THE JOURNAL OF AGRICULTURE OF THE UNIVERSITY OF PUERTO RICO

Issued biannually by the Agricultural Experiment Station of the University of Puerto Rico, Mayagüez Campus, for the publication of articles and research notes by staff members or others, dealing with scientific agriculture in Puerto Rico and elsewhere in the Caribbean Basin and Latin America.

VOL. 98 OCTOBER 2014 No. 2

Response of tanier (*Xanthosoma* spp.) to evapotranspiration deficits estimated with the FAO water balance method[1,2]

Víctor A. Snyder[3], *Wanda I. Lugo*[4], *Miguel A. Vázquez*[5] *and Edwin Acevedo*[6]

J. Agric. Univ. P.R. 98(2):89-117 (2014)

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_y), which must be experimentally determined for each specific crop. The objective of this study was to estimate K_y 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

[1]Manuscript submitted to the Editorial Board 1 May 2014.

[2]The authors acknowledge Dr. Ricardo Goenaga for providing detailed records of irrigation water applied to his experiments, and agronomists Irma Cabrera and Lucas Ramírez for providing daily rainfall and pan evaporation records from the Juana Díaz and Gurabo substations, respectively.

[3]Professor, Department of Crops and Agroenvironmental Sciences. Agricultural Experiment Station, University of Puerto Rico, Mayagüez Campus.

[4]Associate Professor, Department of Crops and Agroenvironmental Sciences.

[5]Research Associate, Department of Crops and Agroenvironmental Sciences.

[6]Agronomist (retired), Department of Agronomy and Soils. Agricultural Experiment Station, Isabela.

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_y. A first analysis yielded K_y 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_y. The minimum K_y 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_y 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_y), el cual se determina para cada cultivo mediante experimentación. El objetivo de este estudio fue estimar K_y 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_y. Un primer análisis arrojó valores de K_y 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_y. Aún así se obtuvieron valores altos de K_y, 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_y 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

patogénico. Los resultados en general confirman las observaciones previas sobre la alta sensitividad 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 sensitividad 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

$$RETD \equiv \frac{ET_c - E_a}{ET_c} \qquad [1]$$

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_c 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]:

$$RYD = \frac{Y_{max} - Y_a}{Y_{max}} \qquad [2]$$

where Y_{max} is maximum yield in absence of water stress and Y_a 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

$$\frac{Y_m - Y_a}{Y_m} = \sum_{i=1}^{I} K_{yi} \left(\frac{ET_{ci} - ET_{ai}}{ET_{ci}} \right) \quad [3]$$

where the subscript i represents the i^{th} growth stage. The parameter K_{yi} 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

$$\frac{Y_m - Y_a}{Y_m} = K_y \frac{ET_c - ET_a}{ET_c} \quad [4]$$

or simply,

$$RYD = K_y RETD \quad [5]$$

where ET_c 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_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_{pan}, as

$$ET_c = K_p \cdot K_c \cdot E_{pan} \quad [6]$$

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

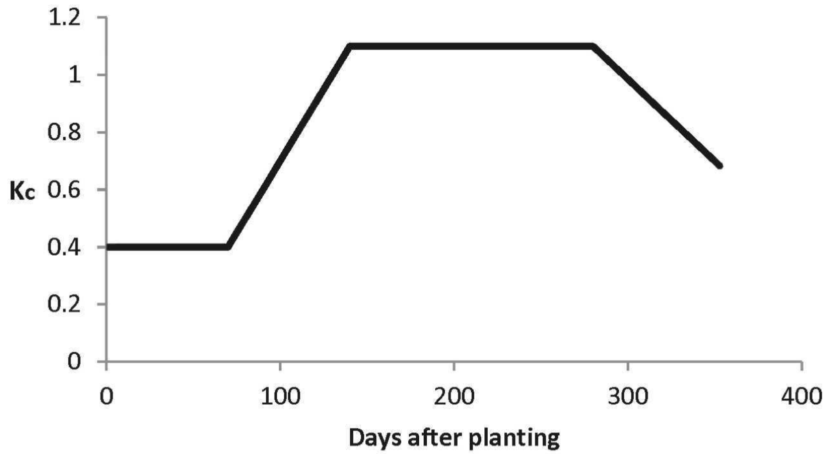

FIGURE 1. Crop coefficient (K_c) values assumed for a tanier crop.

(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_a (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

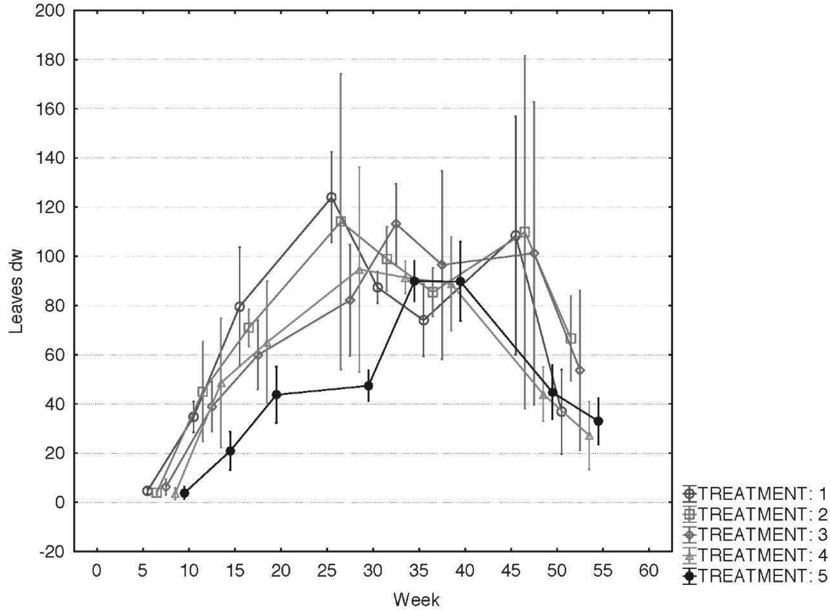

FIGURE 2. Leaf dry matter accumulation for tanier as a function of weeks after planting, for different irrigation treatments at Isabela, Puerto Rico (unpublished data from Snyder et al., 1995). Irrigation treatments 1 through 5 are described later in Materials and Methods.

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

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

$$p \equiv \frac{h}{h_o} \qquad [8]$$

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

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

where D is the effective crop rooting depth, and θ_{fc} and θ_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 $D = 0.5$ 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.

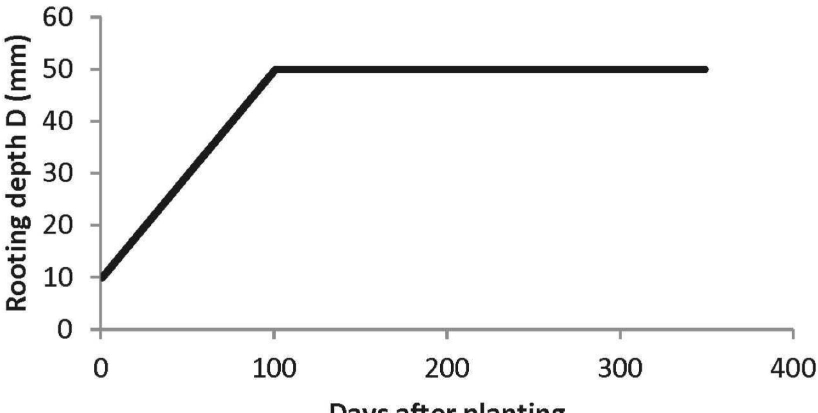

FIGURE 3. Estimated rooting depth for tanier as a function of time.

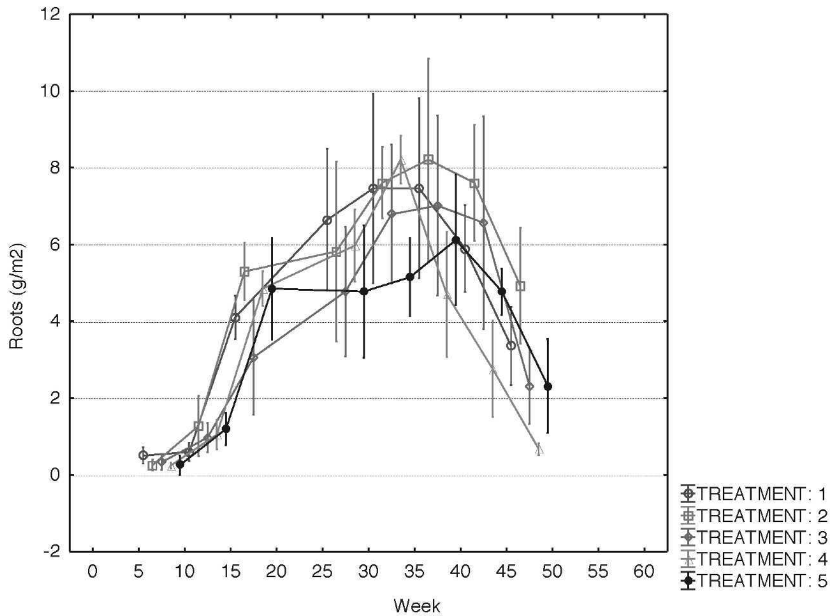

FIGURE 4. Tanier root biomass as a function of time and irrigation treatment at Isabela, Puerto Rico (unpublished data from Snyder et al., 1995). Irrigation treatments 1 through 5 are described later in Materials and Methods.

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

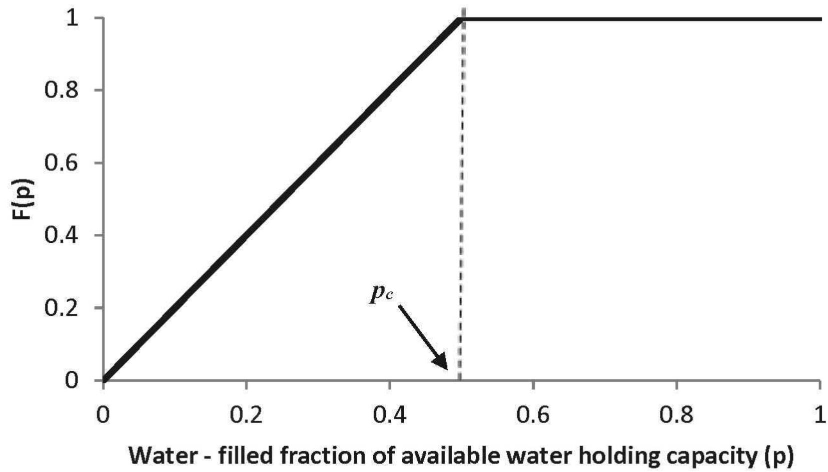

FIGURE 5. Evapotranspiration function *F*(*p*) as a function of water-filled fraction (*p*) of available water holding capacity of soil in the crop rooting zone.

period. Detailed numerical examples are given in Doorenbos and Kassam (1979). We programmed the operations into an Excel™ spreadsheet, 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 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 Eutrustox).

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_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 x 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

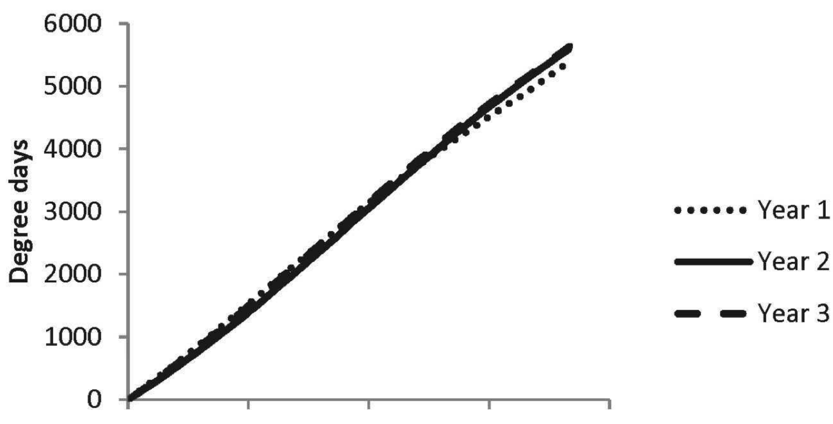

FIGURE 6. Cumulative heat units (degree-days) during the three years of the experiment at Isabela, Puerto Rico.

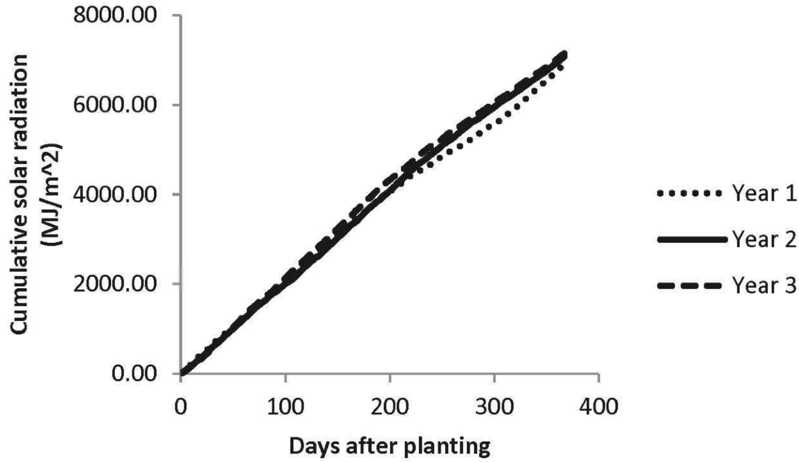

FIGURE 7. Cumulative solar radiation (MJ/m^2) during the three years of the experiment at Isabela, Puerto Rico.

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

$$RETD \equiv \frac{ETD}{ET_c} \qquad [9]$$

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.

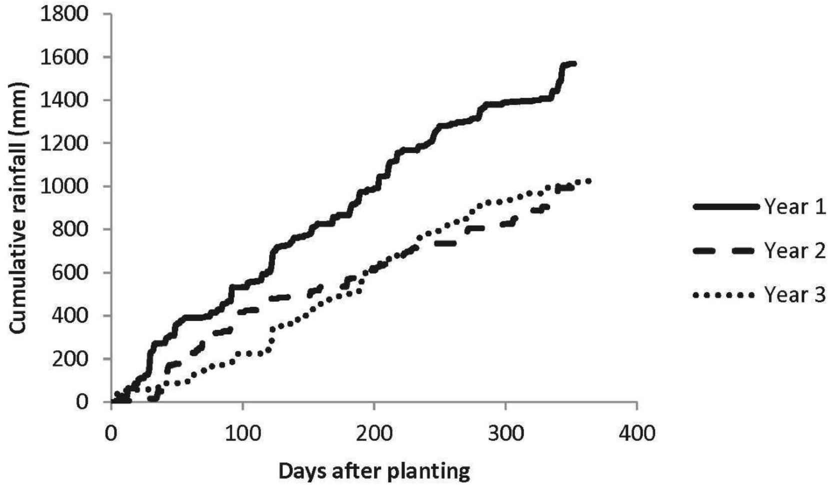

FIGURE 8. Cumulative rainfall distributions in different years at Isabela, Puerto Rico.

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 evapotrans-

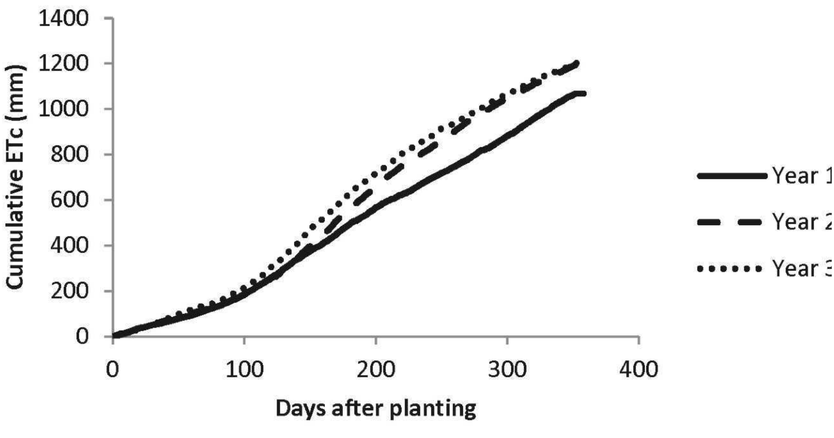

FIGURE 9. Cumulative crop evapotranspiration demand (ET_c) during the three growing seasons.

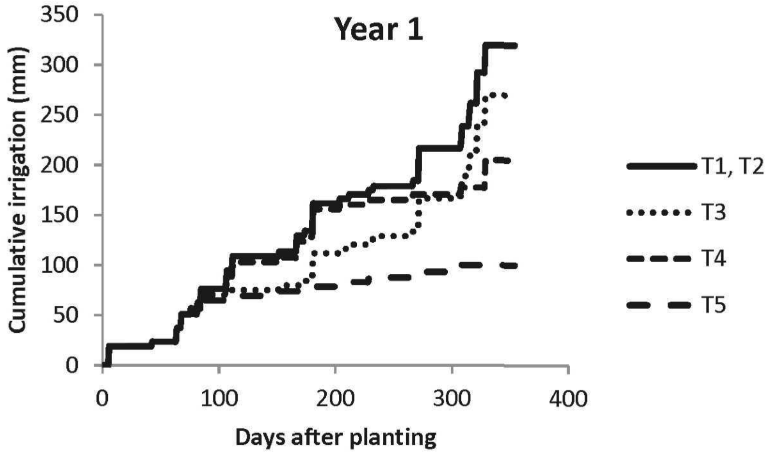

FIGURE 10a. Cumulative irrigation water for different treatments during Year 1.

piration 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_o and crop evapotranspiration demand ET_c at Juana Díaz.

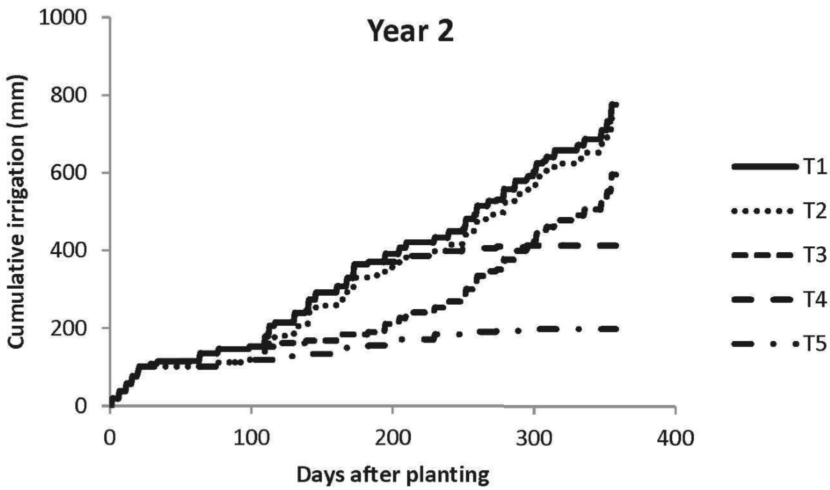

FIGURE 10b. Cumulative irrigation water for different treatments during Year 2.

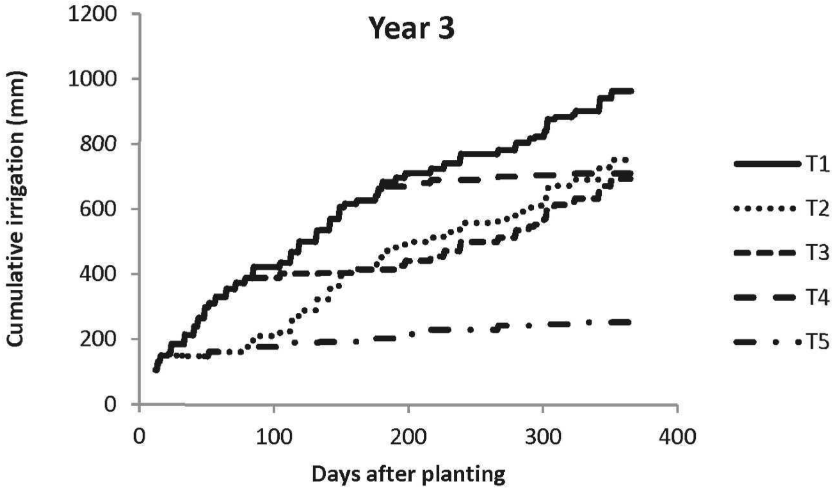

FIGURE 10c. Cumulative irrigation water for different treatments during Year 3.

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.

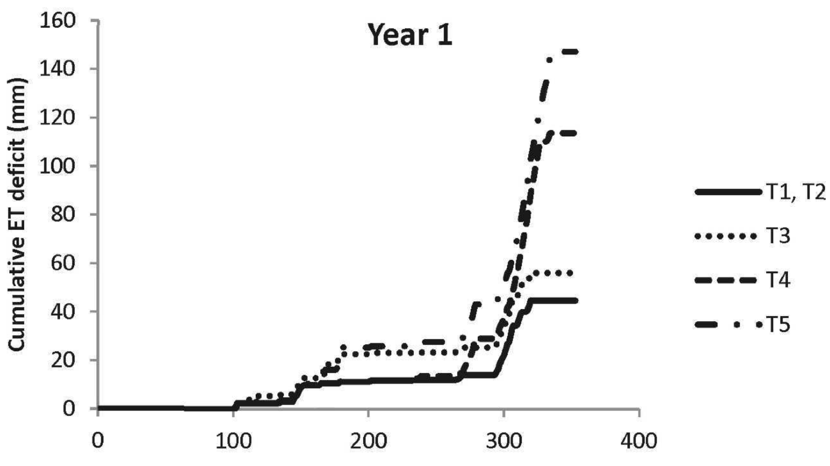

FIGURE 11a. Cumulative evapotranspiration deficits for different treatments in Year 1.

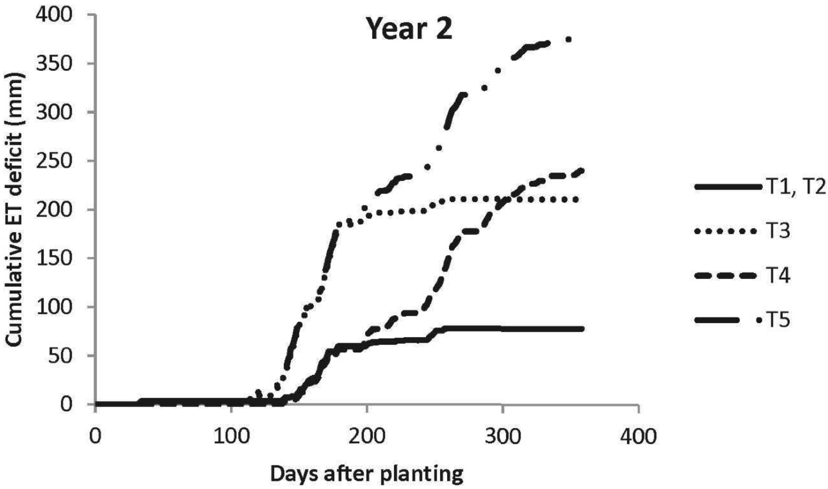

FIGURE 11b. Cumulative evapotranspiration deficits for different treatments in Year 2.

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-

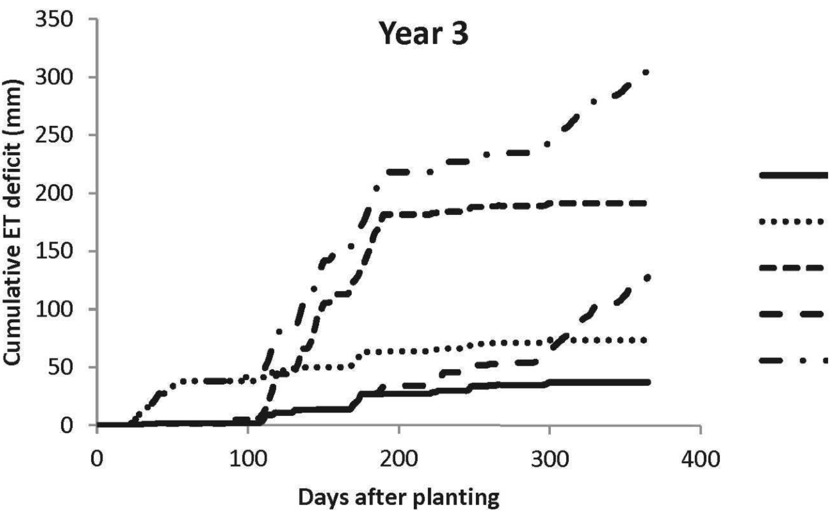

FIGURE 11c. Cumulative evapotranspiration deficits for different treatments in Year 3.

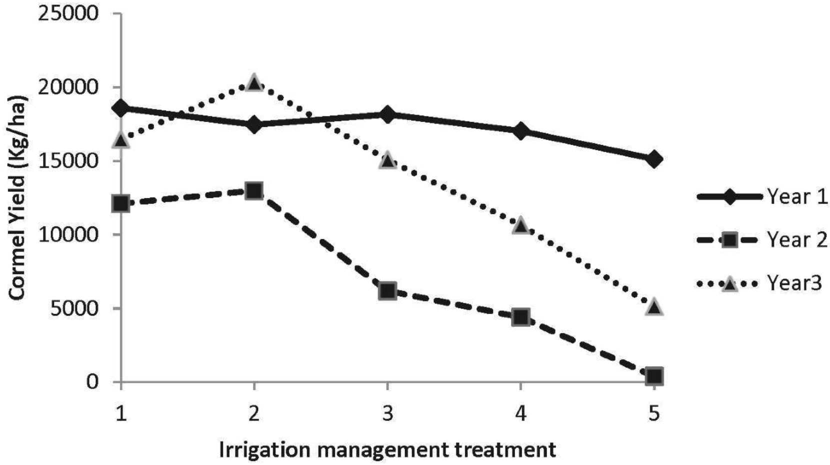

FIGURE 12. Mean yields of marketable cormels for each irrigation management program and year.

ing 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

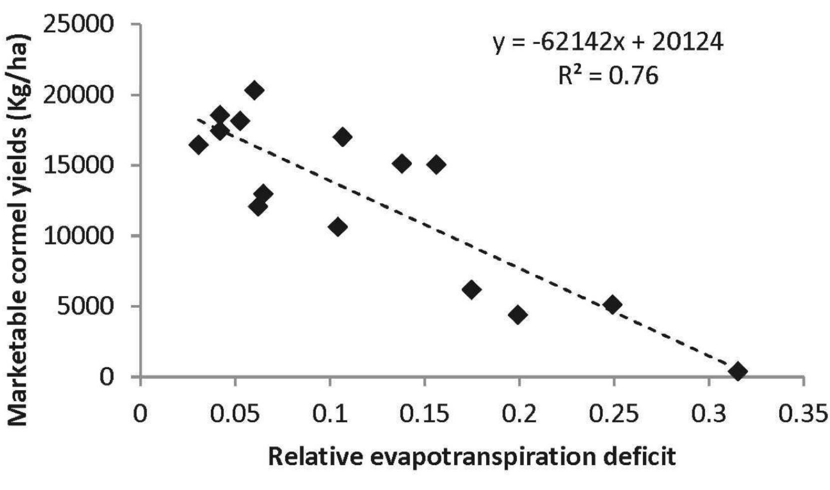

FIGURE 13. Crop yield as a function of relative evapotranspiration deficit (RETD).

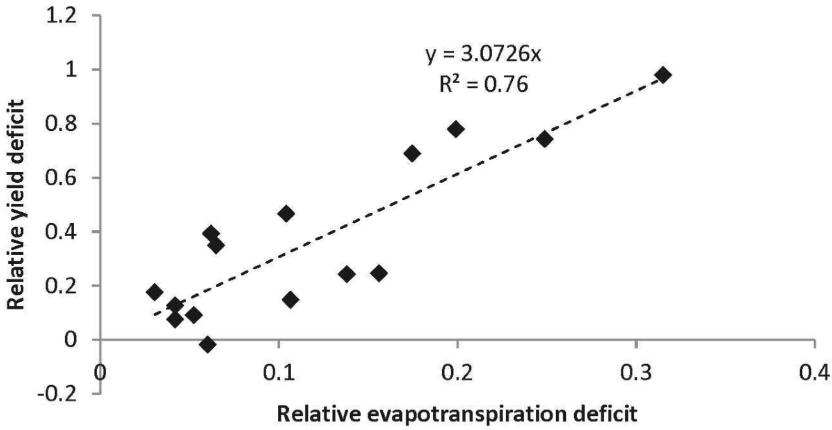

FIGURE 14. Relative yield deficit (RYD) as a function of relative evapotranspiration deficit (RETD).

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

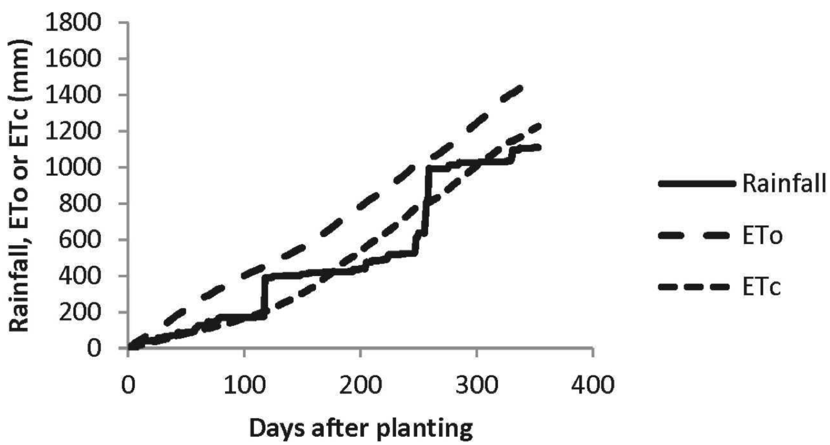

FIGURE 15. Cumulative rainfall, ET_o and ET_c for the experiment at Juana Díaz.

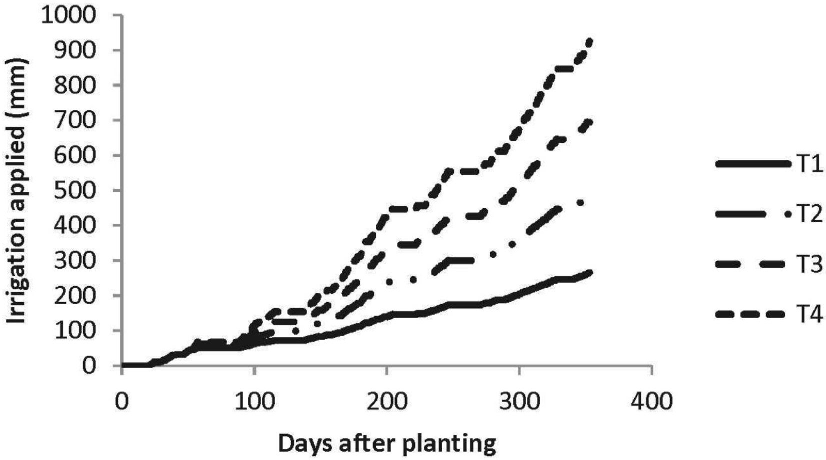

Figure 16. Cumulative amounts of irrigation water applied in experimental treatments at Juana Díaz, Puerto Rico.

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-

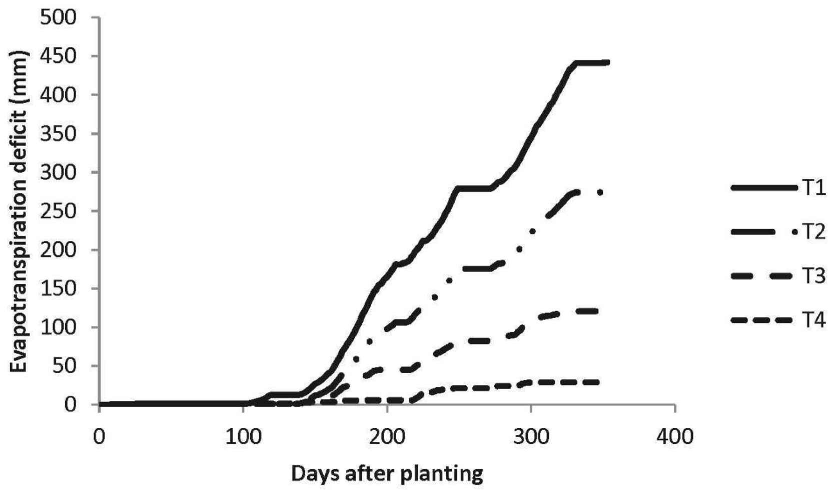

Figure 17. Cumulative evapotranspiration deficits for irrigation treatments at Juana Díaz, Puerto Rico.

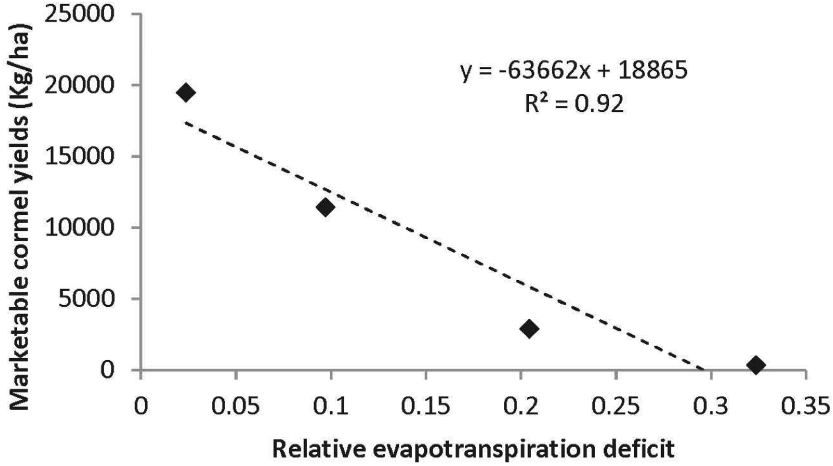

FIGURE 18. Linear regression of cormel yields as a function of relative evapotranspiration deficit at Juana Díaz, Puerto Rico, considering all irrigation treatments.

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

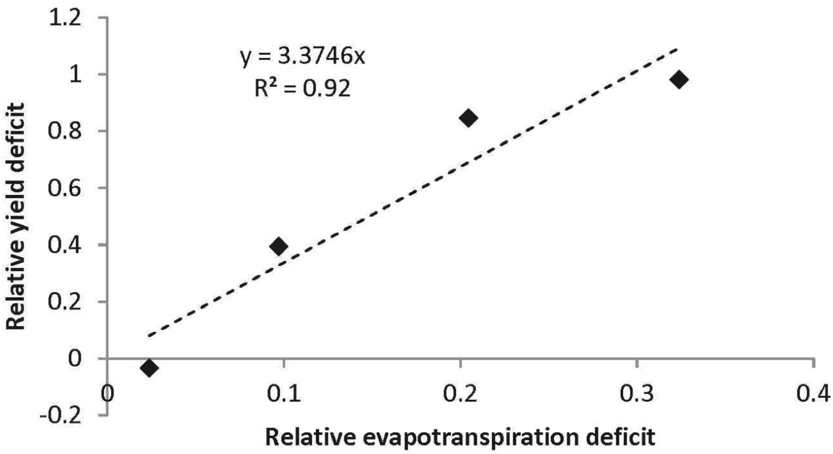

FIGURE 19. Linear regression of relative yield deficit as a function of relative evapotranspiration deficit at Juana Díaz, Puerto Rico, considering all irrigation treatments.

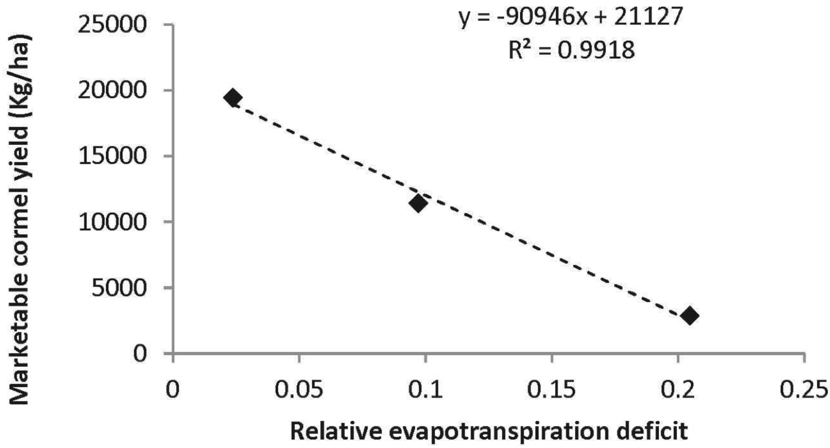

FIGURE 20. Cormel yields as a function of relative evapotranspiration deficit at Juana Díaz, Puerto Rico, considering only the three highest irrigation treatments.

necessarily render it statistically insignificant, since each data point represents the mean of five replications. The estimated K_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.

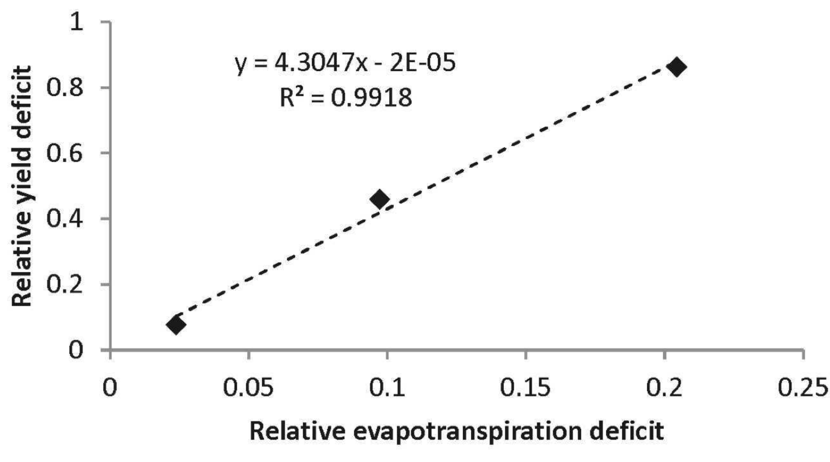

FIGURE 21. Relative yield deficit as a function of relative evapotranspiration deficit at Juana Díaz, Puerto Rico, considering only the three highest irrigation treatments.

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_a. 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-

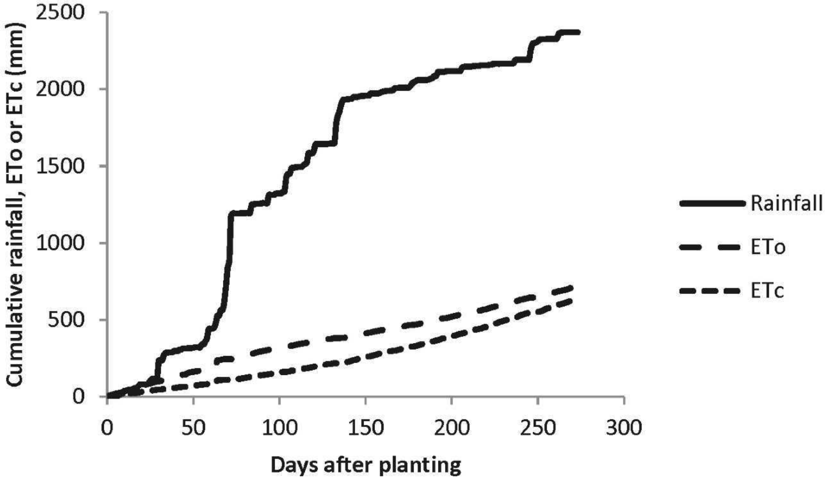

FIGURE 22. Cumulative rainfall, ET_o and ET_c for the Gurabo, Puerto Rico, experiment.

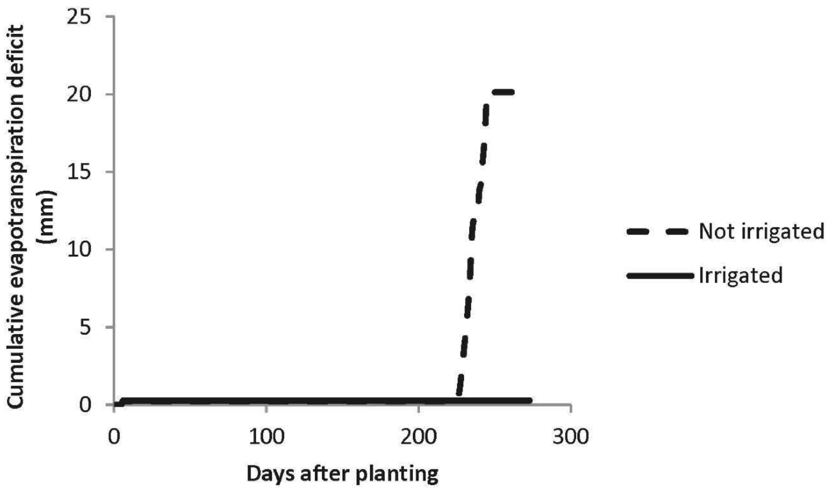

FIGURE 23. Cumulative evapotranspiration deficit for the Gurabo, Puerto Rico, experiment.

mately 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

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

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

$$\binom{n}{s} \equiv \frac{n!}{s!(n\text{-}s)!} \qquad [11]$$

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 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_y 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)

Cultivar	*Irrigated yields*	*Non-irrigated yields*	*RYD*	K_y
Blanca del Pais	17.8	13.9	0.22	4.9
Choubutton	14.9	13.3	0.11	2.4
Drearies	14.8	13.4	0.10	2.1
Kelly	14.6	12.8	0.12	2.7
Rascana	14.3	10.6	0.26	5.6
Viequera	14.1	9.6	0.32	7.1
Charanelle	13.3	12.6	0.05	1.2
Vinola	13.2	10.2	0.23	5.1
Morada	12.7	10.3	0.19	4.2
Bisley	11.4	9.8	0.14	3.2
Inglesa	11.1	8.1	0.27	6.0
Barbados	10.5	7.8	0.26	5.7
Average of means	*13.6*	*11.0*	*0.19 ± 05*	*4.2*

mean irrigated yield for each cultivar could be taken as Y_{max}. The RETD value corresponding to non-irrigated yield Y_a 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).*

Parameters assumed in water balance model	*Isabela*	*Fortuna* (all treatments)	*Fortuna* (highest irrigation treatments)	*Gurabo*
D = 50 cm, p = 0.5	3.1	3.4	4.3	4.2
D = 30 cm, p = 0.7	2.4	2.7	3.3	3.0

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

Abruña, F., J. Vicente-Chandler, E. Boneta and S. Silva, 1967. Experiments on tanier production with conservation in Puerto Rico's mountain region. *J. Agric. Univ. P.R.* 51:167-175.

Agricultural Experiment Station Staff, 1997. Technological package for the production of roots and tubers (in Spanish). Univ. of P.R. Ag. Exp. Sta. Pub. No. 101. 34 pp.

Allen, R. G., L. S. Pereira, D. Raes and M. Smith, 1998. Crop evapotranspiration. FAO Irrigation and Drainage Paper 56, FAO, Rome. 300 pp.

Bury, K., 1999. Statistical Distributions in Engineering. Cambridge University Press.

Cortés, M. and L. Gayol, 2010. Root and Tuber Crops. *In* Cortés, M. and L. Gayol (eds.) Agricultural Commodities. Situation and Perspectives, 2005-2008. University of Puerto Rico Agricultural Experiment Station (in Spanish). 116 pp.

Doorenbos, J. and W. O. Pruitt, 1977. Crop water requirements. FAO Irrigation and Drainage Paper 24, FAO, Rome. 144 pp.

Doorenbos, J. and A. H. Kassam, 1979. Yield response to water. FAO Irrigation and Drainage Paper 33, FAO, Rome. 193 pp.

Goenaga, R. and U. Chardón, 1993. Nutrient uptake, growth and yield performance of three tanier (*Xanthosoma* spp.) cultivars grown under intensive management. *J. Agric. Univ. P.R.* 77:1-10.

Goenaga, R., 1994a. Partitioning of dry matter in tanier (*Xanthosoma* spp.) irrigated with fractions of evapotranspiration. *Ann. Botany* 73:257-261.

Goenaga, R., 1994b. Growth, nutrient uptake and yield of tanier (*Xanthosoma* spp.) grown under semi-arid conditions. *J. Agric. Univ. P.R.* 78:87-98.

Harmsen, E. W., A. González-Pérez and A. Winter, 2004. Re-evaluation of pan evaporation coefficients at seven locations of Puerto Rico. *J. Agric. Univ. P.R.* 88:109-122.

Irizarry, H., M. Capiel and A. Acosta Matienzo, 1977. Yield of twelve tanier cultivars grown with and without irrigation in east-central Puerto Rico. *J. Agric. Univ. P.R.* 61:100-105.

Lugo-Mercado, H. M., J. Badillo-Feliciano and J. López-García, 1978. Effect of soil compaction on tanier yields. *J. Agric. Univ. P.R.* 62:56-63.

Lugo, W. I., H. M. Lugo, J. Badillo, A. Beale, M. Santiago and L. E. Rivera, 1987. Response of taniers to different water regimes. *Proc. Caribbean Food Crops Soc.*, Antigua, 1987, pp 113-117.

Mount, H. R. and W. C. Lynn, 2004. Soil survey laboratory data and soil descriptions for some soils of Puerto Rico and the Virgin Islands. United States Department of Agriculture, Natural Resources Conservation Service, Soil Survey Investigations Report No. 49. 695 pp.

Onwueme, I. C., 1978. The tropical tuber crops. Wiley, New York. 234 pp.

Soil Survey Staff, 1967. Soil survey laboratory data and descriptions for some soils of Puerto Rico and the Virgin Islands. United States Department of Agriculture, Soil Conservation Service, Soil Survey Investigations Report No. 12. 191 pp.

Snyder, V. A., 1994. Plant stresses associated with soil structure. *In*: Davenport, T. L. and H. M. Harrington (eds.). Plant Stress in the Tropical Environment. Proc. CBAG-PBAG Workshop on Plant Stresses in the Environment, Kona, Hawaii, September 20-25, 1992, pp. 34-40.

Snyder, V. A., W. I. Lugo, E. Acevedo and M. A. Vázquez, 1995. Development and validation of a water stress subroutine for the aroid model. Final Research Project Report for CBAG Project PR-50, Agricultural Experiment Station, University of Puerto Rico. 15 pp.

Steduto, P., T. C. Hsiao, E. Fereres and D. Raes, 2012. Crop yield response to water. FAO Irrigation and Drainage paper No. 66. FAO, Rome. 500 pp.

THE JOURNAL OF AGRICULTURE OF THE UNIVERSITY OF PUERTO RICO

Issued biannually by the Agricultural Experiment Station of the University of Puerto Rico, Mayagüez Campus, for the publication of articles and research notes by staff members or others, dealing with scientific agriculture in Puerto Rico and elsewhere in the Caribbean Basin and Latin America.

VOL. 98 OCTOBER 2014 No. 2

Response of tanier (*Xanthosoma* spp.) to evapotranspiration deficits estimated with the FAO water balance method[1,2]

Víctor A. Snyder[3], *Wanda I. Lugo*[4], *Miguel A. Vázquez*[5] *and Edwin Acevedo*[6]

J. Agric. Univ. P.R. 98(2):89-117 (2014)

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_y), which must be experimentally determined for each specific crop. The objective of this study was to estimate K_y 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

[1]Manuscript submitted to the Editorial Board 1 May 2014.

[2]The authors acknowledge Dr. Ricardo Goenaga for providing detailed records of irrigation water applied to his experiments, and agronomists Irma Cabrera and Lucas Ramírez for providing daily rainfall and pan evaporation records from the Juana Díaz and Gurabo substations, respectively.

[3]Professor, Department of Crops and Agroenvironmental Sciences. Agricultural Experiment Station, University of Puerto Rico, Mayagüez Campus.

[4]Associate Professor, Department of Crops and Agroenvironmental Sciences.

[5]Research Associate, Department of Crops and Agroenvironmental Sciences.

[6]Agronomist (retired), Department of Agronomy and Soils. Agricultural Experiment Station, Isabela.

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_y. A first analysis yielded K_y 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_y. The minimum K_y 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_y 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_y), el cual se determina para cada cultivo mediante experimentación. El objetivo de este estudio fue estimar K_y 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_y. Un primer análisis arrojó valores de K_y 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_y. Aún así se obtuvieron valores altos de K_y, 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_y 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

patogénico. Los resultados en general confirman las observaciones previas sobre la alta sensitividad 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 sensitividad 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

$$RETD \equiv \frac{ET_c - E_a}{ET_c} \qquad [1]$$

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_c 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]:

$$RYD = \frac{Y_{max} - Y_a}{Y_{max}} \qquad [2]$$

where Y_{max} is maximum yield in absence of water stress and Y_a 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

$$\frac{Y_m - Y_a}{Y_m} = \sum_{i=1}^{I} K_{yi} \left(\frac{ET_{ci} - ET_{ai}}{ET_{ci}} \right) \quad [3]$$

where the subscript i represents the i^{th} growth stage. The parameter K_{yi} 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

$$\frac{Y_m - Y_a}{Y_m} = K_y \frac{ET_c - ET_a}{ET_c} \quad [4]$$

or simply,

$$RYD = K_y RETD \quad [5]$$

where ET_c 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_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_{pan}, as

$$ET_c = K_p \cdot K_c \cdot E_{pan} \quad [6]$$

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

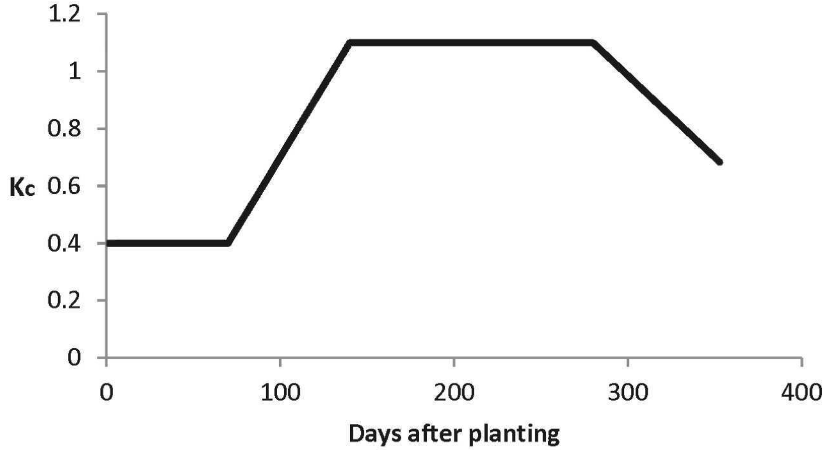

FIGURE 1. Crop coefficient (K_c) values assumed for a tanier crop.

(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_a (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

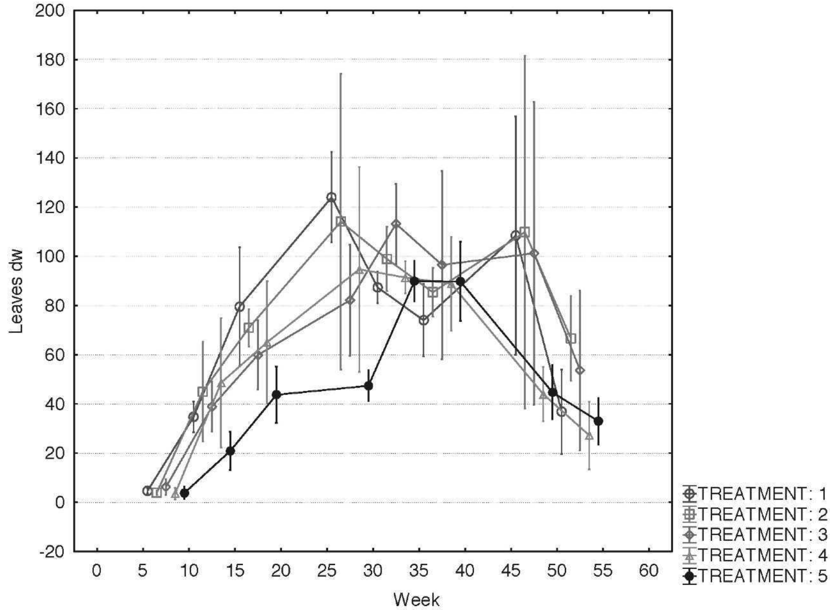

FIGURE 2. Leaf dry matter accumulation for tanier as a function of weeks after planting, for different irrigation treatments at Isabela, Puerto Rico (unpublished data from Snyder et al., 1995). Irrigation treatments 1 through 5 are described later in Materials and Methods.

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

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

$$p \equiv \frac{h}{h_o} \qquad [8]$$

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

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

where D is the effective crop rooting depth, and θ_{fc} and θ_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 $D = 0.5$ 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.

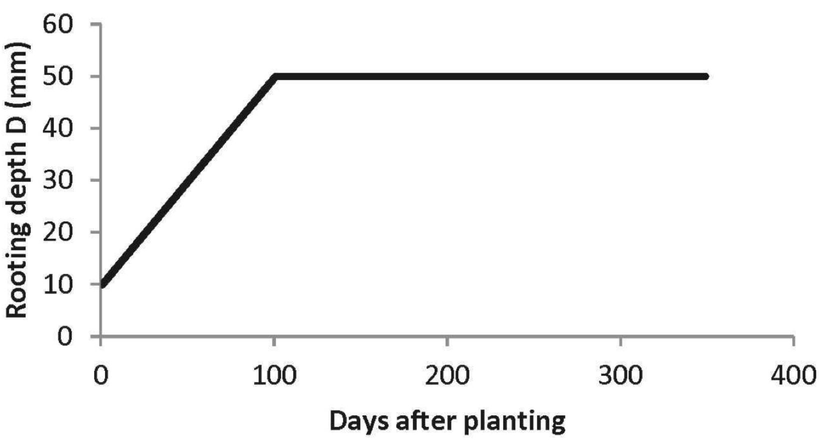

FIGURE 3. Estimated rooting depth for tanier as a function of time.

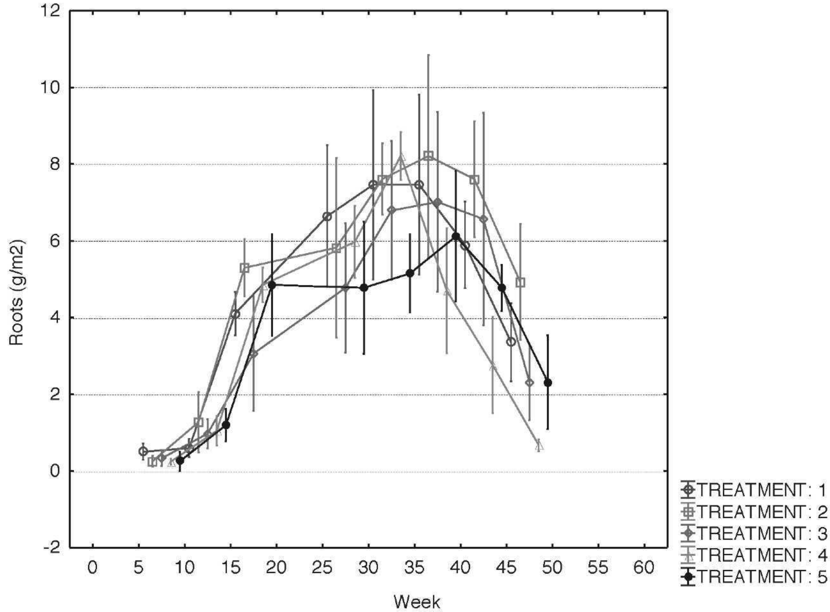

FIGURE 4. Tanier root biomass as a function of time and irrigation treatment at Isabela, Puerto Rico (unpublished data from Snyder et al., 1995). Irrigation treatments 1 through 5 are described later in Materials and Methods.

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

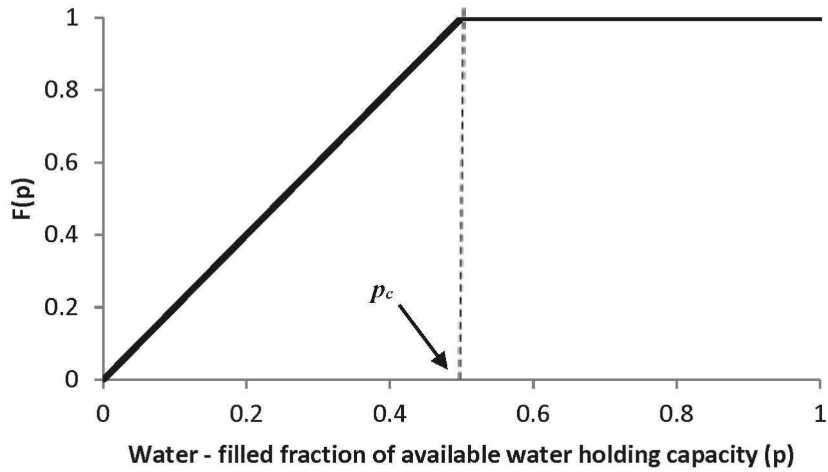

FIGURE 5. Evapotranspiration function $F(p)$ as a function of water-filled fraction (p) of available water holding capacity of soil in the crop rooting zone.

period. Detailed numerical examples are given in Doorenbos and Kassam (1979). We programmed the operations into an Excel™ spreadsheet, 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 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 Eutrustox).

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_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 x 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

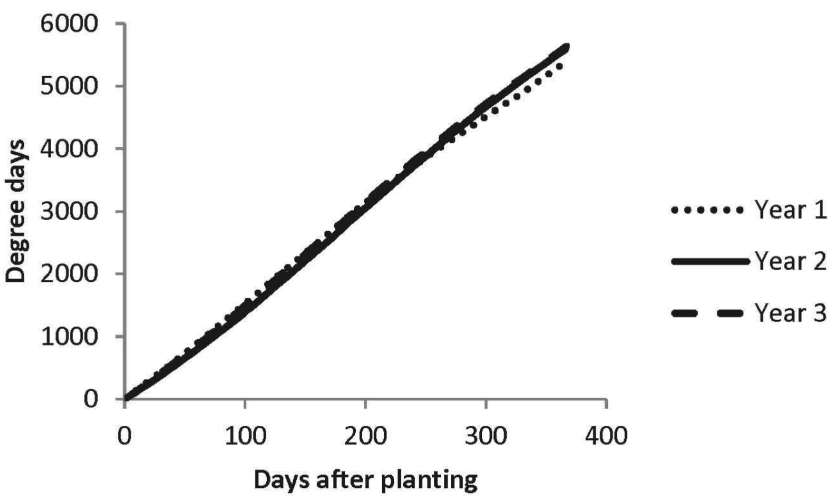

FIGURE 6. Cumulative heat units (degree-days) during the three years of the experiment at Isabela, Puerto Rico.

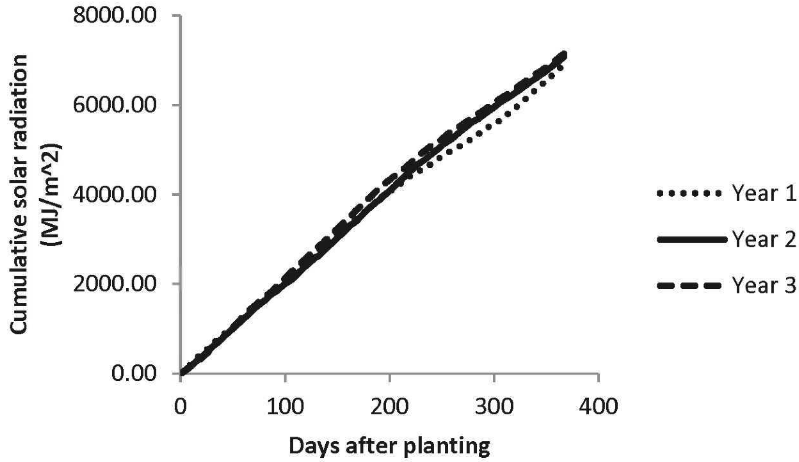

FIGURE 7. Cumulative solar radiation (MJ/m^2) during the three years of the experiment at Isabela, Puerto Rico.

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

$$RETD \equiv \frac{ETD}{ET_c} \quad [9]$$

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.

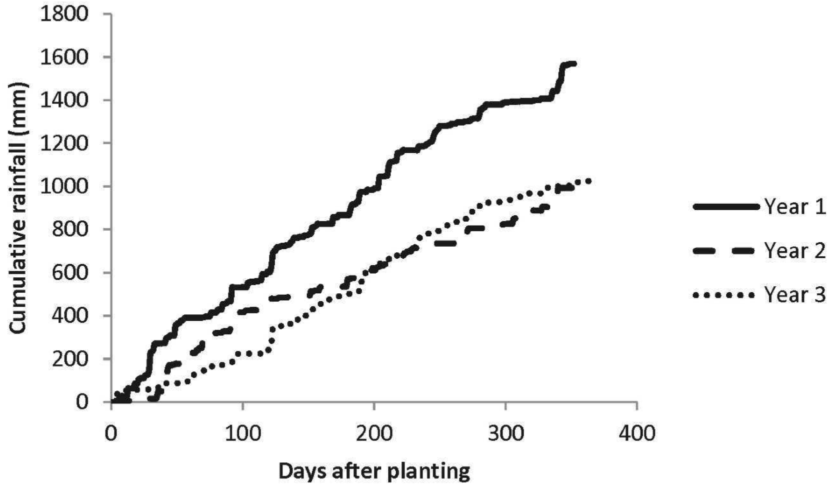

FIGURE 8. Cumulative rainfall distributions in different years at Isabela, Puerto Rico.

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 evapotrans-

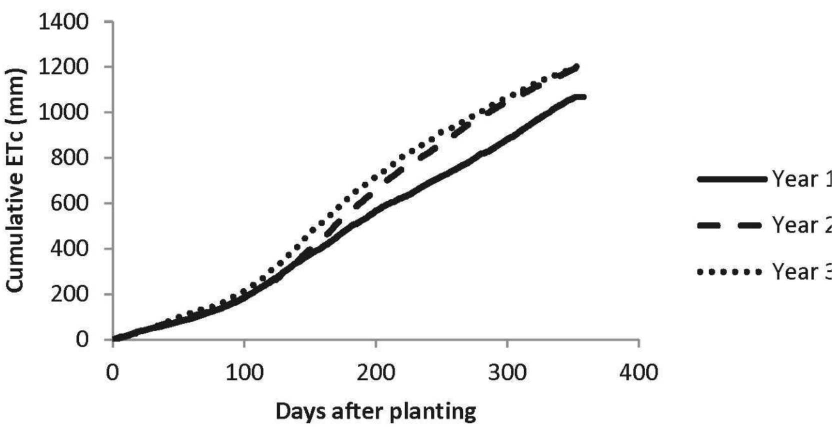

FIGURE 9. Cumulative crop evapotranspiration demand (ET_c) during the three growing seasons.

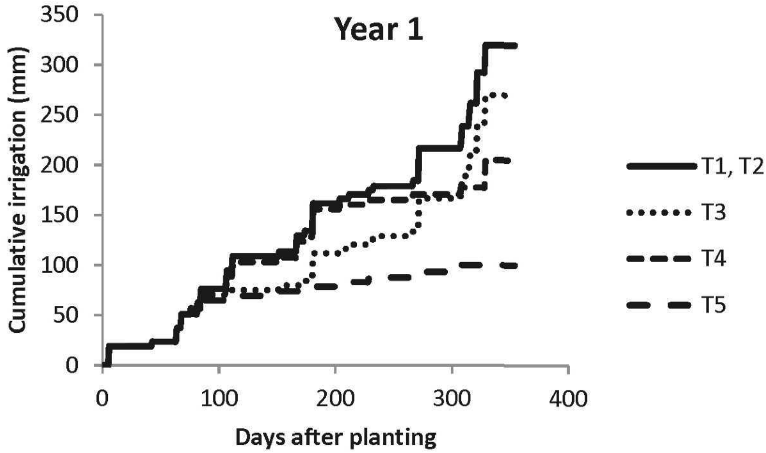

FIGURE 10a. Cumulative irrigation water for different treatments during Year 1.

piration 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_o and crop evapotranspiration demand ET_c at Juana Díaz.

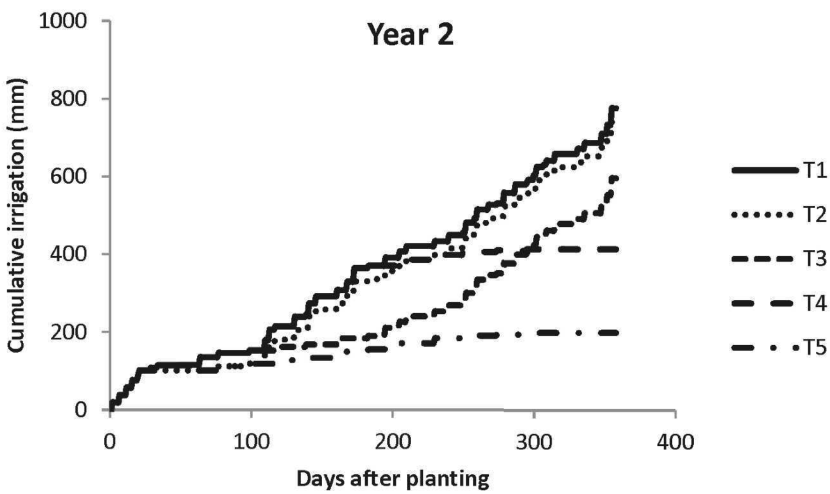

FIGURE 10b. Cumulative irrigation water for different treatments during Year 2.

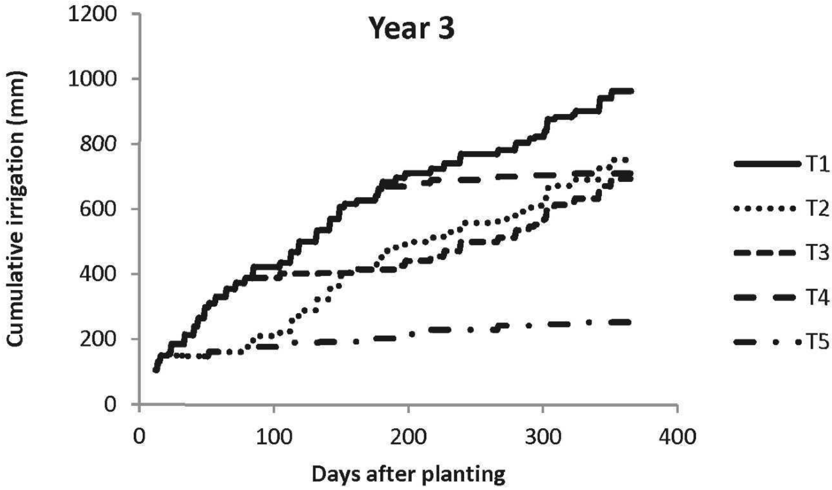

FIGURE 10c. Cumulative irrigation water for different treatments during Year 3.

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.

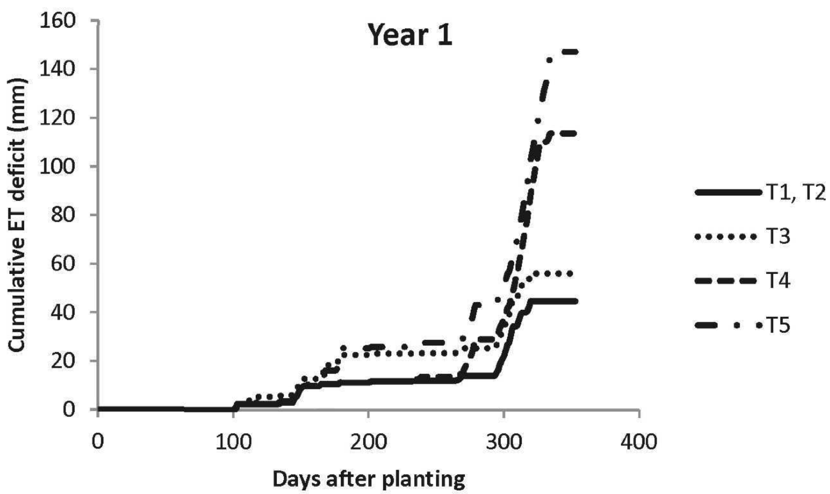

FIGURE 11a. Cumulative evapotranspiration deficits for different treatments in Year 1.

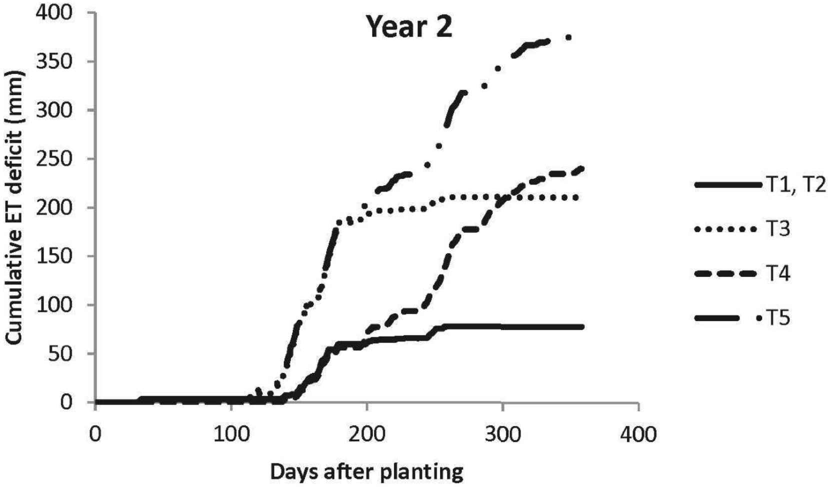

FIGURE 11b. Cumulative evapotranspiration deficits for different treatments in Year 2.

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-

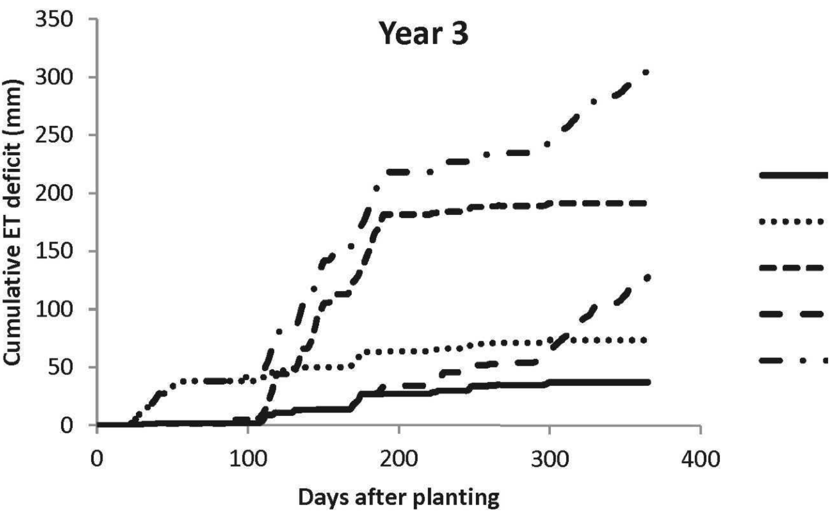

FIGURE 11c. Cumulative evapotranspiration deficits for different treatments in Year 3.

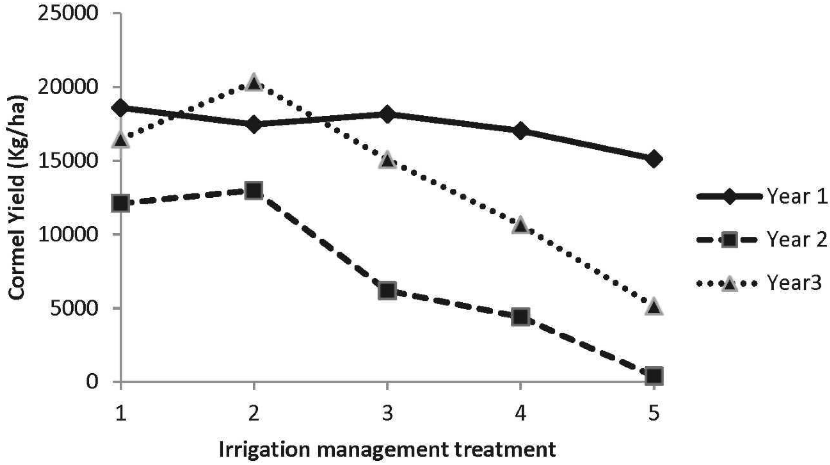

FIGURE 12. Mean yields of marketable cormels for each irrigation management program and year.

ing 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

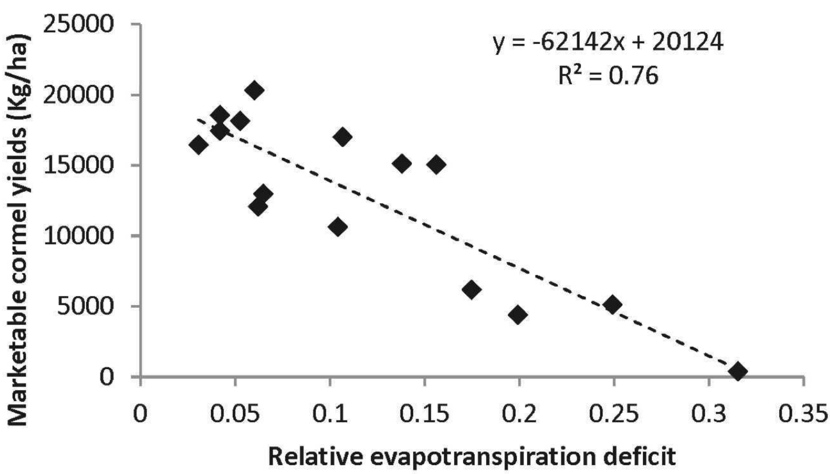

FIGURE 13. Crop yield as a function of relative evapotranspiration deficit (RETD).

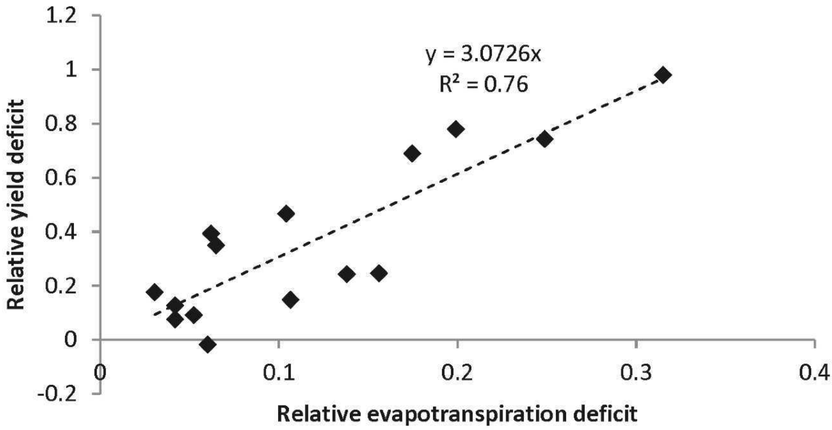

FIGURE 14. Relative yield deficit (RYD) as a function of relative evapotranspiration deficit (RETD).

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

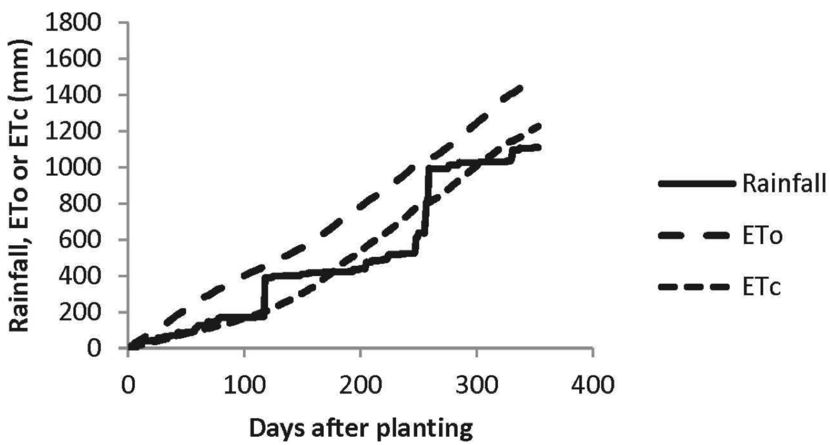

FIGURE 15. Cumulative rainfall, ET_o and ET_c for the experiment at Juana Díaz.

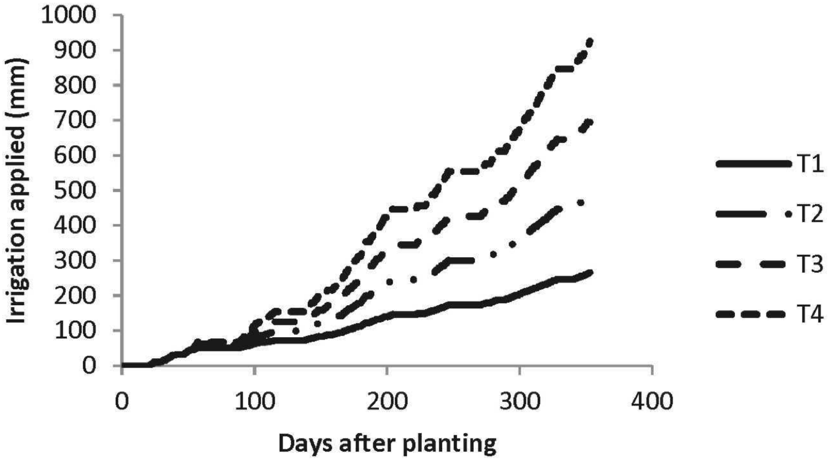

Figure 16. Cumulative amounts of irrigation water applied in experimental treatments at Juana Díaz, Puerto Rico.

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-

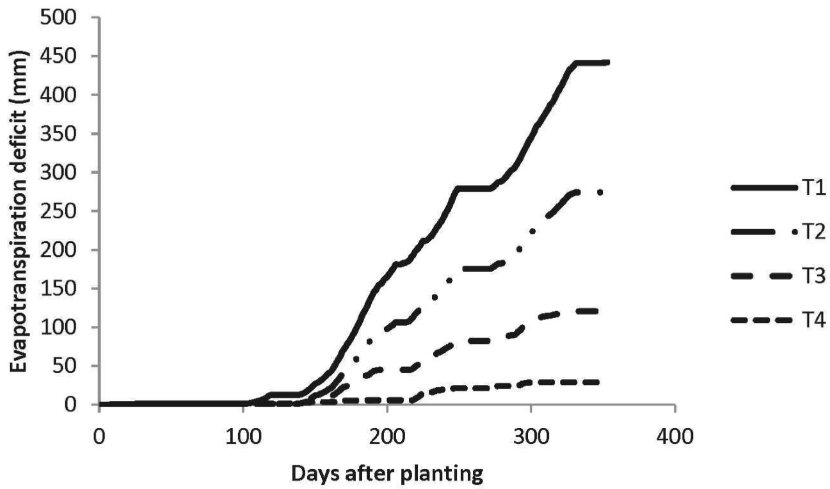

Figure 17. Cumulative evapotranspiration deficits for irrigation treatments at Juana Díaz, Puerto Rico.

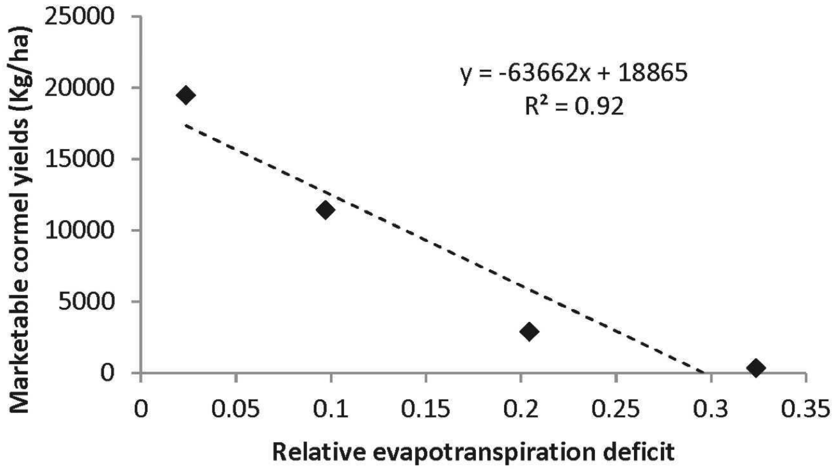

FIGURE 18. Linear regression of cormel yields as a function of relative evapotranspiration deficit at Juana Díaz, Puerto Rico, considering all irrigation treatments.

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

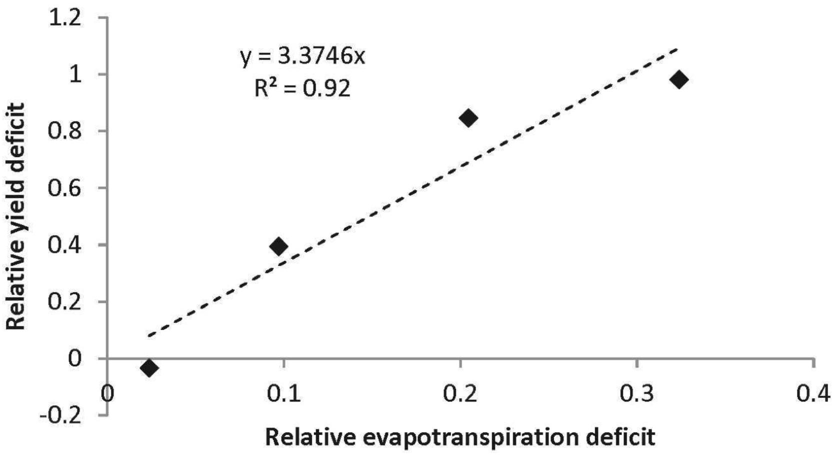

FIGURE 19. Linear regression of relative yield deficit as a function of relative evapotranspiration deficit at Juana Díaz, Puerto Rico, considering all irrigation treatments.

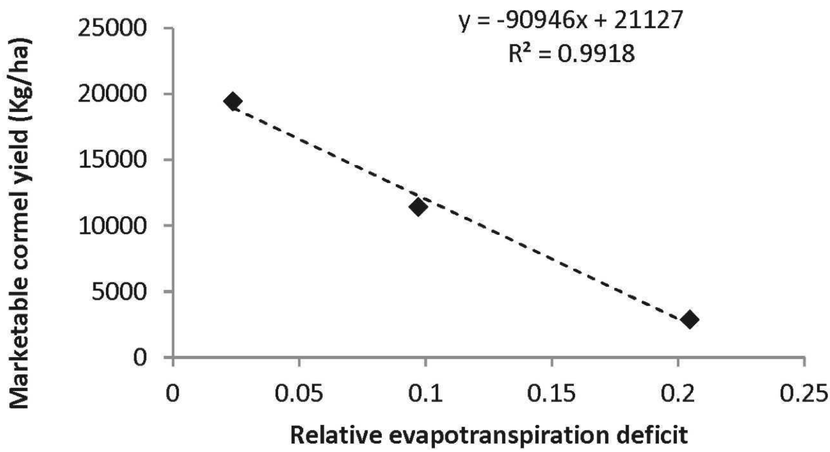

FIGURE 20. Cormel yields as a function of relative evapotranspiration deficit at Juana Díaz, Puerto Rico, considering only the three highest irrigation treatments.

necessarily render it statistically insignificant, since each data point represents the mean of five replications. The estimated K_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.

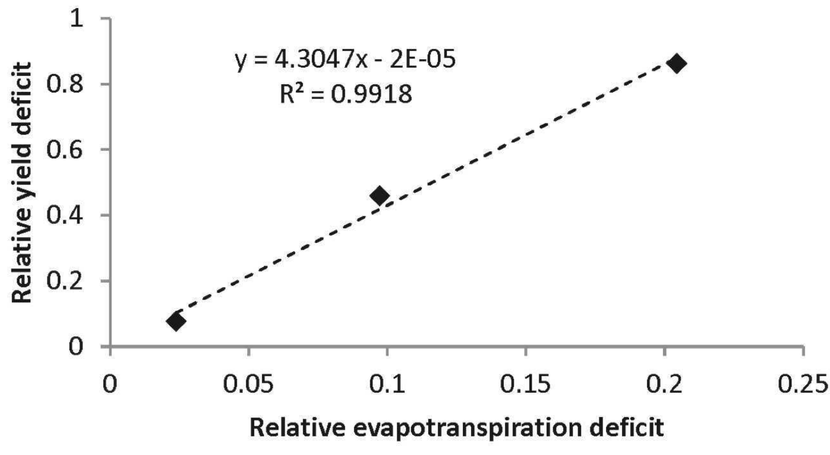

FIGURE 21. Relative yield deficit as a function of relative evapotranspiration deficit at Juana Díaz, Puerto Rico, considering only the three highest irrigation treatments.

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_a. 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-

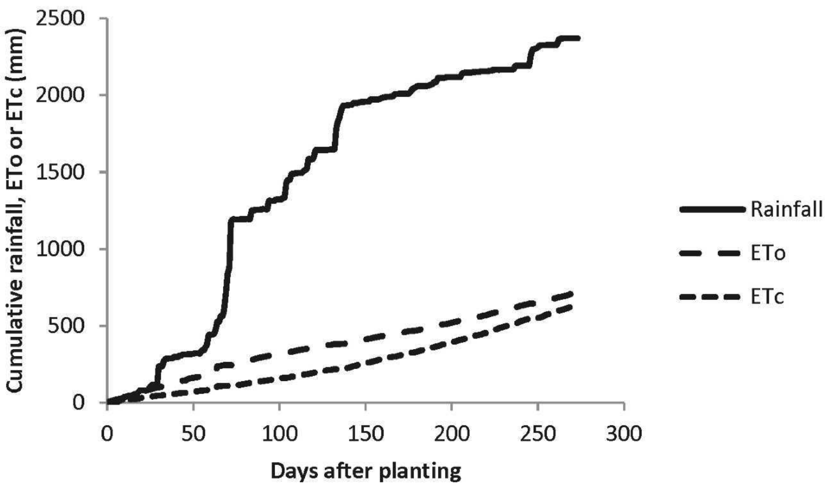

FIGURE 22. Cumulative rainfall, ET_o and ET_c for the Gurabo, Puerto Rico, experiment.

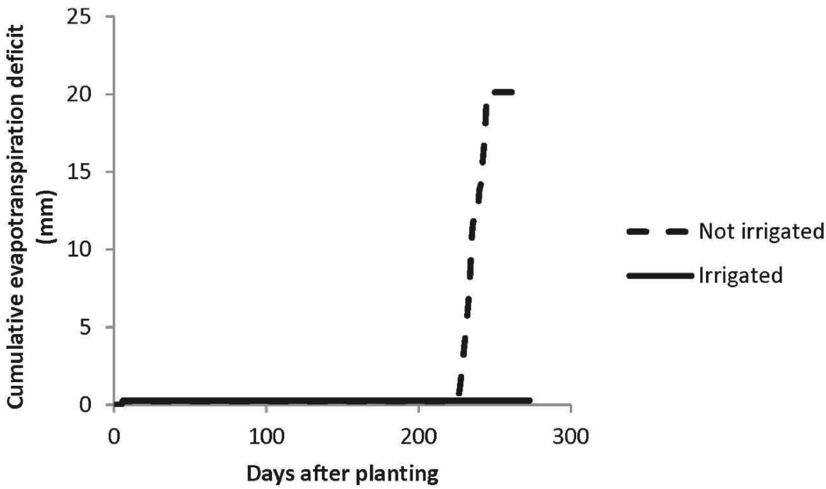

FIGURE 23. Cumulative evapotranspiration deficit for the Gurabo, Puerto Rico, experiment.

mately 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

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

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

$$\binom{n}{s} \equiv \frac{n!}{s!(n\text{-}s)!} \qquad [11]$$

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 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_y 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)

Cultivar	*Irrigated yields*	*Non-irrigated yields*	*RYD*	K_y
Blanca del Pais	17.8	13.9	0.22	4.9
Choubutton	14.9	13.3	0.11	2.4
Drearies	14.8	13.4	0.10	2.1
Kelly	14.6	12.8	0.12	2.7
Rascana	14.3	10.6	0.26	5.6
Viequera	14.1	9.6	0.32	7.1
Charanelle	13.3	12.6	0.05	1.2
Vinola	13.2	10.2	0.23	5.1
Morada	12.7	10.3	0.19	4.2
Bisley	11.4	9.8	0.14	3.2
Inglesa	11.1	8.1	0.27	6.0
Barbados	10.5	7.8	0.26	5.7
Average of means	*13.6*	*11.0*	*0.19 ± 05*	*4.2*

mean irrigated yield for each cultivar could be taken as Y_{max}. The RETD value corresponding to non-irrigated yield Y_a 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).*

Parameters assumed in water balance model	*Isabela*	*Fortuna* (all treatments)	*Fortuna* (highest irrigation treatments)	*Gurabo*
D = 50 cm, p = 0.5	3.1	3.4	4.3	4.2
D = 30 cm, p = 0.7	2.4	2.7	3.3	3.0

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

Abruña, F., J. Vicente-Chandler, E. Boneta and S. Silva, 1967. Experiments on tanier production with conservation in Puerto Rico's mountain region. *J. Agric. Univ. P.R.* 51:167-175.

Agricultural Experiment Station Staff, 1997. Technological package for the production of roots and tubers (in Spanish). Univ. of P.R. Ag. Exp. Sta. Pub. No. 101. 34 pp.

Allen, R. G., L. S. Pereira, D. Raes and M. Smith, 1998. Crop evapotranspiration. FAO Irrigation and Drainage Paper 56, FAO, Rome. 300 pp.

Bury, K., 1999. Statistical Distributions in Engineering. Cambridge University Press.

Cortés, M. and L. Gayol, 2010. Root and Tuber Crops. *In* Cortés, M. and L. Gayol (eds.) Agricultural Commodities. Situation and Perspectives, 2005-2008. University of Puerto Rico Agricultural Experiment Station (in Spanish). 116 pp.

Doorenbos, J. and W. O. Pruitt, 1977. Crop water requirements. FAO Irrigation and Drainage Paper 24, FAO, Rome. 144 pp.

Doorenbos, J. and A. H. Kassam, 1979. Yield response to water. FAO Irrigation and Drainage Paper 33, FAO, Rome. 193 pp.

Goenaga, R. and U. Chardón, 1993. Nutrient uptake, growth and yield performance of three tanier (*Xanthosoma* spp.) cultivars grown under intensive management. *J. Agric. Univ. P.R.* 77:1-10.

Goenaga, R., 1994a. Partitioning of dry matter in tanier (*Xanthosoma* spp.) irrigated with fractions of evapotranspiration. *Ann. Botany* 73:257-261.

Goenaga, R., 1994b. Growth, nutrient uptake and yield of tanier (*Xanthosoma* spp.) grown under semi-arid conditions. *J. Agric. Univ. P.R.* 78:87-98.

Harmsen, E. W., A. González-Pérez and A. Winter, 2004. Re-evaluation of pan evaporation coefficients at seven locations of Puerto Rico. *J. Agric. Univ. P.R.* 88:109-122.

Irizarry, H., M. Capiel and A. Acosta Matienzo, 1977. Yield of twelve tanier cultivars grown with and without irrigation in east-central Puerto Rico. *J. Agric. Univ. P.R.* 61:100-105.

Lugo-Mercado, H. M., J. Badillo-Feliciano and J. López-García, 1978. Effect of soil compaction on tanier yields. *J. Agric. Univ. P.R.* 62:56-63.

Lugo, W. I., H. M. Lugo, J. Badillo, A. Beale, M. Santiago and L. E. Rivera, 1987. Response of taniers to different water regimes. *Proc. Caribbean Food Crops Soc.*, Antigua, 1987, pp 113-117.

Mount, H. R. and W. C. Lynn, 2004. Soil survey laboratory data and soil descriptions for some soils of Puerto Rico and the Virgin Islands. United States Department of Agriculture, Natural Resources Conservation Service, Soil Survey Investigations Report No. 49. 695 pp.

Onwueme, I. C., 1978. The tropical tuber crops. Wiley, New York. 234 pp.

Soil Survey Staff, 1967. Soil survey laboratory data and descriptions for some soils of Puerto Rico and the Virgin Islands. United States Department of Agriculture, Soil Conservation Service, Soil Survey Investigations Report No. 12. 191 pp.

Snyder, V. A., 1994. Plant stresses associated with soil structure. *In*: Davenport, T. L. and H. M. Harrington (eds.). Plant Stress in the Tropical Environment. Proc. CBAG-PBAG Workshop on Plant Stresses in the Environment, Kona, Hawaii, September 20-25, 1992, pp. 34-40.

Snyder, V. A., W. I. Lugo, E. Acevedo and M. A. Vázquez, 1995. Development and validation of a water stress subroutine for the aroid model. Final Research Project Report for CBAG Project PR-50, Agricultural Experiment Station, University of Puerto Rico. 15 pp.

Steduto, P., T. C. Hsiao, E. Fereres and D. Raes, 2012. Crop yield response to water. FAO Irrigation and Drainage paper No. 66. FAO, Rome. 500 pp.