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Crop conceptual model for predicting productivity of bread wheat in semi-arid Kenya

P. K. Kimurto[1], K. Gottschalk[2], M. G. Kinyua[3], J. B. O. Ogola[4], B. K. Towett [1]

(1. *Department of Crops, Horticulture & Soil Sciences, Egerton University, P.O. Box* 536, *Njoro, Kenya*;
2. *Leibniz-Institut für Agrartechnik Potsdam-Bornim e.V. ATB, Max-Eyth-Allee* 100, 14469 *Potsdam, Germany*;
3. *Department of Plant Breeding and Biotechnology, Moi University, P.O. Box* 39000, *Eldoret, Kenya*;
4. *Department of Plant Production, University of Venda, a, Private bag X*5050, *South Africa*)

Abstract: Carrying out field trial-research in dryland areas is usually expensive and costly for most national breeding programmes; hence development of simple crop simulation models for predicting crop performance in actual semi-arid and arid lands (ASALS) would reduce the number of field evaluation trials. This is especially critical in developing countries like Kenya where dry areas is approximately 83% of total land area and annual rainfall in these area is low, unreliable and highly erratic, causing frequent crop failures, food insecurity and famine. This paper used data generated from the rain shelter by measurement of evapotranspiration together with weather variables in Katumani to predict wheat yields in that site. Maximum yield of the wheat genotype considered for genotype Chozi under ideal conditions was 5 t/ha. Total above-ground biomass was obtained and grain yield was to be predicted by the model. Transpiration was estimated from the relationship between total dry matter production and normalised TE (7.8 Pa). The results presented are based on the assumption that all agronomic conditions were optimal and drought stress was the major limiting factor. Predicted grain yield obtained from the conceptual model compares very well with realised yields from actual field experiments with variances of 14% – 43% depending on watering regime. This study showed that it is possible to develop simple conceptual model to predict productivity in wheat in semi-arid areas of Kenya to supplement complicated and more sophisticated models like CERES-maize and ECHAM models earlier used in Kenya. The presence of uncontrolled factors in the simulation not accounted for in the estimation and could have contributed to decrease in observed yield need to be included in the model, hence modulation of the equations by introducing these factors may be necessary to reduce variances; thus need to be quantified. To improve the accuracy of prediction and increase wheat production in these areas measures that conserve water and/or make more water available to the crop such as prevention or minimisation of run-off, and rain water harvesting for supplemental irrigation are necessary.

Keywords: wheat, conceptual model, drought, evapotranspiration, yield response

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1 Introduction

World-wide, arid and semi-arid lands are diverse and widespread (Reynolds et al., 2001; Blum, 1996). In Kenya, drought conditions are frequent and widespread, covering 83% of total land area mainly in northern districts, southern Rift valley, parts of Coastal and Eastern regions (Conen and Lewis, 1991). Therefore carrying out dryland research is usually very expensive

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Biographies: Kimurto Paul K, PhD. Research interest: Drought stress physiology, crop improvement & breeding, Water use. Email: kimurtopk@gmail.com; **JB Ochanda Ogola**, PhD, Prof, Major: Agronomy/Crop Physiology. Email: ochanda@univen.ac.za; **Miriam G. Kinyua**, PhD, Prof. Major: Plant breeding and biotechnology. Email address: mgkinyau@africaonline.co.ke;

Bernard Towett, Major: Agronomy，research interest: Dryland research and crop improvement. Email:Takiptui@yahoo.com.

Corresponding author: Gottschalk Klaus, Ph.D, Prof. Major in Post Harvest Technology, with research interest in Storage climate control, modelling heat and mass transfer, CFD. Email: kgottschalk@atb-potsdam.de.

and time consuming due to the travelling required from one location to another. It is also dependent on annual weather changes (Mahalakshmi, Bidinger and Rao, 1990), which is usually very unreliable. Since shortage of water is a chief cause of variation and low wheat yields in these areas, it is desirable to predict the likely effects of variation in rainfall. Development of a simulation model for predicting the performance of the crop in actual marginal area would reduce costs of carrying out dryland. Simulation is defined as a numerical technique for conducting hypothetical experiments on mathematical models describing the quantitative behaviour of dynamic systems (Hillel, 1977; Ritchie and Otter, 1985). Crop simulation models that accurately predict yield in semi-arid areas would provide appropriate tool for economical testing, screening evaluating the productivity of wheat in semi-arid areas. But before these models can be used, they must be validated using data from field experiments (Asadi and Clemente, 2001). Complex models that need extensive input data are undesirable in many applications and it may be preferable to develop less detailed models that are easy to handle, requiring limited data that is readily available or measurable, which may better serve the practical needs of the breeder.

In the dryland research, the number of costly, multi-treatment, multi-location, and time-consuming field trials can be substantially reduced by crop simulation as crop models can quantify the magnitude and variability in response to various management strategies and weather scenarios. Once developed models could have the ability to account for stress on plant growth, each day, during the season; however, they should be designed for heterogeneous areas since various field conditions such as soil water and other in-season stresses affect variability in crop yield. To achieve the ultimate goal of sustainable cropping systems, variability must be considered both in space and time because the factors influencing crop yield have different spatial and temporal behaviour.

Process oriented crop simulation models, such as Crop Environment Resource System (CERES) (Ritchie and Otter, 1985; Ritchie et al., 1998), have the capability to integrate the effects of temporal and multiple stress interactions on crop growth processes under different environmental and management conditions. The CERES wheat model simulates plant responses to environmental conditions (soil and weather), genetics and management strategies. Such models are useful when they are validated and incorporated into Decision Support System (DSS) (Ritchie, 1995). In Iowa and Central Africa, for example, researchers have used the CERES model to investigate the role of water stress on plant development in cereals, and growth and have developed methodologies to determine optimal variable rate for N and populations across several fields (Paz et al., 1999; Thornton et al., 1995). Phasic development in CERES and most models are quantified with respect to the physiological age of the plant and potential growth is dependent of photosynthetically active radiation and its interception as influenced by leaf area index, row spacing and conversion efficiency (Asadi and Clemente, 2001). Cooper et al. (1997) developed a mixture model concept to investigate the use of appropriate nursery environments to identify reduced set of nursery screening trials under drought to maximize gains in selection for yield. They observed that predicted yield under low-stress nursery conditions was effective predictor of yield under similar low-stress environments ($r=0.89$), but the value of low-stress nursery as a predictor of yield in water-limited target environments decreases with increasing stress (moderate stress r = 0.53, severe stress r = 0.38 and very severe stress r = –0.08). They noted that yield in the stress nur series was a poor predictor of yield in the target environment, though low-stress nursery provides an indication of broad adaptation of germplasm. Hence, they recommended selection in both irrigated low-stress nursery and on-farm trials that sample a range of water-limited environments of the target population of environments.

More recently, Ogola, Wheeler and Harris (2007) developed a crop simulation model, based on FAO water balance model (FAO, 1986; FAO, 1995; FAO, 2002), which was used in predicting the production of maize in semi-arid areas of Kenya. In addition, Hansen and Indeje (2004), managed to predict productivity of maize in semi-arid Kenya by linking CERES-maize and

ECHAM circulation model with dynamic seasonal climatic forecasts and seasonal rainfall hind casts available prior to planting. They found 28% to 33% variance between simulated yield and observed weather.

In this paper, a model for predicting the productivity of bread wheat in semi-arid Kenya was developed using various climatic and crop factors as inputs. Earlier studies under the Rain shelter (AUTHOR, 2008; AUTHOR et al., 2009) at Kenya Agricultural Research Institute (KARI), Njoro, Kenya showed that crop water use increased with water supply. Rain shelter used was similar to that earlier described by Upchurch, Ritchie and Foale (1983) (Figure 1).

Figure 1 Rain out shelter showing neutron access tubes and drip irrigation at KARI Njoro, Kenya

The evapotranspiration (ET_a) data from the rain shelter experiment together with weather variables in Katumani were used to predict wheat yields. Katumani is located in Machakos, Kenya (1°33′ S, 37°14′ E and 1,560 m above sea level). Several weather variables (rainfall, pan evapotranspiration, maximum and minimum air temperatures, solar radiation and relative humidity) were recorded each day during period of experiment at Katumani (Table 1). In addition, Katumani is semi-arid with an annual average rainfall of 755 mm (SD = 150), high rainfall variability between years and seasons and average annual pan evaporation of 1800 mm. There are two distinct rainy seasons, with 330 (SD = 150 mm) in the ‘long rains’ (March to July) and 365 (SD = 125 mm) in the ‘short rains’ (October to February).

In Katumani, the mean annual temperature is 19.2^0C, August being the coldest month with a mean monthly temperature of 17.1^0C and March is the warmest with a mean monthly temperature of 21.3^0C. The soils are Alfisols, Kandic Rhodustalfs (USDA soil taxonomy) (Jaetzold and Schimdt, 1983). Daily weather data for the different seasons were obtained from an automatic weather station located in the area.

Table 1 Monthly total (rainfall and E_{pot}) and daily mean of weather variable during the 2001- 2002 growing seasons at Katumani, Kenya

Year/Month		Total rainfall /mm	Mean/mm E_{pan}/mm	Maximum daily T/℃	Minimum daily T/℃	Mean daily T/℃	Solar radiation (Lang leys m^{-2} d^{-1})	*RH*/%
2001	October	7.3	180.3	27.1	13.6	20.4	630.0	51.5
	November	169	126.1	24.0	14.6	19.3	573.9	69.0
	December	43.6	127.6	24.2	14.4	19.3	552.7	72.5
	January(02)	79.5	148.2	26.9	14.1	20.0	624.4	65.5
	February	7.5	179.0	27.1	13.9	20.0	676.4	53.0
	Mean/Total	306.9	761.2	24.7	14.0	19.5	611.5	62.4
2002	October	21.2	188.2	26.7	14.1	20.4	517.9	38.1
	November	144	167.8	24.9	15.1	20.0	499.0	51.1
	December	183	117.2	24.0	15.2	19.1	452.6	63.1
	January (03)	31.6	130.2	25.3	12.9	19.6	547.7	52.0
	February	17.2	95.9	28.8	12.7	21.4	691.0	32.0
	Mean/Total	397	699.3	24.7	14.0	19.5	541.6	48.4

Year/Month		Total rainfall /mm	Mean/mm E_{pan}/mm	Maximum daily T^0C	Minimum daily ToC	Mean daily ToC	Solar radiation (Lang leys m^{-2} d^{-1})	RH/%
2003	January	31.6	130.2	25.3	12.9	19.6	547.7	52.0
	February	17.2	95.9	28.8	12.7	21.4	691.0	32.0
	March	115.2	172.9	28.6	13.3	20.9	730.1	38.0
	April	153.2	151.3	26.8	14.1	20.6	684.3	47.0
	May	133.8	107.8	23.9	14.5	19.1	614.9	68.0
	June	Nil	52.0	23.2	11.9	21.5	613.2	57.0
	July	Nil	97.5	22.2	10.1	16.1	595.2	51.0
	August	26.3	110.8	22.8	10.4	16.2	622.3	55.0
	September	21.5	187.3	24.9	11.8	18.6	736.5	43.0
	October	30.8	190.8	26.4	13.3	20.1	791.9	42.0
	November	121.1	148.1	24.5	13.8	19.1	784.1	55.0
	December	24.1	169.1	25.1	13.4	19.2	800.3	50.0
	Mean/Total	674.6	1,613.2	25.2	13.6	19.5	684.3	51.4
2004	January	48.0	169.0	25.9	14.4	20.1	796.7	54.0
	February	47.9	165.4	26.6	14.4	20.5	853.3	47.0
	March	83.1	188.9	27.3	14.7	21.0	867.6	42.0
	April	121.5	147.5	25.3	15.2	20.2	840.7	58.0
	May	59.8	123.8	25.1	13.3	19.1	830.7	51.0
	June	0.7	59.0	23.4	11.2	16.4	790.4	47.0
	July	Nil	92.5	24.3	9.4	16.1	838.5	40.0
	August	Trace	120.8	23.6	10.7	17.2	807.9	46.0
	September	1.0	165.3	26.4	12.1	19.1	836.5	39.0
	October	47.6	150.8	25.9	13.7	19.9	799.9	45.0
	November	161.3	148.1	24.7	14.6	19.2	804.1	53.0
	December	89.5	160.1	24.4	14.0	19.2	800.3	56.0
	Mean/Total	660.4	1,693..2	24.7	14.0	19.5	834.3	48.4

Note: *T*-Temperature; *RH*-Relative humidity.

2 Methodology

2.1 Theoretical aspects of the conceptual model

The complex growth mechanisms that related to water use, *WUE* and grain yield is concisely represented by equation:

$$\Delta W = \kappa(ET-Es)/(e^{*}-e) \qquad (1)$$

Where, ΔW is growth, kg/ha; *ET* is evapotranspiration, mm; *Es* is soil evaporation, mm; *e** is saturated vapour pressure, kPa; *e* is actual vapour pressure, kPa. The empirically determined crop-specific constant κ has units of kPa/mm (Angus and Herwaarden, 2001). *ET* is soil moisture absorbed by the crop in the whole life cycle (Angus and Herwaarden, 2001).

In related studies, pioneer scientists working on transpiration ratio showed that the yield of plants was linearly related with evapotranspiration (*ET*) (Briggs and Shantz, 1913; Briggs and Shantz, 1916). Later, Hanks et al. (1969) separated transpiration from water loss beneath the canopy (E_{sc}) in the field and concluded that $ET-Esc$ represents transpiration (*T*). In addition, Briggs and Shantz (1916) and de Wit (1958) observed that transpiration efficiency (*TE*) was low when atmospheric evaporative demand was high and they could not explain the cause. In later studies, Bierhuizen and Slatyer (1965) showed that *TE* was linearly related to Vapour Pressure Deficit (*VPD*), which is defined as the difference between saturated vapour pressure (*e**) and actual vapour pressure (*e*) at the same temperature. *VPD* is proposed as the most appropriate field measure of the evaporative demand because it approximates the gradient in vapour concentration between saturated leaf mesophyll and the atmosphere (Angus and Herwaarden, 2001). Because the value of $e^{*}-e$ can vary greatly throughout the season, *VPD* should be evaluated at short intervals, such as a day or week, if it is used to predict growth (Angus and Herwaarden, 2001). In this chapter, $e^{*}-e$ is presented as mean value for the daylight hours, following Bierhuizen and Slatyer (1965). According to Angus and Herwaarden (2001) and Angus et al. (1993), if the influence of the *VPD* regime on transpiration is accounted for, the scatter shown by *TE* will be reduced to a single linear relation, with a constant slope, κ (kPa). Sinclair, Tanner and Bennett (1984) , Gregory (1988) and Gregory and Simmonds (1992), showed that a strong correlation existed between biomass production and normalised transpiration (ratio of actual transpiration to the vapour pressure deficit of the air). Pilbeam, Simmonds and Kavilu (1995) reported a linear relationship between dry matter production and normalised (by the average seasonal vapour pressure deficit) transpiration in maize and beans grown in semi-arid Kenya.

However, the value of κ (normalized *TE*) has been found to vary considerably in many crops (Turner, 1981; Turner and Jones. 1981; Trebejo and Midmore, 1990), mainly due to several factors like the methodology used to calculate *VPD*, errors in assuming leaf temperature to be close to air temperature and to changes in maintenance respiration. In maize and wheat the value of κ has been found to vary little. For example in maize, Ogola, Wheeler and Harris (2005) found *k* values of 8.4–10.5 Pa in UK, while Howell et al. (1998) found κ values of 9.1 Pa in Bushland, US. In wheat, Richards et al. (2002) found *k* values of 5–8.2 Pa in Australia and Mexico. However, Pilbeam, Simmonds and Kavilu (1995) found a much lower value of κ (5.4 Pa) for maize grown in semi-arid Kenya.

In spite of the shortcomings, the value of κ (normalised *TE*) is still considered to be fairly constant for a given crop (Pilbeam, Simmonds and Kavilu, 1995; Richards et al., 2002; Ogola, Wheeler and Harris, 2007). It is thus possible to estimate *TE* for a given crop and environment provided that mean seasonal *VPD* for that particular site can be determined and normalised *TE* has been obtained for a given location. The same concept was used in this study to predict wheat yields in semi-arid Kenya.

2.2 Inputs to the model

The major inputs to the model were transpiration efficiency (*TE*), crop yield response factor (*Ky*), crop coefficient (*Kc*), potential yield of wheat cultivar *Chozi*, ET_a from both drought simulation studies under the rain shelter and weather variables for the site (rainfall, relative humidity, wind speed and pan evapotranspiration) (Table 1). In both cases, the response of yield to water supply is quantified through the yield response factor (*Ky*) which relates relative yield decrease ($1-Y_a/Y_m$) to relative evapotranspiration deficit ($1-ET_a/ET_m$). Water deficit of a given magnitude, expressed as the ratio of actual evapotranspiration (ET_a) to maximum evapotranspiration (ET_m), may either occur continuously over the total growing period of the crop or it may occur during any one of the individual growth periods, i.e. establishment, vegetative, flowering, yield formation, or ripening period. The magnitude of water deficit refers in the former to the deficit in relation to crop water requirements over the total growing period of the crop and in the latter to the deficit in relation to the crop water requirements of the individual growth period (FAO, 1986; 1998). The *Ky* values for most crops are derived on the assumption that the relationship between relative yield (Y_a/Y_m) and relative evapotranspiration (ET_a/ET_m) is linear and is valid for water deficits of up to about 50% or $1-ET_a/ET_m = 0.5$. The value of *Ky* for wheat is 1.16 for the total growing period and is based on an analysis of experimental field data covering a wide range of growing conditions, with high-producing varieties, well-adapted to the growing environment and grown under a high level of crop vapour pressure deficit (*VPD*), which is defined as the difference between saturated vapour pressure (e^*) and actual vapour pressure (e) at the same temperature. *VPD* is proposed as the most appropriate field measure of the evaporative demand because it approximates the gradient in vapour concentration between saturated leaf mesophyll and the atmosphere (Angus and Herwaarden, 2001; Angus et al., 1993). The yield response factor (*Ky*) was used here to estimate actual grain yield and consequently total above-ground biomass. The amount of water transpired by the crop (and hence E_{sc}) was estimated from the relationship between normalised *TE* (using seasonal *VPD*) and total dry matter yield. Harvest index (*HI*) (0.35) used was obtained from previous experiments in the site (Kinyua, Otukho and Abdalla, 2000; KARI, 2004).

2.3 Calculations and assumptions

The prediction of wheat productivity was done for four seasons; during the 'short rains (SR)' of 2001 and 2002 and 'long rains' of 2003 and 2004. The assumed dates of planting, 50% emergence and harvesting that were used in the model are presented in Table 2. These dates are normally the dates that the rainfall begins in both short and long rains when planting is recommended (KARI, 2000).

Table 2 Planting and harvesting dates used in the model

Planting date	Days to 50% emergence	Harvest maturity	Days to maturity after emergence
SR 2001			
26th Oct 2001	3rd Nov 2002	1st Feb 2002	97
SR2002			
24th Oct 2002	30th Nov 2002	5th Feb 2003	98
LR 2003			
30th March 2003	7th April 2003	12th July 2003	93
LR2004			
30th March 2004	7th April 2004	8th July 2004	95

Note: SR-Short rains, LR-Long rains.

The following calculations were carried out:

1) Reference evapotranspiration representing the mean value in mm day^{-1} was obtained by:

$$ET_o = kpan \cdot Epan \tag{2}$$

Where, *Epan* is evaporation in mm/day from an unscreened evaporation pan (obtained from the automatic weather station at Katumani between Oct-Feb growing period), and kpan is pan coefficient which was estimated to be 0.78 (2001), 0.89 (2002), 0.95 (2003) and 0.68 (2004) for the site and period considered here (FAO, 1986; FAO, 1998).

2) Maximum evapotranspiration (ET_m) was calculated from the relationship

$$ET_m = kc \cdot ET_o \tag{3}$$

Where, *kc* is an empirically-determined crop coefficient and ET_o is the reference evapotranspiration (evaporative demand of the atmosphere). For most crops, the *kc* value increases from a low value at time of crop emergence to a maximum value during the period when the crop reaches full development, and declines as the crop matures.

The *kc* for different growth stages of wheat is: crop establishment 0.25–0.45 (10–20 days), the development stage 0.7–0.80 (20–35 days), the mid-season stage 1.05–1.2 (40–55 days), and during the late season stage 0.8–0.9 (20–40 days) (FAO, 1986; FAO, 1998). The *kc* values used in this study (Table 3) are 0.35, 0.75, 1.15, and 0.45, for crop establishment, development stage, mid-season stage, and late season stage, respectively, were adapted from literature (FAO, 1986; 1998).

3) In both cases, actual evapotranspiration (ET_a) was estimated from the soil water balance equation as:

$$ET_a = \pm\Delta S + P - D - R \tag{4}$$

Where, ±ΔS is the change in storage; P is precipitation; D is drainage; R is runoff. Drainage was assumed to be negligible since it was not detected by Neutron probe measurements while runoff was also negligible because rain shelter area is flat. From the rain shelter, ET_a obtained for low, medium and high moisture regimes that were used in this prediction were 97.9, 132, and 164.8 mm, respectively. These were normalized with *VPD* of Katumani for different years.

Table 3 Value of crop coefficient (*Kc*) and pan coefficient for the long and short periods of 2001-2004 used in the model

Growth stage	Date	Period (DAE)	*kc*	*kpan*
SR 2001				
Crop establishment	3 Nov to 13 Nov 01	1-10	0.35	0.80
Development stage	14 Nov to 4 Dec 01	11-31	0.75	0.80
Mid-season stage	5 Dec to 20 Jan 02	32-77	1.15	0.80
Late season stage	21 Jan to 10 Feb 02	78-98	0.45	0.80
SR 2002				
Crop establishment	1 Nov to 10 Nov 02	1-10	0.35	0.76
Development stage	11 Nov to 31 Nov 02	11-31	0.75	0.76
Mid-season stage	1 Dec to 15 Jan 03	32-77	1.15	0.76
Late season stage	16 Jan to 5 Feb 03	78-98	0.45	0.76
LR 2003				
Crop establishment	7 Apr to 17 Apr 03	-10	0.35	0.87
Development stage	18 Apr to 8 May 03	1-29	0.75	0.87
Mid-season stage	9 May to 20 Jun 03	0-72	1.15	0.87
Late season stage	21 Jun to 12 Jul 03	3-93	0.45	0.87
LR 2004				
Crop establishment	4 Apr to 14 Apr 04	-10	0.35	0.86
Development stage	15 Apr to 4 May 04	1-31	0.75	0.86
Mid-season stage	5 May to 17 Jun 04	2-74	1.15	0.86
Late season stage	18 Jun to 8 Jul 04	75-95	0.45	0.86

Note: DAE-Days after emergence.

At Katumani, ET_a was obtained using above equation, but Runoff was obtained from multipying the total seasonal rainfall by runoff index of 0.4682 developed for the site (Okwach, Williams and Wambua, 1992; Okwach, 1994; Okwach and Simuyu, 1999). Drainage (D) and $\pm\Delta S$ were assumed negligible since the area seldomly receives sufficient rainfall for storage or drainage. The runoff index compares well with the equation $R = 0.482 \cdot P - 4.640$, which relates runoff to precipitation and has been used recently to successfully predict maize productivity in Katumani (Ogola, Wheeler and Harris, 2007).

The ET_a values were divided into 4 growth stages as described above (crop establishment, development stage, mid-season stage and late season stage).

4) Maximum yield (Y_m) of the wheat genotype that was used is cultivar *Chozi* under ideal conditions is 5 t/ha (KARI, 2002; 2004).

5) Actual grain yield (Y_a) was obtained from the relationship:

$$(1 - Y_a/Y_m) = ky \cdot (1 - ET_a/ET_m) \qquad (5)$$

Where, ky is the yield response factor of 1.16.

6) Total above-ground biomass (DM) was obtained from the relationship:

$$HI = GY/DM \qquad (6)$$

Where, HI is harvest index (a value of 0.35 was used) (AUTHOR et al., 2005; Reynolds et al., 1999), and GY was grain yield to be predicted.

7) The transpiration efficiency (TE) of 7.8 Pa was used in the study; this was obtained from literature for wheat grown under similar climatic conditions as Katumani over long period (Reynolds et al. 2002; Abbate et al., 2004; Acevedo et al., 2002 and FAO, 1998).

8) Mean seasonal VPD (kPa) was calculated as difference between the saturated VPD of the air and actual VPD using daily maximum and minimum temperature and daily maximum and minimum RH following the procedure of Allen et al. (1998). VPD obtained from Katumani during the growing season was used to normalise the derived ET_a (water balance equation) and TE. The values used for 2001, 2002, 2003 and 2004 are 1.01, 1.02, 0.96 and 0.78, respectively (KARI-Katumani, 2004).

9) Transpiration was estimated from the relationship between total dry matter production and normalised TE (which was normalized with VPD for different seasons) as expressed below:

$$TE = DM/T \qquad (7)$$

Where, T is transpiration, mm.

10) Direct evaporation from soil beneath the crop canopy (E_{sc}) was obtained by assuming that the two components of ET are independent and additive (Denmead, 1973), hence if any two terms are known then the third can be determined by difference:

$$T = ET - E_{sc} \qquad (8)$$

The conceptual model described by equations 1 to 10 is summarized in Figure 2.

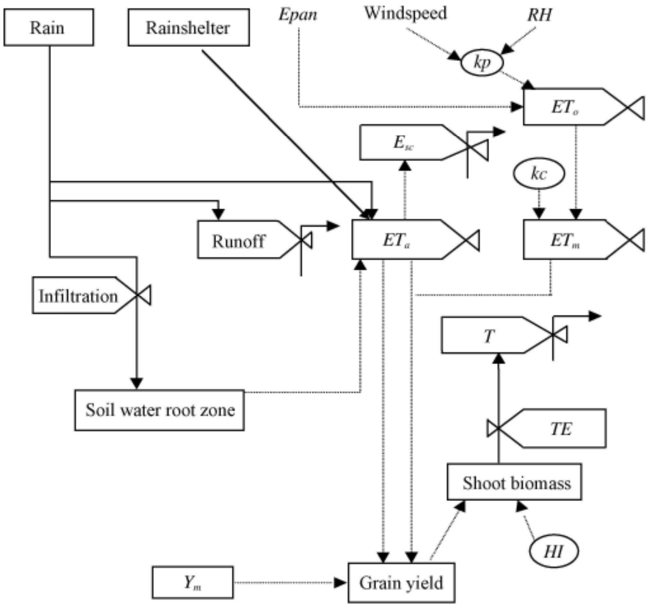

Figure 2 Relational diagram (described by equation 1 to 10) showing how wheat productivity in semi-arid Kenya was predicted. Rectangles represent quantities (state variables); valve symbols are flows (rate variables); circles are auxiliary variables; underlined variables are driving and other external variables. Full lines represent flows of material and dashed lines are information flow

3 Results

The results presented are of estimated wheat production (grain yield and total above-ground biomass) and other related data for four seasons (SR-2001, SR-2002, LR-2003 and LR-2004) using ET_a obtained from low, medium and high moisture regimes (97.9, 132 and 164.8 m, respectively) under the rain shelter. The predicted (equations 1 to 10) wheat productivity under different watering regimes is given in Table 4. The results obtained from the conceptual model showed that under low moisture the predicted grain yield for wheat for 2001, 2002, 2003 and 2004 were 1,287, 1,112.1, 1,126.2 and 907.7 kg/ha, respectively (Table 4). These represented about 25%, 22%, 22.5% and 18%, respectively, of the potential grain yield of 5,000 kg/ha. To validate the model, the actual grain yields obtained from experiments conducted at site during the period of prediction (2001–2004) were used; they were 1,273, 1,798, 1,125.9 and 809.1 kg/ha, respectively (Figure 3). When medium moisture ET_a of 132 mm was used in the prediction, the predicted grain yields for 2001–2004 increased to 2,013, 1,778, 1,797 and 1,597.1 kg/ha, respectively as compared to 2,713.1, 2,418.7, 2,442.4 and 1,879.7 kg/ha, respectively for ET_a under high moisture for the same period (Table 2). These represented 40.2%, 35.6%, 36% and 31% of potential grain yield of 5,000 kg/ha for medium moisture as compared to 54.3%, 48%, 49% and 37.5% under high moisture in 2001–2004 periods, respectively. The actual grain yields obtained from experiments conducted at site during the period of prediction (2001–2004) are presented in Figure 3.

Table 4 Predicted wheat productivity at Katumani using ET_a derived under different watering regimes under rain shelter during the 2001–2004 growing season

Parameter	Years			
	SR-2001	SR-2002	LR-2003	LR-2004
Low ET_a				
Potential ET/mm	274.8	302.9	283.1	220.7
Actual ET/mm	98.8	99.9	93.8	86.3
ET_a/ET_m	0.36	0.29	0.33	0.39
$1\text{-}ET_a/ET_m$	0.64	0.71	0.67	0.61
Grain yield/kg·ha^{-1}	1,287.4	1,112.1	1,126.2	907.7
Biomass/kg·ha^{-1}	3,677.1	3,177.4	3,217.6	3,050.6
Y_a/Y_m	0.25	0.22	0.23	0.22
$1\text{-}Y_a/Y_m$	0.75	0.78	0.77	0.78
Transpiration/mm	46.7	45.77	43.4	46.2
E_{sc}/mm	52.2	41.4	49.6	30.1
T/ET_a/%	47.2	52.3	46.7	53.4
E_{sc}/ET_a/%	52.8	47.5	53.3	35.6
WUE_d/kg·ha^{-1}·mm^{-1}	37.2	36.4	34.6	35.2
WUE_g/kg·ha^{-1}·mm^{-1}	13.1	12.7	12.1	10.5
Medium ET_a				
Potential ET/mm	274.8	302.9	283.1	220.7
Actual ET/mm	133.3	117.9	125.4	113.9
ET_a/ET_m	0.49	0.39	0.44	0.50
$1\text{-}ET_a/ET_m$	0.51	0.61	0.56	0.50
Grain yield/kg·ha^{-1}	2,013.9	1,778.1	2,418.7	1,597.1
Biomass/kg·ha^{-1}	5,753.9	5,080.3	5,134.5	4,908.2
Y_a/Y_m	0.40	0.35	0.35	0.36
$1\text{-}Y_a/Y_m$	0.60	0.65	0.65	0.64
Transpiration/mm	73.1	73.2	69.3	59.0
E_{sc}/mm	60.3	44.3	56.1	54.1
T/ET_a/%	54.2	62.3	55.26	52.5
E_{sc}/ET_a/%	45.8	54	44	48.2
WUE_d/kg·ha^{-1}·mm^{-1}	43.1	43.2	40.9	43.1
WUE_g/kg·ha^{-1}·mm^{-1}	15.1	15.1	14.3	14.2
High ET_a				
Potential ET/mm	274.8	302.9	283.1	220.7
Actual ET/mm	166.5	146.7	156.4	148.9
ET_a/ET_m	0.61	0.50	0.55	0.67
$1\text{-}ET_a/ET_m$	0.49	0.50	0.45	0.32
Grain yield/kg·ha^{-1}	2,713.1	2,418.1	2,442.4	1,879.7
Biomass/kg·ha^{-1}	7,751.7	6,910.1	6,978.1	6,570.7
Y_a/Y_m	0.52	0.49	0.48	0.52
$1\text{-}Y_a/Y_m$	0.48	0.51	0.52	0.48
Transpiration/mm	73.1	73.2	69.3	73.8
E_{sc}/mm	98.2	100.1	94.6	75.1
T/ET_a/%	43.9	49.6	44.9	49.1
E_{sc}/ET_a/%	59.1	68.2	60.7	51.1
WUE_d/kg·ha^{-1}·mm^{-1}	46.5	47.2	44.5	44.0
WUE_g/kg·ha^{-1}·mm^{-1}	15.1	16.5	15.6	12.6

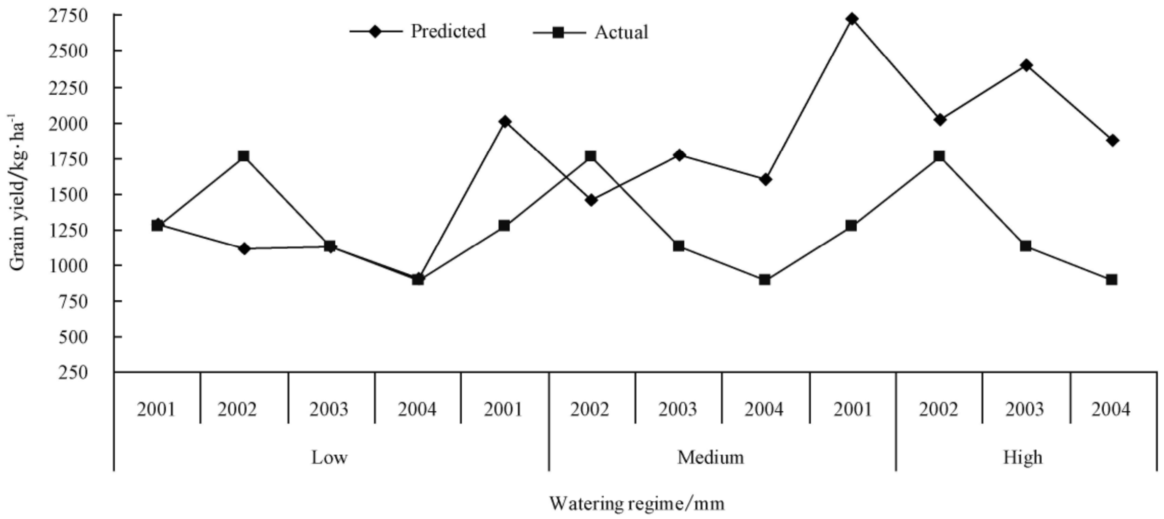

Figure 3 Predicted vs actual grain yield using ET_a from rain shelter moisture regime (low, medium and high) for 2001-2004 growing seasons

The ky values were derived on the assumption that the relationship between the relative yield and relative ETa is linear and is valid for water deficits of up to 50% (i.e. 1–ET_a/ET_m = 0.5), and if water deficits were greater than 50%, then the assumption was that the amount of moisture was not sufficient to produce any yield. From the results, it showed that 1–ET_a/ET_m was greater than 50% under low ET_a in all the four seasons (2001–2004) and three out of four seasons under medium moisture (Table 4). Shoot biomass production for the same period 2001–2004 under low moisture and medium moisture, respectively, were 3,677, 3,177, 3,217.6 and 3,050.5 kg/ha, and 5,753, 5,080.3, 5,134 and 4,908.6 kg/ha, respectively as compared to 7,751, 6,910, 6,978 and 6,570.2 kg/ha for high moisture ET_a over the same period (Table 4). For low moisture ET_a, the biomass obtained also represented 29.9%, 25.4%, 25.7% and 24.4%, respectively of the biomass potential yield of 12,500 kg/ha as compared to 46%, 40.2%, 41% and 39.2%, respectively, under medium moisture regime (Table 4). Crop *ET* (ET_a) under low moisture for 2001–2004 was 98.8, 99.9, 93.9 and 76.3 mm, respectively, out of which 46.7 mm (2001), 45.7 mm (2002), 43.4 mm (2003) and 46.2 mm (2004), was used by the plants in transpiration. This, respectively, accounted for 52.8%, 47.5%, 53.3% and 35.6% of total ET_a in 2001–2004 periods.

Direct evaporation from soil beneath the crop canopy (E_{sc}) for the period 2001–2004, respectively accounted for 52.8%, 47.5%, 53.3% and 35.6% of the total ET_a (Table 4). Medium moisture had 133.3, 117.9, 125.4 and 103.9 mm ET_a compared to 166.5, 146.7, 156.4 and 128.9 under high moisture regime over the same period (Table 4). Direct evaporation from soil beneath the crop canopy (E_{sc}) in 2001–2004, accounted for 45.8%, 54%, 44% and 48.2% of total ET_a under medium moisture, compared to 43.9%, 50%, 44.9% and 40.1% under high moisture (Table 4). *WUE* for biomass varied from 35.2 to 40.2 kg ha^{-1} mm^{-1} under low moisture to 43.1 – 57.3 under high moisture regime in the same period. Similarly, *WUE* for grain yield varied from 10.1–14.2 under low moisture to 12.6 – 17.2 under high moisture over similar period (Table 4). Overall, the 2004 growing period recorded the lowest predicted values of grain yield, biomass and water use efficiencies while 2001 and 2002 recorded highest values (Table 4).

4 Discussion

The results obtained from this simple conceptual model for predicting wheat productivity in semi-arid Kenya compare favourably well with results from actual field experiments conducted at the same site and other semi-arid areas of Kenya (KARI, 2001; 2003; Kinyua, Otukho and Abdalla, 2000; AUTHOR, 2008; AUTHOR et al. 2009). However, the ky values were derived on the assumption that the relationship between the relative yield and relative ET_a is linear and is valid for water deficits of up to 50% (i.e. 1-ET_a/ET_m =0.5), and if water deficits were greater than 50%, then the assumption was that the amount of moisture was not sufficient to produce any yield. From the results, 1-ET_a/ET_m was greater than 50% under low ET_a in all the four seasons (2001–2004) and 3 out of 4 seasons under medium moisture (Table 4). In these seasons, we were to assume total crop failure and no results discussed. However, since the study aimed at predicting the lowest possible yield obtained in Katumani and other ASALs of Kenya, that assumption in the model was ignored and model assumptions were modified. Therefore, using low ETa from the rain shelter, the model predicted grain yield of 1,287, 1,112.1, 1,126.2 and 907.7 kg/ha, for the short rains season of 2001 and 2002 and long rains of 2003 and 2004, respectively. When medium ET_a from the rain shelter was used in the model, the predicted yield for 2001–2004 increased to 2,013, 1,778, 1,797 and 1,597.1 kg/ha, respectively. This compares fairly well with the actual grain yield obtained from experiments at Katumani, where, grain yield obtained were 1,237, 1,798, 1,125 and 890 kg/ha, for 2001, 2002, 2003 and 2004 growing seasons, respectively (Figure 3). However, when ET_a from high moisture was used the predicted yield was higher than actual yield ranging between 1,879.9 to 2,713.1 kg/ha in the 4-four -seasons of study. Overall yield predicted and actual yield varied between 14% to 43% in this study which compare well with those obtained in maize in same site where variance ranged between 28% to 33% between predicted and observed values using ECHAM circulation model (Hansen and Indeje, 2004).

The over prediction when high ET_a was used could be explained by the presence of uncontrolled factors in the trials like pest, weeds and disease damage and soil-limiting factors and micronutrient deficiencies not accounted for in the estimation and could have contributed to decrease in observed yield. In addition, this discrepancy may be attributed to at least in part, to the high irradiances characteristic of the region, which may lead to photo inhibition, and hence a reduction in photosynthetic efficiency and dry matter production and soil characteristics. Similar observations were earlier reported (Asadi and Clemente, 2001; Thornton et al., 1995).

Moreover, the seasonal rainfall received during that period (2001–2004) was 292.2, 358.2, 300.0 and 232.3 mm, respectively (Table 1), correlates (r = 0.44*) with grain yield obtained. In other seasons that received similar rainfall amounts (322 mm and 285 mm, respectively) as the seasons considered in the current study, KARI (2000; 1998) obtained mean grain yield of 1,475 kg/ha, while Kinyua, Otukho and Abdalla (2000) obtained yields of about 1,250 kg/ha.

The predicted biomass production for the same period (2001 – 2004) for low and medium ET_a ranged between 3,050 to 5,753 kg/ha in the four years. These compares well with those earlier reported from experiments at site (KARI, 1998) which ranged between 3,760 to 5,334 kg/ha. Just like grain yield ET_a from high moisture regime over estimated the biomass production (ranging 6,570 – 7,751 kg/ha). The total crop ET_a that was utilized by the plant through transpiration varied from year to year ranged between 43%–62% while the rest was lost through surface evaporation, which increased with increasing rainfall.

From the results presented, several measures such as water harvesting for supplemental irrigation, mulching, growing of cover crops which prevent or minimize runoff and conserve water and/or making more water available to the crop may be of more importance to increased wheat yields in ASALs of Kenya. In addition, developing and growing wheat varieties with higher early season biomass accumulation to utilize the initial available moisture may be desirable, since this will reduce *Esc* and increase transpiration.

5 Conclusions

The major hypothesis tested in this study was that it is possible to develop a simple conceptual model to predict productivity in wheat in semi-arid areas of Kenya to supplement complicated and more sophisticated models like CERES-maize and ECHAM models earlier used in Kenya. The hypothesis was not disapproved. Indeed, the results presented showed that a simple conceptual model developed using evapotranspiration (ET_a) obtained from rain shelter experiments and calibrated and evaluated with weather variables from the target site, performed fairly for tested location in Katumani, Kenya. The comparison between observed and simulated results in the four growing years, showed that the model slightly over predicted wheat productivity. The model proved to be applicable in simulating yields in continuous runs and therefore it can reduce the costs of travelling and time spent by augmenting dryland research activities. The results show that it is possible to apply this model to predict the productivity of bread wheat in semi-arid areas of Kenya. However further work is needed to evaluate the model for its capability to simulate bread wheat yield and productivity in other areas with different weather conditions, soil conditions and cultivars with varied yield potential and also its use in other cereal crops like maize, sorghum and small cereals. In addition, the presence of uncontrolled factors in the simulation like insect pests, weeds and disease damage, soil-limiting factors, radiation and micronutrient deficiencies are not accounted for in the estimation and could have contributed to decrease in observed yield need to be included in the model. Modulation of the equations by introducing these factors may be necessary to reduce variances; thus need to be quantified. There are however some of the limitations of this model as it overestimated the wheat productivity.

Nomenclature

SYMBOL	Definition	Unit
DAE	Days after emergence	Time
DM	Dry matter	kg/ha
$\Delta\Omega$	Growth	kg/ha
e	Actual vapour pressure	kPa
e^*	saturated vapour pressure	kPa
Epan	Pan evaporation	mm
E_s	Direct evaporation from soil surface	mm
E_{sc}	Evaporation beneath crop canopy	mm
ET	Evapotranspiration	mm
ET_a	Actual evapotranspiration	mm
ET_m	Potential evapotranspiration	mm
GY	Grain yield	Kg/ha
HI	Harvest index	Unit less
κ	Kappa	
kc	Crop coefficient	
kpan	Pan coefficient	
ky	Crop response factor	
P	Precipitation	mm
R	Run-off	mm
T	Transpiration	mm/m/sec
TE	Transpiration efficiency	
ITE_o	Instantaneous transpiration efficiency	
VPD	Vapour pressure deficit	
Y_a	Actual yield	Kg/ha
Y_m	Potential yield	Kg/ha

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