MODELLING EVAPOTRANSPIRATION OF A MAIZE CROP

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ABSTRACT

Estimates of crop evapotranspiration (ET) have value in several areas of agronomy including irrigation, evaluation of drought severity, the interpretation of field trial results and in hydrological studies.

This paper discusses a model for predicting ET for a maize crop. Model predictions compared reasonably with estimates made from neutron probe measurements under both dryland and irrigated maize crops, provided soil water did not limit ET. The cumulative ET predicted for the maize growing season were 241 mm and 291 mm, and grain yields were 4,900 and 8,800 kg D.M./ha for the dryland and irrigated crops, respectively.

The model could be used in assessing the effects of water shortages on agronomy trial yields. Effective use of high frequency irrigation will require good estimates of crop ET.

INTRODUCTION

Estimates of crop evapotranspiration have value in several areas of agronomy including irrigation, evaluation of drought severity, the interpretation of field trial results and in hydrological studies. Normally evapotranspiration estimates are based on climatological data but models for crops must take account of the effects of both crop growth and development and soil water. Therefore, in most studies it is useful to compile a daily crop water budget so that changes in soil water status within the root zone can be followed. A simple budget is given in eq. [1].

$$\left\{ \begin{matrix} \text{Soil water} \\ \text{change} \end{matrix} \right\} = \left\{ \begin{matrix} \text{Rainfall + Irrigation - Drainage} \\ \text{- Surface Runoff - Evapotranspiration} \end{matrix} \right\} \quad [1]$$

Soil Water changes both with time and space make sampling a difficult and time consuming task (Neilsen **et al.**, 1973). For this reason investigators may prefer to measure the components on the R.H.S. of (1) (Black **et al.**, 1970) and calculate soil water changes. Measurements of rainfall and irrigation can be made directly but they are subject to significant error. For level sites on soils with reasonable infiltration rates, surface runoff is negligible and can be ignored. Methods of predicting drainage on certain soils are available and an examination of the applicability of these methods to the local Manawatu soils is in progress. However, providing the soil water holding capacity is known drainage can be estimated as the residual term in equation [1]. Evapotranspiration remains the significant component to be estimated.

Development of dryland forage and crop production systems must be based on an understanding of both the size and the seasonal changes in the components of the crop water budget. On the other hand, under irrigation, crop water budgets can be used to develop schedules by which water can be applied (Jensen, 1972). Efficient use of water is important particularly where supplies are limited, where application costs are significant, and where fertiliser leaching losses may result from overwatering (Saffigna **et al.**, 1974). Explanations of differences in crop yields obtained in field trials where water might be limiting, could be helped by a knowledge of the seasonal changes in soil water within the root zone.

This paper discusses a model for predicting the evapotranspiration of a maize crop. Model predictions are compared with neutron probe soil water measurements made under both dryland and irrigated maize crops.

MODEL

The procedure adopted was to determine the daily maximum evapotranspiration and then apply a reduction factor to take account of the significant crop and soil effects.

Maximum evapotranspiration: When soil and plant factors do not restrict evapotranspiration the availability of energy at the crop surface becomes the controlling factor and maximum evapotranspiration is achieved. ET_{max} can be derived from the 'combination' equation (Slatyer and McIlroy, 1961) given in [2].

$$ET = \frac{s}{s+\gamma} (R_N - G) + pc_p h \,(D_z - D_0) \quad [2]$$

If the crop or soil surface is continually wet (i.e. D = 0) the evapotranspiration rate is controlled by the available energy and a maximum evapotranspiration rate can be defined as

$$ET_{max} = \frac{s}{s+\gamma} (R_N - G) + pc_p h \, D_z \quad [3]$$

The first term in the R.H.S. of [3] represents the net radiant energy available for evapotranspiration and becomes the equilibrium evapotranspiration rate (Priestley, 1959; Denmead and McIlroy, 1970; Davies and Allen, 1973) when the air is saturated (Dz = O). The second term in [3] describes the increase in evapotranspiration due to unsaturated air passing over the crop, and is termed the advective component of is difficult to measure and it is more convenient to describe advection as a proportion of the more easily measured radiant energy term, [3] can then be rewritten as

$$ET_{max} = \frac{s}{s+\gamma} (R_N - G) \, (1 + \alpha) \quad [4]$$

When daily totals are computed over a 24-hour period the soil heat flux, G, is approximately zero. Priestley and Taylor (1972) correlated $s/(s+\gamma)$ R and ET_{max} for severall well-watered crop surfaces and found that $(1 + \alpha)$ averaged 1.26 implying that under those conditions advection increased evapotranspiration by 26%. There, ET_{max} can be defined as follows:

$$ET_{max} = 1.26 \frac{s}{s+\gamma} R_N \quad [5]$$

ET_{max} was computed using [5] because there is very little difference in accuracy between [3] and [5] (Tanner and Ritchie, 1975).

Effect of crop and soil factors on ET: In practice the maximum evapotranspiration rate is reduced by certain crop and soil factors such as the area of transpiring leaf surface present, leaf stomatal resistances, and the availability of soil water. The relative influence of these factors changes as the crop develops. The transpiration component increases from zero prior to seedling emergence and reaches a maximum at full crop cover subsequently declining as senescence occurs whereas the soil evaporation component generally follows the opposite trend. Transpiration and evaporation can jointly or separately be reduced by the non-availability of soil water.

The reduction in ET_{max} due to crop and soil factors can be described by the general equation:

$$ET = k \, ET_{max} \quad [6]$$

There are three main cases when $k < 1.0$; namely when

(i) transpiration is restricted due to incomplete crop canopy,

(ii) evaporation from the soil surface is restricted,

(iii) transpiration is restricted due to sub-optimal soil water supply.

Each of these cases is discussed below.

Effects of incomplete crop canopy on ET:
During the early stages of crop growth k can be empirically related to any one of several indexes of crop cover such as LAI, crop height and fractional ground cover. For this model a relationship between k and crop height was obtained using evapotranspiration data from well-watered maize (Kerr et al., 1973) for periods when soil evaporation was small.

$$k = 0.8 \, (H / H_{max}) + 0.2 \quad [7]$$

Other workers have related k to LAI and found that it approaches unity at approximately LAI 3. (Ritchie and Burnett, 1971: Monteith **et al.**, 1965). However, for maize, maximum LAI is reached at least two weeks before maximum crop height and therefore significant changes in surface roughness and radiation attenuation can occur within the crop canopy after maximum LAI has been reached. These changes may affect k. Crop height was a convenient measure of crop development to use in this model.

Effect of soil evaporation on ET: The magnitude of the soil evaporation component of ET is determined by the water content of the soil surface layer and the available energy.

$$\sum E = c \, t^{1/2} \quad [8]$$

where $c = 5.5$ mm/day $^{1/2}$ for a Manawatu fine sandy loam (Kerr, 1974) and t is the number of days since a rainfall or irrigation exceeding 3 mm. If this computed value of E exceeds ET_{max} for any given day then E is set equal to ET_{max}. The value for k is computed using [6] and [8].

Therefore, two estimates of k are computed for a well-watered crop and the larger value used in [6] to calculate ET.

Effects of sub-optimal soil water on ET: Finally, the model must take account of the decline in availability of soil water when the root zone dries below a critical water content, θ_c, and stomatal resistances increase causing a reduction in ET.

Let θ_{max} and θ_{min} represent the upper and lower bounds which define the crop available water content of the soil. A constant B can be used to define the **readily** available soil water such that

$$\theta_c = B \, (\theta_{max} - \theta_{min}) \quad [9]$$

ET is not affected when the soil wafer content exceeds θ_c and the soil water is readily available, but as the soil dries the crop becomes stressed and ET declines to zero at θ_{min}. The following equation was used to compute ET when $\theta < \theta_c$.

$$ET = k \, ET_{max} \, ((\theta - \theta_{min}) / (\theta_c - \theta_{min})) \quad [10]$$

where θ is the estimated soil water storage for a particular day.

METHODS

The model was used to estimate ET and compute the changes in available soil water for both a dryland and an irrigated maize crop for the period 1 November 1974 through 28 February, 1975. Model predictions of ET were then compared with ET estimates based on neutron probe measurements made under the maize crops.

Rainfall and air temperature data required as model inputs were recorded at Plant Physiology Division approximately 0.7 km from the field site and net radiation was measured over a nearby paspalum pasture.

Maize trial: Crop growth and neutron probe measurements were made on a maize trial block with two treatments: viz. (i) irrigation applied when approximately 40% available water removed from soil and (ii) dryland management. A modified randomised block design with four replicates was used. Plot area was 110 m^2 and 8 rows wide. Sprinkler irrigation was applied on 31 December 1974, 10 January and 13 February 1975.

The maize hybrid XL 306 was sown on 6 November 1974 on land ploughed out of grass 6 weeks previously. Prior to sowing urea was broadcast at 110 kg N/ha and harrowed into the soil. Seed was sown at an approximate within row spacing of 7.5 cm and at 0.75 m row widths. A starter fertiliser (N:P:K = 12:5:14) was applied at 250 kg/ha on 28 November.

The maize crop had an established population of 73,000 plants/ha, and reached a maximum LAI about 15 January (dryland, 4.2 ± 0.3: irrigated 4.5 ± 0.3) and attained maximum crop height about 31 January (dryland 2.5 ± 0.16 m; irrigated 2.9 ± 0.14 m). Fifty percent of the plants tasselled on 17 January and silked on 22 January.

The grain yields were determined by harvesting two 2 m row lengths in each plot on 6 March. Silage yields were measured by harvesting plots with a fine-chop forage harvester and weighing the total yield in the forage wagon. The plots were harvested in pairs. Small silage samples were taken from the wagons for dry matter determinations.

Soil Water: The soil was a Manawatu fine sandy loam, underlain by gravels at a depth of 0.55 to 1.0 m. The average soil depth was 0.7. m. Access tubes were installed in the middle of each of the 8 plots, to the maximum depth permitted by the underlying gravels. Neutron probe measurements were made at 10 cm depth intervals in each hole, except that the reading at 20 cm was assumed to apply at the surface. The water content of each profile was found by integration of a spline curve fitted through all the data points.

On the basis of neutron probe measurements made immediately after heavy rain and/or irrigation, was estimated to be 175 mm. The model assumes that drainage occurs whenever θ exceeds θ_{max}, the amount of drainage being $(\theta - \theta_{max})$. θ_{min} was estimated to be 75 mm. At this soil water content neutron probe measurements on the dryland plots showed that $d\theta/dt$ <0.2 mm/day over a 14-day period implying that the available water supply had been exhausted.

There are no data available from which a unique relationship between and ET/ET_{max} can be obtained. Therefore, $B = 0.4$ was chosen and hence from [9], $\theta c =$ 135 mm. Plant water stress symptoms of leaf rolling and firing were first observed at about this soil water content. The model is relatively insensitive to the value of B selected, provided the 1974/75 rainfall distribution data are used.

RESULTS AND DISCUSSION

The model predictions were compared with neutron probe estimates of ET for three periods (Table 1) during which heavy rainfalls and irrigation did not occur, thereby allowing runoff and drainage errors to be minimized (Rouse and Wilson, 1972). Estimates of ET agree reasonably for the irrigated plots but not as well for the dryland plots, particularly in the soil water limited case.

The model prediction ET_{max} for the period was 525 mm (Figure1). Over the same period the cumulative ET predicted for maize was 241 mm for the dryland crop and 291 mm for the irrigated crop.

The first irrigation was nullified by rain the following day so that differences in soil water content did not occur until after the second irrigation on 10 January. Consequently, the divergence in ET began at the critical times of tasselling and silking, suggesting that the dryland crop was under water stress during pollination and grain-filling. The soil water budgets (Table 2) show that the main differences between treatment ET occurred in February.

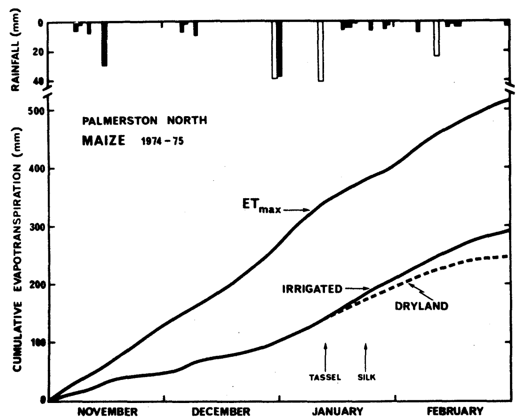

Figure 1: Cumulative ET_{max} and evapotranspiration for dryland and irrigated maize. Irrigation shown by open bars.

TABLE1: Comparison of evatranspiration (mm/day) predicted by model (1) with estimates from neutron probe data (2)

Period	Dryland		Irrigated		ET_{max}
1974/75	(1)	(2)	(1)	(2)	
16-30 Dec	2.2	2.9±0.31	2.2	2.2±0.96	5.5
21 Jan - 10 Feb	2.4	1.9±0.36	3.6	3.5±0.42	4.2
18 Feb - 4 Mar	1.1	0.4±0.14	2.4	2.6±0.84	3.4

Precise estimates of ET using the neutron probe are difficult to obtain partly because of spatial variability in soil water content. The estimates given in table 1 have a coefficient of variation from 11-44%, and the dryland and irrigated estimates for 16-30 December although not significantly different do illustrate the inherent soil variability as both plots received identical treatment. Errors are also introduced because of the inability of the neutron probe to accurately measure water content in the top 20 cm of soil. The neutron probe estimates cannot be used to calibrate the model but they do confirm that the model predictions are realistic.

The 1974/75 season was much drier than normal with rainfall for November-February (incl) totalling 182 mm which was 154 mm below the long-term average for those months. Rainfall was well distributed and drainage was not predicted on the dryland plots after the mid-November rain. On the other hand, 103 mm of irrigation was applied, of which 50 mm was used as ET, 16 mm added to the soil water storage, but 37 mm was lost as drainage.

The budget indicates that approximately 23 mm additional irrigation water should have been applied in February to maintain the available soil water level above 60 mm and therefore not restrict ET. Estimated available

TABLE 2: Monthly soil water budget (mm) for dryland (1) and irrigated (2) maize. Available soil water at 1 November was 100 mm.

	Nov	Dec		Jan		Feb	
		(1)	(2)	(1)	(2)	(1)	(2)
Rainfall 30yr. mean	79	104	*	84	*	69	*
ET_{max}	127	146	*	153	*	100	*
Budget:							
Rainfall	49	34	34	74	74	25	25
Irrigation	-	-	39	-	40	-	24
Drainage	20	-	-	-	37	-	-
ET	47	64	64	86	100	44	80
Available Soil Water (End of month)	82	52	91	40	68	21	37

soil water levels fell below 60 mm on 52 and 26 days on the dryland and irrigated plots, respectively.

The grain yields harvested at the early dent on 6 March were 4,900 and 8,800 kg D.M./ha for the dryland and irrigated crops, respectively. One obvious feature was the presence of only 0-4 green leaves on the dryland plants compared with 6-13 green leaves on the irrigated crop. Silage yields measured on 20 March were 9,300 and 16.600 kgD.M./ha for the dryland and irrigated treatments, respectively.

Linear relationships have been established between yield and water use for several crops and comparative data are available for maize. An estimated 780 kg/ha grain/cm ET from the above data can be compared with estimates of 240 kg/ha grain/cm ET for maize grown in California (Stewart and Hagan, 1973) and 445 kg/ha grain/cm ET for maize grown in Israel (Hillel and Guron,1973). These differences may be due to various management techniques, differences in Et_{max} , errors in measurement of ET, or to differences in yield interaction with environmental factors other than water.

Empirical approaches have been used in the model when allowing for the effects of crop development and soil water availability on ET. These will need to be continually reassessed. Future developments will need to consider plant water status in relation to growth. Input data are relatively simple to obtain and the model could be used in assessing the effects of water shortages on agronomy trial yields. Some difficulty was found in determining the relevant soil water storage capacities.

Recently Rawlins and Raats (1975) concluded that uniform high frequency irrigations will optimise the root environment and increase the effectiveness of water use. This will also help meet the conflicting needs of maintaining a high plant water potential and a sufficient capacity to store erratic rainfalls. Effective use of high frequency irrigation will require good estimates of crop ET.

SYMBOLS

ET	Evapotranspiration	mm/day
ET_{max}	Maximum Evapotranspiration	mm/day
R_N	Net Radiation	mm/day
G	Soil Heat Flux	mm/day
s	Slope of the saturated vapour pressure curve	mb/ °C
γ	Psychrometric constant	mb/°C
ρc_p	Heat capacity of air	mm/°C m
h	Turbulent transfer coefficient	m/day
D_z, D_0	Wet bulb depression at z, and at surface	°C
α	Dimensionless constant (eq.[4])	
k	Dimensionless constant (eq. [6])	
H, H_{max}	Crop height, maximum crop height	m
E	Cumulative Evaporation	mm
c	Constant (eq.[8])	$mm/day^{1/2}$
t	Time	day
θ θ_{max} θ_{min}	Soil water content, maximum, minimum	mm
θ_c	Critical soil water content	mm
θ	Dimensionless constant (eq. [9])	

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