AGRICULTURE

COMPARISON OF CROP SIMULATION AND FIELD PERFORMANCE OF MAIZE UNDER 20-DAY DRY PERIOD IMPOSED DURING SELECTED CRITICAL GROWTH PERIODS IN NAKHON RATCHASIMA PROVINCE, THAILAND

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Abstract

Untimely prolonged dry spells hamper not only the already established maize crop (*Zea mays* L.), but also the farmers' decision making on the succeeding crop. This study was conducted to determine the effect of a 20-day dry period during selected critical growth stages on growth and yield of maize, and apply the CERES-Maize model in DSSAT version 4.0.2.0. Five 20-day dry periods coinciding with selected critical growth stages [viz. 21-40 days from seeding (DFS), 30-49 DFS, 36-55 DFS, 43-62 DFS and 57-76 DFS] were compared with a control treatment maintained with weekly irrigation using two popular maize cultivars ('Suwan 4452' and 'Pacific 224') in a factorial experiment using a split plot design with four replicates. Soil moisture content (SMC) at 0-15 and 15-30 cm depths reached the lowest limit of readily available water (RAW) in eight days after suspension of irrigation, but did not reach permanent wilting point (PWP) during the remaining 12 days. Both leaf area index (LAI) and plant height were significantly decreased (p=0.05) in treatments subjected to a dry period during 21-40 and 30-49 DFS. Grain number per cob, grain yield and harvest index (HI) decreased significantly (11.3%, 11.2% and 13.5%, respectively) when the dry period imposed only occurred during 21-40 DFS. 'Suwan 4452' had a higher grain number per cob than 'Pacific 224', but 100-grain weight was higher for 'Pacific 224'cultivar. The CERES-Maize model showed excellent performance in predicting the time to silking and physiological maturity, 100-grain weight, grain yield and HI. Simulated values of LAI and number of grains per cob showed greater variability based on standardized bias (R) and standardized mean square error (V). Overall, however, the CERES-Maize model was useful in providing approximate information enabling appropriate decision making in the event of dry periods extending up to 20-days.

Keywords: Crop simulation, CERES-Maize, water stress, rainfed maize production, grain yield

Introduction

Water stress caused by erratic rainfall distribution is one of the major causes of maize yield reduction around the world (Bruce *et al*., 2002). Rainfed maize often suffers due to water stress resulting from dry spells in Nakorn Ratchasima Province, Thailand (Jampatong and Balla, 2005). Gerpacio and Pingali (2007) reported significant yield reduction when maize encountered drought during critical growth periods. The most critical growth periods of maize are the two weeks before silking and 2-3 weeks after silking (Singh and Singh, 1995). However, Saini and Westgate (2000) and Pandey *et al*. (2000) observed large reductions of maize yields when water stress coincided with periods immediately after planting and also after silking. In the former, there is a large reduction of plant density, while in the latter affecting grain development. There has been evidence of water stress tolerance of maize during the vegetative stage, but very sensitive during tasseling, silking and pollination, and moderately sensitive during the grain filling period (Hall *et al.,* 1982;

Otegui *et al*., 1995; NeSmith and Ritchie, 1992; and McKersie and Leshem, 1994;). Fengling *et al*. (2002) and Panitnok *et al*. (2005) observed greatest reductions of growth and yield when water deficit occurred at tasseling. This is because drought stress during reproductive development and flowering affects both tasseling and silk development and subsequent pollination and fertilization (Lafitte, 2000).

Nakhon Ratchasima Province is an important maize production region with 51% of the total extent of maize grown in Thailand. Two crops of maize usually are cultivated per year, with the percentage of early and late season crops being approximately 20 and 80%, respectively. These crops face water stress at different growth stages. The risk of water stress is very high during reproductive and grain filling periods in early season maize (March – July), while in the late season (August-December) it coincides with the vegetative development phase (Thiraporn, 1996).

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The length of the dry period cannot be predicted under rainfed agriculture, and the ability to produce satisfactory grain yields is dependent upon the crop cultivar for its ability to tolerate water stress (Banzinger *et al.*, 2002 and FAO, 2008) and soil characteristics - especially the capacity of the soil to retain and release water to the growing crop (Kramer and Boyer, 1995). In areas with irrigation facilities, weekly irrigation of 40 mm has been recommended to maize growers by the National Corn and Sorghum Research Center (NCSRC) in Pak Chong in Nakhon Ratchasima Province, northeastern Thailand.

Recent studies that evaluated imposing a 10-day dry period during each of four critical growth stages [viz. 36 to 46 (growth stage V6 to V9), 46 to 55 (V9 to V14), 55 to 66 (V14 to VT) and 66 to 76 (VT to R2) days from seeding (DFS)] showed no adverse effects on growth or yield of two popular maize hybrids ('Suwan 4452' and 'Pacific 224') compared to the control receiving regular irrigation until physiological maturity (Thongsaga and Ranamukhaarachchi, 2009). Soil moisture content (SMC) in 0-15 and the 15-30 cm profiles was depleted below readily available water (RAW) in 6-8 days after suspension of irrigation, but never reached the permanent wilting point (PWP) during the balance of 10-day period. Simulations of yield, yield components and harvest index using the CERES-Maize model in the Decision Support Systems for Agricultural Technology Transfer (DSSAT Version 4.0.2.0) were similar to observed responses for the 10-day dry period treatments. Furthermore, the study also revealed that irrigation could be rescheduled to 10-day intervals instead of weekly intervals, helping to conserve water and increase water productivity without adverse yield reductions.

In rainfed maize, yield reductions due to water stress periods are typically minimized by adjusting planting dates to patterns of historical rainfall probabilities. However, erratic nature of annual rainfall distribution may still reduce growth and yields. Soil moisture storage was able to support the maize crop during the imposed 10-day dry periods without significant yield reduction (Thongsaga and Ranamukhaarachchi, 2009). Since soil moisture in the lower profiles is moving upward in the vapor form during the dry period (Kramer, 1986), it may help meet water needs of the crop during water deficit periods. Therefore this study was designed to evaluate the a) effects of 20-day dry period occurring during critical growth periods on growth and yield of maize and b) the performance of the CERES-Maize model (DSSAT version 4.0.2.0) under the same dry periods in Nakorn Ratchasima Province of Thailand.

Materials and Methods

This study was conducted during the regular dry period from November 2007 to April 2008 in the National Corn and Sorghum Research Center (NCSRC) located in Pak Chong in Nakhon Ratchasima Province, Thailand (latitude 14.5°N, longitude 101°E, 360 meters above sea level).

Experimental Treatments and procedure

The study was conducted as a 6 x 2 factorial arrangement of six water management practices and two maize cultivars in a split plot design with four replicates. Water management treatments were assigned to main plots and cultivars to subplots. Five 20-day dry periods imposed by suspending irrigation during selected critical growth stages [viz. 21-40 (V4-V10), 30-49 (V6-V12), 36-55 (V8-V14), 43-62 (V10-VT) and 57-76 (V14-R2) days from seeding-DFS) (Figure 1)] and a control (plots were regularly irrigated at weekly intervals until physiological maturity) were the water management levels and 'Suwan 4452' and 'Pacific 224' used as two maize cultivars.

Figure 1. Experimental treatments (dark lines show the period of suspension of irrigation for maize, and broken line indicates irrigation provided on a weekly basis) [Legend: S – seeding; SE - seedling emergence; KH – knee-high stage; VT – tasseling; R1 – Silking; PM – physiological maturity; H – harvesting].
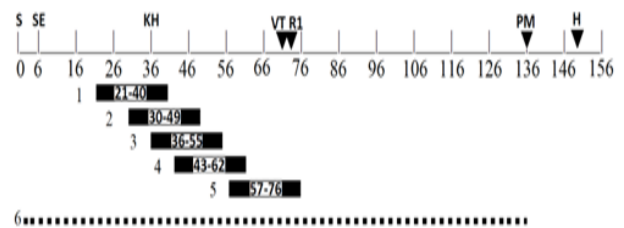
The land was prepared using a disc harrow, with ridges and furrows spaced at 75 cm. Each main plot was 16 m long and 4.5 m wide, and divided length-wise into two subplots to accommodate the two maize varieties. To avoid lateral flow of water and root growth between plots, a thick plastic sheet was placed vertically to a depth of 50 cm around each main plot by making a deep drain, placing the sheet and then covering both sides with soil. Since the usual dry period extends from mid-November 2007 to mid-April 2008, both sprinkler and furrow irrigation systems were set up to facilitate irrigation during the experimental period. N and P fertilizers were band applied prior to establishment at a rate of 20 and 25 kg ha-1, respectively, and incorporated immediately as per recommendation of the NCSRC. Maize seeds were planted by hand with two seeds per hill with an inter- and intra-row spacing of 75 cm (on ridges) and 20 cm, respectively, on 15 November 2007. The following day, plots were irrigated with sprinklers for about four hours which provided approximately 40 mm of water to each plot. Second

irrigation was given five days after the first irrigation, and thereafter irrigation was continued at weekly intervals until maize plants reached 45 cm (knee-high stage). Furrow irrigation was begun one week after the knee-high stage, which provided water for about two hours to each plot at weekly intervals until black layer formation. Irrigation was suspended for 20-days for plots designated during specific growth periods as per treatments and resumed at the end of the 20-days. The dry periods were chosen to coincide with critical growth periods, viz. 21-40 DFS (V3 to V6), 30-49 DFS (V5 to V10) (V10 is the knee-high stage), 36-55 DFS (V6 to V13), 43-62 DFS with V8 to VT (VT is the tasseling stage) and 57-76 DFS (VT to R2) (R2 is the beginning of grain filling) (Ritchie and Hanway, 1982). The control plot received irrigation from planting until physiological maturity. Plots were thinned at two weeks after seeding (WAS) to a plant density of 6.67 plants m-2. Plots were top dressed with 115 kg ha-1 N using urea (46% N) at 30 days after seedling emergence. The crop was examined frequently for insect pests and diseases and maintained using an integrated pest management (IPM) approach as per crop management guidelines of the NCSRC. Hand weeding was used to control weeds.

Observations & measurements

Soil moisture content (SMC) was determined at -0.3 bars (field capacity - FC) and -15 bars (permanent wilting point - PWP) at both 0-15 and 15-30 cm depths for each plot prior to seeding using pressure plate. During the 20-day dry period, soil moisture depletion was monitored using gravimetric method (Ryan *et al.,* 2001) for which soil samples were taken from 0-15 and 15-30 cm layers from three places within each plot in all replicates using a soil auger. Fresh weight was recorded, and then samples were oven-dried at 105ºC until a constant weight was obtained, and percent SMC was computed on a dry weight basis.

Plant height and leaf area were recorded at 50% silking. Plant height was measured from ground level to the tip of the tassel from 10 randomly selected plants in each plot. From the same plants, leaf area was also estimated by measuring the length and the width of the widest point of each leaf and multiplying the product by a factor of 0.72, and leaf area index (LAI) was computed as reported by McKee (1964).

Yield and yield components were determined by harvesting all maize plants in the two center rows of each subplot, excluding plants in one meter wide area on both ends (sampling area of 6 m x 1.5 m = 9 m2). Ten consecutive plants were harvested starting from one randomly selected point from one of the two rows, and cut at the ground level to determine the yield, 100-grain weight and stalk weight. Plant biomass at maturity was estimated by separating plants into grain and stalk,

weighed for fresh weight, oven dried at 80ºC until a constant weight was reached, and dry weights recorded. Remaining plants in the two rows were cut at ground level, separated into grains and stalk, and fresh weights recorded. These fresh weights were converted to dry weight using the data obtained from the 10-plant subsample. Grain yield and 100-grain weight were computed assuming 15% moisture content. Harvest index (HI) was computed using grain yield and total biomass yield at harvest as described by Holiday (1960).

Data analyses

Growth and yield data were subjected to analysis of variance (AOV) for a split plot design, and means were compared with the Fisher's Protected Least Significance Difference (LSD) procedure at p=0.05 (Steel and Torrie, 1980).

Application of CERES-Maize model

The growth and yield simulation was done using the CERES-Maize model of the Decision Support Systems for Agricultural Technology Transfer (DSSAT) Version 4.0.2.0. Model inputs were weather data during the experimental period (solar radiation, maximum and minimum air temperature and precipitation), soil physical and chemical characteristics including drainage, runoff, slope, soil classification containing soil depth, particle size analysis, pH, %C, %N and cation exchange capacity (CEC). Crop management data included management practices as per NCSRC recommendations (Anon, 2001). A crop residue value of 1.3 t/ha was used based on the residue generated in the previous study (Thongsaga and Ranamukhaarachchi, 2009). Genetic coefficient for maize included degree days (base 8oC) from emergence to the end of juvenile phase (P1), from silking to physiological maturity (P5), and for a leaf tip emergence (phyllochron interval, °C d) (PHINT), photoperiod sensitivity coefficient (0-1.0) (P2), potential kernel number (G2), potential kernel growth rate in mg/kernel, and d (G3) for the simulation (Table 1) (Hoogenboom, 2004).

Soils at the experimental site belong to the Pak Chong (PC) soil series. Additional soils information included taxonomy (very-fine, kaolinitic, Isohyperthemic Rhodic Kandiustox) and texture (clay - 53.8 %; sand - 5.6 %). Layer-wise soil analysis was conducted at the Agricultural Technology laboratory at AIT to determine model inputs; parameters included pH (1:1 soil : water and 1:1 soil : KCl) (McLean, 1982); organic C [Walkley-Black method (Nelson and Sommers, 1982; FAO, 1974)]; total N [Kjeldhal method (Bremner and Malvaney, 1982)]; available P [(Bray II method) (Bray and Kurtz, 1945)], exchangeable K (Barker and Surh, 1982) and CEC (Ryan *et al.,* 2001)] (Table 2).

Model Validation

The bias (Eq. 1) and root mean square of error (RMSE, Eq. 2) were used for comparing the difference between simulated values and actual values (Willmott, 1982). The standardized bias (R, Eq. 3) and standardized mean square error (V, Eq. 4) were used as the most appropriate indices to confirm the relationship between simulated and actual results for maize growth, yield and yield components (Graf *et al.,* 1991).

Table 1. Genetic coefficients of maize cultivars 'Suwan 4452' and 'Pacific 224' cultivars.

Genetic coefficient	'Suwan 4452'	'Pacific 224'
Phenological coefficient		
Thermal time from seedling emergence to the end of the juvenile phase (P1), expressed in degree days above a base temperature of 8°C, during which the plant is not responsive to changes in photoperiod.	343.9	346.9
Extent to which development (expressed as days) is delayed (P2), for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (12.5 hours).	0	0
Thermal time from silking to physiological maturity (P5), expressed in degree days above a base temperature of 8°C.	1149	1190
Phyllochron interval (PHINT): the interval in thermal time (degree days) between successive leaf tip appearance	46	46
Growth Coefficient		
G2: Maximum possible number of kernels per plant.	907	907
G3: Kernel filling rate during the grain filling stage and under optimum conditions (mg/day).	6	6

Source: Hoogenboom (2004)

Table 2. Layer-wise soil characteristics for research site at the National Corn and Sorghum Research Centre, Pak Chong, Nakhon Ratchasima Province, Thailand.

Depth, cm	Organic C %	Total N %	Avail. P ppm	Exch. K ppm	pH (1:1 water)	(1:1 KCl)
0-15	4.5	0.14	12	246	7.2	6.8
15-30	4.4	0.14	9	200	7.3	6.8
30-50	4	0.06	3	122	7.2	6.7
50-75	0.03	0.05	4	68	6.4	6.1
75-100	0.03	0.05	4	82	7.1	6.6

Source : Thongsaga and Ranamukhaarachchi (2009)

$$\text{Bias} = \frac{1}{N} \sum_{i=1}^{n} (Si - Ac) \quad \text{..............} \quad (Eq.\ 1)$$

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum (Si - Ac)^2} \quad \text{...............} \quad (Eq.\ 2)$$

$$R = \frac{\sum_{i=1}^{n} (Si - Ac)}{\sum_{i=1}^{n} (Ac)} \quad \text{...................} \quad (Eq.\ 3)$$

$$V = \frac{\sum_{i=1}^{n} (Si - Ac)^2}{\sum_{i=1}^{n} (Ac)^2} \quad \text{......................} \quad (Eq.\ 4)$$

Where n is the number of field observations, and Si and Ac are simulated and actual values, respectively. R and V are estimates of the overall error of the model pertaining to field data. R quantifies the model's ability to reproduce the actual growth pattern. Negative deviations from simulated values (Si-Ac<0) compensate for positive deviations (Si-Ac>0) and vice versa (Eq. 3). V is a measure of the model's tendency to generally over- or under-predict the yield and other parameters. RMSE indicates the reliability of the simulated data. All four indices were used for interpreting data.

Results and Discussion
Weather conditions

Daily weather data for the experimental period are presented in Figures 2 and 3. These data were obtained from the Pak Chong Regional Meteorological Station located within one kilometer of the experimental site. Solar energy (SE) ranged from 6 to 27 Mj m-2 d-1, and minimum (Tmin) and maximum (Tmax) temperatures ranged from 12 to 24°C and from 24 to 37°C, respectively (Figure 2). Relative humidity (RH) ranged from 18 to 92% and evapotranspiration (ETc) calculations for maize ranged from 2 to 10 mm/day (Figure 3). There was no rainfall during the vegetative period of the study, but there was a few storms during the grain filling period.

Figure 2. Solar energy, Mj m^{-2} d^{-1} (SE) and maximum (Tmax) and minimum (Tmin) temperature (ºC) for the period November 2007 to April 2008.

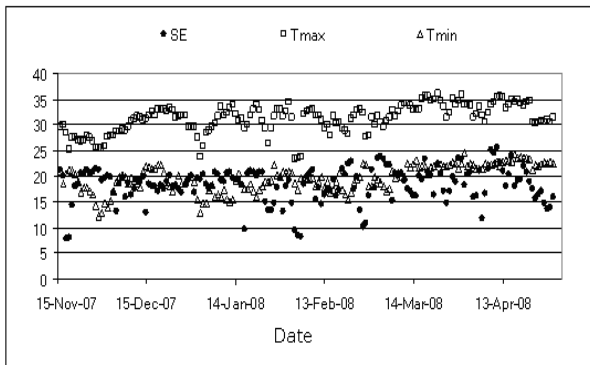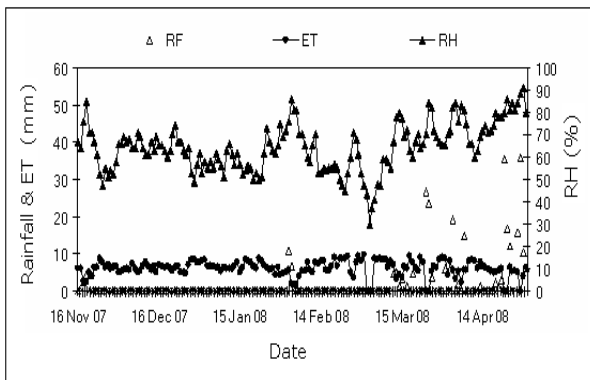
Figure 3. Evapotranspiration, mm d-1 (ETc), rainfall, mm d-1 (RF), and relative humidity, % (RH) during November 2007 to April 2008.

Soil moisture content

Soil moisture content (SMC) at field capacity (FC) and permanent wilting point (PWP) was 64.9 mm and 40.1 mm, respectively. The available soil moisture (ASM) was 24.7 mm in the 0-15 cm depth and 17 mm in the 15-30 cm depths of all treatments. With the suspension of irrigation for 20 days, SMC at both 0-15 and 15-30 cm profiles approached the lowest level of readily available water (RAW) between 8 and 10 days, but did not reach the PWP in the remaining 12 days of the 20-day period (Figure 4 and 5). The SMC was higher in the 15-30 cm profile in every treatment. The lowest SMC in both soil layers was found in treatments subjected to dry period during 30-49 and 36-55 days after seeding (DFS). This indicates that there was no free water available in soil 8-10 days after cessation of irrigation until the next irrigation that was received 10-12 days later. The results also showed that SMC was above PWP, supporting the observation of no plant death. Thus, this study provides an opportunity for examining growth and yield parameters of maize grown under SMCs between RAW and PWP.

The CERES-Maize model overestimated SMC of both depths of soil profile although the trend was similar. The bias (deviation of simulated values from actual values) was wider for the 15-30 cm profile than the 0-15 cm profile (Fig. 4 and 5). Within the 0-15 cm layer, treatments subjected to suspension of irrigation between 36 and 46 DFS had the narrowest bias (Figure 4).

Time to Tasseling, Silking and Tasseling-silking interval

Temperatures during the study were cooler than in typical growing seasons. This prolonged both the vegetative and grain filling periods when compared to the performance of the same varieties grown during warmer seasons in this area (Nakorn Ratchasima Province). Thus, 50% tasseling occurred in 71 days instead of the typical 57 DFS, 50% silking occurred in 74 days instead of 59 days, physiological maturity in 137 days instead of 112 days, and full maturity in 150 days instead of 115 days (Table 3).

Figure 4. Actual and simulated soil moisture content (SMC) at 0-15cm depth during 20-day dry period.
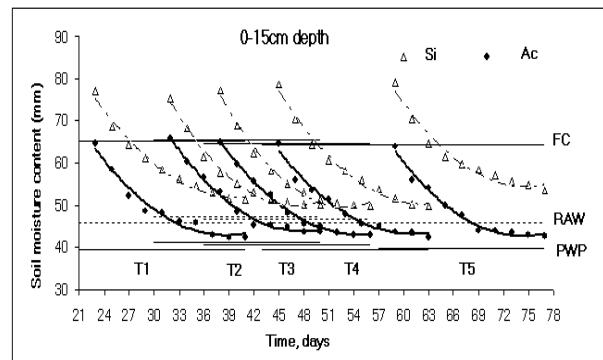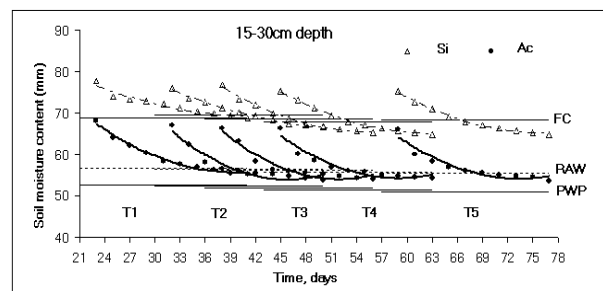

Figure 5. Actual and simulated soil moisture content (SMC) at 15-30cm depth during 20-day dry period.

Growth performance

There was no significant effect of timing of the dry period on the number of days from seeding to tasseling and silking and tasseling-silking interval, but cultivar had

difference in time to tasseling and tasseling-silking interval (TSI) (Appendix Table 1): 'Suwan 4452' reached tasseling 0.7 days after 'Pacific 224' and 'Pacific 224' had a 0.8 days shorter TSI than 'Suwan 4452'. Both cultivars reached silking in 74 DFS. This shows that there was no adverse effect of the length of the vegetative period. The TSI ranged from 2.0 days in the treatment exposed to the dry period between 57 and 76 DFS to 2.9 days in the treatment exposed to the dry period between 36 and 55 DFS. Typically, a TSI of 3-4 days is considered normal. This length of time favors both pollination and fertilization of ovules in maize (Ritchie and Hanway 1982; Paliwal 2000). Thus, neither pollination nor fertilization of maize was adversely affected by the dry period treatments.

Table 3. Time to tasseling and silking, tasselling-silking interval (TSI) and time to physiological maturity (PM) of maize as influenced by timing of the 20- day dry period and maize cultivar

Treatment	Tasselling (days)	Silking (days)	TSI (days)	PM (days)
Time of dry period, DFS 1/				
21-40	71.8 ± 0.6	74.2 ± 0.5	2.4 ± 0.5	136 ± 2
30-49	71.0 ± 0.9	73.5 ± 0.5	2.5 ± 0.9	136 ± 2
36-55	70.5 ± 1.8	73.4 ± 1.1	2.9 ± 1.0	135 ± 2
43-62	71.1 ± 0.6	73.6 ± 0.5	2.5 ± 0.5	137 ± 2
57-76	71.8 ± 0.9	73.8 ± 0.8	2.0 ± 0.8	136 ± 3
Control	71.3 ± 1.3	73.6 ± 1.2	2.3 ± 0.9	138 ± 2
LSD (p=0.05)	ns	ns	ns	ns
Cultivar				
'Suwan 4452'	70.9 ± 1.2 b 2/	73.7 ± 0.8	2.8 ± 0.8 a	137 ± 2 a
'Pacific 224'	71.6 ± 1.0 a	73.7 ± 0.8	2.0 ± 0.6 b	135 ± 2 b
LSD (p=0.05)	0.4	ns 3/	0.4	1.1
CV%	0.93	0.67	31.22	1.38

1/ DFS - days from seeding;
2/ Numbers followed by different letters within a column are significantly different according to Fisher's Protected Least Significance Difference Test (LSD), p=0.05;
3/ ns – Not significant at p=0.05;

The CERES-Maize model showed excellent performance in the simulation of silking time under 20-day dry periods imposed for both maize cultivars. For 'Suwan 4452', bias ranged from -0.25 day in the treatment subjected to the dry period from 21-40 DFS (R=-0.003 and V=0.00005) to 0.50 day in the two treatments not irrigated from 30-49 DFS (R=-0.007 and V=0.0001) and 36-55 DFS (R=-0.007 and V=0.0003) (Figure 6a). For 'Pacific 224', the bias ranged from -0.25 day in treatment experiencing the dry period from 21-40 DFS (R=-0.003 and V=0.00005) to 0.75 day in the 36-55 DFS dry period treatment (R=-0.010 and V=0.0002) (Figure 6b). The bias was zero for the growth stage from 57 to 76 DFS for 'Pacific 224'. These results indicate a high degree of reliability of

predicting the time to silking of maize under 20-day dry periods using the CERES-Maize model.

Plant height

Plant height was affected only by the growth stage encountering of the dry period, but not by cultivar (Appendix Table 2). Plant height at silking ranged from 1.65 m when the dry period occurred from 30 to 49 DFS to 1.90 m in the control which had no exposure to water deficit (Table 4). Both cultivars had similar plant heights, i.e. 1.77 m for 'Suwan 4452' and 1.76 m for 'Pacific 224'. The lowest height was found in plants in the treatment exposed to the dry period 30-49 DFS, the active growth period of maize, but it was significantly different from the control. There was no simulation of plant height attempted in the current study.

Figure 6. Actual and simulated time to silking for a) 'Suwan 4452' and b) 'Pacific 224' cultivars of maize as influenced by timing of the 20-day dry period. [1/ DFS – days from seeding.]
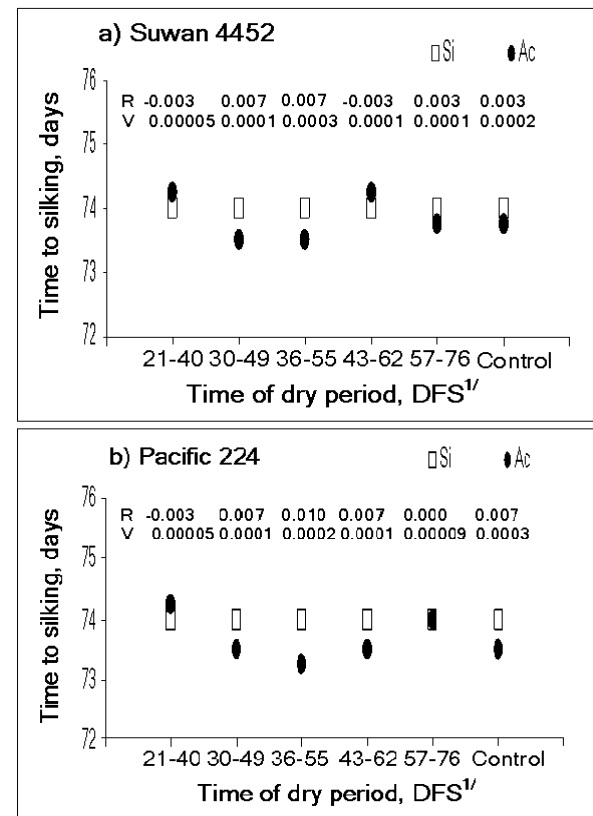
Leaf area index (LAI)

Leaf area index (LAI) showed significant reductions due to dry periods occurring during different growth stages (Appendix Table 2). The dry period imposed during 21 to 40 DFS (LAI of 3.4) and during 30 to 49 DFS (LAI of 3.3)

had significantly lower LAI values, while the water stress imposed during other growth stages (which ranged from 3.7 in plants exposed to dry period during 36 to 55 DFS to 4.3 in 43 to 62 DFS) did not affect LAI significantly (Table 4). The rapid leaf expansion of maize typically occurs between 30 and 49 DFS (Tollenaar and Dwyer, 1999) and water stress during this period affects leaf development and expansion (Passioura *et al.,* 1993). However, there was no suppression of LAI in the current study since dry periods were imposed after about 49 DFS. Cultivar effects were significant, and 'Suwan 4452' had a significantly higher LAI (4.0) than 'Pacific 224' (LAI of 3.6).

Model simulations of LAI were very close to observed values for both maize cultivars (Figure 7a and b). The simulated LAI value for 'Suwan 4452' in the control treatment was 4.40 compared to the observed value of 4.34 with a bias of -0.06 (R= 0.014 and V=0.004). The bias for the restricted irrigation treatments ranged from -1.74 (R=-0.393 and V=0.175) for the 43-62 day dry period to -0.17 (R=-0.042 and V=0.027) in the 57-76 DFS dry period treatment. The simulated values for 'Pacific 224' also closely matched actual values, with bias ranging from -1.39 (R=-0.340 and V=0.127) in treatments experiencing a dry period 43-62 DFS to 0.58 (R=0.152 and V =0.032) in the control. Greater LAI deviations were found in treatments experiencing water deficit in the early part of growth. However, the impact of these reductions needs to be compared with effects on yield and yield components.

Time to Physiological maturity

Although physiological maturity (PM) was delayed by the low temperatures that prevailed during the cropping period, no significant differences on time to PM were seen from the 20-day dry periods (Appendix Table 1 and Table 3). The time to PM ranged from 135 days in plants exposed to a dry period during 36-55 DFS to 138 days in the control, with differences not significant (p=0.05). However, there was a two-day delay in the time to PM for 'Suwan 4452' (137 days) compared to 'Pacific 224' (135 days).

The model overestimated the time to PM for both cultivars, except in one case for 'Suwan 4452' (Figures 8a and 8b). In general, the bias was wider for 'Pacific 224' (i.e. 3.0 to 5.0 days) than that of 'Suwan 4452' (-0.25 to 2.50 days). The simulated values appeared reliable for 'Suwan 4452' due to low R (range of R=-0.002 to 0.018) and V (range of V=0.0001 to 0.0007). For 'Pacific 224', bias ranged from 3.0 days in the control to 5.0 days in the treatment experiencing dry conditions during 30-49 DFS. Overall, performance of the model is considered satisfactory for predicting time to PM.

Table 4. Plant height and leaf area index at 50% silking as influenced by timing of the 20- day dry period and maize cultivar.

Treatment	LAI at silking	Plant height at Silking, m
Time of dry period DFS 1/		
21-40	3.4 ± 0.6 bc 2/	1.71 ± 0.08 cd
30-49	3.3 ± 0.7 c	1.65 ± 0.11 d
36-55	3.7 ± 0.4 b	1.74 ± 0.11 bcd
43-62	4.3 ± 0.6 a	1.76 ± 0.07 bc
57-76	4.1 ± 0.7 b	1.80 ± 0.11 b
Control	4.1 ± 0.4 ab	1.90 ± 0.12 a
LSD (p=0.05)	0.3	0.08
Variety		
Suwan 4452	4.0 ± 0.6 a	1.77 ± 0.13
Pacific 224	3.6 ± 0.7 b	1.76 ± 0.12
LSD (p=0.05)	0.2	ns
CV%	8.2	4.78

1/ DFS - days from seeding;

2/ The numbers followed by different letters within a column ar Significance Difference Test (LSD) at p=0.05

3/ ns – Not significant at p=0.05

Figure 7. Actual and simulated leaf area index (LAI) for a) 'Suwan 4452' and b) 'Pacific 224' cultivars of maize as influenced by timing of the 20-day dry period. [1/ DFS – days from seeding.]
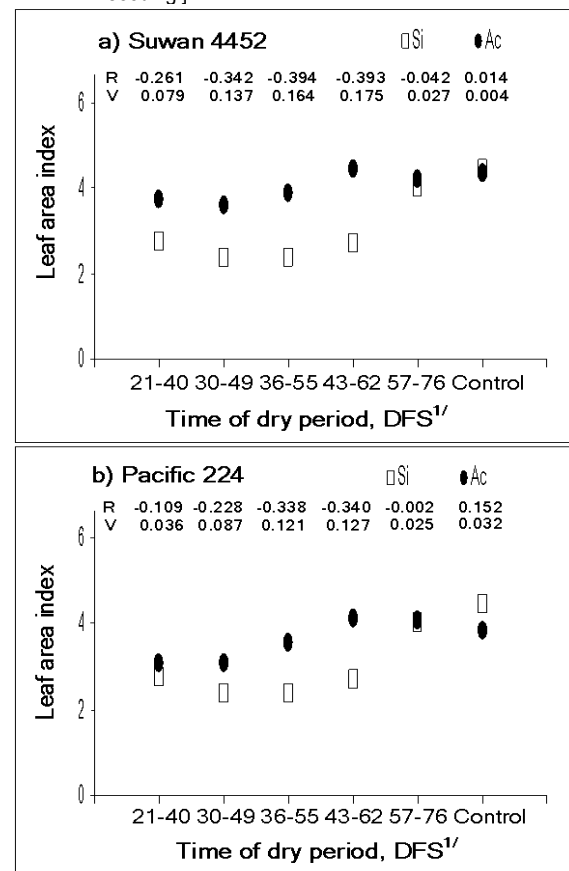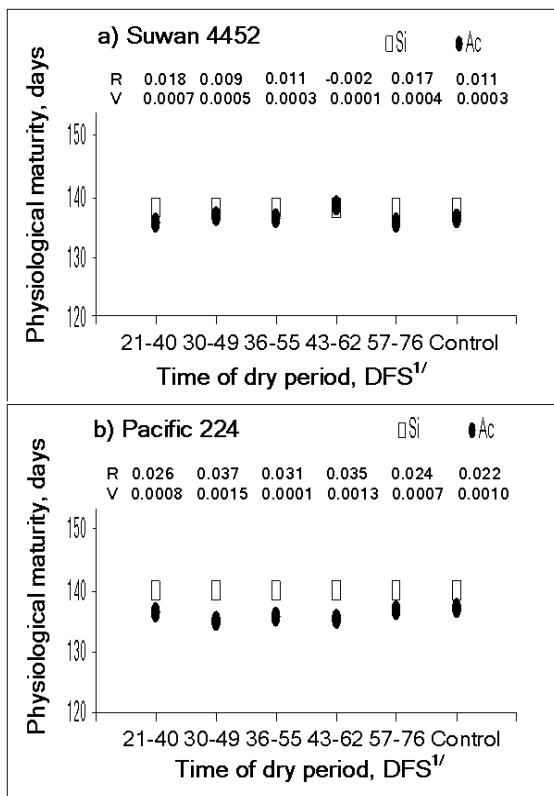
Figure 8. Actual and simulated physiological maturity for a) 'Suwan 4452' and b) 'Pacific 224' cultivars of maize as influenced by timing of the 20-day dry period. [1/ DFS – days from seeding.]

Grain yield and yield components

Number of grains per cob

The number of grains per cob of maize was not significantly affected by the growth stage during which the 20-day dry period was imposed, but varied significantly due to cultivar (Appendix Table 3): 'Suwan 4452' had a higher grain number per cob (492 grains) than 'Pacific 224' (462 grains) (Table 5). The number of grains per cob of 'Suwan 4452' ranged from 455 in the 21-40 DFS dry period treatment to 502-504 grains for other treatments, except for the 43 to 62 DFS dry treatment which had 489 grains per cob. For 'Pacific 224', plants exposed to the dry period during 30-49 DFS had the highest grain number per cob (481 grains) compared to the control with 475 grains (Figure 10).

The CERES-Maize model underestimated grains per cob in all treatments, including the control (Figure 9a and 9b). The bias was large and negative for both cultivars. Predicted values ranged from 244 grains per cob when the 20-day dry period was imposed 57-76 DFS to 411 grains per cob in the control, and both high R and V

values indicated high variability of the simulated values. This indicates that appropriate improvements to the model would be needed to accurately predict the number of grains per cob.

100-Grain weight

The growth periods during which the 20-day dry period was imposed showed no significant effects on 100-grain weight when compared to the control (Appendix Table 3). The 100-grain weight ranged from 32.3 g in the control to 34.7 g in plants with dry period during 43-62 DFS (Table 5). Cultivars had a significant effect on 100-grain weight; 'Pacific 224' had significantly higher grain weight than 'Suwan 4452'. There was no significant interaction between the cultivar and growth period during which the 20-day dry period was imposed for 100-grain weight.

The CERES-Maize model overestimated 100-grain weight of all growth period treatments and the two cultivars, but the bias was narrow (Figure 10a and 10b). The bias ranged from 1.59 g (with R=0.048 and V=0.003) when subjected to a dry period 21-40 DFS to 5.63 g (with R=0.188 and V=0.036) in the control of 'Suwan 4452'. For 'Pacific 224', bias ranged from -0.07 g (with R=-0.002 and V=0.0001) in the 21-40 DFS treatment to 1.32 g (with R=0.038 and V=0.005) in the control. The R and V values indicate that the simulation of 100-grain weight for 'Pacific 224' was more reliable than that for 'Suwan 4452'. The variability may be resulted from the variation in soil moisture content predicted by the model as seen in Figures 4 and 5.

Grain Yield

There was no significant effect of the timing of the 20-day dry period or cultivar on maize grain yield (Appendix Table 3). Grain yield of 'Suwan 4452' ranged from 7.82 t/ha in the 57-76 DFS dry period treatment to 9.10 t/ha when the dry period occurred 43-62 DFS (Table 5). For 'Pacific 224', yields ranged from 7.02 t/ha for the 21-40 DFS dry period treatment to 9.43 t/ha when the dry period occurred 36-55 DFS.

Simulated yields were underestimated, except in the control treatment for 'Suwan 4452', in which the bias was 0.72 t/ha and R and V values were 0.080 and 0.019, respectively (Figure 11a). Treatments experiencing dry periods had a bias ranging from -2.11 t/ha (with R= -0.270 and V= 0.075) in the 57-76 DFS treatment to -0.46 t/ha in the 21-40 DFS treatments (R= -0.052 and V= 0.013).

The 'Pacific 224' control treatment had a bias of 1.24 t/ha (R= 0.142 and V=0.029) (Figure 11b). Suspended irrigation treatments had a bias ranging from -2.93 t/ha for the 57-76 DFS treatment to 1.47 t/ha for the 21-40 DFS treatment. For both cultivars, the major deviation occurred in dry period treatments imposed after 30 DFS. The model

accurately predicted the impact of dry periods during ovule formation and development, tasseling, silking and grain filling. The simulations were close for both cultivars and the bias was mostly negative, indicating under-estimation, although model performance had little variability.

Figure 9. Actual and simulated grain number per cob of a) 'Suwan 4452' and b) 'Pacific 224' cultivars of maize as influenced by timing of the 20-day dry period. [1/ DFS – days from seeding.]
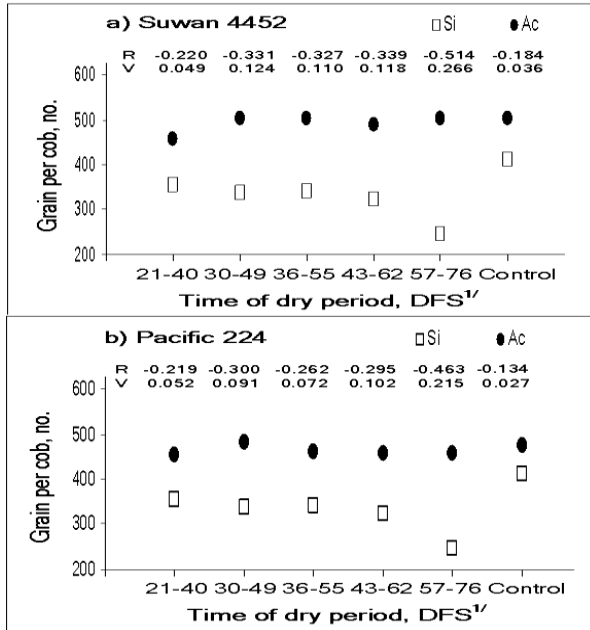
Harvest Index (HI)

Harvest index (HI) is the fraction of economic yield to the total above-ground plant biomass (Holliday, 1960). There was a significant effect of growth stage during which the 20-day dry period was imposed (P=0.01), but not for cultivars (Appendix Table 3). The highest HI of 0.53 was found when the dry period was imposed 36-55 DFS, although this value was not significantly different from the control and the 30-49 DFS dry period (0.51) or 36-55 DFS dry period treatments (0.53) (Table 5). The lowest HIs were found in treatments where the dry period was imposed 21-40 DFS and 57-76 DFS. Cultivar differences were not significant; 'Suwan 4452' had a HI of 0.48 and 'Pacific 224' a value of 0.51.

Overall, the CERES-Maize model provided almost identical estimations for HI for both maize cultivars although the bias was negative and ranged from -0.06 in the control treatment to -0.01 in the dry period treatments imposed 21-40, 36-55 and 43-62 DFS (Figures 12a and 12b). The R and V values ranged from -0.012 to -0.202 and 0.001 to 0.088, respectively for both cultivars indicating satisfactory performance of the model.

Table 5. Grain yield and yield components of maize as influenced by timing of the 20- day dry period and maize cultivar.

Treatment	Grains per cob (number)	100-grain weight (g)	Grain yield (t/ha)	Harvest Index
Time of dry period -DFS 1/				
21-40	454 ± 24	34.6 ± 1.4	7.9 ± 1.7	0.45 ± 0.09 c 2/
30-49	492 ± 51	34.6 ± 3.4	8.4 ± 1.0	0.51 ± 0.05 ab
36-55	481 ± 39	33.4 ± 2.7	9.2 ± 0.8	0.53 ± 0.06 a
43-62	473 ± 51	34.7 ± 2.6	9.0 ± 0.8	0.51 ± 0.04 abc
57-76	478 ± 34	33.6 ± 2.6	8.3 ± 1.1	0.46 ± 0.07 bc
Control	489 ± 40	32.3 ± 3.2	8.9 ± 1.0	0.52 ± 0.06 ab
LSD (p=0.05)	ns 3/	ns	ns	0.06
Cultivar				
'Suwan 4452'	492 ± 40 a	31.9 ± 2.0 b	8.7 ± 0.9	0.48 ± 0.05
'Pacific 224'	462 ± 37 b	35.8 ± 1.7 a	8.5 ± 1.4	0.51 ± 0.08
LSD (p=0.05)	18.24	0.8	ns	ns
CV%	6.29	5.9	13.68	12.13

1/ DFS - days from seeding;
2/ The numbers followed by different letters within a column are significantly different according to Fisher's Protected Least Significance Difference Test (LSD) at p=0.05;
3/ ns – Not significant at p=0.05.

Figure 10. Actual and simulated 100-grain weight of a) 'Suwan 4452' and b) 'Pacific 224' cultivars of maize as influenced by timing of the 20-day dry period. [1/ DFS– days from seeding.]
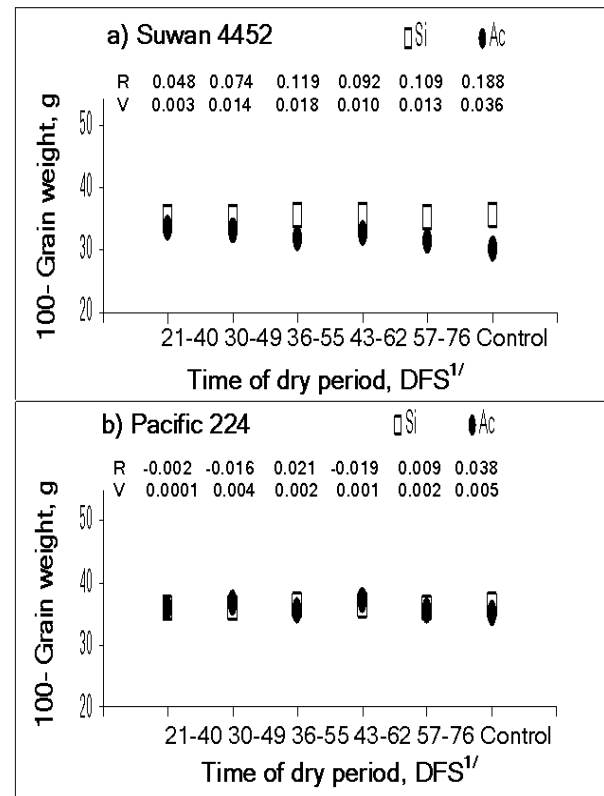
Figure 11. Actual and simulated grain yield of a) 'Suwan 4452' and b) 'Pacific 224' cultivars of maize as influenced by timing of the 20-day dry period. [1/ DFS – days from seeding.]
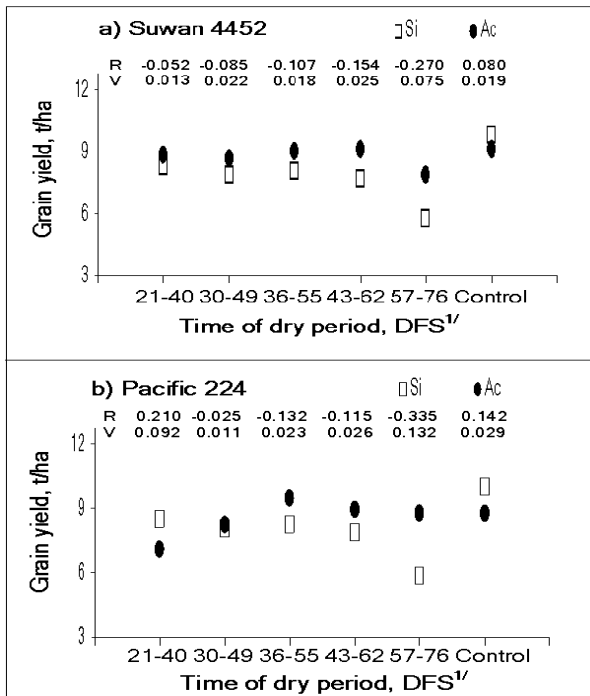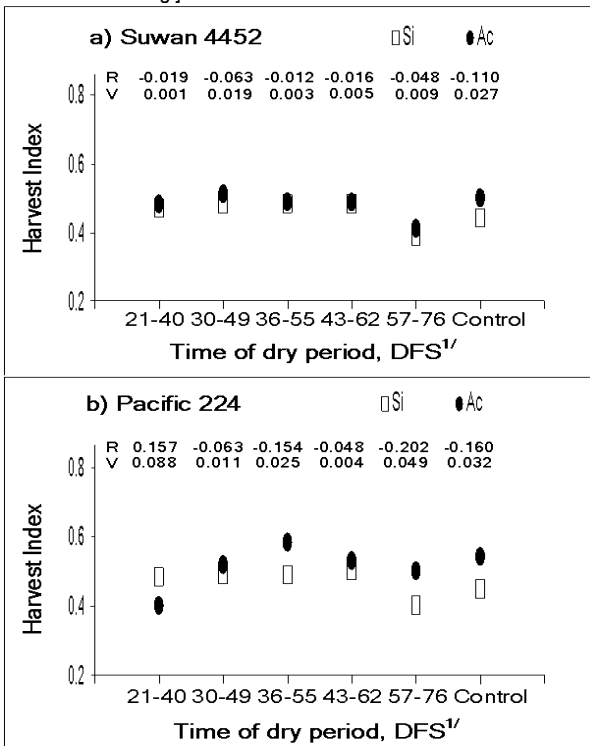

Figure 12. Actual and simulated Harvest Index of a) 'Suwan 4452' and b) 'Pacific 224' cultivars of maize as influenced by timing of the 20-day dry period. [1/ DFS – days from seeding.]

Discussion

Critical growth periods of maize are growth stages during which water and other stresses typically bring about unrecoverable yield losses (Hsiao, 1973; Eck, 1986; NeSmith and Ritchie, 1992; Jensen, 1995; Zinselmeier *et al.,* 1999; Kamara *et al.,* 2003; Kefale and Ranamukhaarachchi, 2004; Yang and Midmore, 2004; Moser *et al.,* 2006). Water stress, when occurring during critical growth periods, is expected to hamper growth and development and lower grain yield through impairment of yield components (Nouna *et al.,* 2000; Boonpradub, 2000; Panitnok *et al.,* 2005; Moser *et al.,* 2006). Rainfed maize often experiences dry periods during critical growth stages eventually affecting yield. In these situations, it is important that the SMC in the root zone remains above the PWP to avoid permanent root damage. Although SMC may fall below RAW, maize plants often are able to maintain active water uptake and water saving mechanisms for their survival and continued growth (Treshow, 1970; Lambers *et al.,* 1998; Huang, 2000). The ability of plants to survive under such condition of low water availability depends on the rate of water retained and released by the soil during dry periods, root depth and the plant's tolerance or avoidance mechanisms (Kramer and Boyer, 1995).

Our previous studies on Pak Chong soils showed that a 10-day dry period imposed by suspending irrigation during selected critical growth periods did not affect growth and yield of maize (Thongsaga and Ranamukhaarachchi, 2009). In the current study, with 20-day dry periods imposed during selected critical growth periods covering V4 to R2 stages, the SMC for the 0-15 cm soil profile fell below RAW in 8-10 days from the date of suspension of irrigation, but did not reach PWP. In the 15-30 cm soil profile, SMC was reduced to below the RAW value in about 10 days from the time of suspension of irrigation, but remained above the PWP until the resumption of irrigation. Under these SMC deficits, the maize crop showed slight leaf wilting towards the latter part of the 20-day dry period, but was not permanently damaged, recovering to some extent each night (Hsiao 1973; Kramer and Boyer 1995). This indicates that some soil moisture remained for plant use. Upward movement of soil moisture due to capillary action and evapotranspiration appeared to contribute to maintaining soil moisture above PWP. Water stressed maize roots have been shown to be able to absorb moisture under such conditions (Ahadiyat and Ranamukhaarachchi, 2007).

LAI was significantly reduced during dry periods induced 21-40 DFS (LAI of 3.4) and 30-49 DFS (LAI of 3.3) as compared to other treatments (LAI range of 3.7 to 4.3) (Table 4). The two former treatments had their leaf development and rapid leaf expansion periods coincide

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with the 20-day dry periods (Tollenaar, 1989), and hence the water deficit led to a reduction of LAI. Maize plants receiving the 20-day dry period during 36-55 DFS faced water stress only after 44-46 DFS as indicated in Figures 4 and 5, and by this time the plants had already developed a sufficient number of leaves, and leaf expansion continued when the irrigation was resumed. This helps explain the difference in LAI in growth stages imposed during 21-40 DFS and 30-49 DFS dry periods. LAI values between 3.5 and 4.5 are considered to be optimum for maize (Gitelson *et al.,* 2003; Amanullah, 2007). If LAI was a limiting factor for dry matter production, this effect would have been expressed in the first two treatments in which leaf growth coincided with the dry period (i.e. 21-40 DFS and 30-49 DFS). Thus, LAI responses indicated it was not a major constraint in this study. Plant height at silking did not show significant variation between the critical growth period treatments and the control (Table 4).

The growth period during which the 20-day dry period was encountered had no significant effect on the time to tasseling, time to silking or the tasseling-silking interval (TSI) (Table 3). Usually, time to tasseling and silking are important with respect to pollination and fertilization for determining the number of filled grains per cob (Dass *et al.* 2001). These two events appear in maize growing under normal conditions within 2 to 4 days, thus favoring pollination and fertilization (Westgate and Boyer 1986; Sing and Sing 1995). Advancement of tasseling and delaying of silking widens the TSI (Bolanos and Edmeades, 1996; Kling and Edmeades, 1997; Kefele and Ranamukhaarachchi, 2004), leading to early pollen shed prior to silks becoming receptive for pollen thus decreasing pollination and fertilization. Water stress occurring four weeks before tasseling advanced the time to tasseling to 56.1 days and water stress at tasseling delayed silking until 61.3 days, thus widening the TSI by 5.2 days (Kongjuntuk, 1998). However, in the current study, imposing the 20-day dry period at selected critical growth stages did not alter the time to either tasseling or silking and hence a favorable TSI was maintained, facilitating normal pollination and fertilization.

The yield components and final yield did not show major differences among selected growth stages undergoing 20-day periods, except during 21-40 DFS which gave the lowest grain number per cob (Table 5). This reduction in the grain number per cob resulted in a reduction in grain yield too, although the difference was not significant. There were insignificant increases in yields during 36-55 DFS and 43-62 DFS. The lack of reduction in grain yield under imposed dry conditions during specific growth periods indicates that the 20-day dry period had no noticeable adverse effect. Maize growers often have noted that dry weather during early growth of early season maize, and during reproductive and grain filling periods of late

season maize as the causes of low grain yield in the Pak Chong district. Since the cob and grains are initiated during the vegetative period (Babalola and Oputa, 1981; Weiss and Piper 1992; Pandey *et al.,* 2000), water stress occurring during this time could impair maize yield potential. This may be the reason for reduced grain number in the plants experiencing a dry period 21-40 DFS, something not observed in treatments having dry periods during other growth stages. This study revealed that on Pak Chong soils, maize could continue to grow and develop successfully in spite of a 20-day dry period. This may vary, however, from location to location depending upon soil characteristics, especially with soil depth (Kramer and Boyer, 1995; Zaidi *et al.,* 2007) and soil texture, which determine the volume of storage and release of soil water (Dennis *et al.,* 2000 and Zaidi *et al.,* 2002) for maize to use during prolonged dry conditions.

The overall results showed that maize could tolerate a dry period of 20 days occurring at any growth stage, except during early growth occurring 21-40 DFS, without any reduction in growth, yield and harvest index and without any change in the time of tasseling and silking. In contrast, Hawkins and Cooper (1981) and Moser *et al.* (2006) reported that water stress during the pre–anthesis period significantly reduced the number of grains per cob and 100-kernel weight, thus reducing grain yield. However, Mohr and Schopfer (1995) reported that maize plants have special adaptations to tolerate short-term stress periods. This would be very much related to the length of the water stress period, moisture retention ability of soils and cultivar used. Similar observations have also been reported by Bruce *et al.* (2002), Campos *et al.* (2004) and Chimenti *et al.* (2006).

Simulation of growth, yield components and yield of maize using the CERES-Maize model in DSSAT software showed minor deviation of simulated and observed values (Figure 6 to 13). The bias was narrow for time to silking and physiological maturity, grain yield and harvest index in the control and growth stage subjected to a dry period except for 21-40 DFS with 'Suwan 4452' and reduction of HI for 'Pacific 224' when the dry period occurred 30-49 DFS. Other variables had wider bias related to the timing of imposing the 20-day dry period. However, there are some modeling difficulties in soil moisture-based simulations in the CERES-Maize model (Piper and Weiss, 1990; Xevi *et al.,* 1996; Garrison *et al.,* 1999; Eitzinger *et al.,* 2004). The bias was also wide for LAI for all irrigation suspension treatments, and for grain number per cob, grain weight and grain yield for all growth stages (except for the 21-40 DFS and control treatment with 'Suwan 4452'), and for the 'Pacific 224' harvest index (except for the 30-49 DFS irrigation suspension and control treatments). Kiniry *et al.* (1997) also showed wider

deviation of simulations from observed values with CERES-Maize.

However, simulation of number of days to silking using version CERES-Maize 3.5 at a moderately high N rate (90 and 120 kg N ha-1) in Nigeria found close agreement between simulated and actual values (Gungula *et al.,* 2003). Asadi and Clemente (2003) reported over-prediction of grain yield of maize with N treatments.

Our present study revealed that modeling for prolonged water stress was somewhat unreliable for LAI and yield components, but that HI was well approximated. Therefore, further development of the model with respect to water stress should be given due attention.

Conclusions

This study showed that a 20-day dry period occurring during critical growth periods following irrigating or receiving water to field capacity of the Pak Chong Series soils did not adversely affect growth or yield of maize compared to a well-irrigated maize crop grown in the Nakhorn Ratchasima Province of Thailand. Results will help decision making in the cultivation of maize during rainless periods. When these periods do not exceed 20 days after receiving adequate rains to satisfy field capacity of the soil, satisfactory grain yields can be expected. This study also revealed that irrigation water could be saved by adjusting the irrigation interval to a period not exceeding 20 days. However, use of the current CERES-Maize model (DSSAT V 4.0.2.0) will require modifications in the model to accurately simulate maize yields under decreased soil moisture conditions as the model performance on soil moisture estimation has not been successful as per some of the studies, and current study supports the same view.

Acknowledgments

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Appendix

Appendix Table 1. Source of variation, degrees of freedom and mean squares from analysis of variance (AOV) for the time to tasseling and silking, tasseling-silking interval (TSI) and time to physiological maturity (PM).

Source of variation [1]	DF	Mean squares [2]			
		Time to tasseling	Time to silking	Tasseling-silking interval	Time to physiological maturity
W	5	2.28	0.78	0.68	6.18
Blocks	3	2.80**	1.02**	0.72	3.69
Error (a)	15	2.13	1.32	0.40	4.06
V	1	5.33**	0.08	6.75**	27.06*
V x W	5	0.13	0.08	0.20	3.10
Error (b)	18	0.44	0.25	0.56	3.58
CV%		0.93	0.67	31.22	1.13

[1] W – Time of water stress (days from seeding); V – Cultivar.
[2] *, ** and *** indicate the level of significance; $p=0.05$, 0.01 and 0.001, respectively.

Appendix Table 2. Source of variation, degrees of freedom and mean squares from analysis of variance (AOV) for leaf area index (LAI) and plant height of 'Suwan 4452' and 'Pacific 224' maize cultivars at 50% silking.

Source of variation [1]	DF	Mean squares [2]	
		Plant height cm	LAI at silking
W	5	569.57*	1.27**
Blocks	3	87.79	2.48***
Error (a)	15	194.10	0.21
V	1	8.33	2.14***
V x W	5	73.37	0.05
Error (b)	18	71.26	0.09
CV%		4.78	8.19

[1] W – Time of water stress (days from seeding); V – Cultivar.
[2] *, ** and *** indicate the level of significance; $p=0.05$, 0.01 and 0.001, respectively.

Appendix Table 3. Source of variation, degrees of freedom and mean squares from analysis of variance (AOV) for grains per cob, 100-grain weight, grain yield and harvest index (HI).

Source of variation [1]	DF	Mean squares [2]			
		Grains per cob (no.)	100-grain weight (g)	Grain yield (g)	HI
W	5	1.45	7.12	1.97	0.010**
Blocks	3	3.91*	1.90	2.16	0.008
Error (a)	15	2.12	2.93	0.80	0.002
V	1	10.01**	180.96***	0.56	0.014
V x W	5	0.56	1.45	1.66	0.007
Error (b)	18	0.90	4.05	1.38	0.004
CV%		6.29	5.94	13.66	12.3

[1] W – Time of water stress (days from seeding); V – Cultivar.
[2] *, ** and *** indicate the level of significance; $p=0.05$, 0.01 and 0.001, respectively.