Determining of Crop Coefficients for Horticultural Crops in Cuba through Field Experiments and Water Balance Simulation

Determinación de coeficientes de cultivo para cultivos hortícola en Cuba, a través de la simulación de balance hídrico y experimentos de campo

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ABSTRACT. Proper management of irrigation water provides an optimal balance. With this objective the water balance simulation model ISAREG was calibrated and validated for micro-sprinkler irrigated sweet pepper, garlic, onion, cabbage and carrots, using field observations performed in the Irrigation Station of Alquizar, south of Havana. Model calibration and validation were performed using two independent data sets for each crop. The calibration referred to the crop coefficients (K_c) and the soil water depletion factor for no stress (p) and to the soil hydraulic properties of a Red Ferralitic compacted soil. The calibration procedure consisted of adjusting first the soil properties and then, through an iterative procedure, to determine the K_c and p values that minimize the differences between observed and simulated soil water content along the crop season. The model validation was performed using the calibrated K_c and p with a different climate and crop data sets. The following indicators of goodness of fitting were used to assess model calibration and validation: regression coefficient forced to the origin (b), determination coefficient (R^2), root mean square error (*RMSE*) and average absolute error (*AAE*). Results show a good agreement between field observations and model predictions, with b close to 1,0; R^2 ranging 0,84–0,95 for the calibration and 0,78-0,90 for the validation for all the five crops. The *RMSE* and *AAE* are small. *RMSE* ranged 0,97–2,08 mm for the calibration and 1,07 to 2,82 mm for the validation. The K_c and p values are in the range suggested in FAO 56. Results allow to further use the ISAREG model to define alternative irrigation schedules and to generate those that may provide for improved water productivity in Cuba.

Keywords: good irrigation, calibrated, validated, vegetables.

RESUMEN. Un manejo adecuado del riego proporciona un balance hídrico óptimo. Con este objetivo se simuló el balance hídrico con el modelo ISAREG el cuál fue calibrado y validado con las observaciones de campo obtenidas en la Estación de Riego de Alquízar al sur de La Habana en los cultivos pimiento, ajo cebolla, col y zanahoria utilizando riego localizado (microaspersión). La calibración y validación del modelo fue obtenida, usando dos series de datos independientes para cada cultivo. La calibración obtenida es referida a los coeficientes de cultivo (Kc), fracción de agotamiento del suelo (p) y propiedades hidráulicas del suelo en suelos Ferralíticos Rojos compactados. El procedimiento empleado consistió en ajustar primeramente las propiedades del suelo siguiendo un procedimiento interactivo para determinar valores de Kc y p que minimizaran las diferencias en el contenido de agua en el suelo, entre los valores observados y simulados durante el ciclo del cultivo. Los siguientes indicadores de ajuste y eficiencia de la validación fueron empleados para asegurar la calibración y validación del modelo: coeficiente de regresión forzado del original (b), coeficiente de determinación (R^2), error cuadrático medio (RMSE) y error absoluto medio (AAE). Los resultados muestran un buen ajuste entre los valores observados en observaciones de campo y las predicciones del modelo, con valores de b cercanos a 1,0; R^2 en el rango de 0,84-0,95 para la calibración y 0,78-0,90 para la validación en todos los cultivos. El RMSE y AAE son pequeños, con valores de RMSE en el rango entre 0,97-2,08 mm para la calibración y 1,07–2,82 mm para la validación. Los valores de Kc y

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p en el rango sugeridos en el FAO 56. Dichos resultados permiten utilizar el modelo ISAREG como alternativa viable en la programación de riego y con esto incrementar la productividad del agua en Cuba.

Palabras clave: prácticas de riego, calibrado, simulado, vegetables

INTRODUCTION

Vegetables are one of the most highly consumed crops in Cuba. Thus, large extensions of land are cultivated to overcome demand. These crops have a high nutrient value for human consumption due to its mineral and vitamins concentration that are essential for a well balanced human diet. According to Depestre (2002) vegetables are becoming more important in Cuba due to the need of diversification within a balanced diet. However, there is the need of breeding new crop varieties, which are more adequate to its multiple uses and to the increase its commercial quality, however production should be sustainable in the long-term. Vegetables are usually cropped, in Cuba, during the dry season. During this season precipitation represents 25% of the total annually amount. Thus, it is insufficient to cope with vegetables water requirements and therefore irrigation is mandatory. Usually the schedules are made using high frequency and small irrigation depths in order to provide for a soil water content of approximately 75% of soil capacity. It is therefore important to study improved vegetables irrigation schedules for water management and conservation.

The use of mathematical models for computing soil water balance, after properly calibrated and validated for the different conditions, have presented good results and are considered a useful tool for irrigation water management (Pereira *et al*., 2003, López *et al.,* 2008). The ISAREG model is an irrigation scheduling simulation model that performs the soil water balance at field level and simulates alternative irrigation schedules (Teixeira and Pereira, 1992; Liu *et al*. 1998). The model also allows assessing the impacts of the irrigation schedules on crop production. This model was selected for the present study since it has been used World-wide for a variety of crops and environments (Oweis *et al.,* 2003; Zairi *et al*., 2003; Liu *et al*., 1998, 2006; Victoria *et al*., 2005; Cancela *et al*., 2006; Popova *et al*., 2006b; Cholpankulov *et al*., 2008).

The following vegetables were selected for this study: garlic (*Allium sativum* L. var. santic spirítus), onion (*Allium cepa* L. var. red creole), cabbage (*Brassica olenacea* L. var. hércules), sweet pepper (*Capsicum annuum* L. var. california) and carrots (*Daucus carota* L. var. chantenay). Few research results have been published on improvement of irrigation management of the selected vegetables (*e.g.* Tiwari *et al*., 2003; Zamora *et al*., 2004; Villalobos *et al*., 2004; Zavadil, 2006; Kifler *et al*., 2008; Chaterlán *et al*., 2008; Bossie *et al*., 2009; López-Urrea *et al*., 2009; Piccinni *et al*., 2009; Sahin *et al*., 2009).

The objectives of the study are to determine the crop coefficients and the soil water depletion factor for no stress (*p*) adapted to the climatic and soil conditions of the experimental site located in the Irrigation Station of Alquízar, South Havana. Furthermore, to provide a useful tool that allows developing irrigation management alternatives for the considered crops.

MATERIALS AND METHODS

The ISAREG model

The ISAREG model is an irrigation scheduling simulation model that performs the soil water balance in the root zone (Teixeira and Pereira, 1992; Liu *et al*., 1998). Input data include precipitation, reference evapotranspiration, total and readily available soil water, soil water content at planting, potential groundwater contribution, crop coefficients and soil water depletion fractions for no-stress relative to defined crop growth stages, root depths and the water-yield response factor. The water balance is performed for various time-step computations depending on weather data availability.

The model computes the potential crop evapotranspiration $ET_c = K_c \cdot ET_o$ from the reference evapotranspiration (ET_o, mm) and the crop coefficients (K_c). The actual evapotranspiration (ET_a, mm) is computed by the model as a function of the available soil water in the root zone: $ET_a = ET_c$ when depletion is smaller than the depletion fraction for no stress (*p*), otherwise $ET_a < ET_c$ and decreases as a function of the available water stored in the root zone. K_c and *p* should therefore be calibrated together when the model is tested by comparing computed and observed soil water content values.

The model windows version, WinISAREG (Pereira *et al*., 2003), was used in the present study. This version of the model allows computing the reference evapotranspiration using the FAO-PM approach (Allen *et al*., 1998). It is also included an algorithm to consider soil salinity impacts on ET_c and yield (Pereira *et al*., 2003) and parametric functions for computation of the groundwater contribution and percolation (Liu *et al*., 2006). The water stress impacts on crop yields are evaluated by estimating the relative yield losses as a function of the relative evapotranspiration deficit through the water-yield response factor K_y (Stewart *et al*., 1977).

The model input data includes: *meteorological data* concerning precipitation, P (mm), reference evapotranspiration, □□$_o$ (mm), or weather data to compute □□$_o$ with the FAO-PM methodology, including alternative computation methods for missing climate data (Allen *et al*., 1998), wind speed ($m \cdot s^{-1}$ or $km \cdot h^{-1}$) and minimum relative humidity (%); *crop data* referring to dates of crop development stages, crop coefficients (K_c); root zone depths Z_r (m); soil water depletion fractions for no-stress (□) for each development stage; and the seasonal water-yield response factor ($K_□$); *soil data for a multi-layer soil* relative to each layer, the respective depth *d* (m); the soil water content at field capacity θ_{FC} ($m^3 \cdot m^{-3}$) and the wilting point θ_{WP} ($m^3 \cdot m^{-3}$), or the total available water (*TAW*, $mm \cdot m^{-1}$); the model also allows to compute the total evaporable water (*TEW*, mm), and the readily evaporable water (*REW*, mm) characterizing the evaporable layer (depth,% sand and clay). An additional file is used to compute the groundwater contribution and percolation using parameterised equations or using known values of groundwater contribution at specific dates; the initial available soil water (*ASW*, mm) is provided by the user.

Experimental site characterization

Field data observations for the considered crops were formerly performed in experimental studies carried out during the 80s and 90s at the Irrigation Station of Alquizar, situated at south of Havana, Cuba. The weather data were observed at the local meteorological station (Latitude 22 46' N; Longitude 82 37'W and altitude 6 m).

Daily data observations for the period 1985-1998 included temperature, precipitation, relative humidity and wind speed observed at 2 m height. The maximum temperature occurs in July-August and the minimum by January. However, the thermal annual and daily variations are very low. The precipitation occurs mainly during the period May to October (rainy season) representing 70% of the annual precipitation. The monthly average precipitation varies within 50-200 mm; and the average annual precipitation is 1 490 mm. The climatic characterization of the experimental site is given in Figure 1. Figure 1 shows that during the dry season the balance between precipitation and ET_o is negative thus irrigation is needed in order to get appropriated productions specially in what concerns vegetables crops.

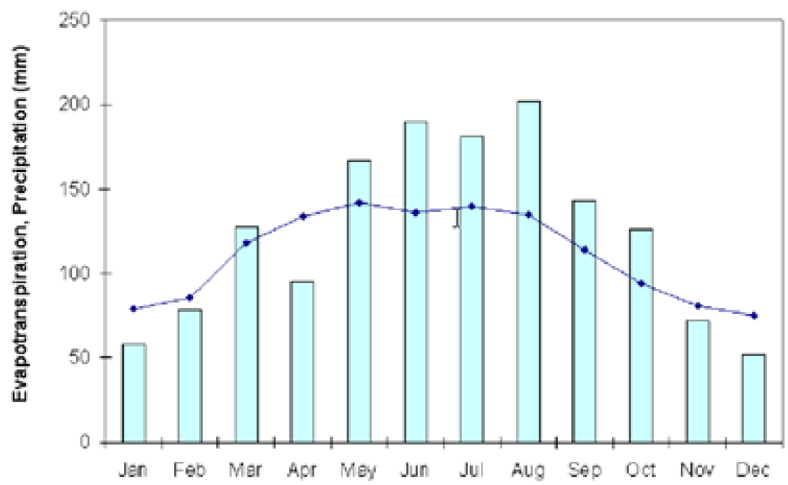

FIGURE 1. Climatic characteristics of the experimental site for the period 1985-1998: average monthly precipitation (▭) and reference evapotranspiration (ET_o) (—•—).

The reference evapotranspiration (ET_o) was computed using the FAO-PM methodology when limited data is available as proposed by Allen *et al*. (1998). In the present study the global radiation data was unavailable and therefore the solar radiation was estimated using maximum and minimum temperatures the procedures are well described in the study by Popova *et al*. (2006a).

The main soils in the Irrigation Station of Alquizar are Red Ferralitic compacted soil or Rhodic Ferralsol according to the FAO/UNESCO classification (Instituto de Suelos, 1996a, b) and usually have 1 m depth. The unsaturated soil hydraulic properties were determined from an appropriate survey and using laboratory methods for the full range of soil water tension. The weighed average values are field capacity, $\theta\theta_{FC}$ = 0,43 $m^3 \cdot m^{-3}$; wilting point, $\theta\ \theta_{WP}$ = 0,29 $m^3 \cdot m^{-3}$; and the total available water, *TAW* = 146 mm m^{-1}.

In all cases studied the crops were irrigated using a micro-sprinkler irrigation system. The irrigation events were determined to be performed whenever 85% of the soil water content at field capacity was reached. The total irrigation depths ranged 152-194 mm for garlic, 170-194 mm for onion, 121-136 mm for cabbage, 192-240 mm for sweet pepper and 179-240 mm for carrots.

Observations of the soil water content were performed with a 10 day frequency during the crops growing seasons. Measurements were made using the gravimetric method until 0,3 m except for the case of sweet pepper that reached 0,4 m soil depth.

Calibration and validation procedures

Observations formerly performed for sweet pepper, garlic, onion, cabbage and carrots crop fields were used to calibrate and validate the ISAREG model for the experimental site conditions and for the derivation of the crop coefficients and depletion fractions for no stress to be used in further studies. Two independent data sets were used respectively for the calibration and validation procedures.

The calibration consisted in searching the crop coefficients and depletion fractions for no stress for the different crop development stages that allowed minimizing the differences between simulated and observed values of the soil water content. The K_c and *p* values initially used for the interactive process were the ones reported when the experiments occurred. For the validation the K_c and p values used are the ones that were obtained for the calibration. Further description of the procedures is described by Popova *et al*. (2006b).

Goodness of the model simulations

In order to assess the goodness of the WinISAREG model predictions qualitative and statistical strategies were used. The first one consisted in representing in a graph the comparison between the soil water content values observed at field and the values simulated by the model. This allows having a good perception of the trends or of the bias in the modeling whenever they occur. The second one is the regression forced to the origin between observed and predicted values. In this case if the regression coefficient (*b*) is close to 1 then the covariance is close to the variance of the observed values which means that the predicted and observed values are statistically close; if the determination coefficient (R^2) is also close to 1.0, then almost the entire variation of the observed values is explained by the model. Additionally, two indicators of residual estimation errors were used the *RMSE* and the *ARE*. The selected indicators are based upon former applications (Loague and Green, 1991; Liu *et al*., 1998; Legates and McCabe, 1999; Tolk and Howell, 2001; Cholpankulov *et al*., 2008).

The goodness of fitting may be assessed through the indicators listed bellow; were X_i [mm] and Y_i (i = 1, 2, n) [mm] are the pairs of observed and model predicted values of a given variable and $\bar{X}$ and $\bar{Y}$ are the respective mean values, then:

- Regression and determination coefficients relating observed and simulated data, *b* (when regression is forced to the origin) and R^2 respectively:

$$b = \frac{\sum_{i=1}^{n} X_i \times Y_i}{\sum_{i=1}^{n} X_i^2} \qquad (1)$$

$$R^2 = \left\{ \frac{\sum_{i=1}^{n}\left(X_i - \bar{X}\right)\left(Y_i - \bar{Y}\right)}{\left[\sum_{i=1}^{n}\left(X_i - \bar{X}\right)^2\right]^{0.5}\left[\sum_{i=1}^{n}\left(Y_i - \bar{Y}\right)^2\right]^{0.5}} \right\}^2 \qquad (2)$$

- Root Mean Square Error [mm], which characterizes the variance of the errors

$$RMSE = \left[\frac{\sum_{i=1}^{n}\left(Y_i - X_i\right)^2}{n} \right]^{0.5} \qquad (3)$$

- Average absolute error [mm], which expresses the size of estimation errors in alternative to *RMSE*:

$$AAE = \frac{1}{n}\sum_{i=1}^{n}\left|X_i - Y_i\right| \qquad (4)$$

RESULTS AND DISCUSSION

The crops parameters obtained from the calibration are presented in Table 1 together with the dates of the crop growth stages.

TABLE 1. Calibrated crop coefficients (K_c) and depletion fractions for no stress (*p*), and dates of crops growth stages for the calibration and validation experiments, La Havana

	Crop growth stages			
	Initial	**Development**	**Mid season**	**End season**
Garlic				
Crop coefficients, K_c	0,70	0,70-0,83	0,83	0,75
Depletion fraction, *p*	0,30	0,30	0,30	0,30
Period length (dates)				
Calibration (1993-94)	04/12-24/12	25/12-28/01	29/01-09/03	10/03-08/04
Validation (1985-86)	23/12-12/01	13/01-16/02	17/02-27/03	28/03-26/04
Onion				
Crop coefficients, K_c	0,40	0,40-1,04	1,04	0,45
Depletion fraction, *p*	0,30	0,30-0,60	0,30-0,60	0,60
Period length (dates)				
Calibration (1997-98)	20/11-20/12	21/12-29/01	30/01-20/03	21/03-17/04
Validation (1996-97)	25/12-24/01	25/01-05/03	06/03-24/04	25/04-24/05
Cabbage				
Crop coefficients, K_c	0,65	0,65-1,05	1,05	0,95
Depletion fraction, *p*	0,40	0,40	0,40	0,40
Period length (dates)				
Calibration (1988-89)	15/12-25/12	26/12-14/01	15/01-13/02	14/02-06/03
Validation (1986-87)	19/12-29/12	30/12-20/01	21/01-19/02	20/02-11/03
Sweet pepper				

	Crop growth stages Initial	Development	Mid season	End season
Crop coefficients, K_c	0,80	0,80-1,22	1,22	0,62
Depletion fraction, p	0,40	0,40	0,40	0,40
Period length (dates)				
Calibration (1991-92)	16/12-20/01	21/01-19/02	20/02-14/03	15/03-18/04
Validation (1987-88)	05/12-09/01	10/01-08/02	09/02-04/03	05/03-07/04
Carrots				
Crop coefficients, K_c	0,55	0,55-0,96	0,96	0,80
Depletion fraction, p	0,30	0,30	0,30	0,30
Period length (dates)				
Calibration (1988-89)	22/11-08/12	09/12-17/01	18/01-11/02	12/02-11/03
Validation (1992-93)	20/11-04/12	05/12-11/01	12/01-30/01	31/01-16/02

The $K_{c\ ini}$ values for all studied crops are relatively lower than those proposed by Allen *et al.* (1998) because of the climatic conditions during the initial period. However, they are higher than those results presented by Zamora *et al.* (2004) for the same climatic conditions. The $K_{c\ mid}$ are similar for the case of onion and cabbage to those recommended by Allen *et al.* (1998); however, they are lower for garlic and carrots and higher for sweet pepper. The same patter occurs when comparing with the results by Zamora *et al.* (2004). $K_{c\ end}$ values are lower than those recommended by Allen *et al.* (1998) except for the case of garlic.

The depletion fractions p are higher than those proposed by Allen *et al.* (1998) for onion and sweet pepper this relate to the varieties used, which were developed aiming at controlling the development of above ground biomass and favour harvestable yield. For the case of cabbage and carrots p values are lower.

An example of the results of comparing the simulated with observed available soil water for the calibration and validation years for carrots is given in Figure 2. Results show a good agreement between observed and computed available soil water, which is confirmed by the parameters used to evaluate the goodness of fitting (Table 2). Results show that the regression coefficients are close to 1,0 for all crops in both the calibration and validation years. R^2 values range 0,79 to 0,96, thus indicating that a large fraction of the variation of observations is explained by the model. The *RMSE* are small, close to 2 mm, and *AAE* ranged from 0.77 to 2.34 mm. All indicators express the ability of the model to predict the available soil water for micro-sprinkled irrigated vegetables. Therefore, the model maybe used for generating alternative irrigation schedules aiming at improving vegetables water productivity in the south of Havana.

TABLE 2. Results of goodness of fitting parameters relative to model calibration and validation for horticultural crops, Cuba120

	b	R^2	RMSE (mm)	AAE (mm)		b	R^2	RMSE (mm)	AAE (mm)
Garlic					Sweet pepper				
Calibration	1,03	0,95	1,35	1,02	Calibration	0,99	0,92	2,05	1,41
Validation	1,06	0,94	1,72	1,15	Validation	1,07	0,83	2,82	2,34
Onion					Carrots				
Calibration	1,03	0,93	2,08	1,47	Calibration	0,99	0,92	0,97	0,78
Validation	1,03	0,90	1,95	1,70	Validation	1,00	0,80	1,07	0,77
Cabbage									
Calibration	1,07	0,96	1,74	1,67					
Validation	1,07	0,94	1,99	1,35					

CONCLUSIONS

- The ISAREG model was successfully calibrated and validated using past observations of available soil water for micro-sprinkler irrigated sweet pepper, garlic, onion, cabbage and carrots. The analysis shows that using past experimental data for updated modelling is appropriate and produces valuable information. Results for all experiments that the regression coefficients relating simulated and observed values were close to 1,0 and the determination coefficients were higher than 0,80. The estimated errors indicators (*RMSE, AAE*) show very good results for both calibration and validation (0,77-2,82 mm). Therefore, it can be concluded that the studies produced good estimates of the crop coefficients and depletion fractions for no stress. Further developments will include the design of improved irrigation strategies for improving water productivity and savings.

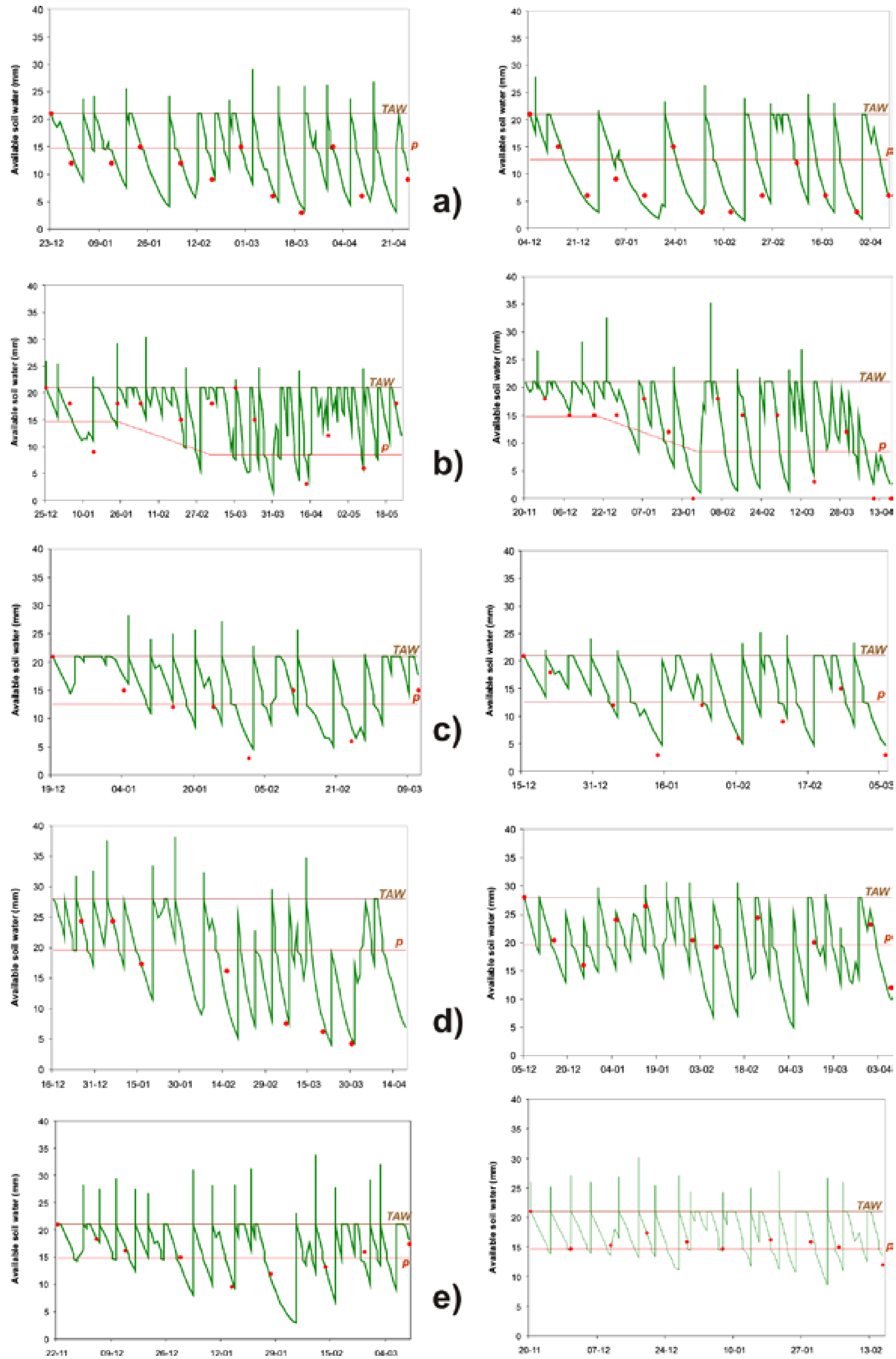

FIGURE 2. Comparison between observed (●) and simulated (——) available soil water content values at the Irrigation Station of Alquízar, Cuba. On the left the calibration and on right the validation for the following crops: a) garlic; b) onion; c) cabbage; d) sweet pepper; and e) carrots.

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