Response of tanier (Xanthosoma spp.) to evapotranspiration deficits estimated with the FAO water balance method\textsuperscript{1,2}

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\section*{ABSTRACT}

Field experiments in Puerto Rico have shown that with adequate drainage and plant nutrition, good yields of tanier (\textit{Xanthosoma} spp.) are consistently obtained under high frequency irrigation. Still lacking, however, is quantitative information on yield variations under different irrigation scheduling scenarios. A well-known tool for this purpose is the FAO (Food and Agriculture Organization) water balance model, which calculates relative decreases in crop yields (RYD) from relative evapotranspiration deficits (RETD) which are estimated from crop, soil, irrigation and weather data. A simple form of the FAO model calculates RYD as the product of RETD for the growing season multiplied times a proportionality constant or yield sensitivity coefficient ($K$), which must be experimentally determined for each specific crop. The objective of this study was to estimate $K$ for tanier, by examining published data from three irrigation experiments conducted at various locations in Puerto Rico over a 20-year period. The FAO model

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was used to estimate seasonal RETD from crop and soil parameters and irrigation and weather records, and this value was used together with experimental yield data to calculate $K_r$. A first analysis yielded $K_r$ values between 3.1 and 4.2, which considerably exceeded values on the order of 1.0 reported in the literature for most crops. Suspecting that the discrepancy could have been due to incorrect tanier crop parameters assumed in the FAO model, we adjusted crop parameters as far as seemed reasonable in ways which would minimize estimation of $K_r$. The minimum $K_r$ values obtained in this manner ranged between 2.4 and 3.3, which are still quite high. They imply that a 10 percent water deficit relative to evapotranspiration demand is sufficient to reduce tanier yields between 24 and 33 percent. It is postulated that the high $K_r$ values for tanier could reflect a synergistic effect of several plant stress factors associated with soil moisture, mainly water stress, soil mechanical impedance and pathogenic stress. Results in general confirm previous observations regarding sensitivity of tanier to drought stress, and indicate a significant response of tanier to irrigation under even moderate drought conditions.

Key words: Tanier, Xanthosoma spp., water balance models, crop growth sensitivity coefficient, irrigation, water deficits, relative evapotranspiration deficiency, relative yield deficiency.

RESUMEN

Respuesta de la yautía (Xanthosoma spp.) a déficits de evapotranspiración estimados con el modelo de balance de agua de la FAO

Experimentos de campo en Puerto Rico han demostrado que con buen drenaje y nutrición de las plantas se logran obtener buenos rendimientos de yautía (Xanthosoma spp.) utilizando riego de alta frecuencia. Sin embargo, aún se requiere información cuantitativa sobre las variaciones de rendimiento bajo diferentes escenarios de programación del riego. Una herramienta bien conocida para este propósito es el modelo de balance de agua de la FAO (por Food and Agriculture Organization), que calcula disminuciones relativas en los rendimientos de los cultivos (DRR) en función de déficits de evapotranspiración relativos (DETR), calculados a partir de datos de cultivos, suelo, evapotranspiración, precipitación y riego. Una forma sencilla del modelo determina la DRR como el producto del DETR promedio durante la vida del cultivo, multiplicado por una constante de proporcionalidad o coeficiente de sensitividad de rendimiento ($K_r$), el cual se determina para cada cultivo mediante experimentación. El objetivo de este estudio fue estimar $K_r$ para yautía, examinando datos de tres experimentos de riego realizadas en varios lugares en Puerto Rico durante un intervalo de 20 años. Se utilizó el modelo de la FAO para estimar DETR, y este valor se utilizó junto con los datos experimentales de rendimiento para calcular $K_r$. Un primer análisis arrojó valores de $K_r$ entre 3.1 y 4.2, superando considerablemente los valores del orden de 1.0 reportado en la literatura para la mayoría de los cultivos. Ante la sospecha de que la discrepancia podría haber sido debido a parámetros incorrectos asumidos para yautía en el modelo de la FAO, se ajustaron los parámetros dentro de los límites razonables, de tal manera que se redujera al mínimo la estimación de $K_r$. Aún así se obtuvieron valores altos de $K_r$ entre 2.4 y 3.3. Tales valores indican que un déficit de agua de 10 por ciento, relativo a la demanda de evapotranspiración, es suficiente para reducir los rendimientos de yautía entre 24 y 33 por ciento. Se postula que los altos valores de $K_r$ para yautía podrían reflejar un efecto sinérgico de varios factores de estrés de las plantas asociados con la humedad del suelo, principalmente estrés hídrico, la impedancia mecánica del suelo y el estrés...
Los resultados en general confirman las observaciones previas sobre la alta sensibilidad de la yautía a los déficits hídricos, e indican una respuesta significativa del cultivo al riego, aún bajo condiciones de sequía moderada.

Palabras clave: yautía, *Xanthosoma* spp., balance de agua, coeficiente de sensibilidad de cultivo, riego, déficit hídrico, deficiencia de evapotranspiración relativa, deficiencia de rendimiento relativo

**INTRODUCTION**

Tanier (*Xanthosoma* spp.), or "yautía" as referred to in Puerto Rico, is a significant component of the Puerto Rican diet, with an average consumption rate of approximately 6 kg/person/yr (Cortés and Gayol, 2010). Prior to the 1950s, local farmers produced most of the tanier consumed on the Island, but local production has decreased dramatically since then (Lugo et al., 1987). Currently only 10% of tanier consumed in Puerto Rico is produced locally, with the remaining 90% being imported (Cortés and Gayol, 2010). Irizarry et al. (1977) suggested that increasingly erratic rainfall distribution since the 1950s was a possible cause of the decline in tanier production, because the crop requires abundant and well distributed rainfall throughout the growing season (Abruña-Rodríguez et al., 1967; Onwueme, 1978). Erratic rainfall distribution appears to increase crop susceptibility to a pathological condition known as "mal seco" or root dry rot (Lugo et al., 1987). Droughts due to erratic rainfall can also result in high soil mechanical impedance (Snyder, 1994), a condition to which tanier yields are highly sensitive (Lugo-Mercado et al., 1978).

The above evidence points to adequate water management as a key element for successful tanier production. Indeed, field experiments over the past 20 years in Puerto Rico have consistently shown that with adequate drainage and nutrient management, excellent tanier yields can be obtained under high frequency irrigation (Lugo et al., 1987; Goenaga and Chardón, 1993; Goenaga, 1994a; Snyder et al., 1995). Given the high market demand and farm-gate value of the crop, the additional cost of irrigation appears more than offset by the probability of consistently high yields. Therefore, irrigated tanier production seems to offer a viable economic opportunity for farmers in Puerto Rico.

Management constraints, such as labor shortage or insufficient irrigation water, often limit the feasibility of irrigating in the full amounts and timing required for maximum yields. Optimal irrigation scheduling under these conditions requires knowledge of crop response to water stress under different water management scenarios. A simple yet effective tool for such purposes is the FAO water balance model.
(Doorenbos and Kassam, 1979; Allen et al., 1998; Steduto et al., 2012). The model assumes that for a given water management scenario, the relative yield deficit (yield reduction relative to maximum yield under no water stress), is proportional to the relative evapotranspiration deficit (evapotranspiration deficit relative to potential crop evapotranspiration). The relative evapotranspiration deficit (RETD) is first estimated from soil and plant parameters and daily records of rainfall, irrigation and reference evapotranspiration, and then the relative yield deficit (RYD) is estimated by multiplying RETD by a crop-specific proportionality coefficient ($K_y$), which must be determined a priori by experiment. Values of $K_y$ have been published for a large number of crops (Doorenbos and Kassam, 1979; Steduto et al., 2012), but information on tanier is still lacking. In this paper, we estimate $K_y$ for tanier by examining data from three different irrigation experiments, performed over a 20-year time span in Puerto Rico at three different locations, Gurabo, Juana Díaz and Isabela. Results will quantitatively confirm the great sensitivity of tanier to water deficits, which has often been noted by researchers working with the crop.

**MATERIALS AND METHODS**

**Brief overview of the FAO water balance model**

The FAO model used quantifies water stress in terms of a relative evapotranspiration deficit (RETD), defined as

$$\text{RETD} = \frac{\text{ET}_c - \text{ET}_a}{\text{ET}_c}$$  \[1\]

where $\text{ET}_c$ is the crop water demand or potential evapotranspiration under non-limiting water supply, and $\text{ET}_a$ is actual evapotranspiration which is generally less than $\text{ET}_c$ when soil water availability becomes limiting. The values of $\text{ET}$ and $\text{ET}_c$ in Eq. [1] are usually cumulative values, or sums of daily $\text{ET}_c$ and $\text{ET}_a$ values taken over a given crop growth stage or entire crop growth season. Methods for their determination are described below. The RETD increases in value from zero when $\text{ET}_a = \text{ET}_c$ (no water stress) to unity when $\text{ET}_a = 0$ (the soil is so dry that evapotranspiration ceases due to permanent plant wilting).

Crop yield response to RETD is described in terms of a relative yield deficit (RYD) similar in structure to Eq. [1]:

$$\text{RYD} = \frac{Y_{\text{max}} - Y_a}{Y_{\text{max}}}$$  \[2\]
where $Y_{max}$ is maximum yield in absence of water stress and $Y$ is actual yield. For a crop with $i = 1, 2, ..., I$ growth stages, the overall relative yield deficit is related to evapotranspiration deficits occurring in the different growth stages by the linear equation

$$\frac{Y_m - Y_a}{Y_m} = \sum_{i=1}^{I} K_y \left( \frac{ET_{ei} - ET_{ai}}{ET_{ei}} \right)$$

where the subscript $i$ represents the $i^{th}$ growth stage. The parameter $K_y$ is the crop sensitivity factor for the $i^{th}$ growth stage, which relates the final relative yield deficit to the relative evapotranspiration deficit occurring in the $i^{th}$ growth stage.

If the sensitivity factor does not vary much for the different growth stages, Eq. [3] simplifies to

$$\frac{Y_m - Y_a}{Y_m} = K_y \frac{ET_{ei} - ET_{ai}}{ET_{ei}}$$

or simply,

$$RYD = K_y RETD$$

where $ET_e$ and $ET_a$ are the cumulative potential and actual evapotranspiration for the entire growth season, respectively, and $K_y$ is the average sensitivity coefficient for the growth period. In the analyses reported here, we only study seasonally averaged $K_y$ values defined by Eqs. [4] or [5].

Potential crop evapotranspiration $ET_e$ may be estimated from climate data or pan evaporation records (Doorenbos and Pruitt, 1976; Allen et al., 1998). In our study, $ET_e$ was determined from records of class-A pan evaporation, $E_{pan}$, as

$$ET_e = K_p \cdot K_c \cdot E_{pan}$$

where $K_p$ is a pan coefficient dependent on climatic and vegetation conditions, and $K_c$ is a crop coefficient which depends primarily on the type of crop and its growth stage. The values of pan coefficient $K_p$ for the three experimental sites considered in this paper were as follows: Isabela: $K_p = 0.89$; Gurabo: $K_p = 0.79$ and Juana Díaz: $K_p = 0.74$. These values represent yearly averages of monthly data given by Harmsen et al. (2004).

Crop coefficient values ($K_c$) for tanier, as a function of days after planting, are shown in Figure 1. Due to lack of published $K_c$ values for tanier, Figure 1 was constructed using available $K_c$ data for banana
FIGURE 1. Crop coefficient ($K_c$) values assumed for a tanier crop.

(Doorenbos and Kassam, 1979), with the length of different growth stages adapted to tanier based on plant phenological data shown in Figure 2. The $K_c$ values for banana were used because of its canopy similarity with tanier (few very large leaves), offering similar aerodynamic resistance in both cases.

In the latter stages of writing this paper, it was brought to our attention that, in light of leaf dry matter accumulation patterns as shown in Figure 2, the initial rising portion of the $K_c$ graph in Figure 1 should probably have been set at 50 to 60 days rather than at 75 days as in Figure 1, with the error causing an overestimate of $ET_c$ in the initial rising stage. We concur with this assessment, but also note that the time shift error is only on the order of two weeks, out of a total of 52 weeks for the overall crop growth period, and furthermore occurs in the zone of the rising curve where $K_c$ is still small. It should also be noted that for reasonably moist soils (value of $F(p)$ close to unity) any overestimate of $ET_c$ is reflected in a roughly proportional overestimate of $ET_o$ (c.f. Eq. [7]), which by virtue of Eq. [1] causes only small error in estimated RETD. The combined effect of these factors is that the error in seasonal RETD (the relevant parameter of interest) was probably negligible. However, to account for this and other sources of error in estimated model parameters, a sensitivity analysis was conducted, which is described later in this paper.

The actual crop evapotranspiration ($ET_a$) in the FAO water balance model is estimated from the formula
FIGURE 2. Leaf dry matter accumulation for tanier as a function of weeks after planting, for different irrigation treatments at Isabela, Puerto Rico (unpublished data from Snyder et al., 1995). Irrigation treatments 1 through 5 are described later in Materials and Methods.

\[ ET_a = ET_c \cdot F(p) \]  \[7\]

where \( ET_a \) is the crop evapotranspiration demand defined above, and \( F(p) \) is a function of the fraction of plant-available water \( p \) remaining in the crop rooting zone.

The fraction of plant-available water is defined as

\[ p = \frac{h}{h_o} \]  \[8\]

where \( h \) is the effective depth of available water (mm) in the rooting zone and \( h_o \) is the maximum available water storage capacity (mm). The maximum storage capacity \( h_o \) is given by

\[ h_o = D(\theta_c - \theta_w) \]  \[9\]

where \( D \) is the effective crop rooting depth, and \( \theta_c \) and \( \theta_w \) represent the volumetric soil water content at field capacity and permanent plant wilting, respectively. Based on soil survey laboratory data for these soils (Soil Survey Staff, 1967; Mount and Lynn, 2004), we assumed
that $\theta_{fc} - \theta_w = 0.10$ for the Oxisol at Isabela, and $\theta_{fc} - \theta_w = 0.15$ for the Vertisol at Gurabo and the Mollisol at Juana Díaz. Since values of rooting depth $D$ were not available for tanier, we assumed maximum values of $D = 0.5 \text{ m}$, similar to published values for banana (Doorenbos and Kassam, 1979) which has a root morphology similar to that of tanier. An initial rooting depth of 0.1 m was assumed at planting, to account for a finite soil volume around seeds (corm sections), which provided water by diffusion even though no roots had yet developed. Rooting depth was assumed to increase linearly with time during the first 100 days after planting, attaining a maximum depth of 0.5 m thereafter (Figure 3).

The assumption of a 100-day root development period was based on measured root biomass in the top 30 cm in the Isabela experiment (Figure 4), showing a rapid increase in biomass during the first 15 weeks (approximately 100 days) after planting, after which root biomass accumulation tended to stabilize. After about 40 weeks the measured root biomass in Figure 4 began decreasing, but we assumed that this applied primarily to root density per unit volume, with depth of rooting remaining the same.

The function $F(p)$ in Eq. [7], relating potential evapotranspiration $ET_c$ to actual crop evapotranspiration $ET_a$, is illustrated graphically in Figure 5. Note that $F(p)$ has a value of unity so long as the available water-filled fraction $p$ of the soil is greater than some critical value $p_c$, but decreases linearly with $p$ when $p < p_c$. Values of the critical available water fraction $p_c$ vary from as low as 0.3 for deep rooted crops and low $ET_c$ conditions, to values as high as 0.8 for shallow rooted crops and high $ET_c$ conditions (Doorenbos and Kassam, 1979). A default value of 0.5 is often used, and was the value assumed for tanier.
To run the FAO water balance subroutine, an initial amount of available water ($h$) is assumed (or preferably measured) for the beginning of day 1. From this value the parameters $p$ and $F(p)$ for that day are estimated from Eq. [8] and Figure 5, respectively. From $F(p)$ and the known potential evapotranspiration $ET_c$ for the day, the actual evapotranspiration $ET_a$ for the day is estimated from Eq. [7]. The available water $h$ remaining in the soil at the end of the day is then calculated by subtracting $ET_a$ from the initial (morning) value of $h$, and adding any amount of rainfall or irrigation occurring during the day. If this calculated value of $h$ exceeds the water holding capacity $h_o$ of the soil, the excess water is assumed to drain immediately leaving the soil at $h_o$. The “end-of-day” value of $h$ is then used as the initial value for the next day to calculate the corresponding values of $p$, $F(p)$ and $ET_a$ as described previously. The procedure is repeated daily over any desired time period (in this case planting until harvest). Daily values of $ET_a$ and $ET_c$ are then summed to determine respective cumulative values for the entire time period, and these cumulative values are used in Eqs. [2] or [3] to calculate relative evapotranspiration deficits for the
Figure 5. Evapotranspiration function $F(p)$ as a function of water-filled fraction ($p$) of available water holding capacity of soil in the crop rooting zone.

Experimental locations and crop management

Isabela experiment

A three-year irrigation experiment (Snyder et al., 1995) was performed at the Isabela Agricultural Experiment Station farm, located in the humid north-west coastal zone of Puerto Rico. The predominant soil at this site was Coto clay (clayey, kaolinitic, isohyperthermic Typic Eutrutox).

Three consecutive crops of tanier 'Blanca', were established in the period 1991-94. The crop was planted in rows, with spacing of 1.5 m between rows and 60 cm between plants in a given row. All experimental plots consisted of four rows 20 m long, with the outer two rows used as borders and the middle rows harvested at the end of the experiment for measuring cormel yields. Pest and weed control, and total N, P and K fertilizer applications were as specified by the Agricultural Experiment Station Staff (1997). Both irrigation water and chemical fertilizers were applied through drip irrigation lines placed alongside each crop row. Irrigation lines consisted of polyethylene T-tape with emitters spaced 30 cm apart, and a nominal discharge rate of 3.8 L/hour (1
gallon per hour) per emitter at a regulated pressure of 100 Kpa (14 psi). The amount of irrigation water applied to each plot was independently controlled, using a metering valve with adjustable shut-off volume control.

Five irrigation management treatments were imposed each year, arranged in a randomized complete block design with four replications. The irrigation treatments consisted of withholding irrigation water during specified periods, and maintaining full irrigation at all other times. The treatments (T) were: T1) irrigation throughout the entire crop growing season; T2) withholding irrigation during the first 11 weeks after planting, supplying irrigation at all other times; T3) withholding irrigation from weeks 11 to 25, maintaining irrigation at all other times; T4) withholding irrigation from week 25 until harvest, supplying irrigation at all other times; and T5) no irrigation at any stage.

The amount of water required for irrigation was determined on an approximately weekly basis, using a water balance approach. The difference between cumulative rainfall and reference evapotranspiration (taken as 0.85 x daily pan evaporation) was determined for a given week. A negative value corresponding to water deficit was considered as the amount of irrigation water required for that week. A zero or positive values indicated minimal water stress and no need for irrigation.

In the respective periods of “no irrigation” in each treatment, a small amount of irrigation water was actually applied associated with fertigation needs of the crop. However, the amount of fertigation water generally constituted only a small fraction of the amount of water applied in irrigation treatments. Fertigation water was always taken into account in the weekly water balance calculations.

At the end of each experiment, approximately 50 weeks after planting, the two middle rows were harvested from each. Marketable cormels, weighing more than 130 g, were counted and weighed.

Weather parameters measured were daily rainfall, pan evaporation, solar radiation and maximum and minimum temperature. These were measured with an automated weather station located at the site.

**Juana Díaz experiment**

An irrigation experiment was conducted at the Juana Díaz experimental farm by Goenaga (1994b), using the same *Xanthosoma* cultivar described above. The farm is located on Puerto Rico’s semi-arid south coast, and the predominant soil is San Anton clay loam (fine-loamy, mixed, superactive, isohyperthermic Cumulic Haplustolls).
In this experiment, crop evapotranspiration demand \((ET)\) was estimated continuously by multiplying pan evaporation (corrected for rainfall) times a pan coefficient \((K_p)\) of 0.70 and an average crop coefficient \((K_c)\) of 0.87. Irrigation treatments consisted of supplementing various fractions (0.33, 0.66, 0.99 and 1.32) of the estimated evapotranspiration deficit in the form of irrigation water. Management and harvest procedures are described in detail by Goenaga (1994b).

In this experiment, sub-plots of tanier were harvested approximately every six weeks, to examine irrigation effects on crop development. The data show that for the highest irrigation treatment \((1.32 \times \text{pan evaporation})\), maximum yields were obtained at 364 days after planting, whereas yields for the other treatments peaked at 278 days and began declining thereafter. In our analysis of these data, we chose to compare the maximum yields for each irrigation treatment. Correspondingly, in each case the water balance routine was run from planting date until the date of maximum yield. The different times until harvest obviously influenced the total (cumulative) evapotranspiration deficit, but since this value was divided by the (also time-dependent) cumulative crop evapotranspiration demand \(ET_c\) to determine the relative evapotranspiration deficit (RETD), time effects tend to cancel each other out.

**Gurabo experiment**

Irizarry et al. (1977) have described an irrigation experiment conducted in 1970 with 12 different tanier cultivars (among them the Blanca cultivar used in the Isabela and Juana Díaz experiments) at the Gurabo experimental farm in the humid east-central region of Puerto Rico. The soil at the site was Toa clay loam (fine, mixed, active, isohyperthermic Fluvaquentic Hapludolls).

Each tanier cultivar was subjected to two irrigation treatments in a factorial experiment with six replications. The treatments were no irrigation (natural rainfall) and irrigation to compensate for differences between rainfall and pan evaporation. Information in the publication indicated the date (week) of each irrigation event. The method of irrigation was by furrow, with sufficient water applied to compensate for surface runoff and uneven deep percolation. Under these conditions we assumed that the amount of water applied on each irrigation date was sufficient to take the entire soil rooting zone to field capacity.

To run the water balance routine for each irrigation treatment, we used daily rainfall and pan evaporation records. Pan evaporation data were multiplied times a pan coefficient of 0.79 to estimate reference evapotranspiration.
RESULTS AND DISCUSSION

Isabela experiment

Cumulative heat units (growing degree days above 10°C) and solar radiation are represented on a weekly basis for each year of the study in Figures 6 and 7. Values for both parameters were similar for all three years. Since the soil series and fertility management were also the same on all three years, we were able to assume that the major variable causing yield variability was the soil moisture regime as influenced by rainfall patterns and irrigation management.

Cumulative rainfall for each of the three years is shown in Figure 8. Year 1 was an unusually wet year, whereas Years 2 and 3 were relatively dry. The total rainfall was similar in both Years 2 and 3, but was not distributed the same. Year 2 was relatively wet early and late in the season, with drier conditions occurring in mid season. This pattern was reversed in Year 3, where dry conditions occurred early and late in the season and wetter conditions prevailed in mid season.

Cumulative crop evapotranspiration demand, $ET_c$, is plotted as a function of time for each year in Figure 9. Daily $ET_c$ values were calculated by multiplying daily reference crop evapotranspiration values times the $K_c$ values given in Figure 1. They were then summed over time to give the cumulative $ET_c$ values of Figure 9. Values of $ET_c$ were very similar for Years 2 and 3, and somewhat lower during Year 1 when considerably more
rainfall occurred. The cumulative amounts of irrigation water applied for each irrigation program and year are shown in Figures 10 a-c.

Making use of the water balance procedure described earlier, cumulative evapotranspiration deficits (ETD) were calculated for each irrigation treatment and year. Results are shown in Figures 11a-c.

From the values of $ET_c$ and ETD in Figures 9 and 11, respectively, the relative evapotranspiration deficit (RETD) for the time interval between planting and harvest was calculated as

$$RETD = \frac{ETD}{ET_c}$$

[9]

where $ETD$ and $ET_c$ are cumulative values of $ETD$ and $ET_c$ over the time interval.

Mean yields of marketable cormels (kg/ha) are shown for each year and irrigation treatment in Figure 12. Mean yields are regressed against RETD values in Figure 13, yielding a significant negative linear relation with a coefficient of determination $R^2$ of 0.76.

Taking the y-intercept (20,124 kg/ha) of the least-squares regression equation as the maximum yield ($Y_{\text{max}}$) at zero evapotranspiration deficit, the yield data were transformed to relative yield deficits (RYD) using Eq. [2]. A plot of relative yield deficit RYD against relative evapotranspiration deficit RETD, together with the corresponding least-squares regression equation, is shown in Figure 14.
The slope of the corresponding regression line, 3.07, represents the yield sensitivity coefficient $K_y$ defined by Eq. [4]. The value $K_y = 3.07$ implies that, for every 10 percent increase in the relative evapotranspiration demand, there is a corresponding increase in the cumulative rainfall.
evapotranspiration deficit (or 10 percent decrease in relative evapotranspiration), a relative yield decrease of approximately 30 percent was obtained.

**Juana Díaz experiment**

Figure 15 gives cumulative values of rainfall, reference evapotranspiration $ET_0$ and crop evapotranspiration demand $ET_c$ at Juana Díaz.
As noted from the cumulative rainfall distribution, most rainfall was concentrated in two short periods, one at approximately 120 days after planting and the other at 250 days. Intervals between these periods were quite dry.

FIGURE 10c. Cumulative irrigation water for different treatments during Year 3.

FIGURE 11a. Cumulative evapotranspiration deficits for different treatments in Year 1.
Cumulative amounts of irrigation applied in the different irrigation treatments are shown in Figure 16, and cumulative evapotranspiration deficits are shown in Figure 17. The seasonal deficits in Figure 17 were transformed to relative evapotranspiration (RETD) deficits us-

Figure 11b. Cumulative evapotranspiration deficits for different treatments in Year 2.

Figure 11c. Cumulative evapotranspiration deficits for different treatments in Year 3.
FIGURE 12. Mean yields of marketable cormels for each irrigation management program and year.

By using Eq. 3 and the seasonal cumulative $ET_c$ value in Figure 17, the resulting RETD values were regressed against measured yields (Figure 18), and the extrapolated maximum yield ($Y_{max}$) was used to transform yields to relative yield deficits (RYD). Regression of RYD against relative evapotranspiration deficit RETD (Figure 19) gave a corresponding

$$y = -62142x + 20124$$

$$R^2 = 0.76$$

FIGURE 13. Crop yield as a function of relative evapotranspiration deficit (RETD).
slope (seasonal $K_y$ value) of 3.37, with an $R^2$ value of 0.92. Note that this $K_y$ value is similar in magnitude to the seasonal $K_y$ value of 3.07 obtained at Isabela.

It can be noted in Figure 18 that yields decreased almost linearly with increasing RETD in the RETD interval between zero and 0.21, corresponding to the three highest irrigation levels. Also note that at RETD = 0.21, yields were already approaching zero, leaving very little

room for further yield decreases with further increases in RETD. Therefore, it is not surprising that in the final RETD interval, between 0.21 and 0.33, only a small yield decrease was observed. This introduced significant non linearity into Figure 18, with corresponding reduction of the coefficient of determination for linear regression. If the regres-

FIGURE 17. Cumulative evapotranspiration deficits for irrigation treatments at Juana Díaz, Puerto Rico.
sion analysis is repeated considering only yields at the more moderate water deficits (RETD values of 0.02, 0.10 and 0.20), a better linear relationship is obtained with $R^2 = 0.99$, as seen in Figure 20. The fact that this new regression is based only on three data points does not
necessarily render it statistically insignificant, since each data point represents the mean of five replications. The estimated $K_y$ value in this case is 4.3 (Figure 21). This value is similar to that inferred from the experiment at Gurabo, which is discussed next.

![Graph showing the relationship between relative evapotranspiration deficit and marketable corn yield. The equation $y = -90946x + 21127$ with $R^2 = 0.9918$ is given.](image)

**Figure 20.** Cormel yields as a function of relative evapotranspiration deficit at Juana Díaz, Puerto Rico, considering only the three highest irrigation treatments.

![Graph showing the relationship between relative evapotranspiration deficit and relative yield deficit. The equation $y = 4.3047x - 2E-05$ with $R^2 = 0.9918$ is given.](image)

**Figure 21.** Relative yield deficit as a function of relative evapotranspiration deficit at Juana Díaz, Puerto Rico, considering only the three highest irrigation treatments.
Gurabo Experiment

Values of cumulative rainfall, $ET_o$, and $ET_c$ for the Gurabo study are given in Figure 22. Cumulative evapotranspiration deficit as a function of time for irrigated and non-irrigated treatments is shown in Figure 23.

For the irrigated treatment, the seasonal relative evapotranspiration deficit (RETD) calculated by water balance was 0.001 (zero for practical purposes), indicating no water stress in the irrigated plots. The RETD for non-irrigated plots was estimated at 0.045, with practically all of this deficit occurring in a narrow time window at about 230 to 260 days after planting.

Mean yields for the 12 tanier cultivars under the two irrigation treatments are shown in Table 1. Also shown are relative yield deficits (RYD) corresponding to the non-irrigated yields, calculated with Eq. [2] taking the irrigated yields as $Y_{max}$ and non-irrigated yields as $Y$. Values of $K_y$ for each RYD value are given in the far right column. The $K_y$ values were obtained by dividing RYD into the RETD value of 0.045.

Because of high yield variability, ANOVA was unable to detect significant differences ($p < 0.05$) between means of irrigated and non-irrigated plots. However, as observed by the authors of the study, the means of the irrigated plots in Table 1 always ranked higher than those of non-irrigated plots. Such a result is highly unlikely under a null hypothesis of no response to irrigation, since in that case approxi-
not irrigated
• Irrigated

### FIGURE 23. Cumulative evapotranspiration deficit for the Gurabo, Puerto Rico, experiment.

approximately half of the irrigated means should rank higher (+) than the non-irrigated means, and that the other half should rank lower (-).

If the null hypothesis were true, the probability $P$ that all 12 sample varieties should yield a (+) result as in Table 1 would be given by the binomial distribution (Bury, 1999) as

$$P(s) = \binom{n}{s} \times (p^+)^s \times (1-p^+)^{n-s}$$

where $\binom{n}{s}$ is the binomial coefficient defined by

$$\binom{n}{s} = \frac{n!}{s!(n-s)!}$$

In these equations, $n=12$ is the number of cultivars tested, $s$ is the observed number of (+) results and $p^+=0.5$ is the probability of encountering a (+) result under the null hypothesis. For the observed case of $s=12$, Eq. [10] yields that $P(s) = < 0.003$. In other words, if the null hypothesis were true, there would be less than a 0.003 probability of encountering the observed results. It is therefore reasonable to reject the null hypothesis and accept the alternative hypothesis that irrigated tanier yields were different (greater in this case) than non-irrigated yields.

To obtain $K_\gamma$ values for the results in Table 1, the RETD value of 0.001 for the irrigated yields was assumed equal to zero, so that the
TABLE 1.—Mean yields of 12 tanier cultivars with and without irrigation at Gurabo.
(EACH MEAN REPRESENTS THE AVERAGE OF SIX REPLICATIONS)

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Irrigated yields</th>
<th>Non-irrigated yields</th>
<th>RYD</th>
<th>K_y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blanca del Pais</td>
<td>17.8</td>
<td>13.9</td>
<td>0.22</td>
<td>4.9</td>
</tr>
<tr>
<td>Choubutton</td>
<td>14.9</td>
<td>13.3</td>
<td>0.11</td>
<td>2.4</td>
</tr>
<tr>
<td>Drearies</td>
<td>14.8</td>
<td>13.4</td>
<td>0.10</td>
<td>2.1</td>
</tr>
<tr>
<td>Kelly</td>
<td>14.6</td>
<td>12.8</td>
<td>0.12</td>
<td>2.7</td>
</tr>
<tr>
<td>Rascana</td>
<td>14.3</td>
<td>10.6</td>
<td>0.26</td>
<td>5.6</td>
</tr>
<tr>
<td>Viequera</td>
<td>14.1</td>
<td>9.6</td>
<td>0.32</td>
<td>7.1</td>
</tr>
<tr>
<td>Charanelle</td>
<td>13.3</td>
<td>12.6</td>
<td>0.05</td>
<td>1.2</td>
</tr>
<tr>
<td>Vinola</td>
<td>13.2</td>
<td>10.2</td>
<td>0.23</td>
<td>5.1</td>
</tr>
<tr>
<td>Morada</td>
<td>12.7</td>
<td>10.3</td>
<td>0.19</td>
<td>4.2</td>
</tr>
<tr>
<td>Bisley</td>
<td>11.4</td>
<td>9.8</td>
<td>0.14</td>
<td>3.2</td>
</tr>
<tr>
<td>Inglesa</td>
<td>11.1</td>
<td>8.1</td>
<td>0.27</td>
<td>6.0</td>
</tr>
<tr>
<td>Barbados</td>
<td>10.5</td>
<td>7.8</td>
<td>0.26</td>
<td>5.7</td>
</tr>
<tr>
<td><strong>Average of means</strong></td>
<td><strong>13.6</strong></td>
<td><strong>11.0</strong></td>
<td><strong>0.19 ± 0.05</strong></td>
<td><strong>4.2</strong></td>
</tr>
</tbody>
</table>

The mean irrigated yield for each cultivar could be taken as \( Y_{\text{max}} \). The RETD value corresponding to non-irrigated yield \( Y_0 \) for all cultivars was set 0.045. Substituting the yield and RETD values into Eq. [5] allowed calculating \( K_y \) values, shown in the right hand column of Table 1. Values of \( K_y \) varied considerably among cultivars, which is not surprising given the high yield variabilities and the low RETD value of 0.045. The mean value of \( K_y \) for all cultivars was 4.2, with a 95 percent confidence interval of 1.2 above and below the mean.

**General discussion concerning \( K_y \) values obtained in the different irrigation experiments**

The \( K_y \) values obtained above for the three-tanier experiments are summarized in the first (upper) row of Table 2. These values were obtained by setting the parameters \( D \) (maximum crop rooting depth) and \( p \) (critical fraction of available water) in the FAO water balance model at 50 cm and 0.5, respectively. The \( K_y \) values are very high compared to results reported for most crops in the literature, where \( K_y \) rarely exceeds 1.3 (Doorenbos and Kassam, 1979; Steduto et al., 2012).

TABLE 2.—Values of \( K_y \) inferred for the different irrigation experiments, obtained by running the FAO water balance model for two different sets of values of the crop rooting depth (\( D \)) and the critical available water fraction (\( p \)).

<table>
<thead>
<tr>
<th>Parameters assumed in water balance model</th>
<th>Isabela (all treatments)</th>
<th>Fortuna (highest irrigation treatments)</th>
<th>Gurabo</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D = 50 \text{ cm}, p = 0.5 )</td>
<td>3.1</td>
<td>3.4</td>
<td>4.3</td>
</tr>
<tr>
<td>( D = 30 \text{ cm}, p = 0.7 )</td>
<td>2.4</td>
<td>2.7</td>
<td>3.3</td>
</tr>
</tbody>
</table>
We initially suspected that the high $K_y$ values could be an artifact, caused by using incorrect parameters $D$ and $p$ in the FAO water balance model. To investigate this possibility, the whole computational procedure described above was repeated by assuming a very shallow rooting depth ($D = 30$ cm) and a very high critical available water fraction ($p = 0.7$). This has the effect of increasing the estimated RETD and thereby decreasing the estimate of $K_y$. The $K_y$ values obtained under the new set of parameters $D$ and $p$ are shown in the second (lower) row of Table 2. The new values, ranging between 2.4 and 3.3, are approximately 30 percent lower than values obtained in the first simulation, but are still much higher than typical values in the literature.

Since high $K_y$ values are obtained even by using conservative values of parameters $D$ and $p$, designed to minimize $K_y$ in the FAO model, it seems that the high $K_y$ is not merely an artifact attributable to incorrect model parameters, but rather reflects a true sensitivity of tanier yields to water stress. It is conceivable that the high $K_y$ values reflect a synergistic (additive or multiplicative) effect of several plant stress factors, including but not restricted to water stress, all of which correlate positively with RETD. An example is soil mechanical impedance, which increases with water deficits (Snyder, 1994) and is known to strongly reduce tanier yields (Lugo-Mercado et al., 1978). A third possible moisture related stress factor is increased sensitivity of tanier roots to soil-borne pathogens (Lugo et al., 1987). Further research is necessary on interactive stress factors affecting tanier yields.

CONCLUSIONS

The well known FAO water balance model has been used to estimate relative evapotranspiration deficits (RETD) for tanier, using experimental data from three irrigation experiments conducted at various times and locations. The RETD was calculated for two scenarios. The first scenario assumed “most likely” values for effective plant rooting depth $D$ and the critical available water fraction $p_c$ at the onset of water stress. The second scenario assumed more conservative conditions, characterized by a very shallow-rooted crop (low $D$) with low capacity to satisfy evapotranspiration demand (high $p_c$). By comparing estimated RETD values under each scenario to measured crop yields, yield sensitivity coefficients $K_y$ were estimated. The $K_y$ values ranged between 3.1 and 4.3 for the “most likely” scenario and between 2.4 and 3.3 for the conservative scenario. Even the conservative estimates of $K_y$ were much higher than those cited in the literature for most crops, confirming previous observations regarding high sensitivity of tanier to water stress. We postulate that the high $K_y$ values for tanier could
reflect a synergistic effect of several plant stress factors augmented by dry soil conditions, among them water stress, soil mechanical impedance and pathogenic stress.

Results confirm that substantial tanier yield reduction may occur even under modest water deficits typical of the humid regions of Puerto Rico. Conversely, the return on investment in irrigation systems under these conditions is likely to be high, provided careful irrigation scheduling is practiced.

**LITERATURE CITED**


Response of tanier (Xanthosoma spp.) to evapotranspiration deficits estimated with the FAO water balance method¹,²

Víctor A. Snyder³, Wanda I. Lugo⁴, Miguel A. Vázquez⁵ and Edwin Acevedo⁶


ABSTRACT

Field experiments in Puerto Rico have shown that with adequate drainage and plant nutrition, good yields of tanier (Xanthosoma spp.) are consistently obtained under high frequency irrigation. Still lacking, however, is quantitative information on yield variations under different irrigation scheduling scenarios. A well-known tool for this purpose is the FAO (Food and Agriculture Organization) water balance model, which calculates relative decreases in crop yields (RYD) from relative evapotranspiration deficits (RETD) which are estimated from crop, soil, irrigation and weather data. A simple form of the FAO model calculates RYD as the product of RETD for the growing season multiplied times a proportionality constant or yield sensitivity coefficient (K), which must be experimentally determined for each specific crop. The objective of this study was to estimate K for tanier, by examining published data from three irrigation experiments conducted at various locations in Puerto Rico over a 20-year period. The FAO model

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²The authors acknowledge Dr. Ricardo Goenaga for providing detailed records of irrigation water applied to his experiments, and agronomists Irma Cabrera and Lucas Ramirez for providing daily rainfall and pan evaporation records from the Juana Díaz and Gurabo substations, respectively.
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was used to estimate seasonal RETD from crop and soil parameters and irrigation and weather records, and this value was used together with experimental yield data to calculate \( K_r \). A first analysis yielded \( K_r \) values between 3.1 and 4.2, which considerably exceeded values on the order of 1.0 reported in the literature for most crops. Suspecting that the discrepancy could have been due to incorrect tanier crop parameters assumed in the FAO model, we adjusted crop parameters as far as seemed reasonable in ways which would minimize estimation of \( K_r \). The minimum \( K_r \) values obtained in this manner ranged between 2.4 and 3.3, which are still quite high. They imply that a 10 percent water deficit relative to evapotranspiration demand is sufficient to reduce tanier yields between 24 and 33 percent. It is postulated that the high \( K_r \) values for tanier could reflect a synergistic effect of several plant stress factors associated with soil moisture, mainly water stress, soil mechanical impedance and pathogenic stress. Results in general confirm previous observations regarding sensitivity of tanier to drought stress, and indicate a significant response of tanier to irrigation under even moderate drought conditions.

Key words: Tanier, \textit{Xanthosoma} spp., water balance models, crop growth sensitivity coefficient, irrigation, water deficits, relative evapotranspiration deficiency, relative yield deficiency.

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**RESUMEN**

La respuesta de la yautía (\textit{Xanthosoma} spp.) a déficits de evapotranspiración estimados con el modelo de balance de agua de la FAO

Experimentos de campo en Puerto Rico han demostrado que con buen drenaje y nutrición de las plantas se logran obtener buenos rendimientos de yautía (\textit{Xanthosoma} spp.) utilizando riego de alta frecuencia. Sin embargo, aún se requiere información cuantitativa sobre las variaciones de rendimiento bajo diferentes escenarios de programación del riego. Una herramienta bien conocida para este propósito es el modelo de balance de agua de la FAO (por Food and Agriculture Organization), que calcula disminuciones relativas en los rendimientos de los cultivos (DRR) en función de déficits de evapotranspiración relativos (DETR), calculados a partir de datos de cultivos, suelo, evapotranspiración, precipitación y riego. Una forma sencilla del modelo determina la DRR como el producto del DETR promedio durante la vida del cultivo, multiplicado por una constante de proporcionalidad o coeficiente de sensibilidad de rendimiento (\( K_r \)), el cual se determina para cada cultivo mediante experimentación. El objetivo de este estudio fue estimar \( K_r \) para yautía, examinando datos de tres experimentos de riego realizados en varios lugares en Puerto Rico durante un intervalo de 20 años. Se utilizó el modelo de la FAO para estimar DETR, y este valor se utilizó junto con los datos experimentales de rendimiento para calcular \( K_r \). Un primer análisis arrojó valores de \( K_r \) entre 3.1 y 4.2, superando considerablemente los valores del orden de 1.0 reportado en la literatura para la mayoría de los cultivos. Ante la sospecha de que la discrepancia podría haber sido debido a parámetros incorrectos asumidos para yautía en el modelo de la FAO, se ajustaron los parámetros dentro de los límites razonables, de tal manera que se redujera al mínimo la estimación de \( K_r \). Aún así se obtuvieron valores altos de \( K_r \), entre 2.4 y 3.3. Tales valores indican que un déficit de agua de 10 por ciento, relativo a la demanda de evapotranspiración, es suficiente para reducir los rendimientos de yautía entre 24 y 33 por ciento. Se postula que los altos valores de \( K_r \) para yautía podrían reflejar un efecto sinérgico de varios factores de estrés de las plantas asociados con la humedad del suelo, principalmente estrés hídrico, la impedancia mecánica del suelo y el estrés...
INTRODUCTION

Tanier (Xanthosoma spp.), or “yautía” as referred to in Puerto Rico, is a significant component of the Puerto Rican diet, with an average consumption rate of approximately 6 kg/person/yr (Cortés and Gayol, 2010). Prior to the 1950s, local farmers produced most of the tanier consumed on the Island, but local production has decreased dramatically since then (Lugo et al., 1987). Currently only 10% of tanier consumed in Puerto Rico is produced locally, with the remaining 90% being imported (Cortés and Gayol, 2010). Irizarry et al. (1977) suggested that increasingly erratic rainfall distribution since the 1950s was a possible cause of the decline in tanier production, because the crop requires abundant and well distributed rainfall throughout the growing season (Abruña-Rodríguez et al., 1967; Onwueme, 1978). Erratic rainfall distribution appears to increase crop susceptibility to a pathological condition known as “mal seco” or root dry rot (Lugo et al., 1987). Droughts due to erratic rainfall can also result in high soil mechanical impedance (Snyder, 1994), a condition to which tanier yields are highly sensitive (Lugo-Mercado et al., 1978).

The above evidence points to adequate water management as a key element for successful tanier production. Indeed, field experiments over the past 20 years in Puerto Rico have consistently shown that with adequate drainage and nutrient management, excellent tanier yields can be obtained under high frequency irrigation (Lugo et al., 1987; Goenaga and Chardón, 1993; Goenaga, 1994a; Snyder et al., 1995). Given the high market demand and farm-gate value of the crop, the additional cost of irrigation appears more than offset by the probability of consistently high yields. Therefore, irrigated tanier production seems to offer a viable economic opportunity for farmers in Puerto Rico.

Management constraints, such as labor shortage or insufficient irrigation water, often limit the feasibility of irrigating in the full amounts and timing required for maximum yields. Optimal irrigation scheduling under these conditions requires knowledge of crop response to water stress under different water management scenarios. A simple yet effective tool for such purposes is the FAO water balance model.
The model assumes that for a given water management scenario, the \textit{relative yield deficit} (yield reduction relative to maximum yield under no water stress), is proportional to the \textit{relative evapotranspiration deficit} (evapotranspiration deficit relative to potential crop evapotranspiration). The relative evapotranspiration deficit (RETD) is first estimated from soil and plant parameters and daily records of rainfall, irrigation and reference evapotranspiration, and then the relative yield deficit (RYD) is estimated by multiplying RETD by a crop-specific proportionality coefficient ($K_y$), which must be determined a priori by experiment. Values of $K_y$ have been published for a large number of crops (Doorenbos and Kassam, 1979; Steduto et al., 2012), but information on tanier is still lacking. In this paper, we estimate $K_y$ for tanier by examining data from three different irrigation experiments, performed over a 20-year time span in Puerto Rico at three different locations, Gurabo, Juana Díaz and Isabela. Results will quantitatively confirm the great sensitivity of tanier to water deficits, which has often been noted by researchers working with the crop.

\section*{MATERIALS AND METHODS}

\textbf{Brief overview of the FAO water balance model}

The FAO model used quantifies water stress in terms of a relative evapotranspiration deficit (RETD), defined as

\begin{equation}
\text{RETD} = \frac{ET_c - ET_a}{ET_c} \tag{1}
\end{equation}

where $ET_c$ is the crop water demand or potential evapotranspiration under non-limiting water supply, and $ET_a$ is actual evapotranspiration which is generally less than $ET_c$ when soil water availability becomes limiting. The values of $ET$ and $ET_a$ in Eq. [1] are usually cumulative values, or sums of daily $ET_c$ and $ET_a$ values taken over a given crop growth stage or entire crop growth season. Methods for their determination are described below. The RETD increases in value from zero when $ET_a = ET_c$ (no water stress) to unity when $ET_a = 0$ (the soil is so dry that evapotranspiration ceases due to permanent plant wilting).

Crop yield response to RETD is described in terms of a relative yield deficit (RYD) similar in structure to Eq. [1]:

\begin{equation}
\text{RYD} = \frac{Y_{\text{max}} - Y_a}{Y_{\text{max}}} \tag{2}
\end{equation}
where $Y_{\text{max}}$ is maximum yield in absence of water stress and $Y$ is actual yield. For a crop with $i = 1, 2, ..., I$ growth stages, the overall relative yield deficit is related to evapotranspiration deficits occurring in the different growth stages by the linear equation

$$\frac{Y_m - Y_a}{Y_m} = \sum_{i=1}^{I} K_y \left( \frac{ET_{ci} - ET_{ai}}{ET_{ci}} \right)$$

where the subscript $i$ represents the $i^{th}$ growth stage. The parameter $K_y$ is the crop sensitivity factor for the $i^{th}$ growth stage, which relates the final relative yield deficit to the relative evapotranspiration deficit occurring in the $i^{th}$ growth stage.

If the sensitivity factor does not vary much for the different growth stages, Eq. [3] simplifies to

$$\frac{Y_m - Y_a}{Y_m} = \frac{ET_{ci} - ET_{ai}}{ET_{ci}}$$

or simply,

$$RYD = K_y \frac{ET_{ci} - ET_{ai}}{ET_{ci}}$$

where $ET_{ci}$ and $ET_{ai}$ are the cumulative potential and actual evapotranspiration for the entire growth season, respectively, and $K_y$ is the average sensitivity coefficient for the growth period. In the analyses reported here, we only study seasonally averaged $K_y$ values defined by Eqs. [4] or [5].

Potential crop evapotranspiration $ET_c$ may be estimated from climate data or pan evaporation records (Doorenbos and Pruitt, 1976; Allen et al., 1998). In our study, $ET_c$ was determined from records of class-A pan evaporation, $E_{\text{pan}}$, as

$$ET_c = K_p \cdot K_c \cdot E_{\text{pan}}$$

where $K_p$ is a pan coefficient dependent on climatic and vegetation conditions, and $K_c$ is a crop coefficient which depends primarily on the type of crop and its growth stage. The values of pan coefficient $K_p$ for the three experimental sites considered in this paper were as follows: Isabela: $K_p = 0.89$; Gurabo: $K_p = 0.79$ and Juana Díaz: $K_p = 0.74$. These values represent yearly averages of monthly data given by Harmsen et al. (2004).

Crop coefficient values ($K_c$) for tanier, as a function of days after planting, are shown in Figure 1. Due to lack of published $K_c$ values for tanier, Figure 1 was constructed using available $K_c$ data for banana
FIGURE 1. Crop coefficient ($K_c$) values assumed for a tanier crop.

(Doorenbos and Kassam, 1979), with the length of different growth stages adapted to tanier based on plant phenological data shown in Figure 2. The $K_c$ values for banana were used because of its canopy similarity with tanier (few very large leaves), offering similar aerodynamic resistance in both cases.

In the latter stages of writing this paper, it was brought to our attention that, in light of leaf dry matter accumulation patterns as shown in Figure 2, the initial rising portion of the $K_c$ graph in Figure 1 should probably have been set at 50 to 60 days rather than at 75 days as in Figure 1, with the error causing an overestimate of $ET_c$ in the initial rising stage. We concur with this assessment, but also note that the time shift error is only on the order of two weeks, out of a total of 52 weeks for the overall crop growth period, and furthermore occurs in the zone of the rising curve where $K_c$ is still small. It should also be noted that for reasonably moist soils (value of $F(p)$ close to unity) any overestimate of $ET_c$ is reflected in a roughly proportional overestimate of $ET_o$ (c.f. Eq. [7]), which by virtue of Eq. [1] causes only small error in estimated RETD. The combined effect of these factors is that the error in seasonal RETD (the relevant parameter of interest) was probably negligible. However, to account for this and other sources of error in estimated model parameters, a sensitivity analysis was conducted, which is described later in this paper.

The actual crop evapotranspiration ($ET_a$) in the FAO water balance model is estimated from the formula
FIGURE 2. Leaf dry matter accumulation for tanier as a function of weeks after planting, for different irrigation treatments at Isabela, Puerto Rico (unpublished data from Snyder et al., 1995). Irrigation treatments 1 through 5 are described later in Materials and Methods.

\[ ET_a = ET_c \cdot F(p) \]  \[\text{[7]}\]

where \( ET_c \) is the crop evapotranspiration demand defined above, and \( F(p) \) is a function of the fraction of plant-available water \( p \) remaining in the crop rooting zone.

The fraction of plant-available water is defined as

\[ p = \frac{h}{h_o} \]  \[\text{[8]}\]

where \( h \) is the effective depth of available water (mm) in the rooting zone and \( h_o \) is the maximum available water storage capacity (mm).

The maximum storage capacity \( h_o \) is given by

\[ h_o = D(\theta_{fc} - \theta_w) \]  \[\text{[9]}\]

where \( D \) is the effective crop rooting depth, and \( \theta_{fc} \) and \( \theta_w \) represent the volumetric soil water content at field capacity and permanent plant wilting, respectively. Based on soil survey laboratory data for these soils (Soil Survey Staff, 1967; Mount and Lynn, 2004), we assumed
that $\theta_f - \theta_w = 0.10$ for the Oxisol at Isabela, and $\theta_f - \theta_w = 0.15$ for the Vertisol at Gurabo and the Mollisol at Juana Díaz. Since values of rooting depth $D$ were not available for tanier, we assumed maximum values of $D = 0.5$ m, similar to published values for banana (Doorenbos and Kassam, 1979) which has a root morphology similar to that of tanier. An initial rooting depth of 0.1 m was assumed at planting, to account for a finite soil volume around seeds (corm sections), which provided water by diffusion even though no roots had yet developed. Rooting depth was assumed to increase linearly with time during the first 100 days after planting, attaining a maximum depth of 0.5 m thereafter (Figure 3).

The assumption of a 100-day root development period was based on measured root biomass in the top 30 cm in the Isabela experiment (Figure 4), showing a rapid increase in biomass during the first 15 weeks (approximately 100 days) after planting, after which root biomass accumulation tended to stabilize. After about 40 weeks the measured root biomass in Figure 4 began decreasing, but we assumed that this applied primarily to root density per unit volume, with depth of rooting remaining the same.

The function $F(p)$ in Eq. [7], relating potential evapotranspiration $ET_c$ to actual crop evapotranspiration $ET_a$, is illustrated graphically in Figure 5. Note that $F(p)$ has a value of unity so long as the available water-filled fraction $p$ of the soil is greater than some critical value $p_c$, but decreases linearly with $p$ when $p < p_c$. Values of the critical available water fraction $p_c$ vary from as low as 0.3 for deep rooted crops and low $ET_c$ conditions, to values as high as 0.8 for shallow rooted crops and high $ET_c$ conditions (Doorenbos and Kassam, 1979). A default value of 0.5 is often used, and was the value assumed for tanier.

![Figure 3. Estimated rooting depth for tanier as a function of time.](image-url)
FIGURE 4. Tanier root biomass as a function of time and irrigation treatment at Isabela, Puerto Rico (unpublished data from Snyder et al., 1995). Irrigation treatments 1 through 5 are described later in Materials and Methods.

To run the FAO water balance subroutine, an initial amount of available water ($h$) is assumed (or preferably measured) for the beginning of day 1. From this value the parameters $p$ and $F(p)$ for that day are estimated from Eq. [8] and Figure 5, respectively. From $F(p)$ and the known potential evapotranspiration $ET_c$ for the day, the actual evapotranspiration $ET_a$ for the day is estimated from Eq. [7]. The available water $h$ remaining in the soil at the end of the day is then calculated by subtracting $ET_a$ from the initial (morning) value of $h$, and adding any amount of rainfall or irrigation occurring during the day. If this calculated value of $h$ exceeds the water holding capacity $h_o$ of the soil, the excess water is assumed to drain immediately leaving the soil at $h_o$. The “end-of-day” value of $h$ is then used as the initial value for the next day to calculate the corresponding values of $p$, $F(p)$ and $ET_a$ as described previously. The procedure is repeated daily over any desired time period (in this case planting until harvest). Daily values of $ET_a$ and $ET_c$ are then summed to determine respective cumulative values for the entire time period, and these cumulative values are used in Eqs. [2] or [3] to calculate relative evapotranspiration deficits for the
period. Detailed numerical examples are given in Doorenbos and Kas-
sam (1979). We programmed the operations into an Excel™ spread­
sheet, in a way that allowed examining “what if” scenarios involving
changes in parameters such as $h_o$ and $f_c$.

Experimental locations and crop management

Isabela experiment

A three-year irrigation experiment (Snyder et al., 1995) was per­
formed at the Isabela Agricultural Experiment Station farm, located
in the humid north-west coastal zone of Puerto Rico. The predominant
soil at this site was Coto clay (clayey, kaolinitic, isohyperthermic Typic
Eutruxt).  

Three consecutive crops of tanier ‘Blanca’, were established in the
period 1991-94. The crop was planted in rows, with spacing of 1.5 m
between rows and 60 cm between plants in a given row. All experimen­
tal plots consisted of four rows 20 m long, with the outer two rows used
as borders and the middle rows harvested at the end of the experiment
for measuring cormel yields. Pest and weed control, and total N, P and
K fertilizer applications were as specified by the Agricultural Experi­
ment Station Staff (1997). Both irrigation water and chemical fertil­
izers were applied through drip irrigation lines placed alongside each
crop row. Irrigation lines consisted of polyethylene T-tape with emitt­
ers spaced 30 cm apart, and a nominal discharge rate of 3.8 L/hour (1
gallon per hour) per emitter at a regulated pressure of 100 Kpa (14 psi). The amount of irrigation water applied to each plot was independently controlled, using a metering valve with adjustable shut-off volume control.

Five irrigation management treatments were imposed each year, arranged in a randomized complete block design with four replications. The irrigation treatments consisted of withholding irrigation water during specified periods, and maintaining full irrigation at all other times. The treatments (T) were: T1) irrigation throughout the entire crop growing season; T2) withholding irrigation during the first 11 weeks after planting, supplying irrigation at all other times; T3) withholding irrigation from weeks 11 to 25, maintaining irrigation at all other times; T4) withholding irrigation from week 25 until harvest, supplying irrigation at all other times; and T5) no irrigation at any stage.

The amount of water required for irrigation was determined on an approximately weekly basis, using a water balance approach. The difference between cumulative rainfall and reference evapotranspiration (taken as 0.85 x daily pan evaporation) was determined for a given week. A negative value corresponding to water deficit was considered as the amount of irrigation water required for that week. A zero or positive values indicated minimal water stress and no need for irrigation.

In the respective periods of “no irrigation” in each treatment, a small amount of irrigation water was actually applied associated with fertigation needs of the crop. However, the amount of fertigation water generally constituted only a small fraction of the amount of water applied in irrigation treatments. Fertigation water was always taken into account in the weekly water balance calculations.

At the end of each experiment, approximately 50 weeks after planting, the two middle rows were harvested from each. Marketable cormels, weighing more than 130 g, were counted and weighed.

Weather parameters measured were daily rainfall, pan evaporation, solar radiation and maximum and minimum temperature. These were measured with an automated weather station located at the site.

**Juana Díaz experiment**

An irrigation experiment was conducted at the Juana Díaz experimental farm by Goenaga (1994b), using the same *Xanthosoma* cultivar described above. The farm is located on Puerto Rico’s semi-arid south coast, and the predominant soil is San Anton clay loam (fine-loamy, mixed, superactive, isohyperthermic Cumulic Haplustolls).
In this experiment, crop evapotranspiration demand ($ET_c$) was estimated continuously by multiplying pan evaporation (corrected for rainfall) times a pan coefficient ($K_p$) of 0.70 and an average crop coefficient ($K_c$) of 0.87. Irrigation treatments consisted of supplementing various fractions (0.33, 0.66, 0.99 and 1.32) of the estimated evapotranspiration deficit in the form of irrigation water. Management and harvest procedures are described in detail by Goenaga (1994b).

In this experiment, sub-plots of tanier were harvested approximately every six weeks, to examine irrigation effects on crop development. The data show that for the highest irrigation treatment ($1.32 \times$ pan evaporation), maximum yields were obtained at 364 days after planting, whereas yields for the other treatments peaked at 278 days and began declining thereafter. In our analysis of these data, we chose to compare the maximum yields for each irrigation treatment. Correspondingly, in each case the water balance routine was run from planting date until the date of maximum yield. The different times until harvest obviously influenced the total (cumulative) evapotranspiration deficit, but since this value was divided by the (also time-dependent) cumulative crop evapotranspiration demand $ET_c$ to determine the relative evapotranspiration deficit (RETD), time effects tend to cancel each other out.

**Gurabo experiment**

Irizarry et al. (1977) have described an irrigation experiment conducted in 1970 with 12 different tanier cultivars (among them the Blanca cultivar used in the Isabela and Juana Díaz experiments) at the Gurabo experimental farm in the humid east-central region of Puerto Rico. The soil at the site was Toa clay loam (fine, mixed, active, isohyperthermic Fluvaquentic Hapludolls).

Each tanier cultivar was subjected to two irrigation treatments in a factorial experiment with six replications. The treatments were no irrigation (natural rainfall) and irrigation to compensate for differences between rainfall and pan evaporation. Information in the publication indicated the date (week) of each irrigation event. The method of irrigation was by furrow, with sufficient water applied to compensate for surface runoff and uneven deep percolation. Under these conditions we assumed that the amount of water applied on each irrigation date was sufficient to take the entire soil rooting zone to field capacity.

To run the water balance routine for each irrigation treatment, we used daily rainfall and pan evaporation records. Pan evaporation data were multiplied times a pan coefficient of 0.79 to estimate reference evapotranspiration.
RESULTS AND DISCUSSION

Isabela experiment

Cumulative heat units (growing degree days above 10°C) and solar radiation are represented on a weekly basis for each year of the study in Figures 6 and 7. Values for both parameters were similar for all three years. Since the soil series and fertility management were also the same on all three years, we were able to assume that the major variable causing yield variability was the soil moisture regime as influenced by rainfall patterns and irrigation management.

Cumulative rainfall for each of the three years is shown in Figure 8. Year 1 was an unusually wet year, whereas Years 2 and 3 were relatively dry. The total rainfall was similar in both Years 2 and 3, but was not distributed the same. Year 2 was relatively wet early and late in the season, with drier conditions occurring in mid season. This pattern was reversed in Year 3, where dry conditions occurred early and late in the season and wetter conditions prevailed in mid season.

Cumulative crop evapotranspiration demand, $ET_c$, is plotted as a function of time for each year in Figure 9. Daily $ET_c$ values were calculated by multiplying daily reference crop evapotranspiration values times the $K_c$ values given in Figure 1. They were then summed over time to give the cumulative $ET_c$ values of Figure 9. Values of $ET_c$ were very similar for Years 2 and 3, and somewhat lower during Year 1 when considerably more...
rainfall occurred. The cumulative amounts of irrigation water applied for each irrigation program and year are shown in Figures 10 a-c.

Making use of the water balance procedure described earlier, cumulative evapotranspiration deficits (ETD) were calculated for each irrigation treatment and year. Results are shown in Figures 11a-c.

From the values of $ET_c$ and ETD in Figures 9 and 11, respectively, the relative evapotranspiration deficit (RETD) for the time interval between planting and harvest was calculated as

$$RETD = \frac{ETD}{ET_c}$$ [9]

where $ETD$ and $ET_c$ are cumulative values of $ETD$ and $ET_c$ over the time interval.

Mean yields of marketable cormels (kg/ha) are shown for each year and irrigation treatment in Figure 12. Mean yields are regressed against RETD values in Figure 13, yielding a significant negative linear relation with a coefficient of determination $R^2$ of 0.76.

Taking the $y$-intercept (20,124 kg/ha) of the least-squares regression equation as the maximum yield ($Y_{max}$) at zero evapotranspiration deficit, the yield data were transformed to relative yield deficits (RYD) using Eq. [2]. A plot of relative yield deficit RYD against relative evapotranspiration deficit RETD, together with the corresponding least-squares regression equation, is shown in Figure 14.
The slope of the corresponding regression line, 3.07, represents the yield sensitivity coefficient $K_y$ defined by Eq. [4]. The value $K_y = 3.07$ implies that, for every 10 percent increase in the relative evapotranspiration demand ($ET_c$) during the three growing seasons.
plication deficit (or 10 percent decrease in relative evapotranspiration), a relative yield decrease of approximately 30 percent was obtained.

**Juana Díaz experiment**

Figure 15 gives cumulative values of rainfall, reference evapotranspiration $ET_r$ and crop evapotranspiration demand $ET_c$ at Juana Díaz.

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**Figure 10a. Cumulative irrigation water for different treatments during Year 1.**

**Figure 10b. Cumulative irrigation water for different treatments during Year 2.**
As noted from the cumulative rainfall distribution, most rainfall was concentrated in two short periods, one at approximately 120 days after planting and the other at 250 days. Intervals between these periods were quite dry.
Cumulative amounts of irrigation applied in the different irrigation treatments are shown in Figure 16, and cumulative evapotranspiration deficits are shown in Figure 17. The seasonal deficits in Figure 17 were transformed to relative evapotranspiration (RETD) deficits us-

![Cumulative evapotranspiration deficits for different treatments in Year 2.](image1)

**Figure 11b.** Cumulative evapotranspiration deficits for different treatments in Year 2.

![Cumulative evapotranspiration deficits for different treatments in Year 3.](image2)

**Figure 11c.** Cumulative evapotranspiration deficits for different treatments in Year 3.
Irrigation management treatment

**FIGURE 12.** Mean yields of marketable cormels for each irrigation management program and year.

Using Eq. 3 and the seasonal cumulative $ET_c$ value in Figure 17. The resulting RETD values were regressed against measured yields (Figure 18), and the extrapolated maximum yield ($Y_{max}$) was used to transform yields to relative yield deficits (RYD). Regression of RYD against relative evapotranspiration deficit RETD (Figure 19) gave a corresponding

**FIGURE 13.** Crop yield as a function of relative evapotranspiration deficit (RETD).

- $y = -62142x + 20124$
- $R^2 = 0.76$
slope (seasonal $K_y$ value) of 3.37, with an $R^2$ value of 0.92. Note that this $K_y$ value is similar in magnitude to the seasonal $K_y$ value of 3.07 obtained at Isabela.

It can be noted in Figure 18 that yields decreased almost linearly with increasing RETD in the RETD interval between zero and 0.21, corresponding to the three highest irrigation levels. Also note that at RETD = 0.21, yields were already approaching zero, leaving very little

FIGURE 14. Relative yield deficit (RYD) as a function of relative evapotranspiration deficit (RETD).

FIGURE 15. Cumulative rainfall, $ET_r$, and $ET_{c}$ for the experiment at Juana Díaz.

Room for further yield decreases with further increases in RETD. Therefore, it is not surprising that in the final RETD interval, between 0.21 and 0.33, only a small yield decrease was observed. This introduced significant non linearity into Figure 18, with corresponding reduction of the coefficient of determination for linear regression. If the regres-

FIGURE 17. Cumulative evapotranspiration deficits for irrigation treatments at Juana Díaz, Puerto Rico.
sion analysis is repeated considering only yields at the more moderate water deficits (RETD values of 0.02, 0.10 and 0.20), a better linear relationship is obtained with $R^2 = 0.99$, as seen in Figure 20. The fact that this new regression is based only on three data points does not
Figure 20. Cormel yields as a function of relative evapotranspiration deficit at Juana Díaz, Puerto Rico, considering only the three highest irrigation treatments.

necessarily render it statistically insignificant, since each data point represents the mean of five replications. The estimated $K_e$ value in this case is 4.3 (Figure 21). This value is similar to that inferred from the experiment at Gurabo, which is discussed next.

Figure 21. Relative yield deficit as a function of relative evapotranspiration deficit at Juana Díaz, Puerto Rico, considering only the three highest irrigation treatments.
Gurabo Experiment

Values of cumulative rainfall, $ET_o$ and $ET_c$ for the Gurabo study are given in Figure 22. Cumulative evapotranspiration deficit as a function of time for irrigated and non-irrigated treatments is shown in Figure 23.

For the irrigated treatment, the seasonal relative evapotranspiration deficit (RETD) calculated by water balance was 0.001 (zero for practical purposes), indicating no water stress in the irrigated plots. The RETD for non-irrigated plots was estimated at 0.045, with practically all of this deficit occurring in a narrow time window at about 230 to 260 days after planting.

Mean yields for the 12 tanier cultivars under the two irrigation treatments are shown in Table 1. Also shown are relative yield deficits (RYD) corresponding to the non-irrigated yields, calculated with Eq. [2] taking the irrigated yields as $Y_{max}$ and non-irrigated yields as $Y$. Values of $K_y$ for each RYD value are given in the far right column. The $K_y$ values were obtained by dividing RYD into the RETD value of 0.045.

Because of high yield variability, ANOVA was unable to detect significant differences ($p < 0.05$) between means of irrigated and non-irrigated plots. However, as observed by the authors of the study, the means of the irrigated plots in Table 1 always ranked higher than those of non-irrigated plots. Such a result is highly unlikely under a null hypothesis of no response to irrigation, since in that case approxi-
Figure 23. Cumulative evapotranspiration deficit for the Gurabo, Puerto Rico, experiment.

approximately half of the irrigated means should rank higher (+) than the non-
irrigated means, and that the other half should rank lower (-).

If the null hypothesis were true, the probability P that all 12 sample
varieties should yield a (+) result as in Table 1 would be given by the
binomial distribution (Bury, 1999) as

$$P(s) = \binom{n}{s} \times (p^+)^s \times (1-p^+)^{n-s}$$  \[10\]

where \(\binom{n}{s}\) is the binomial coefficient defined by

$$\binom{n}{s} = \frac{n!}{s!(n-s)!}$$  \[11\]

In these equations, \(n=12\) is the number of cultivars tested, \(s\) is the
observed number of (+) results and \(p^+ = 0.5\) is the probability of en-
countering a (+) result under the null hypothesis. For the observed
case of \(s = 12\), Eq. [10] yields that \(P(s) = < 0.003\). In other words, if the
null hypothesis were true, there would be less than a 0.003 proba-
bility of encountering the observed results. It is therefore reasonable to
reject the null hypothesis and accept the alternative hypothesis that
irrigated tanier yields were different (greater in this case) than non-
irrigated yields.

To obtain \(K_f\) values for the results in Table 1, the RETD value of
0.001 for the irrigated yields was assumed equal to zero, so that the
TABLE 1.—Mean yields of 12 tanier cultivars with and without irrigation at Gurabo. (Each mean represents the average of six replications)

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Irrigated yields</th>
<th>Non-irrigated yields</th>
<th>RYD</th>
<th>( K_y )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blanca del Pais</td>
<td>17.8</td>
<td>13.9</td>
<td>0.22</td>
<td>4.9</td>
</tr>
<tr>
<td>Choubobutton</td>
<td>14.9</td>
<td>13.3</td>
<td>0.11</td>
<td>2.4</td>
</tr>
<tr>
<td>Drearies</td>
<td>14.8</td>
<td>13.4</td>
<td>0.10</td>
<td>2.1</td>
</tr>
<tr>
<td>Kelly</td>
<td>14.6</td>
<td>12.8</td>
<td>0.12</td>
<td>2.7</td>
</tr>
<tr>
<td>Rascana</td>
<td>14.3</td>
<td>10.6</td>
<td>0.26</td>
<td>5.6</td>
</tr>
<tr>
<td>Viequera</td>
<td>14.1</td>
<td>9.6</td>
<td>0.32</td>
<td>7.1</td>
</tr>
<tr>
<td>Charanelle</td>
<td>13.3</td>
<td>12.6</td>
<td>0.05</td>
<td>1.2</td>
</tr>
<tr>
<td>Vinola</td>
<td>13.2</td>
<td>10.2</td>
<td>0.23</td>
<td>5.1</td>
</tr>
<tr>
<td>Morada</td>
<td>12.7</td>
<td>10.3</td>
<td>0.19</td>
<td>4.2</td>
</tr>
<tr>
<td>Bisley</td>
<td>11.4</td>
<td>9.8</td>
<td>0.14</td>
<td>3.2</td>
</tr>
<tr>
<td>Inglesa</td>
<td>11.1</td>
<td>8.1</td>
<td>0.27</td>
<td>6.0</td>
</tr>
<tr>
<td>Barbados</td>
<td>10.5</td>
<td>7.8</td>
<td>0.26</td>
<td>5.7</td>
</tr>
<tr>
<td>Average of means</td>
<td>13.6</td>
<td>11.0</td>
<td>0.19 ( \pm 0.05 )</td>
<td>4.2</td>
</tr>
</tbody>
</table>

The mean irrigated yield for each cultivar could be taken as \( Y_{\text{max}} \). The RETD value corresponding to non-irrigated yield \( Y_{\text{n}} \) for all cultivars was set 0.045. Substituting the yield and RETD values into Eq. [5] allowed calculating \( K_y \) values, shown in the right hand column of Table 1. Values of \( K_y \) varied considerably among cultivars, which is not surprising given the high yield variabilities and the low RETD value of 0.045. The mean value of \( K_y \) for all cultivars was 4.2, with a 95 percent confidence interval of 1.2 above and below the mean.

**General discussion concerning \( K_y \) values obtained in the different irrigation experiments**

The \( K_y \) values obtained above for the three-tanier experiments are summarized in the first (upper) row of Table 2. These values were obtained by setting the parameters \( D \) (maximum crop rooting depth) and \( p \) (critical fraction of available water) in the FAO water balance model at 50 cm and 0.5, respectively. The \( K_y \) values are very high compared to results reported for most crops in the literature, where \( K_y \) rarely exceeds 1.3 (Doorenbos and Kassam, 1979; Steduto et al., 2012).

**Table 2.—Values of \( K_y \) inferred for the different irrigation experiments, obtained by running the FAO water balance model for two different sets of values of the crop rooting depth (\( D \)) and the critical available water fraction (\( p \)).**

<table>
<thead>
<tr>
<th>Parameters assumed in water balance model</th>
<th>Isabela (all treatments)</th>
<th>Fortuna (highest irrigation treatments)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D = 50 cm, ( p = 0.5 )</td>
<td>3.1</td>
<td>3.4</td>
</tr>
<tr>
<td>D = 30 cm, ( p = 0.7 )</td>
<td>2.4</td>
<td>2.7</td>
</tr>
</tbody>
</table>
We initially suspected that the high $K_y$ values could be an artifact, caused by using incorrect parameters $D$ and $p$ in the FAO water balance model. To investigate this possibility, the whole computational procedure described above was repeated by assuming a very shallow rooting depth ($D = 30$ cm) and a very high critical available water fraction ($p = 0.7$). This has the effect of increasing the estimated RETD and thereby decreasing the estimate of $K_y$. The $K_y$ values obtained under the new set of parameters $D$ and $p$ are shown in the second (lower) row of Table 2. The new values, ranging between 2.4 and 3.3, are approximately 30 percent lower than values obtained in the first simulation, but are still much higher than typical values in the literature.

Since high $K_y$ values are obtained even by using conservative values of parameters $D$ and $p$, designed to minimize $K_y$ in the FAO model, it seems that the high $K_y$ is not merely an artifact attributable to incorrect model parameters, but rather reflects a true sensitivity of tanier yields to water stress. It is conceivable that the high $K_y$ values reflect a synergistic (additive or multiplicative) effect of several plant stress factors, including but not restricted to water stress, all of which correlate positively with RETD. An example is soil mechanical impedance, which increases with water deficits (Snyder, 1994) and is known to strongly reduce tanier yields (Lugo-Mercado et al., 1978). A third possible moisture related stress factor is increased sensitivity of tanier roots to soil-borne pathogens (Lugo et al., 1987). Further research is necessary on interactive stress factors affecting tanier yields.

**CONCLUSIONS**

The well known FAO water balance model has been used to estimate relative evapotranspiration deficits (RETD) for tanier, using experimental data from three irrigation experiments conducted at various times and locations. The RETD was calculated for two scenarios. The first scenario assumed “most likely” values for effective plant rooting depth $D$ and the critical available water fraction $p_c$ at the onset of water stress. The second scenario assumed more conservative conditions, characterized by a very shallow-rooted crop (low $D$) with low capacity to satisfy evapotranspiration demand (high $p_c$). By comparing estimated RETD values under each scenario to measured crop yields, yield sensitivity coefficients $K_y$ were estimated. The $K_y$ values ranged between 3.1 and 4.3 for the “most likely” scenario and between 2.4 and 3.3 for the conservative scenario. Even the conservative estimates of $K_y$ were much higher than those cited in the literature for most crops, confirming previous observations regarding high sensitivity of tanier to water stress. We postulate that the high $K_y$ values for tanier could
reflect a synergistic effect of several plant stress factors augmented by dry soil conditions, among them water stress, soil mechanical impedance and pathogenic stress.

Results confirm that substantial tanier yield reduction may occur even under modest water deficits typical of the humid regions of Puerto Rico. Conversely, the return on investment in irrigation systems under these conditions is likely to be high, provided careful irrigation scheduling is practiced.

**LITERATURE CITED**


