WATER PRODUCTION FUNCTION OF MAIZE FOR NORTHEAST BRAZIL[1]

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ABSTRACT - The results of the randomized block experiment with four growth stages and four nitrogen levels to determine the water production function of maize (*Zea mays* L.) for Northeast Brazilian conditions are reported. The yield response factors as per Doorenbos and Kassam's equation are found to vary drastically not only for different growth stages but also with different nitrogen levels and with different water levels. Thus, this equation is not a true representation of yield response to water. A modified linear equation with an intercept (K_2) has been suggested. The coefficients of this modified equation (intercept K_1 and the slope K_2) are the modified yield response factors. These factors for maize have been developed here for all the four stages and for all the four nitrogen levels. The average highest water use efficiency of approximately 57.5 kg/ha-cm of water can be obtained but it shows no increase with increase in applied nitrogen up to 120 kg/ha. Finally crop coefficients (K_c) have been calculated. The overall values of K_c are much below the FAO estimates for all nitrogen levels. All the above information developed here will help in better irrigation scheduling and better planning of supplemental irrigation projects in the Northeast Brazil.

Index terms: irrigation systems management, irrigation scheduling, yield response factors.

FUNÇÃO DE PRODUÇÃO DE MILHO COM ÁGUA PARA O NORDESTE DO BRASIL

RESUMO - Estudou-se através de um experimento em blocos ao acaso, os efeitos de quatro níveis de nitrogênio, em diferentes condições de umidade, sobre os estágios de crescimento, embonecamento, formação de grãos e produtividade do milho (*Zea mays* L.) e as relações entre a produtividade e os três primeiros estágios. Os fatores da resposta de produção baseados na equação de Doorenbos e Kassam variaram acentuadamente, não só com os diferentes estágios de crescimento, mas também com diferentes níveis de nitrogênio e os diferentes níveis de água. Assim, esta equação não pareceu ser válida para explicar a resposta de produtividade a níveis de água. Sugeriu-se uma equação linear modificada. Nesta equação, a intercessão K_1 e inclinação K_2 são os fatores da resposta de produção. Estes fatores para a cultura do milho foram desenvolvidos para todos os quatro estágios de crescimento e níveis de nitrogênio. Pode-se obter uma eficiência média do uso de água, em termos de produtividade, de, aproximadamente, 57,5 kg/ha-cm de água, sendo, contudo, pequeno o incremento, em face dos níveis crescentes de nitrogênio aplicado até 120 kg/ha. Os coeficientes de cultura (K_c) calculados estão muito abaixo da estimativa da FAO, para todos os níveis de nitrogênio. Por essa razão, deve haver considerável economia de água se estes coeficientes forem usados em lugar da estimativa da FAO. A informação mostrada pode imediatamente ser utilizada para turno de irrigação e para projetos de irrigação suplementar planejado para as condições do Nordeste do Brasil.

Termos para indexação: manejo de sistema de irrigação, planejamento de irrigação, fatores de resposta de produtividade.

INTRODUCTION

Northeast Brazil is climatically one of the most erratic regions of the world. Water often is not available in sufficient quantity at right time and right place. Supplemental irrigation projects are being proposed to minimize these imbalances in rainfall. These irrigation projects usually involve high expenditures. Often, in the past, these supplemental irrigation projects have been planned without adequate knowledge of water production functions of the dry land crops. To fill this gap in information a research project for determination of water production functions of major NE Brazilian dry land crops was started here in 1983.

The results of the present efforts for the experiment on sorghum that was carried out in

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1983 have been reported earlier by Sharma & Alonso Neto (1986). This paper reports the results of the experiment on maize that was conducted in 1984. The water production functions for various levels of irrigation deficit at different phenological stages and with no irrigation deficit, at various nitrogen levels, are reported. In addition the yield response factors (K) based on the crop yield response to the water equation of Doorenbos & Kassam (1979) were determined. These factors were found to vary drastically at different water levels even for same crop development stage. The same observation was made in the case of sorghum also (Sharma & Alonso Neto 1986). Sharma & Alonso Neto (1986) suggested a modification to this equation and developed the modified yield response factors for sorghum. The modified equation of Sharma & Alonso Neto was also found suitable to the case of maize reported here. Hence based on this, new modified yield response factors for maize at various growth stages and various levels of nitrogen are being reported. These factors can be used to aid future irrigation project planning. Finally crop coefficients based on pan evaporation method have been determined for proper irrigation scheduling.

MATERIALS AND METHODS

The methodology of the experiment is similar to the one reported earlier by Sharma & Alonso Neto (1986). The experiment was conducted on an Oxisol field in the San Francisco River Basin at CPATSA, Petrolina, PE, Brazil. The physical and hydraulic characteristics of the soil of the experimental site and its past history have already been described elsewhere (Choudhury & Millar 1981). Briefly, the soil texture of the site is sandy in first 30 cm depth, sandy loam at 30-60 cm depth and loamy sand in both 60-90 cm and 90-120 cm depth intervals. The field capacity and permanent wilting points in the same depth intervals are 8.94%, 9.00%, 9.2% and 9.00%, and 1.84%, 2.52%, 3.07% and 3.22% respectively. The chemical analysis of the soil of the experimental site before the experiment on May 15, 1984 was made and is reported in Table 1. The site was kept fallow from Jan. 1, 1984 to July 1, 1985 for six months, during which there was a rainfall of 493.2 mm.

The experiment was designed in two randomized blocks, each block representing a replication thus utilizing only half perpendicular side of line source as explained by Sharma & Alonso Neto (1986) and consisting of four growth stages and four levels of nitrogen. The four growth stages were with irrigation deficit at vegetative, silking and grain formation stages, and no deficit treatment. The four levels of nitrogen applied were 0, 40, 80 and 120 kg/ha. Uniform basal doses of 30 kg/ha K_2O and 60 kg/ha of P_2O_5 were applied. The nitrogen was applied in two parts, half as basal and remaining half as top dressing, three weeks after germination. The method of line source sprinkler as described by Hanks et al. (1976) was utilized in applying continuously variable irrigation. The perpendicular plots of 15 m x 4.5 m for each of the treatments were layed out in each block. The typical water distribution pattern and lay out of the experiment (except for randomization) is exactly similar as given by Sharma & Alonso Neto (1986).

The experiment was carried out using the Jatina C-3 Anão variety of maize. The plant population was maintained at 52,630 plants/ha. Each plot consisted of six rows spaced at 75 cm. The distance between plants was 50 cm, each hill consisting of two plants. Two of the six rows on the sides were borders. Six levels of irrigation and soil moisture by neutron probe to 120 cm soil depth were monitored at 1.25 m, 3.75 m, 6.25 m, 8.75 m, 11.25 m and 13.75 m, perpendicular to line source. Climatic data on wind velocities, rainfall, daily evaporation rates and mean relative humidity were obtained from the nearby meteorological station of the CPATSA, Petrolina, PE, (Brazil) research centre for irrigation scheduling.

In total nine irrigations were given. The first three irrigations totaling 54.11 mm were given uniformly on July 6 (soon after planting); July 16, and July 26, 1984 for establishing the crop. The other six irrigations were continuously varying along the perpendicular distance from centre of line source and given on Aug. 3, Aug. 14, Aug. 23, Sept. 10, Sept. 21 and Oct. 1, 1984, respectively. All the irrigations were scheduled by Pan Evaporation method at 50% moisture depletion level in first 100 cm of soil profile. The pan coeficients and crop coefficients were those recommended by FAO (Doorenbos & Kassam 1979) for calculating timing and quantity of irrigation at the point of maximum water application which is at the centre of line source. For giving deficit at a particular stage, the irrigation was skipped on that stage while all other stages were irrigated. The fourth irrigation which was after 30 days of planting was skipped for giving deficit in vegetative stage. The seventh (after 70 days of planting) and 8^{th} irrigation (after 80 days of planting) were skipped to give deficit in silking and grain formation stages while the no deficit stage got all the nine irrigations. The crop was harvested at 115 days after sowing.

Sprinkler irrigation quantity was monitored by cans and soil moisture was monitored in one replicate of each of the four growth stages for each nitrogen treatment by neutron probe at the six places. The water use was calculated by summing up the irrigation quantity applied at

TABLE 1. Chemical analysis of the experimental site (Average values), at CPATSA, Petrolina, PE, Brazil.

pH H_2O (1:25)	Electrical conductivity (25°C) St. Ext ($S\ m^{-1}$)	Exchangeable cations (meq/100 g of soil)					Al^{3+} (meq)	P (ppm)
		Ca^{2+}	Mg^{2+}	Na^+	K^+	S		
5.0	0.035	1.5	0.5	0.01	0.16	1.4	0.12	18.96

the six locations from the line source, soil moisture contribution calculated by subtracting the value of soil moisture before previous irrigation from the value of soil moisture before an irrigation is to be given, and rainfall. The deep percolation was monitored by taking soil moisture readings after an irrigation of the soil profile between 90 and 120 cm depth.

A total of 36 mm rainfall took place during the period of the experiment. The first event of the rainfall of 20 mm was on Sept. 4, 1984 during flowering stage of the experiment and the second event of 17 mm rainfall took place on Sept. 26, 1984 during harvest, rest all rainfall was in small quantity. There was no runoff loss from any rainfall event. The growth stage (T) has been represented by number of days from planting to the day when water deficit started (or irrigation skipped). Crop grain yield samples of 3 m x 1 m size were collected at the same 6 places of each treatment i.e. 1.25 m, 3.75 m, 6.25 m, 8.75 m; 11.25 m and 13.75 m, perpendicular to line source.

RESULTS AND DISCUSSION

The observed maize grain yield (Y) at different water use (Q) levels for the four stages (T) and for all the four nitrogen levels (N) have been reported elsewhere (Sharma 1985). For saving space, only a summary of the observed data is given here in Table 2. This Table also shows the range of variation of the FAO (Doorenbos & Kassam 1979) yield response factor (K) within the observed water use and yield data range. Yield response to various variables.

The nature of crop response (yield) to water use was found to be of quadratic nature. Regression coefficients at 1% level of significance for the quadratic equations developed for different stages (T in days) at different levels of nitrogen (N, kg/ha), between grain yield, Y in kg/ha (dependent variable) and water use, Q in mm (independent variable), the value of R^2 and standard error (σ) for each regression equation are given in Table 3. Sometimes these equations do give negative values of Y for the lowest values of water use in the data set hence should be used with this caution in mind.

Table 3 clearly shows that no significant relationship was found even at 10% level when water deficit occurred during silking stage (even though there was a 20 mm rainfall during this stage) which is due to the well known fact (and as confirmed by range of yield data in Table 2) that any deficit during this stage is disastrous.

When nitrogen (N in kg/ha) is introduced as another independent variable, the multiple regression analysis gives the following equation (significant at 1% level) for different stages:

Vegetative stage (T = 30 days):

$$Y = 0.039\,Q^2 + 0.025\,N^2 - 0.002\,QN - 8.62\,Q - 2.18\,N + 469.44,$$
$R^2 = 0.81$, $\sigma = 380.79$.

Silking stage (T = 70 days):
Not significant even at 10% level, complete failure due to water deficit.

Grain formation stage (T = 80 days):

$$Y = 0.014\,Q^2 + 0.036\,N^2 - 9.18\,QN - 2.25\,Q - 2.86\,N + 76,$$
$R^2 = 0.51$, $\sigma = 225.15$

No deficit stage (T = 115 days):

$$Y = 0.008\,Q^2 - 0.02\,N^2 + 0.004\,QN + 3.54\,Q + 1.35\,N - 646.43,$$
$R^2 = 0.81$, $\sigma = 353.35$

Finally the growth stage represented by time of beginning of deficit (Vegetative T = 30 days, Silking T = 70 days, Grain formation T = 80 days and No deficit T = 115 days) was also introduced as an independent variable along with nitrogen and

TABLE 2. Summary of the observed water use and grain yield data, and variation of FAO yield response factor and maximum water use efficiency within the observed data range.

Water deficit stage, T (days)	Nitrogen level, N (kg/ha)	Range of observed values (rounded)						
		Water, Use, Q (mm)		Grain yield, Y ($kg\ ha^{-1}$)		FAO yield response factor, K		Maximum water use efficiency ($kg\ ha^{-1}\ cm^{-1}$ of water)
		from	to	from	to	from	to	
Vegetative (30)	0	143	343	8	2517	1.61	0.77	73.38
	40	113	322	0	1750	1.43	1.47	54.34
	80	134	327	0	1500	1.56	-0.65	45.87
	120	115	335	42	2058	1.40	0.08	61.40
Flowering (70)	0	123	307	0	350	1.50	5.00	11.4
	40	129	325	0	650	1.50	5.00	20.0
	80	130	312	0	141	1.50	5.50	4.50
	120	131	316	0	141	1.50	5.80	4.60
Grain formation (80)	0	55	288	0	617	1.18	3.04	21.4
	40	117	299	0	1141	1.45	2.39	38.2
	80	134	314	0	458	1.54	4.71	14.6
	120	118	256	0	1067	1.45	1.66	41.6
No deficit (115)	0	146	387	0	2351	1.64	2.00	60.8
	40	139	377	0	2250	1.59	0.00	59.6
	80	131	378	0	2059	1.54	-45.0	54.4
	120	138	372	0	2059	1.59	9.00	55.3

water use. The quadratic multiple regression analysis nature gives the following equation (significant at 1% level):

$$Y = 0.03\,Q^2 + 0.016\,N^2 + 0.33\,T^2 + 1.02\times10^{-4}\,QNT - 8.88\,QN - 0.036\,QT - 0.027\,NT - 5.78\,Q + 0.15\,N - 39.9\,T + 1529.3,$$
$$R^2 = 0.74,\ \sigma = 374.26$$

These equations can be used for yield prediction under varying levels of water, fertility or expected water deficit in any of the stages.

Water use efficiency (WUE)

The water use efficiency, calculated by dividing the grain yield by the quantity of water use, in kg/ha-cm of water, for maximum yield level at different nitrogen and for different crop stages is given in Table 2. The highest WUE values are for the vegetative state followed by no deficit, grain formation and silking stages. This demonstrates that the water is most efficiently utilized by the maize plant when stress is given at vegetative stage. The effect of nitrogen levels on the WUE in both vegetative (WUE between 54 and 73 kg/ha-cm of water) and no deficit case (WUE between 54 and 61 kg/ha-cm of water) is very limited.

It can be generalized from the values of the WUE in Table 2 that if quantity of water available is limited, the water deficit could deliberately be allowed to occur during vegetative stage. However, any water deficit at silking stage is going to be disastrous and water deficit at the grain filling stage is very harmful. Yield response factors (K).

Doorenbos & Kassam (1979) have used the following equation for predicting relative yield decrease for relative evapotranspiration deficit:

$$(1 - Y/Y_m) = K\,(1 - Q/Q_m) \quad \ldots (1)$$

where Y is actual yield (in kg/ha) and Q is the corresponding water use or actual evapotranspiration (in mm), Y_m is maximum obtainable

TABLE 3. Regression coefficients of the quadratic water production function equation for maize for different water deficit at different growth stages and various applied nitrogen levels (a, b and c are the coefficients in the equation $Y = aQ^2 + bQ + c$). Level of significance = 1%.

Water deficit in crop growth stage, T	Nitrogen level, N kg/ha	Regression coefficients		Intercept	R^2	Standard error, σ
		a	b	c		
	0	0.034	- 5.08	- 40.16	0.84	407.28
Vegetative	40	0.025	- 2.50	- 73.31	0.81	349.80
(T = 30 days)	80	0.410	-10.24	659.24	0.71	496.87
	120	0.051	-13.35	921.65	0.88	363.44
	0					
Silking	40	Not significant up to 10 % level				
(T = 70 days)	80	for all four N values				
	120					
	0	0.021	- 4.27	170.17	0.68	203.2
Grain formation	40	0.41	-13.61	1078.89	0.71	196.5
(T = 80 days)	80	0.013	- 3.65	246.56	0.87	–
	120	Not significant up to 10% level				
	0	0.031	- 9.48	993.39	0.8	369.73
No deficit	40	-0.001	8.03	-1238.32	0.81	389.97
(T = 115 days)	80	0.02	- 1.59	- 172.48	0.94	243.48
	120	-0.017	16.6	-2105.73	0.79	397.68

yield (in kg/ha) and Q_m is the corresponding maximum evapotranspiration (in mm). The coefficient K has been termed as the yield response factor. Y_m is the global maximum yield obtained under best conditions of soil and crop management (Doorenbos & Kassam 1979). Hence the term $(1\text{-}Y/Y_m)$ becomes the relative yield decrease and $(1\text{-}Q/Q_m)$ becomes the relative evapotranspiration deficit. The factor K relates the two. Doorenbos & Kassam (1979) consider equation (1) to be valid up to 50% relative evapotranspiration deficit.

The maximum obtainable yield was taken to be 2250.5 kg/ha (Y_m) at 377.38 mm (Q_m) of water use from our data in Table 2 for 40 kg/ha of nitrogen at no deficit stage. Although genetic yield potential of the variety has been reported to be 5500 kg/ha, the dry season yield has never been found to exceed 2400 kg/ha, which is very close to our maximum. When yield response factors are calculated by equation (1) they are found to vary within various stages, nitrogen and water use levels as demonstrated in Table 2. While according to equation (1) there should be a fixed value or at the most a narrow range for each stage and N level. Similar variations were also found for sorghum crop reported earlier (Sharma & Alonso Neto 1986). Thus it is now proved that equation (1) is not a valid representation of yield response to water in general. This problem is resolved if equation (1) is modified, as suggested earlier (Sharma & Alonso Neto 1986), as following:

$$(1 - Y/Y_m) = K_1 + K_2 \quad (1 - Q/Q_m) \qquad \ldots (2)$$

where K_1 and K_2 are new or modified yield response factors which are to be determined by experimentation. Linear regression analysis of the data was carried out to determine the values of K_1 and K_2 in equation (2). These values are reported in Table 4. Equation (2) also shall be valid only up to about 50% water level deficit.

The modified yield response factor K_1 gives the minimum relative yield decrease which shall always take place soon the nitrogen level is different from the optimum or soon one of the critical growth stages suffers from water deficit, even when there is no overall relative evapotranspiration (ET) deficit. The factor K_2 is a multiplier to the relative ET deficit and weights the yield deficit

TABLE 4. Modified yield response factors K_1 and K_2 in equation (2) for maize. (sinificant at 1% level).

Crop stage at which water deficit occurred, T	Nitrogen level, N	Modified yield response factors		R^2	Standard error, σ	$(K_1 + ½K_2)$
		K_1	K_2			
	0	0.4	1.68	0.71	0.22	1.24
Vegetative	40		Not significant up to even 10% level.			
	80	0.14	1.45	0.67	0.21	0.86
	120	0.041	1.59	0.68	0.24	0.85
	0		Not significant even at 10% level.			
Silking	40		This stage was a complete disaster			
	80		due to water deficit at the stage.			
	120		So a value of K_1 = 1 and K_2 = 0 can be used.			
	0	0.65	0.49	0.54	0.1	0.89
Grain formation	40	0.63	0.66	0.51	0.11	0.97
	80	0.81	0.33	0.77	0.03	0.98
	120	0.61	0.59	0.37	0.14	0.91
	0	0.23	1.23	0.74	0.18	0.85
No deficit	40	0.15	1.39	0.81	0.16	0.85
	80	0.12	1.48	0.92	0.12	0.86
	120	0.2	1.26	0.77	0.17	0.83

according to water deficit. Thus the higher is the value of K_1, more critical is growth stage for irrigation.

In the vegetative stage at 120 kg/ha of nitrogen the value of K_1 is only 0.041; however it has one of the highest values of K_2 (= 1.59). The equation (2) being valid only up to 50% ET deficit, the combined effect of both K_1 & K_2 can be evaluated by $(K_1 + ½K_2)$. Only this gives the maximum yield response factor and shall not exceed 1.0 (100%). In Table 4 this calculation is also shown. The least value of this maximum factor $(K_1 + ½K_2)$ is for 0 and 40 kg/ha nitrogen treatment for no deficit stage (also K_1 has one of the lowest values except for N = 80) for these treatments. Hence the case of N = 0 kg/ha is the optimum combination of nitrogen and irrigation since it will have least yield deficit at various evapotranspiration deficit levels.

Theoretilally speaking the K_1 value for the optimum combination should be zero. However, as argued by Sharma & Alonso Neto (1979), it is rather rare in the real world as well as in any controlled experimentation with the best efforts, that this theoretical value can be achieved. The value of K_1 = 0.23 for N = 0 kg/ha and K_1 = 0.15 for N = 40 kg/ha for no deficit case are thus more realistic than the theoretical value of zero.

From Table 4 many combinations can be made. For example, if water is not limiting, then nitrogen up to 120 kg/ha has very limited response to water. Similary if water deficit occurs while the combined effect of $(K_1 + ½K_2)$ is lower for higher N levels, the WUE increase is low (Table 2).

Crop coefficients (K_c)

The crop coefficients (K_c) which are used for irrigation scheduling have been calculated by Pan Evaporation method. The pan coefficients were those given by FAO (Doorenbos & Kassam 1979) for the climatic conditions of the location of the experiment. Water balance method has been used for finding K_c values. This is done by simply dividing the actual evapotranspiration (Q), for no water deficit case, by the reference crop evapotranspiration (ET). Actual ET (Q) for each nitrogen level for no deficit case is found by summing the applied irrigation, soil moisture balance and rainfall, for each growth period. Deep percolation losses and runoff were always zero. ETo is found by multiplying the sum of tank evaporation values for each growth period by appropriate pan coefficients (K_p) which is chosen depending on wind velocity, relative humidity and pan location (Doorenbos & Kassam 1979). Table 5 gives the final results of such a calculation for each growth period at each nitrogen level for no water deficit case. The duration of growth periods in days, is also given in Table 5. The initial period consisted of the first two irrigation, crop development period consisted of third to fifth irrigation, mid season consisted of sixth and seventh irrigation, late season had the eighth irrigation and harvest period is from 9th irrigation to the date of harvest (Oct. 26, 1985).

The crop coefficients (K_c) for the N = 0 kg/ha for optimum water level are 0.47 for initial period (0-19 days), 0.9 for crop development period (20-48 days), 0.71 for mid season (49-77 days), 0.73 for late season (78-90 days) and 0.5 for harvest period (91-115 days), respectively. The K_c value for total period is 0.6. These coefficients for both N = 0 kg/ha and N = 40 kg/ha, for the first two growth periods are higher than the estimates of the FAO (Doorenbos & Kassam 1979), but the K_c values for all other growth periods are lower than the estimates of the FAO. The overall K_c value in all cases was found to be lower than the FAO estimate. Thus by using the coefficients in Table 5, there will be considerable saving of water as compared to the FAO estimates.

CONCLUSIONS

The multiple regression equations developed here for maize can be utilized for economic analysis of new supplemental irrigation projects. The new modified yield response factors (K_1 & K_2) developed here are a better representation of the yield response to water than suggested earlier by Doorenbos & Kassam 1979) and can be utilized for irrigation project planning. The related cropping system choices also can be made based on these factors for areas where water is limiting (NE Brazil), since the higher is this factor, more risky is a crop to water deficits. The crop coefficients developed can be utilized for irrigation scheduling. The average highest water use efficiency is 57.5 kg/ha-cm of water for no water deficit situations and does not increase with increase in applied nitrogen levels for maize in NE Brazil. The value of modified yield response factors K_1 & K_2 are 0.15 and 1.39, and the value of K_c for development period, for mid season, for late season and for harvest period, for four levels of applied nitrogen, are determined.

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TABLE 5. Values of crop coefficients (K_c) for maize at different nitrogen levels for no water deficit case.

Nitrogen level, (kg/ha)	Value of K_c at different growth periods					
	Initial (0 - 19 days)	Crop development (20 - 48 days)	Mid season (49 - 77 days)	Late season (78 - 90 days)	Harvest (91-115 days)	Total period (0 - 115 days)
0	0.47	0.9	0.71	0.73	0.50	0.6
40	0.37	0.8	0.79	0.67	0.54	0.6
80	0.29	0.81	0.83	0.59	0.60	0.6
120	0.37	0.75	0.77	0.58	0.61	0.59
FAO values	0.35	0.75	1.05	0.85	0.60	0.75

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