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The SALTMED model calibration and validation using field data from Morocco

A. Hirich [1*], R. Choukr-Allah [1], R. Ragab [2], S-E. Jacobsen [3]
L. El youssfi [4], H. El omari [1]

[1] *Agronomic and Veterinary Hassan II Institute, Complex of Horticulture, Agadir, Morocco.*
[2] *Center for Ecology and Hydrology, Wallingford, UK*
[3] *University of Copenhagen, Faculty of Life Sciences, Department of Agriculture and Ecology, Denmark.*
[4] *National school of applied ascience, University Ibn Zohr, Agadir, Morocco.*

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* Corresponding author. A. Hirich, Email: hirich_aziz@yahoo.fr, Tel: +212 673 53 09 63, Fax: +212 528 242243

Abstract
The objective of this study was to calibrate and validate the SALTMED model using field data of three growing seasons of quinoa (*Chenopodium quinoa* Willd.), chickpeas *(Cicer arietinum)* and sweet corn (*Zea mays* Saccharata) which were grown in the south of Morocco and subjected to six treatments of deficit irrigation with treated wastewater.
The calibration focussed primarily on soil moisture related to quinoa in the field, measured yield and dry matter. The validation process of biomass production was based on use of the calibrated photosynthesis efficiency value of the control treatment. Plant parameters such as plant height and rooting depth, duration of each growth stage, sowing date, harvesting date, harvest index and leaf area index were based on field measurements and records. Crop coefficients Kc, Kcb, Fc were based on FAO56 paper. Soil parameters such as water retention curves were based on laboratory measurements. Initial soil water content and salinity were based on measurements either in the laboratory or in the field. Fine tuning of some crop and soil parameters was carried out in order to obtain a good calibration.
Following successful calibration and validation, the SALTMED model proved its ability to predict soil moisture, yield and total dry matter for three growing seasons under several deficit irrigation strategies using treated wastewater. The model showed a very good agreement between the observed and simulated data, as well as being able to reveal the same difference between deficit irrigation strategies in terms of measured yield and total dry matter.

Key words: Deficit irrigation, soil moisture, quinoa, chickpea, sweet corn, yield

1. Introduction
Demographics and the increasing consumption that comes with rising per capita incomes are important drivers on water demand. Agriculture is, by far, the largest consumer of freshwater with about 70% of all freshwater withdrawals going to irrigated agriculture. Water scarcity may limit food production and supply, putting pressure on food prices and increasing countries dependence on food imports [1]. Production and productivity must be increased to meet rapidly growing demands, while natural resources must be protected. New agricultural research is needed to supply information to farmers, policy makers and other decision makers on how to accomplish sustainable agriculture within wide variations in climate around the world [2].
Crop models have the capability to predict crop development and grain yield as influenced by climatic conditions, soil characteristics, and agricultural practices. Modelling is becoming a more and more efficient tool in the management of water resources. Models can provide quantitative estimates of grain yield under

different environmental conditions, as well as simulation of water and nutrients balance. They may also be used to test the crop response to environmental stresses, e.g. drought and salinity [2 - 9].
SALTMED model has been developed for such generic applications. The model employs established water and solute transport, evapotranspiration and crop water uptake equations [4]. The SALTMED model has been calibrated using drip irrigation water treatment in Syria and Egypt, primarily focused on yield prediction [6].
Quinoa (*Chenopodium quinoa* Willd.) is an Andean crop well adapted to poor soil and unfavourable climatic conditions [10 – 11]. It has the ability to tolerate high levels of frost [12 – 13], drought [14 - 15] and salinity [16 – 20]. The high nutritional value and protein content is one of the important characteristics of this crop [21 - 23]. Quinoa is a facultative halophyte [24] and has been shown to grow in extreme, saline conditions with a soil electrical conductivity of up to 52 dS m^{-1} [25]. A Bolivian cultivar Utusaya was able to maintain K^+/Na^+ and Ca^+/Na^+ selectivity in the leaf tissue under saline treatment [20]. It was demonstrated recently [26 – 27] that increasing salinity decreased seed radiation use efficiency, seed yield, harvest index and number of seeds, and increased transpiration water use efficiency and radiation use efficiency of straw significantly. A significant difference existed in the responses of different quinoa varieties to salinity, which suggests a potential for selection and breeding of quinoa for its cultivation in a range of salt affected areas.
Chickpea is normally grown as rainfed crops on marginal areas, where they often suffer from drought and salinity stresses. Considerable variability exists with respect to yield and stress tolerance among species and accessions. It is affected by drought during early and reproductive stages of growth, so supplemental irrigation during those periods will reduce pod abortion and is expected to have a significant impact on final yield. The adaptation of chickpea and other grain legumes to water limited Mediterranean conditions comprises various mechanisms. In the arid conditions of the Mediterranean countries chickpea has demonstrated deep roots, osmotic adjustment, and a general high level of drought resistance and cold tolerance. A serious disease in chickpea is Ascochyta blight in temperate areas, and Fusarium in warmer climates, controlled through agronomic management [28].
Different grain legumes respond differently to salinity (NaCl, $CaCl_2$) [29]. The drought sensitive varieties are able to maintain water use efficiency when irrigated with saline water due to larger biomass production owing to late senescence and late flowering. These characteristics may be useful for identifying salt-tolerant varieties of grain legumes. Moderate tolerance was found in soybean and faba bean, and least tolerance was found in chickpea and lentils [30].
Field corn was grown in North America before 200 B.C. Field corn is produced primarily for animal feed and industrial uses such as ethanol, cooking oil, etc. In contrast, sweet corn is produced for human consumption as either a fresh or processed product. The specific time when sweet corn originated cannot be pin-pointed; however, sweet corn was grown by the American Indian and first collected by European settlers in the 1770's. The first variety, Papoon, was acquired from the Iroquois Indians in 1779 [31]. According to Smith *et al*. [32], temperatures for optimal germination of sweet corn seed are 18°C and above. Optimal temperatures for growth are 16° to 24°C, with 10°C as a minimum and 35°C as a maximum, Sweet corn is available as yellow, white, or bicolored ear types. Cultivars vary in their days to maturity; they are classified as early, mid, and late season [33].
Many studies have reported that under scarce availability of water, higher water use efficiency can be realized by compromising on productivity and by irrigating at deficit levels of water supply. However, as a response to water deficit, yield was reduced [34 – 37]. Based on the results found by Farré and Faci [38] we can conclude that it is possible to implement deficit irrigation strategies for reducing agricultural water use by increasing the interval between irrigations during the periods other than around flowering. Nesmith and Ritchie [39] have reported that stressing the maize crop during grain filling stage lead to yield reductions ranging from 21% to 40%, with kernel weight being the most affected component.
The objective of this study was to calibrate and to validate the SALTMED model using field data of three growing seasons of quinoa, chickpeas and sweet corn which were grown in the south of Morocco and subjected to six treatments of deficit irrigation with treated wastewater.

2. Materials and methods

2.1. Brief description of the SALTMED model

The SALTMED model [4], which was designed to be generic, physically based, and friendly to use and includes a number of physical processes acting simultaneously under field conditions, was evaluated in experimental work. The model, under all irrigation systems, incorporates: evapotranspiration, plant water uptake, water and solute transport and crop yield and biomass production based on a relationship between

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water uptake and biomass. Two target sites in Egypt and Syria were chosen to cover different hydrological conditions [2, 5, 6].

2.2. The experimental design

The experiment was performed on the IAV-CHA farm in Agadir. Three crops were cultivated: quinoa (Var. D0708), sweet corn (Var. 7210R) and chickpeas (local variety).
The design was completely randomized with 6 treatments and 4 repetitions, that is a total of 24 plots (Table 1 and Figures 1 and 2).

Table 1**.** Deficit irrigation treatments, percentage of full irrigation

Treatment	**Germination**	**Vegetative**	**Flowering**	**Grain filling**	**Senescence**
T1 (control)	100	100	100	100	0
T2	100	50	50	50	0
T3	100	100	50	100	0
T4	100	100	100	50	0
T5	100	50	100	100	0
T6	100	50	50	100	0

For the application of irrigation, a drip irrigation system was installed with two different discharges: 2 l/hr to apply 100% of the maximal evatranspiration (ETm) and 1 l/hr to apply 50% of ETm. The plot dimensions are shown in Figure 2.

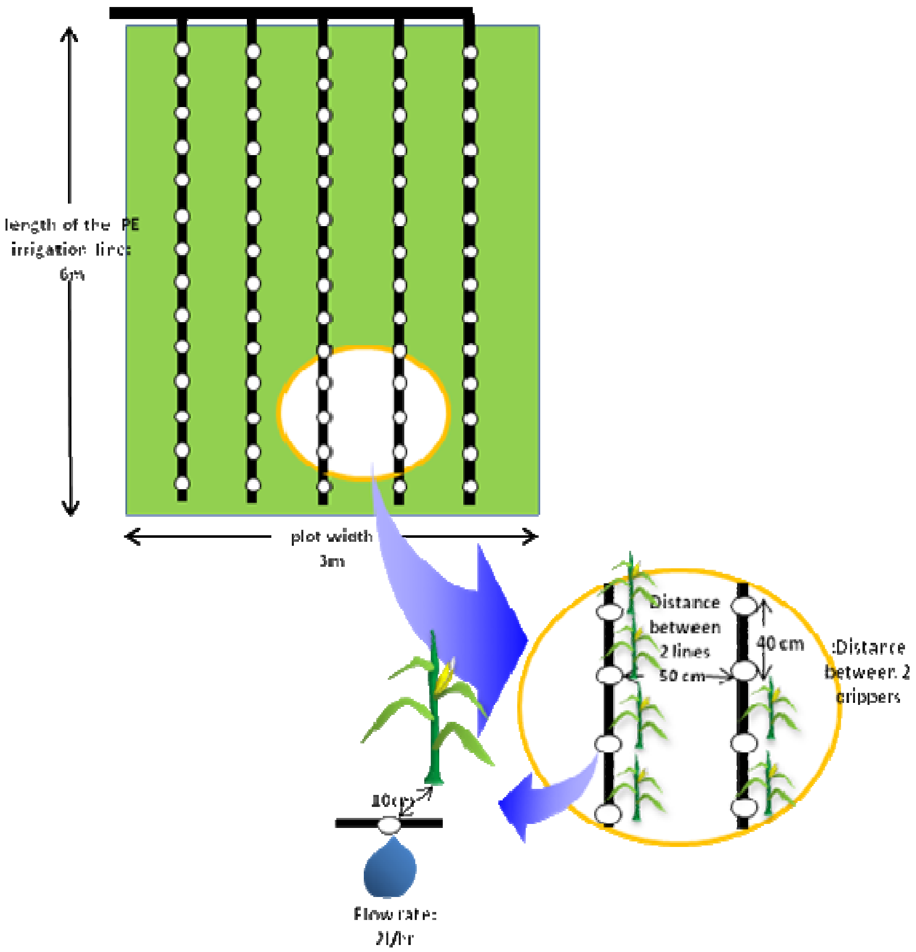

Figure 1. Experiment design at the plot scale

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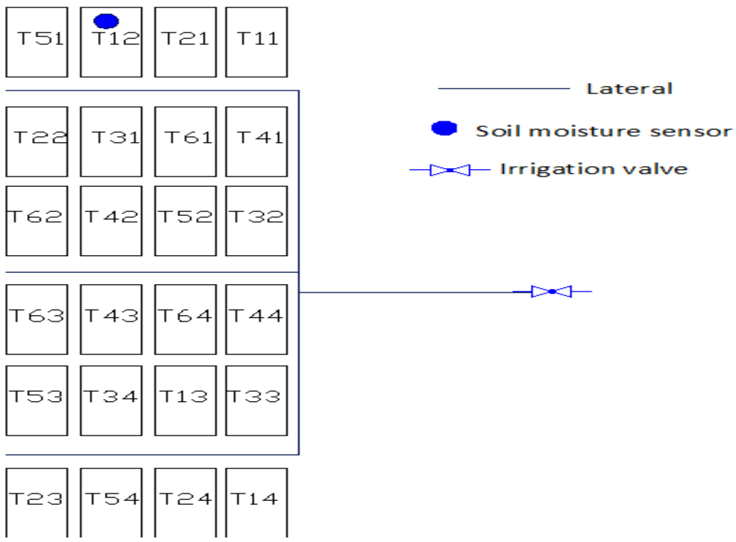

Figure 2. Experimental design at the crop field scale

2.3. Soil analysis

The physical and chemical soil properties are given in Tables 2 and 3 respectively.

Table 2. Soil texture and organic matter analysis

Parameters		**0 – 20 cm**	**20 – 40 cm**	**40 – 60 cm**
Particle size distribution (%)	Coarse sand 200µm to 2mm	07.34	06.88	06.01
	Fine sand 50 to 200 um	33.01	39.28	36.92
	Coarse silt 20 to 50 um	19.71	19.34	17.78
	Fine silt 2 to 20 um	19.25	18.80	20.45
	clay 0 to 2 um	20.70	15.70	18.85
Texture		Loamy	Loamy	Loamy
Organic Matter	%	01.34	02.02	01.41

Table 3. Soil chemical analysis

Parameters		**0 – 20 cm**	**20 – 40 cm**	**40 – 60 cm**
pH		08.00	08.30	08.70
EC[1]	mmhoscm^{-1}	00.24	00.18	00.09
NO_3^-	ppm	14.50	08.90	07.00
Total P_2O_5		130.00	163.00	206.00
Total K_2O		572.00	783.00	1024.00
Na_2O		77.00	39.00	39.00
CaO		2439.00	2800.00	2981.00
MgO		461.00	415.00	465.00
Fe		08.50	08.70	07.90
Mn		02.50	01.60	02.40
Cu		01.20	01.20	01.90
Zn		11.00	13.10	06.80
CEC	meq/100 gr of soil	20.80	18.00	22.00

[1] The soil electrical conductivity was measured using the 1:5 method

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The soil texture was loamy, and was moderately rich in organic with high pH and low electric conductivity (EC).

2.4. Irrigation water analysis

The irrigation water analysis is given in Table 4.

Table 4. Treated wastewater analysis

Parameter	**Content in mg.l^{-1}**
NH_4^+	64.80
NO_3^-	99.20
P	15.00
K	08.19
Ca	66.80
Na	51.29
Cl	101.50
Mg	39.60
Total suspended matter	55.46
Suspended mineral matter	29.20
pH	07.77
EC (µscm^{-1})	1448

Irrigation water was a treated wastewater, very rich in nutrients, since 1000 m^3 can provide 22 kg of nitrogen, 15 kg of phosphorus and 8 kg of potassium.

2.5. Soil moisture sensing: telemetry system

The water quantity required by each treatment was supplied, as any control loss in treatment application or soil moisture sensing will affect negatively the experiment results.

Two kinds of telemetry system were installed: short and long range telemetry (Figure 1 a). The short range telemetry is based on the installation of a capacitance based continuous logging probe (AquaCheck Wireless Probe ACBIIW) in the control plot (Figure 1 b1). These sensors can be controlled by a mobile datalogger (AquaCheck BII Logger) (Figure 2 b1) which collects data automatically, from a maximum of 6 depths (10, 20, 30, 40, 50 and 60 cm) (Figure 1 b2). In each soil depth is achieved moisture and temperature, the data downloaded can be transferred to the computer in which they can be analyzed by a special program CropGRAPH.

In the long range telemetry a fixed sensor with analogical output was used, combined with other sensors for monitoring climate or plants. The communication was made in two different ways, by radio from the field to the server and by GPRS (General Packet Radio Service) that offer unlimited access to data via the internet where the graphs related to the soil moisture was showed and treated by addVANTAGE Pro 5.4.

2.6. Soil solution extraction using suction cup lysimeters

Suction cup lysimeters allowed the characteristics of the soil solution in the root zone (soil depth: 25 cm) to be followed; especially EC, pH, and nitrate (NO_3^-) during all the stages of crop growth. Before the extraction of the soil solution a depression in the lysimeter of 70 cBar must be achieved, this being the same pressure as the one at which the plant absorbs the soil solution. This solution is then taken to the laboratory for analysis.

2.7. Data requirements

Plant characteristics include, for each growth stage; the crop coefficients, Kc, Kcb [41], root depth and lateral expansion, crop height, and maximum and potential final yield observed in the region under optimum conditions (control treatment).

Soil characteristics include depth of each soil horizon, saturated hydraulic conductivity, saturated soil water content, salt diffusion coefficient, longitudinal and transversal dispersion coefficients, initial soil moisture and

salinity profiles, and tabulated data of soil moisture versus soil water potential and soil moisture versus hydraulic conductivity.
Meteorological data include daily values of maximum temperature, minimum temperature, relative humidity, net radiation, wind speed, and daily rainfall. Those data were provided by the meteorological station of IAV-CHA, located 100 m from the experimental site.
Water management data include the irrigation date, the amount of irrigation water applied, and the salinity level of the irrigation water at each irrigation time.

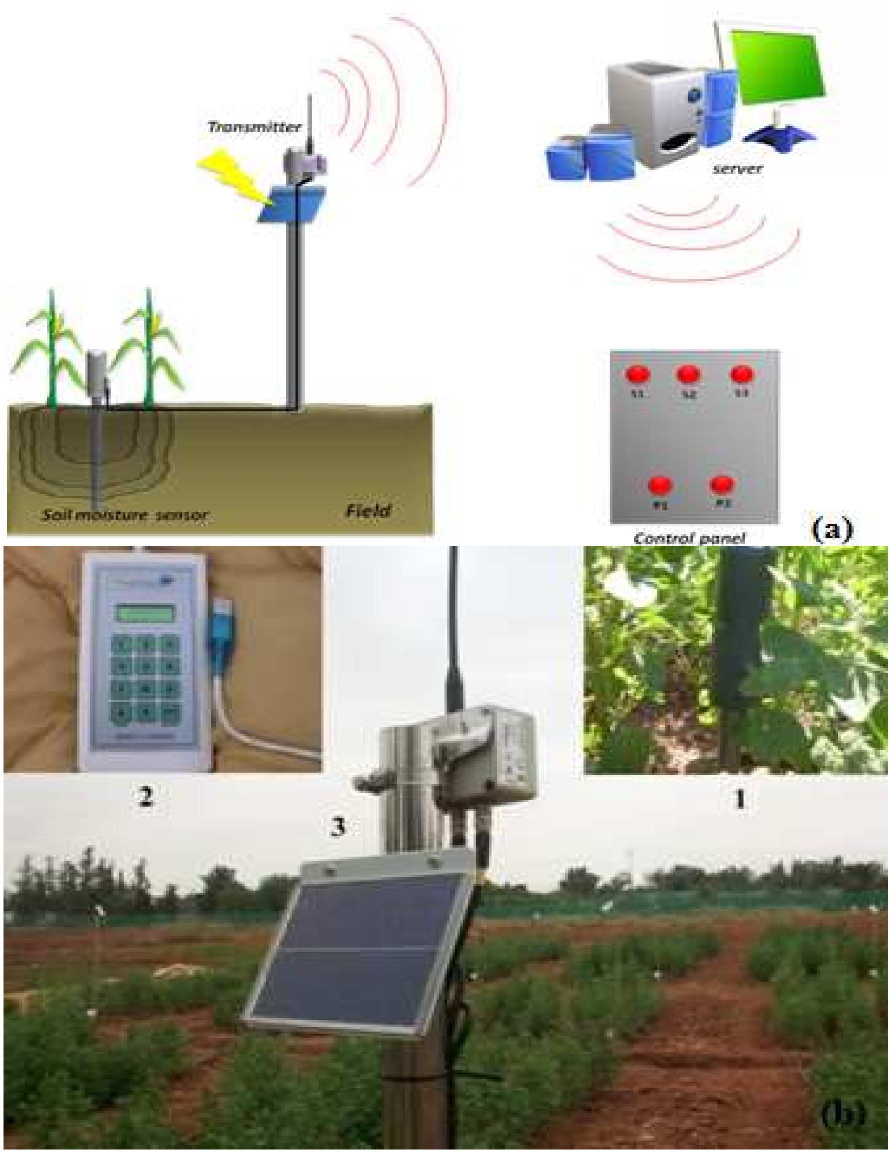


Figure 1. Long range telemetry system design (a), soil moisture sensor (b1), Datalogger (b2) and soil moisture data transmitter (b3) [40]

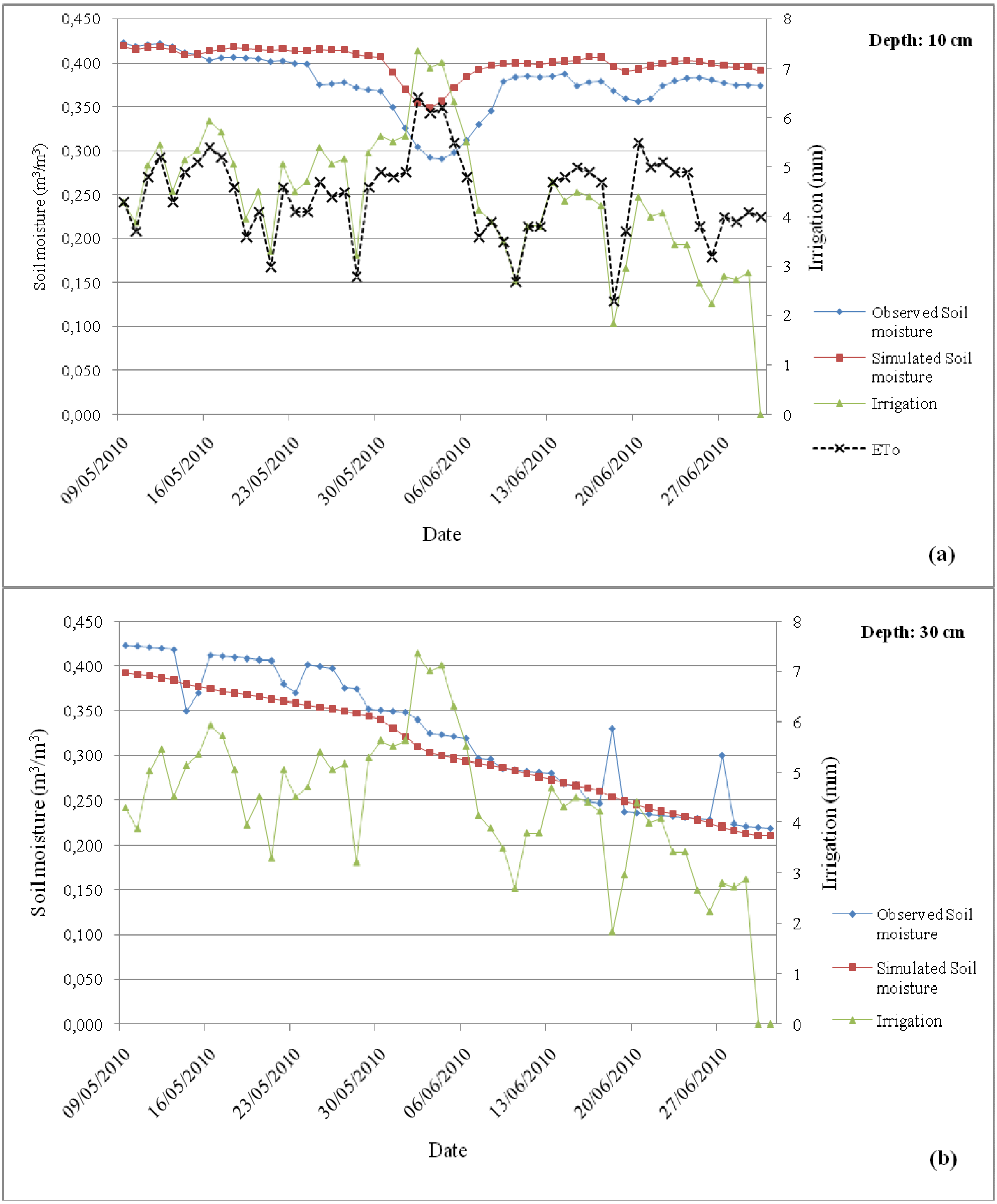
3. Results and discussion

3.1. Soil moisture calibration

Since soil moisture is difficult to calibrate, the calibration for this variable was carried out first. Some unmeasured soil parameters such as pore size distribution index, lambda, saturated hydraulic conductivity, residual water content and bubbling pressure needed to be adjusted. The saturated moisture content, soil moisture at field capacity and wilting point were measured in the laboratory using a pressure cell, which measures water retention up to the potential -1500 kPa (wilting point). Air pressures are imposed on initially saturated soil samples placed on very fine porous ceramic plate.

The original soil moisture data recorded by the capacitance-based sensors were calibrated against the gravimetric soil moisture measured in the laboratory using soil samples from each depth. The bulk density was measured for each sample and multiplied by the gravimetric moisture in order to obtain the volumetric soil moisture expressed in m^3 of water per m^3 of soil.

The soil moisture calibration was carried out for the treatment control of quinoa, where the sensors were installed. In the model application, the simulated soil depth was divided into 3 layers with different initial soil moisture. Figure 4 shows the amount of irrigation water supplied, ETo (Figure 4 a) and the observed and simulated soil moisture for the 10, 30, 40 and 50 cm depths. Figure 5 shows the correlation between the observed and simulated soil moisture.



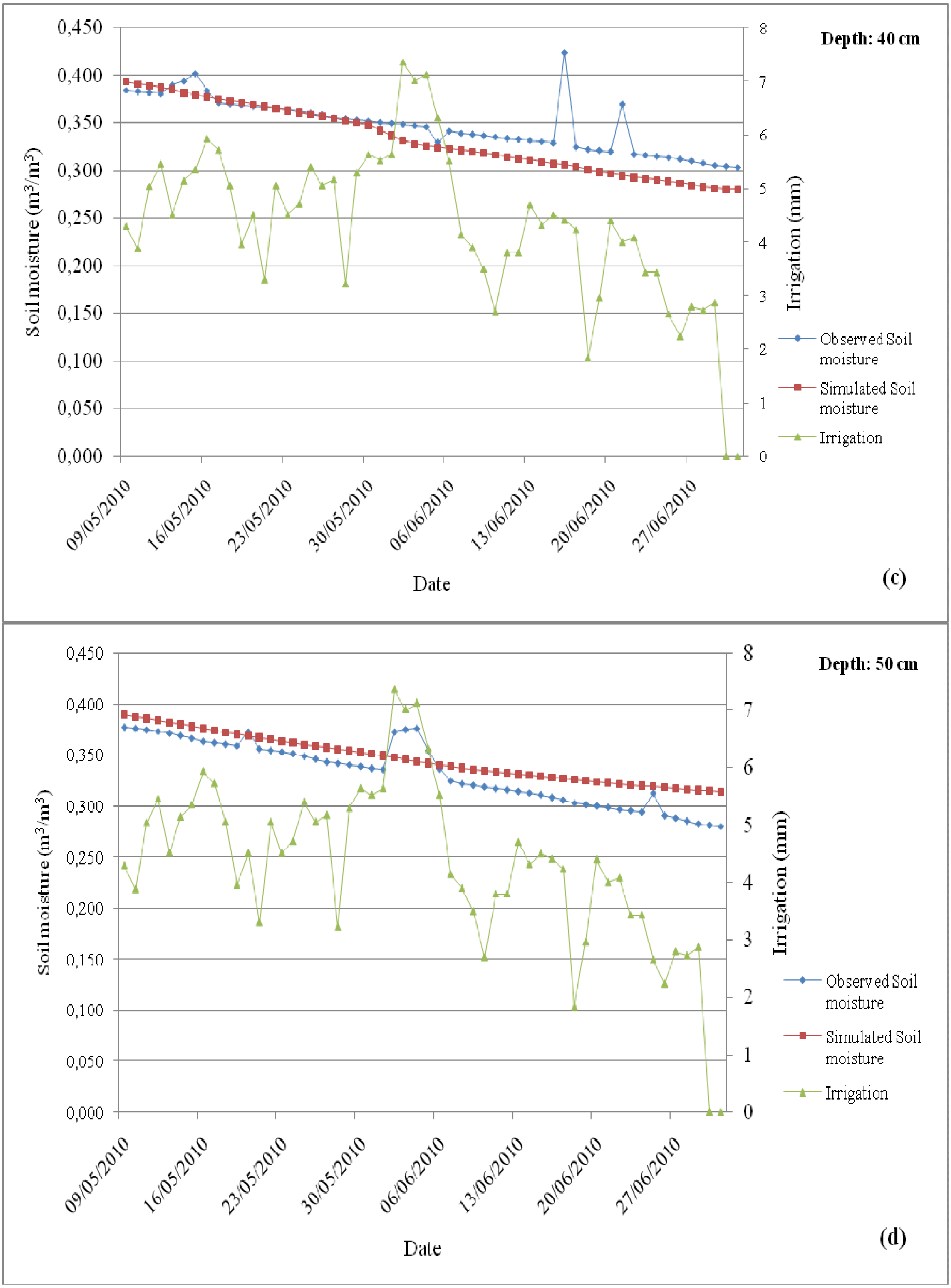
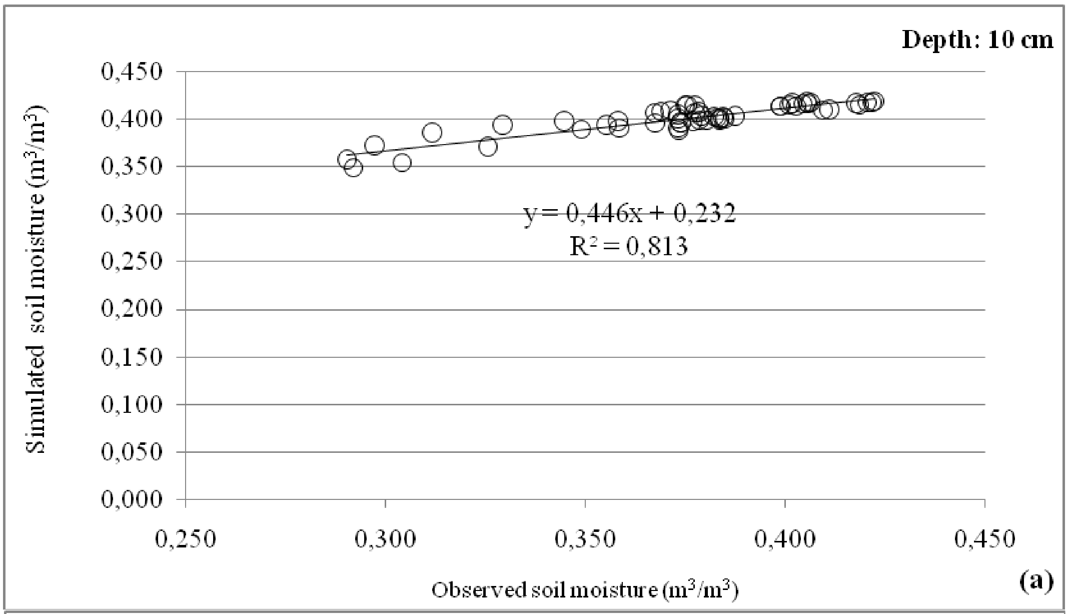
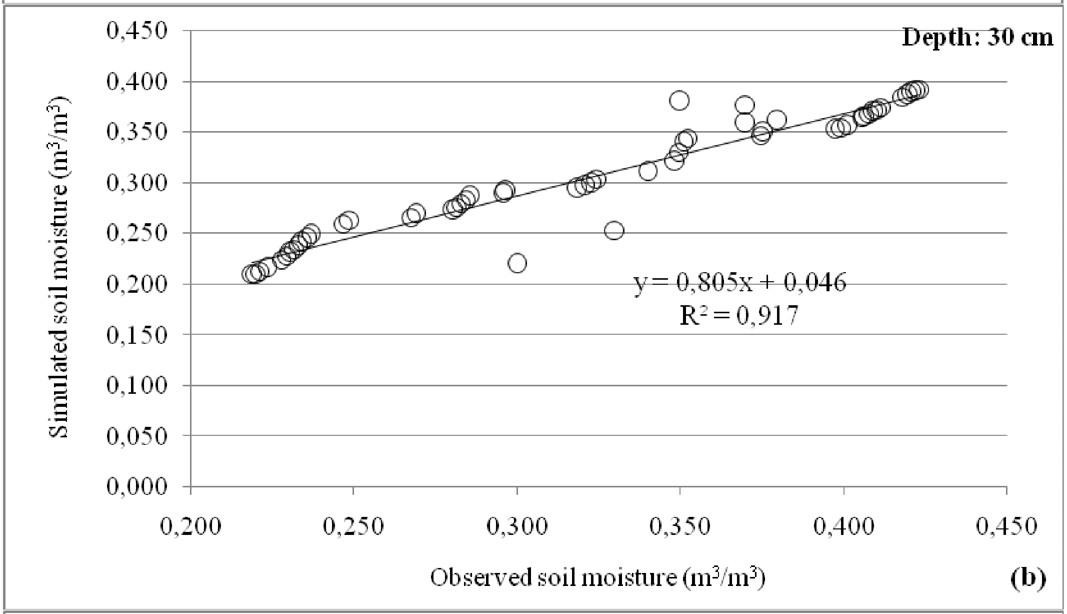
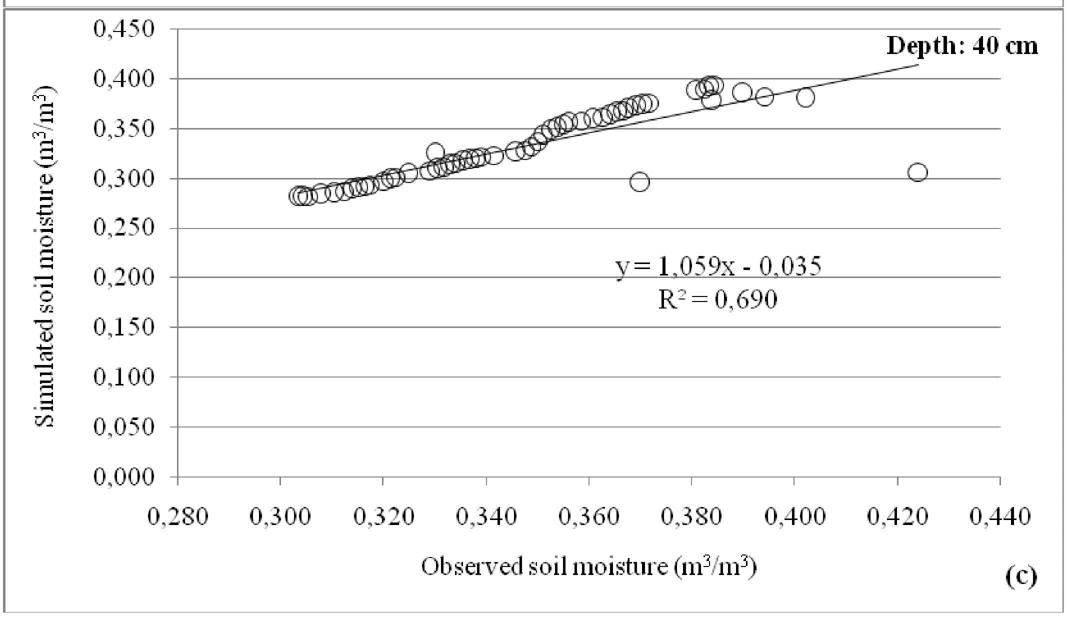


Figure 4. Observed and simulated soil moisture at 10 cm (a), 30 cm (b), 40 cm (c) and 50 cm (d)


Depth: 10 cm
0,450
0,400
0,350
0,300
0,250
0,200
0,150
0,100
0,050
0,000
0,250
0,300
0,350
0,400
0,450
Simulated soil moisture (m3/m3)
Observed soil moisture (m3/m3)
y = 0,446x + 0,232
R² = 0,813
(a)


Depth: 30 cm
0,450
0,400
0,350
0,300
0,250
0,200
0,150
0,100
0,050
0,000
0,200
0,250
0,300
0,350
0,400
0,450
Simulated soil moisture (m3/m3)
Observed soil moisture (m3/m3)
y = 0,805x + 0,046
R² = 0,917
(b)


Depth: 40 cm
0,450
0,400
0,350
0,300
0,250
0,200
0,150
0,100
0,050
0,000
0,280
0,300
0,320
0,340
0,360
0,380
0,400
0,420
0,440
Simulated soil moisture (m3/m3)
Observed soil moisture (m3/m3)
y = 1,059x - 0,035
R² = 0,690
(c)

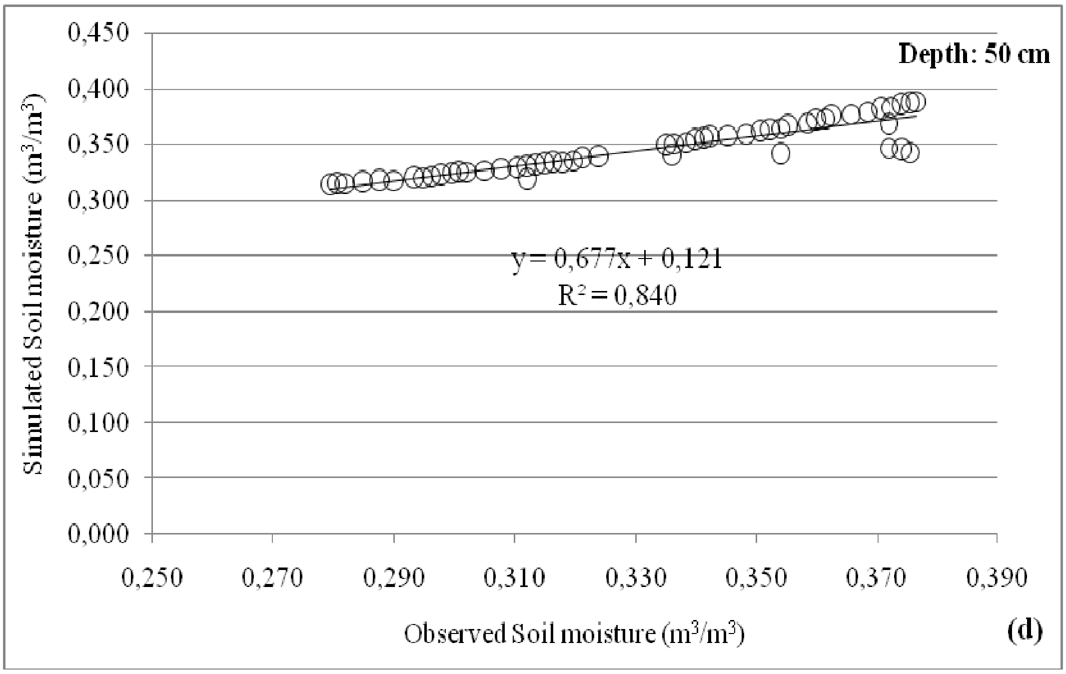


Figure 5. Correlation between observed and simulated soil moisture at 10 cm (a), 30 cm (b), 40 cm (c) and 50 cm (d) of depth

It was observed that there was more variation in soil moisture in the 0 – 10 cm layer, compared with the rest of the profiles. This is due to more dynamic and faster processes operating at the surface (infiltration, evaporation and plant water uptake). It is known that when irrigating with drip irrigation in a loamy soil, plants tend to develop their root system in the upper zone (10 – 20 cm) [42, 43]. The top layer is also more prone to water loss by evaporation. The irrigation scheduling method was focusing on bringing water inside a rooting depth of about 25 cm, accepting a depletion of 10% of effective water storage (Hcc-Hpfp) to determine the number of irrigation frequencies.
During the middle of the crop cycle a reduction in soil moisture at 10 cm depth was recorded. This was due to evaporation rather than to water uptake by the crop, as the ETo during this period was very high. For the other depths (30, 40 and 50 cm) the modelled and measured soil moisture decreased slightly during the crop cycle. This was in response to water uptake, which increased as the crop grew, and also in response to irrigation supplied, which was decreased as Kc decreased, especially during the later stages.
For all depths there was a very good agreement between simulated and observed soil moisture. In most cases the R^2 was over 80%. The R^2 of 69% for the 40 cm depth was relatively low. This is because measurements at 2 points disturbed the correlation as a result of irrigation excess or measurement error due to existence of stones or earthworms galleries.

3.2. Dry matter and yield calibration and validation

The calibration method aimed at adjusting the photosynthesis efficiency as a crop growth parameter of the model until a minimal difference between observed and modelled yield had been achieved. The calibrated photosynthesis efficiency value of the control treatment (well irrigated) was used in the validation of the other treatments. Harvest index, yield, total dry matter, leaf area index (LAI), and crop stage duration were measured in the field. Photosynthesis efficiency is the only parameter which was estimated and adjusted during the calibration.

3.2.1. Quinoa yield

Generally there was a very good agreement between the measured and simulated quinoa yield (Figure 6). Under different deficit irrigations, the results showed a very highly significant difference between treatments in terms of yield. This difference was mainly due to differences in terms of LAI in response to applied drought stress degrees. The photosynthesis efficiency that was applied for validation is equal to 1.64 g/MJ.

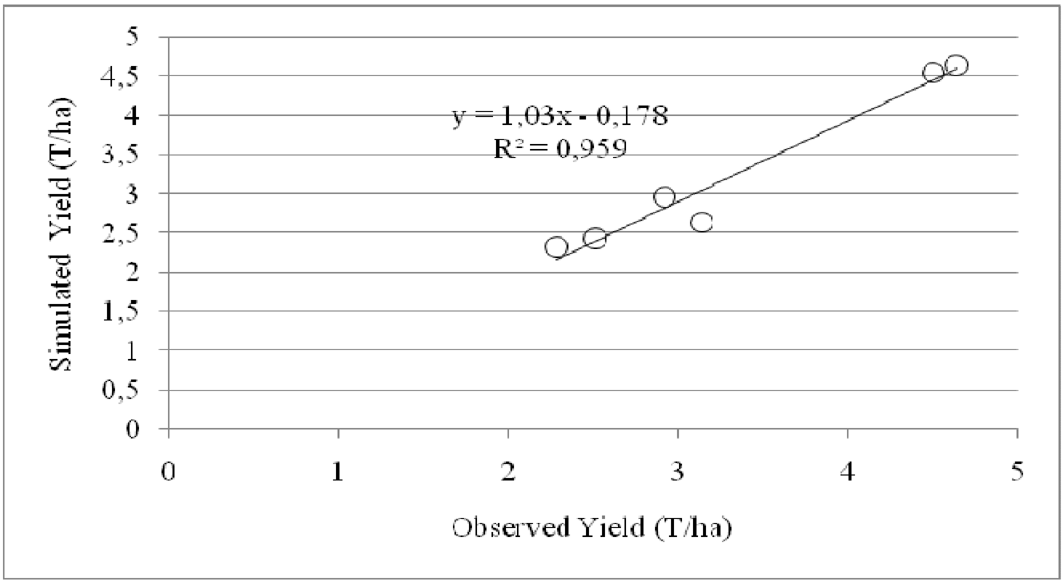


Figure 6. Correlation between observed and simulated yield of quinoa

According to Table 5 the model has successfully predicted the yield in response to deficit irrigation with treated wastewater, even without adjusting the measured LAI. In most cases, the relative error was less than 5%. Treatment Q5 showed the highest water productivity. Under that treatment plants were subjected to water deficit during the vegetative growth stage, and in response to drought stress the crop developed preferentially its root system. The plants devoted most of their biomass to the roots (the ratio of root/shoot was in favour of roots) while during the well watered period, the plants developed their leaf area (as the root/shoot ration was in favour of shoots). This explains why the yields, and the water productivity, were high [15, 44, 45].

Table 5. Harvest Index , yield and water productivity of quinoa

Treatment	Harvest Index	Observed Yield	Simulated Yield	Relative Error (%)	Irrigation +Rainfall (27mm)	Observed Water Productivity	Simulated Water Productivity
Q1 fully irrigated	0.39	4.64	4.64	0.00	384	1.20	1.20
Q2 fully stressed	0.25	2.28	2.32	-1.75	205	1.11	1.12
Q3 stressed in Fl, 50%	0.32	3.14	2.63	16.24	352	0.89	0.74
Q4 stressed in G.F, 50%	0.24	2.92	2.96	-1.37	306	0.95	0.96
Q5 stressed in V.G, 50%	0.39	4.50	4.54	-0.89	315	1.42	1.44
Q6 stressed in V.G and Fl, 50%	0.24	2.51	2.43	3.19	283	0.88	0.85
			Average	**2.57**			

Fl = flowering, G.F. = grain filling, V.G. = vegetative growth

3.2.2. Quinoa total dry matter

During the crop cycle agronomic parameters were measured on 3 occasions. Figure 7 shows the observed and simulated total dry matter at different dates. Figure 8 shows the correlation between observed and simulated total dry matter. Here again the SALTMED model has been successful to predict dry matter production over time and there was a very good agreement (R^2 = 98%) between observation and simulation.

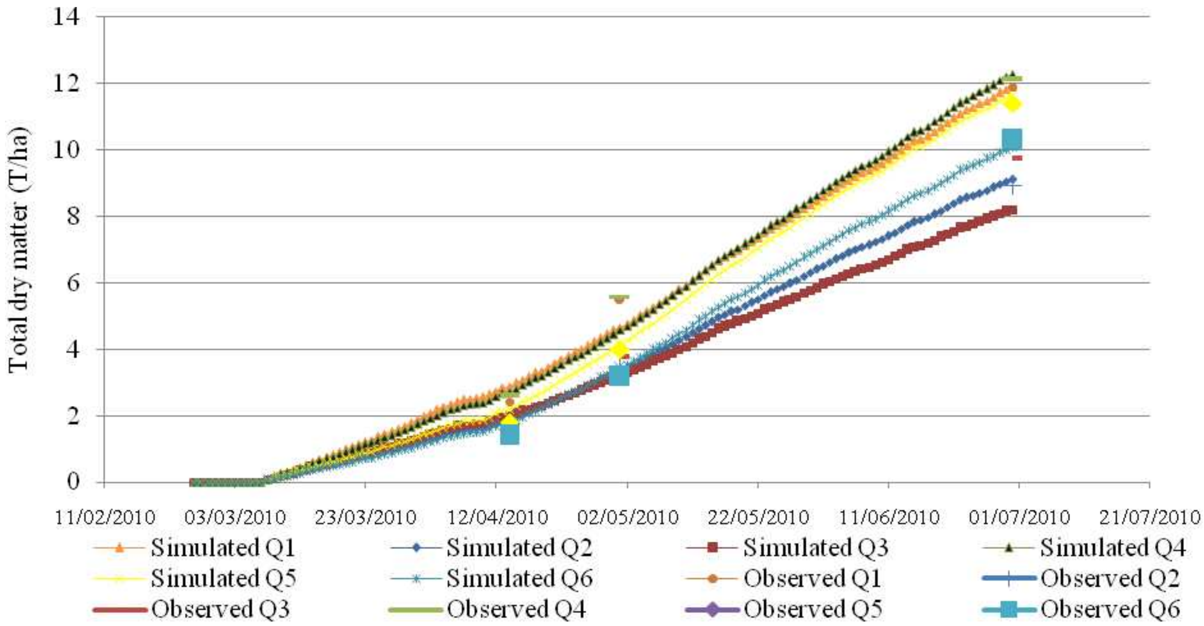


Figure 7. Observed and simulated total dry matter production during the crop cycle of quinoa

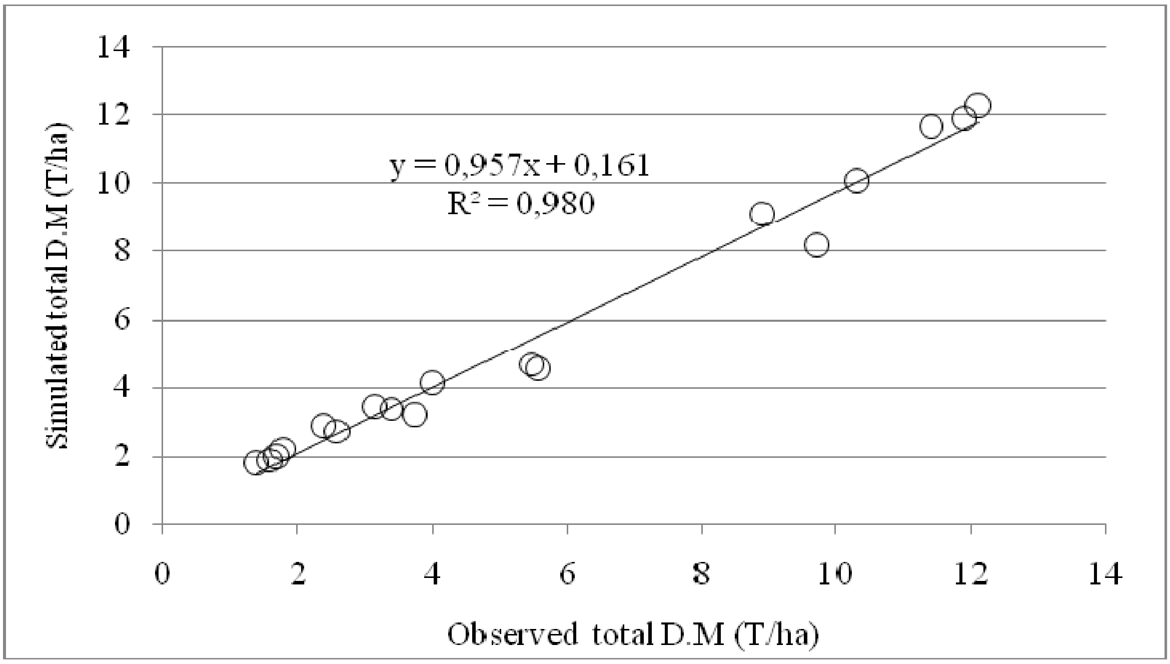


Figure 8. Correlation between observed and simulated total dry matter of quinoa

3.2.3. Chickpea yield

The simulated yield of chickpeas under drip irrigation when applying deficit irrigation with treated wastewater, showed a very good agreement with the observed data. The SALTMED model, using photosynthesis efficiency equal to 2.125 g/MJ for validation was able to predict the yield under field conditions (Figure 9).

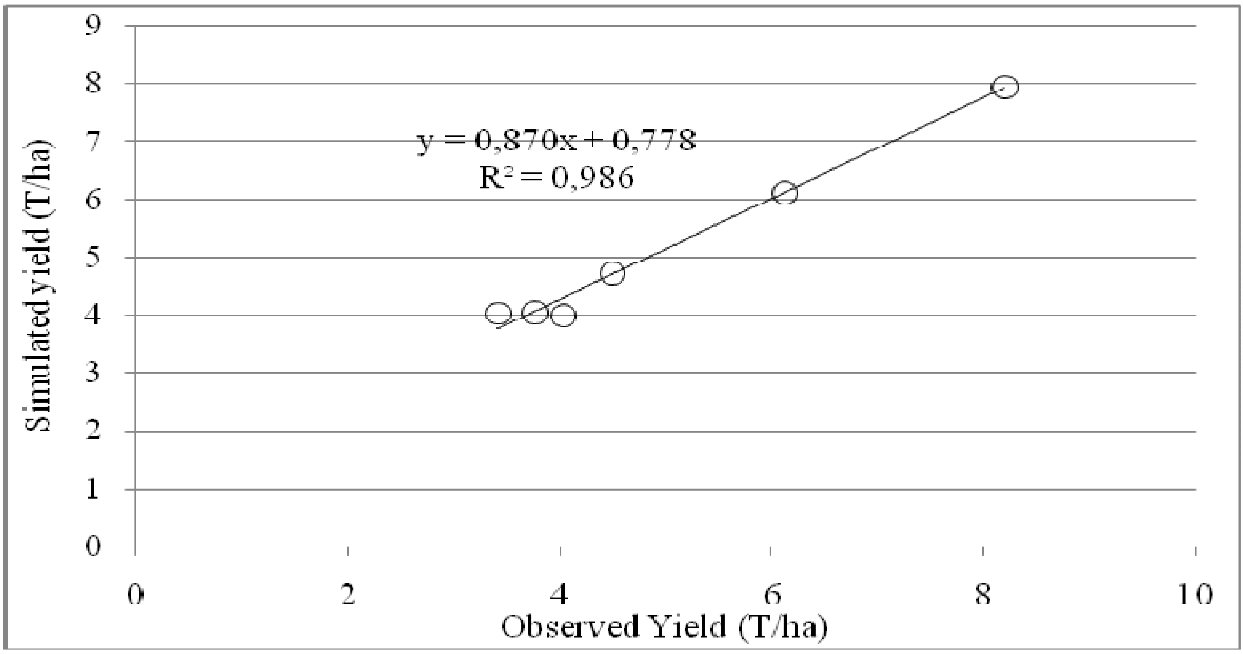


Figure 9. Correlation between observed and simulated yield of chickpeas

For most treatments, the relative error of SALTMED simulated yield was less than 8%. The model overestimated yield for fully stressed treatments, but was successful in predicting yield and water productivity for the other treatments (Table 6).

Table 6. Harvest Index , relative error (%) and observed and simulated water productivity of chickpeas

Treatments	Harvest Index	Observed Yield	Simulated Yield	Relative Error (%)	Irrigation +Rainfall (6mm)	Observed Water Productivity	Simulated Water Productivity
C1 fully irrigated	0.44	6.12	6.12	0.00	284	2.15	2.15
C2 fully stressed	0.46	3.42	4.03	-17.84	145	2.35	2.77
C3 stressed in Fl, 50%	0.37	4.50	4.72	-4.89	241	1.86	1.95
C4 stressed in G.F, 50%	0.39	3.77	4.04	-7.16	231	1.63	1.74
C5 stressed in V.G, 50%	0.50	8.20	7.95	3.05	240	3.41	3.31
C6 stressed in V.G and Fl, 50%	0.41	4.04	3.98	1.49	197	2.05	2.02
			Average	**-4.23**			

3.2.4. Chickpeas total dry matter

Figure 10 shows the total dry matter production, simulated by the SALTMED model, during the crop cycle. Dry matter measurements were carried out in three occasions. On the first measurement (June 1st, 2010), the model overestimated the dry matter production, but on the second measurement date (June 29th, 2010) SALTMED was able to show a good agreement with the observed data and at the last measurement (July 1st, 2010) the model showed 97% of correlation between simulated and observed total dry matter (Figure 11). Overall a 93.2% of correlation between observed and simulated total dry matter was observed.

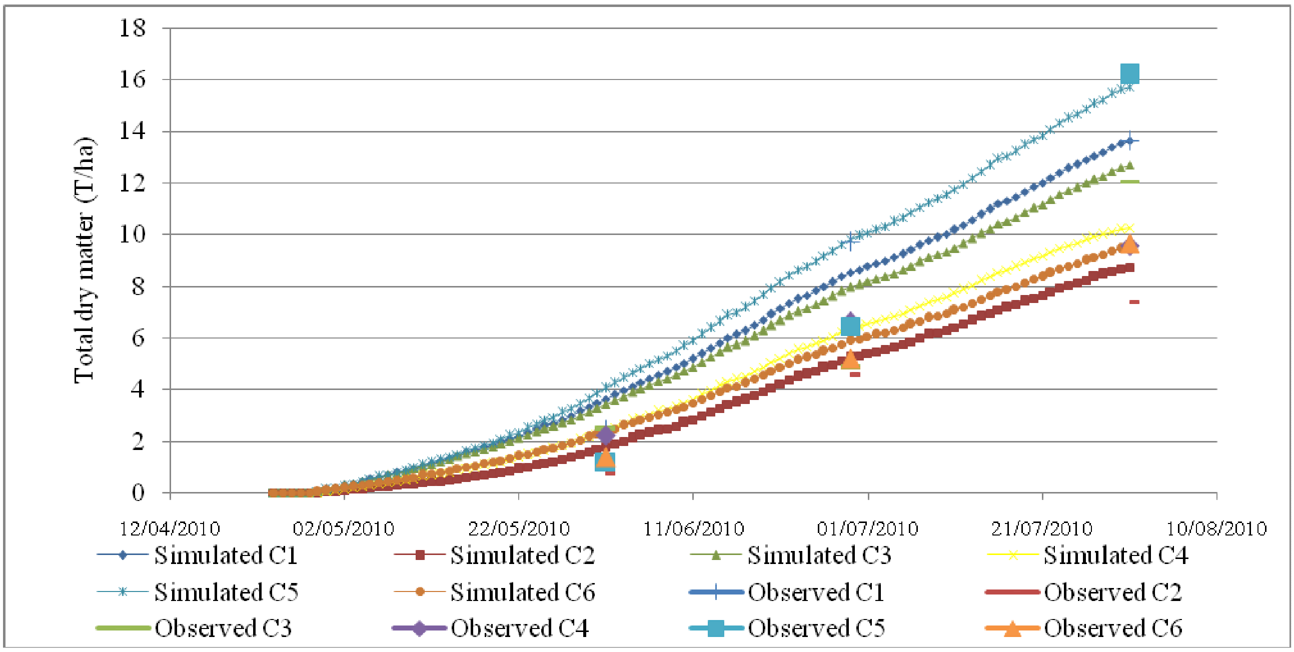


Figure 10. Observed and simulated total dry matter evolution during the crop cycle of chickpeas

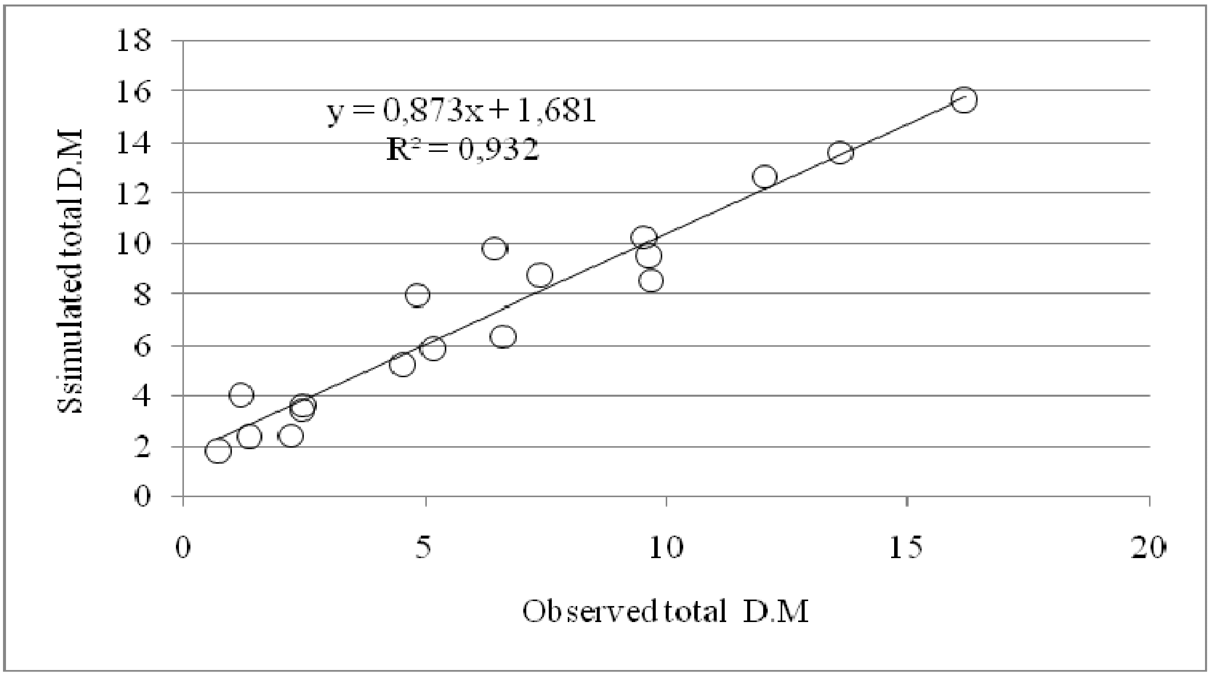


Figure 11. Correlation between observed and simulated total dry matter of chickpeas

3.2.5. Sweet corn yield

Sweet corn yield was measured as 'dry ear' yield. For this reason the harvest index was high. As sweet corn is a C4 crop, the photosynthesis efficiency is high. Here again the calibration process proved this information as well as the measured photosynthesis efficiency of the control treatment was high and equal to 2.827 g/MJ. The simulated and observed dry ear yields are in a good agreement with R^2 equal to 86.6% (Figure12).

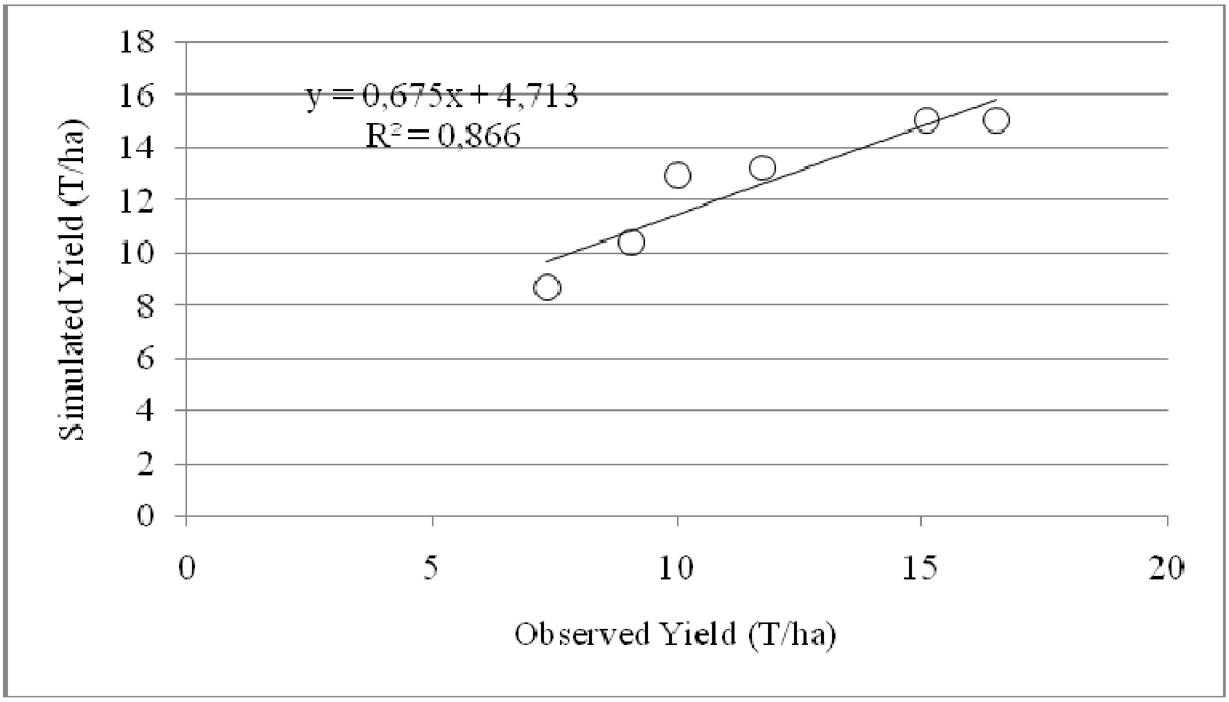


Figure 12. Correlation between observed and simulated yield of sweet corn

The SALTMED model overestimated yield for treatment S2. S3, S4 and S6 and underestimated yield for treatment S5, but generally and even without adjusting LAI, SALTMED was successful in predicting sweet corn yield under deficit irrigation with treated wastewater (Table 7).

Table 7: Harvest Index , relative error (%) and observed and simulated water productivity of sweet corn

Treatments	Harvest Index	Observed Yield	Simulated Yield	Relative Error (%)	Irrigation +Rainfall (6mm)	Observed Water productivity	Simulated Water productivity
S1 fully irrigated	0.55	15.09	15.09	0.00	469	3.220	3.220
S2 fully stressed	0.43	7.36	8.66	-17.66	237	3.101	3.649
S3 stressed in Fl, 50%	0.53	11.74	13.26	-12.95	421	2.785	3.146
S4 stressed in G.F, 50%	0.53	10.04	12.96	-29.08	393	2.558	3.302
S5 stressed in V.G, 50%	0.54	16.52	15.08	8.72	361	4.582	4.183
S6 stressed in V.G and Fl, 50%	0.54	9.09	10.41	-14.52	313	2.900	3.322
			Average	**-10.92**			

3.2.6. Sweet corn total dry matter

According to Figure 13 SALTMED showed a very good agreement between observed and simulated total dry matter; the localisation of the three measurement points in the total dry matter production curve is perfect with regard to each treatment. At the end of the crop cycle SALTMED showed a good correlation (R^2 = 80%) while for the total dry matter measurements a very high correlation (R^2 = 91.5%) was obtained between observed and modelled values (Figure 14).

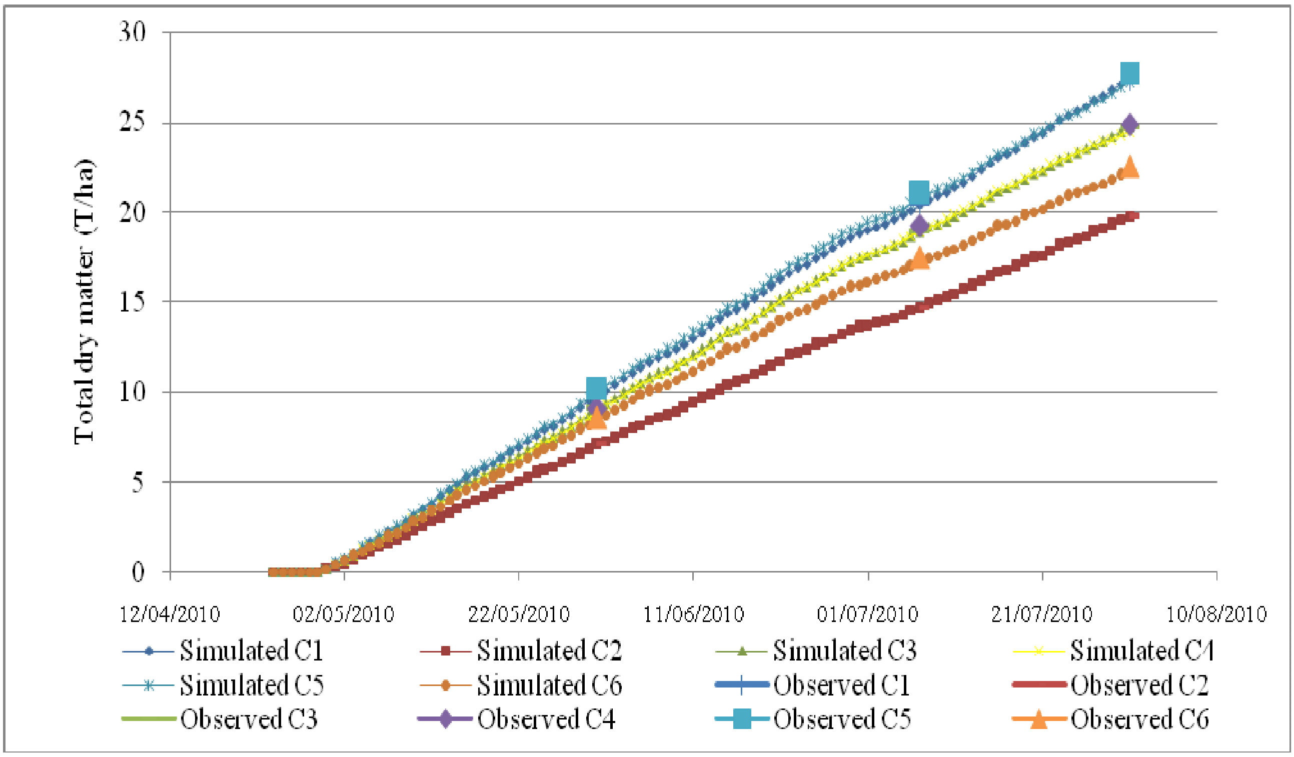


Figure 13. Observed and simulated total dry matter evolution during the crop cycle of sweet corn

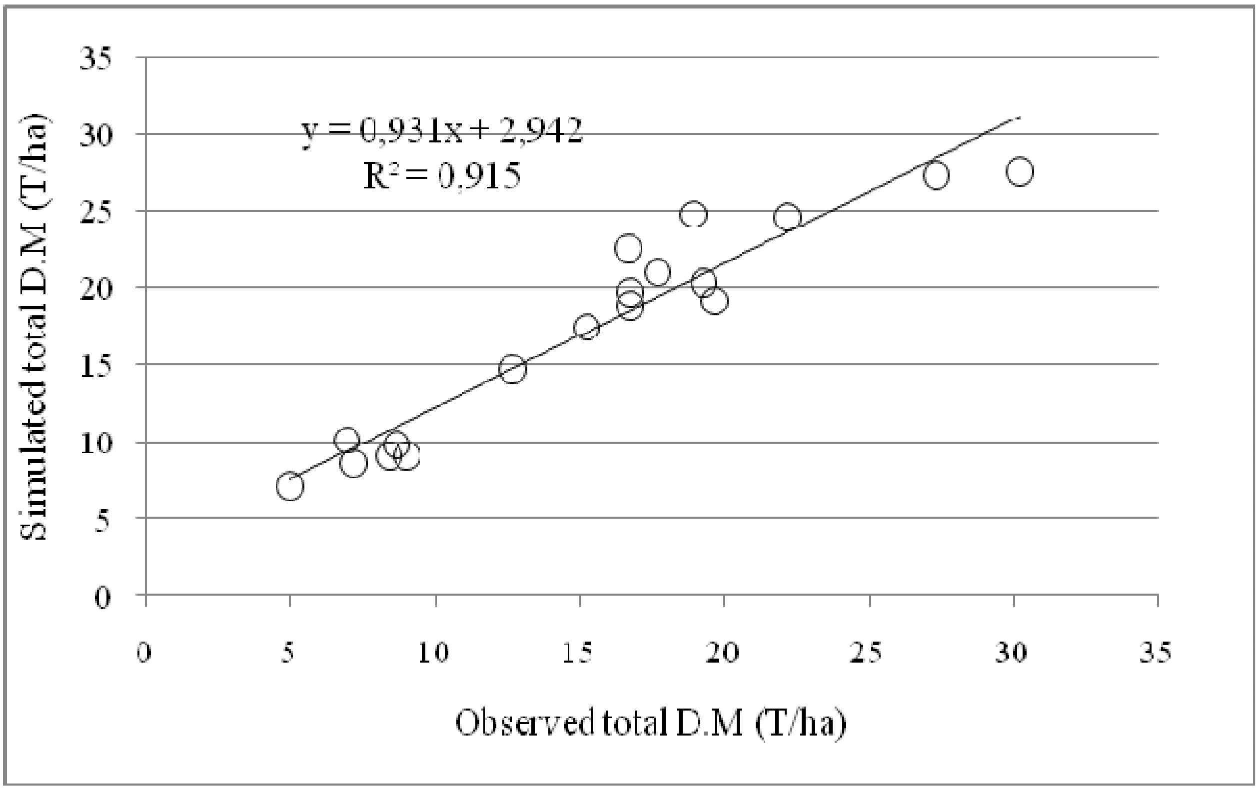


Figure 14. Correlation between observed and simulated total dry matter of sweet corn

Conclusion

Following successful calibration and validation, the SALTMED model proved its ability to predict soil moisture, yield and total dry matter for three growing seasons under several deficit irrigation strategies using treated wastewater. In this study the model calibration highlighted the need for dividing the soil into several horizons; the use of three soil horizons resulted in a better soil moisture calibration and correlation than use of two or one horizons. The model proved its ability to handle several hydrodynamic processes acting at the same time through soil moisture and its reaction with crop and atmosphere. Good estimation of soil moisture has practical implications, it means that the model is able to estimate the amount of irrigation supplies required to bring soil moisture profile from a given soil moisture to a desired soil moisture, usually soil moisture at the desired depletion allowable.

The finding of higher photosynthesis efficiency for sweet corn during the calibration process proved the ability of the SALTMED model to distinguish between two kinds of crop: C3 crops (quinoa and chickpea) and C4 crops (sweet corn). C4 crops are known for their higher photosynthesis efficiency.

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