

Regional mechanistic estimations of sugar-cane water use

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Abstract The application of a sugar-cane model, evolved from the mechanistic model SWAP, in the assessment of the sugar-cane water use and yields in Havana Province is shown. The model was interfaced to the GIS ILWIS in order to produce regional results. The soil hydraulic properties of all the sugar-cane cropping areas in the province were calculated through pedotransfer functions using available information from a 1:25 000 soil map. The daily values of the modified Penman evapotranspiration (ETP) were considered as the top boundary condition in the simulations. Free drainage was assumed as the bottom boundary condition of the 2-m layer. A weather generator was used to generate 50 years of daily rainfall and maximum ETP records. Site-specific assessments of water effects on sugar-cane yields were carried out, as well as water-management recommendations for each location. The present results can be used as a methodological guide for recommending the sugar-cane water management in any other part of the world.

Key words mechanistic modelling; sugar-cane; crop water use; GIS; weather generator; Havana Province, Cuba

INTRODUCTION

Sugar-cane grows only in tropical regions and is often cropped under rainfed conditions, owing to financial problems in the establishment of irrigation. Rainfall is seasonally distributed in the tropics, hence the effects of climate variability on sugar-cane growing are very important. Accordingly, the use of crop modelling combined with a climate forecast could be an effective aid for sugar-cane farmers and decision makers in selecting the seeding date and in water management. In particular, mechanistic models, i.e. those based on the Richards equation for calculating soil water flow, can simulate capillary rising, fast and low drainage and several other features that yield accurate simulation results when compared to non-mechanistic models (Gabrielle *et al.*, 1995; Maraux & La Folie, 1998). Mechanistic models, rather than functional models, can account for the effects of excess water on crop growth (Leenhardt *et al.*, 1995).

Unfortunately, local climatic variable series are usually not long enough for assessing climate effects on sugar-cane yields. In such cases, a weather generator could be used to produce a long and site-specific climate series (Semenov & Jamieson, 1999).

Several authors have combined geographical information systems (GIS) with hydrological models (e.g. Zhang *et al.*, 1996; Rosenthal *et al.*, 1998) in order to obtain

spatial results. Moreover, a GIS interface allows the model parameters to be introduced at a detailed scale, which could improve the model results for specific sites.

The aim of this paper is to show a methodology for estimating sugar-cane water use in relatively large regions by combining mechanistic modelling with a weather generator and a GIS.

MATERIALS AND METHODS

The experiment was conducted on the Havana Plain. It is located in the west of Cuba, ranging from Artemisa (22°53'N, 83°14'E) to Nueva Paz (22°41'N, 83°89'E). The climate at the experimental site is characterized by a mean annual precipitation of 1349 mm and a mean annual evaporation (from class "A" pan measurements) of 1977 mm. About 80% of total precipitation falls from April to September. Mean annual temperature is 24.0°C; maximum and minimum daily mean annual temperatures are 29.0 and 18.5°C, respectively.

The mechanistic Soil Water Atmosphere Plant model, SWAP (Van Dam *et al.*, 1997) was used in the present study. The SWAP model is a functional combination of advanced soil water simulation models and a crop-growth simulation code. The Richards equation for soil-water movement is solved in SWAP by a numerical scheme, including different practical options for the initial and boundary conditions. Water effects on crop yields can be estimated in the SWAP model through two different procedures. The simplest procedure is based on the Smith (1992) approach. Relative final yields can be estimated from the equation:

$$1 - \frac{Y_{a,k}}{Y_{p,k}} = K_{y,k} \left(1 - \frac{T_{a,k}}{T_{p,k}} \right) \quad (1)$$

where $Y_{a,k}$ and $Y_{p,k}$ are the actual and potential yields, respectively, for the period k ; $T_{a,k}$ and $T_{p,k}$ are the actual and potential crop transpiration, respectively; and $K_{y,k}$ is a coefficient which depends on both the crop and the crop-growing period, k . Final relative yields are calculated as the product of the relative yields of each growing stage, k .

Ruiz *et al.* (1999) provided all the sugar-cane functions for use in SWAP and other mechanistic models. In addition, an interface between the SWAP model and the GIS ILWIS 2.2 (Integrated Land and Water Information System) was used for the spatially-distributed sugar-cane water-use and yield estimations.

The soil hydraulic properties were calculated using the Rawls *et al.* (1982) as well as the Rawls *et al.* (1998) pedotransfer functions, considering the soil database of the 1:25 000 soil map of Havana. The coefficients of the Van Genuchten (1980) model parameters (α , n , and residual water contents) were estimated using the RETC code (Van Genuchten *et al.*, 1991). The total porosity was assumed as the saturated water content. All this information was introduced in ILWIS as punctual layers and converted in raster layers. The sugar-cane cropping areas of the province were digitized and introduced in ILWIS.

The basic statistics of the estimated soil hydraulic properties are shown in Table 1. According to Carsel & Parrish (1988), the soils of Havana rank from sandy loam to

Table 1 Characteristics of the hydraulic conductivity and the parameters of the van Genuchten model for the soil water retention curve, as well as the bulk density (*BD*), and organic matter content (*OM*).

	Mean	SD	<i>CV</i>	Max.	Min.
θ_s (cm ³ cm ⁻³)	0.58	0.03	5.6	0.64	0.47
θ_r (cm ³ cm ⁻³)	0.12	0.04	33.3	0.27	0.00
α	0.0175	0.0602	344.9	1.0200	0.0085
<i>N</i>	1.736	0.158	9.1	2.147	0.136
<i>BD</i> (g cm ⁻³)	1.13	0.09	7.9	1.43	0.98
<i>OM</i> (%)	2.06	0.91	44.1	5.02	0.72
<i>Ks</i> (cm day ⁻¹)	83.4	46.66	56.0	214.27	0.26

SD: standard deviation; *CV*: coefficient of variation.

Min., Max.: minimum and maximum values.

clay loam. Furthermore, the hydraulic properties show a very high spatial variability, as reported by Warrick & Nielsen (1980).

A daily series of precipitation, maximum, minimum and mean temperatures, wind speed, solar radiation and relative humidity are available from 1987 to 1996, as measured in Guines, south Havana. Daily values of the Penman-Monteith (PM) reference evapotranspiration were computed from this data. The daily basin weather generator GT (Reynaldo *et al.*, 1999) was used for generating 50 years of daily evapotranspiration (ETP) and precipitation records.

Simulations were carried out for rainfed sugar-cane cropping. The emergence date and the harvest date were 1 January and 1 December, respectively, in all cases. Free drainage at the bottom of the soil layer was considered as the bottom boundary condition of the 2-m soil layer.

RESULTS

The raster layers of each soil hydraulic properties were polygon-averaged through a GIS operation. Consequently, average values of each of these properties were obtained for each farm-polygon. Figure 1 depicts the averaged values of the hydraulic

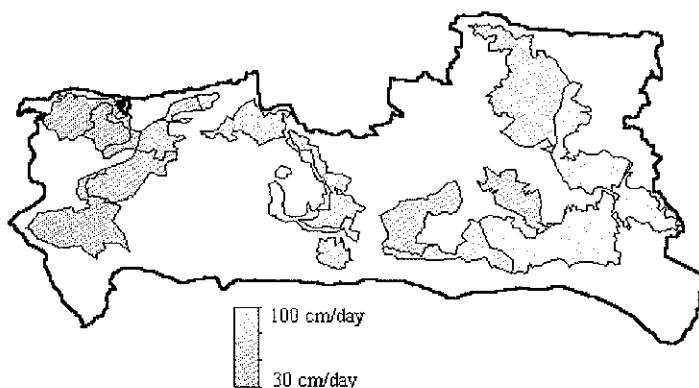


Fig. 1 Average hydraulic conductivity of the sugar-cane farms at Havana Province.

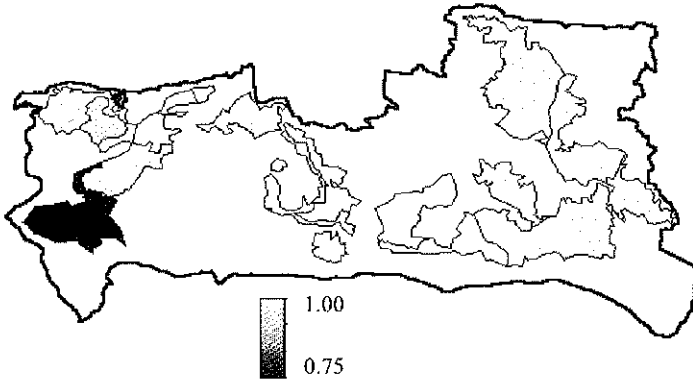


Fig. 2 Mean simulated relative yield, averaged for each sugar-cane farm.

conductivity for each sugar-cane farm. As can be seen from the figure, the farms on the western side of the province show lower K_s rates, compared to the farms located on the eastern side. According to the soil map, the main soil type in the southeastern part of the province is ferralsol. This is a very-well drained soil and hence, on average, sugar-cane farms located in that zone show higher hydraulic conductivity values. Similar dependence on soil distribution was found for the rest of the estimated hydraulic properties.

The mean simulated relative yields, obtained from the 50-year simulations, averaged for each sugar-cane farm, are depicted in Fig. 2. As can be seen in the figure, the sugar-cane farms located in the southwestern part of the province show the lowest estimated yields. Conversely, according to the simulation results, the sugar-cane farms located over ferralsols show the highest yields.

According to the above, Fig. 3 depicts the time behaviour of the simulated relative yield for the sugar-cane farms corresponding to the highest and lowest mean relative

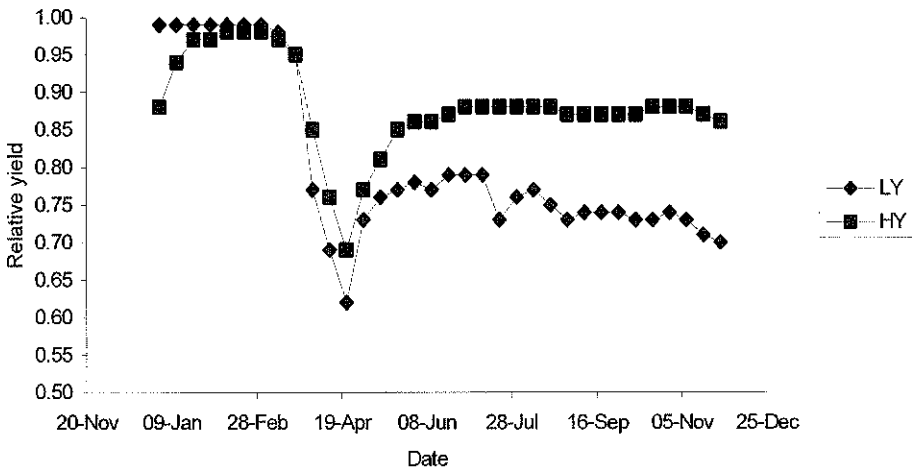


Fig. 3 Relative yields in the farms where higher (HY) and lower (LY) mean relative yields were obtained.

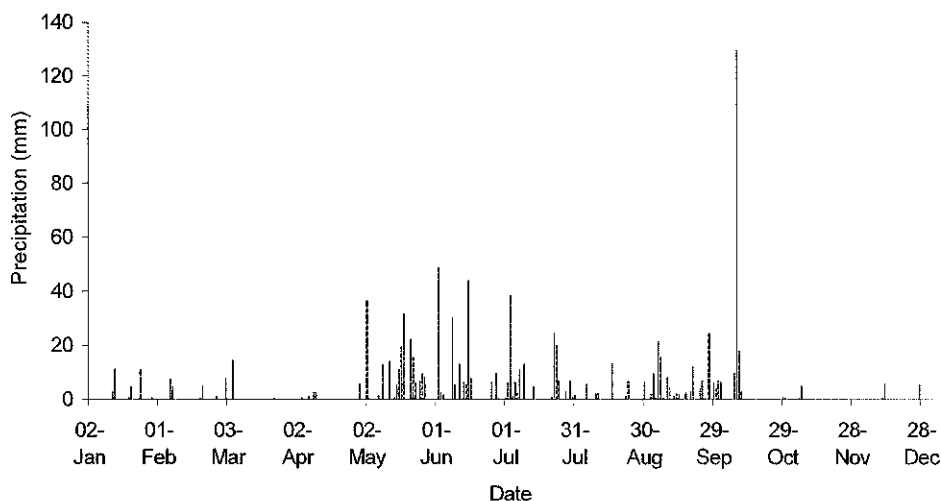


Fig. 4 Recorded precipitations in the extreme-event year where the lowest mean relative yield was obtained.

yields; and for the year corresponding to the lowest yield. In addition, Fig. 4 depicts the precipitation time behaviour in that year. As can be noted by comparing Figs 3 and 4, the rainfall deficits during April in this year (the start of the wet season) gave rise to a significant drop of the relative yields in both the sugar-cane farms. However, according to the simulation results, the final effect of this water stress is higher in one farm than the other.

The simulated water balances for these two sugar-cane farms and for this particular year are shown in Table 2. The simulated water-balance results comprise the ratio between potential and actual (simulated) crop transpiration (RT) and soil evaporation (RE), water flux at the bottom of the simulated layer (WF) and the initial (IW) and final (FW) water storage in the simulated layer. According to the ratios between actual and potential transpiration shown in Table 2, the sugar-cane water requirements are almost completely satisfied in the farm where higher simulated yields were predicted, whereas a relatively significant deficit is predicted for the other farm. Besides, soil evaporation is also higher in the first case. Conversely, the water storage and the simulated initial and final soil water content in the considered soil layer are lower in the farm where higher yields are predicted. Accordingly, the simulated downward water flux in the bottom of the soil layer is considerably lower in the farm of the predicted higher yields. It has been shown that sugar-cane roots are able to extract water from deeper depths than the root-active zone under rainfed conditions,

Table 2 Simulated relative transpiration (RT), relative evaporation (RE), water flux (WF) and initial (IW) and final (FW) water contents in the sugar-cane farms where the lowest and highest mean relative yields were obtained—denoted LY and HY respectively—for the year of the average lowest yield.

Case	RT	RE	WF (mm)	IW	FW
LY	0.73	0.35	296	57.5	58.6
HY	0.91	0.40	164	49.4	47.9

particularly in ferralsols (Rivero, 1985). Hence, according to our simulated results, the sugar-cane farm located in soils of relatively higher hydraulic conductivity rates shows higher sugar-cane yields in rainfed conditions, due to capillary rise. In the other farm the hydraulic conductivity in the top layer is lower, hence the soil evaporation rates are also lower and, conversely, the water flux at the bottom of the considered 2-m soil layer is higher whilst the free drainage condition is met. Therefore, based on this simulated assessment, there is a greater need for irrigation supply in the farms located in the southwestern side of Havana Province than in those located in the southeastern side. Particularly, irrigation should be provided at the beginning of the wet season in those farms, preventing against droughts in this period.

These results are not conclusive and rely on the simulation assumptions and soil hydraulic properties. However, the present methodology, which combines a mechanistic crop modelling, a weather generator and a GIS; could be used in decision making assessments of water effects on rainfed sugar-cane. The accuracy of the simulated results can be improved if a reliable local input is provided to the model. This can be done through the GIS.

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