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WATER PRODUCTION FUNCTIONS OF SORGHUM FOR NORTH EAST BRAZIL[1]

BY

Prem N. Sharma[2]

Faustino B. Alonso Neto[3]

Petrolina - PE
EMBRAPA - CPATSA
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[2]Irrigation Specialist, IICA/EMBRAPA/CPATSA, Cx.P.- 23, 56.300 , Petrolina, PE., Brazil.

[3]Agricultural Engineering Trainee, CNPq/CPATSA/EMBRAPA program, Cx.P.- 23, 56.300, Petrolina, PE., Brazil.

EMBRAPA

FUNÇÕES DE PRODUÇÃO COM ÁGUA DO SORGO PARA O NORDESTE DO BRASIL

Prem N. Sharma
Faustino B. Alonso Neto

RESUMO

Os resultados do experimento para determinar a função de produção com água do sorgo para as condições no Nordeste do Brasil são descritos. O experimento foi desenvolvido em blocos casualizados, consistindo de quatro estágios de desenvolvimento da cultura, para déficit de irrigação e quatro níveis de adubação nitrogenada. Os tratamentos dos estágios de desenvolvimento da cultura consistiu de: estágio vegetativo, estágio de floração, estágio de formação dos grãos e tratamento com nenhum déficit de irrigação. Os níveis de adubação nitrogenada foram: 0 kg/ha, 45 kg/ha, 90 kg/ha e 135 kg/ha, para cada tratamento. Foram seis níveis de irrigação e a umidade do solo determinada até a profundidade de 120 cm, a partir de, 1,25; 3,75; 6,25; 8,75; 11,25 e 13,75 m distanciado perpendicularmente da linha de aspersores (sprinkler line source), para que se conseguisse a evapotranspiração atual (ETa) exata. O experimento consistiu de 2 repetições situadas na direção do vento, perpendicular à linha de aspersores (sprinkler line source).

Foram aplicados, no total, oito (8) irrigações. Inicialmente aplicou-se 84,2 mm (três irrigações iniciais), uniformemente em todos tratamentos, para o desenvolvimento inicial das plantas. Todas as irrigações foram planejadas pelo método do tanque de evaporação. Os

coeficientes do tanque de evaporação e os coeficientes da cultura foram tentativamente utilizados como o recomendado pela FAO; para cálculos do turno de rega e lâmina de irrigação, para o ponto de máxima aplicação de água. A quantidade de irrigação aplicada às parcelas, foi determinado com recipientes (pluviômetros), e a umidade do solo determinada em uma das repetições de cada um dos quatro estágios de desenvolvimento, pela sonda de neutrons, nos seis locais. A precipitação pluviométrica diária (a qual foi muito pequena, exceto um evento ocorrido no período de maturação dos grãos), o balanço de umidade do solo e a quantidade de irrigações foram quantificados para dar o valor da ETa. Foi tomada amostras de 3 x 1 m^2, para determinação da produtividade dos grãos e palha. Foram coletados seis amostras destas, em cada tratamento.

A natureza da resposta da cultura para a água, foi estabelecida para ser de natureza quadrática. Equações de regressões foi desenvolvida para cada níveis de nitrogênio e para cada tratamento dos estágios de desenvolvimento, entre o uso d'água e a produtividade dos grãos e palha. O nitrogênio e estágios de desenvolvimento (em termos de dias para irrigação após o plantio), teve introduzidos para uma análise de regresso multivariável. O estágio mais crítico foi o estágio de floração, seguido pelo vegetativo e estágio de formação dos grãos. O fator de resposta da cultura, Ky, foi determinado como sendo maior do que: 1,9 para o estágio de floração; 1,4 para o vegetativo e formação de grãos, e sempre maior do que 1,23 para o período total de desenvolvimento da cultura, quando do nível de nitrogênio igual a 0 kg/ha. O fator Ky para N= 45 kg/ha são: > 1,73 (floração); > 1,62 (formação de grãos); > 1,46 (vegetativo) e > 1,52 para o período total de desenvolvimento da cultura. Esses fatores estão acima da estimativa generalizada pela FAO. A maior de todas as produtividades, foi observada no estágio sem déficit de água, sendo de 4,92 ton/ha (grãos), com 424,6 mm de uso total de água e nível de nitrogênio igual a 45 kg/ha.

O coeficiente de cultura (Kc) calculado com o método do tanque de evaporação, são: 0,40 para o período inicial (0-17 dias); 0,74 para o período de desenvolvimento da cultura (18-44 dias); 0,81 para estação média (45,68 dias); 0,75 para estação tardia (69.85 dias) e 0,5 para o período de colheita (86-106 dias). O valor de Kc para o período total é 0,75. Estes coeficientes estão geralmente próximos da classificação oferecida pela FAO, exceto na estação média (Kc= 0,81), onde o valor é menor do que o proposto pela FAO (Kc= 1,05).

Essas informações descritas, podem ser imediatamente utilizadas para programação de irrigação e planejamento de projetos de irrigação suplementar no Nordeste do Brasil.

WATER PRODUCTION FUNCTION OF SORGHUM FOR NORTH EAST BRAZIL

Prem N. Sharma[1] and Faustino B. Alonso Neto[2]

[1]Inter-American Institute of Cooperation on Agriculture (IICA)/Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA)/Centro de Pesquisa Agropecuária do Trópico Semi-Árido (CPATSA)

[2]CNPq/EMBRAPA/CPATSA

Address: EMBRAPA/CPATSA, Caixa Postal- 23, 56.300 Petrolina, PE., Brazil.

ABSTRACT

Sharma, P.N. and Alonso Neto, F.B., 1984. Water production function of sorghum for North-East Brazil.

The results of the experiment to determine the water production function of sorghum for North East Brazilian conditions are reported. The experiment was designed in random blocks consisting of four growth stages for irrigation deficit and 4 levels of nitrogen (N). The growth treatments consisted of vegetative stage, flowering stage, grain formation stage and no deficit treatment. The nitrogen levels were 0 kg/ha, 45 kg/ha, 90 kg/ha and 135 kg/ha for each treatment. Six levels of irrigation and soil moisture up 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 sprinkler line source, to give exact actual evapotranspiration (ETa). The experiment consisted of 2 replications layed out in the direction of the wind perpendicular to sprinkler line source.

In total 8 irrigations were given. First 3 irrigations totaling 84.2 mm were given uniformly for establishing the crop. All the irrigations were scheduled by Pan Evaporation method. The pan coefficients and crop coefficients were tentatively taken as recommended by FAO for calculating timing and quantity of irrigation at the point of maximum water application. Irrigation quantity was monitored by cans and soil moisture was monitored in one replication of each of the 4 growth stages by neutron probe at the 6 places. The daily rainfall (which was very little except one event in the maturity period), soil moisture balance and quantity of irrigation were summed up to give the values of ETa. Crop yield samples of 3 m x 1 m size for grain and fodder were collected at the same 6 places of each treatment.

The nature of crop response to water was found to be of quadratic nature. Regression equations are developed for each nitrogen and growth stage treatment between water use and grain yields. Then nitrogen and growth stage (in terms of days to irrigation after planting) has been introduced for multivariable regression analysis of quadratic nature. The most critical stage was found to be flowering stage followed by vegetative and grain formation stages. The crop response factors, Ky were found to be always greater than, 1.9 for flowering stage, 1.4 for vegetative and grain formation stages and always more than 1.23 for total growing period when nitrogen level was 0 kg/ha. The Ky factors at N= 45 kg/ha are respectively; > 1.73 (flowering), > 1.62 (grain formation), > 1.46 (vegetative) and > 1.52 for total growth period. These factors are much above the generalized estimates of the FAO. The highest obtainable yield was observed to be 4.92 metric ton/ha at 424.6 mm of actual water use at N= 45 kg/ha for the no deficit case.

The crop coefficients (Kc) calculated from observed data by pan evaporation method are; 0.40 for initial period (0-17 days), 0.74 for crop development period (18-44 days), 0.81 for mid season (45-68 days), 0.73 for late season (68-85 days) and 0.5 for harvest period (86-106 days), respectively for N= 45 kg/ha. The Kc value for total period is 0.75. These coefficients are in general around the range suggested by the FAO except in the mid season (Kc= 0.81) where the value in lower than the FAO value of Kc= 1.05.

The information reported can immediately be utilized for irrigation scheduling and for supplemental irrigation project planning in North East Brazil.

INTRODUCTION

North East 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 in general to minimize these imbalances in natural water supply for rainfed areas. These irrigation projects usually involve high expenditures. Most often, in 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 N-E Brazilian dry land crops was started here in 1983. This paper reports the results of the experimentation for sorghum. 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 crop response factors (Ky) based on the crop yield response to water model of the FAO (Doorenbos and Kassam, 1979) have been determined to aid future irrigation project planning and crop coefficients based on pan evaporation method have been determined for proper irrigation scheduling.

MATERIALS AND METHODS

The experiment was conducted on Latossols. The physical and hydraulic characteristics of these soils have been described in detail (Choudhury and Millar, 1981) in Table 1. The experiment was designed in randomized blocks consisting of 4 growth stages for irrigation deficit and 4 levels of nitrogen. The 4 growth stages were; vegetative, flowering, grain formation and no deficit treatment. The 4 levels of nitrogen applied were 0 kg/ha, 45 kg/ha, 90 kg/ha and 135 kg/ha. Uniform basal doses of 30 kg/ha K_2O and 90 kg/ha of P_2O_5 were applied. The nitrogen was applied in two parts, half as basal and remaining half as top dressing after 3 weeks of germination. The method of line source sprinkler as described by Hanks et al. (1976) was utilized for giving continuously variable irrigation. The perpendicular plots of 15 m x 4.5 m for each of the treatments were layed out to give 4 replications by locating two replications on either side of the sprinkler line. However as the wind velocities often exceeded 300 km/day, the two replications against wind direction were rejected due to poor distribution of water. Thus only two replications of each treatment were utilized for final analysis.

Table 1: Physical and hydraulic characterization of the Latossols of the experimental site (Choudhury and Millar, 1981).

Characteristics	Depth , cm			
	0 - 30	30 - 60	60 - 90	90 - 122
Texture:				
Gross Sand (%)	4	5	3	3
Fine Sand (%)	87	81	79	76
Silt (%)	4	5	6	8
Clay (%)	5	9	12	13
Textural Classification (USDA)	Sandy	Sandy Loam	Loamy Sand	Loamy Sand
Apparent Density (g/cm^3)	1.62	1.68	1.64	1.62
Real Density (g/cm^3)	2.72	2.74	2.74	2.82
Field Capacity (%)	8.94	9.00	9.20	9.00
Permanent Wilting Point (15 atm), %	1.84	2.52	3.07	3.22
Available Water, cm	3.45	3.27	3.00	3.01

The experimentation was carried out for the IPA 7301011 granifero variety of sorghum as this variety is one of the highest grain yielding varieties of the region. The plant population was maintained at 100,000 plants/ha. Each plot consisted of 6 rows spaced at 75 cm. Two of these 6 rows on the sides were borders. Six levels of irrigation and soil moisture up to 120 cm soil depth were monitored at 1.25m, 3.75m, 6.25m, 8.75m, 11.25m 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 irrigation research center for irrigation scheduling.

In total 8 irrigations were given. First 3 irrigations totaling 84.2 mm were given uniformly for establishing the crop. All the irrigations were scheduled by Pan Evaporation method. The pan coefficients and crop coefficients were tentatively taken as recommended by FAO (Doorenbos and Kassam, 1979) for calculating timing and quantity of irrigation at the point of maximum water application. Irrigation quantity was monitored by cans and soil moisture was monitored in one replication of each of the 4 growth stages for each nitrogen treatment by neutron probe at the 6 places. The daily rainfall (which was very little except one event in the maturity period), soil moisture balance and quantity of irrigation were summed up to give the values of actual evapotranspiration (ETa) i.e. water use, presuming no deep percolation losses. Crop yield samples of 3 m x 1 m size for grain and fodder were collected at the same 6 places of each treatment.

RESULTS AND DISCUSSION

The observed sorghum grain yield (y) at different water use (Q) levels for the 4 stages (T) and for all the 4 nitrogen levels (N) are given in Table 2. The water use was calculated by summing up the irrigation quantity applied at the 6 locations from the line source, soil moisture contribution calculated by substracting the value of soil moisture before previous irrigation from the value of soil moisture before an irrigation is to be given and rainfall. Deep percolation losses were assumed to be negligible. The irrigation scheduling was done by pan evaporation method at 50% moisture depletion level. A total of 61.9 mm rainfall took place during the period of the experiment. Except for one event of 39 mm in the last week of the experiment, all other rainfall was in small quantities. There was no runoff loss from any rainfall event. The growth stages have been represented by number of days, T from planting to the day when water deficit started (or irrigation omitted).

Six samples of yield were taken for each nitrogen treatment for all the stages however some of the data in Table 2 have been omitted since these omitted points either had severe bird damage or suffered from poor pollination for some unknown reason.

Yield response to various variables

The nature of crop response (yield) to water use was found to be of quadratic nature. The observations that have an asterisk (*) on the values of water use in Table 2 were deleted in the regression analysis as some of them are very much off the general nature and some removed to avoid negative predictions at lower values of water use. Regression equations developed for different stages (T in days) at

Table 2: Observed sorghum grain yield at different water use levels for various stages and nitrogen levels, and calculated values of crop response factors and water utilization efficiency.

Water Use, Q, (mm)	Grain Yield, y, (kg/ha)	Crop Response factor, Ky	Water utilization efficiency (kg/ha-cm of water)
VEGETATIVE STAGE (T= 30 days)			
At N= 0 kg/ha;			
Rep. I:			
130.6	93.3	1.42	7.14
155.6*	626.6	1.38	40.27
291.9	436.6	2.92	14.95
343.0	760.0	4.41	22.15
Rep. II:			
141.1	0	1.50	0.00
183.5	113.3	1.72	6.17
250.0	353.3	2.26	14.13
338.5	806.6	4.12	23.83
388.5	1420.0	8.37	36.55
409.4	1186.6	21.20	28.98
At N= 45 kg/ha;			
Rep. I:			
132.7*	0	1.46	0.00
151.9	16.6	1.55	1.09
178.8	120.0	1.69	6.71
254.2	886.6	2.04	34.88
330.5	603.3	3.96	18.25
394.5	1053.3	11.09	26.70
Rep. II:			
151.2	36.6	1.54	2.42
178.6	93.3	1.69	5.22
259.0	386.6	2.36	14.93
322.1*	1953.3	2.50	60.64
400.6	1066.6	13.86	26.63
At N= 90 kg/ha;			
Rep. I:			
158.9	0	1.60	0.00
171.9	46.6	1.66	2.71
268.7	136.6	2.65	5.08
331.9*	426.6	4.18	12.89
392.1	1170.0	9.96	29.84
Rep. II:			
150.7	46.6	1.54	3.09
184.9	46.6	1.76	2.52
253.1	443.3	2.25	17.51
325.5	800.0	3.59	24.58
391.5	2286.6	6.86	58.41
400.0	1593.3	11.67	39.83
At N= 135 kg/ha;			
Rep. I:			
129.5*	0	1.44	0.00
156.6	43.3	1.57	2.77
185.3*	40.0	1.76	2.16
265.1	393.3	2.45	14.84
340.2	603.3	4.41	17.73
388.1	823.3	9.69	21.21
Rep. II:			
144.2	36.6	1.51	2.54
320.2	686.6	3.50	21.44
385.6	1046.6	8.55	27.14
401.0	713.3	15.27	17.79

Table 2: Continuation

FLOWERING STAGE (T= 56 days)

Water Use, Q, (mm)	Grain Yield, y, (kg/ha)	Crop Response factor, Ky	Water utilization efficiency, (kg/ha-cm of water)
At N= 0 kg/ha;			
Rep. I:			
179.4*	0.0	1.73	0.00
213.0	0.0	2.01	0.00
277.4	470.0	2.61	16.94
349.9	920.0	4.62	26.29
393.8	1070.0	10.79	27.17
Rep. II:			
179.4*	460.0	1.57	25.64
213.0	253.3	1.90	11.89
277.4	826.6	2.40	29.80
349.9	1446.6	4.01	41.34
393.8	1703.3	9.01	43.25
412.5	1903.3	21.52	46.14
At N= 45 kg/ha;			
Rep. I:			
185.1*	0.0	1.77	0.00
219.7	0.0	2.07	0.00
287.1	170.0	2.98	5.92
353.7	736.6	5.09	20.83
420.5	1003.3	82.44	23.86
422.6	936.6	171.88	22.16
Rep. II:			
185.1*	103.3	1.74	5.58
219.7	120.0	2.02	5.46
287.1	866.6	2.54	30.19
353.7	1070.0	4.69	30.25
420.5	1636.6	69.11	38.92
422.6	1686.6	139.50	39.91

Water Use, Q, (mm)	Grain Yield, y, (kg/ha)	Crop Response factor, Ky	Water utilization efficiency, (kg/ha-cm of water)
At N= 90 kg/ha;			
Rep. I:			
177.1	0	1.72	0
213.1	16.6	2.00	0.78
283.3	36.6	2.98	1.29
356.8	320.0	5.86	8.97
415.1	1153.3	34.20	27.78
418.7	836.6	59.71	19.98
Rep. II:			
177.1	80.0	1.69	4.52
213.1	70.0	1.98	3.29
283.3	820.0	2.50	28.94
356.8	1470.0	4.39	41.20
415.1	1820.0	28.13	43.84
418.7	1880.0	44.46	44.90
At N= 135 kg/ha;			
Rep. I:			
168.6	0.0	1.66	0.00
225.8*	70.0	2.11	3.10
287.6	970.0	2.49	33.73
357.0*	870.0	5.18	24.37
403.2	1076.6	15.50	26.70
422.0	1460.0	114.87	34.60
Rep. II:			
168.6	20.0	1.65	1.19
225.8	463.3	1.94	20.52
287.6	1103.3	2.41	38.36
357.0	1103.3	4.87	30.91
403.2	1136.6	15.26	28.19
422.0	1220.0	122.88	28.91

Table 2: Continuation

Water Use, Q, (mm)	Grain Yield, y, (kg/ha)	Crop Response factor, Ky	Water utilization efficiency, (kg/ha-cm of water)
GRAIN FORMATION STAGE (T= 68 days)			
At N= 0 kg/ha;			
Rep. I:			
171.1*	803.3	1.40	46.95
172.0	100.0	1.65	5.81
260.1	1403.3	1.85	53.95
282.5	2520.0	1.46	89.20
297.5	3193.3	1.17	107.34
332.7	2833.3	1.96	85.16
Rep. II:			
171.1*	26.6	1.67	1.56
172.0	60.0	1.66	3.49
260.0*	553.3	2.30	21.27
282.5	3520.0	0.85	124.60
297.5	2866.6	1.40	96.36
332.7	3333.3	1.50	100.19
At N= 45 kg/ha;			
Rep. I:			
171.2	0.0	1.68	0.00
194.0	50.0	1.82	2.58
244.0*	66.6	2.32	2.73
275.3	1400.0	2.03	50.85
335.8	2453.3	2.40	73.06
343.0	2403.3	2.67	70.07
Rep. II:			
156.5*	0.0	1.59	0.00
175.0	226.6	1.62	12.95
229.4	620.0	1.90	27.03
269.2	993.3	2.18	36.90
347.9	2120.0	3.14	60.94
369.9	2086.6	4.47	56.41

Water Use, Q, (mm)	Grain Yield, y, (kg/ha)	Crop Response factor, Ky	Water utilization efficiency, (kg/ha-cm of water)
At N= 90 kg/ha;			
Rep. I:			
171.7*	66.6	1.66	3.88
231.9	836.6	1.83	36.08
273.5	813.3	2.35	29.74
311.0	1786.6	2.38	57.45
325.2	2200.0	2.36	67.65
368.7	1870.0	4.70	50.72
Rep. II:			
171.7*	40.0	1.66	2.33
231.9	50.0	2.18	2.16
273.5	136.6	2.73	5.00
311.0	2733.3	1.66	87.89
325.2	1636.6	2.85	50.33
368.7	2720.0	3.39	73.77
At N= 135 kg/ha;			
Rep. I:			
157.7*	0.0	1.59	0.00
189.0	136.6	1.75	7.23
259.7	666.6	2.23	25.67
299.5	1300.0	2.50	43.41
338.1	2036.6	2.87	60.24
Rep. II:			
189.0	333.3	1.68	17.64
231.9	386.6	2.03	16.67
259.7	1786.6	1.64	68.80
299.5	2486.6	1.68	83.03
338.1	1536.6	3.37	45.45
370.6*	3666.6	2.01	98.94

Table 2: Continuation

Water Use, Q, (mm)	Grain Yield, y, (kg/ha)	Crop Response factor, Ky	Water utilization efficiency, (kg/ha-cm of water)
NO DEFICIT STAGE (T= 100 days)			
At N= 0 kg/ha;			
Rep. I:			
205.1	853.3	1.60	41.61
257.2	236.0	1.32	91.76
366.2	4086.6	1.23	111.60
413.9	3060.0	15.00	73.93
419.1	3833.3	17.00	91.47
426.8	3433.3	58.30	80.44
Rep. II:			
205.1	10.0	1.93	0.49
257.2	270.0	2.40	10.50
366.2*	333.3	6.75	9.10
413.9	2033.3	23.29	49.13
419.1	3653.3	19.85	87.17
426.8	3903.3	39.36	91.46
At N= 45 kg/ha;			
Rep. I:			
200.4	666.6	1.638	33.27
250.8	1853.3	1.523	73.90
339.3	4366.6	0.562	128.70
424.6	4366.6	∞	102.84
434.8*	2520.0	- 20.33	57.96
462.1	2600.0	- 5.35	56.27
Rep. II:			
220.4	106.6	1.85	5.32
250.8	786.6	2.05	31.37
339.3	2100.0	2.85	61.89
424.6	4920.0	0/0	115.87
434.8*	1833.3	- 26.13	42.17
462.1	3453.3	- 3.38	74.73

Water Use, Q, (mm)	Grain Yield, y, (kg/ha)	Crop Response factor, Ky	Water utilization efficiency, (kg/ha-cm of water)
At N= 90 kg/ha;			
Rep. I:			
192.1	133.3	1.78	6.94
230.4	270.0	2.07	11.72
347.2	1770.0	3.52	50.98
421.5*	2950.0	54.80	69.99
422.5	3036.6	77.37	71.87
441.7	3000.0	-9.68	67.92
Rep. II:			
160.6*	0.0	1.61	0.00
166.5*	16.6	1.64	1.00
176.9	86.6	1.68	4.90
233.4	160.0	2.15	6.86
300.2	1753.3	2.20	58.41
386.0	2420.0	5.58	62.69
At N= 135 kg/ha;			
Rep. I:			
153.5*	0.0	1.57	0.00
160.6	16.6	1.60	1.04
223.5	33.3	2.10	1.49
302.7	1420.0	2.48	46.91
386.8	3186.6	3.96	82.39
449.0	3066.6	- 7.89	68.93
Rep. II:			
Rejected completely due to heavy bird damage.			

different levels of nitrogen (N, kg/ha), between grain yield, y in kg/ha(dependent variable) and water use, Q in mm (independent variable) and the value of R^2 for each regression equation are as following (all equations significant at 1% level except where otherwise marked):

Vegetative Stage (T= 30 days):

At N= 0, $y = 267.359 - 3.73186Q + 0.0155982Q^2$, $R^2 = 0.94$

At N= 45, $y = -943.719 + 7.18158Q - 5.63288 \times 10^{-3}Q^2$, $R^2 = 0.86$

At N= 90, $y = 892.674 - 9.67966Q + 0.0274038Q^2$, $R^2 = 0.91$

At N= 135, $y = -538.874 + 4.00191Q - 1.1981 \times 10^{-3}Q^2$, $R^2 = 0.90$

Flowering Stage (T= 56 days):

At N= 0, $y = -1126.83 + 5.06409Q + 4.27556 \times 10^{-3}Q^2$, $R^2 = 0.84$

At N= 45, $y = -1534.86 + 7.84808Q - 2.58923 \times 10^{-3}Q^2$, $R^2 = 0.75$

At N= 90, $y = 151.184 - 3.67749Q + 0.0161397Q^2$, $R^2 = 0.69$

At N= 135, $y = -2403.02 + 18.1206Q - 0.0225658Q^2$, $R^2 = 0.94$

Grain Formation Stage (T= 68 days):

At N= 0, $y = -7721.99 + 58.1631Q - 0.0758758Q^2$, $R^2 = 0.87$

At N= 45, $y^* = -2515.14 + 15.3217Q - 0.0051198Q^2$, $R^2 = 0.93$

At N= 90, $y = -760.476 + 45.0886Q - 0.0485702Q^2$, $R^2 = 0.65$[a]

At N= 135, $y = -4362.19 + 30.3986Q - 0.0345647Q^2$, $R^2 = 0.71$[a]

No Deficit Stage (T= 100 days):

At N= 0, $y = -8265.87 + 55.0203Q - 0.0647574Q^2$, $R^2 = 0.73$

At N= 45, $y = -9919.42 + 66.0057Q - 0.0789173Q^2$, $R^2 = 0.76$

At N= 90, $y^* = -1834.3 + 8.77258Q + 5.70488 \times 10^{-3}Q^2$, $R^2 = 0.96$

At N= 135, $y^* = -2013.1 + 10.2593Q + 4.29153 \times 10^{-3}Q^2$, $R^2 = 0.92$[b]

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[a] significant at 5% level

[b] significant at 10% level

The equations which have an asterisk (*) on y are those equations which give negative value of y for the first point in Table 2 hence should not be used at such low values of Q. In general these equations are valid within the range of data set only.

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

Vegetative Stage (T= 30 days):

$$y = -83.2419 + 2.05688\ N - 0.107914\ N^2 - 0.747286Q + 0.0100705Q^2 - 5.62799 \times 10^{-3}\ NQ, \quad R^2 = 0.86$$

Flowering Stage (T= 56 days):

$$y = -1778.82 + 0.214481\ N + 0.0461677\ N^2 + 9.61182Q - 3.35078 \times 10^{-3}\ Q^2 - 0.207424\ NQ, \quad R^2 = 0.76$$

Grain Formation Stage (T= 68 days):

$$y = -4855.47 - 16.2039\ N + 0.141945\ N^2 + 35.5054Q - 0.0334574Q^2 - 0.0372201\ NQ, \quad R^2 = 0.80$$

Total Growth Period (T= 100 days):

$$y = -4677.61 + 3.92332\ N - 0.0263966\ N^2 + 30.3803Q - 0.0254922Q^2 - 0.0148113\ NQ, \quad R^2 = 0.77$$

Finally the growth stage represented by time of beginning of deficit (Vegetative T= 30 days, Flowering T= 56 days, Grain formation T= 68 days and No deficit T= 100 days) was also introduced as an independent variable along with nitrogen and water use. The multivariable regression analysis of quadratic nature gives the following equation (significant at 1% level):

$$y = -1526.55 - 26.714\ T - 0.0295695\ T^2$$
$$-2.65839\ N + 0.0408066\ N^2 + 14.1741Q$$
$$-0.0280272Q^2 - 0.0511639\ T\,N$$
$$+ 0.172276\ TQ - 0.0076658\ T\,NQ \quad , R^2 = 0.75$$

These multivariable regressions in general are valid within the range of data set. However some times these equations do give negative values of y for the lowest values of water use in the data set and should be utilized with this caution in mind.

Water utilization efficiency (WUE)

The water utilization efficiency is calculated by dividing the grain yield by the quantity of water use in kg/ha-cm of water and is given in Table 2. The highest values of the WUE were for no deficit case followed by the grain filling stage. The WUE for both vegetative and flowering stage were low. The highest average (of the two repetitions) water utilization efficiency was observed to be 109.3 kg/ha-cm of water at 424.6 mm water use for 45 kg/ha applied nitrogen and the no deficit stage. The average (of the two repetitions) highest grain yield was also obtained at the same point. It can be generalized from the values of the WUE in Table 2 that if quantity of water available is limited the deficit should not be allowed to occur during vegetative and the flowering stages otherwise the WUE can drastically fall.

Crop response factors (Ky)

Doorenbos and Kassam (1979) have developed the following model for predicting relative actual yield decrease for relative actual evapotranspiration deficit:

$$\left(1 - \frac{ya}{ym} \right) = Ky \left(1 - \frac{ETa}{ETm} \right).$$

Where:

ya= actual yield, kg/ha

ym= maximum obtainable yield, kg/ha

ETa= actual evapotranspiration, mm

ETm= maximum evapotranspiration for maximum obtainable yield, mm

Ky= crop response factor

The term (1 - ya/ym) becomes the relative actual yield decrease and (1 - ETa/ETm) becomes the relative actual evapotranspiration deficit. The factor Ky relates the two.

The maximum obtainable yield was taken as 4.92 ton/ha (= ym) at 424.6 mm (ETm) of water use. Based on this the values for Ky have been calculated for all levels of nitrogen for the 4 growth stages and are given in Table 2. The values of (1 - ETa/ETm) and (1 - ya/ym) have been plotted as shown in Fig. 1(a), (b), (c) and (d). In general, there is a wide spread in the values of Ky. The values are always above one (slope > 45°). The minimum values of Ky are shown by a line through the center for different stages and different nitrogen levels. From Fig. 1, the most critical stage was found to be

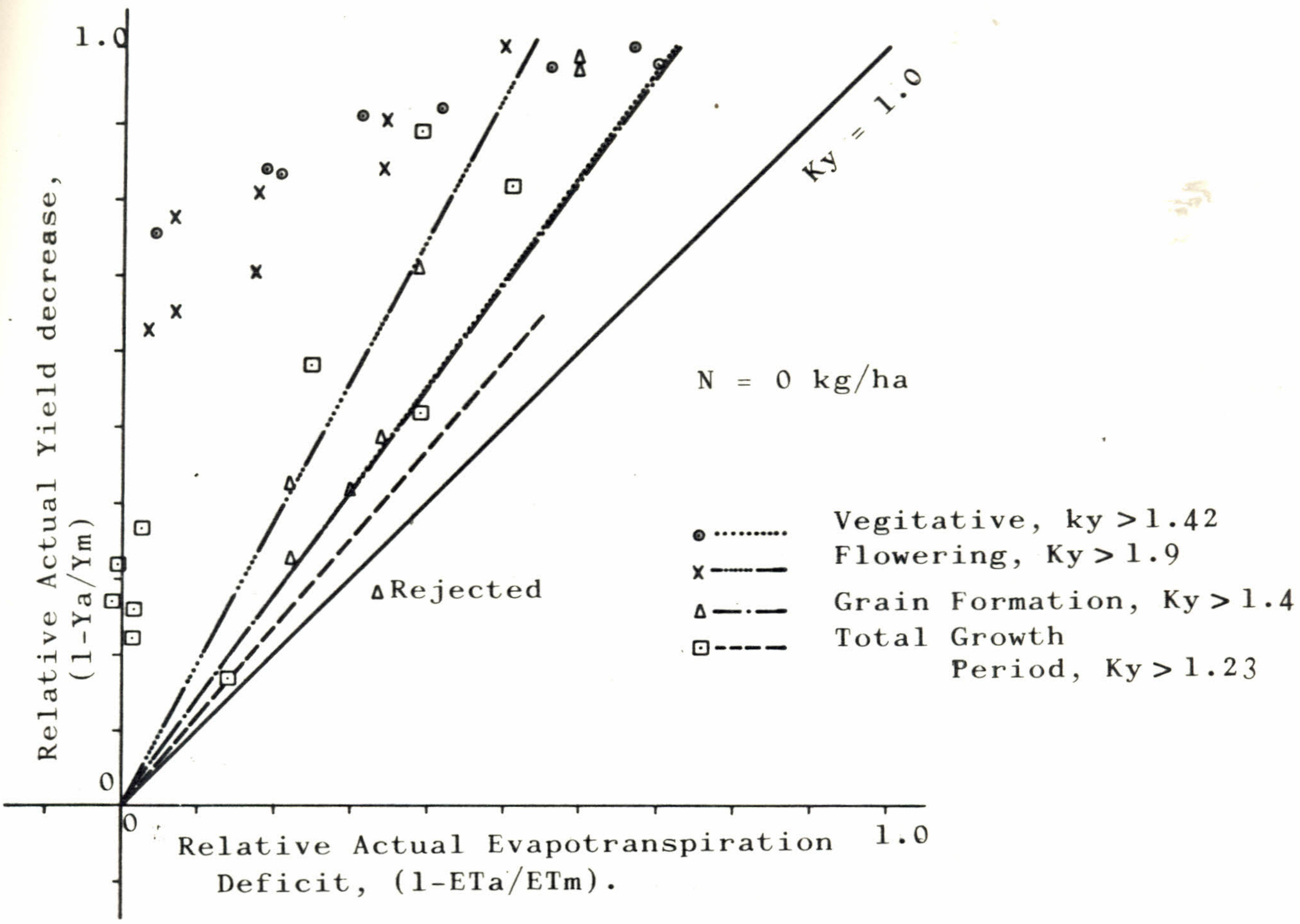

Fig. 1 (a): Relationship of relative actual evapotranspiration deficit with relative actual yield decrease at 0 kg/ha nitrogen level.

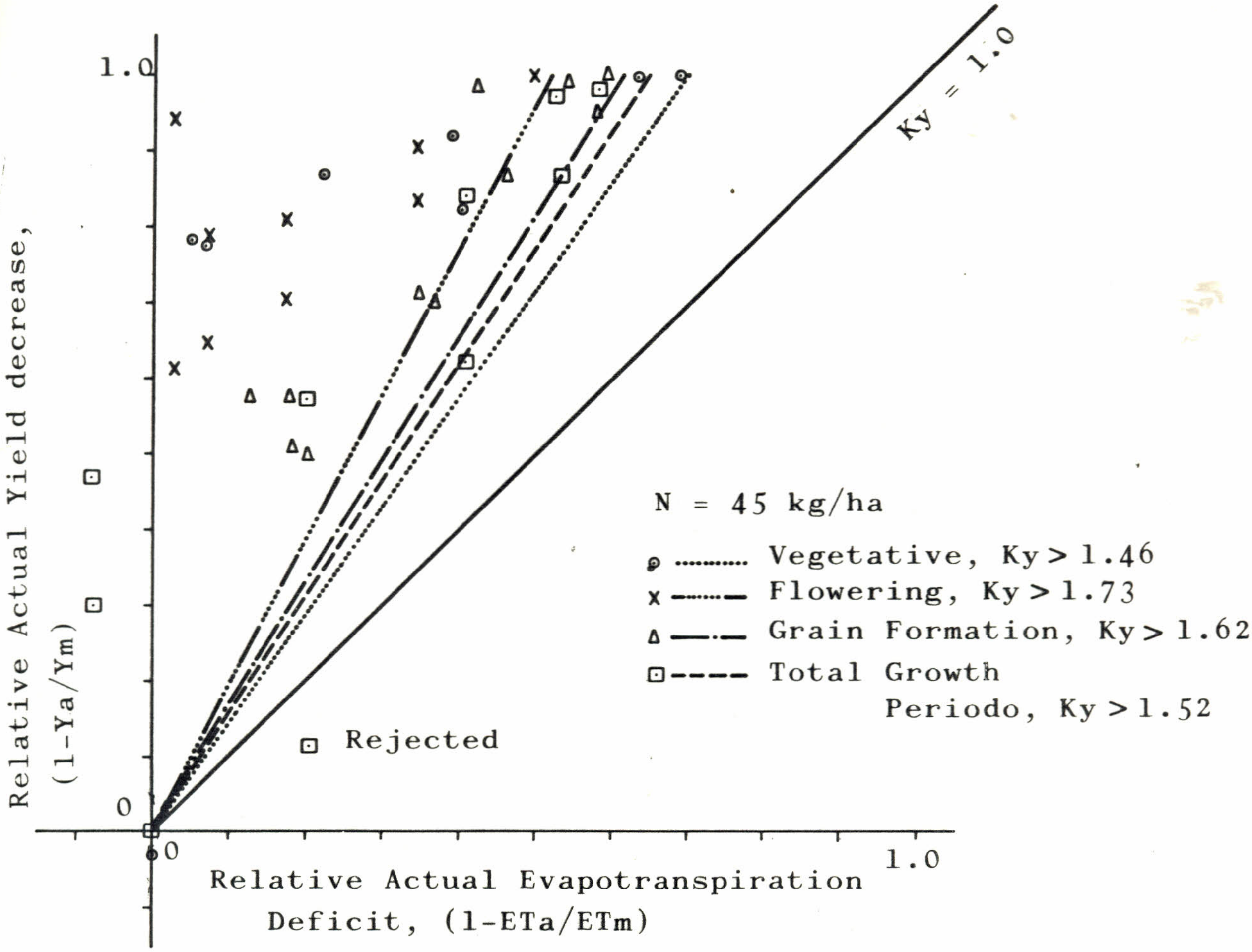

Fig. 1 (b): Relationship of relative actual evapotranspiration deficit with relative actual yield decrease at 45 kg/ha nitrogen level.

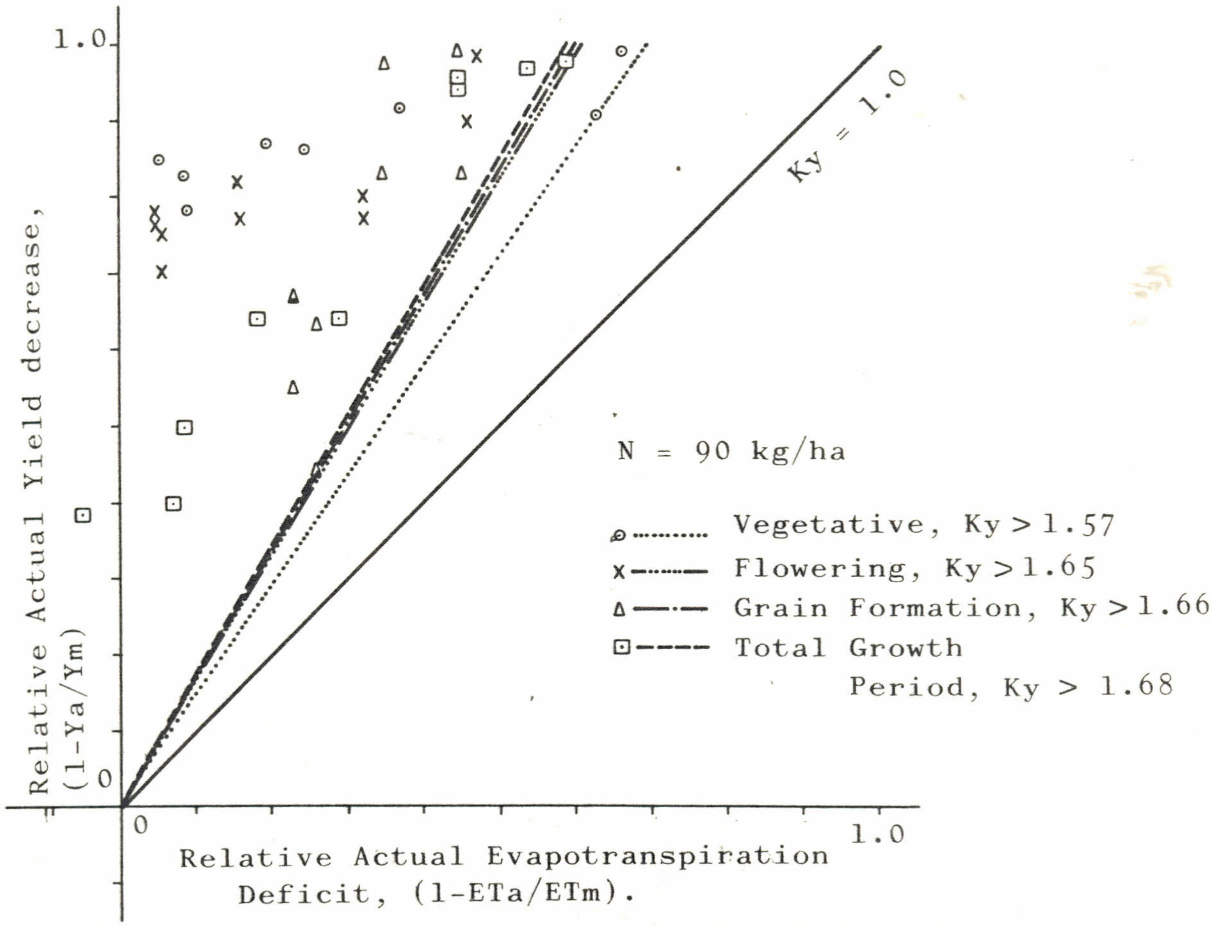

Fig. 1 (c): Relationship of relative actual evapotranspiration deficit with relative actual yield decrease at 90 kg/ha nitrogen level.

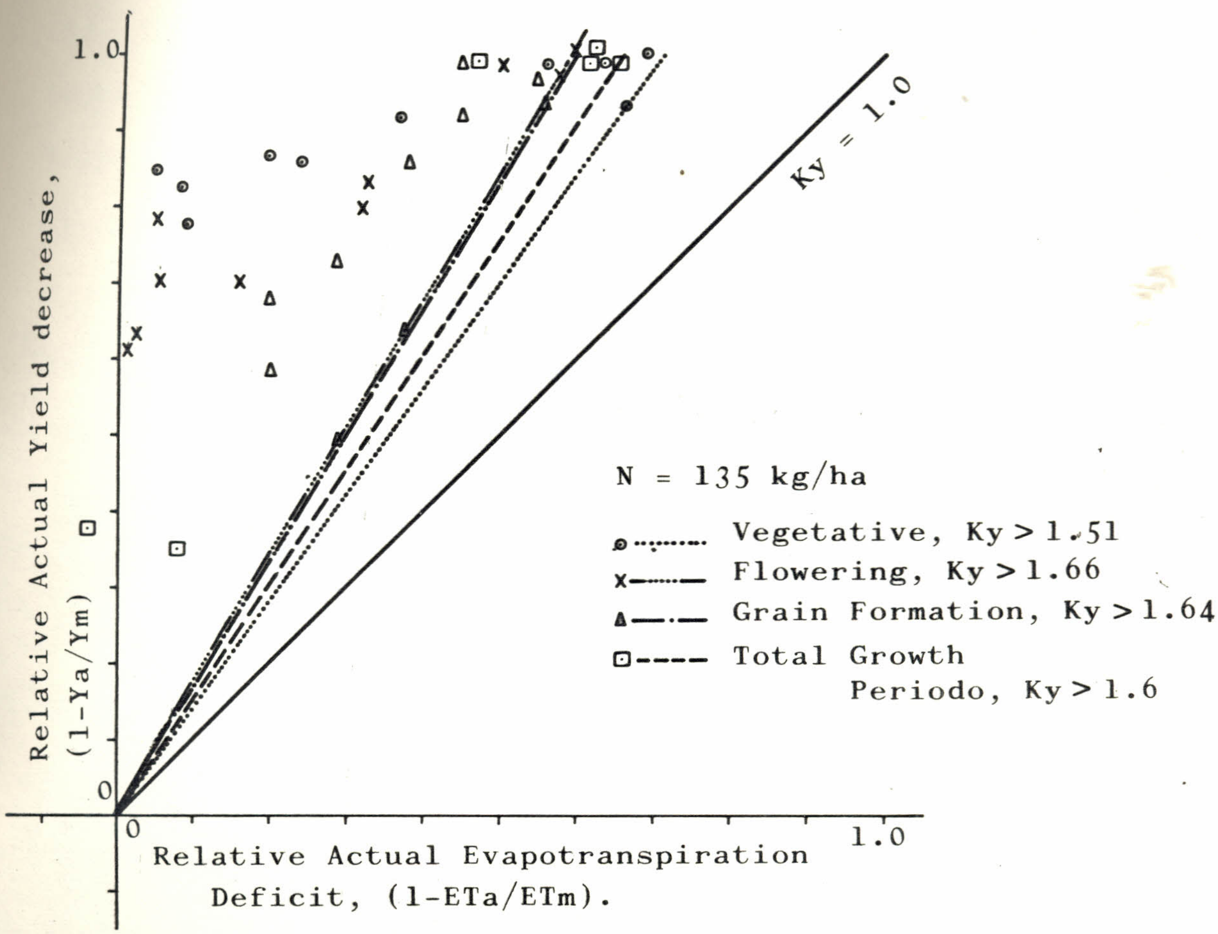

Fig. 1 (d): Relationship of relative actual evapotranspiration deficit with relative actual yield decrease at 135 kg/ha nitrogen level.

flowering stage followed by vegetative and grain formation stages. The crop response factors, Ky were found to be always greater than, 1.9 for flowering stage, 1.4 for vegetative and grain formation stages and always more than 1.23 for total growing period when nitrogen level was 0 kg/ha. The Ky factors at N= 45 kg/ha are respectively > 1.73 (flowering), > 1.62 (grain formation), > 1.46 (vegetative) and > 1.52 for total growth period. The minimum values of Ky for other N levels are given in Fig. 1 (c) & (d).

In general the relative decrease in yield with respect to decrease in relative ETa deficit is much lower (see the band of points in Fig. 1) for total growth period and grain formation stages compared to vegetative and flowering stages.

The factors Ky given here are much above the estimates of FAO (Doorenbos and Kassam, 1979) and have much wider scatter than the FAO estimates due to different climatic conditions.

Crop coefficients (Kc)

The crop coefficients (Kc) which are used for irrigation scheduling have been calculated by Pan Evaporation Method. The pan coefficients were taken as given by FAO (Doorenbos & Kassam) for the climatic conditions of the location of the experiment. The sample calculations for Kc at N= 45 kg/ha for no deficit growth stage and water use (ETa) = 424.6 mm case are shown in Table 3. This case was chosen as it gives the maximum WUE and yield and hence the optimum water use level. The water balance data for calculating the actual evapotranspiration (ETa) during different growth periods are also given in Table 3.

Table 3: Calculation of crop coefficients (Kc) for sorghum at N= 45 kg/ha, No deficit stage and maximum average water utilization efficiency and yield location.

Crop Development Periods	Initial	Crop Development	Mid-Season	Late Season	Harvest	Total
Duration from planting, day	0 - 17	18 - 44	45 - 68	69 - 85	86 - 106	0 - 106
Irrigation, mm	59.13	95.6	123.0	69.3	54.6	401.7
Soil moisture contribution to ETa (at N= 45)	-17.4	10.7	10.2	-3.2	- 48.0	- 39.0
Rainfall, mm	—	—	2.6	11.4	47.9	61.9
Actual Evapotranspiration (ETa)[1], mm (N= 45)	41.73	106.3	135.8	77.5	54.5	424.6
Pan Coefficient, K_p^2	0.65	0.65	0.65	0.65	0.65	0.65
Evaporation, Ev, mm	158.94	221.34	256.84	162.36	168.63	868.11
Ref.Crop ET, ETo= K_pEv, mm	103.31	143.87	166.95	105.53	109.6	564.27
Kc= ETa/ETo (Calculated)	0.40	0.74	0.81	0.73	0.5	0.75
FAO, Kc values	0.3	0.7	1.05	0.75	0.5	0.75

[1]ETa= (Irrigation + Soil Moisture Contribution + Rainfall), assuming no deep percolation and there was no runoff.

[2]For moderate wind velocities (175-425 km/day) and high mean relative humidity (RH_{mean} > 70%), FAO source,Doorenbos and Kassam (1979). The pan is located in the green grass cover (< 1 m).

The crop coefficients (kc) for the N= 45 kg/ha for optimum water level are 0.40 for initial period (0-17 days), 0.74 for crop development period (18-44 days), 0.81 for mid season (45-68 days), 0.73 for late season (69-85 days) and 0.5 for harvest period (86-106 days), respectively. The Kc value for total period is 0.75. These coefficients are in general around the range suggested by the FAO except in the mid season (Kc= 0.81) where the value is lower than the FAO value of Kc= 1.05.

Table 4 gives the values of Kc calculated for different N levels at their optimum water use levels. Crop coefficients for N= 0 kg/ha and N= 45 kg/ha for different growth periods are about equal. The Kc values for N= 90 kg/ha and N= 135 kg/ha are generally lower than the Kc values for N= 0 kg/ha and 45 kg/ha except for initial period and mid season in the case of N= 90 kg/ha. This explains why the yields were lower at these higher N levels though over all the value of Kc for total period may be equal as in the case for N= 90 kg/ha.

CONCLUSIONS

The multivariable regression equations developed here can be utilized for economic analysis of new supplemental irrigation projects. The crop response factors Ky developed here can also be utilized for irrigation project planning or for decisions on the choice of sorghum as a crop in the cropping mix of an irrigation project to predict in advance the effect of limited quantities of water for irrigation. The crop coefficients developed can be utilized for irrigation scheduling. The highest average water

Table 4: Values of Crop Coefficients (Kc) for Sorghum at different nitrogen levels.

Nitrogen level, (kg/ha)	Value of Kc at different growth periods					
	Initial (0-17 days)	Crop development (18-44 days)	Mid Season (45-68 days)	Late Season (69-85 days)	Harvest (86-106 days)	Total period
0	0.4	0.74	0.86	0.74	0.45	0.76
45	0.4	0.74	0.81	0.73	0.5	0.75
90	0.4	0.59	0.91	0.64	0.58	0.75
135	0.4	0.65	0.59	0.65	0.68	0.68
FAO Values	0.3	0.7	1.05	0.75	0.5	0.75

utilization efficiency of 109.3 kg/ha-cm of water and highest grain yield of 4.92 tons/ha was obtained at 424.6 mm of water use at 45 kg/ha of applied nitrogen for no water deficit in total growth stage case of which the value of Ky is always > 1.52 and the value of Kc for total period is 0.75. The value of Kc for initial period is 0.4, for crop development period is 0.74, for mid season is 0.81, for late season is 0.73 and for harvest period is 0.5 (at N= 45 kg/ha). The recommendations can immediately be used.

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FIGURE CAPTIONS

Fig. 1 (a): Relationship of relative actual evapotranspiration deficit with relative actual yield decrease at 0 kg/ha nitrogen level.

Fig. 1 (b): Relationship of relative actual evapotranspiration deficit with relative actual yield decrease at 45 kg/ha nitrogen level.

Fig. 1 (c): Relationship of relative actual evapotranspiration deficit with relative actual yield decrease at 90 kg/ha nitrogen level.

Fig. 1 (d): Relationship of relative actual evapotranspiration deficit with relative actual yield decrease at 135 kg/ha nitrogen level.