ASSESSMENT OF THE AQUACROP MODEL IN SIMULATING RAINFED AND SUPPLEMENTALLY IRRIGATED SWEET SORGHUM GROWTH

EVALUATION DU MODELE AQUACROP POUR SIMULER LA CROISSANCE DU SORGHO SUCRE PAR IRRIGATION PLUVIALE ET IRRIGATION D'APPOINT

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ABSTRACT

Crop growth for biofuel production is gaining importance in developed European countries. This trend will unavoidably spread to neighboring countries, and change the cropping pattern in Serbia in the near future. Sweet sorghum, along with rapeseed and miscanthus, will be a crop of great research interest. The goal of the project reported in this paper was to examine the FAO AquaCrop model for the simulation of biomass, yield and evapotranspiration, in order to assess whether sweet sorghum may be grown on marginal soils in different areas without irrigation, or if supplementary irrigation would increase yield to an economically viable level. The results show that the FAO AquaCrop model can simulate evapotranspiration, biomass and yield of sweet sorghum with an index of agreement of 0.91, 0.85 and 0.72, respectively. Statistical parameters indicate that the two years of research with three irrigation treatments were not sufficient to calibrate and validate the model for practical use. More data need to be collected in the field to improve simulation under extreme weather conditions.

Key words: *AquaCrop model, Biofuel, Sweet sorghum, Marginal soil, Serbia.*

RESUME ET CONCLUSIONS

Le sorgho sucré n'est pas largement cultivé en Serbie. Aujourd'hui, de nouvelles technologies agricoles sont recherchées afin d'obtenir une meilleure production de bio-carburant. Dans la

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dernière décennie, un changement soudain des inondations et de la sécheresse ont causé une diminution drastique du rendement de la plupart des grandes cultures cultivées en condition pluviale, ce qui est pratique courante en Serbie. Pour une prédiction rapide de la sécheresse et des conséquences qu'elle entraîne, l'utilisation d'outils modernes tels que les modèles de croissance des cultures qui pourraient donner des résultats rapides et objectifs est souhaitable. Les modèles sont destinés aux décideurs, consultants, ingénieurs d'agronomie et autres utilisateurs qui ont besoin d'informations sur le potentiel de la biomasse et le rendement d'une plante cultivée à différents niveaux hydriques et d'apport d'éléments nutritifs. Dans le cas de la Serbie, les modèles peuvent montrer si le sorgho peut être cultivé sur des sols marginaux dans différents domaines, sans irrigation, ou si des irrigations supplémentaires pourraient augmenter le rendement et le rendre suffisant pour être économiquement justifié. Le nouveau modèle FAO AquaCrop a montré de bons résultats dans la simulation de la croissance et de la biomasse de cultures différentes, par conséquent, le but de cet article est l'utilisation de ce modèle dans la simulation de croissance de sorgho sucré cultivé dans des conditions d' irrigation supplémentaires et dans des conditions sans irrigation.

Les données d'entrée nécessaires pour le modèle de la FAO AquaCrop ont été prélevées sur le site expérimental Becej (47o 37'; de latitude N; 20 ° 02'; de longitude E). Il s'agit d'un climat tempéré avec quatre saisons bien déterminées. Les précipitations mesurées étaient de 245 et de 133 mm durant la période de végétation en 1992 et 1993, respectivement. La profondeur des racines était de 1,85 m. La température moyenne journalière supérieure ŕ 10°C commence le 4 avril et dure jusqu'au 15 octobre. La moyenne annuelle de degrés en jours (avec une température de base 0 °C) est de 3288 °C.

Le sol du site expérimental est représenté comme un sol limoneux, de prairie à horizon mollique profond avec des engrais chimiques favorables, mais avec des propriétés physiques moins favorables. La valeur moyenne de la teneur du sol en eau volumique à la capacité au champs est de 41,2% et au point de flétrissement 23,17%. La densité de plantation a été 150000 à l'hectare. La date de semis a été le 2 mai 1992 et le 5 mai 1993. Dans les deux années, le sorgho à sucre a été cultivé avec 3 traitements d'irrigation différents, l'irrigation complète (FI), l'irrigation déficitaire (DI) et le traitement pluvial (RF).

Pour simuler la croissance du sorgho sucré avec le modèle AquaCrop, le stress de fertilité n'a pas été considéré. La température de stress pour la production de biomasse utilisée est de 11,1 C ° et le stress thermique lors de la pollinisation de 35 à 40 °C. La valeur du coefficient cultural pour la transpiration était de 1,05, le couvert coefficient de croissance de 12,3%. La productivité de l'eau a été présumée à 33,2 g· m^{-2} et l'indice de récolte 25%.

Les paramètres utilisés dans cette étude portent sur la procédure d'étalonnage adoptée dans ce travail et les données expérimentales disponibles. On peut noter que le modèle simule mieux la biomasse que le rendement. Selon l'indice de l'accord, une meilleure simulation de la biomasse et du rendement a été obtenue pour le sorgho cultivé durant «l'année normale» de 1992. L'année 1993 a été considérée comme extrême, en regard de la température et des précipitations et la simulation n'était acceptable que pour le sorgho pluvial (d = 0,967). Le résultat obtenu montre que le modèle du FAO AquaCrop peut simuler une évapotranspiration, la biomasse et le rendement du sorgho à sucre avec un index de l'accord 0,92, 0,85 et 0,72, respectivement. Le sorgho à sucre a été cultivé pour la production d'alcool, et le

rendement principal était la tige, non le grain. Pour des cultures spécifiques, des données supplémentaires, recueillies sur le terrain, sont nécessaires afin d'améliorer la simulation de conditions météorologiques extrêmes.

Mots clés : *Modèle AquaCrop, bio-carburant, sorgho sucré, sol marginal, Serbie.*

(Traduction française telle que fournie par les auteurs)

1. INTRODUCTION

The production of sweet sorghum is not widespread in Serbia. A study of the technological properties of 27 varieties of rainfed and irrigated sweet sorghum, grown as both a regular crop and aftercrop, showed an alcohol yield of 4700 to 9200 l from the sweet sorghum produced in one hectare (Kisgeci and Pekic; 1983, Stricevic, 1996), which is comparable to the levels reported in other countries (Bassam, 1990; Copani et al., 1989; Tsuchihashi and Goto, 2005). However, despite encouraging results, the production of sweet sorghum has not spread. The main reason is a lack of processing facilities. Today, suitable agronomic solutions are again being sought for the production of biofuel. The top three candidates are certainly sweet sorghum, rapeseed and miscanthus (Dzeletovic, 2009).

In order to plan a programmed expansion of the production of any crop, it is necessary to provide good conditions for high and stable yield. Soil fertility is achieved by agri-technical measures, but the key issue is sound management of water resources. A crop can be grown without irrigation because there are frequent years with an average precipitation of 300-400 mm, which, along with soil moisture reserves, ensures a sufficient amount of water for high yield (Stricevic et al., 2011). Maize, soy bean and sugar beet, which are grown on more than 50% of arable land in Serbia, experience a yield decline during dry years by as much as 60% (Pejic, 2009; Maksimovic and Dragovic, 2004; Matovic, 2002). However, during the past decade, floods and droughts alternated and resulted in a dramatic yield decline of all crops.

A well-timed prediction of drought and its impact on agriculture requires the use of appropriate tools to enable producing the needed results quickly and accurately. Due to its stochastic nature, it is difficult to predict when a drought event will occur and how long it will last, and it is even more difficult to envisage how it will impact agricultural production. Past experience shows that investment in irrigation systems in this region is profitable only for vegetable growing. However, the production of key crops and the provision of biofuel are in the general public interest. The state administration is required to ensure basic conditions for a production which will be competitive in the market. This is generally achieved through subsidies. However, to properly determine appropriate subsidy levels, it is necessary to impartially assess the impact of drought on yield and make strategic decisions for the future. Today, this is made possible by a variety of plant growth simulation models, such as: FAO AquaCrop, WOFOST, Cropsyst, Ceres, EPIC, adaptive artificial neural networks, regression trees, and a number of other models. Although they differ among themselves, in essence, all these models are able to simulate plant production with a higher or lower degree of accuracy (Steduto, 2009; Zand-Parsa et al., 2006; Abraha and Savage, 2008; Park et al., 2005; Stöckle, 2003; van Diepen, 1989). Models such as AquaCrop target a wide circle of users (farmers, consultants,

water managers and policymakers), who need information about biomass production and the yield of crops grown under different water and nutrient supply conditions. If the correlations between soil, water, plant and atmosphere are well known, it is relatively easy to obtain needed climate, soil and agri-technology data and use the model. Based on model calibration and validation for local conditions, it is safe to say that the model can be used to simulate plant production for practical purposes (Hsiao, 2009; Todorovic, 2009). Since water is the most frequent limiting factor in Serbia, the FAO AquaCrop water-driven model was selected for the simulation of sweet sorghum biomass and yield under good nutrient availability conditions, but with different levels of water supply.

2. MATERIALS AND METHODS

The input data needed for the FAO AquaCrop model were collected at the Becej experimental site (47° 37' N latitude; 20° 02' E longitude). To characterize the climate of the trial area, meteorological data measured over a period of 55 years (1980-1990) by the Becej meteorological station were used. The climate is moderate, with four distinct seasons. Minimal, maximal and mean annual precipitation levels are 269 mm, 925 mm and 585 mm, respectively. During the growing season (April-September), the corresponding averages are 142 mm, 563 mm and 342 mm. The mean annual temperature is 10.5°C. At Becej, mean daily temperatures higher than 10°C start on 4 April and end on 15 October. The average temperature sum (with a 0°C base) is 3288°C.

The soil of the experimental site is highly calcareous loam, overlaying a mollic horizon of alkaline chernozemollic meadow soil with favorable chemical, but less favorable physical properties. The deep, dark grey-brown, (nearly black) mollic horizon is also of loam texture. The soil structure is crumby to dusty. Bulk density ranged from 1.33 to 1.45 g·cm^{-3}. Air porosity varied from 3.7 to 9.4%. The mean value of volumetric soil water content across the soil profile at field capacity and the wilting point were 41.2% and 23.17%, respectively. Total available soil water (TAW) was calculated from the field capacity and wilting point difference as 144 mm to a depth of 0.8 m, or 180 mm·m^{-1}.

Sowing dates of sweet sorghum, hybrid NS, were 2 May 1992 and 5 May 1993. Row spacing of 0.45 m and 0.1-0.12 m between plants in a row produced a final plant population density of 15 plants per m2. The experiments were based on a randomized block design with three replications. Irrigation in the research area was mainly supplemental and its aim was to supply plants with water during short drought periods. In order to use sudden rainfalls which usually occur during the summer more efficiently, as well as to ensure adequate aeration, water content in the soil under irrigation was maintained within the range of assumed upper to lower limits. Readily available water was considered to be between -0.03 and -0.35 MPa. Irrigation was based on soil water content measurements by both a TDR probe and gravimetric methods. As a result, irrigation treatments included: full irrigation (FI), deficit irrigation (DI) at 80% of full irrigation supply, and rainfed treatment (RF). Soil was fertilized before sowing with 450 kg·ha^{-1} of N:P:K = 17:13:10 and cultivated twice before stem elongation during each year of research.

The average temperature (T), precipitation sum and measured evapotranspiration (ETm) during the growing cycle of sweet sorghum are shown in Table 1. It should be noted that the

growing cycle in the first year of research was characterized by moderate climate conditions and precipitation events before the pre-maturity period. This was followed by drought and high temperatures (26.08oC daily average), causing the need for irrigation. The growing cycle in the second year was characterized by high air temperatures and extreme drought with only 133 mm rain, which was at the absolute minimum level in this area. Under these highly unusual circumstances, irrigation started before sowing, to ensure proper germination, and lasted through the end of the growing cycle.

Table 1.   Main weather characteristics and irrigation depth during the growing cycles (Caractéristiques climatiques et normes d'arrosage pendant la période végétative)

Year	Growing cycle (days)	T (°C)	RH (%)	P (mm)	Treatments	ETm (mm)	Irrigation depth (mm)
1992	130	25.1	57	245	FI	384	130
					DI	350	100
					RF	281	0
1993	120	20.95	59	133	FI	457	215
					DI	386	182
					RF	160	0

To simulate sweet sorghum growth using the AquaCrop model, fertility stress was not considered. A temperature stress for biomass production of 11.1°C and a heat stress during pollination of 35-40°C were used. Root depth was 1.85 m.

The FAO AquaCrop model has been described in detail by Steduto et al., 2009 and Raes et al., 2009. This paper will mention only those parameters which are significant for biomass and yield simulation of sweet sorghum. Climate input data included: daily value of reference evapotranspiration calculated by the FAO Penman-Monteith method (Allen et al., 1998), daily values of maximal and minimal air temperatures, daily sums of precipitation during the period of research, irrigation depth, and dates of irrigation.

Given that AquaCrop does not include a default file for sweet sorghum, the default file for maize was used as a starting point, assuming both a C_4 crop and a great similarity in: leaf structure, biomass accumulations, request for soil fertility, and climate conditions.

The model was calibrated through an iterative process, using measured crop growth variables, observed phenological stages, parameters estimated from available data, and derived growing coefficients of fully irrigated sweet sorghum grown in 1992. Parameters such as the canopy growth coefficient, crop coefficient for transpiration, canopy decline, harvest index, water productivity and water stress were the same for all treatments during the two years of research, and these values are presented in Table 2.

Table 2. Some relevant crop parameters used for sweet sorghum hybrid NS growth simulation (Quelques paramètres importants de la plante utilisés pour la simulation de croissance des hybrides NS du sorgho sucré)

Parameter	Value	
Crop coefficient for transpiration at CC = 99%	1.05	
Canopy growth coefficient (CGC) Reduction with age	12.3% 0.3% per day	
Canopy decline - slow	10.9%	
	in 1992 (days)	in 1993 (days)
Emergency Maximum canopy Senescence Maturity Flowering	12 70 115 132 72	7 66 105 122 68
Water productivity	33.2 g·m²	
Harvest index	25%	
Water stress Leaf expansion growth (p_upper, p_lower and shape factor) Stomatal closure (p_upper limit, shape factor) Early canopy senescence (p_upper threshold; shape factor) Aeration stress Harvest index – before flowering – during flowering – during yield formation	0.25, 0.6; 4.0 0.65; 4.0 0.65; 2.9 5% Small positive effect 5% Sensitive to water stress Moderate effect	

2.3 Data Analysis

Three statistical methods were used to analyze and compare yield, biomass and evapotranspiration data derived from field investigations and from simulations. The first was the root mean square error (*RMSE*) method:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - M_i)^2}$$

[1]

where: S_i and M_i = simulated and measured values, respectively, and n = number of observations. The unit of *RMSE* is the same for both variables, and the model's fit improves as *RMSE* tends toward zero.

The index of agreement (*d*) was calculated using the Willmott (1982) equation:

$$d = 1 - \frac{\sum_{i=1}^{n}(S_i - M_i)^2}{\sum_{i=1}^{n}(|S_i - \bar{M}| + |M_i - \bar{M}|)^2} \qquad [2]$$

where: $\bar{S}$ and $\bar{M}$ = average values of measured data. The index of agreement is a descriptor and its values range from 0 to 1. The model simulates the studied parameter better as the value approaches 1.

The third parameter is the coefficient of efficiency (Nash and Sutcliffe, 1970). Compared to *RMSE*, this parameter is a better indicator of the goodness of the model for biomass or leaf area simulation during the entire growing cycle. It recognizes that the difference between measured and simulated biomass values may vary during the growing cycle, e.g. the difference can be significant at the beginning of the cycle, smaller in the mid-season, and negligible at the end of growing cycle. This parameter was selected for data analysis of biomass simulation during the growing cycle of 1992.

$$E = 1 - \frac{\sum_{i=1}^{n}(M_i - S_i)^2}{\sum_{i=1}^{n}(M_i - \bar{M})^2} \qquad [3]$$

The coefficient of efficiency (E) varies from $-\infty$ to 1. A value approaching 1 indicates a better agreement between measured and simulated data.

3. RESULTS

Sweet sorghum biomass and yield simulation results for the data set used for model calibration are shown in Table 3. The best simulation results were obtained for biomass (- 0.27 %), then grain yield, and finally evapotranspiration. Any further variation resulted in major ET or yield changes, so that these results were retained for model validation.

Table 3. Simulation results for the calibrated data set and deviation from measured values (Résultats de la simulation d'un set de données utilisées pour la simulation et la déviation des valeurs mesurées)

Variable	Measured	Simulated	Deviation (%)
Biomass (Mg·ha⁻¹)	26.1	26.17	-0.27
Yield (Mg·ha⁻¹)	7.0	6.09	12.99
ET (mm)	384	445.5	16

The data set used for model validation was also used for the three different treatments during the two years of research, as shown in Table 4. Based on these results, it is safe to

say that the model simulated biomass better than grain yield in both years of research. The difference between simulated and measured values varied from -16.1% to 22.16%, which is comparable to maize simulation results (Hsiao, 2009; Heng, et al., 2009). However, the grain yield simulation was within acceptable limits for the first year under all scenarios, but only rainfed sweet sorghum was within such limits for the second year, where deviations ranged from -6.21% to 12.99%. The largest deviations were noted for fully irrigated (FI) crops (-89.6%) and supplementally irrigated (DI) crops (-58.2%).

Table 4. Simulation results for the validated data set and deviation from measured values of above-ground biomass and grain yield of sweet sorghum grown in Serbia (Résultats de la simulation d'un set de données utilisées pour la validation du modèle et la déviation des valeurs de la biomasse et de rendement du grain de sorgho sucré cultivé en Serbie mesurées)

Year	Treatment	Grain yield			Final biomass		
		Measured ($Mg \cdot ha^{-1}$)	Simulated ($Mg \cdot ha^{-1}$)	Deviation (%)	Measured ($Mg \cdot ha^{-1}$)	Simulated ($Mg \cdot ha^{-1}$)	Deviation (%)
1992	DI	7.0	6.09	12.99	25.9	25.19	2.75
	RF	4.1	3.83	6.63	16.2	18.81	-16.09
1993	FI	3.1	5.88	-89.61	33.0	25.69	22.16
	DI	3.6	5.70	-58.22	30.8	25.07	18.62
	RF	2.4	2.55	-6.21	16.6	15.50	6.6

It should be noted that climate conditions in the second year of research were extreme with regard to precipitation. During both years of research, it was noted that deficit irrigation (DI) fostered yield formation (i.e. increased the harvest index due to mild stress). This small water deficit was recorded after flowering, at the grain formation stage. The model, adjusted accordingly, could simulate neither biomass nor grain yield any better during the second year of research. The explanation for this perhaps lies in the fact that favorable heat conditions and sufficient water availability led to the formation of a larger green mass at the expense of yield, which exceeded the characteristics of this particular hybrid. The true characteristics of the hybrid are evident from the rainfed scenario. Similar biomass was achieved during both years of research, and severe drought during the entire growing cycle of the second year caused yield to be 40% lower. Because of the large differences in weather conditions during the two years of research, the model predicted lower yield (by 6.6%) for one year and higher yield (by about as much, -6.2%) for the other year, and vice-versa for biomass. Such large deviations were also noted during the simulation of biomass and yield of partially irrigated maize grown in Spain, except that yield and biomass were overestimated there, while rainfed maize grown in Florida was underestimated (Heng et al, 2009). In the case discussed here, biomass was underestimated and grain yield was overestimated.

Although the stem of sweet sorghum constitutes its principal yield, stem yield simulations were conducted but are not presented in this paper. The first reason for this is that the selected crop is a C_4 fruit/grain production crop, and the second reason is that all statistical indicators suggested that the model simulates grain (final product) yield better than stem yield.

Even though the model was adjusted based on the actual durations of the phenological stages of the crop, there was a large difference in biomass accumulation between measured

and simulated levels (Fig. 1) during the growing season. Smaller differences were obtained for irrigated than rainfed sweet sorghum, as corroborated, in addition to the graphic, by the statistics shown in Table 5. This is unequivocally confirmed by the coefficient of efficiency under the rainfed scenario, as well as by other statistical parameters - *RMSE* and *d*.
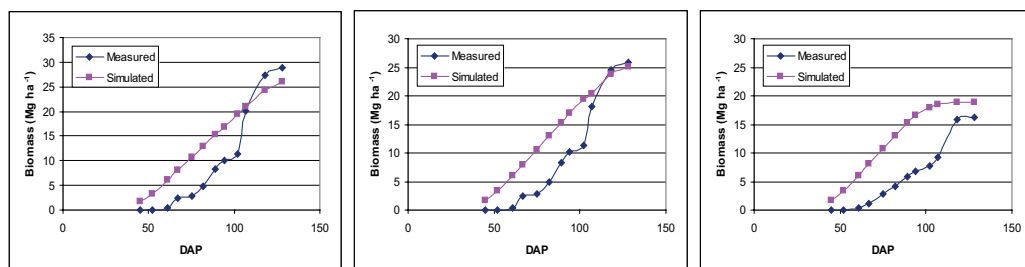

Fig. 1. Simulated and measured biomass accumulation of sweet sorghum for three irrigation treatments (FI, DI and RF) in 1992. (Valeurs simulées et mesurées de la biomasse du sorgho sucré avec trois options d'arrosage au cours de l'année 1992)

Table 5. Statistical indices derived for evaluating the performance of the AquaCrop model in simulations of final above-ground biomass for each modeled treatment (Indices statistiques des caractéristiques du modèle AquaCrop dans la simulation de la biomasse de chaque traitement utilisé dans le modèle)

Year	Treatment	*RMSE* (Mg·ha⁻¹)	*E*	*d*
1992	FI	5.66	0.676	0.9
	DI	5.57	0.607	0.89
	RF	7.21	-0.762	0.71

The statistical indicators for the evaluation of the suitability of the AquaCrop model for biomass, yield and evapotranspiration simulations are shown in Table 6. The index of agreement clearly shows that the model best simulated total evapotranspiration. The simulation may be considered as reliable since measured values were always lower than simulated values, which was a result of ET measurements based on the water balance, taking into account soil moisture variation only to a depth of the root system of 0.8 m, while the model took the actual depth of the root system of 1.85 m. Further, the model simulated biomass better than grain yield.

Table 6. Statistical indices derived for evaluating the performance of the AquaCrop model in simulations of final above-ground biomass, grain yield and evapotranspiration for two years of research, using the validated data set. (Indices statistiques d'évaluation du modèle Aquacrop pour une simulation de la biomasse, de rendement du grain et de l'évapotranspiration pour deux années de recherche)

	RMSE	*E*	*d*
Biomass (Mg·ha⁻¹)	3.98	0.62	0.85
Yield-grain (Mg·ha⁻¹)	1.47	-0.04	0.72
ET (mm)	62.9	0.56	0.91

Since sweet sorghum data were available only for the two years of research and the three treatments, the results are quite satisfactory. Of course, the model should be fine-tuned as measured data become available. No discussion of sweet sorghum parameter simulation, applying one of the well-known methods for the simulation of plant growth, was found in literature. There are only statements to the effect that deviations resulting from the application of the model are quite common. Similar statistical indicators were derived from maize and wheat simulations with the Root Zone Water Quality Model and the Ceres Model, over a longer period of time (Yu et al., 2006), as well as from sweet sorghum grain yield simulations with the SORKAM model (Gerik et al., 1988).

4. CONCLUSIONS

AquaCrop is a sufficiently complex model, which describes rather well the impact of both mild and severe water stress on biomass, evapotranspiration and ultimate yield, as shown through a two-year case study of sweet sorghum under extreme climate conditions. In this case study, the model best simulated evapotranspiration, followed by biomass and yield. Statistical indicators clearly show that two years of research and three treatments were not sufficient to adjust the model and use it in practice. As such, the model should be tested with additional data from experimental research of sweet sorghum, to verify the validity of the model for application in Serbia, and to assess whether rainfed sweet sorghum could be grown on marginal soils in different areas, or if supplementary irrigation would increase yield to an economically viable level.

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