Assessing yield for rainfed sunflowers in a Mediterranean environment using simulation modelling

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ABSTRACT

- Under the increase of the concern for food security in the world, mainly caused by water resources shortages, the forecast and determination of crop yield at regional scale has been considered as a strategic topic. Climate change contributes to increase the uncertainty on crops yield, promoting the development of crop simulation models for yield assessment. Yield estimation has been an important issue in irrigated crops, entailing the obtention of some indicators, as water productivity, essential for a correct water management.
- In this study, a methodological proposal considering a simplified approach using a simplified optimized model (SOM) has been carried out. This model under semi-arid conditions for rainfed sunflower located in southern Spain has provided very satisfactory results.
- The model results described accurately the observed temporal and spatial yield variability (Root Mean Square Error = 350 kg ha-1), and even when soil data were not available, SOM results were equally satisfactory, obtaining reduced RMSE (361 kg ha-1) with uniquely weather data.
- Simple and empirical models using uniquely weather data are able to provide accurate yield estimations, even better than more complex and physically based models.
- The satisfactory results for assessing yield obtained in this study demonstrate the utility of empirical models calibrated with field data for sunflower under semi-arid conditions, providing an excellent decision tool for farm planning and risk management for farmers and technicians.

Key words: Sunflower – rainfed – yield – empirical modeling – rainfall – maximum temperature.

INTRODUCTION

Climate change contributes to increase the uncertainty on crops yield, promoting the development of crop simulation models for yield assessment (White et al., 2011). The ability to determine crop yield at regional scale with a reasonable accuracy would provide an excellent tool for planning, management, research and policy decisions, being also an useful tool for technicians and farmers.

Traditionally, yield estimation has been based on empirical data and, lately, on simulation models (Cabelguenne et al., 1999). The complexity of these simulation models has varied from deterministic or physically based models which determine yield using physical equations and parameters (such as AquaCrop; Steduto et al., 2009 or OILCROP-SUN; Villalobos et al., 1996) to simple evapotranspiration (ET) based models (Doorenbos and Kassam, 1979). Physically based models such as AquaCrop or OILCROP-SUN have provided accurate results in the past, however, a limiting aspect of this type of models is the numerous data requirements for an appropriate simulation. Thus, an accurate crop and soil characterization is required.

In order to evaluate different simulation models for yield assessment, a semiarid region located in Southern Spain was selected. Accordingly, a traditional rainfed crop in this region as sunflower was chosen for the analysis.

Sunflower (*Helianthus annuus* L.) is an oilseed plant grown in Spain since the 60's and is characterized by its adaptability to a wide range of environments. Sunflower crop is an important component of the traditional crop rotation systems in the rainfed areas placed in Southern Spain.

MATERIALS AND METHODS

The Andalusian Network of Agricultural Trials (RAEA in Spanish) was started in 1986 and since then has been producing data from different varietal trials. The sunflower cultivar testing subnet has provided results annually since then, becoming a reference for the oilseeds sector (farmers, private seed companies, agricultural cooperatives, agricultural associations, etc.) in the region, meeting its goal of furnishing the information generated by on farm testing. The plant material used in the trials has been provided by companies and seed breeders based in Spain and abroad.

To carry out the analysis of different methodologies for yield estimation, five experimental locations were selected. These fields are included in the RAEA network previously described. For the proposed simplified simulation model, three locations and several years have been considered for calibration purposes (Carmona, Osuna and Trigueros). The validation process cannot be limited to use the same locations and years as used for calibration. Thus the model has been validated in two different climatic environments (Córdoba and Jerez).

Trials were carried out on either Randomized Complete Block Designs or squared or rectangular lattice designs (depending on the number of cultivars / year). Experimental plots consisted on 4 rows, 10 m long, 70 cm apart, 25 cm between plants within row. Only the two central rows were harvested. Crop management followed that carried out by the farmers in the region: rainfed conditions, no fertilizer application, and integrated in the biyearly rotation wheat – sunflower.

Soil characteristics (water holding capacity and depth) are described in Table 1, and were determined with specific texture analysis for each location.

Weather data from five weather stations provided by the Spanish National Meteorology Agency (AEMET, in Spanish) were used in this study.

Table 1.- Experimentation field, soil and weather conditions characterization for the five locations considered in the study

	Carmona (SE)	Osuna (SE)	Trigueros (HU)	Córdoba (CO)	Jerez (CA)
Experimental Field					
Average cultivars per year	30	31	35	36	33
Average sowing date	18 March	7 March	14 March	1 March	10 March
Average yield (kg ha^{-1})	1601	1544	1764	1897	2284
Temporal yield variability; CV (%)	26	37	37	29	19
Average cultivars variability; CV (%)	11	12	13	12	11
Analyzed years	15	14	11	10	13
Period	1987-2009	1987-2009	1996-2007	1987-1998	1987-2009
Soil					
Water Holding Capacity (mm m^{-1})	240	170	165	200	200
Depth (m)	1.8	2.2	2.1	2.3	2.2
Weather conditions					
Average Rainfall (mm)	537	482	644	634	573
Temporal Rainfall variability; CV (%)	28	24	30	26	32
Maximum Temperature on flowering (ºC)	37.3	36.8	36.5	36.2	34.5
Average Humidity on summer (%)	42.9	42.5	51.1	43.4	55.9
Location					
Altitude (m)	140	163	74	120	34

Simulation models: 1.- AquaCrop has been developed by FAO and simulates attainable yields for the main extensive herbaceous crops. The model simulates a yield-response to water model with a limited number of parameters (Steduto et al., 2009). Recently some studies have provided regional or local calibration for crops as maize or sunflower (Stricevic et al., 2011). In our study, regional calibration for sunflower was made based on previous studies (García-Vila and Fereres, 2011) and the assistance of experts and farmers from the area.

2.- A daily water-balance model was used to simulate water management at field-plot level based on FAO methodology (Allen et al., 1998). The components of the water balance model were: rainfall, irrigation, soil evaporation, transpiration, run-off and drainage.

Effective rainfall is defined as the water from rain that really could be used by the crops for transpiration. Using simulation models, the effective rainfall is computed as the rainfall minus the deep percolation and the surface run-off. Thus, for deep soils with high water holding capacity and reduced slope the effective rainfall will be similar to total rainfall. In the opposite case, in those locations with shallow soils, sandy texture and steep slope, the accurate determination of the effective rainfall will require the use of a detailed soil and field characterization.

When the effective rainfall cannot be calculated by modelling due to the lack of information about soil or field characteristics, the following formulae could be considered to estimate the effective rainfall:

$$R_{Effective} = a \cdot R \quad \text{with} \quad R_{Effective} \le b \qquad [1]$$

where R is the total rainfall, and a and b are parameters that must be adapted to regional conditions depending on soil characteristics and rainfall regime. In this study a and b parameters were fixed to 0.9 and 600 respectively. In Figure 1 the relationship between effective rainfall determined by the water balance models previously described and total rainfall is shown. A clear polynomial relation between observed and calculated values was detected ($R^2 \geq 0.84$; Fig. 1). Thus, when rainfall is lower than around 600 mm, a linear relation between rainfall and effective rainfall was observed. On the other hand, when rainfall exceeds 600 mm, the effective rainfall is almost constant due to the increase in runoff and deep percolation.

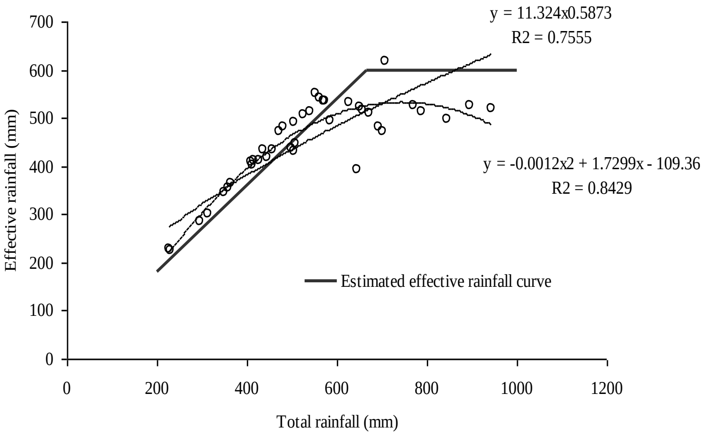

Figure 1.- Relationship between total rainfall and effective rainfall, and proposed estimated effective rainfall curve

3.- The Stewart function is used to estimate crop yield, proposed by (Doorenbos and Kassam, 1979) according to Stewart et al. (1977). These authors presented the following linear relationship between relative yield and relative evapotranspiration:

$$\left(1 - \frac{Y}{Y_{\max}}\right) = K_y \cdot \left(1 - \frac{T}{T_{\max}}\right) \qquad [2]$$

where Y is the calculated yield, Y_{max} is obtained from the regional analysis of the yields (here 3200 kg), K_y is the crop response factor, T the observed transpiration and T_{max} the measured T when T_{max} was obtained. Seasonal crop response factors proposed by Doorenbos and Kassam (1979) were adjusted according to local experience (K_y = 1.2; Lorite et al., 2005).

4.- Simplified optimised model (SOM): The third simulation model was developed to estimate sunflower yield under rainfed conditions using an empirical multiplicative function, requiring the analysis of current data provided by the RAEA network for the calibration and validation process.

This function is able to reproduce the reality, allowing that f_{Rain} and f_{Temp} affect independently the estimated yield. Thus, a severe water stress or temperature stress could reduce (even abolish) yield, independently of the other component.

$$Y_{estimated} = Y_{\max} \cdot f_{Rain} \cdot f_{Temp} \quad [3]$$

with

$$0 \leq f_{Rain} \leq 1 \text{ and } 0 \leq f_{Temp} \leq 1$$

where f_{Rain} is the reduction factor related to the insufficient rainfall, and f_{Temp} is the reduction factor related with high temperatures during the flowering period. Y_{max} is the maximum yield for the analyzed area in this study, 3200 kg ha^{-1}, based on previous data and on the analysis of current yield in the area.

The functions f_{Rain} and f_{Temp} could have a linear, polynomial, potential or exponential form, being the selected one that maximizing the R^2 coefficient between estimated yield and rain and temperature respectively.

RESULTS AND DISCUSSION

For the selected fields, considering average values AquaCrop generated a slight underestimation. Thus, estimated average sunflower yield by AquaCrop was 1684 kg ha^{-1} (compared with the observed average yield of 1805 kg ha^{-1}, implied an underestimation of 6.7%; Figure 2).

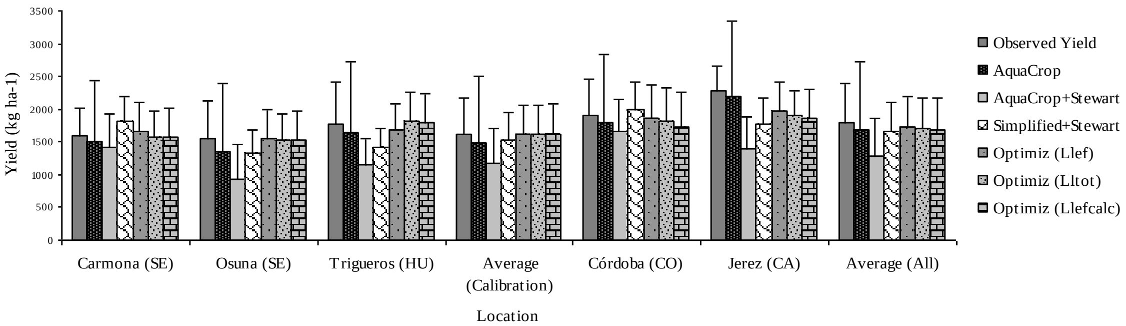

Figure 2.- Average sunflower yield observed and determined by Aquacrop, Stewart function and SOM.

AquaCrop underestimated sunflower yield under dry conditions (during 3 years no yield was simulated when observed yields were around 1000 kg ha^{-1}). In the opposite case, a clear overestimation was observed under good (more humid) conditions. Thus, yields higher than 3000 kg ha^{-1} were estimated for some years, when observed yields stayed lower than that yield in all the years and locations.

On the other hand for large scale analysis, the use of simpler models with low data requirements is due. A simplified methodology for yield assessment is the Stewart function (Doorenbos and Kassam, 1979). This equation requires the knowledge of crop transpiration (T) or crop evapotranspiration (ET_c), and these data can be provided by any crop simulation model (as AquaCrop) or by any water balance model (as the based on FAO methodology).

In our study, yield estimation provided by the Stewart function using AquaCrop data, was clearly unreliable, generating an obvious underestimation (average estimated yield 1171 kg ha^{-1} vs. 1626 kg ha^{-1}, observed yield, with a RMSE = 667 kg ha^{-1}).

In order to determine the variables affecting sunflower yield, in the simplified optimized model (SOM), weekly values of effective rainfall, total rainfall, average maximum weekly temperature and average weekly temperatures, were analysed. Thus, accumulated rainfall (total and effective) in the 26th week was the period in which correlation between yield and accumulated rainfall values was the highest. In the case of temperatures, the selected period ranged between 24-27th weeks, then the determination coefficients between temperatures and yield showed the highest figures. This period roughly coincides with the flowering stage of sunflower.

Thus, a potential function for rainfall, and a polynomial of second order function for temperature provided the best goodness of fit .

In order to determine the f_{Rain} and f_{Temp} components (see equation 3), an independent analysis was made correlating observed yield with rainfall and maximum temperature. For the calibration process the locations of Carmona, Osuna and Trigueros were used.

Considering the calculated effective rainfall (CER), computed using a simplified simulation model (see section 2.2.b.), and the maximum temperature (T_M) the equations obtained were:

$$f_{Rain} = 0.00236247 \cdot CER^{0.92295276} \quad [4]$$

$$f_{Temp} = -0.00122752 \cdot T_M^2 + 0.05119014 \cdot T_M + 0.54290904 \quad [5]$$

However, the accurate determination of the effective rainfall required a significant amount of data related with soil characteristics: water holding capacity, soil depth, slope, soil water content at the beginning of the crop cycle, etc. To solve this lack of information, a similar analysis to the described previously was made using total rainfall (TR) and using an estimated effective rainfall (EER):

$$f_{Rain} = 0.00565401 \cdot EER^{0.78279734} \quad [6]$$

$$f_{Temp} = -0.00104325 \cdot T_M^2 + 0.03560488 \cdot T_M + 0.83867028 \quad [7]$$

Finally using the total rainfall (TR), the parameters that minimized the RMSE generated the following equations:

$$f_{Rain} = 0.03120514 \cdot TR^{0.50171429} \quad [8]$$

$$f_{Temp} = -0.0012944 \cdot T_M^2 + 0.05171429 \cdot T_M + 0.53781203 \quad [9]$$

The described equations considering the five locations provided very good results. Thus, the goodness-of-fit indicators were improved significantly compared with other methodologies. Thus, averaging the three optimized alternatives, RMSE was around 360 kg ha^{-1}, E was 0.62 and d = 0.88. Finally, R^2 was 0.64. In addition, the regression line between observed and simulated yield was very close to 1:1. Figure 3 shows the comparison between observed and estimated yield using CER, TR and EER, plus maximum temperature (T_M).

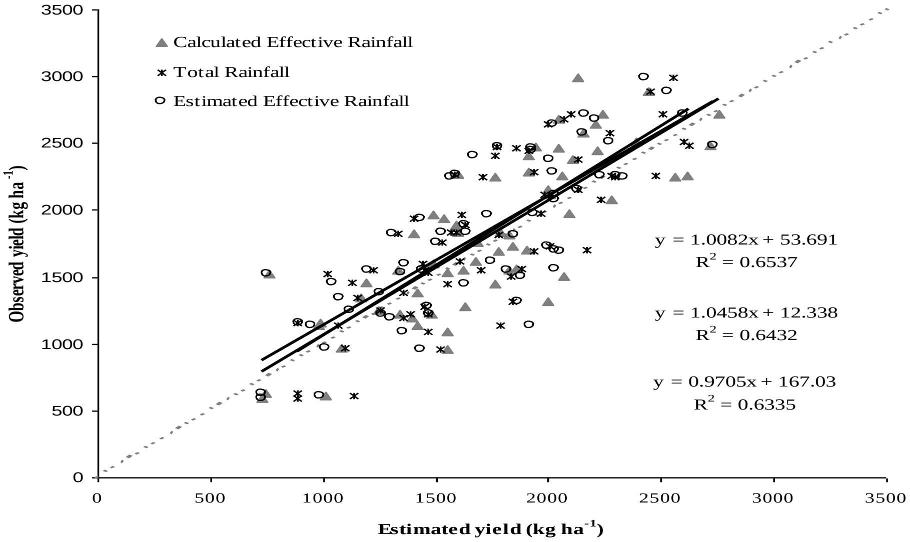

Figure 3.- Relation between observed and estimated sunflower yield using SOM model (CER+T_M, TR+T_M and EER+T_M).

Comparing the goodness-of-fit indicators (Table 2) and the relations described in Figure 3, the optimization using CER+T_M was the option most accurate (with lowest RMSE and highest d). The other two alternatives (TR+T_M and EER+T_M) do not require the computation of terms as deep percolation or runoff, reducing absolutely the information required about soil parameters, initial conditions or depth. Due to this fact, the obtained results have been slightly poorer than using CER+T_M.

According with these results, if there are available data, the use of the calculated effective rainfall (CER) is recommended rather than the other two alternatives.

Table 2.- Goodness-of-fit parameters for SOM (considering three different variables), Aquacrop, and Stewart function (considering two different variables).

Methodology	RMSE	N-S	d	R^2	Equation
SOM (Using CER + T_M)	350.4	0.64	0.88	0.65	Yobs = 1.0082Yest + 53.691
SOM (Using TR + T_M)	361.2	0.62	0.87	0.64	Yobs = 1.0458Yest + 12.338
SOM (Using EER + T_M)	372.8	0.59	0.87	0.63	Yobs = 0.9705Yest + 167.03
Aquacrop	724.5	-0.54	0.80	0.64	Yobs = 0.4291Yest + 1081.9
Stewart + Aquacrop	667.0	-0.30	0.72	0.51	Yobs = 0.7589Yest + 822.46
Stewart + Watwer Balance - FAO	453.6	0.40	0.79	0.47	Yobs = 0.8935Yest + 322.82

The proposed methodology was validated using 10 years data of the Cordoba location and 13 of Jerez (Table 1). These datasets were uniquely used for validation and included a wide range of different rainfall and temperatures (Cordoba is an inland location while Jerez is located near the coast).

The validation results are described in Table 3. RMSE obtained applying the optimized functions for CER+T_M in Cordoba and Jerez was 363 kg ha^{-1}, with E=0.47 and d=0.86. Using TR+T_M and EER+T_M the model produced poorer results (RMSE was equal to 391 and 423 kg ha^{-1} respectively; Table 3).

Table 3.- Goodness-of-fit parameters for SOM (considering three different variables) in two locations considered for validation (Córdoba and Jerez).

Methodology		RMSE	N-S	d	R^2	Equation
SOM (Using CER + T_M)		363.1	0.47	0.86	0.64	Yobs = 0.8389Yest + 499.55
	Cordoba (CO)	291.7	0.73	0.92	0.73	Yobs = 0.9347Yest + 153.34
	Jerez (CA)	409.7	-0.24	0.77	0.63	Yobs = 0.667Yest + 967.67
SOM (Using TR + T_M)		390.9	0.38	0.84	0.65	Yobs = 0.8997Yest + 438.81
	Cordoba (CO)	278.6	0.75	0.93	0.78	Yobs = 0.9387Yest + 194.25
	Jerez (CA)	459.0	-0.55	0.72	0.58	Yobs = 0.7554Yest + 847.06
SOM (Using EER + T_M)		422.5	0.28	0.83	0.69	Yobs = 0.8484Yest + 582.96
	Cordoba (CO)	271.7	0.76	0.94	0.85	Yobs = 0.98Yest + 196.05
	Jerez (CA)	509.0	-0.91	0.71	0.60	Yobs = 0.6362Yest + 1099.8

Thus, when the validation conditions were similar to the calibration ones (Cordoba location), the use of CER+T_M, TR+T_M or EER+T_M produced similar results. However, when the environmental conditions were different (Jerez location), CER+T_M validation results demonstrated to be the most accurate methodology for yield estimation.

Traditionally complex models have been recommended for assessing yield due to a better adaptation to extreme weather and management conditions (Cabelguenne et al., 1999) rather than empirical models as SOM. However, in this study the results obtained in locations quite different from locations used for the calibration of SOM (Jerez location), produced more reliable results with SOM model than with AquaCrop (RMSE for SOM in Jerez =410 kg ha^{-1} vs. 916 kg ha^{-1} using AquaCrop), indicating that models requiring a high quality of data are not the best option, even when a good environmental characterization is made.

CONCLUSIONS

The use of models with high quantity of data requirements is limited to areas/fields well characterized. However, at regional scales the use of simplified models is a preferable alternative. In this study it has been demonstrated that simple and empirical models using uniquely weather data are able to provide accurate yield estimations, even better than more complex and physically based models. Thus, while the yield assessing errors induced by the physically based models as AquaCrop were high (RMSE = 725 kg ha^{-1}), the results obtained using empirical models (SOM), considering uniquely meteorological data and soil parameters, were improved significantly (with CER+T_M, RMSE was 350 kg ha^{-1}). Stewart function provided also satisfactory results (RMSE = 454 kg ha^{-1}), demonstrating its potential use for assessing yield considering crop evapotranspiration from energy balance models.

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