EFFECT OF FERTIGATION FREQUENCY AND DURATION ON YIELD AND WATER PRODUCTIVITY OF WHEAT: FIELD AND MODELLING STUDY USING SALTMED MODEL[†]

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ABSTRACT

This study investigated the impact of fertigation frequency and fertigation time on wheat production. The field experiment included nine treatments during two seasons, 2014/2015 and 2015/2016. The same amount of water and nitrogen fertilizer was given for all treatments, either over one day, divided over two days or over three days. Three fertigation times FT (period of injecting fertilisers in irrigation water) as a fraction of irrigation period were also applied. In FT strategies, nitrogen is given either during the same period of the irrigation from the start to the end, at the last three quarters of the irrigation period or at the second half of the irrigation period, IT [FT = IT, FT = 0.75IT and FT = 0.5 IT]. The observed and simulated nitrogen uptake and grain nitrogen content showed increasing trend when fertigation frequencies increased and the fertigation time decreased. The field and modelling results, indicated that increasing fertigation frequencies and decreasing fertigation time has benefits particularly for sandy soils including higher yields, and less pollution. In conclusion, the use of the fertigation frequency of three days and fertilizer injection in the second half of the irrigation period is a good fertigation strategy for sandy soils.

KEY WORDS: SALTMED modelling; soil moisture; irrigation; wheat crop; fertigation frequency; fertigation time.

[†] Effet de la fréquence et de la durée de la fertigation sur le rendement et la productivité de l'eau du blé :: étude de terrain et de modélisation à l'aide du modèle SALTMED

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RÉSUMÉ

Cette étude porte sur l'impact de la fréquence de fertigation et du temps de fertigation sur la production de blé. L'expérience de terrain a inclus neuf traitements pendant deux saisons, 2014/2015 et 2015/2016. La même quantité d'eau et d'engrais azoté a été donnée pour tous les traitements, répartis sur un, deux ou trois jours, Trois périodes de fertigation FT (période d'injection d'engrais dans l'eau d'irrigation) en tant que fraction de la période d'irrigation ont également été appliquées. Dans les stratégies FT, l'azote est donné soit pendant toute la période de l'irrigation, du début à la fin, soit au cours des trois derniers quarts de la période d'irrigation ou à la seconde moitié de la période d'irrigation, IT [FT = IT, FT = 0.75 IT et FT = 0.5 IT]. L'absorption d'azote observée et simulée et la teneur en azote des grains ont montré une tendance croissante lorsque les fréquences de fertigation ont augmenté et que le temps de fertigation a diminué. Les résultats sur le terrain et la modélisation indiquent que l'augmentation des fréquences de fertigation et la diminution du temps de fertigation présentent des avantages, en particulier pour les sols sableux, avec des rendements plus élevés et moins de pollution. La période d'irrigation de trois jours et une fertigation appliquée pendant la deuxième moitié de la periode d'irrigation est une bonne stratégie de fertigation pour les sols sableux.

MOTS CLÉS : modélisation SALTMED ; 'humidité du sol ; irrigation ; culture de blé ; fréquence de fertigation ; temps de fertigation.

INTRODUCTION

Application of chemical fertilizers is vital for crop growth and yields. Fertigation is the addition of fertilizers through irrigation water. Fertilizer management is particularly important for irrigated agriculture of sandy soils where large quantities of fertilizers, if not managed properly, could be lost by deep percolation to the groundwater. The characteristics of soil moisture movement and nutrient dynamics influence the growth and yield of crops substantially.

The split application of water and nitrogen fertiliser according to crop requirements at different growth stages and the application of the fertiliser closer to the roots would increase the nitrogen use efficiency and reduce nitrogen losses to the environment (Kennedy *et al*., 2013).

Fertigation frequency affects the amount of water and N per application and, consequently, the soil moisture and nutrient concentration in the rhizosphere (Zotarelli *et al*., 2009; Abalos *et al*., 2014). The fertigation–irrigation frequency may also affect crop biomass accumulation and partitioning, i.e. root growth and the shoot/root ratio (Sensoy *et al*., 2007), as well as the water and N uptake efficiency and yield (Katerji *et al*., 2008; Zotarelli *et al*., 2009).

High fertigation frequency is often recommended as it maintains a stable soil moisture and nutrient concentration in the root zone (Segal *et al*., 2006). High fertigation frequency has been found to improve crop performance in bell peppers (Sezen *et al*., 2006), melon (Sensoy *et al*., 2007) and processing tomato (Badr, 2007); however, these results differ according to the climate, soil, and experimental treatments (i.e., water volumes and time intervals between irrigations). A simultaneous reduction in irrigation and N availability would increases the harvest index due to the reduction in vegetation growth (Zegbe *et al*., 2004).

One can design a field experiment to test a number of treatments. However, that number will be limited by labour and equipment cost. Tested and verified models can be useful in that respect. Once validated against a limited number of treatments, the models can run with 'what if' scenarios, depicting the other set of untried treatments in the field to select the optimum treatment. Therefore, validated models that are able to predict crop growth under different water qualities, fertilizer applications, irrigation managements and strategies can be very useful tools to improve water and nutrient use efficiency and productivity without the need for extensive field trials.

The SALTMED model (Ragab, 2015) is one of the models that has adopted such integrated approach. It has been developed for generic applications and has proved its ability to simulate several crops under different field managements. The model accounts for different irrigation systems, irrigation strategies, different water qualities, different crops and soil types, N-fertilizer applications, fertigation, impact of biotic stresses such as salinity, temperature, drought and the presence of shallow groundwater and a drainage system.

SALTMED 2015 allows real-time simultaneous simulation of 20 fields, each of which would have different irrigation systems, irrigation strategies, crops, soils and N-fertilizers. The model simulates the evapotranspiration, crop water uptake, soil temperature, soil salinity and soil moisture profiles, dry matter, yield, salinity and N-leaching, soil nitrogen dynamics, groundwater level and its salinity, and drainage flow to open and tile drains. The model has been calibrated and validated with field data of drip irrigation on tomato and potato crops (Ragab *et al*., 2005b and 2015), on sugar cane using sprinkler irrigation (Golabi *et al*., 2009), on quinoa, sweet corn and chickpea using drip irrigation (Hirich *et al*., 2012) on vegetable crops (Montenegro *et al*., 2010), on quinoa using saline water (Pulvento *et al*., 2013), on amaranth using saline water (Pulvento *et al*., 2015a), on rainfed and irrigated chickpea (Silva *et al*., 2013), on quinoa under deficit drip irrigation (Fghire *et al*., 2015), on sweet pepper in green houses

(Rameshwaran *et al*., 2015) and on potato using gated pipes (El-Shafie *et al*., 2016). In all these studies the model proved its reliability and ability to predict the field measured yield, dry matter, soil moisture and salinity. The model was also used to predict the impact of climate change on the amaranth and corn water requirement, yield, sowing and harvest dates and the length of the growing season (Pulvento *et al*., 2015b; Hirich *et al*., 2016).

The objective of this study was to identify the best fertigation scheduling and duration for wheat production under sandy soil conditions through field and modelling study using SALTMED model.

MATERIALS AND METHODS

Location and climate of experimental site

Field experiments were conducted during 2014/2015 and 2015/2016 at the research farm of the National Research Centre (NRC) (latitude 30º 30' 1.4'' N, longitude 30º 19' 10.9'' E, and mean altitude 21m+ MSL (mean sea level)) at Nubaria Region, Al Buhayra governorate, Egypt. The experimental area has an arid climate with cool winters and hot dry summers. The data of maximum and minimum temperature, relative humidity, and wind speed as shown in Figure 1were obtained from the local weather Station at El-Nubaria Farm.

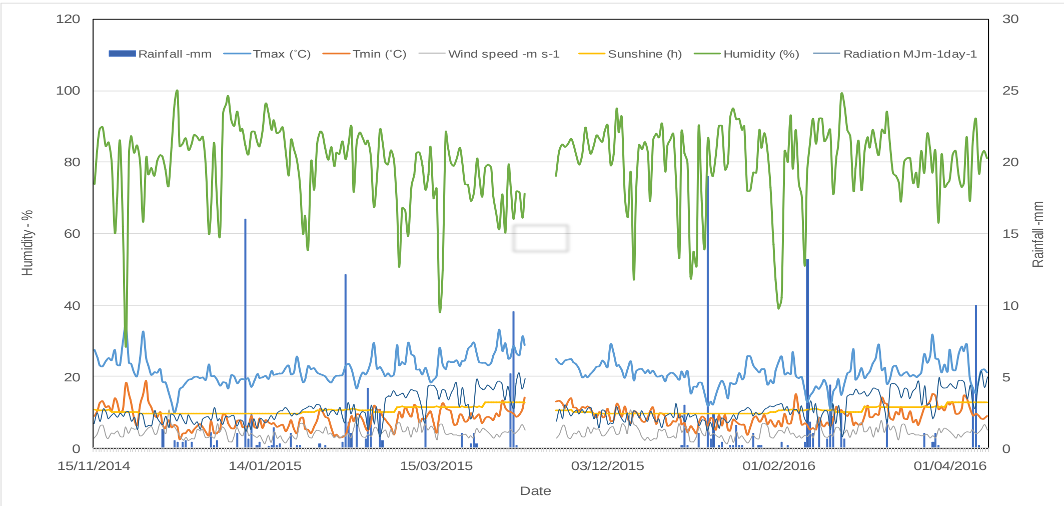


Figure 1. Daily meteorological data in the research farm of the National Research Centre (NRC) in Nubaria, Egypt, during wheat growth seasons 2014/2015 and 2015/2016

Physical and chemical properties of soil and irrigation water

Irrigation water was supplied by an irrigation channel passing through the experimental area. The irrigation water had a pH of 7.35 and an electrical conductivity of 0.41 dS m^{-1}. The main physical and chemical properties of the soil were determined in situ and in the laboratory at the beginning of the field trial (Table I). The main physical, and chemical properties of irrigation water are reported in Table II.

Table I. Main physical and chemical characteristics of the soil of the experimental area ***(Note: three significant figures imply already an accuracy of better than one promille, which you cannot achieve in practice. Please check the whole text and the Tables and Graphs for not more than three significant figures)***

Soil Characteristics	Soil layer (cm) 0–20	20-40	40-60	60-80	80-120
Physical parameters					
Texture	Sandy	Sandy	Sandy	Sandy	Sandy
Course sand (%)	47.8	56.7	36.8	35.8	33.3
Fine sand (%)	49.8	39.6	59.4	60.1	62.3
Silt + clay (%)	2.49	3.72	3.84	4.12	4.32
Bulk density (t m^{-3})	1.69	1.68	1.67	1.69	1.65
Chemical parameters					
$EC_{1:5}$ (dS m^{-1})	0.35	0.32	0.44	0.45	0.53
pH (1:2.5)	8.7	8.8	9.3	9.0	9.2
Total $CaCO_3$ (%)	7.02	2.34	4.68	5.01	5.2
Organic matter (%)	0.65	0.40	0.25	0.24	0.21

Table II. Main characteristics of irrigation water of the experimental area

Parameter	Irrigation canal water, IW
Electric Conductivity, dS m^{-1}	0.41
pH	7.35
Chemical characteristics, concentrations in mmole l^{-1}	
Calcium, Ca^{2+}	1.00
Magnesium, Mg^{2+}	0.50
Sodium, Na^{2+}	2.40
Potassium, K^{+}	0.20
Carbonate, CO_3^{2-}	< 0.01
Bicarbonate, HCO_3^{-}	0.10
Chloride, Cl^{-}	2.70
Sulphate, SO_4^{2-}	1.30
Nitrogen, N(NH_4^{+}+NO_3^{-})	< 0.01
Phosphorus, P (PO_4^{3-})	0.20
Copper, Cu^{++}	0.02
Nickel, Ni^{++}	0.01
Zinc, Zn^{++}	1.00

Calcium, Ca^{2+}	1.00

Experimental Design

The planting and harvesting dates for wheat were 15th of November and 15th of April for both seasons 2014/2015 and 2015/2016. The growth period for wheat was 152 days. The statistical design of this experiment was a split design. The experimental design included nine treatments: three irrigation times (IT) [1, 2and 3 days] as main plot and three fertigation times (FT) as sub main plot, where the irrigation water is dosed with the nitrogen fertiliser during the complete irrigation time, during the last three quarters of the irrigation time, or during the second half of the irrigation time, the treatments are referred to as FT = IT, FT = 0.75 IT and FT = 0.5 IT.

The same recommended amount of nitrogen fertilizer, 192 kg N ha^{-1} $season^{-1}$ in the form of ammonium nitrate (33.5%N), was applied for all treatments.

The irrigation amount was calculated using the modified Penman-Monteith equation according to Allan *et al*., 1998). The daily values of crop evapotranspiration, ETc, were calculated. In daily irrigation, the daily ETc was added while in two days irrigation frequency, the sum of the two days, previous day and current day ETc was added. The same principle for the three days irrigation frequency, the amount applied is the sum of the ETc of the previous two days and the current day. The total number of plots was 27 and each plot area was 720 m^2. The 27 plots were divided into three replicates of 9 plots each. The statistical design of this experiment was a split design. The soil moisture profile probe access tubes were placed in each plot to measure the soil moisture (Figure 2 and Table III).

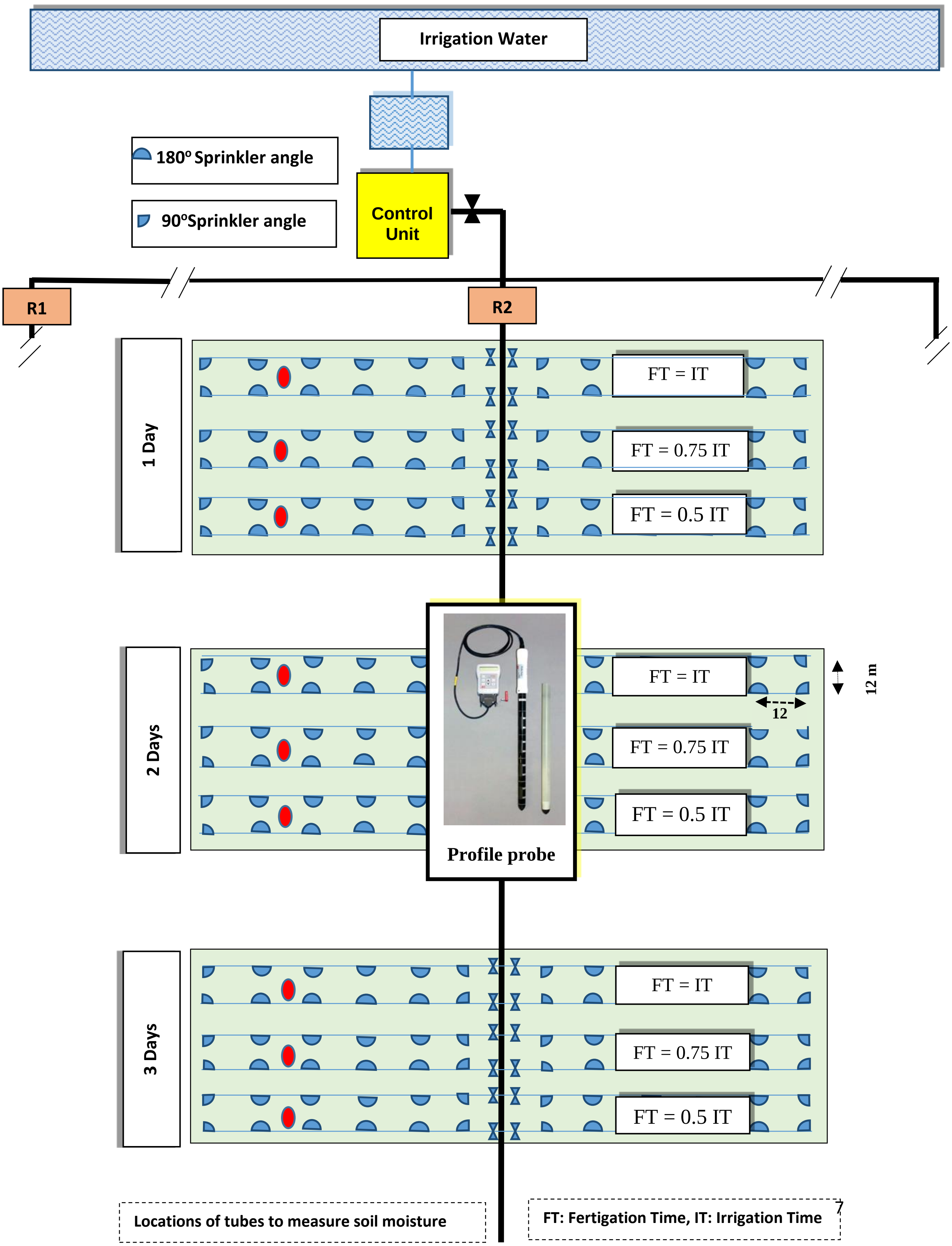
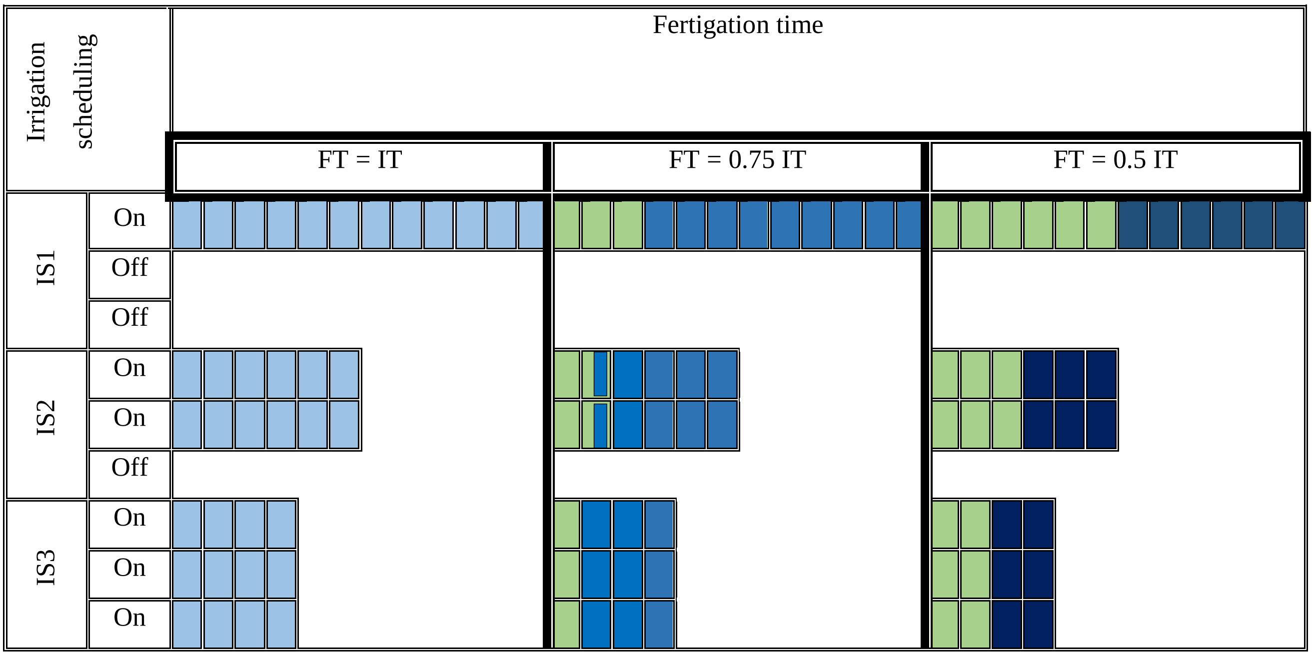

Irrigation Water
180° Sprinkler angle
90°Sprinkler angle
Control Unit
R1
R2
1 Day
FT = IT
FT = 0.75 IT
FT = 0.5 IT
2 Days
Profile probe
FT = IT
FT = 0.75 IT
FT = 0.5 IT
12 m
12
3 Days
FT = IT
FT = 0.75 IT
FT = 0.5 IT
Locations of tubes to measure soil moisture
FT: Fertigation Time, IT: Irrigation Time

Figure2. Layout of the experimental design.

Table III. The irrigation and fertigation frequencies (Nitrogen fertigation scheduling)



FT: Fertigation Time IT: Irrigation Time

Nitrogen with low concentration

Nitrogen with medium concentration

Nitrogen with high concentration

IS1: Irrigation scheduling for one day on and 2 days off, IS2: Irrigation scheduling for 2 days on and 1 day off, IS3: Irrigation scheduling for 3 days on and no days off

Treatment Number	Irrigation time (IT) days	Fertigation time, FT, as fraction of IT	Dosing of specific amount of N-fertiliser
T1	1	FT = IT	Fertilizer is added from the start till end of the irrigation period
T2	1	FT = 0.75IT	1st quarter of irrigation time no fertilizer is added
T3	1	FT = 0.5IT	1st half of the irrigation time no fertiliser is added
T4	2	FT = IT	Fertilizer is added from the start till end of the irrigation period
T5	2	FT = 0.75IT	1st quarter of irrigation time no fertilizer is added
T6	2	FT = 0.5IT	1st half of the irrigation time no fertiliser is added
T7	3	FT = IT	Fertilizer is added from the start till end of the irrigation period
T8	3	FT = 0.75IT	1st quarter of irrigation time no fertilizer is added
T9	3	FT = 0.5IT	1st half of the irrigation time no fertiliser is added

Irrigation requirements for wheat

The daily irrigation water requirement was calculated using Penman Monteith equation and the crop coefficient, according to Allen *et al*. (1989). The seasonal irrigation water applied was 3220 and 2710 m^3 ha^{-1} $season^{-1}$ for 2014/2015 and 2015/2016, respectively. Sprinkler irrigation system has been used with 85% efficiency.

Acquiring the model parameters

The data required for the model calibration and validation were taken during each growth stage. The soil moisture was measured using the profile probes at four depths 0-20, 20-40, 40-60 and 60-80 cm. All the required climatic variable data were collected *in situ* from the site weather station. Climate data required as input to the model consisted of precipitation, maximum temperature and minimum temperature, the relative humidity, wind speed, and net and total radiation. In addition, dry matter and total leaf area, required to calculate the Leaf Area Index (LAI), were obtained at regular intervals. At harvest, a random plant sample was taken from each plot to determine grain yield, which was then converted to yield in ton ha^{-1}. Other plant parameters, such as plant height, root depth, length of each growth stage and harvest index, were also based on field measurements. Grain nitrogen content was determined in the lab using the standard method based on digestion and distillation by Micro Kjeldahl apparatus. Water productivity of wheat was calculated according to James (1988) as follows:

$$WP_{wheat} = Ey/Ir \tag{1}$$

Where: WP is the water productivity of wheat (kg $_{grains}$ $m^{-3}{}_{water}$), Ey is the marketable yield (kg $_{grains}$ ha^{-1} $season^{-1}$) and Ir is the amount of applied irrigation water (m^3 $_{water}$ ha^{-1} $season^{-1}$).

SALTMED MODEL

The new version of SALTMED (Ragab, 2015) which accounts for surface and subsurface irrigation, partial root drying (PRD) or deficit irrigation, fertigation, soil nitrogen fertiliser application and plant nitrogen uptake, biomass and dry matter production and nitrate leaching was used in this study. A detailed description of the SALTMED model is provided in Ragab (2015), Ragab *et al*. (2005a), and Ragab *et al*. (2015). The SALTMED model is a free download from the Water4Crops EU funded project web site: http://www.water4crops.org/saltmed-2015-

integrated-management-tool-water-crop-soil-n-fertilizers/and from the International Commission on Irrigation and Drainage, ICID, web site: http://www.icid.org/res_tools.html#saltmed_2015

Model calibration

During the calibration, fine tuning of the relevant SALTMED model parameters was carried out to obtain good agreement between the simulated and observed soil moisture, dry matter, and crop yield. For the calibration, the 'FT = IT, 1day' treatment was selected. Different soil parameters such as soil hydraulic properties including bubbling pressure, saturated hydraulic conductivity, saturated soil water content and pore distribution index, 'lambda' were fine-tuned until close matching between the simulated and observed soil moisture values was achieved. In addition to the soil parameters, crop parameters such as the crop coefficient, Kc that is used to predict crop evapotranspiration (ETc), and basal crop coefficient, Kcb (represents the crop transpiration part of the Kc), were also slightly tuned to find the best fit of the soil moisture against the observed soil moisture for each soil layer (Tables IV and V). After achieving a good fit for the soil moisture, only fine tuning was needed for dry matter and crop yield. The key parameter that was required to be fine-tuned for the crop yield was photosynthetic efficiency.

The goodness of fit expressions used were the root mean square error (RMSE), the coefficient of determination (R^2), and the coefficient of residual mass (CRM). The RMSE values, calculated using Equation 2, indicate by how much the simulations under or overestimate the measurements.

$$RMSE = \sqrt{\frac{\sum(y_o - y_s)^2}{N}} \tag{2}$$

Where: $\boldsymbol{y_o}$= predicted value, $\boldsymbol{y_s}$ = observed value, $\boldsymbol{N}$= total number of observations.

The R^2 statistics demonstrate (Equation 3) the ratio between the scatter of simulated values to the average value of measurements:

$$R^2 = \left\{\frac{1}{N}\frac{\sum(y_o - \bar{y_o})(y_s - \bar{y_s})}{\sigma y_o - \sigma y_s}\right\} \tag{3}$$

Where: $\bar{y_o}$ = averaged observed value, $\bar{y_s}$ = averaged simulated value, σy_o = observed data standard deviation, σy_s = simulated data standard deviation.

The coefficient of residual mass (CRM) is defined by Equation 4:

$$\text{CRM} = \frac{(\sum y_o - \sum y_s)}{\sum y_o} \tag{4}$$

The CRM is a measure of the tendency of the model to over or underestimate the measurements. Negative values for CRM indicate that the model underestimates the measurements and positive values for CRM indicate a tendency to overestimate. For a perfect fit between observed and simulated data, values of RMSE, CRM and R^2 should equal 0.0, 0.0, and 1.0, respectively.

Table IV. Main calibrated and observed input parameters used in the study for wheat, 2014/2015, Egypt

Parameter	Developmental Stage	Observed	Calibrated
Cultivation dates			
Sowing (day)		15 November	
Emergence (day after sowing)		1	
Harvest (day after sowing)		152	
Growth stages duration in days			
Initial		29	
Development		35	
Middle		50	
Late		37	
Crop inputs			
Crop coefficient, Kc	Initial		0.7
	Middle		1.15
	End		0.45
Transpiration crop coefficient, Kcb	Initial		0.6
	Middle		0.8
	End		0.4
Fraction cover, FC	Initial	0.4	
	Middle	1	
	End	1	
Plant height (m), h	Initial	0.45	
	Middle	0.85	
	End	0.8	
Leaf area index, LAI	Initial	0.5	
	Middle	3.7	
	End	3.2	
Minimum root depth (m)		0	
Maximum root depth (m)		1	
Photosynthesis efficiency			2.5
Water uptake effect	Initial		0.9
	Middle		0. 5

	End		0.75
Harvest index, HI		0.43	

Table V. Main calibrated and observed input parameters used in the study for sandy soil

Parameter	Observed	Calibrated
Saturated moisture content ($m^3\,m^{-3}$)	0.25	
Field capacity ($m^3\,m^{-3}$)	0.15	
Wilting point ($m^3\,m^{-3}$)	0.04	
Lambda pore size		0.2
Residual water content ($m^3\,m^{-3}$)		0.0
Root width factor	0.30	
Saturated hydraulic conductivity (mm day^{-1})	2900	
Max. depth for evaporation, mm		50
Bubbling pressure, cm		10

RESULTS AND DISCUSSION

Soil moisture

Initially the soil moisture was calibrated with ‘FT = IT, 1 day’ and validated against all the other treatments for two seasons 2014/2015 and 2015/2016. The model calibration simulated the soil moisture for all layers (0-20, 20-40, 40-60, and 60-80 cm depth) as shown in Figure 3 for the 2014/2015 season and was validated for the 2015/2016 season (Figure 4). Only the soil moisture of the ‘FT = IT, 1 day’ treatment is shown here, as other treatments received the same amount of water and showed similar results. Overall the model was able to simulate reasonably well the observed data both during the calibration and validation processes. These results are consistent with those obtained by Pulvento *et al*. (2013), Pulvento*et al*. (2015a), Hirich *et al*. (2012), Silva *et al*. (2013) Ragab *et al*. (2015), Fghire *et al*. (2015) and Rameshwaran *et al*. (2015).

The model showed increasing correlation (i.e. increasing R^2 values) with depth during 2014/2015. The values of R^2 were 0.91, 0.92, 0.94 and 0.97 for the soil layers 0-20, 20 – 40, 40-60 and 60-80 cm, respectively. Also, during 2015/2016, the model showed increasing R^2 values with increasing the soil depth. The values of R^2 were 0.89, 0.90, 0.93 and 0.95 for the soil layers

0-20, 20-40, 40-60 and 60-80 cm, respectively (Table VI). Similar tabulated results were obtained for 2014/2015, not shown here.

SALTMED proved its ability to simulate the soil moisture changes caused by irrigation events. Overall the simulated and the observed soil moistures for all treatments combined showed a strong correlation for both the 2014/2015 and 2015/2016 seasons. The implication of good soil moisture prediction is that there is a good chance to also simulate reasonably well other chemical elements such as nitrogen that move together with water.

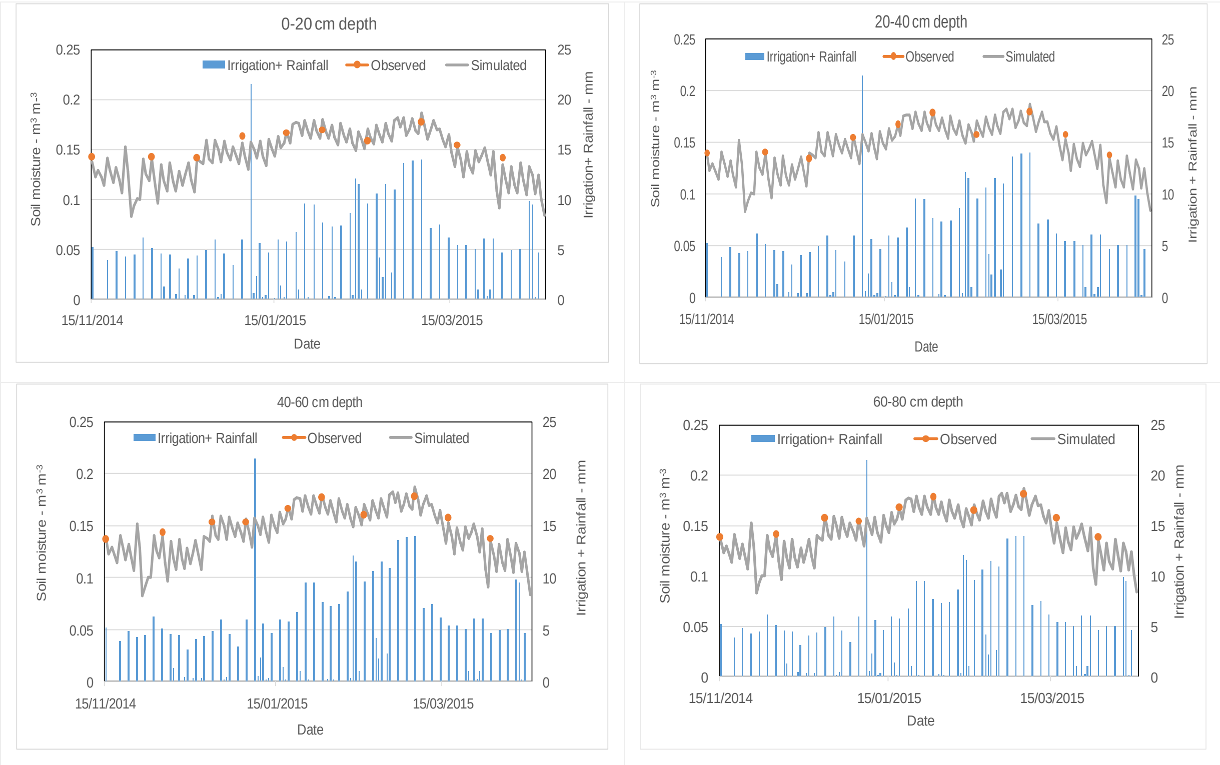


Figure 3. Observed and simulated soil moisture for 0-80 cm depth under FT = IT, 1 day (calibration treatment), 2014/2015

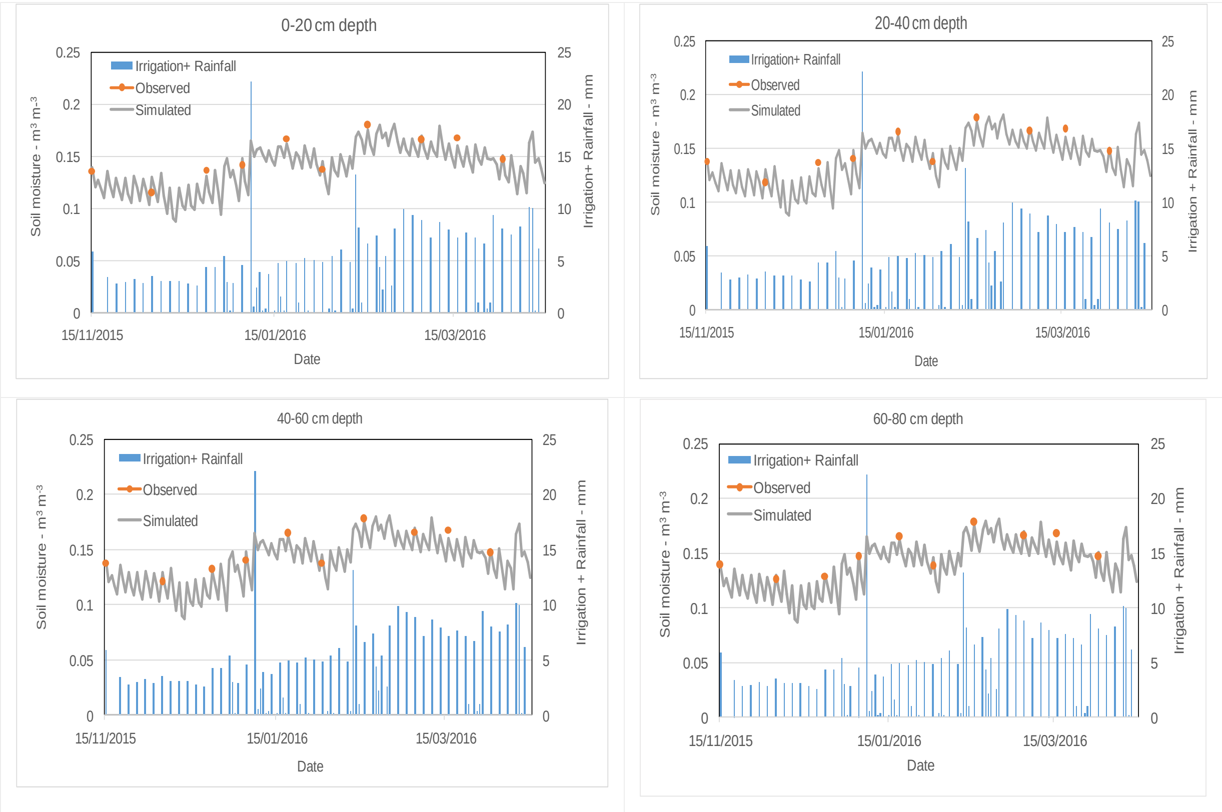


Figure 4. Observed and simulated soil moisture for 0-80 cm depth under FT = IT, 1 day, (selected example from validation treatments), 2015/2016

Table VI. The coefficient of determination, RMSE and CRM for soil moisture in the layers from 0-80 cm, 2015/2016

Fertigation Frequency	Fertigation Time	Soil layers cm														
		0-20 cm			20 – 40 cm			40 – 60 cm			60 – 80 cm			Overall 0-80 cm		
		R^2	RMSE	CRM	R^2	RMSE	CRM	R^2	RMSE	CRM	R^2	RMSE	CRM	R^2	RMSE	CRM
1 Day	FT = IT	0.89	0.039	-0.015	0.90	0.039	-0.013	0.93	0.005	-0.014	0.95	0.004	-0.007	0.92	0.005	-0.005
	FT = 0.75 IT	0.90	0.039	-0.013	0.91	0.039	-0.014	0.93	0.005	-0.009	0.95	0.005	-0.013			
	FT = 0.5IT	0.89	0.039	-0.015	0.90	0.039	-0.008	0.94	0.004	-0.007	0.96	0.003	-0.005			
2 days	FT = IT	0.90	0.036	0.002	0.92	0.036	0.001	0.95	0.004	-0.006	0.96	0.004	-0.008			
	FT = 0.75 IT	0.92	0.036	-0.001	0.94	0.036	-0.004	0.95	0.004	-0.007	0.96	0.004	-0.004			
	FT = 0.5 IT	0.86	0.036	0.010	0.94	0.003	0.004	0.96	0.003	0.001	0.97	0.003	-0.008			
3 Days	FT = IT	0.94	0.035	-0.006	0.95	0.035	-0.008	0.95	0.004	-0.010	0.98	0.002	-0.011			
	FT = 0.75 IT	0.90	0.006	- 0.00.001	0.94	0.005	-0.007	0.95	0.004	-0.005	0.96	0.003	0.003			
	FT = 0.5 IT	0.93	0.005	-0.009	0.94	0.004	-0.001	0.95	0.003	0.002	0.98	0.002	-0.006			

FF: Fertigation Frequency, FT: Fertigation Time, IT: Irrigation Time, HI: Harvest Index, RMSE: Root Mean Square Error, CRM: Coefficient of Residual Mass, R^2: Coefficient of determination/correlation coefficient

Nitrogen dynamics

Accumulative nitrogen (N) uptake, N uptake efficiency (uptake to applied N ratio), and grain N content for observed and simulated values increased with increasing fertigation frequencies and decreasing fertigation time (period of injection of fertilisers into irrigation water) for 2014/2015 and 2015/2016, as shown in Figures 5, 6 and 7. This is mainly due to the better containment of nitrogen in the sandy soil profile and minimizing N-losses by leaching below the root zone. Sandy soil has high permeability and N leaching is likely to take place under high dose of irrigation that is associated with low frequency and high fertigation duration. Neelam *et al*. (2015) reported that the distribution of nutrients in soil profile is greatly influenced by fertigation frequency in sandy-loam soil.

Valkama *et al.* (2013) derived a relation between N uptake, yield and protein content for cereals. This relation has been adopted to obtain the wheat nitrogen uptake from the grains protein content and yield.

Despite that accumulative N uptake in 2014/2015 was higher than 2015/2016, the yields of 2015/2016 were higher than those of 2014/2015 as the protein content of the grains of 2014/2015 was higher than that of 2015/2016, as shown in Figure 8.

The higher values of N uptake during 2014/2015 compared with 2015/2016 may be due to the increasing salinity level of the root zone during 2015/2016 in comparison with 2014/2015 as shown in Figure 9.

Nitrogen uptake efficiency, accumulative N uptake and grain N content for observed and simulated values for 2014/2015 and 2015/2016 followed the same trend under all treatments. A linear relationship was found between observed and simulated values of accumulative N uptake with R^2 of 0.94 and 0.96 for 2014/2015 and 2015/2016, respectively. A similar relation was established for grain N content with R^2 values of 0.94 and 0.96 for 2014/2015 and 2015/2016, respectively. This indicates a strong correlation between observed and simulated values.

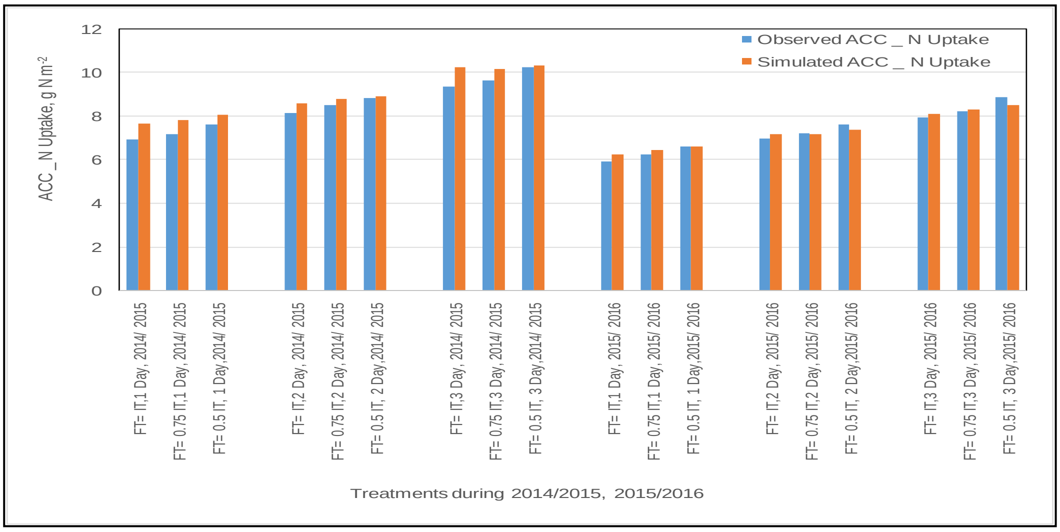


Figure 5. Observed and simulated accumulative N uptake for 2014/2015 and 2015/2016

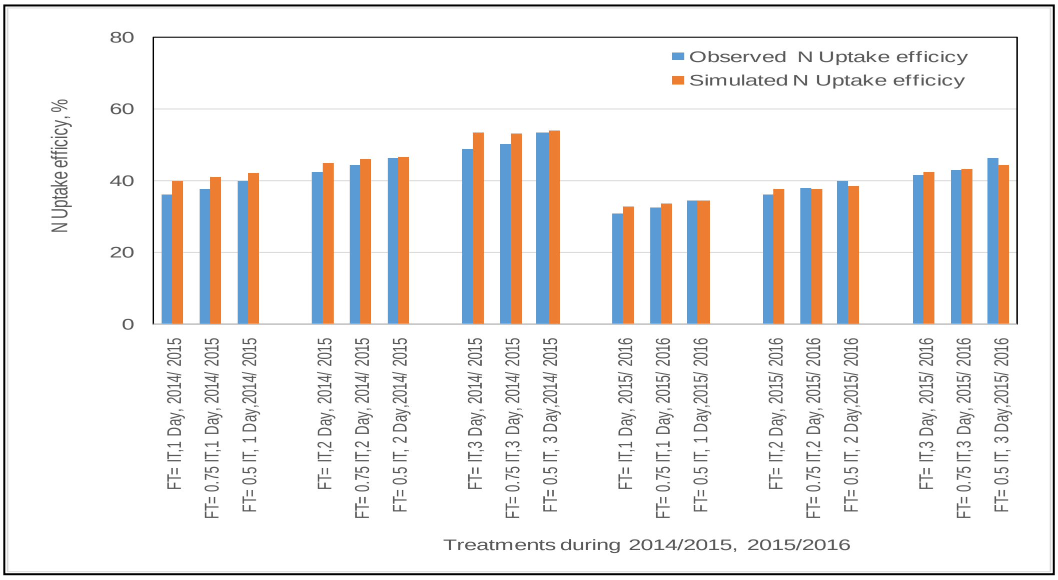


Figure 6. Observed and simulated N uptake efficiency for 2014/2015 and 2015/2016

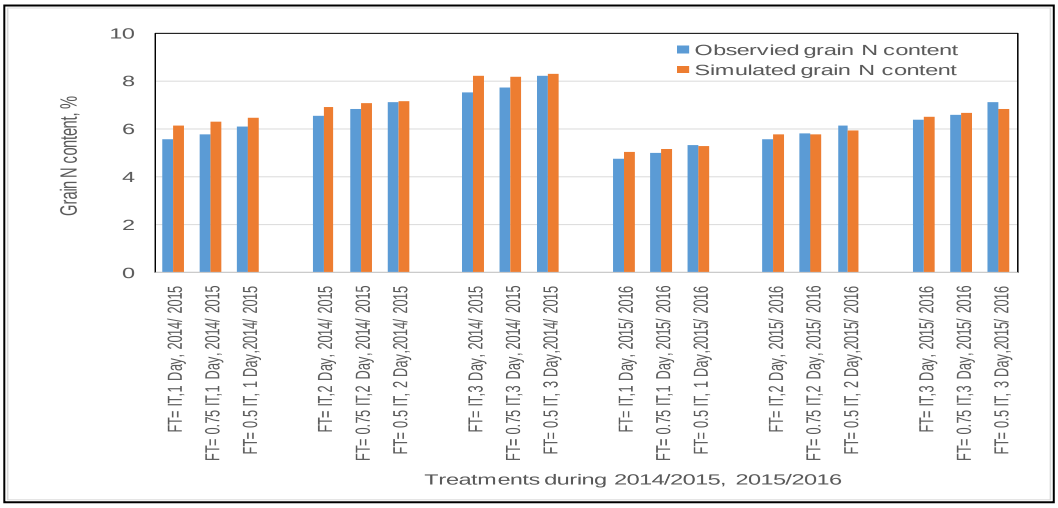


Figure 7. Observed and simulated grain N content for 2014/2015 and 2015/2016

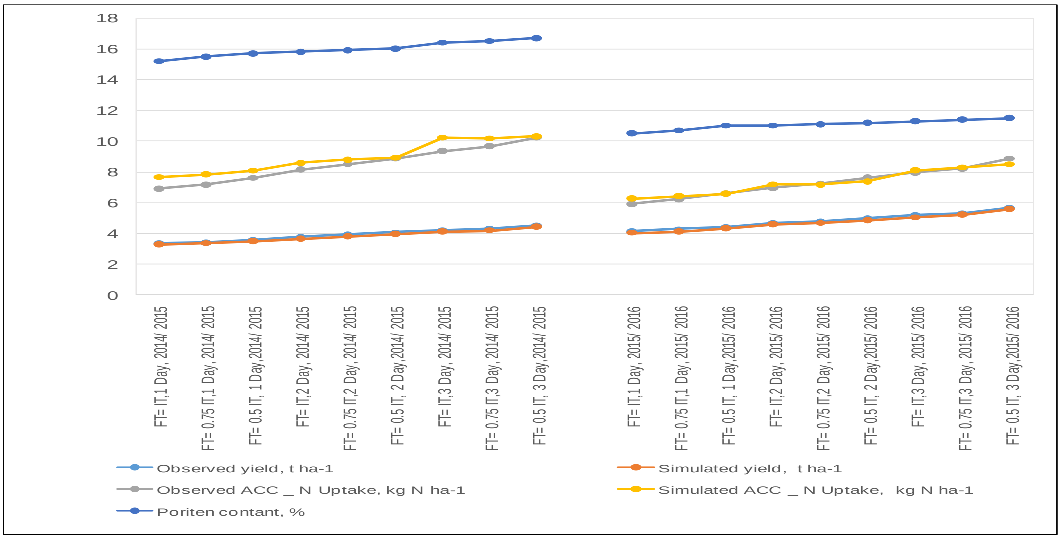


Figure 8. Relation between accumulative N uptake and yield and protein content for 2014/2015 and 2015/2016

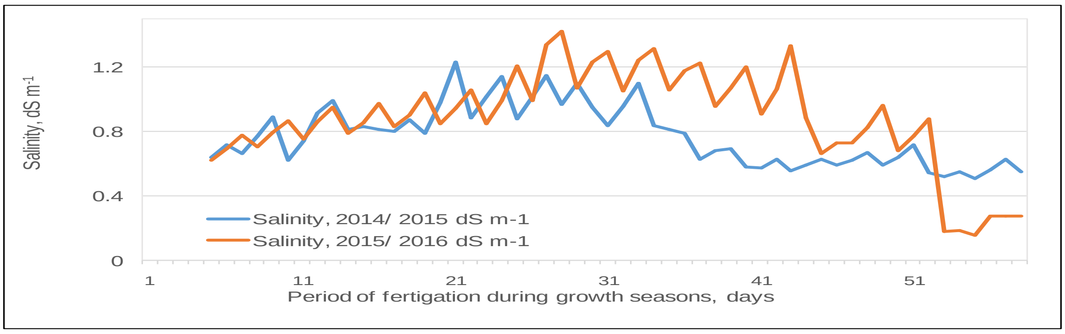
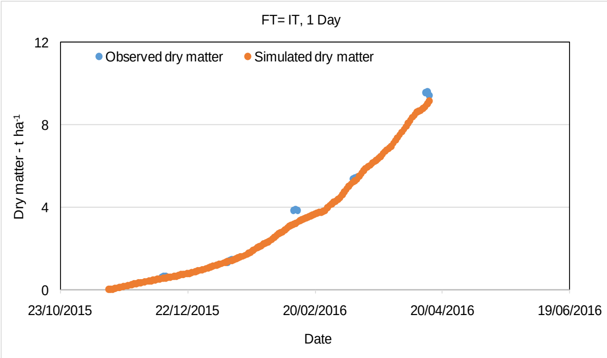


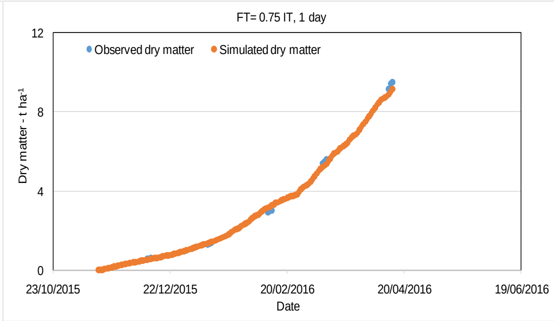
Figure 9. Comparison between simulated salinity during the period of fertigation for 2014/2015 and 2015/2016presented as average of all treatments for the root zone (0 – 80 cm)

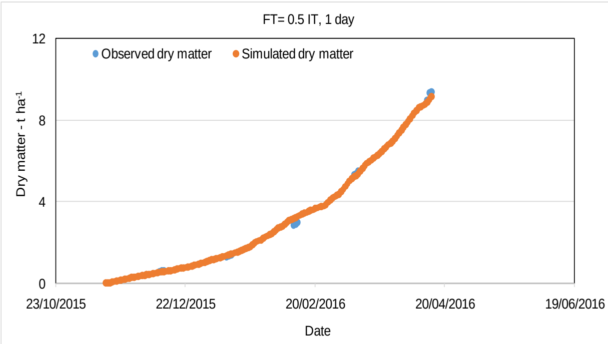
Dry matter

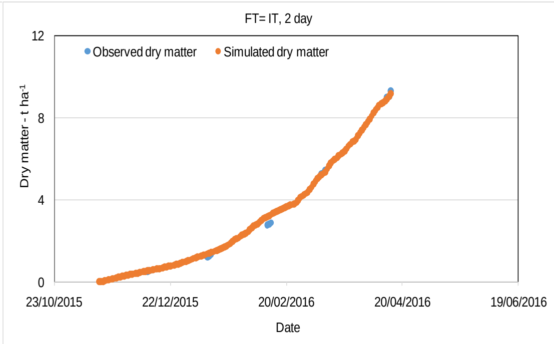
The results showed that there were no significant differences between total dry matter values under all treatments during the two seasons, 2014/2015 and 2015/2016, there were significant differences between harvest index values under all treatments during the two seasons 2014/2015 and 2015/2016 (Table VII). The observed and the simulated total dry matter were in good agreement at all stages for all treatments. The intermediate observed and the simulated dry matter have shown a good agreement over the entire growth period as shown in Figure 10 for 2015/2016 (2014/2015 was similar).

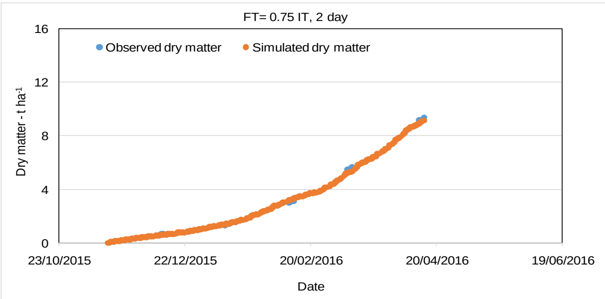
The correlation analysis between the observed and the simulated dry matter shows that the model was able to simulate the total dry matter with R^2 of 0.99 for all treatments during the two seasons 2014/2015 and 2015/2016.

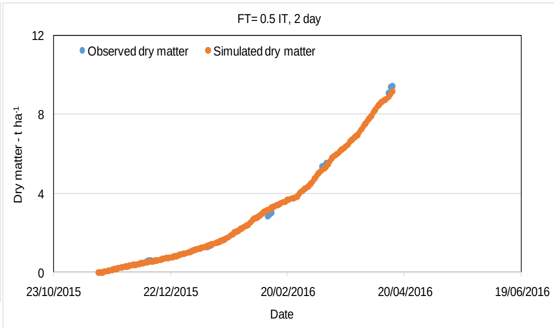

FT= IT, 1 Day
Observed dry matter
Simulated dry matter
Dry matter - t ha^{-1}
0
4
8
12
23/10/2015
22/12/2015
20/02/2016
20/04/2016
19/06/2016
Date

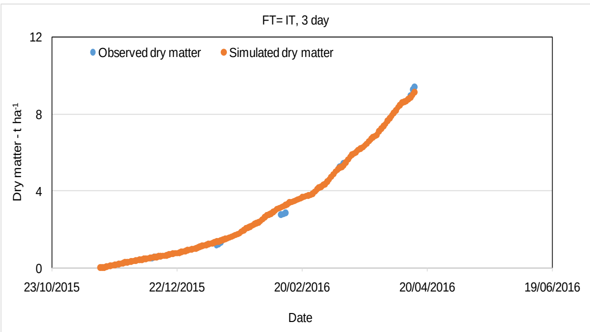

FT= 0.75 IT, 1 day
Observed dry matter
Simulated dry matter
Dry matter - t ha^{-1}
0
4
8
12
23/10/2015
22/12/2015
20/02/2016
20/04/2016
19/06/2016
Date

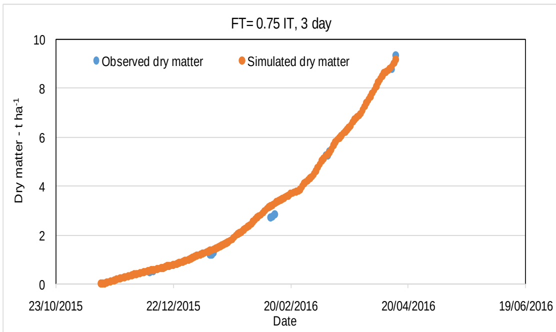

FT= 0.5 IT, 1 day
Observed dry matter
Simulated dry matter
Dry matter - t ha^{-1}
0
4
8
12
23/10/2015
22/12/2015
20/02/2016
20/04/2016
19/06/2016
Date


FT= IT, 2 day
Observed dry matter
Simulated dry matter
Dry matter - t ha^{-1}
0
4
8
12
23/10/2015
22/12/2015
20/02/2016
20/04/2016
19/06/2016
Date


FT= 0.75 IT, 2 day
Observed dry matter
Simulated dry matter
Dry matter - t ha^{-1}
0
4
8
12
16
23/10/2015
22/12/2015
20/02/2016
20/04/2016
19/06/2016
Date


FT= 0.5 IT, 2 day
Observed dry matter
Simulated dry matter
Dry matter - t ha^{-1}
0
4
8
12
23/10/2015
22/12/2015
20/02/2016
20/04/2016
19/06/2016
Date


FT= IT, 3 day
Observed dry matter
Simulated dry matter
Dry matter - t ha^{-1}
0
4
8
12
23/10/2015
22/12/2015
20/02/2016
20/04/2016
19/06/2016
Date


FT= 0.75 IT, 3 day
Observed dry matter
Simulated dry matter
Dry matter - t ha^{-1}
0
2
4
6
8
10
23/10/2015
22/12/2015
20/02/2016
20/04/2016
19/06/2016
Date

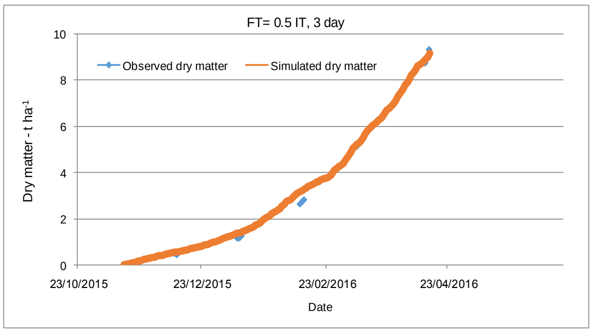


Figure 10. Observed and simulated dry matter for different treatments, 2015/2016

Crop yield

The impact of fertigation frequency and fertigation time on the crop yield of wheat during 2014/2015 and 2015/2016 is shown in Table VII and Figure 11. There was a positive impact on the yield by increasing the fertigation frequency and decreasing the fertigation time in both seasons 2014/2015 and 2015/2016. The yield under 3 days fertigation frequency treatment was higher than the yield under 2 days and 1day treatments for 2014/2015 and 2015/2016. This is mainly due to the increased availability of nitrogen in soil profile and prevention of possible water and N losses by leaching under low fertigation frequency in such high permeable sandy soil. This result is in agreement with the findings of Neelam *et al*. (2015). The relative yield calculated as a ratio of yield to the maximum yield obtained under 3 days IT frequency with fertigation in the second half of irrigation time showed (Table VII) that a 1day irrigation frequency on average produced 24% less yield and 2 days IT frequency on average produced 13% than the 3 days IT frequency. Within each IT frequency, the yield was higher for fertigation at the second half of the irrigation time.

The statistical analysis indicated that there were significant differences among crop yield values under all treatments during the two seasons 2014/2015 and 2015/2016. The yield was found to be decreasing in the following order for season 2014/2015 and 2015/2016:

FT = 0.5IT on 3 days > FT = 0.75 IT on 3 days FT = IT on 3 days >FT = 0.5IT on 2 days > FT = 0.75 IT on 2 days FT = IT on 2 days> FT = 0.5IT on 1 day > FT = 0.75 IT on 1day FT = IT on 1 day.

Good correlation between observed and the simulated crop yield was obtained during the two seasons, with R^2 of 0.99 for all treatments.

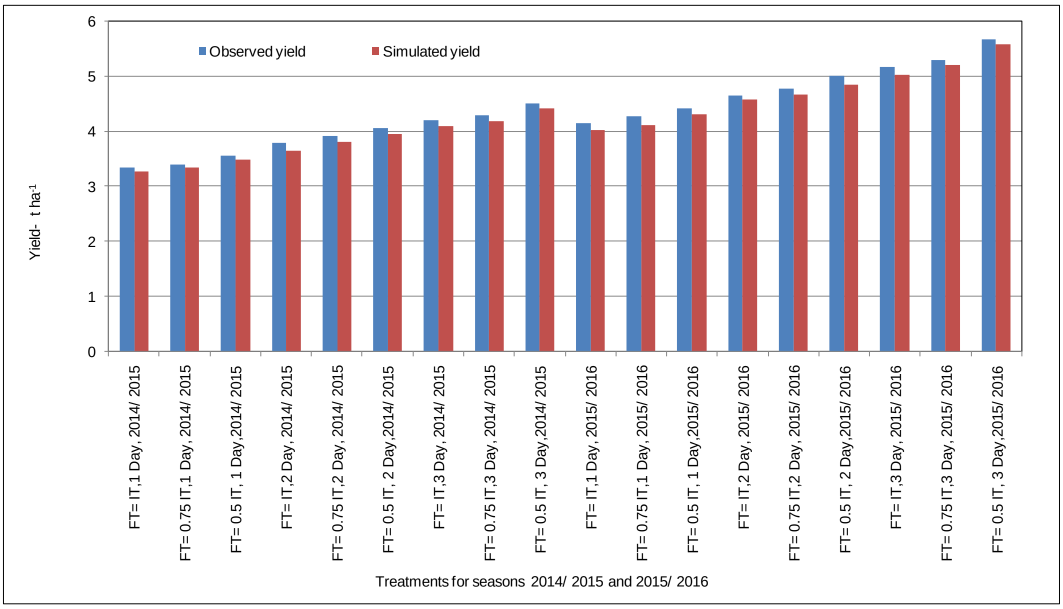


Figure 11. Observed and simulated yield for all treatments for seasons 2014/2015 and 2015/2016

Water productivity

The water productivity was calculated as the amount of grain yield produced per unit of irrigation water applied, expressed in kg per cubic meter. Total water volume (irrigation and rainfall) was 3990m^3 for 2014 and 3500m^3 for 2015. Water productivity values in 2015/2016 were higher than in 2014/2015 and may be due to increasing the yields values during 2015/2016 compared to 2014/2015, in addition to that the total water volume was smaller in 2015/2016 than in 2014/2015.The water productivity, WP showed a similar trend as it increased by increasing fertigation frequency and also by decreasing fertigation time, as shown in Figure 12.

The correlation analysis between the observed and the simulated water productivity showed a good agreement, with R^2 of 0.99 for all treatments during the two seasons.

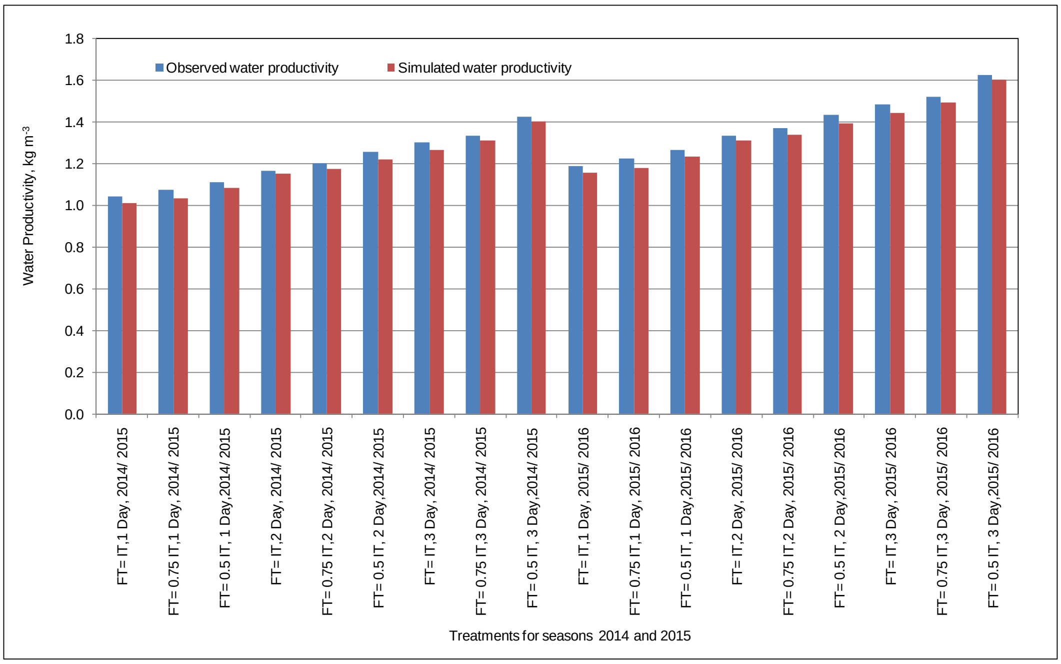


Figure 12. Observed and simulated water productivity for all treatments for seasons 2014/2015 and 2015/2016

CONCLUSION

This study investigated the impact of fertigation frequencies and fertigation times (period of injection fertilisers in irrigation water) on the crop yield of wheat during 2014/2015 and 2015/2016 through a field and modelling study using SALTMED model.

Nitrogen uptake efficiency, accumulative N uptake and grain N content for observed and simulated values increased with increasing fertigation frequencies and decreasing fertigation time for 2014/2015 and 2015/2016.This is mainly due to the fact that the soil is sandy and has a high permeability that would allow fast percolation of water and leaching of nitrogen below the root zone if the fertigation was conducted in a relatively large dose rather than in small doses. Applying water and nitrogen on small doses and shorter time of injection will allow high containment and presence of nitrogen in the root zone available for plant uptake.

The modelling results indicated that there were linear relationships between observed and simulated values of N uptake efficiency, accumulative N uptake and grain N content for 2014/2015 and 2015/2016, with R^2 ranging between 0.94 and 0.96. This indicates a strong correlation between observed and simulated values. Although, there were no significant differences between dry matter values under all treatments during both the 2014/2015 and 2015/2016 seasons, there were significant differences between harvest index values under all treatments during the two seasons and that led to the differences in yields. There was a positive impact on the yield by increasing of fertigation frequencies and decreasing fertigation time in both seasons 2014/2015 and 2015/2016. The yield under the 3 days frequency treatment was higher than the yield under 2 days and 1day treatments for 2014/2015 and 2015/2016. This was mainly due to the increased availability of nitrogen in such sandy soil profile. The same was observed under shorter fertigation time.

In summary, the field and modelling results, indicated increasing fertigation frequencies and decreasing fertigation time has some benefits particularly for sandy soils that include a higher yield, and less pollution to the environment by decreasing N leaching through deep percolation process. Therefore, this study recommends dividing the water and nitrogen amounts on small applications by using fertigation frequency of three days and fertilisers injecting time to take place at the second half of irrigation period as a good fertigation management strategy for sandy soils.

Table VII. Impact of water quality and fertigation rate of nitrogen on Harvest Index, yield and water productivity of wheat during 2014/2015 and 2015/2016

Seasons	FF	FT	HI	Observed yield t ha^{-1}	Simulated yield t ha^{-1}	% Relative error	Irrigation + Rainfall mm	Observed water productivity kg m^{-3}	Simulated water productivity kg m^{-3}	(Yield / Yield3d0.5IT)* 100
2014/ 2015	1 Day	FT = IT (Calib.)	0.43	3.35i	3.27	2.89	3990	1.04	1.01	74.3
		FT = 0.75 IT	0.44	3.41 h	3.35	3.74	3990	1.07	1.03	75.6
		FT = 0.5 IT	0.46	3.57 g	3.50	2.49	3990	1.11	1.08	79.0
	2 days	FT = IT	0.48	3.79 f	3.66	1.51	3990	1.17	1.15	84.0
		FT = 0.75 IT	0.50	3.93 e	3.81	2.51	3990	1.20	1.17	87.1
		FT = 0.5 IT	0.52	4.07 d	3.96	2.99	3990	1.26	1.22	90.2
	3 Days	FT = IT	0.54	4.20 c	4.11	2.70	3990	1.30	1.26	93.1
		FT = 0.75 IT	0.55	4.30 b	4.19	1.69	3990	1.33	1.31	95.3
		FT = 0.5 IT	0.58	4.51 a	4.42	1.41	3990	1.42	1.40	?
	LSD at 5%			0.04						
2015/ 2016	1 Day	FT = IT	0.44	4.15i	4.03	2.89	3500	1.19	1.15	73.2
		FT = 0.75 IT	0.45	4.28 h	4.12	3.74	3500	1.22	1.18	75.5
		FT = 0.5 IT	0.47	4.42 g	4.31	2.49	3500	1.26	1.23	78.0
	2 days	FT = IT	0.50	4.65 f	4.58	1.51	3500	1.33	1.31	82.0
		FT = 0.75 IT	0.51	4.79 e	4.67	2.51	3500	1.37	1.34	84.5
		FT = 0.5 IT	0.53	5.01 d	4.86	2.99	3500	1.43	1.39	88.4
	3 Days	FT = IT	0.55	5.18 c	5.04	2.70	3500	1.48	1.44	91.4
		FT = 0.75 IT	0.57	5.31 b	5.22	1.69	3500	1.52	1.49	93.7

		FT = 0.5 IT	0.61	5.67 a	5.59	1.41	3500	1.62	1.60	
	LSD at 5%			0.05						

F: Fertigation Frequency, FT: Fertigation Time, IT: Irrigation Time, HI: Harvest Index

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