Experiment 2 : Morphological and Physiological Responses of Maize Genotypes to Drought Stress under Different Soil Moisture Regimes

Objectives

The objective of this experiment was to study the growth dynamic of maize genotypes differing in drought tolerance levels when grown under different soil moisture regimes and identify morphological and physiological aspects of differing maize genotypes responses to drought stress.

Materials and Methods

The experiment was conducted on sandy loam soil at the farm of the Phitsanulok Field Crops Experiment Station, Phitsanulok, Thailand from December 1997 to April 1998 and repeated again during December 1998 to April 1999. Soil samples were collected and analyzed for soil physical and chemical properties at each plot differing in soil depth prior to sowing as showed in Appendix Table 1.

Three maize genotypes (NS 1, NSX 9210; SW 3601 represented as drought-susceptible, moderate drought tolerance and drought-tolerance genotypes) were subjected to variable level of drought by supplying a decreasing gradient of water through a line source sprinkler irrigation system. A strip plot in randomized complete block design with four replications was used. Each plot (15 x 12 m) of a maize genotype was subdivided into five subplots (12 x 3 m) representing five moisture regimes: one closest and five farthest from the line source. The cultural practices of this experiment was also undertaken the same as those in Experiment 1.

Plants from an area of 1.5 m^2 in all plots was sampled for growth analysis. Plant samples were collected at 7 day intervals from 14 DAE until physiological maturity. Both senescent leaves and dropped leaves were included in the total dry matter. Plant

samples of each plot was separated into stem, leaf blade , leaf sheath ,and ear in terms of kernel, shank; cob (when present), and dried at 60 °C for 48 h. Green leaf area was measured using an automatic leaf area meter (Model AM 100, Analytical Development Co. Ltd.). Leaf area index (LAI) was calculated as the ratio of total leaf area to total ground area. Specific leaf weight (SLW) was determined by dividing leaf dry weight by total leaf area. Leaf area duration (LAD) was computed as described by Hunt (1978). Crop growth rate (CGR) was calculated as the slope of the linear regression between total dry weight accumulation and the day duration which was the linear phase of crop growth (Senthong,1979). Stalk growth rate(SGR), leaf growth rate (LGR) ,and kernel growth rate (KGR) were also determined by linear regression method.

Root length density was determined by a soil core sampling technique (Bohm *et al.*,1977) at 5 growth stages : sixth fully developed leaves (V_6), twelveth fully developed leaves (V_{12}), silking (R_1), dough (R_4), and physiological maturity (R_6) as described by Ritchie and Hanway (1984). Soil core samples 7.62 cm in diameter was taken in three moisture regimes at three sample : in row (at the plant hill) , between row (at the middle or 0.38 m from plant hill) and a half of between row (0.19 m from plant hill) in 0.2 m increments to the 1.0 m depth. The root lengths were measured by a line intersection technique as described by Newmann (1966) as shown in the following equation.

$$R = \frac{\pi NA}{2H}$$

Where R is the total length of root , N , the number of intercepts between the root and the straight lines, A, the area of the square or rectangle , and H , the total length of the straight lines. Root length density was calculated as the ratio of total of root length to volume of soil where the roots have been collected.

Leaf death was recorded at R_1, R_2, R_3 , R_4 , R_5 and R_6. The visual score was calculated as a percentage of dead leaves out of in the total number of leaves. Canopy temperature was measured with an infrared thermometer (Telatemp Model AG-42) during 1300 to 1400 h at 71 to 81 DAE in both years. The instrument was pointed away from the sun at an angle of depression of 20° and at an angle of incidence to the row of 20° (Bolaños *et al.*, 1993). Leaf water status was measured with a pressure chamber (Soil Moisture Equipment) during 1300 to 1400 h. Second fully developed leaves from the top of the main stem was used to determine the water potential for each treatment on the same time and dates as indicated for canopy temperature. Stomatal resistance was determined simultaneously using an automatic porometer (Model MK 3, Delta-T devices) during 1300 to 1400 h at 71 to 75 DAE in 1998. All measurements of leaf water potential, canopy temperature and stomatal resistance were taken from the same row and on the plant close to where soil moisture measurements were taken.

Experimental areas was irrigated uniformly until 2 weeks after emergence and a line source sprinkler irrigation system was then installed in perpendicular to the rows until the crop reaches physiological maturity (Appendix Table 2). Catch cans for measuring the amount of water application was installed above the canopy at 3.50, 6.50, 9.50, 12.5 and 15.5 m from the line source. Weekly irrigation was scheduled. The amount of water applied for wet regime was also calculated the same as those in Experiment 1. Water applied by line source sprinkler system decreased with increasing distance from the line (Figure 4).

Yield data were collected from four, 4-m long rows from each subplot. Yield and yield components were also measured the same as in Experiment 1. Crop drought susceptibility index (DSI) was determined the same as in Experiment 1.

The change in soil moisture, soil water table and soil analysis were determined as described in Experiment 1. Field determination of hydraulic conductivity was obtained

by using the method of Bouwer (1962). Total water use was calculated from applied irrigation water, rainfall, and the change in stored-soil moisture with the assumption of negligible drainage (Turk *et al.*,1980). Water use efficiency (WUE) was obtained by dividing seed yield by total water use (WU).

The weather data recorded during the two growing seasons are presented in Figure 2. The growing conditions during the two years were substantially different. Weather was warmer throughout the growing stage of the crop in 1998 than in 1999. The evaporation demand and solar radiation were lower in 1999 than in 1998 as the result of a larger in the amount of rainfall. Due to more rainfall occurred during the crop growth period in 1999, the maize plants appeared less affected by drought stress in 1999 compared with 1998.

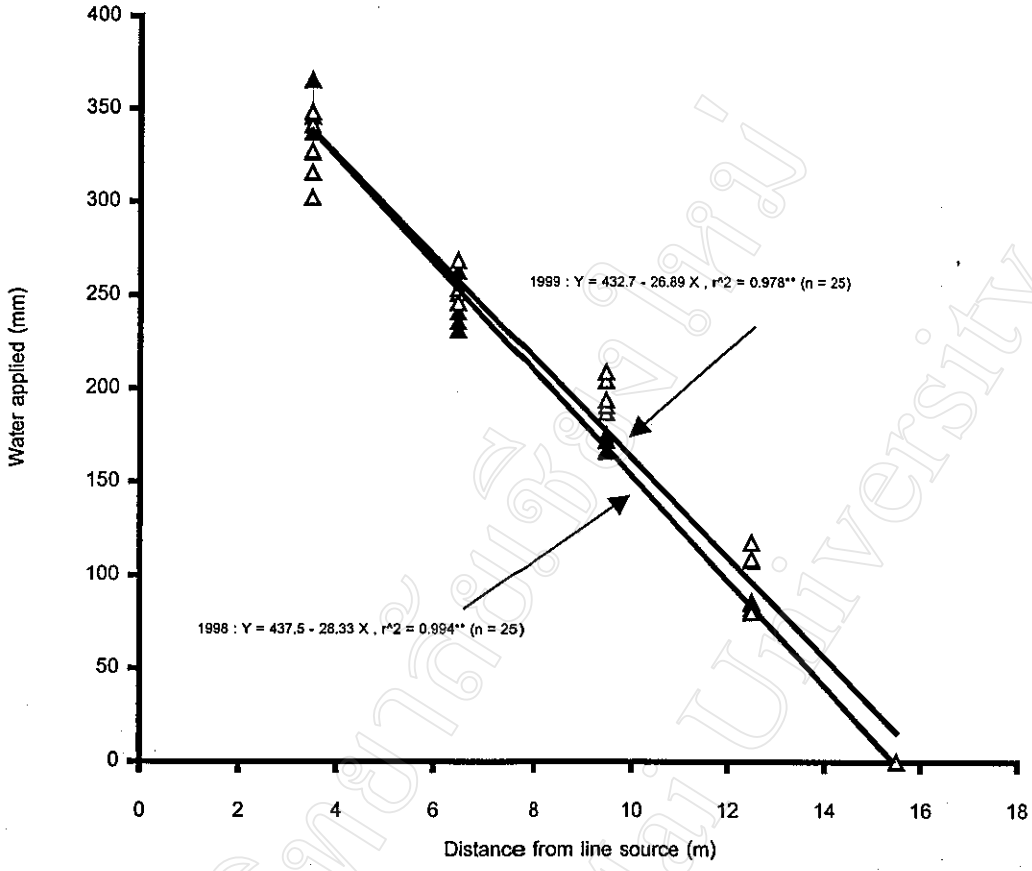


Figure 4 Relationship of water applied and distance from line source for maize experiment 2 in 1998 and 1999.

Results and Discussion

Growth and Development

The growth and development of maize genotypes under different moisture regimes during the two years were quite different. In 1998, maize seeds in all three genotypes emerged at 6 days after sowing while in 1999, they emerged within 5 days after sowing. FAO (1980) also reported that the time taken between planting and emergence depended mainly on the temperature. Maize emerged within 6 days at 21 °C, within 8 – 10 days at 16-18 °C and needed 18 – 20 days when temperature was about 10 to 13 °C (Blacklow, 1972 ; FAO, 1980).

Flowering in maize genotypes during the two years was substantially different. All the three genotypes in 1998 were quite faster silk emerged than in 1999. SW 3601 genotype was earlier silking and maturity than NS 1 and NSX 9210 genotypes, respectively in both years. It is therefore clear that all genotypes grown in 1999 were quite delayed in flowering and maturity than in 1998 due to cooler temperature throughout the growing period and more rainfall during the vegetative growth phase (Figure 2).

It is also confirmed that in the driest treatment showed a delay in flowering in terms of silking in both years as compared to the wettest plot. However, anthers emergence had a little affected by drought. Fischer and Turner (1978) also reported that earlier flowering in wheat were found under mild stress environment and delayed in flowering when faced severe stress condition. Delayed silk emergence was associated with a reduce rate of silk elongation which was strongly affected by plant water status (Edmeades *et al.*, 1993 ; Herrero and Johnson, 1981; Westgate and Boyer, 1986).

Total Dry matter

Total dry matter of all genotypes showed a positive linear relationship with irrigation application (Table 4). The total dry matter in 1998 was also more responsive to water applied plus rainfall than those in 1999 due to the weather differences between the two years (Figure 2). Senthong and Pandey (1989) also stated that total dry matter in food legume crops showed a linear relationship with water applied plus rainfall in both years. Drought adversely affected total dry weight, however, the relationship varied with genotypes. Among the three genotypes, SW 3601 responded least to water application followed by NSX 9210 and NS 1. Water stress reduced the total dry weight by 23% in SW 3601, 31% in NSX 9210 and 33 % in NS 1.

Table 4 Linear regression parameters for responses of total dry matter to mm of irrigation plus rainfall received by three maize genotypes in 1998 and 1999.

Genotypes	1998			1999		
	Intercept	Slope	r^2	Intercept	Slope	r^2
			Total dry weight (g/m^2)			
NS 1	1,192	1.71	0.801*	842	1.37	0.828*
NSX 9210	1,066	2.44	0.976**	941	1.00	0.991**
SW 3601	1,265	1.52	0.869*	952	0.70	0.867*

*, ** Significant at 0.05 and 0.01 probability levels, respectively

ns = not significant at P =0.05

Growth Rate

The growth of three maize genotypes are presented in Figures 5 and 6. The total dry weight of all genotypes in both years was quite different. In 1998, the final biomass of all genotypes in wet and dry regimes produced greater than those in 1999 due to variation in the amount of rainfall in 1999 (Figure 2). During the first five

weeks total dry weight of the three genotypes in both water regimes were exponential. The linear growth phase were started about 35 days after emergence (DAE) and reached the physiological maturity phase at 98 DAE. In 1998, total dry matter of all genotypes in the dry treatment (91 DAE) reached to the peak earlier than those in the wet regime (98 DAE). Plant had accelerated their metabolic processes by hastens flowering and grain filling allowing them to avoid soil moisture depletion before maturity when faced to drought stress (Turk and Hall, 1980). Whereas, vegetative parts, i.e., leaves, leaf sheath, stalk, produced a lot of biomass at the end of vegetative growth period (56 DAE) and declined after. Tollenaar (1977) stated that during the grain filling period, the corn plant will partition of it assimilate from vegetative plant parts (a source) to kernel as a strong sink.

The crop growth rate (CGR) from 35 to 91 DAE of all genotypes was greatly affected by water stress in both years (Table 5). All genotypes in both wet and dry plots in 1998 produced a high crop growth rate than those in 1999. The significant difference in crop growth rate of all genotypes between 1998 and 1999 was a result of heavy rains during the vegetative growth phase in 1999 which cause waterlogging problem (Figure 2). Peak of CGR in this experiment was approximately 30 g/m^2 per day compared with a peak of CGR of 49, 40, 32, and 28 g/m^2 per day for maize in the US (Stewart, 1970). The photosynthesis pathway of maize provides growth advantages in tropical environments due to higher optimum temperature for photosynthesis (Evan, 1975). The production of total biomass was also not a limiting factor to yield. A conversion of visible radiation into dry matter of 5.1-7.2 % in the tropical environments (Goldsworthy, 1974) compared with 4.6-6.4 % in the US (Stewart, 1970). However, the low yields in tropics cause poor partitioning of total dry matter to grain (Goldsworthy and Colegrove, 1974; Goldsworthy, 1974 ; Yamagushi, 1974). The wettest treatment of all genotypes exhibited greater crop growth rate than the driest treatment in both years. In the driest plot, a drought tolerance genotype (SW

3601) had the highest CGR of 21.69 and 18.10 g/m^2/day in 1998 and 1999, respectively, followed by NSX 9210 and NS 1. Senthong *et al.* (1986) stated that soybean cultivars which had a high CGR tended to produce a higher yield in the dry environment and had high partitioning efficiency of photosynthate into seed.

Stalk growth rate (SGR) and leaf growth rate (LGR) of all genotypes calculated as the slope of linear growth stage from 28 to 56 DAE in 1998 and those from 35 to 70 DAE in 1999(Table 5). They were greatly affected by water stress in both years. All genotypes in both wet and dry plot produced a higher value of SGR and LGR in 1998 than those in 1999 due to variation in rainfall.

All genotypes began the kernel filling period at 56 DAE in 1998 and 63 DAE in 1999 when kernel presented and continued to the highest kernel yield at 98 DAE in both years, except 91 DAE for dry regime in 1998 (Figure 5 and 6). Among the three genotypes, SW 3601 produced the greatest dry weight accumulation in kernel during kernel filling phase at both wet and dry regimes in both years as compared with NSX 9210 and NS 1(Figure 5 and 6). SW 3601 also gave the highest kernel yield in both wet and dry regimes in both years followed by NSX 9210 and NS 1. The linear kernel growth rate (KGR) of all genotypes was started from 56 to 91 DAE in 1998 and from 63 to 98 days in 1999 (Table 5). All genotypes in both wet and dry plots produced a higher KGR in 1998 more than those in 1999. In the driest treatment, SW 3601 gave the highest KGR (16.41 and 14.12 g/m^2/day) as compared to NSX 9210 (11.48 and 12.65 g/m^2/day) and NS 1(10.12 and 11.59 g/m^2/day), respectively, in both years. Senthong (1979) reported that the higher yielding peanut genotypes were partitioning more assimilate to the fruits than the low-yielding ones. He found that UF 77416 genotype had a high pod growth rate of 9.5 g/m^2/day compared to Dixie Runner cultivar which had only 3.6 g/m^2/day for the pod growth rate.

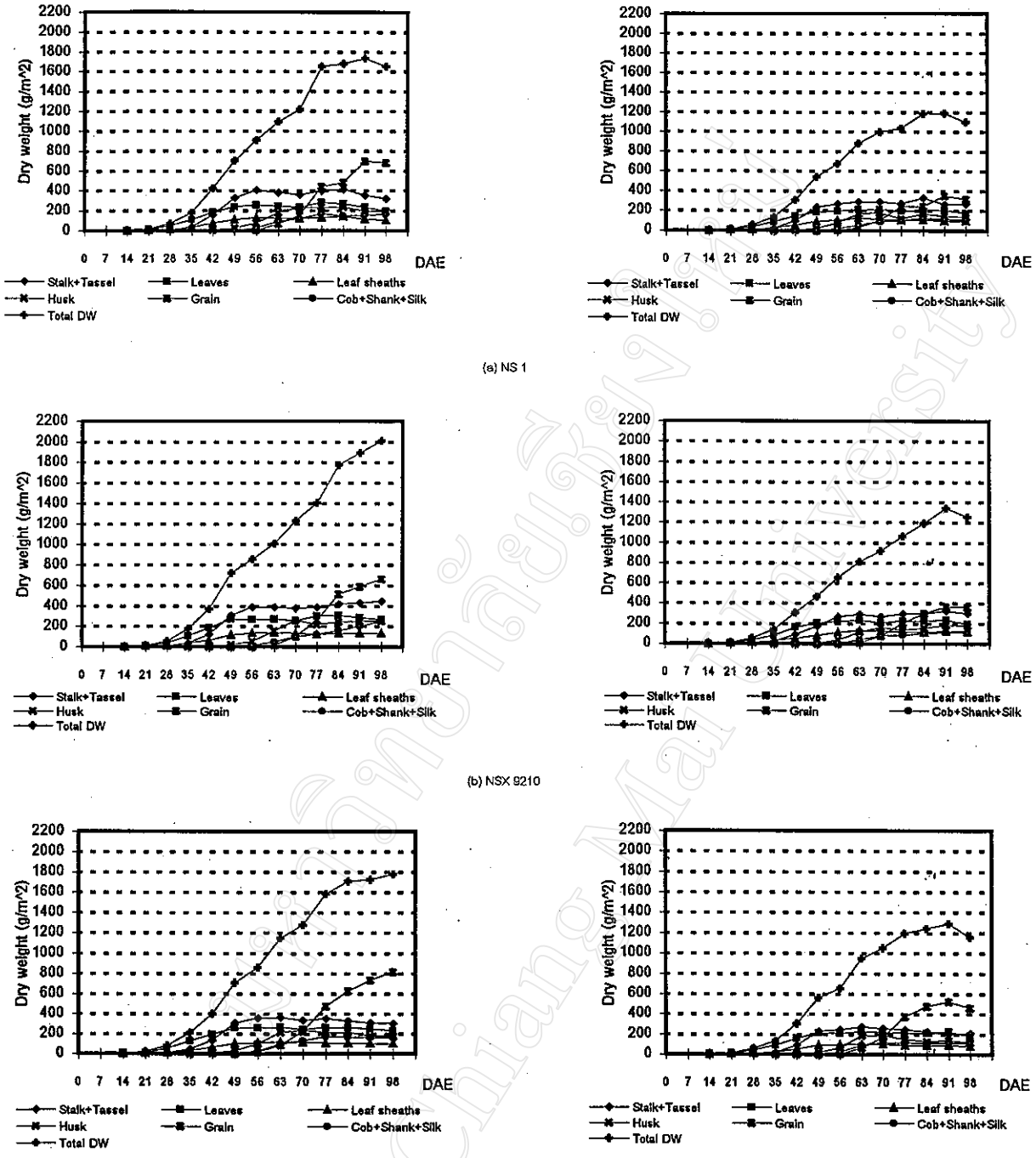


Figure 5 Dry matter accumulation in different plant parts of maize genotypes at wet and dry regimes in 1998.

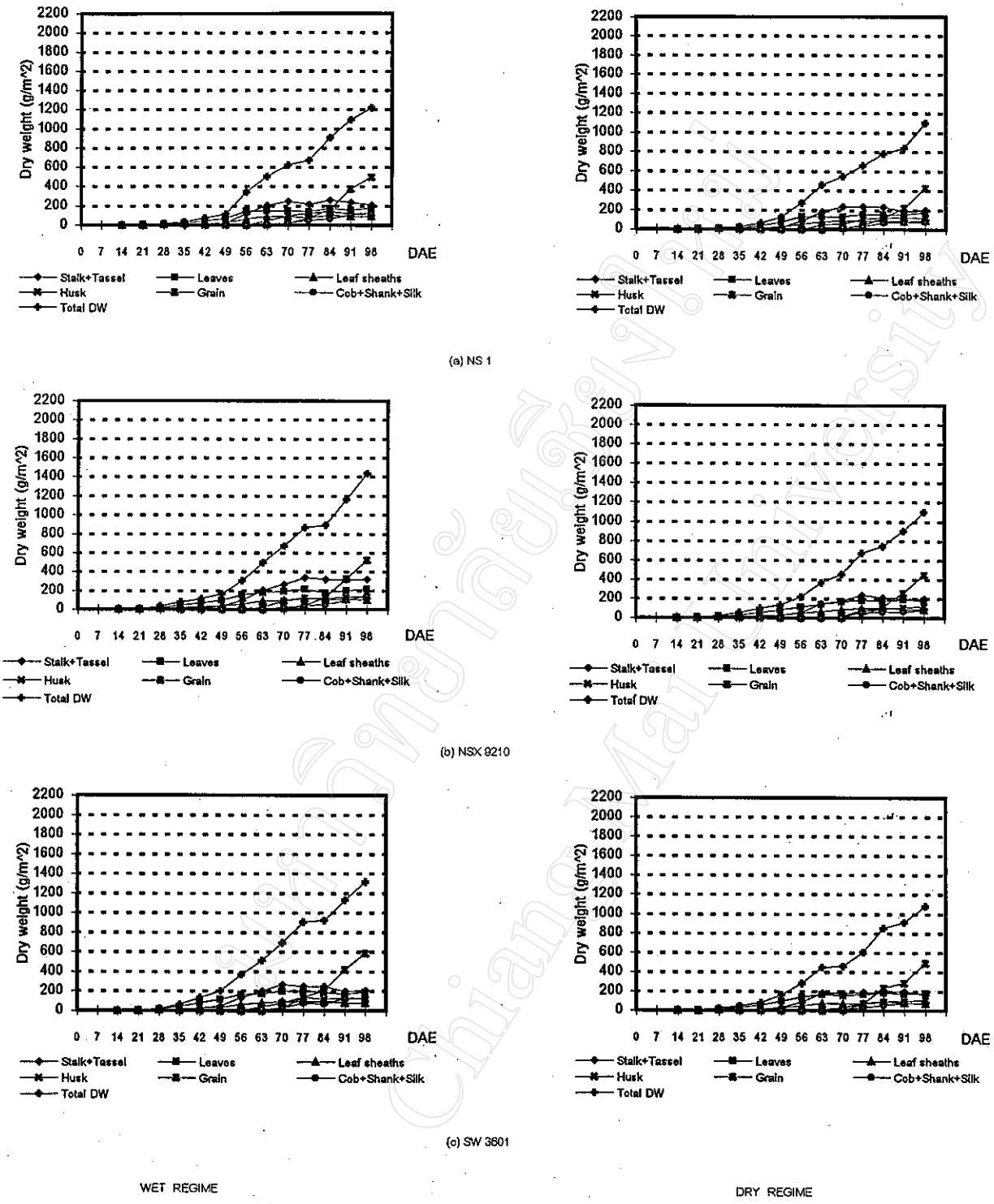


Figure 6 Dry matter accumulation in different plant parts of maize genotypes at wet and dry regimes in 1999.

Table 5 Crop growth rate(CGR), Stalk growth rate(SGR), Leaf growth rate(LGR) and Kernel growth rate (KGR) of three maize genotypes in wet and dry regimes in 1998 and 1999.

Genotypes	1998				1999			
	Wet	r^2	Dry	r^2	Wet	r^2	Dry	r^2
				CGR ($g/m^2/da$)				
NS 1	29.02	0.974**	19.38	0.956**	20.04	0.987**	17.80	0.985**
NSX 9210	30.53	0.990**	21.27	0.995**	23.39	0.978**	18.29	0.978**
SW 3601	29.01	0.979**	21.69	0.958**	20.75	0.989**	18.10	0.979**
				SGR ($g/m^2/da$)				
NS 1	15.53	0.960**	10.56	0.941**	7.73	0.914**	7.06	0.898**
NSX 9210	14.74	0.943**	9.66	0.956**	7.76	0.891**	5.16	0.871**
SW 3601	13.47	0.953**	9.92	0.918**	7.88	0.952**	5.88	0.895**
				LGR ($g/m^2/da$)				
NS 1	7.72	0.967**	5.96	0.942**	4.02	0.915**	3.55	0.907**
NSX 9210	8.81	0.931**	7.02	0.959**	4.48	0.975**	3.77	0.991**
SW 3601	7.66	0.935**	6.59	0.925**	4.61	0.981**	4.04	0.936**
				KGR ($g/m^2/da$)				
NS 1	20.23	0.952**	10.12	0.955**	13.97	0.892**	11.59	0.850**
NSX 9210	20.22	0.963**	11.48	0.956**	14.96	0.856**	12.65	0.849**
SW 3601	22.29	0.977**	16.41	0.968**	16.16	0.947**	14.12	0.919**

*, ** Significant at 0.05 and 0.01 probability levels, respectively

ns = not significant at P =0.05

Dry matter partitioning

The percentage of dry matter partitioning of three maize genotypes in wet and dry regimes are presented in Figures 7 and 8. Partitioning of dry matter in both wet and dry regimes between the two years were not significantly different. At the physiological maturity, the dry matter was partitioned to kernel by 37-45 % in 1998 compared to 35-46 % in 1999 under wet condition. While partitioned of dry matter to the kernel in the driest plot was 39-45 % in 1998 and 29-41 % in 1999. Among the three genotypes, SW 3601 had the highest partitioned of its dry matter to the kernel in both years followed by NS 1 and NSX 9210. Reduction in total dry matter imposed by drought was 38 % in 1998 and 17% in 1999. The dry matter was reduced by 33 % in the stalk+tassel, 24% in the leaf, 17% in the leaf sheath, 33% in the husk+silk, 45% in the ear in 1998, and was reduced by 21% in the stalk+tassel, 9% in the leaf, 11% in the leaf sheath, 9% in the husk+silk, 28% in the ear in 1999. Thus, dry matter partitioned to the ear was affected by drought more than the other plant parts. Fischer and Palmer (1983) also reported that ear dry matter yield in maize was more sensitive to stress conditions than the other plant parts.

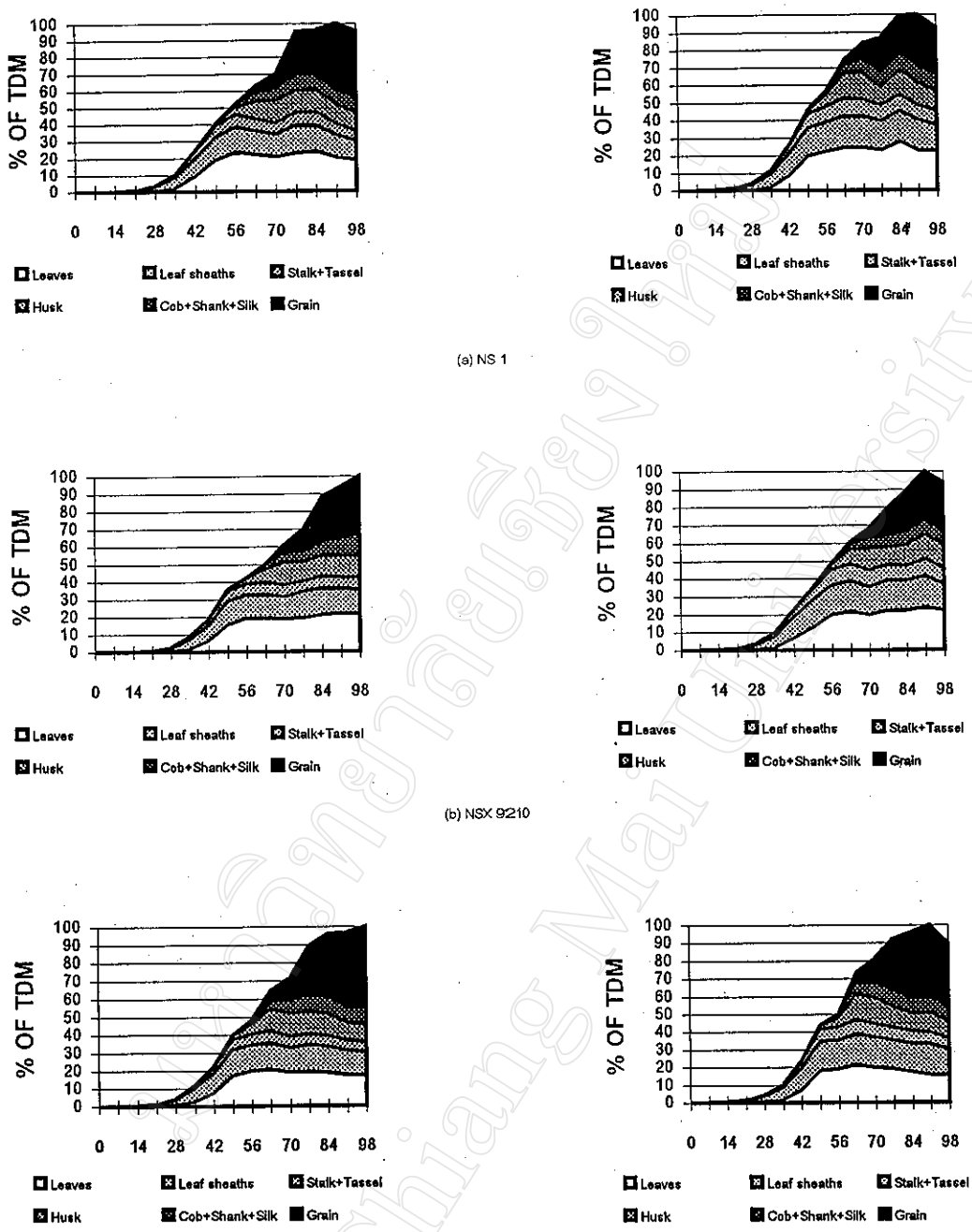


Figure 7 Percentage of total dry weight at various stages of growth and distribution of weight among plant parts of three maize genotypes at wet and dry regimes in 1998.

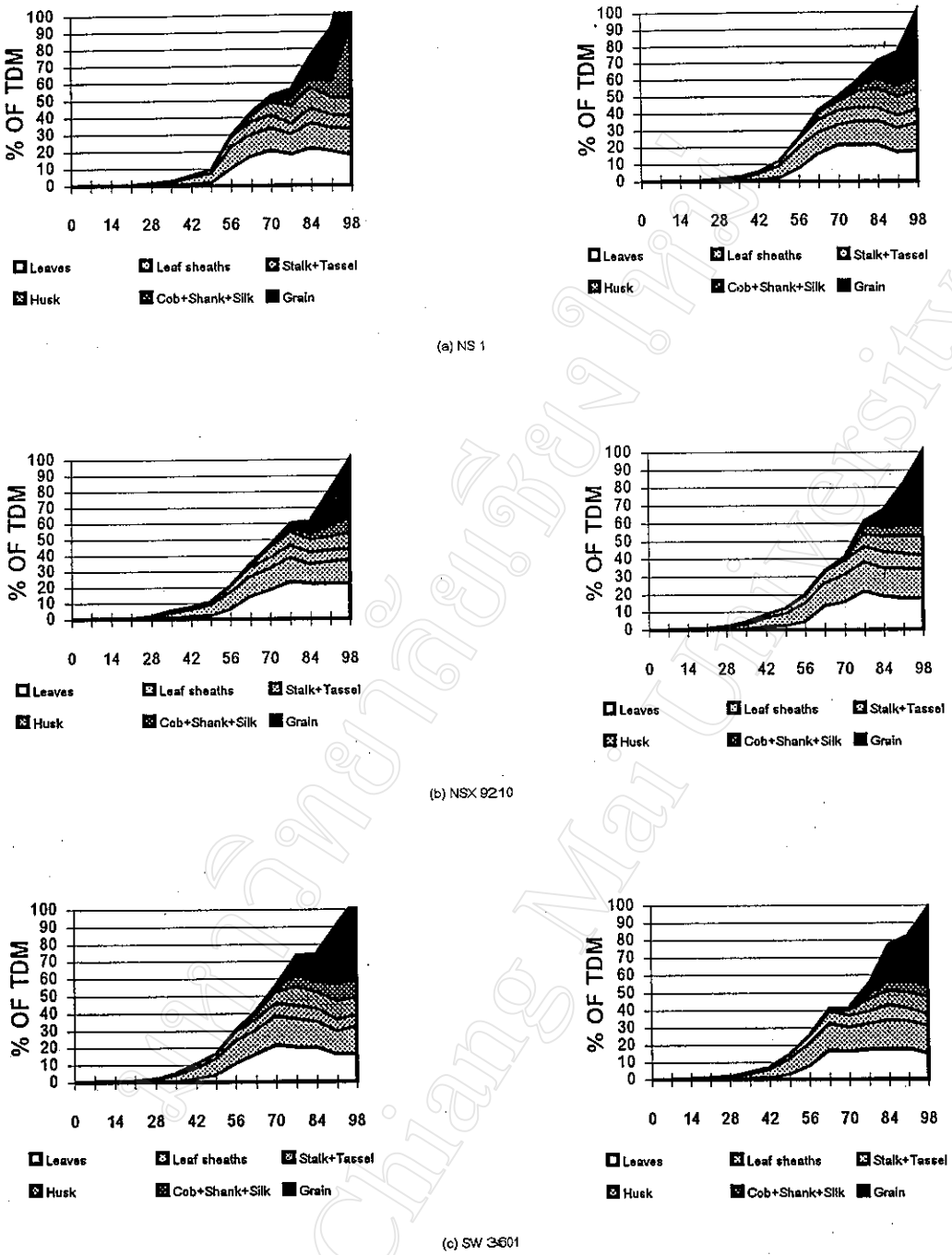


Figure 8 Percentage of total dry weight at various stages of growth and distribution of weight among plant parts of three maize genotypes at wet and dry regimes in 1999.

Partitioning coefficient

Partitioning coefficient of three maize genotypes in wet and dry regimes are presented in Table 6. Partitioning coefficient in the wet regime between the two years was not significantly different, but was significantly different in the dry plot. In the dry regime, SW 3601 had the highest partitioning coefficient of 75.7 and 78.0 % compared to NSX 9210 which gave 54.0 and 69.2 % and NS 1 which produced only 52.2 and 65.1 % of partitioning coefficients in 1998 and 1999, respectively. It is therefore confirmed that SW 3601 genotype produced a larger kernel yield than the other genotypes under drought stress due to a higher assimilate partitioning factor. Duncan *et al.* (1978) and Senthong (1979) also reported that the low-producing peanut cultivars were partitioning less assimilate to the fruit and more to continuing top growth than the high producing cultivars.

Table 6 Partitioning coefficient* (%) of three maize genotypes in wet and dry regimes in 1998 and 1999.

Genotypes	1998		1999	
	Wet regime	Dry regime	Wet regime	Dry regime
NS 1	69.7	52.2	69.7	65.1
NSX 9210	66.2	54.0	63.9	69.2
SW 3601	76.8	75.7	77.8	78.0

* Partitioning coefficient (%) = Kernel growth rate (KGR) / Crop growth rate (CGR) x 100

Relationship between Leaf Area Index(LAI), Leaf Area Duration(LAD), Specific Leaf Weight(SLW) and Yield

LAI and LAD are positively correlated with grain yield of all three maize genotypes under increasing drought stress in both years (Table 7). The adverse effects of water stress on these growth attributes led to low grain yield. Wolfe *et al.* (1988) working with maize and Pandey *et al.* (1984c) working with four grain legumes have shown the relation of LAI and LAD with grain yield. After flowering, reduction in leaf area due to drought was partially due to accelerated leaf senescence (Pandey *et al.*, 1984c) and senescence was accelerated by plant water status (Evan *et al.*,1975). Conversely, SLW in all genotypes increased with decreasing grain yield in both years (Table 7). Pandey *et al.* (1984c) also found that SLW exhibited a negative linear relation with grain yield in all grain legumes. However, the relationship between SLW and yield was not significantly different in this experiment due to a lesser degree of drought stress. This was probably due to a high water table in the paddy fields (Appendix Table 1).

Table 7 Regression equation showing the relationship between growth attributes (X) and kernel yield (Y) of three maize genotypes in 1998 and 1999.

Genotypes	Regression equation			
	1998		1999	
---------- Leaf area index ----------				
NS 1	Y = -11609+4687X	$r^2 = 0.934^{**}$	Y = -2091+2249X	$r^2 = 0.799^{*}$
NSX 9210	Y = -11048+4070X	$r^2 = 0.996^{**}$	Y = -1195+1939X	$r^2 = 0.841^{*}$
SW 3601	Y = -17072+6797X	$r^2 = 0.972^{**}$	Y = -7729+4626X	$r^2 = 0.864^{*}$
---------- Leaf area duration (weeks) ----------				
NS 1	Y = -8196+867X	$r^2 = 0.953^{**}$	Y = -1591+694X	$r^2 = 0.934^{**}$
NSX 9210	Y = -3363+518X	$r^2 = 0.894^{*}$	Y = -556+509X	$r^2 = 0.807^{*}$
SW 3601	Y = -7325+935X	$r^2 = 0.905^{*}$	Y = 848+461X	$r^2 = 0.810^{*}$
---------- Specific leaf weight (g/m^2) ----------				
NS 1	Y = 61365-932X	$r^2 = 0.723^{ns}$	Y = 8057-78X	$r^2 = 0.475^{ns}$
NSX 9210	Y = 30251-387X	$r^2 = 0.703^{ns}$	Y = 13308-190X	$r^2 = 0.780^{ns}$
SW 3601	Y = 39066-498X	$r^2 = 0.693^{ns}$	Y = 15449-196X	$r^2 = 0.699^{ns}$

*, ** Significant at 0.05 and 0.01 probability levels, respectively

ns = not significant at P =0.05

Relationship between LAI, LAD, SLW and Irrigation Water Application

The relationship between LAI, LAD and SLW, in all genotypes and irrigation water application are presented in Table 8. LAI and LAD exhibited similar a positive linear relation with irrigation water application in all genotypes in both years, whereas SLW showed a negative linear relation.

LAI in all genotypes exhibited a positive linear relationship with the amount of water applied plus rainfall in both years (Table 8). Among the three genotypes, SW 3601 showed the least response to drought as compared to NSX 9210 and NS 1 genotypes due to less reduction in leaf area. Pandey *et al.* (1984c) found that reduction in leaf area in grain legumes appeared to be an adaptive mechanism to drought.

LAD in all three genotypes also showed a positive increase with the amount of water applied plus rainfall in both years (Table 8). A similar observation was done by Wolfe *et al.*(1988) which reported that LAD from anthesis to harvest was linearly related to final grain dry weight under water deficit. In 1998, LAD in NSX 9210 genotype respond most to irrigation water application while in 1999, those in SW 3601 genotype was the most responsive. Pandey *et al.* (1984c) also reported that the difference in LAD in grain legumes were primarily due to leaf senescence, leaf area and crop duration.

Drought stress in increased in SLW in all genotypes in both years (Table 8). In 1998, NS 1 genotype showed the least change in SLW whereas in 1999, SW 3601 was the most responsive. Changes in SLW due to drought has previously reported in cowpea (Turk and Hall, 1980), grain legumes (Pandey *et al.*, 1984c). and in desert shrubs (Fisher and Turner, 1978). Increases in leaf thickness of grain legumes appeared to be an adaptive mechanism for their drought resistance (Pandey *et al.*, 1984c).

Table 8 Linear regression parameters for responses of growth attributes to mm of irrigation plus rainfall received by three maize genotypes in 1998 and 1999.

Genotypes	1998			1999		
	Intercept	Slope	r^2	Intercept	Slope	r^2
---------- Leaf area index ----------						
NS 1	3.17	0.0017	0.799*	2.31	0.0027	0.917**
NSX 9210	3.45	0.0018	0.868*	2.24	0.0032	0.989**
SW 3601	3.22	0.0012	0.831*	2.59	0.0012	0.938**
---------- Leaf area duration (weeks) ----------						
NS 1	12.87	0.0106	0.812*	6.68	0.0093	0.847*
NSX 9210	12.29	0.0146	0.957**	7.36	0.0119	0.980**
SW 3601	13.15	0.0078	0.792*	7.463	0.0126	0.965**
---------- Specific leaf weight (g/m^2) ----------						
NS 1	62.4	-0.009	0.919**	59.4	-0.062	0.939**
NSX 9210	69.5	-0.017	0.902*	52.9	-0.031	0.946**
SW 3601	68.1	-0.014	0.825*	56.4	-0.027	0.966**

*, ** Significant at 0.05 and 0.01 probability levels, respectively

ns = not significant at P =0.05

Root Growth

Root growth pattern at different growth stages of maize genotypes grown under three moisture regimes: wet, moderate and dry, are presented in Figure 9. Root density at various moisture regimes decreased with increasing the depth of soil profile. The result may be related to the increased in bulk density at the lower depths of soil profile (Appendix Table 1). Klodpeng *et al.* (1985) also found that most of the roots of upland crops including maize were observed on the top soil and decreased rapidly as increased in soil bulk density at the lower depths.

Root density at various moisture regimes and at each depth, particularly at soil surface (0-0.2 m), increased rapidly from V_6 to R_1 and increased gradually until the peak at R_4 and decreased sharply at R_6 (Figure 9). Klodpeng *et al.* (1985) reported that maximum root densities of maize were observed near the soil surface and occurred about 60 DAE. Maize grown under wet regime produced the highest root densities at 0 to 0.2 m soil depths followed by moderate and dry regimes. While root densities at the deeper soil (0.4-0.8 m) profile increased with decreasing in irrigation water application was probably due to the ability of the root to extract of more water from deeper soil profile (Pandey *et al.*,1984b). Michell and Russell (1971) found that the root penetrated rapidly was stimulated by lower moisture content and higher temperature at the soil surface zone.

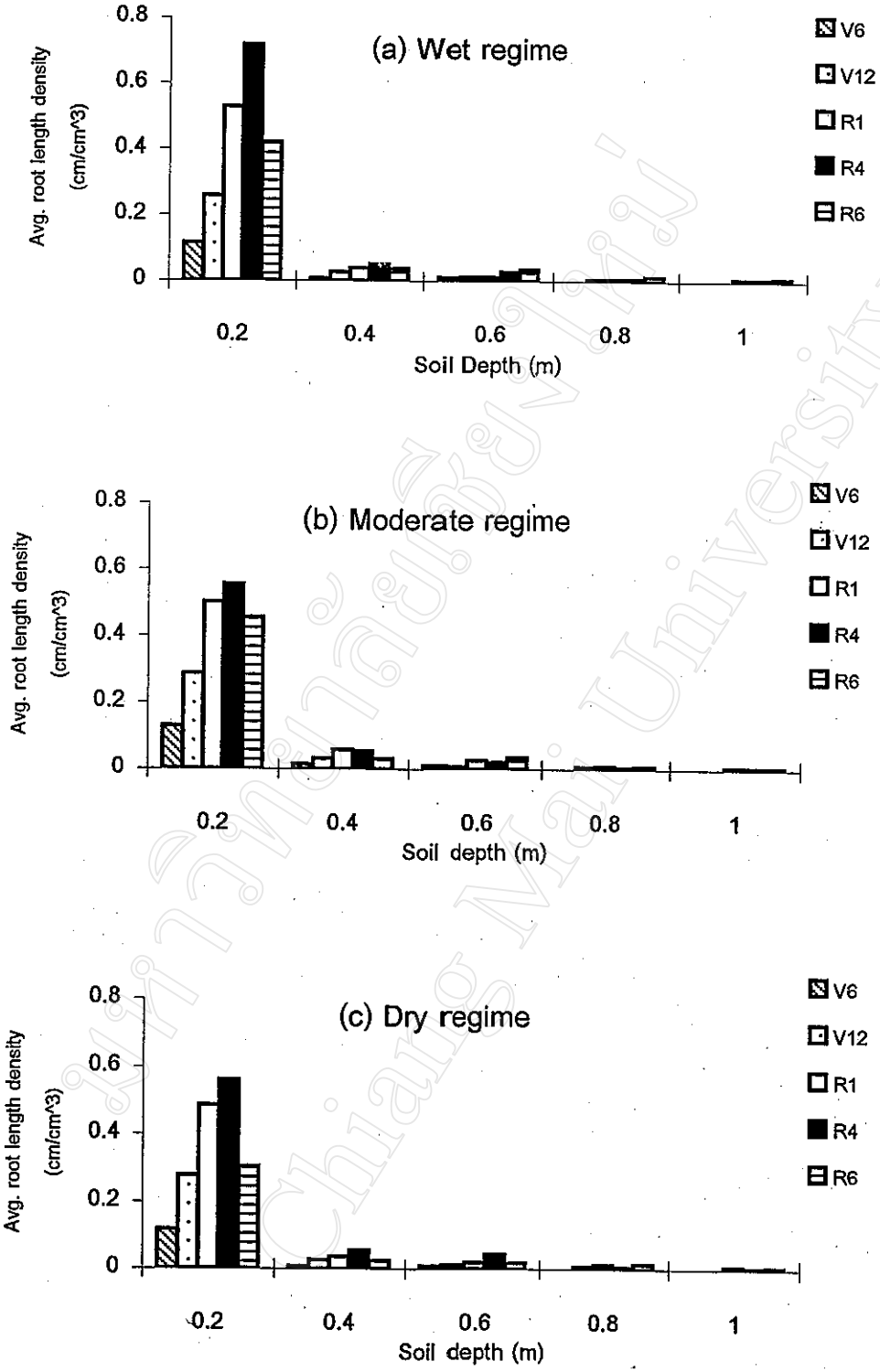
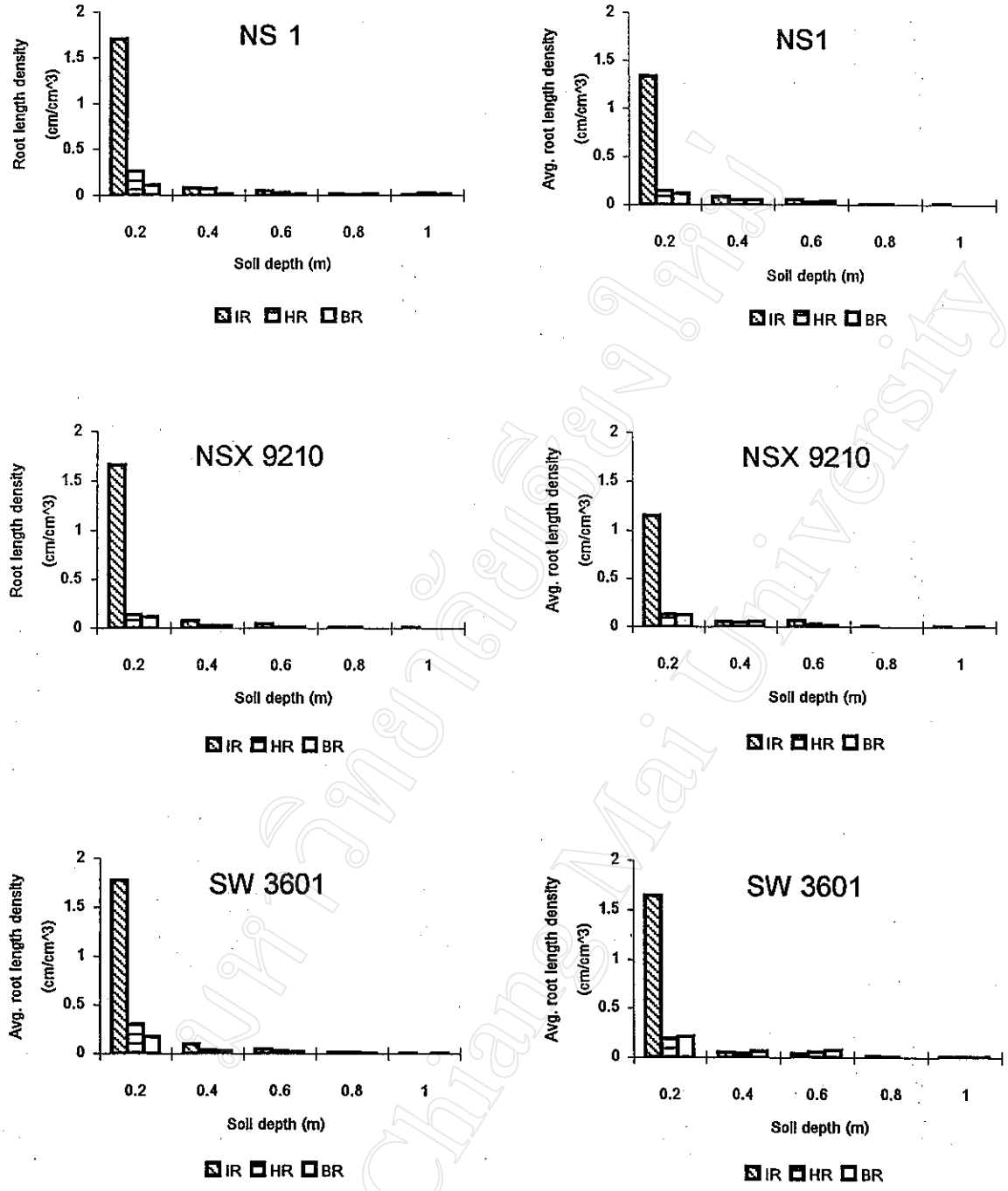


Figure 9 Average root length density at different growth stages of maize genotypes grown under wet (a), moderate (b) and dry (c) regimes in 1998.

Root Distribution

Root distribution at the R_4 (dough stage) of the three maize genotypes was determined at various positions and different water regimes under field situation (Figure 10). There was a significant difference in root length density at various positions and at different depth of soil profile. The highest root density were found at the soil surface (0-0.2 m) and decreased rapidly with increasing depth of soil profile. Sanchez (1976) reported that for the rice crop, the soil needs to be above saturation as the results of puddling which breaks down soil aggregates into particles, increases soil bulk density upon settling which then becomes compact and hard upon drying. Both physical and chemical of soil in this experiment are suitable for root growth especially at the soil surface. It is also found that soil moisture and soil aeration were suitable for root growth in the top layer (whole plow layer) throughout the growth period. Zanstra (1980) reported that oxygen contents decreased with increasing soil depths and also limited root growth of upland crop to penetrate the deeper soil when grown after puddled-rice due to high water table. Syarifuddin (1979) found that corn planted on a recently drained previously puddled clay loam with a water table at 0.65 m still had an active roots down to 0.50 m depth. The soil fertility was also high at the 0 to 0.2 m soil depth but much lower in subsurface layer (Appendix Table 1). Syarifuddin and Zandstra (1978) found that the low fertility of many paddy subsoil was associated with the reduction in root growth of corn and soybean. Among the three genotypes, SW 3601 had the highest root densities in all soil depths under dry condition. It is therefore clear that the most drought resistant maize genotypes had more root distribution and more root densities in all deeper soil profiles than the susceptible genotypes.



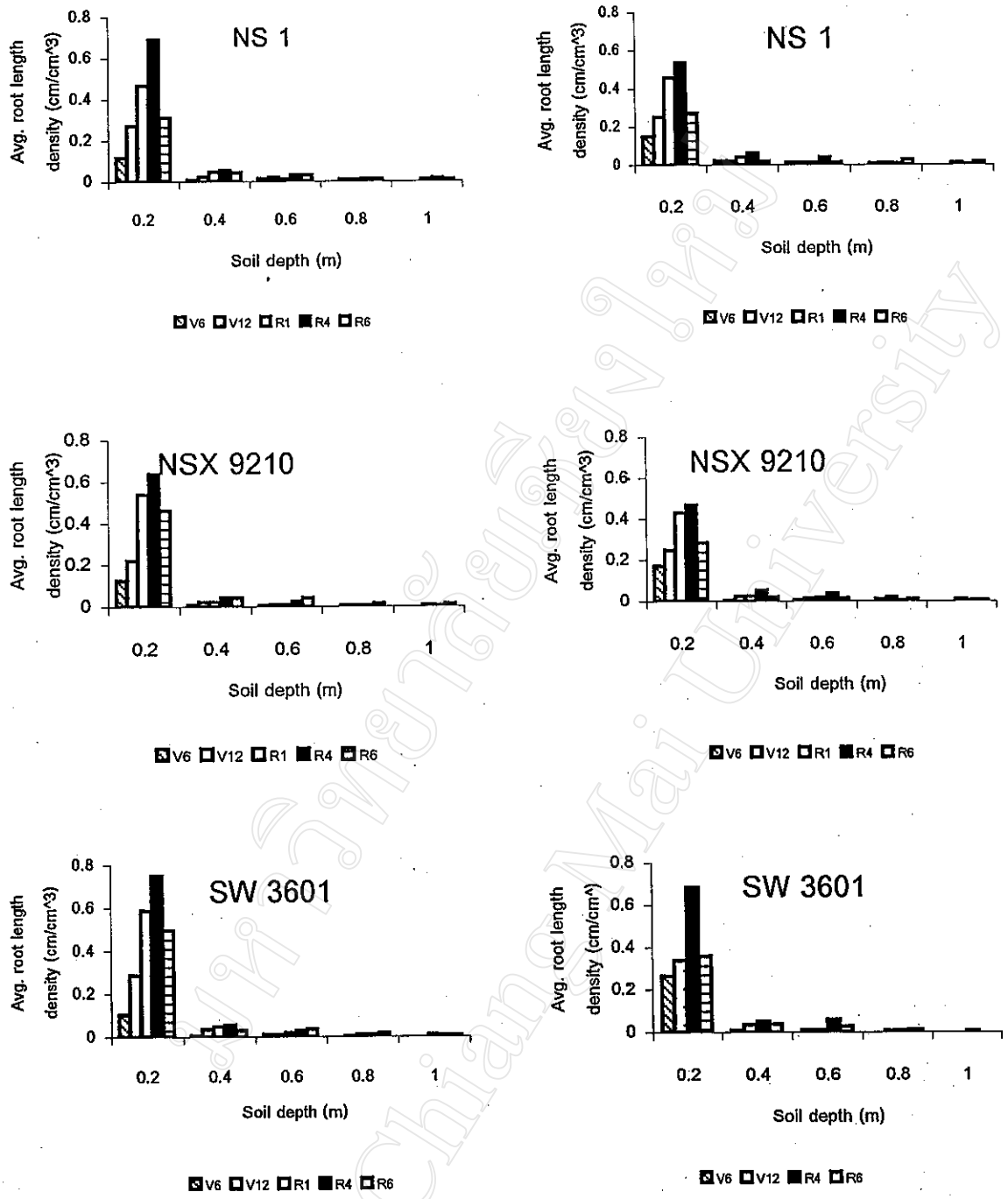
(a) Wet regime (b) Dry regime

IR = in row HR = half of between row BR = between row

Figure 10 Average root length density at R4, various positions and different soil depths of 3 maize genotypes under wet (a) and dry (b) regimes in 1998.

Root Length Density and Irrigation Water Application

Irrigation water application affected maize root as presented in Figure 11. Root length density in all three genotypes was greater in the 0-0.2 m depth for the wet regime during the reproductive phase. Whereas during late vegetative growth stage it was greater for the dry regime. This difference in pattern could have been caused by the fact that new roots was developed rapidly under dry conditions at early stage was probably due to the more extract of soil water from deeper soil profile. Mengel and Barber (1974) reported that during vegetative growth of plants, roots grew rapidly in few if any roots died; thus the amount of root present increased exponentially. Resulted also showed that the root density in all genotypes was rapidly decreased at the final of reproductive growth phase. There was probably due to the production of new root was lower than senescence of old roots so that the new root present decreased rapidly during the late reproductive growth (Mengel and Barber, 1974). No variation in root density in all three genotypes at the deeper of soil profile was probably due to increasing in bulk density at various soil depths.



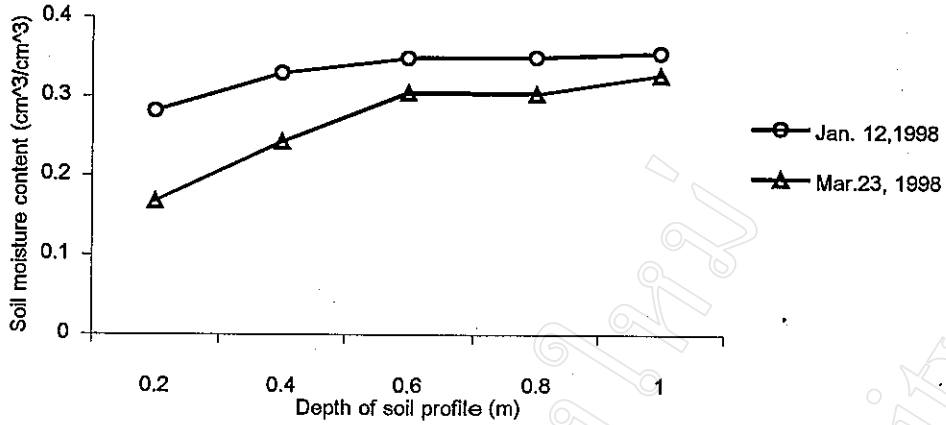
(a) Wet regime

(b) Dry regime

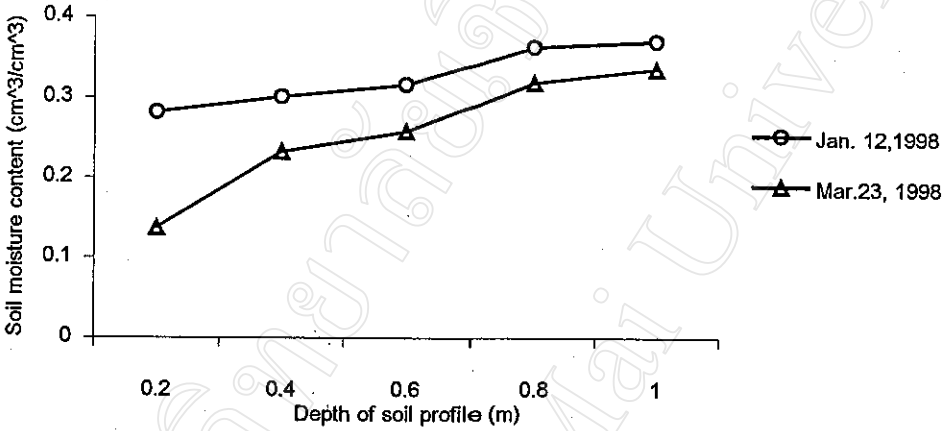
Figure 11 Average root length density at various growth stages and different soil depths of 3 maize genotypes under wet (a) and dry (b) regimes in 1998.

Relationship between Root length Density and Soil Water Extraction

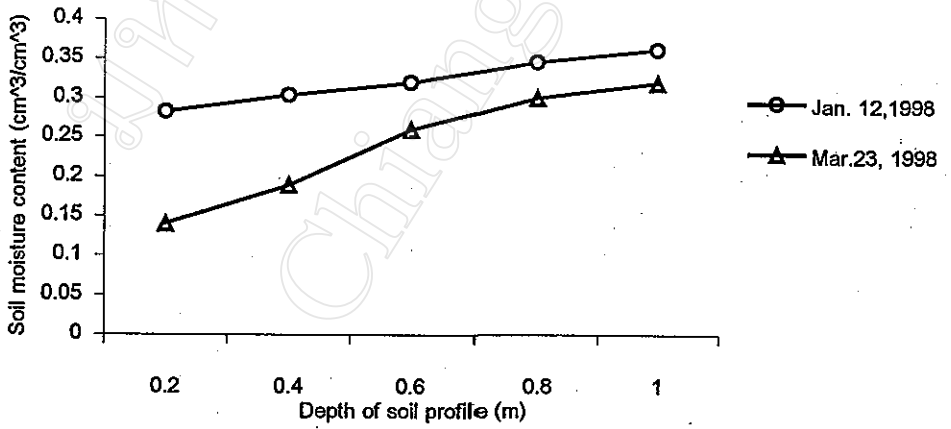
The water extraction pattern of three maize genotypes in the dry regime at different depth of soil profile are presented in Figure 12. Among the three genotypes, SW 3601 extracted greater water at the lower depths (0.4-0.6 m) as compared to NSX 9210 and NS 1. The ability to extract more water by SW 3601 was probably due to higher density of roots in the deeper layer of soil profile (Figure 11). Pandey *et al.* (1984c) reported that cowpea had higher root densities at 0.4-0.8 m soil depths than soybean or mungbean and this appeared to be a major adaptive mechanism for their drought resistance (Cox and Joliff, 1986). Senthong *et al.*(1986) also found that drought resistance in soybean genotypes was associated with larger root density and greater extraction of water from a deeper soil profile. However, differences in water extraction pattern at the lower depths of 0.6-1.0 m among three genotypes were smaller due to higher water table in the paddy fields (Appendix Table 1).



(a) NS 1



(b) NSX 9210



(c) SW 3601

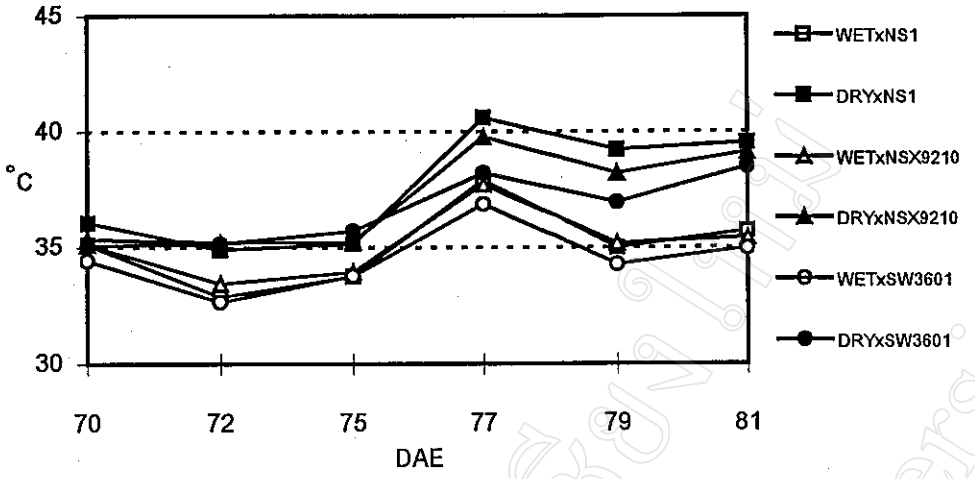
Figure 12 The water extraction pattern of NS 1(a), NSX 9210(b) and SW 3601(c) in dry regime at different depth of soil profile in 1998.

Canopy Temperature

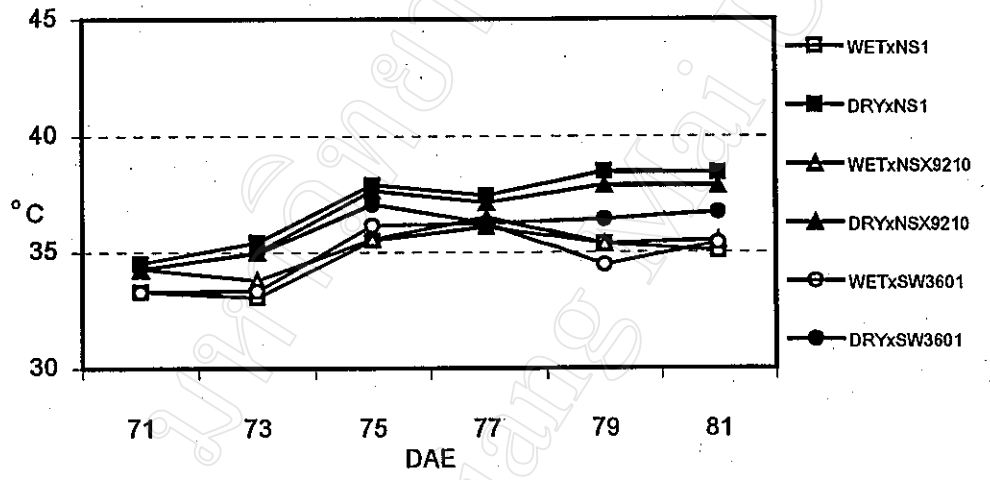
Changes in canopy temperature in three maize genotypes in the wet and dry regimes are presented in Figure 13. Canopy temperature was always lower in the wet regime than in the dry regime. SW 3601 genotype maintained their lower canopy temperature during the kernel-filling period (R_4 to R_6) than NSX 9210 and NS 1 at the given date. Genotypes, which maintained a cooler canopy temperature in the dry regime, had the highest yield under drought stress condition (Senthong *et al.*, 1986). Canopy temperature was associated with the productivity under drought stress in maize (Fisher *et al.*, 1983), wheat (Blum, 1988) and soybean (Senthong *et al.*, 1986).

Leaf Senescence

Leaf senescence in all genotypes in wet and dry regimes are presented in Figure 14. Among the three genotypes, SW 3601 gave lower leaf senescence during R_4 to R_6 in dry regimes than NSX 9210 and NS 1 in both years. It is therefore clear that SW 3601 produced higher grain yield due to be able to maintain green leaves under drought stress condition. The reduction in yield induced by drought due to decrease leaf area have been reported (Boyer and McPherson, 1976; Grant *et al*., 1989; Rhoads and Bennett, 1990). Turk and Hall (1980) also reported that reduction in leaf area represents a possible drought avoidance mechanism since increased leaf senescence results in less water use. Jordan (1983) suggested that accelerated post-anthesis senescence under water stress conditions is the result of a insufficient supply of current photosynthate and reduced N in the presence of a strong reproductive sink. Senthong *et al.* (1986) also found that soybean genotypes which had high leaf senescence during pod filling (R_5 to R_7) had lower total dry matter and seed yield

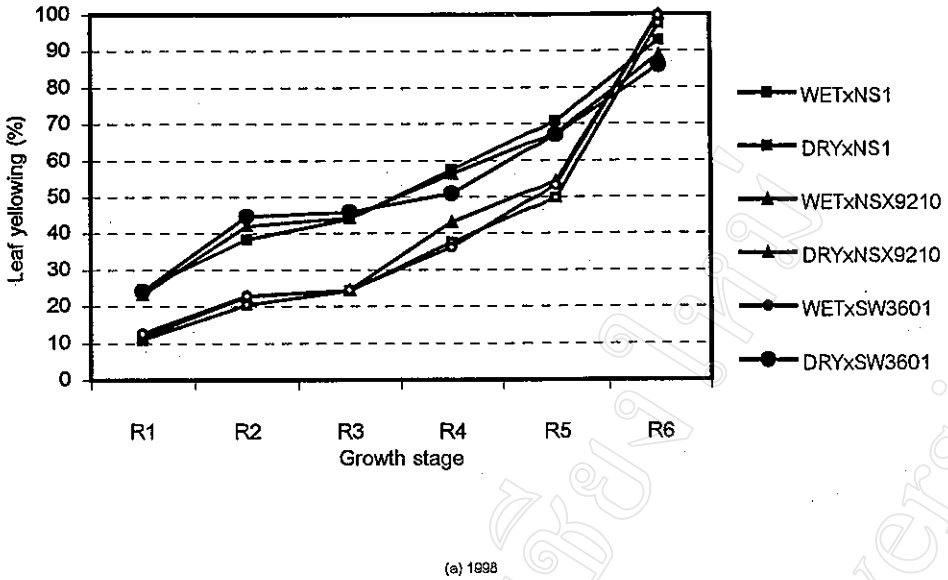


(a) 1998

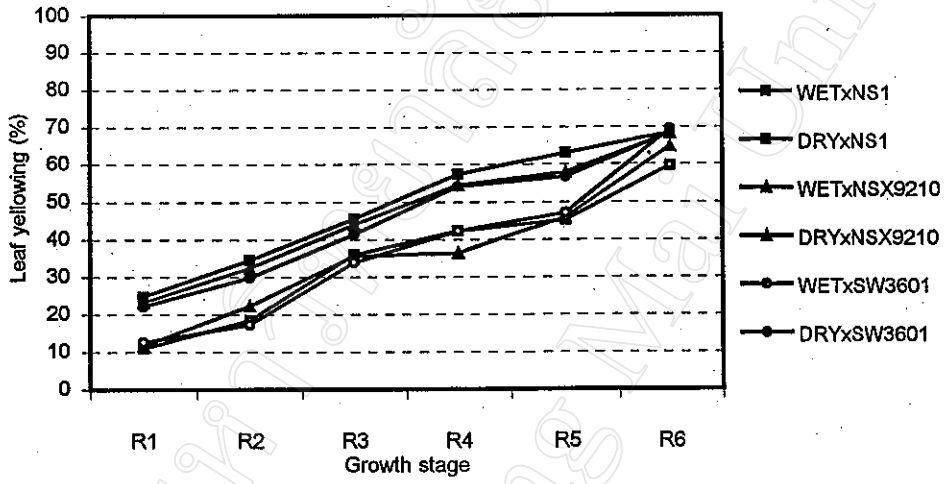


(b) 1999

Figure 13 Changes in canopy temperature of three maize genotypes in wet and dry regimes in 1998 and 1999.



(a) 1998



(b) 1999

Figure 14 Percentage of leaf yellowing in three maize genotypes during six growth stages in 1998 and 1999.

Relationship between Canopy Temperature and Leaf Senescence

SW 3601 genotype which had the lowest canopy temperature during the kernel-filling phase, had low leaf senescence followed by NSX 9210 and NS 1. Pandey *et al.* (1984b) suggested that genotypes, which maintain a cooler canopy temperature and have less leaf senescence in the dry treatment, will be able to maintain their physiological function to thereby produce higher seed and dry matter yields.

Leaf Water Potential

Changes in leaf water potential in three maize genotypes in the wet and dry regimes are presented in Figure 15. Leaf water potential was always lower in the wet regime than in the dry regime. The minimum value of leaf water potential in dry regime on day 77, -1.14 and –0.87 in NSX 9210, and –1.45 and –0.96 MPa in NS 1 which were significantly lower than the value -0.86 and –0.82 MPa for SW 3601. Higher leaf water potential in SW 3601 genotype was probably due to extract more water from the deeper soil profile (Pandey *et al.*, 1984b) or due to stomatal and osmotic adjustment (Sharp and Davies, 1979).

Relationship between Canopy Temperature and Leaf Water Potential

The relationships between canopy temperature and leaf water potential of three maize genotypes are presented in Figure 16. There was a negative linear relationship between canopy temperature and leaf water potential. The increase in canopy temperature tended to decrease leaf water potential in all genotypes. Pandey *et al.* (1984b) also mentioned that a crop is subjected to high atmospheric demand between 1300-1400 h, partial stomata closure occurs and transpiration decreases when water extraction by roots is not adequate. The decrease in transpiration tends to increase canopy temperature. The variation among genotypes in the relationship between

canopy temperature and leaf water potential due to differing in behavior and number of stomata and water extraction from the soil are presented in Table 9 and Figure 12. The canopy temperature in 1998 was also more responsive to leaf water potential than those in 1999 due to the weather differences between the two years (Figure 1). SW 3601 genotype generally exhibited the most drought tolerance as compared to NSX 9210 and NS 1. This was primarily due to maintain of higher leaf water potentials and cooler canopy temperature which maintained physiological functions favorable to higher grain yield and dry matter production (Pandey *et al.*, 1984b).

Table 9 Stomata number at lower and upper leaf surface of three maize genotypes under different moisture regimes in 1998.

Genotype	Stomata number / mm^2		Mean
	Upper leaf blade	Lower leaf blade	
NS 1	185±14	190±19	188±17
NSX 9210	159±13	197±18	178±16
SW 3601	173±15	237±23	205±19

± standard deviation

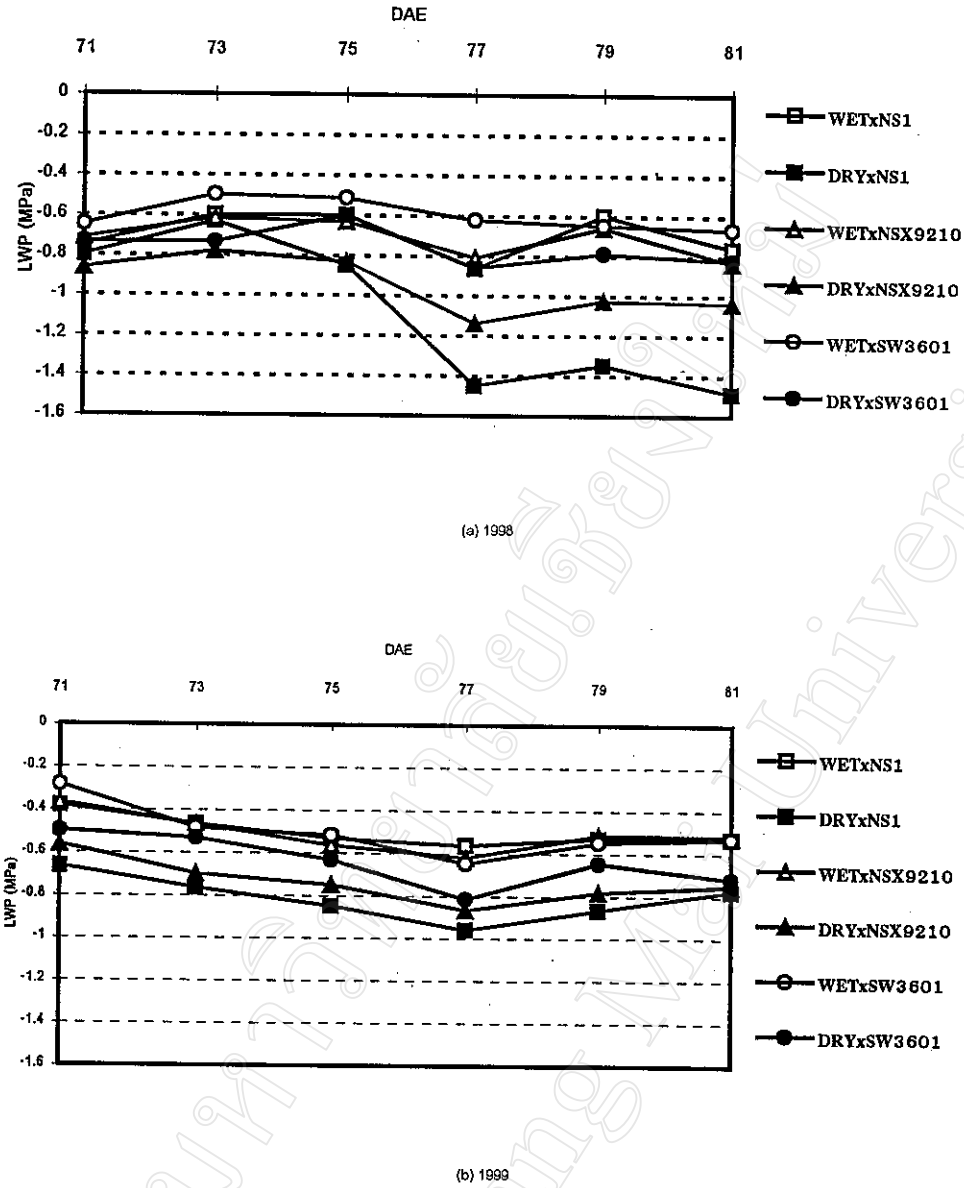


Figure 15 Changes in leaf water potential of three maize genotypes in wet and dry regimes in 1998 and 1999.

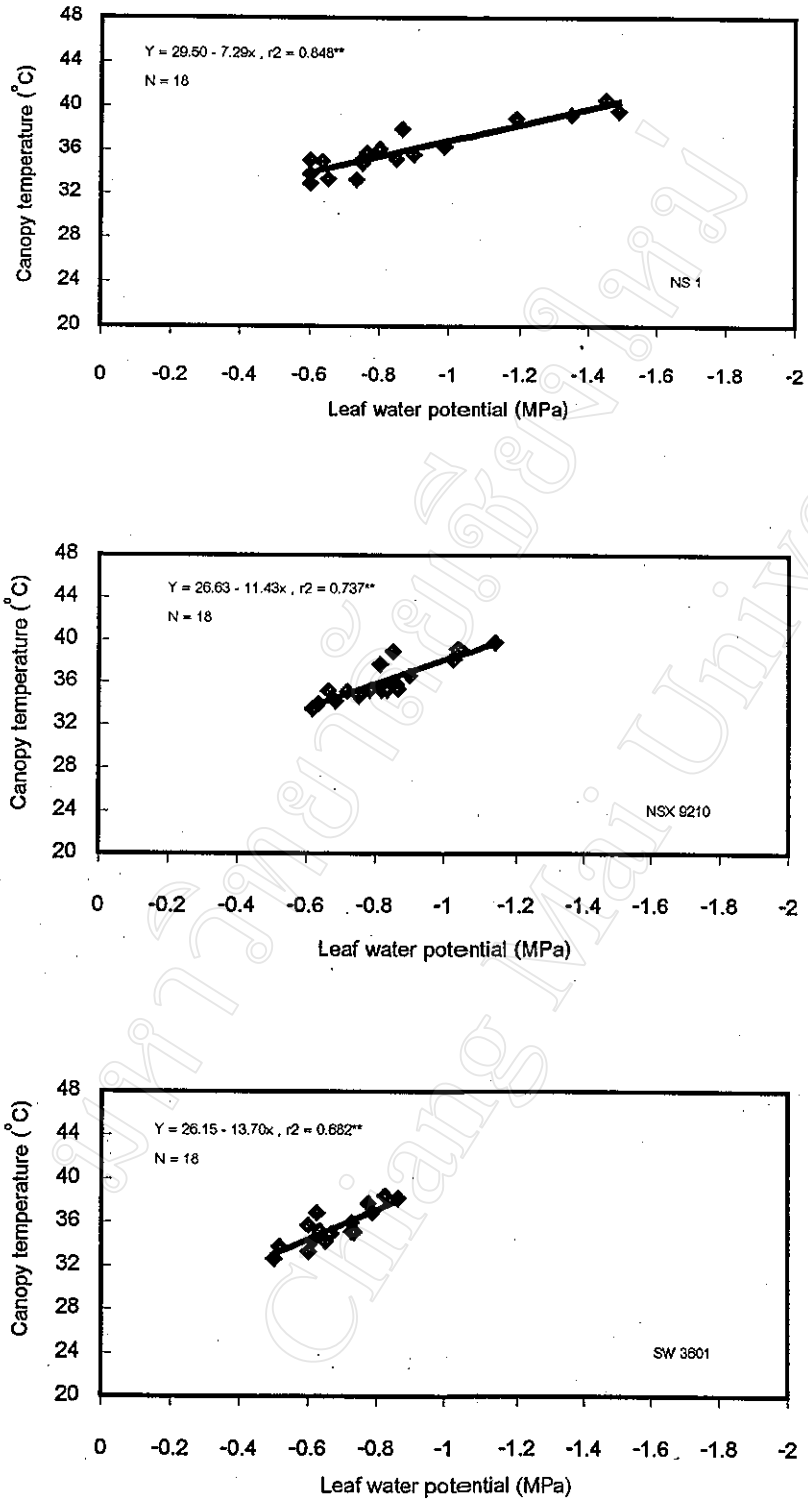


Figure 16 Relationship between leaf water potential and canopy temperature of three maize genotypes at five moisture regimes during the six periods (71-81 DAE) in 1998.

Stomatal Resistance

Stomatal resistance increased indicating stomatal closure when maize was subjected to reduced soil moisture content (Figure 17). Partial closure of stomates resulted in reduced leaf water potential and increased canopy temperature (Figure 13 and 15). Numerous studies have been reported on the relationship between stomatal resistance, leaf water potential and canopy temperature in rice (O'Toole and Cruz, 1980), grain legumes (Pandey *et al.*, 1984c), sunflower (Sionit and Kramer, 1976); and maize (Turner, 1974). The three maize genotypes were exposed to the same soil moisture gradients, however, they differed markedly in their ability to maintain relatively stomatal resistance of leaf surface and leaf water potential. Similar results have been reported in rice (O'Toole and Cruz, 1980) and sorghum (Blum, 1974). Among three genotypes, SW 3601 maintained lower stomatal resistance than NSX 9210 and NS 1. O'Toole and Cruz (1980) also illustrated that an upland rice adapted cultivar maintained greater leaf water potential and lower stomatal resistance of leaf surface than a hybrid rice selected in irrigated condition.

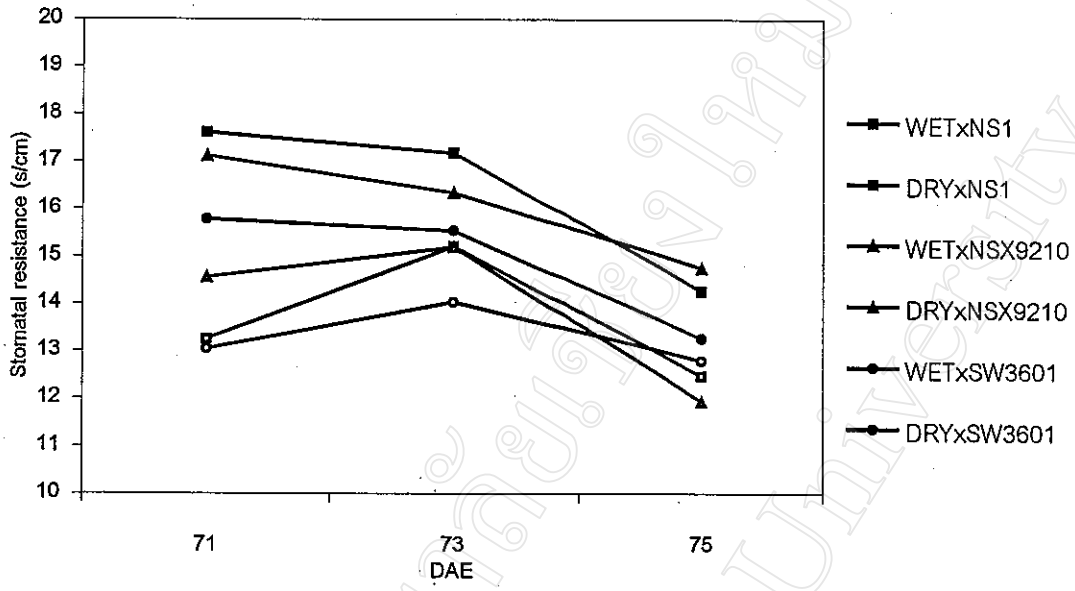


Figure 17 Stomatal resistance in three maize genotypes in wet and dry regimes in 1998.

Water Use and Water Use Efficiency

The total water use and water use efficiency of three maize genotypes in the wet and dry regimes are presented in Table 10. All maize genotypes in 1999 had greater total water use than those in 1998 in both wet and dry regimes due to more rainfall occurred during the growing period in 1999. Among the three genotypes in wet regime, NS 1 had the highest total water use in 1998 whereas SW 3601 showed the greater total water use in 1999. SW 3601 genotype showed the highest total water use in the dry regime in both years. However, total water use among the three genotypes at each moisture regime was not different in both years.

All maize genotypes under wet regime gave lower water use efficiency as compared to dry regime in both years (Table 10). Among the three genotypes, SW 3601 was the highest water use efficiency followed by NSX 9210 and NS 1 in both water regimes and in both years. Genotypes which had greater water use and water use efficiency under drought stress conditions can maintained their physiological metabolism to thereby produced higher grain yield (Del Rosario and Fajadordo, 1988 ; Senthong *et al.*(1986). Kramer (1983) reported that differences in water use efficiency was associated with crops yield. Jones (1993) also noted that high water use efficiency may be associated with low productivity and decreased amount of water transpired by the crop.

Yield response to irrigation plus rainfall

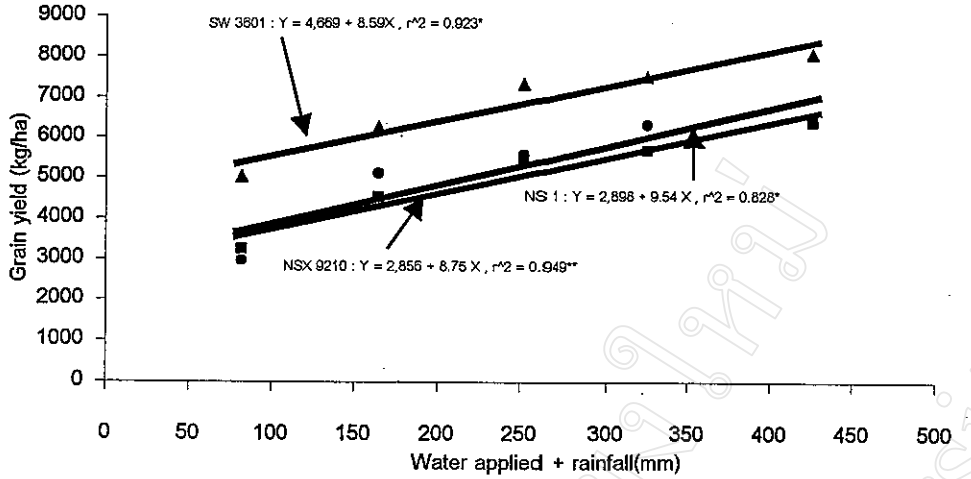
Kernel yield in all three genotypes showed a linear increase with the amount of water applied plus rainfall in both years (Figure 18). It is clear that SW 3601 genotype produced significantly greater grain yield in all water application than NSX 9210 and NS 1 genotypes in both years. This result suggested that SW 3601 appears to be the best genotype to be grown both in the drought prone and in the partially irrigated areas. Senthong and Pandey (1998) also mentioned that cowpea cv. Vita 4, which

showed a larger response to irrigation water application, could perform well under rainfed condition as well as with supplementary irrigation.

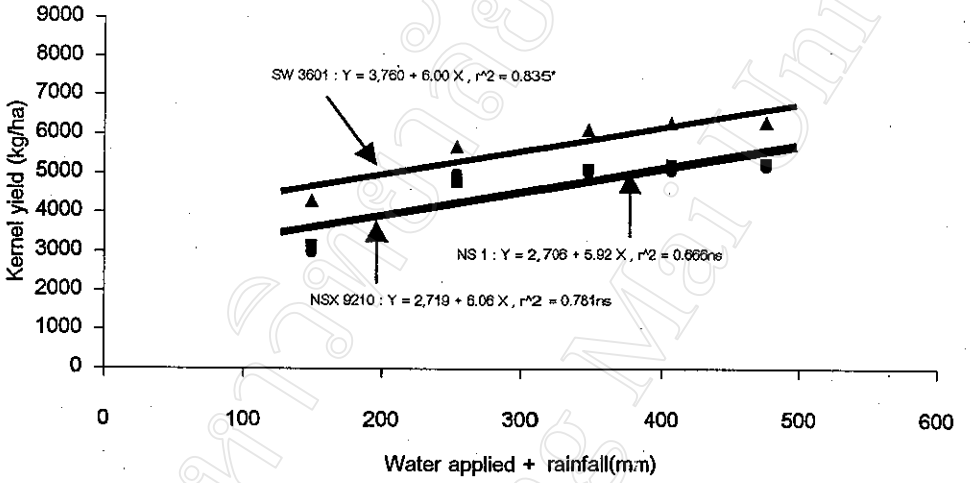
Table 10 Water use efficiency of 3 maize genotypes in wet and dry regimes in 1998 and 1999.

Genotype	Total water use (mm)		Kernel yield (kg/ha)		Water use efficiency (kg/ha/mm)	
	Wet regime	Dry regime	Wet regime	Dry regime	Wet regime	Dry regime
----------1998----------						
NS 1	455	116	6,451	2,962	14.1b*	25.5b
NSX 9210	446	119	6,390	3,248	14.3b	27.2b
SW 3601	448	125	8,053	5,019	17.9a	40.1a
Mean	449	120	6,964	3,743	15.4	30.9
----------1999----------						
NS 1	483	167	5,182	2,982	10.7b	17.8b
NSX 9210	485	174	5,258	3,163	10.8b	18.1b
SW 3601	493	176	6,290	4,284	12.8a	24.3a
Mean	487	172	5,576	3,476	11.4	20.1

* Values within a column followed by the same letter are not significantly different at the 5% level of probability using DMRT.



(a) 1998



(b) 1999

Figure 18 Relationship between kernel yield and water applied plus rainfall for three maize genotypes in 1998 (a) and 1999 (b).

Effect of water deficit on kernel yield

Kernel yield in all three maize genotypes reduced with increased water stress in both years but the reduction was greater in 1998 than in 1999 due to the variation in the amount of rainfall (Figure 2). Drought susceptibility index (DSI) as proposed by Fischer and Wood (1979) indicated that SW 3601 genotype showed the least drought susceptibility in both years compared with NSX 9210 and NS 1 genotypes. Drought index (DI) as described by Fischer *et al.*(1983) indicated that SW 3601 genotype also showed the most drought tolerance in both years (DI > 1) whereas NS 1 was the most drought susceptible followed by NSX 9210 (DI < 1).

It can be concluded that SW 3601 showed the most drought tolerance due to the least of DSI (35.1%) and the highest value of DI (1.13) while NS 1 genotype was the most drought susceptible (DSI = 48.9% and DI = 0.89) followed by NSX 9210 (DSI = 45.1% and DI = 0.95) which classified as the moderately drought tolerance genotype (Table 11). Senthong and Pandey (1989) found that in medium and late maturity genotypes showed the less value of DSI tended to have a higher grain yield and tolerated greater water stress than the short duration ones. Manupeerapan *et al.* (1997) also demonstrated that drought tolerance maize genotypes produced the largest value of DI and had a relatively short anthesis-silking interval.

Table 11 Effect of moisture regimes on kernel yield (kg/ha) of three maize genotypes for Experiment 2 in 1998 and 1999.

Maize genotype	Moisture regime 1	2	3	4	5	DSI**	DI***
----------1998----------							
NS 1	6451bc*	6326cd	5578d-f	5114fi	2962k	54.1	0.91
NSX 9210	6390cd	5695c-f	5374e-i	4528i	3248j	49.2	0.95
SW 3601	8053a	7495a	7306ab	6235c-e	5019fi	37.7	1.19
----------1999----------							
NS 1	5182bc	5065bc	5004b-d	4991b-d	2982e	42.5	0.92
NSX 9210	5258bc	5218bc	5103bc	4775cd	3163e	39.8	0.97
SW 3601	6290a	6279a	6107a	5668ab	4284d	31.9	1.10
----------1998 & 1999----------							
NS 1	5816cd	5695cd	5291cde	5052de	2972f	48.9	0.89
NSX 9210	5837bcd	5456cde	5238cde	4651e	3205f	45.1	0.95
SW 3601	7171a	6887a	6706ab	5951bc	4651e	35.1	1.13
CV.(%)	8.5 (1998)		10.1 (1999)			7.7 (1998&1999)	

* Values within a column followed by the same letter are not significantly different at the 5% level of probability using DMRT

** Drought susceptibility index (DSI) = 1 - dry plot /wet plot

*** Drought index (DI) = the ratio of yield of each genotype under dry plot to wet plot, relative to the ratio of the mean yield of all genotypes under dry plot to wet plot.

Yield Components Response to applied irrigation water

Number of ears. The number of ears per square meter was less affected by water stress in both years (Table 12). Ear number of all genotypes in the driest treatment were 1.8% lower than those in the wettest treatment in both years (Table 13). A change in ear number unaffected the grain yield in all genotypes in both years (Table 14). Conversely, Bolaños and Edmeades, (1996) and Edmeades *et al.* (1996) reported that ear number per plant was the most responsive to drought, particularly under severe drought stress.

Number of kernels per ear. Kernel number including ear length were the yield components most sensitive to water stress, except, ear width was less affected by drought stress (Table 12). Kernel number of SW 3601, NSX 9210 and NS 1 genotype in the driest treatment were 11.9, 19.5; 21.5 in 1997/98 and 16.3, 15.5 ; 8.5 % in 1998/99 lower than those in the wettest treatment in both years (Table 13). The reduction in kernel number in the driest plot was probably due to delayed silking resulting in an increase in length of the ASI (Bolaños and Edmeades, 1993b). Boyle *et al.*(1991) reported that silk delay may be a symptom of limited assimilate supply rather than the primary cause of barrenness. Edmeades *et al.* (1993) confirmed that a decreased ASI arising from selection in the lowland tropical maize population was due to largely to an increased rate of biomass accumulation per spikelet and development of fewer spikelets per ear is a sensitive measure of genotypic tolerance to reduced photoassimilation per plant. A change in kernel number affected the yield of SW 3601 genotype followed by NS 1 and NSX 9210 (Table 14).

Kernel weight. Kernel weight was also increased by water application and have the same degree when compared with kernel number. It is also demonstrated that a positive linear relationship between water application and genotypes in both years (Table 12). Kernel weight of SW 3601, NSX 9210 and NS 1 genotypes in the driest treatment were 26.6, 20.9; 20.1 % in 1997/98 and 12.1, 11.7; 10.8 % in 1998/99 which

lower than in the wettest regime (Table 13). Kernel weight is the product of the duration of effective kernel-filling period and the rate of kernel growth (Fischer and Palmer, 1983). A change in kernel weight affected the kernel yield in NSX 9210 more than SW 3601 and NS 1 genotypes (Table 14).

Table 12 Linear regression parameters for responses of yield components to mm of irrigation plus rainfall received by three maize genotypes in 1998 and 1999.

Genotypes	1998			1999		
	Intercept	Slope	r^2	Intercept	Slope	r^2
----------Total ears/m^2----------						
NS 1	5.42	0.00023	0.489^{ns}	5.35	0.00022	0.424^{ns}
NSX 9210	5.45	0.00035	0.728^{ns}	5.33	0.00037	0.788^{ns}
SW 3601	5.37	0.00045	0.534^{ns}	5.38	0.00042	0.416^{ns}
----------Ear width (cm)----------						
NS 1	4.41	0.0012	0.489^{ns}	4.12	0.0010	0.765^{*}
NSX 9210	4.11	0.0008	0.708^{ns}	3.70	0.0011	0.814^{*}
SW 3601	4.52	0.0008	0.708^{ns}	4.08	0.0005	0.595^{ns}
----------Ear length (cm)----------						
NS 1	15.4	0.0069	0.982^{**}	14.3	0.0049	0.869^{*}
NSX 9210	16.5	0.0058	0.799^{*}	14.8	0.0045	0.943^{**}
SW 3601	16.9	0.0058	0.796^{*}	14.7	0.0046	0.898^{*}
----------Kernels/ear----------						
NS 1	393.9	0.387	0.764^{*}	370.9	0.208	0.835^{*}
NSX 9210	408.7	0.322	0.600^{ns}	382.8	0.192	0.619^{ns}
SW 3601	409.6	0.375	0.803^{*}	395.2	0.138	0.827^{*}
----------100 kernel weight (g)----------						
NS 1	21.5	0.022	0.902^{*}	25.1	0.009	0.882^{*}
NSX 9210	20.1	0.013	0.684^{ns}	20.3	0.008	0.839^{*}
SW 3601	23.7	0.017	0.864^{*}	24.8	0.009	0.797^{*}

*, ** Significant at 0.05 and 0.01 probability levels, respectively

ns = not significant at P =0.05

Table 13 Effect of moisture regimes on yield components of three maize genotypes for Experiment 2 in 1998 and 1999.

Maize genotype	Moisture regime 1	2	3	4	5	Mean	DSI
			Total ears/m^2 in 1998				
NS 1	5.5a*	5.5a	5.5a	5.5a	5.4a	5.5	1.8
NSX 9210	5.6a	5.6a	5.5a	5.5a	5.5a	5.6	1.8
SW 3601	5.5a	5.6a	5.5a	5.4a	5.4a	5.5	1.8
			Total ears/m^2 in 1999				
NS 1	5.5a	5.4a	5.4a	5.4a	5.4a	5.4a	1.8
NSX 9210	5.5a	5.5a	5.5a	5.4a	5.4a	5.5a	1.8
SW 3601	5.5a	5.6a	5.6a	5.5a	5.4a	5.5a	1.8
			Kernels/ear in 1998				
NS 1	543ab	521abc	503bc	498c	426d	498	21.5
NSX 9210	521abc	519abc	513abc	504bc	438d	499	15.9
SW 3601	555a	528abc	526abc	500bc	489c	520	11.9
			Kernels/ear in 1999				
NS 1	465a	452ab	448ab	442ab	389c	439	16.3
NSX 9210	462a	462a	453ab	461a	390c	446	15.5
SW 3601	447ab	450ab	438abc	444ab	409bc	438	8.5
			100 kernel weight (g) in 1998				
NS 1	30.5a	29.6a	26.8abc	26.6a	22.4cd	27.5	26.6
NSX 9210	24.9bc	24.4bc	24.0c	23.8c	19.7d	23.4	20.9
SW 3601	30.2a	29.9a	29.1a	27.1ab	24.1bc	28.1	20.1
			100 kernel weight (g) in 1999				
NS 1	29.8a	29.2ab	28.5ab	28.5ab	26.2cd	28.4	12.1
NSX 9210	23.9e	23.9e	23.8e	22.9e	21.1f	23.1	11.7
SW 3601	28.7ab	28.7ab	28.5ab	27.9bc	25.6d	27.9	10.8

* Values within a column followed by the same letter are not significantly different at the 5% level of probability using DMRT

Table 14 Relationship between kernel yield and yield components of three maize genotypes under different moisture regimes in 1998 and 1999.

Genotypes	Regression equation			
	1998		1999	
	Total ears/ m^2 (X)			
NS 1	Y = -15396+29060X	$r^2 = 0.848^{*}$	Y = -31750+6715X	$r^2 = 0.103^{ns}$
NSX 9210	Y = -86870+16591X	$r^2 = 0.566^{ns}$	Y = -62127+12240X	$r^2 = 0.578^{ns}$
SW 3601	Y = -53117+10937X	$r^2 = 0.578^{ns}$	Y = -41123+8487X	$r^2 = 0.707^{ns}$
	Kernels/ear(X)			
NS 1	Y = -6162 +23.3X	$r^2 = 0.970^{**}$	Y = -9016 +31.1X	$r^2 = 0.955^{**}$
NSX 9210	Y = -4353 +19.2X	$r^2 = 0.792^{*}$	Y = -7483 +27.3X	$r^2 = 0.943^{**}$
SW 3601	Y = -3614 +20.7X	$r^2 = 0.941^{**}$	Y = -11958+40.1X	$r^2 = 0.860^{*}$
	100 kernel weight (g) (X)			
NS 1	Y = -6537+435.0X	$r^2 = 0.956^{**}$	Y = -13738+646.4X	$r^2 = 0.895^{*}$
NSX 9210	Y = -7411+533.3X	$r^2 = 0.851^{*}$	Y = -12021+723.4X	$r^2 = 0.977^{**}$
SW 3601	Y = -6403+470.9X	$r^2 = 0.981^{**}$	Y = -12137+640.7X	$r^2 = 0.997^{**}$

*, ** Significant at 0.05 and 0.01 probability levels, respectively

ns = not significant at P =0.05