	1.40	40.6	48.0
	50	0.249	0.166	1.41	49.0	41.2
	57	0.249	0.166	1.41	49.0	41.2
Wang Hai (Wi)	17	0.248	0.114	1.41	17.5	53.0
	35	0.278	0.145	1.41	24.5	50.5
	50	0.313	0.183	1.42	33.0	45.5
	55	0.313	0.183	1.42	33.0	45.5
	90	0.383	0.258	1.38	50.0	34.0
	120	0.358	0.238	1.47	47.0	32.0
Wang Saphung (Ws)	12	0.271	0.145	1.50	24.5	36.0
	33	0.315	0.195	1.49	37.0	31.0
	50	0.357	0.240	1.50	47.5	24.5
	55	0.357	0.240	1.50	47.5	24.5
	80	0.245	0.171	1.53	52.5	18.0
Muak Lek (Ml)	19	0.378	0.256	1.37	50.2	30.5
	40	0.386	0.263	1.39	51.8	32.9
	50	0.307	0.231	1.40	71.5	16.0
	112	0.307	0.231	1.40	71.5	16.0
	133	0.136	0.097	1.39	59.7	24.6

Table 9. Simulation analysis for soybean in the Tad Fa watershed, Phu Pha Man, Khon Kaen, Thailand.							
Planting date	Fertilizer (kg N ha^{-1})	Rainfall (mm)	T max. (°C)	T min. (°C)	Radiation (MJ $m^{-2}day^{-1}$)	Potential mean yield (kg ha^{-1})	Yield loss as percentage of potential yield (%)
				Water and N nonlimiting			
15 May	-	-	33.0	24.5	20.0	3120	-
30 May	-	-	32.7	24.4	19.7	3360	-
15 Jun	-	-	32.5	24.2	19.2	3570	-
30 Jun	-	-	32.3	24.0	18.6	3630	-
15 Jul	-	-	32.1	23.8	17.8	3470	-
30 Jul	-	-	31.9	23.4	16.9	3210	-
15 Aug	-	-	31.7	22.9	16.0	2810	-
				Water and N limiting			
15 May	0	737	33.0	24.5	20.0	1630	48
	10					1730	46
	20					1740	44
	30					1750	44
30 May	0	732	32.7	24.4	19.7	1910	43
	10					2010	40
	20					2030	40
	30					2050	39
15 Jun	0	720	32.5	24.2	19.2	2740	23
	10					2980	16
	20					3001	16
	30					3030	15
30 Jun	0	680	32.3	24.0	18.7	2520	31
	10					2710	25
	20					2740	25
	30					2770	24
15 Jul	0	624	32.1	23.8	17.9	2500	28
	10					2680	23
	20					2710	22
	30					2730	21
30 Jul	0	582	31.9	23.5	17.0	2340	27
	10					2500	22
	20					2530	21
	30					2560	20
15 Aug	0	493	31.7	22.9	16.0	2420	14
	10					2430	13
	20					2450	13
	30					2470	12

Table 10. Simulation analysis for maize in Tad Fa watershed, Phu Pha Man, Khon Kaen, Thailand.							
Planting date	Fertilizer (kg N ha^{-1})	Rainfall (mm)	T max (°C)	T min. (°C)	Radiation (MJ m^{-2} day^{-1})	Potential mean yield (kg ha^{-1})	Yield loss as percentage of potential yield (%)
				Water and N nonlimiting			
15 May	-	-	33.2	24.5	20.2	6090	-
30 May	-	-	32.8	24.4	19.7	6030	-
15 Jun	-	-	32.5	24.3	19.4	6040	-
30 Jun	-	-	32.3	24.0	18.4	6030	-
15 Jul	-	-	32.0	23.7	17.3	6130	-
30 Jul	-	-	31.8	23.1	16.3	4360	-
15 Aug	-	-	31.5	22.2	15.5	4650	-
				Water and N limiting			
15 May	0	597	33.2	24.5	20.3	1050	83
	30					2480	59
	50					2840	53
	70					3100	49
30 May	0	638	32.8	24.4	19.7	1400	77
	30					2840	53
	50					3180	47
	70					3400	44
15 Jun	0	687	32.5	24.3	19.4	1510	75
	30					3180	47
	50					3590	41
	70					3890	36
30 Jun	0	675	32.3	24.0	18.4	1630	73
	30					3370	44
	50					3840	36
	70					4240	30
15 Jul	0	644	32.0	23.7	17.3	1680	73
	30					3400	45
	50					3930	36
	70					4380	29
30 Jul	0	591	31.8	23.1	16.3	1240	71
	30					2240	49
	50					2560	41
	70					2850	35
15 Aug	0	492	31.5	22.2	15.5	1380	70
	30					2160	54
	50					2420	48
	70					2620	44

Yield Gap Analysis for Phu Pha Man, Thailand

Methodology

An analysis of yield gap between simulated potential and actual observed yield levels was carried out for soybean and maize for the Phu Pha Man district. The observed values for soybean yield for both the rainy and dry season and for maize for the rainy season were obtained from the Office of Agricultural Economics of Thailand for a period of 10 years from 1993 to 2002. For the simulation of yield potential, the year-to-year variability in planting dates was generated by using the automatic planting option in DSSAT 4.0 (Hoogenboom et al. 2004), using a planting window between May 15 and June 15 for the early rainy season planting date, July 15 to August 15 for the late rainy season planting date and December 15 to January 15 of the subsequent year for the dry season planting date. The crops were planted when the water content in the top soil layer of the profile was at least 40% of available or plant extractable water. The plant population that is commonly used by the local farmers in Phu Pha Man, i.e., 40 plants m^{-2} for soybean and five plants m^{-2} for maize, was also used for simulation of soybean and maize. The general recommendation for the nitrogen fertilizer application was defined as 28 kg N ha^{-1} for soybean and 66 kg N ha^{-1} for maize. The CSM-CROGRO-Soybean and the CSM-CERES-Maize models were used for this production period with the combination of all seven soil series in Phu Pha Man, commercial cultivars CM 60 and SJ 5 for soybean and CP-DK 888 for maize and the general crop managements recommendation for Phu Pha Man production area.

Results and Discussions

The analysis results for soybean indicated that the climatic yield potential for the rainy season ranged from 1990 to 4190 kg ha^{-1} and the observed mean yield under rain-fed conditions ranged from 1160 to 2380 kg ha^{-1} (Table 11). For the dry season, the climatic yield potential ranged from 2790 to 3380 kg ha^{-1} and the observed mean yield ranged from 1350 to 1810 kg ha^{-1} (Table 11). The yield gap between simulated potential and observed yield from 1993 to 2002 during the rainy season varied from 770 to 2810 kg ha^{-1} (39 to 67% of simulated potential yield), only a very small gap was found for 1993. The yield gap between simulated potential and observed yield during the dry season varied from 1230 to 1820 kg ha^{-1} (41 to 57% of simulated potential yield); only a small gap was found for 2000 (Table 11). A larger amount of nitrogen fertilizer and less serious pest and disease infestations were probably the main factors that contributed to these small gaps between potential and actual yield.

The difference in potential yield for maize during the rainy season varied from 4730 to 6000 kg ha^{-1}, while the observed yield ranged from 3180 to 5520 kg ha^{-1} (Table 12). The yield gap between potential yield and actual yield from 1993 to 2002 ranged from 16 to 1690 kg ha^{-1} (0.3 to 34.7% of simulated potential yield). The smallest yield gap was found for 1994 (Table 12). Similar to the analysis for soybean, a high amount of nitrogen fertilizer and a less serious infestation of pests and diseases were probably the main contributors.

Table 11. Mean simulated potential yield (Sim.), observed yield (Obs.), yield gap and yield difference (%) for soybean in the Phu Pha Man district.

Year	Rainy season				Dry season			
	Sim (kg ha^{-1})	Obs. (kg ha^{-1})	Gap (kg ha^{-1})	%[a]	Sim. (kg ha^{-1})	Obs. (kg ha^{-1})	Gap (kg ha^{-1})	%[a]
1993	1990	1220	770	38.6	3110	1370	1740	55.9
1994	2870	1160	1700	59.4	3140	1350	1790	56.9
1995	4190	1380	2810	67.2	3150	1410	1740	55.2
1996	2280	1200	1080	47.3	3220	1440	1780	55.3
1997	2430	1450	980	40.4	2940	1470	1460	49.8
1998	3470	1670	1800	51.8	3380	1560	1820	53.8
1999	3190	1560	1620	50.9	2790	1560	1230	44.0
2000	4090	1560	2530	61.8	3080	1810	1270	41.2
2001	3960	2380	1590	40.1	3270	1690	1580	48.3
2002	2450	1230	1220	50.0	3300	1690	1610	48.8
Mean	3090	1480	1610		3140	1540	1600	

a (Simulated yield - Observed yield) x 100/ Simulated yield

Table 12. Mean simulated potential yield (Sim.), observed yield (Obs.), yield gap and yield difference (%) for maize in the Phu Pha Man district.

Year	Sim. (kg ha^{-1})	Obs. (kg ha^{-1})	Gap (kg ha^{-1})	%[a]
1993	4870	3180	1690	34.7
1994	5540	5520	16	0.3
1995	6000	-	-	-
1996	4730	-	-	-
1997	4790	-	-	-
1998	5420	5230	190	3.6
1999	4820	4690	130	2.7
2000	5640	5060	570	10.2
2001	5680	5000	680	11.9
2002	5640	4820	820	14.6
Mean	5310	4790	590	

a (Simulated yield - Observed yield)x 100/ Simulated yield.

7. Conclusions

From the simulation study the following conclusions are drawn:

- the cultivar coefficients of the two soybean cultivars CM 60 and SJ 5 provided simulated values of various development and growth parameters that were in good agreement with their corresponding observed values for almost all parameters. These cultivar coefficients were, therefore, sufficiently accurate for further applications in Thailand and South East Asia;
- the results of model evaluation indicated a good agreement between simulated and observed data and demonstrated the potential of the models to simulate growth and yield for local environments in Thailand;

- the linkage of the crop growth model and GIS for simulating crop yield for the district of Phu Pha Man, Thailand, showed that the soybean cultivar CM 60 had a higher yield potential than the soybean cultivar SJ 5 for all planting dates. For peanut, the cultivar KK 60-3 had a higher yield potential than the cultivar Tainan 9 for all planting dates. A comparison of two planting dates of the rainy season showed that the early planting date of June 15 had a higher yield potential for soybean, maize and peanut than the August 15 planting date. The higher yield for the June 15 planting date could be attributed to higher rainfall and solar radiation during the actual growing season compared to later August 15 planting date;
- using a crop growth model and GIS for simulating regional peanut yield of the major peanut production regions in Thailand, provided the information that a lower temperature during early development in the dry season delayed flower initiation and extended maturity. More rainfall for May 15 planting date contributed to higher simulated seed yield for both the cultivars Tainan 9 and KK 60-3 compared to the August 15 planting date. The northeastern region was identified as a more productive area for rain-fed conditions and the northern area was more suitable to produce peanut under well-irrigated conditions during the dry season;
- the results of yield gap analysis for soybean in the Tad Fa watershed indicated that reduction in soybean yield due to water and nitrogen limitations ranged from 12% to 48% when compared to the actual yield potential. Increasing the amount of N fertilizer slightly decreased the percentages of yield reduction for all planting dates. The June 15 planting date was more appropriate for soybean production for Tad Fa watershed when compared to the other planting dates;
- an analysis for maize in the Tad Fa watershed showed that a reduction in maize yield due to water and nitrogen limitations ranged from 29% to 83% of potential yield. One or more applications of nitrogen fertilizer can eliminate most of the yield reduction for all planting dates. The July 15 planting date is more suitable for maize production for the Tad Fa watershed when compared to the other planting dates;
- the yield gap analysis for soybean and maize for the entire district of Phu Pha Man indicated that the amount of nitrogen fertilizer applied and pests and diseases were the main factors that contributed to the differences between potential yield and actual yield. The attainable yield could be increased through the application of nitrogen fertilizer and pesticides.

This research demonstrated the potential of using a dynamic crop simulation model in assisting with strategic decision-making for crop production and land use planning in the Phu Pha Man district and some of the major agricultural production areas in Thailand. It also indicated the possibility of using crop simulation model as an information technology tool to increase yield of soybean, peanut and maize for the other agricultural production areas in Thailand.

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