Accuracy of vegetation evaporation ratio formulae for estimating final wheat yield

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Abstract

Vegetation evaporation ratio was here defined as the ratio of actual vegetation evaporation rate to potential vegetation evaporation rate. The accuracies of 5 different yield formulae based upon 5 different ways of combining vegetation evaporation ratio simulated for the different growth stages of wheat were compared. Additive, multiplicative and exponential combination methods were tested on wheat grown under 29 different water stress treatments. The multiplicative model proved most accurate, closely followed by the additive and exponential models and a model utilising a single vegetation evaporation ratio for the entire season, in that order. Mean absolute errors ranged from 9 to 12% of the mean of the measured values. This accuracy is acceptable for decision support purposes.

Notation

D	atmospheric saturation vapour pressure deficit (kPa)
E_o	reference crop evaporation (here short grass) (mm)
E_s	evaporation from the soil surface (mm)
E_{so}	potential soil evaporation (mm)
E_v	evaporation from the vegetation component of the cropped surface (mm)
E_{vo}	potential evaporation from the vegetation component of the cropped surface (mm)
$F_s = E_s/E_o$	soil evaporation ratio - the fraction of reference crop evaporation rate equivalent to actual soil evaporation rate
$F_v = E_v/E_{vo}$	vegetation evaporation ratio - the fraction of potential (water non-stressed) vegetation evaporation rate equivalent to actual vegetation evaporation rate under the existing atmospheric evaporative demand and soil water conditions
FI	green leaf fractional radiation interception - the fraction of incoming solar radiant flux density intercepted by live vegetative cover
$k_s = E_s/E_o$	the soil surface evaporation coefficient quantifying the ratio of actual soil evaporation rate to reference crop evaporation rate under the same atmospheric conditions
$k_{so} = E_{so}/E_o$	the potential soil evaporation coefficient quantifying the ratio of potential soil evaporation rate of a given soil surface to reference crop evaporation rate under the same atmospheric conditions
$k_v = E_v/E_o$	the vegetation evaporation coefficient quantifying the relationship between actual vegetation evaporation rate and reference crop evaporation rate under the same atmospheric conditions
$k_{vo} = E_{vo}/E_o$	the potential vegetation evaporation coefficient quantifying the relationship between potential evaporation rate from the vegetation of a given crop to the reference crop evaporation rate under the same atmospheric conditions
L	crop total leaf area (green plus senesced) per unit of ground surface area
t	time elapsed since the last wetting event (d)
Y	wheat grain yield (kg·ha^{-1})
Y_b	total dry biomass production over a given period (kg·ha^{-1})
Y_o	seasonal potential wheat grain yield (here 7 150 kg·ha^{-1})
Y/Y_o	relative grain yield
β	yield-water stress response factor

In the text, subscripts will be used as follows:

i	the ith growth stage in a growing season with a total of G growth stages.
n	the nth value in a data set totalling N values
o	the potential, or maximum value
v	appertaining to the vegetative component of the crop
s	appertaining to the soil surface of the cropped area.

Superscripts:

$\hat{}$	simulated value of the relevant variable
$\bar{}$	arithmetic mean of the relevant variable

Following this notation the following hold:

$\hat{Y}_n$	simulated grain yield for the nth year (kg·ha^{-1})
Y_n	measured grain yield for the nth year (kg·ha^{-1})
$\bar{Y}$	arithmetic mean of the measured grain yields (kg·ha^{-1})
$\bar{\hat{Y}}$	arithmetic mean of the simulated grain yields (kg·ha^{-1})

Introduction

In recent times, plant water stress has been evaluated in terms of the ratio of actual to potential evaporation from vegetation. This ratio will be referred to as the vegetation evaporation ratio.

Early, simple growth models of Jensen (1968) related crop grain yields reduced by plant water stress to the ratio of actual to potential vegetation evaporation. Furthermore, Jensen (1968) showed that yield reduction per unit vegetation evaporation ratio (water stress sensitivity) varies with crop growth stage (see also Hanks and Hill, 1980). Jensen (1968) proposed a maize grain yield-vegetation evaporation ratio model of the form:

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$$Y/Yo = \overset{i=G}{\underset{i=1}{\pi}} F_{vi}^{\beta_i} \qquad (1)$$

This will be referred to as the exponential type model.

A general equation defining the relationship between relative yield deficit ($1 - Y/Y_o$) and relative vegetation evaporation deficit ($1 - F_v$) may be derived from the work of Stewart and Hagan (1973). The general form of the equation here tested is the following:

$$Y/Yo = 1 - \beta(1 - F_v) \qquad (2)$$

In this study, the vegetation evaporation ratio , F_v, replaces the original evapotranspiration ratio and relative grain yield, Y/Y_o, replaces the original relative dry matter yield. The parameter β is known as the yield-water stress response parameter.

In order to apply Eq. (2), however, it is necessary to find some method of combining the yield reductions due to water stress in each of the growth stages so as to obtain an estimate of final grain yield. This has been undertaken in various ways. Multiplicative and additive laws have been proposed (Stewart et al., 1977; De Jager et al., 1987; Smith, 1990).

While multiplicative and exponential types have frequently featured in the literature, the additive types have only lately acquired significance. Their value manifests itself in linear programming applications for optimising irrigation efficiency such as those developed by De Jager and Mottram (1994). This procedure holds much promise for optimising both water applications and the area planted under water-limited irrigation situations. The technique, however, is only valid if the yield losses due to water stress computed in each growth stage can be summed to provide the overall yield decrement. Hence, this approach warrants attention here.

Essentially, 5 different ways of combining vegetation evaporation ratios simulated for different growth stages were investigated. These fall into 3 main categories, viz. multiplicative, additive and exponential. Whereas Doorenbos and Kassam (1979) and Smith (1990) used the Stewart and Hagan (1973) formula (Eq. 2) in a multiplicative mode, the original exponential type follows Eq.(1) of Jensen (1968). Furthermore, two forms of additive model have also been suggested, one by Stewart et al. (1977), and one by De Jager et al. (1987). Thus, 5 forms of model are available for testing. They are the exponential (Jensen 1968), the full season (Stewart and Hagan 1973, see Eq. 2), the multiplicative (Stewart et al. 1977), and the additive of Stewart et al. (1977) and the additive of De Jager et al. (1987).

The overall objective of this paper is the assessment of the accuracy of several evaporation ratio formulae. The specific objective here was to determine the accuracies of all 5 types of model mentioned.

Method

Cultivation practices

Field measured data from Roodeplaat Experimental Station were used to calibrate and validate the models. Data for 1986 and 1988, which appeared in unpublished reports (Laarman and Berliner, 1988; Nel and Dijkhuis, 1990) of the Soil and Irrigation Research Institute, were made available by kind permission of Dr. Sue Walker and the Director of the Institute for Soil, Climate and Water Research (ISCW), Pretoria.

A field experiment with a split-plot design was conducted at Roodeplaat (latitude 25°35' S, longitude 28°21' E) during 1986. Spring wheat (*Triticum aestivum, L.*, cv. Zaragosa) grown on a Hutton form Shorrock series (Rhodic Paleustalf) soil, was sown on 16 June 1986 (i.e. calendar day, DOY = 167). Plant density was 180 plants·m^{-2} in a row width of 0.25 m. The essential soil characteristics of the Rhodic Paleustalf are as follows: effective rooting depth 1.8 m; drained upper limit (DUL) 200 mm·m^{-1}; lower limit of soil water extraction (LL) 100 mm·m^{-1}; clay content 26 to 38%; silt 16% and bulk density 1.47 to 1.64 g·cm^{-3}.

During 1988, also at Roodeplaat, the spring wheat cultivar SST 66 was planted on 8 June 1988 (DOY 160) at a rate of 64 kg·ha^{-} in 0.25 m rows on a Shorrock series soil. Emergence took place from 16 to 20 June, 8 to 12 d after planting, resulting in a density of 140 plants·m^{-2}. The essential soil characteristics of the Hutton form Shorrock series (Rhodic Paleustalf) were identical to those for 1986 except for a clay content of 12 to 21%; silt content of 10% and bulk density of 1.47 to 1.64 g·cm^{-3}.

The researchers applied 39 different irrigation strategies over the 2 seasons. This produced 39 different sets of growing conditions and 39 corresponding yields which could be used for calibration (10) and validation (29) of the models.

Measured yields varied from 1 400 kg·ha^{-1} to 7 150 kg·ha^{-1}.

Climate data

The daily maximum temperature, minimum temperature, rainfall and sunshine duration for the experimental periods during both 1986 and 1988 seasons were supplied by the ISCW. All weather, soil and plant data were manipulated by means of the standard procedures found in the PUTU-System (De Jager, 1992).

Model calibration

The study commenced with calibration of 3 of the yield models described below. This was done using trial and error to determine the appropriate β-values for each. The procedure which was followed entailed minimising differences between measured and simulated yields for the arbitrarily selected first 10 plots in the Roodeplaat data list for 1988. All calibration commenced with the cultivar-specific β-parameters for wheat suggested by Doorenbos and Kassam (1979). First, these were adjusted by trial and error to produce new β-parameters for the De Jager additive model (denoted Model I) and presented in Column 4 of Table 1. Thereafter, the β-values for the Stewart additive (Model IV) and exponential (Model V) models were similarly obtained by trial and error. They are presented in Columns 7 and 8 respectively of Table 1.

The β-values for the multiplicative model (Model II, Column 5) and full season model (for which β = 1.7 over the entire season for Model III, see Column 6, Table 1), were taken directly from Doorenbos and Kassam (1979).

The other crop-specific model input required, was FI, the green leaf fractional interception. This can depend upon the treatment applied and should either be based on measured fractional interception, or estimated from measured L. Here it was based upon knowledge of the seasonal growth pattern of wheat at Roodeplaat. Water non-stressed estimates of FI were used in all cases as required by PUTU-Irrigation. This is a valid assumption considering the fact that irrigation generally strives toward seasonal growth without water stress. Including estimates of FI based upon measured, or simulated, L could improve model performance. The maximum wheat-grain yield measured in the experiments, viz. 7 150 kg·ha^{-1} was adopted as the yield potential for Roodeplaat.

TABLE 1
DAY OF THE GROWING SEASON (DOG); GREEN LEAF FRACTIONAL INTERCEPTION (FI); AND THE CULTIVAR SPECIFIC YIELD-WATER STRESS RESPONSE PARAMETERS, βi, FOR WHEAT AS USED IN THE 5 MODELS DENOTED I (DE JAGER ADDITIVE), II (STEWART MULTIPLICATIVE), III (STEWART-HAGAN FULL SEASON), IV (STEWART ADDITIVE) AND V (JENSEN EXPONENTIAL)

Growth stage	DOG	FI	β-values used in different models				
			I	II	III	IV	V
Rest	0	0.00	0.00	1.00	0.99	0.88	0.00
Sow	1	0.00	0.00	0.00	1.70	0.00	0.00
Establishment	2	0.25	0.10	0.20	1.70	0.70	0.10
Development	49	0.63	0.10	0.20	1.70	0.70	0.10
Mid-season	70	0.92	0.30	0.30	1.70	1.05	0.30
Flowering	100	1.00	0.40	0.65	1.70	2.25	0.60
Grain fill	110	0.83	0.35	0.55	1.70	2.00	0.45
Ripening	138	0.54	0.00	0.00	1.70	0.00	0.00
Rest	139	0.17	0.00	0.00	1.70	0.00	0.00

Model description

The yield models

The PUTU-Irrigation model (De Jager, 1992) offers a choice among all 5 of the above-mentioned methods of combining evaporation ratios. The rapid estimation of final seasonal yield using each model is therefore possible. Furthermore, each utilises the same iterative vegetation evaporation and multi-layered soil water balance model common to all PUTU models. The iterative routine is described in detail by De Jager et al. (1987). As such, PUTU-Irrigation offered a most convenient basis for the experiment.

From the defining equations, Eq. (1) or Eq. (2), the 5 sub-models (Model I to V) for computing final wheat-grain yields from vegetation evaporation ratios simulated during each of the crop growth stages were derived and tested. The multiple-period models considered here were derived from the equation of Tanner and Sinclair (1983). This showed that biomass production, Y_b, is directly related to vegetation evaporation, E_v, and inversely related to atmospheric saturation vapour pressure deficit, D. Apart from being crop cultivar specific, such relationship is also dependent, however, upon climate-crop architecture interaction as influenced by:

- the ratio of shaded to non-shaded leaf area; and
- the effect of warm or cold climates on leaf air temperature differentials.

These cause seasonal variations in the $Y_b = f(E_v / D)$ relationship. Here, however, short intervals during the growing season are considered during which canopy characteristics may be deemed to be constant and hence Y_{bi} is directly proportional to E_{vi}/D_i. The relevant constant of proportionality is now purely cultivar specific. This relationship agrees with the findings of Kieselbach (1916) as early as 1916 and with the case of conservatism made by Monteith (1990). In the present study, however, the theory is strengthened by considering individual growth stages rather than attempting to use a mean constant of proportionality for the entire season as suggested by the above two scientists among others.

Now, provided that excessive water stress during which the crop architecture is completely modified, does not occur, then relative biomass production $Y_{bi} / Y_{boi} = E_{vi} / E_{voi} = F_{vi}$, because the constant of proportionality and D will cancel out. This relationship is in accordance with the work of Hanks (1974).

The assumption made in this work is that final grain yield decreases are related to the magnitude of the growth stage relative biomass production, that is say, growth stage relative vegetation evaporation F_{vi}. This relationship is quantified by the yield-stress response parameter, β_i. In some cases the model considered uses a slightly different definition of β_i. The definitions chosen are similar to those suggested by Jensen (1968), Stewart et al. (1977) for crop total evaporation and De Jager et al. (1987) for vegetation evaporation. Combinations of the final grain yield response to individual growth stage F_{vi} were effected using either multiplicative or additive laws of mutual limitation. Because water stress effects are best measured using relative grain yield deficits and relative vegetation evaporation deficits this approach was adopted here.

Here, the growth stage yield-water stress response parameter, β_i, is defined as the decrease in relative final grain yield deficit per unit relative vegetation evaporation deficit occurring in the i^{th} growth stage.

Jensen (1968) stated that for indeterminate crops, the effects of water stress during specific crop growth stages are independent of stress influences during other growth stages. Mallett and De Jager (1971) found this to be true for maize and in addition that the effects of stress within a given growth stage whether on consecutive or intermittent days, were also independent and constant. Hence, the assumption is here made that the effects of water stress occurring during a given growth stage upon final grain yield is independent of the influence of water stress occurring during any other crop growth stage.

As a result decrements in relative yield deficit due to water stress in given growth stages may be added or multiplied (mutual independent limitation).

The models were expressed mathematically as follows:

(I) De Jager additive

$$\hat{Y}/Y_o = 1 - \sum_{i=1}^{i=G} \beta_i (1 - \hat{F}_{vi}) \qquad \text{(De Jager et al., 1987)}$$

(II) Stewart multiplicative

$$\hat{Y}/Y_o = \pi_{i=1}^{i=G} [1 - \beta_i (1 - \hat{F}_{vi})] \qquad \text{(Stewart et al., 1977)}$$

(III) Stewart-Hagan full season

$$\hat{Y}/Y_o = 1 - \beta(1-\hat{F}_v) \qquad \text{(Stewart and Hagan, 1973)}$$

Here, β and F_v refer to a single β-value for the entire growing season and F_v is the growing season vegetation evaporation ratio, viz.:

$$\hat{F}_v = \frac{\sum_{i=1}^{i=G} \hat{E}_{vi}}{\sum_{i=1}^{i=G} \hat{E}_{voi}}$$

(IV) Stewart additive

$$\hat{Y}/Y_o = 1 - [\sum_{i=1}^{i=G} \beta_i (E_{voi} - \hat{E}_{vi})] / \sum_{i=1}^{i=G} \hat{E}_{voi} \qquad \text{(Stewart et al., 1977)}$$

(V) Jensen exponential

$$\hat{Y}/Y_o = \pi_{i=1}^{i=G} \hat{F}_{vi}^{\beta_i} \qquad \text{(Jensen, 1968)}$$

The values of the β-parameters either derived during calibration or from the literature which were used in the validation of the different models are given for each growth stage in Table 1. Potential yield was taken to be the maximum grain yield measured, i.e. $Y_o = 7\ 150$ kg·ha^{-1}.

Vegetation evaporation model

Evaporation from the vegetative component of the cropped surface was computed in PUTU-Irrigation using the evaporation coefficient theory developed by De Jager and van Zyl (1989). Basically this may be considered either for growing conditions with no water stress, or for conditions exhibiting water stress.

No water stress: Here water non-stressed, or potential, vegetation evaporation, E_{vo}, is assumed to:

- be directly proportional to the fraction of incoming solar radiant flux density intercepted by green leaves in the crop canopy, FI; and also
- bear a strict relationship to E_o. This relationship is quantified by the factor k_{vo}.

These assumptions may be defined mathematically by:

$$E_{vo} = FI\ k_{vo}\ E_o \qquad (3)$$

where, k_{vo}, the potential vegetation evaporation coefficient, is an empirical coefficient reflecting the interaction between climate and crop morphology and crop physiology for a given crop growth stage. Therefore several different k_{vo} values exist for a particular crop. It may thus be conceived as a means of converting a short grass reference into say a wheat reference, but at the same time accounting for the effects of incomplete cover.

In practice, fractional radiation interception may be obtained in one of 3 ways, viz.:

1. simulation using $FI = 1 - e^{-0.7L}$ (Ritchie, 1972); (4)
2. measuring the sun fleck area per unit ground surface with any simple shade fraction meter; and
3. setting FI equal to the visually estimated vertical projection of green vegetative cover per unit of ground surface area.

Option 3 of these approximation methods was employed here. It represents an approach similar to the methods of estimating the crop evaporative coefficient adopted for example by Abbaspour et al. (1992) and Smith (1990) - the former in a modelling exercise and the latter for practical irrigation scheduling. In South Africa, irrigation managers also follow Option 3 with success (see Mottram and De Jager, 1993).

Water stress conditions: Under water stress conditions, the interaction between atmospheric evaporative demand, crop physiological characteristics and soil water limitation inhibits the conductance of water through the vegetation. The vegetation evaporation ratio, F_v, quantifies this process. It quantifies the influence of the hydraulic conductance of the soil-plant-atmosphere system and is sometimes calculated as the relative hydraulic conductance, i.e. the ratio of crop hydraulic conductance under the existing soil-plant-atmospheric conditions (which could be water-stressed) to the hydraulic conductance under no water stress. F_v is defined by:

$$E_v = F_v\ E_{vo} \qquad (5)$$

Thus, by substituting for E_{vo} from Eq. (3):

$$E_v = F_v\ FI\ k_{vo}\ E_o \qquad (6)$$

which yields an expression for the vegetation evaporation coefficient:

$$k_v = F_v\ FI\ k_{vo} \qquad (7)$$

for use in:

$$E_v = k_v E_o \quad (8)$$

In all crop models in the PUTU-System the evaluation of F_v reduces to the solution of a non-linear equation. This is undertaken by an iterative technique described in De Jager et al. (1987).

Cause for much concern in practical irrigation scheduling is the climatic dependence of evaporation coefficients as demonstrated for example by Van Zyl and De Jager (1992). It is evident that, by definition, the influence of climate upon the vegetation evaporation coefficient manifests itself entirely in k_{vo}. Here, as a first approximation for wheat, k_{vo} was taken to equal 1.1.

It is also evident that the water non-stressed vegetation evaporation, E_{vo}, is a special case of Eq. (6) for which $F_v = 1$ (see Eq. 3).

Soil evaporation model

By similar argument De Jager and Van Zyl (1989) defined soil evaporation coefficients, viz:

$$E_s = k_s E_o \quad (9)$$

or:

$$E_s = F_s k_{so} E_o \quad (10)$$

F_s effectively describes the limitation placed on soil evaporation by the gradual drying out of the soil surface layer. The potential soil evaporation coefficient, k_{so}, relates potential soil evaporation to reference crop evaporation. Thus,

$$E_{so} = k_{so} E_o \quad (11)$$

Hence:

$$k_s = F_s k_{so} \quad (12)$$

wherein:

$$F_s = e^{-0.4t} \quad (13)$$

Here also the climate dependence of the soil evaporation coefficient is accounted for in the potential soil evaporation coefficient, k_{so}. At present k_{so} is assumed equal to unity. It could be a function of surface roughness and climate, but needs to be evaluated in future research.

Model validation

After calibration, simulated yields obtained with all 5 models were compared with the wheat-grain yields measured during 1986 and 1988. Data sets other than the 10 used for calibration purposes were used. The slope through the origin, coefficient of determination, index of agreement, mean absolute error, root mean square error and 80% accuracy frequency were calculated and are presented in Table 2. Graphs obtained during validation of the additive (Model I) and multiplicative (Model II) models, are given in Fig. 1a and Fig. 1b respectively.

Reference crop evaporation

Reference crop evaporation, E_0, was computed using automatic weather station data and the form of the Penman-Monteith equation as applied in the PUTU-System (De Jager, 1992).

Statistical analyses

Five different validation characteristics were used to assess each model's accuracy when simulated wheat-grain yields were compared to their corresponding measured values. The statistical parameters determined, were denoted:

S	slope through the origin
r^2	coefficient of determination
D	index of agreement of Willmot (1982)
RMSE	root of the mean square error
MAE	mean absolute error expressed as a percentage of the mean of the measured values
D80	the 80% accuracy frequency.

TABLE 2
MODEL VALIDATION. SLOPE THROUGH THE ORIGIN (S), THE COEFFICIENT OF DETERMINATION (r^2), INDEX OF AGREEMENT (D), MEAN ABSOLUTE DIFFERENCE (MAE), ROOT MEAN SQUARE ERROR (RMSE), 80% ACCURACY FREQUENCY (D80) AND NUMBER OF COMPARISONS (N) OBTAINED FROM THE TESTS CARRIED OUT ON THE FIVE DIFFERENT VERSIONS OF EVAPORATION RATIO YIELD MODEL TOGETHER WITH THE CRITERIA FOR MODEL RELIABILITY.

Statistical parameter	Model					Reliability criterion
	I	II	III	IV	V	
S	0.97	1.03	1.07	1.05	1.02	0.9 - 1.1
r^2	0.90	0.91	0.91	0.93	0.92	>0.8
D	0.97	0.98	0.97	0.98	0.97	>0.8
MAE (%)	12	10	11	9	11	<20%
RMSE (kg·ha^{-1})	675	599	676	595	615	<700
D80 (%)	83	90	72	86	76	>80%
N	29	29	29	29	29	

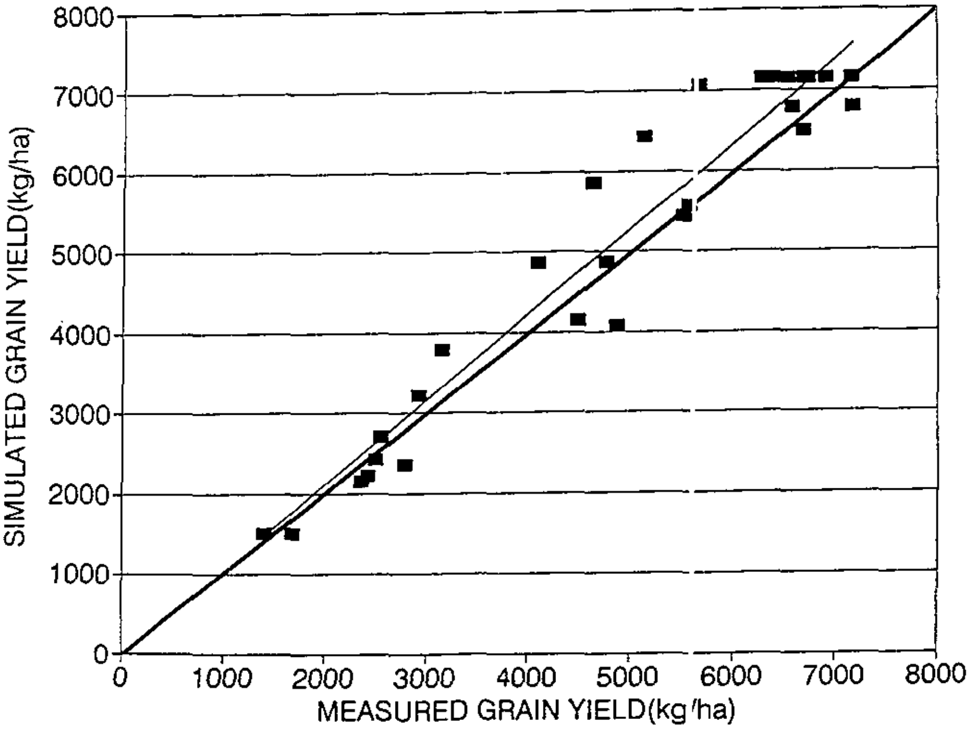

Figure 1(a)

Simulated versus measured wheat-grain yields (■), the 1:1 line and line of best fit obtained at the Roodeplaat experimental station during 1986 and 1988. Simulations were made using the De Jager additive version of the evaporation ratio formula (Model I).

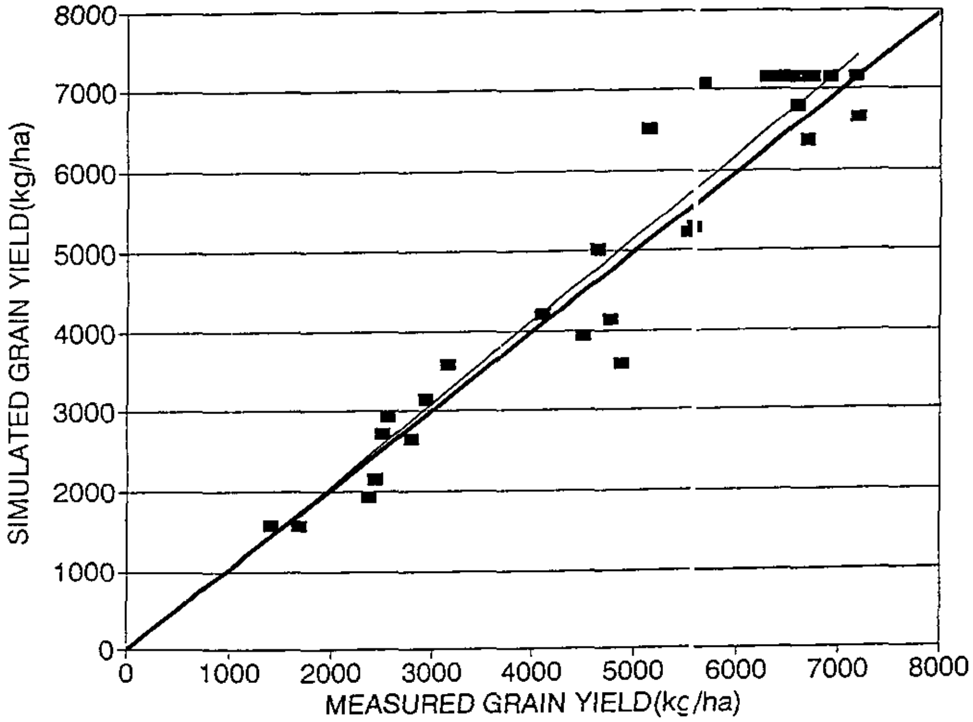

Figure 1(b)

Simulated versus measured wheat-grain yields (■), the 1:1 line and line of best fit obtained at the Roodeplaat experimental station during 1986 and 1988. Simulations were carried out using the Stewart multiplicative version of the evaporation ratio formula (Model II).

These are defined:

$$r^2 = \left[\sum_{n=1}^{n=N} (\hat{Y}_n - \overline{\hat{Y}})(Y_n - \overline{Y})^2 / \sum_{n=1}^{n=N} (\hat{Y}_n - \overline{\hat{Y}}) \right]^2 (Y_n - \overline{Y})^2$$

$$D = 1 - \sum_{n=1}^{n=N} (\hat{Y}_n - Y_n)^2 / \sum_{i=1}^{n=N} (|\hat{Y}_n - \overline{Y}| + |Y_n - \overline{Y}|)^2 \qquad 0 \leq D \leq 1$$

$$RMSE = [\sum_{n=1}^{n=N} (\hat{Y}_n - Y_n)^2 / (N - 1)]^{0.5}$$

$$MAE = 100 \sum_{n=1}^{n=N} |\hat{Y}_n - Y_n| / N\overline{Y}$$

The D80 statistic was computed as the percentage of simulated values agreeing within 20% of the measured values.

It is generally accepted (Ritchie, 1990) that models can perform with an accuracy of 20%. Criteria against which the above statistics may be tested in order to assess how close the model comes to achieving this requirement were established. The chosen criteria are listed in the last column of Table 2.

Results and discussion

Calibration

Tests on the calibrated versions of Models I, IV and V yielded model reliabilities acceptable to permit further validation of these models. The model input parameters resulting from the calibration of Models I, IV and V and those obtained from the literature for Models II and III are given in Table 1.

The statistical tests showed that marked improvement in r^2, index of agreement (D) and the 80% accuracy frequency (D80), were attained with particularly the re-calibrated version of the additive model (Model I). The original β-values (De Jager et al., 1987) tended to lead to underestimation of grain yield under high water stress conditions.

Model validation

Results of the model validations are given in Table 2. With the exception of only Model III with D80 = 72% and Model V with D80 = 76% all the statistics tested met the requirements listed in the last column of Table 2. The r^2, D and MAE obtained for all models were approximately the same. However, the low RMSE = 599 kg·ha^{-1}, S = 1.03 and high D80 = 90% for Model II (Stewart multiplicative) suggest that it is marginally more accurate than Model IV (Stewart additive) with RMSE = 595 kg·ha^{-1}, S = 1.05 and D80 = 86%. These are closely followed in descending order of accuracy by the De Jager additive Model I (RMSE = 675 kg·ha^{-1}, S = 0.97 and D80 = 83%,) and the Jensen exponential Model V (RMSE = 615 kg·ha^{-1}, S = 1.02 and D80 = 76%). Possibly the least accurate proved to be the Stewart-Hagan Model III, which utilised a single entire season evaporation ratio, (RMSE = 676 kg·ha^{-1}, D80 = 72% and S = 1.07). In summary then, when tested against the selected validation criteria, Models I, II, IV and V proved satisfactory for use for decision support purposes. Only the full season Model III with a D80 of 72% and S of 1.07 yielded marginally unacceptable test results.

When the suitably calibrated β-parameters (see Table 1) were used, an accurate (S = 0.97 and D80 = 83%) decision support tool resulted for the De Jager additive Model I. Furthermore, the Stewart additive Model IV also performed most satisfactorily (S = 1.05, and D80 = 86%). It is thus possible to report that either of these models contain adequate accuracy permitting their application in, for example, linear programming procedures.

It is noteworthy that this approach requires local knowledge for setting the duration of the individual growth stages and the magnitudes of the FI factors. Such an approach has been applied in numerous studies, notably Abbaspour, et al. (1992), Smith (1990) and Doorenbos and Kassam (1979). It needs to be stressed here that model reliability is sensitive to both duration of growth phase and the magnitude and rate of change of the green leaf fractional interception factors, FI. Great care needs to be exercised to ensure selection of realistic values. The models would be improved by simulating leaf area development using thermal time and then estimating FI from the simulated values. The effect of restricted water supply on FI would then also be included. Such procedures exist in the PUTU-Anycrop version and are being tested at present.

Howell (1990) reporting on the work of among others Stewart et al. (1977) suggests that relative yield deficit/total evaporation deficit relationships might not be climate dependent and that little advantage might be gained from multiple-period models for maize, wheat, grain, sorghum and soya crops. He does, however, list the most critical periods (usually around anthesis) in which water deficits adversely affect crop yield for no fewer than 29 different crops. Water deficits during anthesis cause reduction in seed or grain numbers. After anthesis water deficits adversely affect grain filling.

The relationship between biomass production and plant evaporation is influenced by climate and crop architecture. Evaporation ratios, however, are not. Previous attempts to remove accounting for climatic influences by normalising evaporation in terms of either pan evaporation or crop total evaporation have met with limited success, because both pan evaporation and total evaporation adjust to climate in a manner which differs from that in which plant evaporation does (see Kanemasu, 1983). Van Zyl and De Jager (1992) showed that such normalisation is climate dependent. These concerns are eliminated here however, because the influences of D and climate-crop architecture cancel out in the ratios F_{vi} and hence Y_{bi}/Y_{boi}. Furthermore, De Wit (1958) suggested that even the relationship between biomass production and plant evaporation might be independent of soil nitrogen level within reasonable limits. The yield response parameter, β, as here defined, is purely a plant physiological entity and thus determined by crop genetics and not climate. Thus, since harvest index is not employed to estimate final yield in the models; this form of climatic influence, also indentified by Kanemasu (1983), has been removed as well. The β-parameter should thus be neither site- not climate-specific.

It is also worthy of mention that during the course of the Roodeplaat experiments total soil water content down to 5 different levels (viz. 0.52 m, 0,67 m, 0.97 m, 1.27 m and 1.90 m) was recorded at approximately 2 to 3-day intervals. The measured soil water content for each of these zones was compared to those estimated by the PUTU-Irrigation model. For modelling purposes, the soil profile was assumed to be at field capacity at the beginning of the season. It is not known whether this was indeed the case with the Roodeplaat experiment. Nevertheless, good agreement between measured and simulated soil water content was evident (see Mottram and De Jager, 1993). This provides added evidence supporting the validity of the values of FI selected, the techniques used for estimating FI and the model as a whole.

Conclusions

The validation tests proved that given suitable yield-water stress response parameters, all 5 types of evaporation ratio model described, provide accuracies acceptable for use in decision support applications. The multiplicative type model (Model II) on this evidence proved to be the most accurate. Importantly, the validity of at least 2 forms of additive model (viz. Model I and Model IV) for use in linear programming, or other optimisation procedures, was also proved.

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