

## PERFORMANCE EVALUATION OF SELECTED CROP YIELD-WATER USE MODELS FOR WHEAT CROP

Igbadun, H.E.<sup>1</sup>, O.J. Mudiare<sup>1</sup> and A. Ahmed<sup>1</sup>

### Abstract

Crop yield-water use models that provide useful information about the exact form of crop response to different amounts of water used by the crop throughout its growth stages, and those that provide adequate information for decisions on optimal use of water in the farm were evaluated. Three crop yield models: Jensen (1968), Minhas *et al.*, (1974) and Bras and Cordova (1981) additive type models were studied.

Wheat (*Triticum aestivum*) was planted at the Institute for Agricultural Research Farm during the 1995/96 and 1996/97 irrigation seasons of November to March. The data collected from the field experiments during the 1995/96 planting season were used to calibrate the models and their stress sensitivity factors estimated for four selected growth stages of the wheat crop.

The ability of the model to predict grain yield of wheat with the estimated stress sensitivity factors was evaluated by comparing predicted grain yields by each model with those obtained in the field during the 1996/97 season. The three models performed fairly well in predicting grain yields, as the predicted results were not significantly different from the field measured grain yield at 5% level of significance.

### 1. Introduction

In order to study the question of economic optimal use of water by crop in the farm, we need to know the exact shape of the crop response function to different amounts of water used by the crop throughout the growth stages. It is a well-known fact that certain growth stages of crop are more sensitive to water deficits than others. Thus, knowledge of the marginal productivity of water allocated to each crop at different stages of growth is required to arrive at an optimal set of decisions. According to Stewart *et al.* (1973) and Minhas *et al.* (1974), crop water use function (also called crop yield water use models) for crops in which crop yield is related to water inputs will provide such knowledge. Crop water production functions attempt to express crop yield as a dependent variable of water applied at various crop growth stages. Crop water production functions also serve as a powerful tool for a rational design and effective management of irrigation systems. (See DeWit, 1958; Hillel and Guron, 1973; Hanks and Hills, 1980, for a comprehensive background on crop water production functions).

According to Taskiris (1982), crop water production functions derived from experiments are usually valid only near the location where they are provided. This is because the absolute quantity of water to produce a given yield differs greatly between locations. More so, no crop-water function is universally applicable to all crops, growing season and climate (Rhenals and Bras, 1981). It is therefore necessary to formulate, validate or evaluate crop yield models for different locations and crops. In the experiment reported herein, three crop production functions were evaluated for wheat crop grown in Samaru, Zaria, Nigeria. The general objective is to study

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<sup>1</sup> Department of Agricultural Engineering, Ahmadu Bello University Zaria

the models' capability in predicting grain yield, given the input parameters. The specific objectives are to estimate the models stress sensitivity factors for four selected growth stages of the crop, and test their applicability and accuracy in predicting relative grain yield of the wheat crop.

## 2. Materials and methods

### 2.1 The crop production model

The three crop water use functions (crop yield models) studied were those of Jensen (1968), Minhas *et al.* (1974) and Bras and Cordova (1981). Jensen (1968) developed a crop production function, which divided the crop-growing season into stages, with evapotranspiration deficit in each stage having a unique effect on crop yield. The production function expresses relative grain yield (ratio of grain yield from stressed treatment,  $Y_o$ , to grain yield from control plot,  $Y_m$ ) as a function of relative evapotranspiration (actual evapotranspiration from stress treatment,  $ET_a$ , divided by maximum evapotranspiration, from control treatment,  $ET_m$ ). The expression is given as:

$$\frac{Y_o}{Y_m} = \prod_{i=1}^n \left[ \frac{ET_a}{ET_m} \right]^{\lambda_i} \quad (1)$$

Where  $\lambda$  = the relative sensitivity of the crop to water stress in the growth stage and is a parameter to be estimated;  
 $n$  = the number of growth stages considered  
 $\Pi$  = multiplicative sign

Other terms are as previously defined.

Minhas *et al.* (1974) production function is also based on relative evapotranspiration given as:

$$\frac{Y_o}{Y_m} = \prod_{i=1}^n \left[ 1.0 - \left( 1.0 - \frac{ET_a}{ET_m} \right)^2 \right]^{b_i} \quad (2)$$

in which  $b_i$  is the parameter to be estimated, defined as the relative sensitivity factor of the crop to water stress in  $i$ th growth stage.

The Bras and Cordova (1981) model is given by the expression:

$$\frac{Y_o}{Y_m} = \sum_{i=1}^n A_i \left[ \frac{ET_a}{ET_m} \right]_i \quad (3)$$



where  $A_i$  = the crop sensitivity parameter to be estimated.

The Jensen (1968) and Minhas *et al.* (1974) models are multiplicative models in which the crop yield becomes zero if evapotranspiration becomes zero at any growth stage; while the Bras-Cordova (1981) model is an additive one.

## 2.2 Experimental procedure

The study was carried out at the Institute for Agricultural Research (I.A.R.) Farm in Samaru, Zaria during the 1995/96 and 1996/97 cool harmattan seasons of November to March. Some meteorological data for the two seasons of study as obtained from the I.A.R.'s meteorological station located 150m away from the experimental site are shown in Table 1; and some physical properties of the soil of the experimental plots are shown in Table 2.

**Table 1: Selected meteorological data for the two seasons of the study area**

Data	December		January		February		March	
	1995	1996	1996	1997	1996	1997	1996	1997
Max. temp. (°C)	29.6	32.6	28.	32.5	31.9	29.4	33.6	35.1
Min. temp. (°C)	11.1	11.7	13.5	13.3	15.7	13.4	17.2	19.0
Rel. humidity (%)	27.0	16.2	22.1	17.8	17.8	14.3	15.5	23.8
Pan evaporation (mmday <sup>-1</sup> )	10.8	8.3	9.3	8.4	10.0	13.4	11.1	11.4

**Table 2: Soil physical properties of the experimental plot**

Soil profile depth (mm)	Field capacity at 0.3 x 10 <sup>2</sup> kPa, (%)	Wilting point at 15 x 10 <sup>2</sup> kPa, (%)	Soil bulk density (gcm <sup>-3</sup> )	Soil textural class
0-150	14.7	3.1	1.58	loam
150-300	12.0	4.5	1.60	clay loam
300-450	16.9	8.7	1.61	clay loam
450-600	16.3	10.6	1.62	clay loam

Check basins of size 2.0m x 2.5m were seeded to wheat (*Triticum aestivum* L. Cv. *Siete cerros*) during the 1995/96 planting season. Planting was done on 25th November 1995. Check basins of size 2.0m x 3.0m were used for the 1996/97 season, and planting was done on 26th of November, 1996. The 1995/96 season experiment was designed with the aim of using the data collected to estimate the stress sensitivity factors of the models while the 1996/97 season experiment were conducted to test the applicability and reliability of the stress sensitivity factors estimated in predicting relative grain yield for the wheat crop. The wheat seeds were broadcast within the levelled check basins at a rate of 100 kg ha<sup>-1</sup>. Compound fertilizer (NPK 27:13:10) was applied at the rate of 120 kg ha<sup>-1</sup> in two equal split doses, at planting and 4 weeks after germination.



Thirteen irrigation experimental treatments were used during the 1995/96 season while twelve were used during the 1996/97 season. The irrigation treatment was based on the time of application of water. The treatments were replicated thrice in a randomized complete block design for each season. Table 3 shows the description of the selected crop growth stages used for the study. Tables 4 and 5 show the treatment description for the 1995/96 and 1996/97 seasons respectively.

**Table 3: Description and length of growth stages**

Growth stage	Description	Days after planting
I	Stem elongation to booting initiation	40-56
II	Full booting to heading	57-70
III	Flowering to milk dough	71-84
IV	Soft dough to hard dough	85-92

The design of the treatments for the 1995/96 planting season were slightly different from the 1996/97 season. During the 1995/96 season, treatment design was such that irrigation was delayed for some days beyond the regular 7-day irrigation interval at each of the selected crop growth stages. The control treatment and the other treatments not subjected to stress at that stage were irrigated at 7-day interval. Irrigation was delayed for 4 days, 7 days and 9 days beyond the regular 7-day interval at each of the growth stages. The 1996/97 treatment variation was by skipping the 7-day irrigation interval (that is, withholding irrigation for one week) at selected growth stages of the crop after the initial irrigation at the beginning of that growth stage until that growth stage is passed, while the control treatment was irrigated at the regular 7-day irrigation interval.

Check basin irrigation method was used during the two seasons. Water was released from the main canal into the furrow that served the check basins. The flow rate estimated using the velocity - area method was  $2.25 \text{ ls}^{-1}$ . One basin was opened at a time to allow all the water to enter the basin. An average time of 2.5 minutes was taken to pond each basin. The average depth of water applied per irrigation was 60 mm. The flow rate for the 1995/96 season could not be maintained at  $2.25 \text{ ls}^{-1}$  per irrigation due to constant water demands by other farmers downstream. However, the basins were adequately ponded at each irrigation.

**Table 4: Treatment description for 1995/96 planting season**

Growth stage	Treatment	Description
Control I	1	Irrigated at 7-day interval throughout the season
	2	Irrigation delayed for 4 days beyond the regular 7 days interval at stage I
	3	Irrigation delayed for 7 days beyond the regular 7 days interval at stage I
	4	Irrigation delayed for 9 days beyond the regular 7 days interval at stage I
II	5	Irrigation delayed for 4 days beyond the regular irrigation interval at stage II
	6	Irrigation delayed for 7 days beyond the regular irrigation interval at stage II
	7	Irrigation delayed for 9 days beyond the regular irrigation interval at stage II
III	8	Irrigation delayed for 4 days beyond the regular irrigation interval at stage III
	9	Irrigation delayed for 7 days beyond the regular irrigation interval at stage III
	10	Irrigation delayed for 9 days beyond the regular irrigation interval at stage III
IV	11	Irrigation delayed for 4 days beyond the regular irrigation interval at stage IV
	12	Irrigation delayed for 7 days beyond the regular irrigation interval at stage IV
	13	Irrigation delayed for 9 days beyond the regular irrigation interval at stage IV

**Table 5: Treatment description for 1996/97 planting season**

Treatment	Description
1	Irrigated at 7 day interval throughout the season (control treatment)
2	Regular irrigation interval skipped once at growth stage I only
3	Regular irrigation interval skipped once at growth stage II only
4	Regular irrigation interval skipped once at growth stage III only
5	Regular irrigation interval skipped once at growth stage IV only
6	Regular irrigation interval skipped once at growth stages I and IV only
7	Regular irrigation interval skipped once at growth stages I and II only
8	Regular irrigation interval skipped once at growth stages II and IV only
9	Regular irrigation interval skipped once at growth stages II and III only
10	Regular irrigation interval skipped once at growth stages III and IV only
11	Regular irrigation interval skipped once at growth stages I, II and IV only
12	Regular irrigation interval skipped once at all growth stages.



Soil moisture content was monitored throughout the crop growing season for each treatment by gravimetric method. Samples were collected on second and seventh day after each irrigation. The soil samples were collected at 150 mm depth intervals down to 600 mm in two replications, and oven dried at 105<sup>0</sup>C for 24 hours for the determination of moisture content. Crop water use was calculated based on the difference in soil moisture depth between the two samples. Drainage was assumed negligible two days after irrigation. This is because soil moisture content at two days after irrigation was relatively close ( $\pm 1\%$ ) to that at field capacity ( $0.3 \times 10^2$  kPa). The crops were harvested manually and threshed to obtain the grain yield.

### **2.3 Model parameter determination**

The parameters estimated in each of the three models (Equations 1, 2 and 3) were the stress sensitivity factors for the four growth stages used in the study. The grain yield from the control treatment was considered as the maximum yield ( $Y_m$ ) while the yields from the other plots were regarded as  $Y_o$ . The highest evapotranspiration value recorded for a growth stage was taken as the maximum evapotranspiration ( $ET_m$ ) for that growth stage. The stress sensitivity factors for the growth stages were then estimated using the multiple linear regression technique. The multiplicative models were first transformed to logarithmic equations for the regression analysis. The relative grain yields ( $Y_o/Y_m$ ) were the dependent variables while the relative evapotranspiration ( $ET_o/ET_m$ ) for the growth stages were the independent variables in Equations 1, 2 and 3. Grain yield and evapotranspiration data for the 1995/96 season were used to estimate the stress sensitivity parameters of the models. The models were then tested with the 1996/97 yield data to see how close the simulated grain yield was to the actual grain yield.

## **3. Results and discussion**

Tables 6 and 7 show the crop water use at various growth stages and the average grain yield during the 1995/96 and 1996/97 irrigation seasons, respectively. It was observed that the total seasonal evapotranspiration for the 1995/96 season was higher than that of the 1996/97 season. This could be attributed to the fact that more water was applied in 1995/96 compared with 1996/97 and hence the higher evapotranspiration values. The peak consumptive use was recorded at the third growth stage between the 57th and 70th days after planting. Grain yield and seasonal evapotranspiration were highest in the control treatment and were lowest in treatments 8, 9 and 10 where the crops were stressed at the flowering to milk dough stage during the 1995/96 season. Similarly, seasonal evapotranspiration was also found to be lowest in treatment 12 during 1996/97 season where the crops were stressed at all the growth stages.



**Table 6: Crop water use at different growth stages for the 1995/96 season**

Growth stage	Treatment	Evapotranspiration (mm)						Total ET (mm)	Grain yield (tha <sup>-1</sup> )
		Days after planting							
		1-27	28-42	43-56	57-70	71-84	85-92		
Control	1	41.4	63.1	92.0	99.1	83.2	29.7	409	2.70
I	2	37.3	56.1	96.3	96.1	82.8	29.9	389	2.50
	3	39.8	48.5	85.5	98.1	81.0	29.5	383	2.46
	4	40.2	45.5	85.0	92.2	81.6	30.9	375	2.45
II	5	43.3	64.0	72.3	90.5	82.2	34.0	387	2.48
	6	45.6	61.8	60.7	97.4	82.4	36.9	375	2.34
	7	40.6	62.2	55.9	85.8	84.0	31.0	360	2.07
III	8	38.0	62.0	87.9	74.3	76.0	30.7	369	2.11
	9	37.2	61.7	87.6	61.9	76.3	30.0	355	2.00
	10	38.7	58.4	89.6	57.8	70.9	34.9	350	1.98
IV	11	42.1	60.0	90.0	97.1	65.2	29.2	384	2.47
	12	40.7	58.6	89.7	98.8	58.1	30.0	376	2.39
	13	38.6	63.0	87.1	89.6	52.8	37.8	369	2.36

**Table 7: Crop water use at different growth stages for the 1996/97 season**

Growth stage	Treatment	Evapotranspiration (mm)						Total ET (mm)	Grain yield (tha <sup>-1</sup> )
		Days after planting							
		1-27	28-42	43-56	57-70	71-84	85-92		
Control	1	44.0	58.2	88.8	98.1	58.7	20.3	368	3.11
I	2	44.0	44.3	79.9	98.1	58.7	20.5	346	2.90
II	3	44.0	58.2	58.6	83.4	58.7	17.4	320	2.41
II	4	44.0	58.2	88.6	54.0	50.7	19.4	315	1.99
IV	5	44.0	58.2	88.6	98.1	35.2	15.3	339	2.78
I & IV	6	44.0	44.2	80.9	98.1	40.5	13.2	321	2.75
I & II	7	44.0	44.2	58.6	98.1	58.7	18.1	322	2.73
II & IV	8	44.0	58.2	53.3	83.2	40.5	14.3	294	2.20
II & III	9	44.0	58.2	53.3	49.0	47.0	10.4	262	1.75
III & IV	10	44.0	58.2	88.6	61.2	345	16.3	300	2.23
I, II & IV	11	44.0	44.2	58.6	88.6	40~5	13.4	289	1.96
All stages	12	44.0	44.0	58.6	52.0	35.2	14.3	248	1.47

Table 8 shows the relative evapotranspiration ( $ET/ET_m$ ) for the four growth stages and the relative grain yield ( $Y_\sigma/Y_m$ ) for the 1995/96 season. The data in Table 8 was used to determine the parameters in Equations 1, 2 and 3 as explained above which quantify the stress sensitivity factors of the growth stages. Table 9 shows the estimated stress sensitivity factors for each model. The results show the dominating influence of growth stage III, that is, the flowering to milk dough development on wheat grain production. However, the results show that moisture stress at any of the four selected crop growth stages will have significant effect on the grain yield.

**Table 8: Relative evapotranspiration for the four growth stages and relative yield for the 1995/96 season.**

Treatment	Relative evapotranspiration ( $ET_\sigma/ET_m$ )				Relative yield $Y_\sigma/Y_m$
	Growth stage				
	I	II	III	IV	
1	0.99	1.00	1.00	0.99	1.00
2	0.88	0.94	0.97	0.98	0.93
3	0.76	0.93	0.97	0.96	0.91
4	0.71	0.92	0.93	0.97	0.91
5	1.00	0.97	0.91	0.98	0.92
6	0.97	0.66	0.98	0.98	0.87
7	0.97	0.61	0.87	1.00	0.77
8	0.97	0.96	0.75	0.90	0.78
9	0.97	0.95	0.62	0.91	0.74
10	0.91	0.97	0.58	0.84	0.73
11	0.94	0.98	0.98	0.78	0.92
12	0.92	0.97	1.00	0.69	0.89
13	0.99	0.95	0.90	0.63	0.88

**Table 9: Estimated stress sensitivity factors for the models**

Model	Growth stage					$r^2$
	Control	I	II	III	IV	
Bras-Cordova (1981)	$A_0$ -0.0626	$A_1$ 0.089	$A_2$ 0.302	$A_3$ 0.477	$A_4$ 0.175	0.954
Minhas <i>et al.</i> (1974)	$b_0$ -0.024	$b_1$ 0.383	$b_2$ 0.925	$b_3$ 1.468	$b_4$ 0.	0.962
Jensen (1968)	$\lambda_0$ -0.006	$\lambda_1$ 0.114	$\lambda_2$ 0.289	$\lambda_3$ 0.518	$\lambda_4$ 0.156	0.962

Table 10 shows the relative evapotranspiration for the 1996/97 season that was used to test the accuracy of the models. Relative grain yields for the 1996/97 season and the predicted relative grain yield for the three models are given in Table 11.



**Table 10: Relative evapotranspiration for the 1996/97 Season.**

Treatment	Relative evapotranspiration ( $ET_d/ET_m$ )			
	Growth stage			
	I	II	III	IV
1	1.00	1.00	1.00	1.00
2	0.76	0.90	1.00	1.00
3	1.00	0.66	0.85	1.00
4	1.00	0.99	0.56	0.86
5	1.00	0.99	1.00	0.60
6	0.76	0.91	1.00	0.69
7	0.76	0.66	1.00	1.00
8	1.00	0.66	0.85	0.69
9	1.00	0.60	0.50	0.80
10	1.00	1.00	0.62	0.59
11	0.76	0.66	0.90	0.69
12	0.76	0.66	0.53	0.60

**Table 11: Measured and predicted relative yields of the models**

Treatment	Measured relative yield	Predicted relative yield		
		Jensen	Minhas <i>et al.</i>	Bras-Cordova
1	1.00	1.00	1.00	1.00
2	0.93	0.93	0.94	0.93
3	0.77	0.81	0.84	0.81
4	0.64	0.72	0.70	0.74
5	0.89	0.93	0.89	0.91
6	0.88	0.88	0.90	0.88
7	0.88	0.85	0.84	0.86
8	0.71	0.74	0.76	0.73
9	0.56	0.58	0.58	0.59
10	0.71	0.71	0.71	0.33
11	0.63	0.76	0.79	0.75
12	0.47	0.57	0.53	0.556
Mean difference		-0.034	-0.034	-0.035
S.E.		0.047	0.051	0.045

It can be observed that each model simulated the relative grain yield very well. The absolute mean difference values between the measured relative yield and the predicted relative yield were less than 0.05 in all the models. This implies that each model adequately predicted relative grain yield, and that the sensitivity factors estimated for each model are reliable.

#### 4. Conclusion

The three models were found to adequately predict relative grain yield as the predicted results were not significantly different from the measured grain yield at the 5% level of significance. The stress sensitivity factors estimated for the models are therefore reliable.

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