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Full Length Research Paper

Estimating crop coefficient model for upland rice (NERICA) under sprinkler irrigation system

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Efficient crop coefficient (K_c) estimation is very important to adequately determine water use of a selected crop. In this study, crop coefficient was determined for upland rice (NERICA) under a sprinkler irrigation system. The estimation was derived from the relationship $f_c = \int(LAI, MTA)$, where LAI is leaf area index and MTA is the mean tilt angle, under standard environmental conditions in Ibadan, Nigeria. The fraction of the wetted surface f_c was determined for initial, mid season and maturity growth stages. These were then incorporated into the model flowchart that produced soil water coefficient for evaporation, K_e, basal crop coefficient, K_{cb} and crop coefficient for evapotranspiration, K_c. Several assumptions were made and a visual basic (VB) 6.0 software was used as programming language. The derived K_c was compared with existing crop coefficients and results were subjected to statistical analysis. The f_c models derived for initial, mid season and maturity growth stages are $f_c = 0.9392 - 0.0095LAI + 0.0010COSMTA$, $1.1917 - 0.0753LAI + 0.0164COSMTA$ and -0.1308 + 0.1193LAI - 0.024COSMTA respectively. The f_c model incorporating all growth stages of the form, $f_c = 0.9167 - 0.026LAI + 0.219COSMTA$. The K_c values for the three growth stages were 0.9 (initial), 1.12 (mid season) and 0.7 (maturity). The coefficient of distribution, R^2 between the modeled K_c and those using FAO-24 and FAO-56 guidelines were 0.99 and 0.98 respectively indicating a good agreement with the existing coefficients. The result also supported the improvised conversion factor from K_c (paddy) to K_c (upland) as it is used in FAO-24 paper. The dominant effect of f_c, LAI and MTA on the crop coefficient of upland rice is evident from the results.

Key words: Crop coefficient, upland rice, sprinkler irrigation.

INTRODUCTION

Crop coefficient (K_c) is necessary in determining the consumptive water use of selected crops. This is due to the fact that potential evapotranspiration ET_o estimation is purely based on climatic data. The introduction of crop and soil effect into ET_o in order to determine actual or crop water use, K_c is very important. Several methods and models have been adopted to determine crop coefficient for rice in different regions of the world with varying degree of success. Allen et al. (1998), in FAO-56 irrigation and drainage paper determined the K_c of rice and quoted as; 1.0, 1.15 and 0.7 for vegetative, mid season and maturity stages respectively. Doorenbos and Pruitt (1992) also came up with respective values of 1.1, 1.25 and 1.0 in the FAO-24 paper. Seung Hawn et al. (2006) values ranged between 0.78 and 1.58 for Penman-Monteith (PM) derived K_c and 0.65- 1.35 for FAO modified Penman derived crop coefficients. This was after they

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were compared with FAO-33 and FAO-56 papers. All the researchers were unanimous that these estimates are applicable for paddy rice only leaving a knowledge gap for K_c determination for upland rice. Allen et al. (1998) and Doorenbos and Pruitt (1992) also agreed that the usage of this K_c in upland situation overestimates the consumptive water use of upland rice. They introduced a conversion factor, which, according to the authors, make the K_c for paddy rice to be useful for upland rice situations. It is in line of the above that an attempt was made to determine the crop coefficient K_c for upland rice under standard conditions in Ibadan, Nigeria. The study also aims at comparing the K_c values in upland conditions with already existing K_c values and therefore examine its degree of significance with the improvised versions from different FAO estimates.

MATERIALS AND METHODS

Modeling crop coefficient

The factors considered in modelling the crop coefficient include; weather parameters, crop factors, management and environmental conditions.

Weather parameters affecting evapotranspiration include; rainfall, solar radiation, air temperature, relative humidity and wind speed (Allen et al., 1998: Pandey et al., 2006). All these weather parameters had been put into consideration when modeling the crop coefficient (K_c).

Model development

Modeling K_c for this study becomes imperative due to the overestimation of the crop ET by most K_c values. This was confirmed by Allen et al (1998) that most crop coefficient was determined in lowland conditions (paddy rice). Doorenbos and Pruitt (1992) introduced a factor to convert the K_c values for lowland to be useful for upland rice conditions. It was remarked that the reduction of 15 to 20% in K_c values will only take place during initial crop stage.

The model is constructed using dual crop coefficient according to Allen et al. (1998).

$$K_c = K_{cb} + K_e \quad (1)$$

Where:
K_{cb} = basal crop coefficient to describe plant transpiration.
K_c = crop coefficient for evapotranspiration.
K_e = soil water coefficient for evaporation.
K_{cb} is basal Crop Coefficient. It is defined as the ratio of the crop evapotranspiration to the reference evaporation when the soil such is dry but transpiration is occurring at a potential rate. K_{cb} is obtained from Allen et al. (1998). However, when K_{cb} at middle and end values are larger than 0.45, the following relationship holds (Allen et al., 1998).

$$K_{cb} = K_{cb\ (Tab)} + (0.04\ (U_2 - 2) - 0.004\ (Rh_{min} - 45)\ (h/3)^{0.3} \quad (2)$$

Where:
U_2 = wind speed (m/s)
Rh_{min} = Relative humidity (%)
h = mean plant height during the mid or end stage (m)
The daily value of K_{cb} can be determined from:

$$K_{cb} = K_{cb}\ prev + \left[\frac{i - \Sigma\left(L_{prev}\right)}{L_{stage}}\right]\left(K_{cb}\ next - K_{cb}\ prev\right) \quad (3)$$

Where prev and next stands for previous and next values of the listed parameters.

L_{stage} = length of the stage under consideration (days).

$\Sigma\left(L_{prev}\right)$ = sum of lengths of all previous stages (days).

Soil evaporation coefficient, K_e

Since evaporation from the soil occurs at the maximum rate when the soil is wet, the crop coefficient K_c evaluated as the sum of K_{cb} and K_e can never exceed a maximum value. Thus, its value is determined by the energy available for evapotranspiration at the soil surface, that is:

$$K_e \leq (K_c max - K_{cb}) \quad (4)$$

$$K_e = K_r\ (K_c max - K_{cb}) \leq F_{ew}\ K_c max \quad (5)$$

F_{ew} = fraction of soil not covered by vegetation and that is wetted by irrigation.

The calculation procedure for estimating K_c involved the determination of upper limit, $K_c$max, the soil evaporation reduction coefficient, Kr (which requires a daily water balance computation for the surface soil layer) and F_{ew}, the exposed and wetted soil fraction from Allen *et al,* 1998 and Vu *et al* (2005). The relationship for $K_c$max is:

$$K_c max = max\left[\left(1.1 + \left[0.04(U_2 - 2) - 0.004(RH_{min} - 45)\right]\left(\frac{h}{3}\right)^{0.3}\right), K_{cb} + 0.05\right]$$
(6)

The coefficient "1.1" is chosen due to the fact that the soil has less opportunity to absorb heat between wettings due to low irrigation interval (usually 1 - 2 days).
The maximum amount of water that can be evaporated from the soil is given by;

$$TEW = (1000)\ \left(\vartheta_{fc} - \vartheta_{wp}\right) Ze \quad (7)$$

Where:
TEW = maximum cumulative depth of evaporation (depletion) from the soil surface layer, when K_r = 0, total evaporable water.

Ze = depth of the surface soil layer that is subject to drying by way of evaporation.
ϑ_{wp} = Soil water content at wilting point (m^3/m^3).
ϑ = Soil water content at field capacity (m^3/m^3).

From D_{ei-i} > REW

$$K_r = \frac{TEW - D_{ei-i}}{TEW - REW} \quad (8)$$

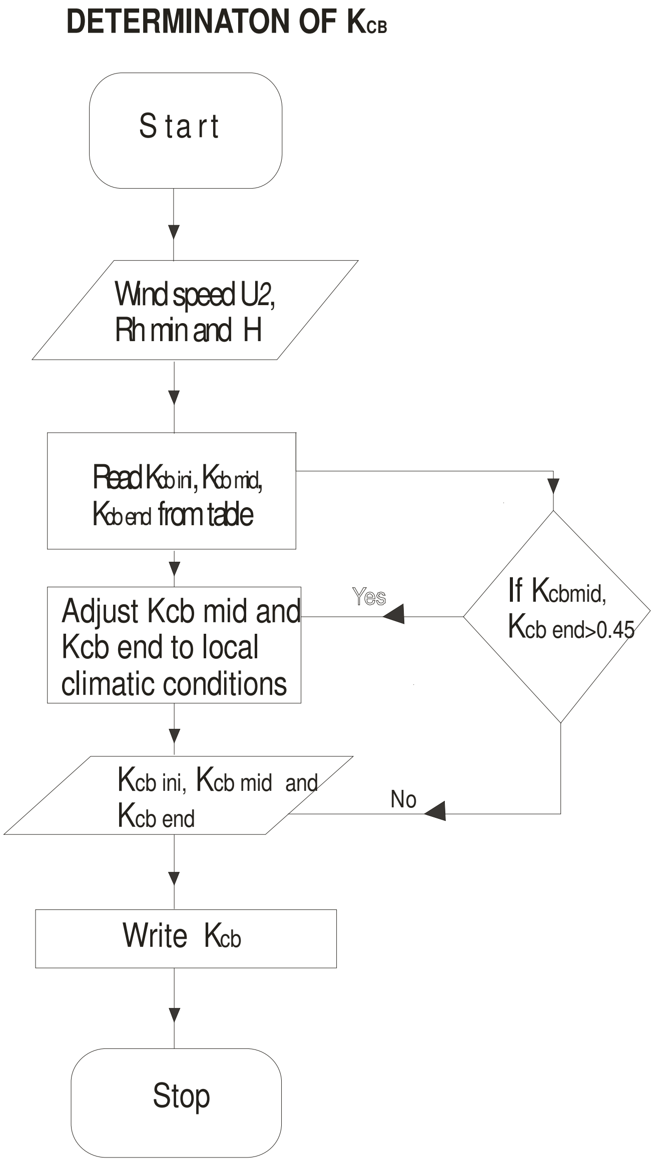

Figure 1. Flowchart of crop transipiration coefficient Kcb determination.

Where:

K_r = is expressed regressively as the soil surface dries after rain or irrigation and becomes zero with no water is left for evaporation in the upper soil layer. K_r = dimensionless evaporation reduction coefficient dependent on the cumulative depth of water depleted from the topsoil

R*EW* = cumulative depth of evaporation at the end of energy limiting stage, readily evaporable water

D_{ei-i} = cumulative depth of evaporation from the soil surface layer at the end of day 1 – i (mm)

Fraction of wetted soil surface subjected to evaporation

The fraction of the soil surface exposed to sunlight change to some degree with the time of the day. The fraction of the soil surface subjected to loss of water by evaporation coincides with the total fraction of the soil exposed to sunlight in case of overhead sprinkler irrigation system, where virtually all the ground surface area is wetted. Since, LAI is the foliage area per ground area, a new parameter, mean tilt angle (MTA) is introduced. The MTA value is an indication of the average orientation of the foliage tend towards 0^o and 90^o when all the foliages are horizontal and vertical respectively. The LAI together with MTA determine the actual ground area covered by the vegetation and that obstructed by direct sunlight, F_c. The fraction of wetted surface F_c is thus expressed mathematically as;

$$F_c = f\,(\text{LAI, MTA}) \quad (9)$$

This relationship was developed based on field observations for different plant stages viz; emergence, mid season and maturity and later introduced into the FAO-56 model to determine the crop coefficient and make it practicable in Nigeria.

Program model and flowchart

A program model on the K_{cb}, K_e and K_c, of the crop (rice) was produced using a 6.0 version of visual basic (VB) as the programming language with some assumptions going into the model. The flowcharts for crop coefficient due to evaporation K_e, and basal crop coefficient due to transpiration K_{cb} are as in Figures 1 and 2.

Assumptions of the model

1. The percentage ground cover and leaf area index is assumed to have anenormous influence on K_c. Thus, close-laying of leaves is assumed to be negligible.
2. The soil evaporation coefficient is dependent on the cumulative depth of water depleted from the topsoil alone.
3. The water content of the evaporating layer of the soil is at field capacity; θ_{Fc} shortly after a major wetting event and the soil can dry to soil water content at wilting point, θ_{wp} before the next irrigation.
4. The mean tilt angles of the foliages range between 24^o to 64^o.
5. The average fraction of soil wetted by irrigation, F_{ew}, equal to 1, for sprinkler irrigation system. This means that under the irrigation system, the entire ground surface is wetted by water.
6. The applied irrigation water ranged between 2000 and 5000 mm and water application in excess of estimated moisture was considered a loss.

RESULTS AND DISCUSSION

The 3 set of equations derived for initial, mid season and maturity growth stages of upland rice are as follows:

$$F_c = 0.9392 - 0.0095\text{LAI} + 0.0010 \text{ Cos MTA} \quad (10a)$$

$$F_c = 1.1917 - 0.0753\text{LAI} + 0.0164 \text{ Cos MTA} \quad (10b)$$

$$F_c = -0.1308 + 0.1193\text{LAI} - 0.024 \text{ Cos MTA} \quad (10c)$$

The final equation that described Fc irrespective of growth stage is:

$$F_c = 0.9167 - 0.026\text{LAI} + 0.219 \text{ Cos MTA} \quad (11)$$

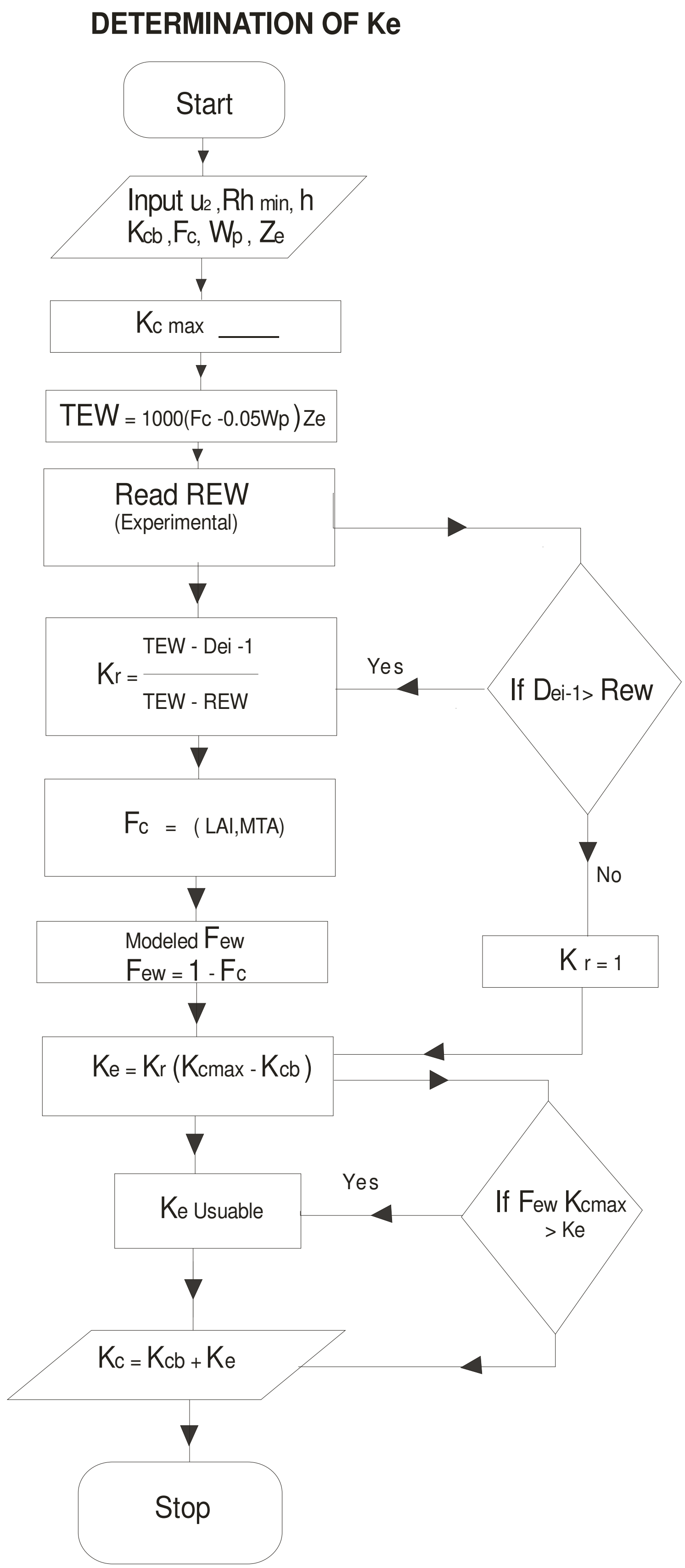

Figure 2. Flowchart for the combination of crop evaporation Ke and crop transipiration coefficient, Kc.

Table 1. Variation of days after planting (DAP) with the rice crop's coefficient.

DAP	41	42	43	44	45	46	78	79	80	81	82	83	100	101	102	103	104	105
K_c	0.86	0.84	0.88	0.92	0.95	0.83	1.03	1.11	1.12	1.15	1.09	1.11	0.70	0.75	0.73	0.77	0.71	0.70

Table 2. Comparisons between modeled K_c and K_c from FAO-24 and FAO-56 estimates.

Stages	K_c model	K_c FAO-24	K_c FAO-56
Vegetative	0.9	1.1	1
Mid season	1.12	1.25	1.15
Maturity	0.7	1	0.7

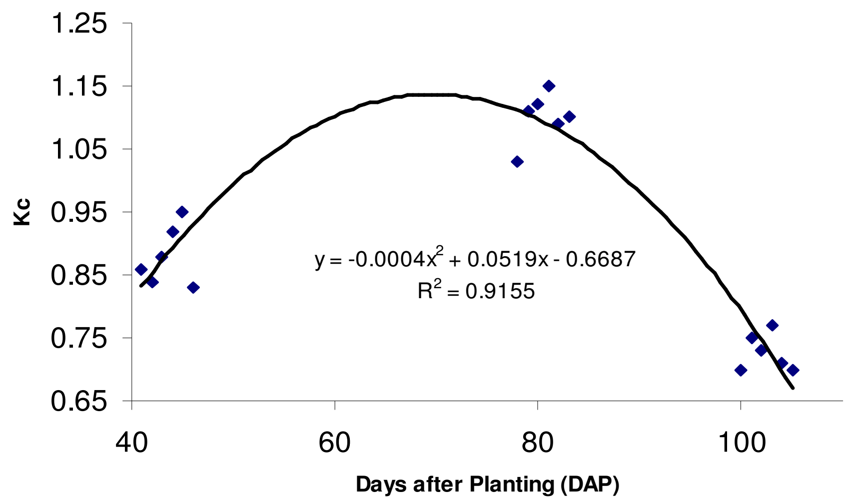

Figure 3. Variation of crop growth coefficient (Kc) with days after planting (DAP) in the 2006\2007 experiment.

The result of the modeled crop coefficient with some selected days after planting (DAP) is as shown on Table 1. The average K_c for each of the three stages identified compared with K_c of FAO-24 and FAO-56 is also shown on Table 2. From Table 1, the crop coefficient ranged from 0.9, 1.12 and 0.7 for vegetative, mid season and maturity stages in that order. The coefficient of distribution R^2 between the modeled K_c and FAO-24 and FAO-56 were 0.99 and 0.98 respectively (Table 2). This shows that was a strong positive correlation between the FAO56 and 24 values when compared with the developed values.

From Figure 3, the crop coefficient K_c increases steadily from emergence to vegetative (43 DAP) with its value reaching about 0.9, thereafter, it increases up to the flowering stage (81DAP) with K_c reaching about 1.15 and then declined until it reaches about 0.75 at maturity (101 DAP). The relationship between the crop coefficient K_c and the days after planting (DAP) as well as the R^2 values is indicated in Figure 3.

Conclusion

An attempt has been made to estimate the crop coefficient K_c of upland rice (NERICA) under standard environmental conditions in Ibadan, Nigeria. This was aimed at ensuring adequate estimation of consumptive water use of rice without overestimating it with improvised K_c values that were derived from paddy rice. A relationship between the fraction of the wetted surface, F_c, leaf area index (LAI) and the mean tilt angle (MTA) was established. Some assumptions were also considered during the formulation stage of the model. Three F_c models were generated from the programming which represents the three stages of rice crop development namely: initial, mid season and maturity stages. Average K_c values for initial, mid season and maturity were: 0.9, 1.12 and 0.7 respectively. R^2 values close to unity suggests good agreement with existing notably, FAO-56 and FAO-24 values.

The results were subject to the assumptions made during the model and may not be the same if the assumptions were altered. The use of trickle as opposed to sprinkler irrigation on which the model was based will affect the fraction of wetted surface and the leaf orientation and subsequently the individual F_c values. Therefore, the dominant effect of fraction of wetted surface f_c, leaf area index (LAI) and mean tilt angle (MTA) in influencing the crop coefficient of upland rice was evident from the study. Soil characteristics such as aggregation, type and class, evapotranspiration potential, windspeed, degree of saturation, the fraction covered by vegetation (1- f_c) and fraction not covered by vegetation but wetted by irrigation (F*ew*) are also considered to have direct effect on K_c measurements.

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