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Analysis of deficit irrigation strategies by using SUBSTOR-Potato model in a semi-arid area

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Abstract

In areas where water is scarce, the use of regulated deficit irrigation, combined with decision support system tools, may decrease the impact of agriculture on natural water resources, as well as on energy consumption, thereby improving the profitability of farms. With this aim, the SUBSTOR-Potato model (incorporated in the DSSAT Program) was evaluated with a 2-year field test (2011 and 2012) conducted in a semi-arid area (Albacete, Spain) applying four irrigation levels (120, 100, 80 and 60% of irrigation requirements). Subsequently, the model was used for simulating the potato yield under several deficit irrigation strategies (ISs) during 30 years of a semi-arid climate (1988–2017) and determining the most profitable option. The considered ISs were deemed those most suitable from the yield and water productivity point of view by some authors. The model performance for tuber yield was satisfactory with an index of agreement >0.91 and errors between 0.71 and 3.06×10^3 kg/ha. The ISs simulated with SUBSTOR-Potato showed that slight deficit irrigation (5–10%) may increase the water productivity and profitability of the farms. Moreover, tuber formation (from onset of tuber initiation to harvest) was shown to be the most sensitive stage, therefore it is highly recommended to avoid deficit during this stage, which would cause a large reduction in yield (around 8 t/ha, depending on the level of deficit suffered by the crop).

Introduction

In semi-arid regions, such as the south-east of Spain, irrigation water resources are becoming increasingly scarce (Ortega *et al*., 2005). Furthermore, society demands suitable ecological conditions of water – together with the efficient use and management of this resource by the different productive sectors. In this context, agricultural systems are forced to conduct an optimal and rational use of irrigation water.

The potato crop (*Solanum tuberosum* L.) is the second most important non-cereal crop after sugar cane, with an approximate global production of 370 million tonnes (FAO, 2018). Albacete province (Spain) is the main producer within the region of Castilla-La Mancha (MAPAMA, 2018) and the 1600 ha of potato cultivated area represent approximately 1.7% of the regional gross domestic product. The high variability in seasonal sale price forces farmers to reduce costs, mainly those related to the use of water and energy in the farms (Ortega Álvarez *et al*., 2004; Córcoles *et al*., 2010; Moreno *et al*., 2010; Carrión *et al*., 2013).

Deficit irrigation, defined as an optimization strategy in which irrigation is applied during drought-sensitive growth stages (GSs) of a crop (Geerts and Raes, 2009), may be a useful strategy to reach these goals in arid and semi-arid regions (Fereres and Soriano, 2007; Domínguez *et al*., 2012*b*), since it would allow an increase in crop profitability through better water use efficiency. The deficit irrigation effect on potato yield and quality depends on the intensity of the water deficit, the stage when it occurs as well as the cultivar duration (early, medium or late maturing) (Shock *et al*., 1998; Vos and Haverkort, 2007). In this sense, a significant number of studies has shown that yield reduction is greater during the tuberization period (from onset of tuberization to harvest, GSs 400–409 according to the *Biologische Bundesanstalt, Bundessortenamt and Chemical Industry* (BBCH) scale; Meier, 2001) than the vegetative stage (GS 101-109) (Nelson and Hwang, 1975; Shock *et al*., 1998; Onder *et al*., 2005; Vos and Haverkort, 2007; Camargo *et al*., 2015*b*; Daryanto *et al*., 2016; Kifle and Gebretsadikan, 2016; Paredes *et al*., 2018). This highlights both tuber initiation and tuber bulking as the most sensitive stages to water deficit (Shock *et al*., 1998; Hassan *et al*., 2002; Paredes *et al*., 2018). However, only a few studies have been conducted under semi-arid conditions (Fabeiro *et al*., 2001; Karam *et al*., 2014) and they have shown that water deficit from onset of leaf senescence to harvest caused a large reduction in yield (between 11 and 12%), contrasting with some studies previously cited (Shock *et al*., 1998; Hassan *et al*., 2002). This could be partly explained due to the variable tolerance to drought of the varieties used in those experiments, as pointed out by Vos and Haverkort (2007). Despite the high number of deficit irrigation studies for potato, none has reached consistent conclusions

Table 1. Soil physical properties of the experimental plots (2011 and 2012)

Cropping season	Depth (m)	Texture	Water content			Bulk density (g/m^3)	K_{sat} (mm/day)	CN
			FC (vol.%)	WP (vol.%)	Sat (vol.%)			
2011	0.00–0.22	FA	30.2	15.0	44.9	1.45	191.1	85
	0.22–0.43	FA	30.2	15.0	44.5	1.48	215.1	
	0.43–0.70	AF	17.3	6.7	35.7	1.68	1846.4	
2012	0.00–0.25	FAA	29.4	12.1	46.4	1.40	137.1	
	0.25–0.42	FAA	29.4	12.1	46.9	1.40	117.6	
	0.42–0.70	F	22.8	9.0	47.2	1.35	142.5	
	0.70–0.95	FL	30.0	12.5	47.8	1.37	264.1	

FC, field capacity; WP, Wilting point; Sat, saturation; K_{sat}, saturated hydraulic conductivity; CN, runoff curve number; FA, clay loam; AF, sandy loam; FAA, sandy clay loam; F, loam; FL, silt loam.

about which is the best irrigation strategy (IS) to achieve the highest profitability through the use of water deficit during all or certain stages of the growing season.

Decision support systems (DSSs) – such as crop simulation models – are tools that allow this challenge to be achieved under different management conditions (Boote *et al*., 2010). The SUBSTOR-Potato model (Griffin *et al*., 1993) has been widely used for simulating potato growth under different irrigation and nitrogen (N) management conditions (Mahdian and Gallichand, 1995; Travasso *et al*., 1996; Snapp and Fortuna, 2003; Šťastná *et al*., 2010; Arora *et al*., 2013; Woli *et al*., 2016; Raymundo *et al*., 2017). Most of these studies showed that this model was suitable for simulation of potato growth (mainly for potato yield) but was less accurate for other crop growth variables (Raymundo *et al*., 2017) and extreme weather conditions (i.e. low amount of precipitation and its disordered distribution during the growing season) (Šťastná *et al*., 2010); or high mean air temperatures (Šťastná *et al*., 2010; Raymundo *et al*., 2017).

Camargo *et al*. (2015*a*, 2015*b*, 2016) reported a field data set with potato (phenological stages, crop growth evolution, growth indices, light interception, and relationships of quality and quantity of the potato crop with several irrigation depths) which may be suitable for evaluating the SUBSTOR-Potato model as well as to optimize the management of irrigation water in the area. In this sense, to apply an evaluated DSS such as SUBSTOR-Potato, simulating different ISs over a long period of time, would allow a consistent profitability analysis to be achieved.

Therefore, the goals of the current study are: (i) to calibrate and evaluate the SUBSTOR-Potato model for an Agria cultivar under the semi-arid conditions of Albacete (Spain) and (ii) to propose the best IS in terms of total yield, water productivity and profitability based on the simulation of different ISs during 30 growing seasons.

Materials and methods

Location of the experiment

The data used were obtained from a field experiment that was conducted during the 2011 and 2012 cropping seasons on a commercial potato farm located in Aguas Nuevas (Albacete, Spain; 38°56′N, 1°53′W, 695 m.a.s.l.) (Camargo *et al*., 2015*a*, 2015*b*, 2016). For both cropping seasons, the climatic data were obtained from a weather station that was placed on the farm. The daily reference evapotranspiration (ET_0) was computed using the FAO-Penman-Monteith equation (Allen *et al*., 1998). The highest temperatures were reached in July and August (35.1 and 36.2 °C, respectively, in 2011; 37.1 and 41 °C, respectively, in 2012) as well as the highest number of days with temperatures >35 °C (7 days in 2011 and 19 days in 2012). The accumulated rainfall during the crop cycle was 160 mm (2011) and 130 mm (2012), with half of the rainfall occurring between sowing and flowering.

The climate of the study area is categorized as warm Mediterranean (Papadakis, 1966). The highest summer temperatures in 2011 were average for the area in that season (33 °C). Nevertheless, the maximum temperatures reached in the summer of 2012 were higher than normal (between 35 and 41 °C for 19 days). The accumulated rainfall (P) was 360 mm/year (in spring and winter) and the accumulated annual ET_0 was around 1300 mm/year.

The soil was classified as a torriorthent (Soil Survey Staff, 2006), with a depth ranging from 40 to 55 cm. The average available soil water content was around 15.0% in volume for each 0.10 m of soil depth (Table 1). Soil physical properties such as bulk density, texture, field capacity and wilting point were obtained in the laboratory (Table 1). The saturation and saturated hydraulic conductivity were determined using empirical equations (Saxton *et al*., 1986), whereas the runoff curve number (CN) was determined following the USDA NRCS (2004) methodology.

Crop management

In both cropping seasons, the potato cultivar Agria was cultivated, which is one of the most common in the area; the crop was sown in the second week of March, with a density of 5.9 plants/m in 2011, and 5.7 plants/m in 2012. Potato seeds were planted at 0.20 m depth using a precision seeder, which formed hills 0.75 m apart. Tubers were harvested 152 (2011) and 173 (2012) days after planting (DAP). Other cultivation techniques followed the traditional farming practices in the area (De Juan Valero *et al*., 2003) for maximizing crop yield and tuber quality, where all treatments were non-N limited (Table 2).

Experimental design

The experimental plot covered 4.9 ha of a total of 18.4 ha, within a centre pivot irrigation system. The pivot system had a total length of 238 m and a system capacity of 1.3 litres/s ha. The Rotating

Table 2. Potato crop management

Month	Labour/operation	Equipment	Raw material 2011	Raw material 2012	Costs (€) 2011	Costs (€) 2012
January	Land rental				750.00	750.00
	Insurance		60 000 kg	60 000 kg	300.00	300.00
	Primary tillage	Chisel and tractor			15.91	15.91
	Organic fertilization and incorporation	Spreader trailer, cultivator and tractor	15 000 kg/ha	17 000 kg/ha	362.57	404.57
March	Fertilization: N-P-K (8-15-15)	Centrifugal fertilizer and tractor	800 kg/ha	900 kg/ha	294.00	330.09
	Insecticide treatment: Tiametoxan 35%	Sprayer equipment	441 ml/ha	420 ml/ha	82.01	78.10
	Planting operation (kg)	Precision seeder and tractor	2100 kg/ha	2000 kg/ha	1624.08	1528.38
April	Hill ascend tillage	Hill plough and tractor			13.90	13.90
	Herbicide application: Metribuzin 70%	Pulverizer and tractor	0.6 kg/ha	0.6 kg/ha	29.22	29.22
May	First cover fertilization: N-S (21-8)	Centrifugal fertilizer and tractor	600 kg/ha	425 kg/ha	103.59	74.89
	Fungicide treatment: Folpet 40% + Metalaxil-M 4.8%	Pulverizer and tractor	1.5 litres/ha		40.44	
June	Second cover fertilization N-S (21-8)	Centrifugal fertilizer and tractor		375 kg/ha		66.69
July	Fungicide treatment: Folpet 40% + Metalaxil-M 4.8%	Pivot system		1.5 litres/ha		59.32
	Insecticide treatment: Clorpirifos 48%	Pivot system	4.0 litres/ha		84.52	
	Insecticide treatment: Tiametoxame 25%	Pivot system		200 g/ha		75.72
August	Insecticide treatment: Clorpirifos 48%	Pivot system	4.0 litres/ha	4.0 litres/ha	84.52	84.52
	Herbicide treatment: Dicuat 20% + non-ionic wetting 20%	Pulverizer and tractor	3.0 litres/ha		54.33	
	Commercial harvest and trucking	Potato harvester and truck			794.71	783.79
				Total costs:	**4633.80**	**4595.10**

Spray Plate Sprinklers (Rotator™, Nelson Irrigation Co., Walla Walla, USA) were installed at a height of 1.4 m in all spans with 1.5 m between sprinklers. The sprinklers had pressure regulators with output pressure set to 140 kPa and a 9 m wide spray pattern.

According to Camargo *et al.* (2015*a*, 2015*b*, 2016), within a section of a centre pivot irrigation system, the experimental design considered four irrigation treatments, which were a percentage (120, 100, 80 and 60%) of the crop water requirements (CWR) computed using the FAO methodology (Allen *et al.*, 1998) during the growing season. The average amounts of total water received by the reference treatment (100%) were 598.2 and 791.1 mm for 2011 and 2012, respectively. Each irrigation treatment had three replicates, whose experimental plots were 10 m long × 6 m wide (60 m^2).

Crop growth and development

Experimental plots were monitored once per week to determine the crop GS, using the BBCH scale (Meier, 2001). According to this scale, the end of flowering and the onset of senescence should occur at the same time, but these two stages were not simultaneous in 2012 (Camargo *et al.*, 2015*a*, 2015*b*). In addition, the crop cycle length during the two experimental seasons was not shorted by the water stress effects, with crop maturity being attained in all treatments at the same time (Camargo *et al.*, 2015*a*).

Selecting two plants from each experimental plot, the crop was sampled eight (2011) and nine (2012) times between establishment and harvest to measure the dry matter content and leaf area index (LAI), which was obtained using a LI-COR-3100C automated infrared imaging system (LI-COR Inc., Lincoln, USA) (Camargo *et al.*, 2015*a*, 2016). Moreover, a SunScan™ canopy analysis system (Delta-T Devices Ltd., Cambridge, UK) was used to compute the absorbed photosynthetically active radiation (PAR) (Varlet-Grancher *et al.*, 1989; Camargo *et al.*, 2016). Harvesting was performed manually in the central 18 m^2 of each sub-plot (60 m^2) to determine crop yield, total dry matter (TDM), tuber dry matter (TubDM) and the harvest index.

Irrigation management and crop evapotranspiration

According to Allen *et al.* (1998), a simplified water balance in the root zone was used to schedule the irrigation requirements of the

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reference treatment (100% CWR). The following crop coefficients (Kc) were used: 0.50 during establishment, 1.15 at tuber formation and 0.75 at the end of the growing period (Allen *et al.*, 1998). To guarantee the emergence and establishment of the crop, all irrigation treatments received the same amount of water until plants reached the 'nine unfolded (>4 cm) leaves on the main stem' stage (GS 109). The actual amount of water received by each treatment was established according to Camargo *et al.* (2015*b*) and Montoya *et al.* (2016).

Crop evapotranspiration (ET) was computed by the soil water content variations measured by using EnviroScan™ (Sentek Sensor Technologies, Stepney, Australia) probes (with sensors at 0.1, 0.2, 0.3 and 0.4 m depth) and Watermark™ (Irrometer Corp., Riverside, USA) sensors (placed at 0.2, 0.3 and 0.4 m depth). The potential readings were used for determining the zero flux plane (Jiménez *et al.*, 2010; Camargo *et al.*, 2015*b*) at a depth of 0.3 m, while the volumetric readings were used to calculate the ET (WBS_{ET}) for the days between two consecutive irrigation events: in addition, a Bowen Ratio Station (Campbell Scientific Ltd. Loughborough, UK) was placed four times (after planting, at flowering, at maximum crop growth and at senescence) in the middle of the second pivot span (120% irrigation treatment) to calculate the ET (BR_{ET}), following the methodology proposed by Allen *et al.* (2011):

$$\mathrm{ET} = I + \mathrm{Pe} - \Delta S \qquad (1)$$

where ET is the actual evapotranspiration (mm); I is the net irrigation (mm); Pe is the effective rainfall (mm) calculated according to the CN (NRCS, 2004) and ΔS is the variation of the soil moisture content (mm).

SUBSTOR-Potato model

The SUBSTOR-Potato model (Griffin *et al.*, 1993) is part of the Decision Support System for Agrotechnology Transfer (DSSAT-CSM; Jones *et al.*, 2003). This package has a modular structure that simulates production over time and space for different purposes. This model simulates the effects of weather and soil characteristics, genotype, cultivar and management (tillage, irrigation and fertilization) on crop growth and development on a daily basis. The phenological development, biomass formation and partitioning, and soil water and nitrogen balances are the four primary sub-models that affect the description of the plant–soil–atmosphere system (Griffin *et al.*, 1993). Version 4.6 of DSSAT was used in the current study (Hoogenboom *et al.*, 2015).

The SUBSTOR-Potato model uses cultivar-specific coefficients (genetic coefficients) to control tuber initiation (GS 401) by the critical temperature ('TC coefficient'; °C) and sensitivity to photoperiod ('P2 coefficient'; dimensionless); while potential tuber growth rate ('G3 coefficient'; g/m^2/day), leaf area development ('G2 coefficient'; cm^2/m^2/day) and an index that suppresses tuber growth (PD, dimensionless) affect biomass accumulation (Griffin *et al.*, 1993). Tuber initiation is a key stage in the model, which is defined by the cultivar's response to both temperature (TC) and photoperiod (P2), with these responses modified by soil water content and plant N status (Griffin *et al.*, 1993).

Biomass accumulation is simulated by potential photosynthetic carbon assimilation (PCARB), which is affected by the carbon dioxide (CO_2) concentration: it changes with atmospheric CO_2 concentration by applying a relative CO_2 response factor (PCO_2) for C3 crops. This factor is 1 at atmospheric CO_2 concentration of 330 ppm and increases asymptotically up to 1.43 at a CO_2 concentration of 990 ppm (Curry *et al.*, 1990):

$$\mathrm{PCARB} = \frac{\mathrm{RUE} \times \mathrm{PAR}}{\mathrm{DENS}} \times (1{\cdot}0 \times e^{(-K \times \mathrm{LAI})}) \times \mathrm{PCO_2} \qquad (2)$$

where PCARB is the potential photosynthetic carbon assimilation (g/plant day), RUE is the radiation use efficiency (g/MJ), PAR is the photosynthetically active radiation (MJ/m^2), DENS is the plant density ($plant/m^2$), K is the extinction coefficient (0.55; dimensionless), LAI is the green leaf area index (m^2/m^2) and PCO_2 is the relative CO_2 response factor (dimensionless).

The actual carbon fixation rate is calculated by multiplying the potential carbon fixation rate with the minimum reduction factors for water shortage (SWDF), nitrogen stress (NDEF) or temperature factor that affects photosynthesis (PRFT) (Griffin *et al.*, 1993). In addition, half of the carbon in senesced leaves (DDEADLF) is translocated prior to abscission (Griffin *et al.*, 1993):

$$\mathrm{CARBO} = \mathrm{PCARB} \times \mathrm{MIN}(\mathrm{PRFT},\ \mathrm{SWDF}, \mathrm{NDEF}) + 0{\cdot}5 \times \mathrm{DDEADLF} \qquad (3)$$

where CARBO is the actual fixation rate (g/plant day), PCARB is the potential photosynthetic carbon assimilation (g/plant day), MIN is the minimum value from a list of constraint factors, PRFT is the factor for temperature stress (dimensionless), SWDF is the factor for soil water deficit (dimensionless), NDEF is the factor for nitrogen deficit (dimensionless) and DDEADLF is the carbon in senesced leaves (dimensionless).

Growth of all organs have equal priority during the vegetative stage, while after tuber initiation the model computes the crop growth in two steps, which is due to tuber bulking (Griffin *et al.*, 1993). Thus, SUBSTOR-Potato estimates, firstly, the priority for maximum tuber growth (TIND) using the sink strength (DTII) and the carbon demand of tubers after tuber initiation (DEVEFF) (Griffin *et al.*, 1993). Then, the potential tuber growth rate (PTUBGR) is estimated as a function of maximum tuber growth rate (G3) and soil temperature. Finally, actual tuber, leaf, stem and root growth are calculated according to Griffin *et al.* (1993).

In addition, the SUBSTOR-Potato algorithms take into account two aspects; on the one hand, it considers two RUE values depending on the vegetative GS (from emergence to the beginning of tuber formation; GS 101–401) and tuber-bulking stage (from the beginning of tuber formation to harvest; GS 401–409) (3.5 and 4.0 g/MJ, respectively) and, on the other hand, biomass partitioning is a dynamic process largely influenced by many factors (mainly temperature, water and N) where tuber growth has priority over vine growth (Griffin *et al.*, 1993). Finally, the model uses the sub-modules of soil water and N balances belonging to DSSAT-CSM (Godwin and Singh, 1998; Ritchie, 1998).

Calibration and evaluation of the model

The model was calibrated using the experimental data from 2011 and model evaluation used the data from 2012 (Camargo *et al.*, 2015*a*, 2015*b*, 2016). Two types of data were used: field data and default values appearing in the user's manual (Griffin *et al.*,

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1993). In both simulated cropping seasons, the sowing and maturity dates were specified by the user. The climatic data required to run the model are maximum and minimum air temperature, solar radiation, wind speed and rainfall.

The SUBSTOR-Potato model differentiates between conservative and non-conservative variables. The first are considered constant and depend on the cultivar, being independent of both the location of the cultivated area and crop management (Jones *et al.*, 2003). The two most important conservative variables are genetic coefficients and RUE, which may be modified in the cultivar and ecotype coefficient files. To calibrate the model, G2 and G3 genetic coefficients and RUE (second stage) were obtained previously from the results of the reference treatment (100%, no deficit) in 2011, while the first stage of RUE was obtained from the 100% treatment in 2012, because the Agria cultivar had not been previously parametrized for the DSSAT modelling system (Hoogenboom *et al.*, 2015; Raymundo *et al.*, 2017). These computed parameters, together with the remaining genetic coefficients (TC, P2 and PD), were adjusted by consecutive iterations (trial and error) until reaching a close match between simulated and observed values for the calibration year.

A first approximation of RUE was obtained as a ratio between above-ground biomass and accumulative photosynthetic active radiation (PARac) for the two stages considered, using the experimental data from the reference treatment (100%). For the first stage (between planting and onset of tuber formation), RUE was estimated with two crop samples measured during 2012 cropping season, since it was not measured in 2011. However, RUE of the second stage (from onset of tuber formation to ripening) was estimated through eight crop growth samples and six field samples of radiation balance (Camargo *et al.*, 2016). The absorbed PAR was measured using a SunScan™ (Delta-T Devices Ltd, Cambridge, UK) to calculate RUE and the extinction coefficient (K) according to Camargo *et al.* (2016).

The parameters G2 and G3 are related to the progression of the LAI and the TubDM, respectively. Therefore, both were obtained by fitting the trajectory of observed LAI and TubDM with quadratic expo-polynomials and Gompertz sigmoid curve functions, respectively (Camargo *et al.*, 2015*a*, 2016). The genetic coefficients were calculated as the maximum leaf expansion ratio (G2) and maximum tuber growth rate (G3) from both models, respectively. The leaf area to leaf weight ratio (LALWR) was calculated as the average of the measurements obtained during the early GSs (2.27 m^2/kg; the same value as that used by the model, Griffin *et al.*, 1993), which is constant for the whole growing season (Confalonieri *et al.*, 2009). The average value of the K coefficient for the 100% treatment was around 0.60, close to the value used by SUBSTOR-Potato (0.55) and within the range proposed by Villalobos *et al.* (2009).

Evaluation model

To evaluate the goodness of fit between measured and simulated data during the calibration and evaluation years, some of the main statistical indicators considered by other authors to evaluate the performance of a crop model were used: the root mean square error (RMSE) and the Willmott's index of agreement (d) (Willmott, 1982). The model performance was analysed for tuber initiation date, date of the maximum LAI and its value, both obtained from the quadratic expo-polynomial curve function fitted by Camargo *et al.* (2015*a*, 2016) to the same monitoring data used in the current research, TDM and TubDM evolution during both growing seasons, total biomass and yield at harvest and harvest index. Additionally, ET was also analysed. The RMSE and d index values for LAI, total biomass and yield at harvest and harvest index were computed with the data set obtained from the four treatments, while statistics were calculated for TDM, TubDM and ET evolution using the number of independent observations for each treatment. The model was considered well calibrated and evaluated when the measured and simulated data for maximum LAI, TDM and TubDM evolution, and ET reached 'd' values higher than 0.9 and RMSE values close to 0 (Benli *et al.*, 2007; Todorovic *et al.*, 2009; Araya *et al.*, 2010; Raes *et al.*, 2012). Furthermore, the total biomass production and crop yield simulations were acceptable when the differences between measured and simulated data were ±10% (Farahani *et al.*, 2009) and when the percentage of simulated data for each parameter that satisfied this requirement was ⩾70% (Domínguez *et al.*, 2012*b*; Montoya *et al.*, 2016). On the other hand, analysis of variance (PolyANOVA) was performed for total biomass, yield and harvest index of the simulated and observed data obtained at harvest, using the repetitions of each treatment as fixed factor. In this analysis the effect of irrigation treatment, the cropping season and their interaction were taken into account, studying both the performance treatments and the model. Duncan's test was applied to compare the means of each group (not significant, $P \geqslant 0.05$; significant, $0.01 \leqslant P < 0.05$; $P < 0.01$ highly significant):

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)^2} \tag{4}$$

$$d = 1 - \frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(|S_i - \mathrm{MO}| + |O_i - \mathrm{MO}|)^2} \tag{5}$$

where S_i is the simulated value, O_i is the measured value, n is the number of measurements and MO is the average value of 'n' measured values.

Strategies for improving the water productivity

The model was used for determining the IS that reached the highest total gross water productivity in terms of yield (WPY) and profitability (WPP). Water productivity in terms of yield (kg/m^3) was calculated as the relationship between the simulated crop yield and the total water depth received by the crop (rainfall and the simulated irrigation water), while WPP (€/m^3) was calculated as the ratio between the crop profitability and the irrigation water depth received by the crop. Hence, six ISs, considered by some authors as the most suitable from the point of view of yield and WPY for a potato crop growing under semi-arid conditions (Fabeiro *et al.*, 2001; Karam *et al.*, 2014; Camargo *et al.*, 2015*b*) (Table 3), were simulated under the climatic conditions of the study area for a 30-year period (from 1988 to 2017).

The climatic series (temperature, rainfall, wind speed and solar radiation) were registered by two nearby weather station (around 4.0 km from the study site). The data for the 1988–1999 period were obtained from the 'Los Llanos Airport' weather station, which belongs to the Meteorological National Agency (http://www.aemet.es/en/). The climatic data for the 2000–2017 period were registered by the agrometeorological weather station

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Table 3. Potato yield, irrigation water depth, water use efficiency and profitability during the 30 simulated potato crop seasons for the most suitable ISs according with the results of several authors

	Percentage of CWRs per growing stage												Profitability	
			Tuber formation											
IS	Establishment	Growth	From tuber initiation to onset of senescence[b]	From onset of senescence to harvest[c]	Expected result	Yield (× 10^3 kg/ha)[a]	SD (×10^3 kg/ha)[a]	IW (mm)[a]	IW ratio	WPY (kg/m^3)	WPP (€/m^3)	Area (ha)	(€/ha)	(€)
1[d,e,f]	100	100	100	100	Maximum yield	54.49a	7.71	525.2a	1.00a	8.17abc	0.963ab	1.00	4950.97a	4950.97
2[d]	80	80	80	80	High WPY	43.78c	7.82	420.2d	0.80f	7.77bc	0.758b	1.25	3073.16c	3841.45
3[e]	100	100	0–100[g]	100	High WPY	53.45a	7.96	479.0b	0.91c	8.60ab	1.030a	1.10	4822.66a	5288.56
4[f]	80	80	100	100	High WPY	55.36a	7.67	497.6b	0.95b	8.66a	1.056a	1.06	5156.23a	5442.07
5[f]	80	100	80	80	High WPY	44.21c	7.56	432.6d	0.82e	7.68c	0.750b	1.21	3135.82c	3806.94
6[f]	80	80	80	100	High WPY	48.91b	8.18	458.3c	0.87d	8.14abc	0.896ab	1.15	3991.14b	4574.12
P value	–	–	–	–	–	**	–	**	**	*	*	–	**	–

IS, irrigation strategy; SD, standard deviation; IW, irrigation water; WPY, irrigation water productivity in terms of yield; WPP, irrigation water productivity in terms of profitability.
[a]Data obtained from the simulations.
[b]Tuber initiation calculated by the SUBSTOR-potato.
[c]Leaf senescence obtained using GGD threshold.
[d]Camargo *et al*. (2015*b*).
[e]Karam *et al*. (2014).
[f]Fabeiro *et al*. (2001).
[g]No irrigation during 2 weeks, and full irrigation from that date.
*$P < 0.05$; **$P < 0.01$; means in the columns followed by different letters are significantly different according to the Duncan's test.

'Albacete', which belongs to the Spanish Agroclimatic Information Service for Irrigation (http://eportal.mapama.gob.es/websiar/Inicio.aspx) and is located at the farm where the field experiment was carried out.

The profitability of the different strategies was calculated for determining the WPP of each strategy:

$$GM = Y_f \times HP - C - I_T \times C_w \quad (6)$$

where GM is the gross margin (€/ha), Y_f is simulated potato fresh yield (kg/ha), HP is the harvest sale price of the main product (0.19€/kg) (average price from 2008 to 2013; ITAP, 2017), C is the potato crop cost (4615€/ha) (average price for the two experimental years) (Table 1), I_T is the total irrigation water depth applied to each scenario (m^3/ha) and C_w is the cost of irrigation water (0.15€/m^3) (Tarjuelo *et al*., 2015).

The SUBSTOR-Potato model was used to obtain the irrigation schedule for the reference IS (IS1; Table 3) in each simulated growing season. To obtain the reference irrigation schedule, SUBSTOR-Potato considered the maximum root depth as 0.40 m since it is the maximum effective soil depth in this area, which is limited by a petrocalcic horizon. The shallow profile of the soil conditioned the management of irrigation events, which were characterized by a high frequency and low irrigation depths. Thus, the upper and lower thresholds of the soil water content to irrigation management were 95 and 80%, respectively, allowing supply of around 18 mm as net irrigation water depth per irrigation event by the irrigation system. Moreover, the average duration of the phenological stages in growing-degree-days (GDD) for this cultivar in the area were established by Montoya *et al*. (2016). For the simulations, 9 March was considered as the sowing date, while harvest date was reached when 2324 GDD were accumulated, using 26 and 2 °C as the upper and lower threshold temperatures, respectively (Montoya *et al*., 2016). Since the GDD accumulated are different for each growing season, total days for each crop cycle as well as the growing stages were established with the average GDD duration (Montoya *et al*., 2016). According to Table 3, the ISs (from IS2 to IS6) were computed applying the percentage of irrigation requirement per growing stage to the reference ISs simulated with the SUBSTOR-Potato model. Thereupon, the six irrigation schedules generated were simulated with the model.

Statistical analysis

Analysis of variance (ANOVA) was used to evaluate the variables obtained with the ISs used during the 30 simulated years. Duncan's test was applied to compare the means of each group (not significant, $P \geqslant 0.05$; significant, $0.01 \leqslant P < 0.05$; $P < 0.01$ highly significant).

Results

Calibration and evaluation of the model

Tuber initiation is a key stage in the SUBSTOR-Potato model due to its effect on the simulation of the accumulated dry matter progression. According to the field data, the coefficients TC and P2 were calibrated as 18 °C and 0.2, respectively. Thus, the tuber initiation date simulated by the model was the same for all the treatments (60 DAP in 2011 and 71 DAP in 2012), which was similar to those observed in the field tests (57 DAP in 2011 and 73 DAP in 2012).

In the simulation of potato growth, the genetic coefficients G2 and G3 were calibrated as 1800 cm^2/m^2 day and 24.0 g/m^2 day, respectively (Table 4). The values of RUE calculated for the two considered stages were 1.63 g/MJ and 1.90 g/MJ, respectively. After calibration, they were established as 1.6 g/MJ (from emergence to the beginning of tuber formation) and 2.0 g/MJ (from the beginning of tuber formation to ripening) (Table 4). With these calibrated values, the date of maximum LAI was properly simulated by SUBSTOR-Potato during both cropping seasons, being similar to the differences between observed and simulated data (between 1 and 10 days for 2011 and between 2 and 13 days for 2012; Table 5; Camargo *et al*., 2016). The onset of senescence in 2012 was at 144 DAP, when the crop started to show yellowing leaves, while the maximum observed LAI was reached between 131 and 113 DAP depending on the irrigation treatment (Camargo *et al*., 2016). However, the simulated value of maximum LAI was consistently higher than observed data, except for the 60% treatment during the first cropping seasons (Table 5). In this case, the mean difference for all treatments was around 1.0 m^2/m^2. Thus, the statistical results were suitable ($d > 0.90$ and low errors) for the first experimental year, while the d index was poor for both variables in 2012 (Table 6) because of the higher differences obtained between simulated and observed data (Table 5).

The simulated TubDM showed a suitable progression for the majority of treatments in both experimental years (Figs 1(*e–h*)). Nevertheless, the model mainly underestimated the 100% treatment in 2011 (Fig. 1(*f*)), and overestimated the 60 and 80% treatments during the evaluation year (Figs 1(*g*) and (*h*)). The errors in the simulation of TubDM were low (Table 6). In general, the statistics determined a high agreement between simulated and observed data ($d > 0.90$) (Table 6).

Similarly, the accumulated TDM fitted the field data closely (Figs 1(*a–d*); Table 6). In both years, this parameter was slightly underestimated except for the 80% treatment in 2012 (Fig. 1(*c*)) because of the TubDM overestimation (Fig. 1(*g*)). Nevertheless, RMSE and d were acceptable in all the treatments (Table 6).

The simulated total biomass and yield at harvest were similar to the values obtained in the field (Table 7). Deviations between observed and simulated values were within the ±10% interval, with the exception of the 80% treatment where yield was slightly overestimated in the evaluation year. The ANOVA for yield did not find significant differences between simulated and observed results for the 100 and 120% treatments, showing a biomass production significantly higher ($P < 0.01$) for the 100% than for the 120% treatment (Table 7). However, the 60 and 80% treatments were significantly different ($P < 0.01$) from each other, as well as with respect to the 100 and 120% treatments for both variables (Table 7). The effect of the climatic conditions of each experimental year over biomass and yield did not show significant differences, except for observed yield. The suitable fit of parameters related to the simulation of TubDM and TDM (Fig. 1) reached an agreement between the observed and simulated values of biomass and final yield, whose statistics determined good performance (Table 6). Finally, the simulated harvest index (HI) conformed to the observed data (deviations within the ±10% interval, Table 7), where the '*d*' score shows a low goodness of fit in both years (Table 6).

In both simulation years, progression of the simulated actual evapotranspiration (ET) fitted with the ET values of the 120%

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Table 4. Parameters required for the simulation of a potato crop (Agria cultivar) using the SUBSTOR-Potato model under semi-arid conditions

Parameters	Value	Source
Phenology		
Emergence (days)^{NC}	37	m
Maturation-harvest (days)^{NC}	152	m
Growing and crop development		
Plantation density (plants/m^2)^{NC}	5.3	m
Plantation depth (m)^{NC}	0.20	m
Maximum root water uptake (cm^3/cm of root)^{NC}	0.03	b[a]
Radiation use efficiency (g/MJ)^{C}		
From emergence to beginning of tuberization	1.6	cv
From beginning of tuberization to maturation	2.0	cv
Genetic coefficients^{C}		
G2 (cm^2/m^2 day)	1800	cv
G3 (g/m^2 day)	24.0	cv
TC (°C)	18	e
P2 (dimensionless)	0.2	e
PD (dimensionless)	0.1	e
Water stress (dimensionless)^{C}	1.5	b[a]

C, conservative; NC, non-conservative; cv, calibrated and validated using field data; b, value from the bibliography; e, estimated from field data; m, measured in the experiments.
[a]Griffin *et al.* (1993).

Table 5. Comparison between observed and simulated maximum LAI

Cropping season	Treatment	Observed		Simulated	
		Value (m^2/m^2)	DAP	Value (m^2/m^2)	DAP
2011	120	5.7	112	6.3	107
	100	5.7	112	6.5	111
	80	5.2	112	5.7	112
	60	5.7	99	5.0	109
2012	120	5.1	131	6.7	118
	100	5.6	131	6.9	124
	80	4.3	113	6.5	120
	60	2.7	113	4.3	115

DAP, days after planting.

treatment measured by the Bowen ratio (BR_{ET}) device (Figs. 2(*a*) and (*b*)). The maximum simulated ET was lower than 10 mm/day, which coincides with the maximum value measured by the Bowen ratio device, and also with the calculated value obtained through the readings of the EnviroScan™ sensors (Fig. 2). Furthermore, errors in the estimation were low, '*d*' indices were excellent, and the coefficients of determination were high (Table 6). The comparison between simulated and calculated ET by using the data registered by the EnviroScan™ sensors (WBS_{ET}) presented moderated ($0.70 < d < 0.85$) and acceptable ($d > 0.85$) agreements for the majority of the treatments, with estimation errors between 0.96 and 2.46 mm/day (Table 6). Thus, after the calibration and evaluation of the model, the values assigned to the parameters required for the simulation of a potato crop (Agria cv.) under the semi-arid conditions of the study area are presented in Table 4.

Strategies for improving the irrigation water productivity

Treatment IS1 (no deficit) should be the strategy reaching the highest yield due to the fact that it was the one using the greatest volume of irrigation water and did not cause water deficit stress to the crop (Table 3). Nevertheless, the average yield of IS4 was slightly higher (1.6%), although no significant differences were found between the two strategies. In addition, IS3 also showed no significant differences compared to IS1, although the average yields were 1.9% lower. On the other hand, and as expected, IS2 and IS5 obtained the lowest yields (around 19.3% lower than IS1) because they suffered higher levels of water deficit stress caused by a lower supply of irrigation water (around 18.8%). However, the yield simulated by IS6 showed an intermediate yield level with regards to the other strategies, reaching an average simulated harvest around 10.2% lower than IS1.

These differences were relevant in the calculation of the irrigation water productivity in terms of yield (WPY). Thus, the highest values were obtained by IS4 and IS3, while the lowest corresponded to IS5 and IS2 (around 10.5% less than IS4). This result was expected because the decrease of yield in IS2 and IS5 (19.3% average) was higher than the amount of saved water (18.8% average) in comparison with IS1 (Table 3).

The former results condition the profitability in the use of irrigation water (WPP). Hence, IS4 together with IS3 reached a higher WPP (9.7 and 7.0%, respectively) than IS1 (Table 3). Therefore, these results must be taken into account when deciding the IS to use in a real farm with a low amount of available water, compared with the area of land able to be cultivated, as usual in semi-arid regions. Thus, considering a volume of irrigation water similar to the one used by the IS1 strategy, in that case, it would be possible to irrigate just 1 ha. Notwithstanding, it would be possible to irrigate up to 1.06 ha if IS4 was used, allowing the farm's profitability to increase by 9.9%. Treatment IS2 could increase the irrigated area up to 1.25 ha. However, due to the low WPY and WPP, this option is not translated into a higher total profitability (Table 3).

Discussion

Calibration and evaluation of the model

Griffin *et al.* (1993) highlighted that simulation of the tuber initiation stage is difficult for indeterminate potato cultivars such as Agria. Nevertheless, in the current study, the simulation of tuber initiation dates achieved a suitable fit with differences between simulated and observed data lower than the errors obtained by Raymundo *et al.* (2017) (10.5 days).

The over-estimation of maximum LAI values reached by SUBSTOR-Potato was also stated by Griffin *et al.* (1993): they pointed out that the use of disease and/or insect defoliation subroutines by the model could constrain leaf area. In both experimental years, crop management was carried out to maintain the crop free of pests and diseases or at least as low as was possible. This fact could partially justify the slight over-estimation of LAI by SUBSTOR-Potato.

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Table 6. Statistical comparison between simulated and observed values for tuber and total dry matter, maximum LAI, biomass, yield and harvest index at harvest and ET for the two experimental years

Parameter	Treatment (%)	Calibration			Evaluation		
		n	RMSE	*d*	*n*	RMSE	*d*
Tuber dry matter	120	8[a]	2.12[1]	0.95	9[a]	0.71[1]	0.99
	100	8[a]	3.06[1]	0.91	9[a]	0.92[1]	0.99
	80	8[a]	0.71[1]	0.99	9[a]	1.76[1]	0.96
	60	8[a]	1.79[1]	0.95	9[a]	1.52[1]	0.95
Total dry matter	120	8[a]	2.33[1]	0.96	9[a]	1.60[1]	0.98
	100	8[a]	2.32[1]	0.96	9[a]	1.89[1]	0.98
	80	8[a]	0.93[1]	0.99	9[a]	1.80[1]	0.97
	60	8[a]	2.30[1]	0.94	9[a]	0.33[1]	1.00
Value of maximum LAI	–	4[b]	0.66[2]	0.94	4[b]	1.71[2]	0.62
Day of maximum LAI	–	4[b]	5.61[3]	0.95	4[b]	8.23[3]	0.59
Biomass at harvest	–	4[c]	0.90[1]	0.88	4[c]	1.87[1]	0.89
Yield at harvest	–	4[c]	0.63[1]	0.92	4[c]	1.60[1]	0.84
HI at harvest	–	4[c]	0.05	0.36	4[c]	0.06	0.33
WBS_{ET}	120	35[a]	1.55[4]	0.72	50[a]	1.33[4]	0.77
	100	15[a]	0.96[4]	0.91	33[a]	1.07[4]	0.90
	80	35[a]	1.52[4]	0.71	50[a]	1.94[4]	0.73
	60	35[a]	1.56[4]	0.74	50[a]	2.46[4]	0.83
BR_{ET}	120	4[a]	0.69[4]	0.99	4[a]	0.72[4]	1.00

HI, harvest index; WBS_{ET}, ET by water balance simplify; BR_{ET}, ET by the Bowen Ratio Device; [a], number of independent observations; [b] and [c], number of compared treatments using the values showed at Tables 5 and 7, respectively; RMSE, root mean square error; [d], Willmott's index of agreement (dimensionless); [1]: $\times 10^3$ kg/ha; [2]: m^2/m^2; [3]: days; [4]: mm.

With respect to the simulated date of maximum LAI, the deficit irrigation treatments were slightly delayed *v.* the observed data, contrary to the results obtained by Griffin *et al.* (1993) when they simulated the lack of irrigation (around 30 days of difference). Nevertheless, differences in all treatments and experimental seasons can be acceptable, taking into account results stated by other authors using SUBSTOR-Potato (differences between 10 and 15 days and LAI errors of 2.2 m^2/m^2) (Raymundo *et al.*, 2017).

Similar differences have been found in other crop cycles grown in the same area, such as garlic (Domínguez *et al.*, 2013), maize (Domínguez *et al.*, 2012*b*) and onions (Domínguez *et al.*, 2012*a*). The above studies showed that it is common to find a certain variability in crop growth length (calculated either as accumulated days or as accumulated GDD), including no water stress conditions. In this sense, fewer differences were obtained as the crop cycle progressed, being between 6 and 12 days' variability for whole crop cycle. In addition, the above authors determined that the calculated coefficient of variation using GDD had a variability around 6.0% for the whole crop cycle while it was higher for the first growing stage (around 12.3%) (Domínguez *et al.*, 2012*a*, 2012*b*, 2013).

The water deficit levels proposed in the current research did not affect the length of the crop cycle, as has been reported by other authors (Fabeiro *et al.*, 2001; Karam *et al.*, 2014; Camargo *et al.*, 2015*b*). On the other hand, there is no clear evidence that water or N stress has an impact on crop senescence and the maturity type of cultivar (Mackerron and Davies, 1986; Khan *et al.*, 2013; Raymundo *et al.*, 2017). Thus, it was assumed that the crop cycle could be related to the total GDD accumulated for the conditions in the current experiment. Moreover, for a better fit it was necessary to include the phenological stage 'onset of senescence' (not considered by SUBSTOR-Potato as an input model), which was reached after 1468 GDD (Montoya *et al.*, 2016). Taking into account that GDD method has a certain variability and, on the other hand, the crop growth length is similar as the crop cycle attains maturity, we consider that the average GDD required to reach the different phenological stages may be usefully applied to improve irrigation water productivity.

In general, the statistical values (RMSE, slope, coefficients of determination and '*d*' index) showed that SUBSTOR-Potato attained a suitable performance, with similar values to those obtained by other authors evaluating the same crop variables (Griffin *et al.*, 1993; Daccache *et al.*, 2011; Arora *et al.*, 2013; Woli *et al.*, 2016; Raymundo *et al.*, 2017). The suitable agreement between simulated and observed values of biomass and final yield allowed the evaluation of all genetic coefficients and RUE values. The genetic coefficients values are similar to those parametrized by Raymundo *et al.* (2017) using several cultivars of *S. tuberosum* (not, however, including the cultivar Agria). Although the values of calibrated RUE for cultivar Agria in the current study were close to those reported by Camargo *et al.* (2016) during both experimental years (1.85 and 1.51 g/MJ) and very similar to results from other studies (between 1.45 and 2.7 g/MJ; Fahem and Haverkort, 1988; Jefferies and Mackerron, 1989; Sinclair and Muchow, 1999; Zhou *et al.*, 2016), they were significantly

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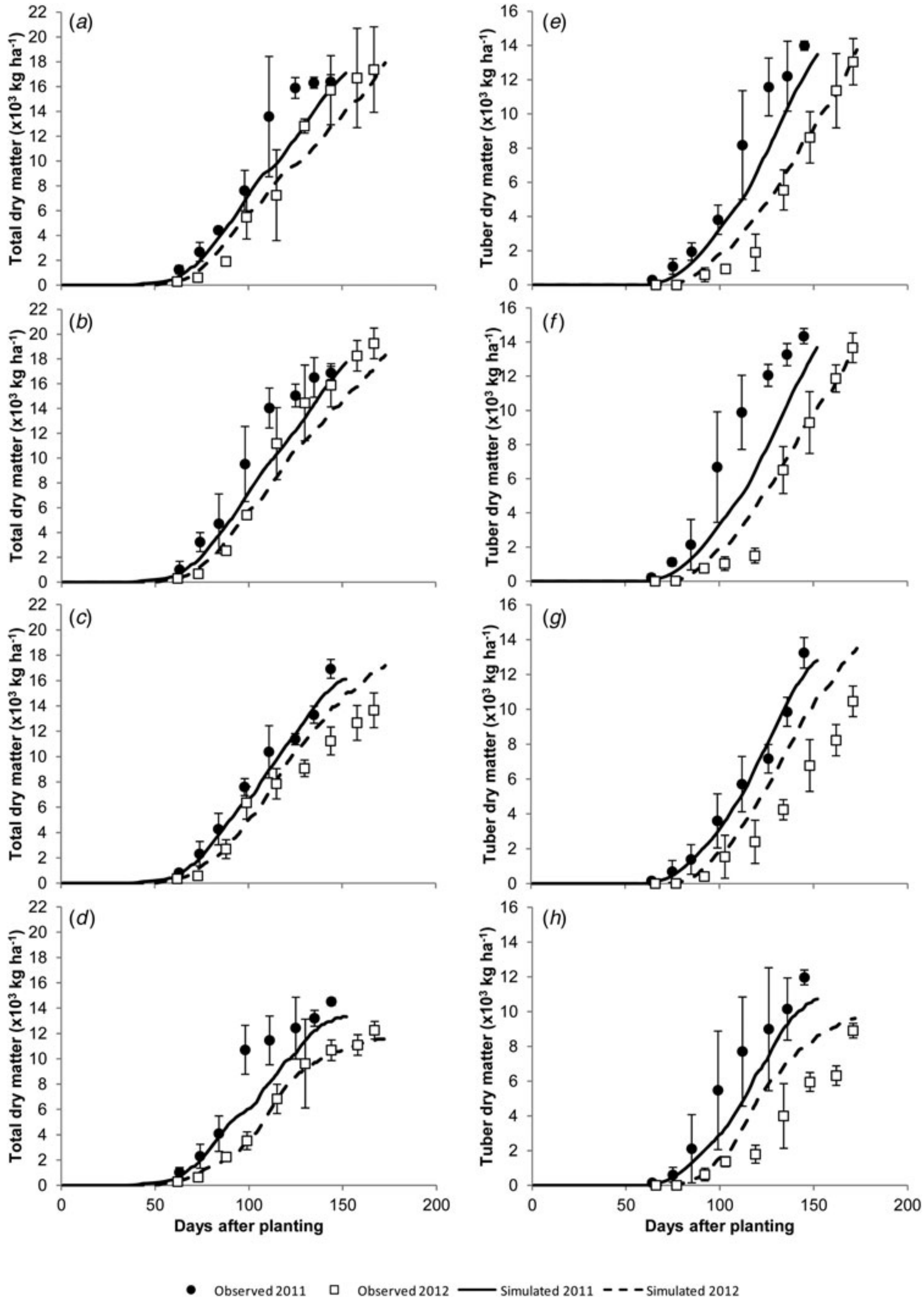

Fig. 1. Progression of simulated and observed total dry matter ((*a*) 120%; (*b*) 100%; (*c*) 80%; (*d*) 60%) and tuber dry matter ((*e*) 120%; (*f*) 100%; (*g*) 80%; (*h*) 60%) during 2011 and 2012 for the different water irrigation treatments. Vertical bars: standard deviation of the average data.

lower than those reported by Griffin *et al.* (1993) (3.5 and 4.0 g/MJ) for several cultivars whose weather conditions were different to that reported in the current experiment. Nevertheless, some information such as initial water content and initial mineral N were not available during calibration and evaluation of the model, being necessary to adjust the RUE factor.

With respect to the differences obtained between HI simulated and observed data for deficit treatments, as well as the low *d* values, SUBSTOR-Potato prioritizes tuber growth ahead of other parts of the plant under water scarcity conditions after the beginning of tuberization (Griffin *et al.*, 1993; Raymundo *et al.*, 2017). This priority may justify the high HI values of the simulated deficit treatments, contrary to other models, such as AquaCrop (Steduto *et al.*, 2009) or CropSyst (Stöckle *et al.*, 2003). In these models, yield is estimated using a reference HI that decreases with the stress level suffered by the crop. The simulated ET values by SUBSTOR-Potato are suitable for the semi-arid conditions of the experimental area. Although ET was slightly over-estimated by SUBSTOR-Potato, the results were similar to those obtained by other authors using dynamic models, such as AquaCrop (Heng *et al.*, 2009) or CropSyst (Stöckle *et al.*, 2003; Benli *et al.*, 2007).

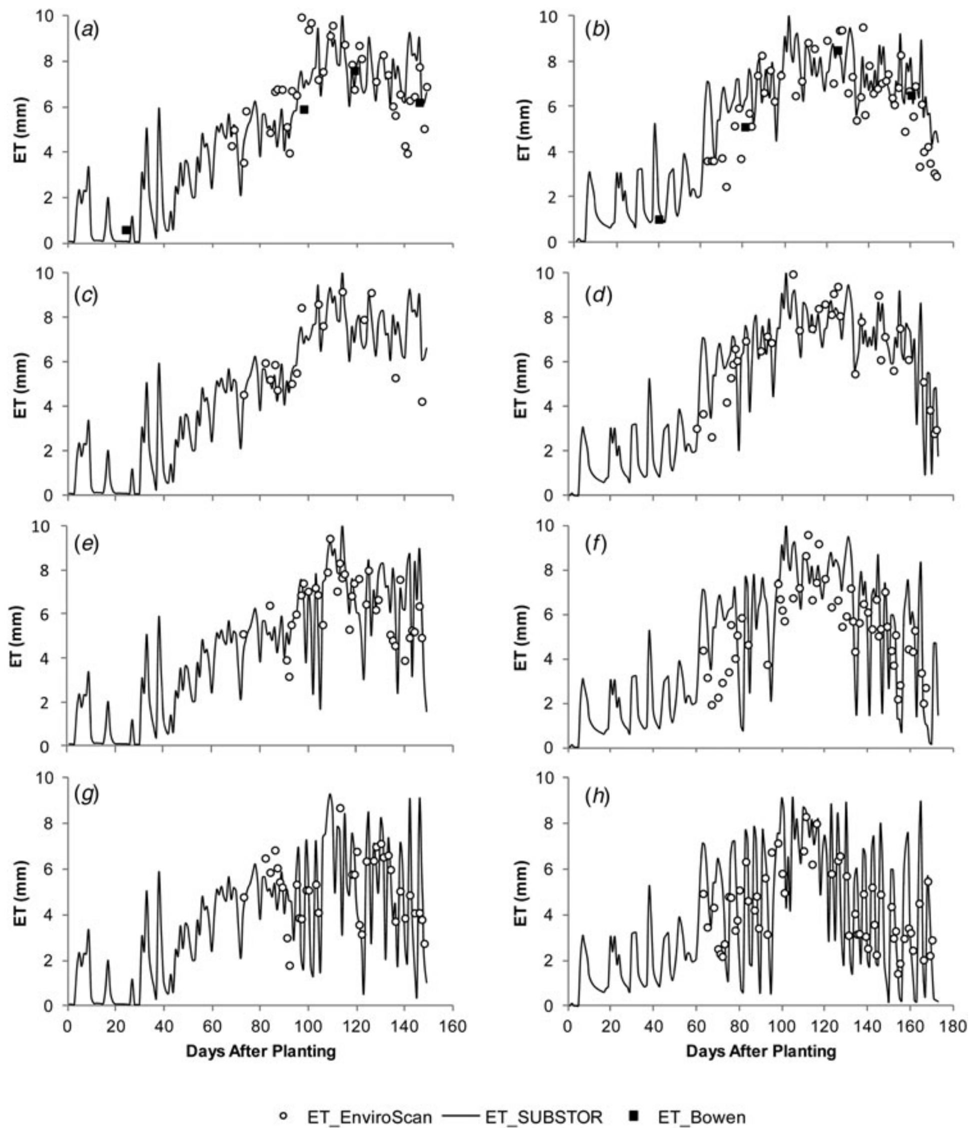

Fig. 2. Simulated, observed (Bowen Ratio device), and calculated (simplified water balance using EnviroScan™ sensors) evapotranspiration in 2011 ((*a*) 120% treatment; (*c*) 100% treatment; (*e*) 80% treatment and (*g*) 60% treatment) and 2012 ((*b*) 120% treatment; (*d*) 100% treatment; (*f*) 80% treatment and (*h*) 60% treatment).

Although the conservative values (RUE, genetic coefficients and water stress) should be similar for any potato cultivar cultivated in any other area in the world, it is not true for RUE, where values were lower than those reported by Griffin *et al.* (1993), as it was evidenced by Camargo *et al.* (2016). However, the genetic coefficients G2, G3, TC, P2 and PD values were similar to those calibrated for other cultivars (Raymundo *et al.*, 2017). Finally, non-conservative values should be used with caution under different climatic conditions and/or cultivars.

Strategies for improving the irrigation water productivity

The high yield results obtained by IS3 and IS4 may be explained by a more efficient use of rainfall and soil moisture than IS1. In fact, the stages in which deficit is caused in those former strategies coincide with the rainfall period in the study area (mainly in the case of IS4). Although IS6 was subjected to a similar level of deficit with respect to IS2 and IS5 during the first three growing stages, it reached a suitable yield, highlighting the importance of avoiding water deficit during tuber formation, including from onset of senescence to harvest. Treatment IS4 also generated a similar conclusion.

These results are in line with those obtained by other authors who, under water scarcity conditions, recommend supplying crops with irrigation water amounts slightly lower than their maximum water requirements (Shock *et al.*, 1998; Fabeiro *et al.*, 2001; Karam *et al.*, 2014; Camargo *et al.*, 2015*b*). This strategy allows increases in irrigation water productivity thanks to lower percolation and better use of the rainfall and soil moisture content. In real farming conditions, the recommended level of deficit for the crop is determined by its profitability. Thus, for highly profitable crops, such as potato, low deficits are recommended (below 10%), while for less profitable crops, such as barley, it could reach up to 30% (Domínguez *et al.*, 2017). Water deficits >10% should be proposed with caution (as demonstrated by IS6), although it would be suitable to use when there is less irrigation water available or when a humid year is forecast as a way to achieve a higher efficiency in the use of rainfall and soil moisture. Therefore, water

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Table 7. Observed and simulated biomass, yield, and harvest index taking into account the effect of the irrigation treatment, cropping season and their interaction

			Biomass (×10^3 kg/ha)			Yield (×10^3 kg/ha)			Harvest index		
		n	Obs.	Sim.	Dev. (%)	Obs.	Sim.	Dev. (%)	Obs.	Sim.	Dev. (%)
Crop water treatment	120%	6[&]	16.89ab	17.51b	3.66	13.61a	13.61a	0.00	0.81a	0.78b	−4.32
	100%	6[&]	18.07a	18.00a	−0.37	13.85a	13.72a	−0.92	0.78ab	0.76a	−2.08
	80%	6[&]	15.29b	16.64c	8.84	11.88b	13.15b	10.63	0.78ab	0.79c	0.86
	60%	6[&]	13.38c	12.48d	−6.76	10.25c	10.21c	−0.40	0.76b	0.82d	7.37
	S.E.M.	–	0.59	0.15	–	0.32	0.11	–	0.01	0.00	–
Year	2011	12[#]	16.18	16.06	−0.75	13.28a	12.67	−4.55	0.83a	0.79a	−4.56
	2012	12[#]	15.64	16.26	3.96	11.52b	12.67	9.99	0.74b	0.78b	5.88
	S.E.M.	–	0.54	0.11	–	0.23	0.08	–	0.01	0.00	–
Main effect	Treatment		**	**	–	**	**	–	*	**	–
	Year		ns	ns	–	**	ns	–	**	*	–
	Treatment × Year		*	**	–	*	**	–	ns	**	–

n: [&], total number of repetitions for the two experimental seasons; [#], total number of repetitions for each experimental season; Obs, average observed value; Sim, average simulated value; Dev, deviation between simulated and observed data; S.E.M., standard error of the mean; ns, not significant; *0.05 > *P* > 0.01; ***P* < 0.01, ANOVA using Duncan's test.

productivity, in terms of the profitability of IS6, did not show differences with respect to the reference strategy (IS1).

In this sense, moderate irrigation deficit during the vegetative stage (IS4) or from tuber initiation to onset of senescence (IS3), allowed similar simulated yields to be achieved compared with the reference scenario (IS1). In these irrigation managements, little or no deficit irrigation was applied (IS3 and IS4, respectively) during tuber formation. Therefore, this stage was revealed to be the most sensitive to water deficit and stress should be avoided during this period, as also concluded Fabeiro *et al.* (2001), Karam *et al.* (2014) and Daryanto *et al.* (2016).

The simulated potato yield for the IS4 strategy is in agreement with Fabeiro *et al.* (2001), who achieved a potato yield with the same IS even higher than the reference treatment (IS1). Regarding the IS3 strategy, Karam *et al.* (2014) found no significant yield differences from the control treatment. In contrast, the potato yield simulated by IS2 was comparatively lower with respect to the result attained by Camargo *et al.* (2015*b*), where this treatment received a higher amount of water that may be the cause of the yield differences. As regards the IS5 strategy, Fabeiro *et al.* (2001) also achieved low yield and medium/high WPY. Camargo *et al.* (2015*b*) and Fabeiro *et al.* (2001) stated values between 8.5 and 8.9 kg/m^3, which are similar to those in the current study.

The current study also highlights the convenience of using methodologies for determining the most appropriate regulated deficit ISs. In this sense, in many crops managed using the optimized regulated deficit irrigation strategy (ORDI) (Domínguez *et al.*, 2012*b*), i.e. when water is supplied at 10–20% less than CWRs, WPY reaches higher values than those under no deficit conditions, such as maize (Domínguez *et al.*, 2012*b*), onion (Domínguez *et al.*, 2012*a*), garlic (Domínguez *et al.*, 2013), melon (Leite *et al.*, 2015) and carrot (Léllis *et al.*, 2017). The use of this methodology in cropping systems similar to those proposed by Domínguez *et al.* (2017) may reach a similar profitability increase (by 2.8% on average thanks to a higher WPP; Domínguez *et al.*, 2017).

Conclusions

The parametrization of SUBSTOR-Potato model (4.6 version) for cultivar Agria reached a suitable goodness of fit for date of tuber initiation, total biomass, crop yield and ET (index of agreement >0.90 and low RMSE). Therefore, SUBSTOR-Potato can be used as a DSS for the management of this cultivar in semi-arid areas. Simulations carried out for 30 growing seasons highlighted that slight water deficit levels (<10%) increase the irrigation water productivity in terms of yield, thanks to low or no effect on final yield. Causing slight water deficit to the crop may be used for increasing water productivity in terms of profitability, which allows an increase in the income of irrigated farms located in areas where water is scarce. Finally, it is not advisable to cause water deficit during tuber formation, since it was the most sensitive stage.

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Conflict of interest. The authors declare that there are no conflicts of interest.

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