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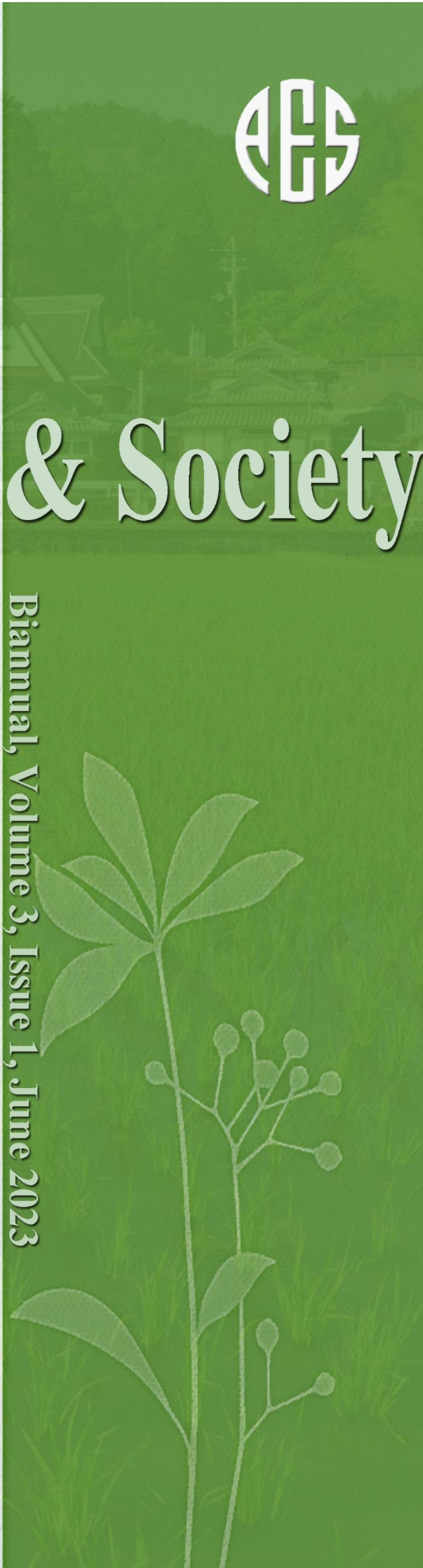

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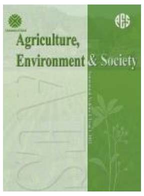

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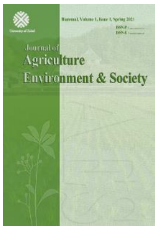

Carbon sequestration in soybean agroecosystems

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ABSTRACT

Today, the DeNitrification DeComposition (DNDC) is model used to anticipate soil organic carbon (SOC) turnover and crop growth under various field management practices. Gorgan County is an important region for soybean production in Iran. We aimed to 1) validate the DNDC model for modeling SOC dynamic in croplands under soybean cropping, 2) simulate the total topsoil (0–30 cm) SOC stocks of soybean cropping systems, 3) quantify the spatial distributions of carbon sequestration potential of soybean-grown croplands by Geographic Information System (GIS) techniques. In this research, soil samples were taken from 150 fields at depth of 0–30 cm before soybean cultivation and after crop harvesting. In this research, we used the site simulation type of DNDC model for simulation and denitrification/decomposition procedure. Inputs in the DNDC model included information on survey region, climate, soil, crop properties, and farmland management practices. The soil and crop properties categorized into farming management practices such as fertilization, tillage, grazing or plant cutting, and irrigation. The climatic data were obtained from one meteorological station located within the study area. To continue, crop parameters were provided based on field survey and laboratory work. Also, the soil properties (including texture, bulk density, pH, SOC, soil total N, field capacity, wilting point, hydro-conductivity point, porosity and clay fraction) were obtained from sampling sites distributed in soybean croplands of Gorgan county. Results indicated that the DNDC model can simulate the SOC values for soybean fields. Based on the results, there was correlation between the simulated and measured data for SOC. The average concentration and storage of carbon sequestration were as 3.97 and 1.42 Mg ha^{-1} for observed situation and in predicted situations obtained as 2.60, and 1.42 Mg ha^{-1}, respectively. The highest content of SOC was related to the east, southeast, and central parts toward the south of the county, which was affected by several factors such as soil bulk density, regional climatic condition, using conservation cropping systems, improved irrigation systems, and fertilization management type. The study provided new information on how improvements in the process-based DNDC model in Iran. Therefore, it can be utilized to determine SOC change and dynamism and carbon sequestration potential on the regional scale.

Highlights

- The spatial distribution of carbon sequestration potential was quantified using GIS techniques.
- The DNDC model was used for simulation, incorporating data on region, climate, soil, crop properties, and management practices.
- The DNDC model effectively simulated SOC values for soybean fields.
- The highest SOC content was observed in the east, southeast, and central parts of the county.
- The study provided new information on using the DNDC model for regional-scale SOC assessment in Iran.

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1. Introduction

Croplands can be a source or sink of carbon dioxide (CO_2). CO_2 fluxes are often deduced based on the changes in measured carbon stocks (Mosier et al., 2006). A minor change in soil organic carbon (SOC) may cause significant changes in the concentration of atmospheric CO_2 (Schlesinger, 1984). Global carbon sequestration potential in croplands has been estimated to be of "40–60 Pg at the rate of 0.4-1.0 Pg C yr^{-1}, which is about 12–30% of the current rate of increase in the CO_2 atmospheric concentration (Lal and Bruce, 1999; Lal, 2004; Smith, 2004b). Carbon sequestration in croplands is a partial and short-term solution. Also, it is cost-effective, and critical for meeting the global climate targets. On the other hand, it buys time during which new technologies for carbon emission reduction or accumulation in other divisions could be developed (Lal, 2001, 2003; Smith, 2004a; Bajzelj et al., 2014).

Lokupitiya et al., (2009) believe to optimize the climate change mitigation and carbon sequestration potential in croplands, assessment, quantification, and evaluation of carbon balance and its components are required under crop type, management practices and rotation. However, some researchers believe that processed-based models are important tools to use as supplementary information to gap-fill incomplete measurements to capture the full carbon budget, evaluation of alternative management practices for improved carbon balance and assessing mitigation strategies under future scenarios (Grant et al., 2007; Smith and Smith, 2007; Wallach et al., 2014). Based on this viewpoint, different models have been developed to simulate carbon dynamics in different ecosystems particularly agroecosystems (Li et al., 1992; Li et al., 1994; Li., 2000).

The DeNitrification DeComposition (DNDC) model is one of the most widely admitted agroecosystem models in the world (Gilhespy et al., 2014). Hopeful performances of the DNDC model has been validated in Asia (Wang et al., 2013), Europe (Abdalla et al., 2011) and America (Tonitto et al., 2007). The DNDC model is midway and comparatively simple, and simulates detailed SOC dynamics, daily carbon exchange, carbon balance, and crop growth and production based on crop management, soil characteristics and climatic conditions (Gollany et al., 2012a; Zhang et al., 2015; Del Grosso et al., 2016).

The simulation results of the DNDC model reported by Zhang et al., (2016) showed a strong correlation between simulated and measured winter wheat SOC contents. Also, they reported that the DNDC model can be used to anticipate SOC turnover and crop growth under different fertilization and straw return conditions in the studied area. In other research, Yan et al., (2016) evaluated the simulated results with the SOC values found in Huantai county China, from 1982–2011 by the DNDC model.

They expressed that the simulated values were more consistent with the observed ones in the two different modeling parts. The simulated findings achieved by Hua-Jun et al., (2010) indicated that the total SOC storage and SOC density in the croplands of China were 4.7-5.2 Pg C, and 3.9 to 4.4 kg C m^{-2}, respectively, which these amounts were much lower than the world average level. In another study, the model results applied by Tang et al., (2006) revealed that the total SOC storage in croplands in China was about 3,968 Tg C; and SOC was lost at a rate of 78.89 Tg Cyear^{-1}. Based on these results and with regard to the potential of global warming, SOC loss in croplands could be a serious contributor. The strategies to reduce the SOC loss in croplands are suggested based on the DNDC model under different management practices and scenarios. For example, Zhang et al., (2015) demonstrated that SOC stocks in the semiarid regions in China amounted to 1.15 Pg C and the SOC content of 65% farmlands was below national average level.

Soybean, an oilseed crop, has many benefits that attracted much attention in Iran, typically in Golestan province. Gorgan County is one of the most important regions for soybean production in Golestan Province. In 2017, the total soybean cropping area and grain yield in this county were 11,200 ha and 2,400 kg ha^{-1}, respectively (Agricultural Organization of Golestan, 2018). This crop is suitable in the current rotation systems in Golestan province. Because of intensive farming in Gorgan county, there is a significant lack of specific information on the carbon sequestration potential of soybean in this region. Therefore, we aimed to 1) validate the DNDC model for modeling SOC dynamic in croplands under soybean cropping, 2) simulate the total topsoil (0–30 cm) SOC stocks of soybean cropping systems, (3) quantify the spatial distributions of carbon sequestration potential of soybean-grown croplands by Geographic Information System (GIS) techniques.

2. Materials and methods

2.1. Study area

The research area was located in the Gorgan county in Golestan province, north of Iran. The region coordinates range from 53° 57′ and 56° 32′ E longitudes and 36° 30′ and 38° 8′ N latitudes (Figure 1). Gorgan has a semi-Mediterranean and semi-humid climate with a mean annual rainfall of 422.5 mm per year (Golestan Province Meteorological Office, 2016). This county borders by Aq-Qala County by the north, Semnan Province by the south, Kordkouy County by the west and AliAbad Katool County in the east. In Gorgan county, soybean is sown during May and June and is harvested in October and November every year.

2.2. Selected fields and data collection

In this research, the croplands of the Gorgan county as an important region for soybean production in Iran were selected as studied areas. The surveyed fields were selected in four main directions of the county with a regular distribution in agricultural areas under soybean cultivation. All geographic coordinates of sampling fields were recorded by a GPS, model Garmin 60. The location of sampling sites showed in Figure 2. Soil samples were taken from 150 fields at depth of 0–30 cm before soybean sowing and after crop harvesting, during 2017.All soil samples transported to the crop research laboratory of Gorgan

University of Agricultural Sciences and Natural Resources (GUASNR), then air-dried to remove stones and coarse plant residues. Then,organic carbon storage was calculated by the Eq. 1(Lema et al.,2006):

$$SCS = SOC \times BD \times H \times 10 \qquad (1)$$

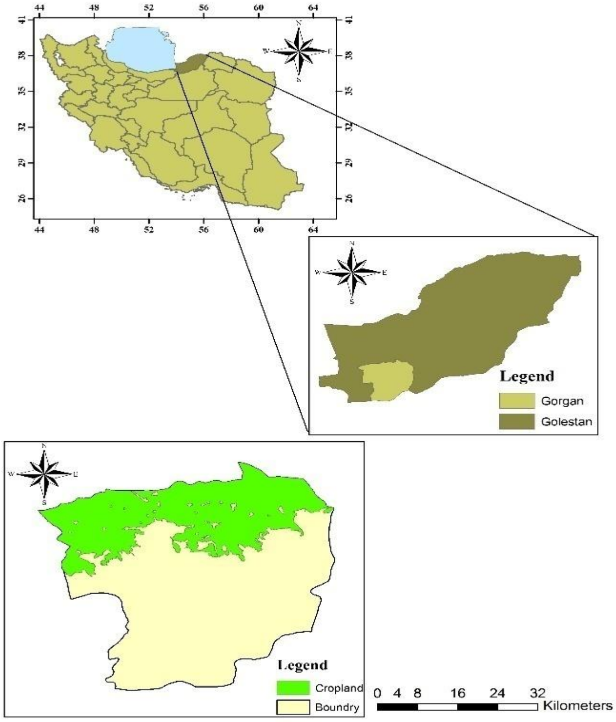

Figure 1. The location of Gorgan county in Golestan province, Iran.

Where, SCS is the soil organic carbon storage (Mg ha^{-1}), SOC is the soil organic carbon content (g kg^{-1}), BD is the soil bulk density (Mgm^{-3}), H is the thickness of the soil layer (m), and 10 is the coefficient for converting Mg m^{-3} into Mg ha^{-1}. In this research, soil texture and pH were obtained by the hydrometry method and pH meters, respectively. Also, soil bulk density (BD) was determined by Archimede's method (Blake and Hartge, 1986). Also, the Walkley and Black method was used to determine the carbon contents of samples (Walkley and Black, 1934; Nelson et al., 1996). Finally, carbon sequestration was calculated by Eq. 2 (Li et al., 2016)**:**

$$CSeqsoil = SOC_{after} - SOC_{before} \qquad (2)$$

Where, *CSeqsoil* is the soil carbon sequestration, SOC_{before}; organic carbon content in the soil before soybean sowing and SOC_{after}; organic carbon content in the soil after soybean harvesting.

Also, plant samples were randomly taken from selected fields based on W-shaped pattern by 0.5×0.5 m^2 quadrate. In the final sampling, total plant samples transported to the crop research laboratory of GUASNR, then oven-dried at 70 °C for 48 h and weighed.

2.3. DNDC model

2.3.1. Description of the model

In the DNDC model, the first part has three sub-models including soil organic matter decomposition, soil climate, and crop growth. It simulates the soil environmental condition according to ecological driving factors. The second part is made up of three sub-models including nitrification, denitrification, and fermentation. This part simulates the effects of the soil environmental condition on microbial activity and corresponding dynamic change of soil carbon and nitrogen (Li, 2001). The DNDC simulates SOC dynamics by quantifying the turnover of four major SOC pools including microbial biomass, plant residue, active humus, and passive humus (Pathak et al., 2005). This model can describe the interactions between the driving factors. Therefore, it can simulate the carbon and nitrogen biogeochemical cycle (Li, 2007).

2.3.2. Model inputs

Inputs in the DNDC model included information on survey region, soil, climate and crop properties. The soil and crop properties categorized into farming management practices such as fertilization, irrigation, tillage, and grazing or plant cutting. The DNDC model runs in two forms: region simulation type and site simulation type. In this research, we used the site section for simulation and denitrification/decomposition procedure. Therefore, the input parameters included meteorology, soil, crop and farmland management practices data. The details of these inputs were listed in Table 1. The data of farmland management practices was collected by in-person interviews with 150 farmers in Gorgan county. This data included straw incorporation, fertilizer date, fertilizer applied amounts, and irrigation date and amounts. Also, some required data such as soybean growing season, planting date, harvesting date, and cropping rotation collected from the Agricultural Organization of Golestan province.

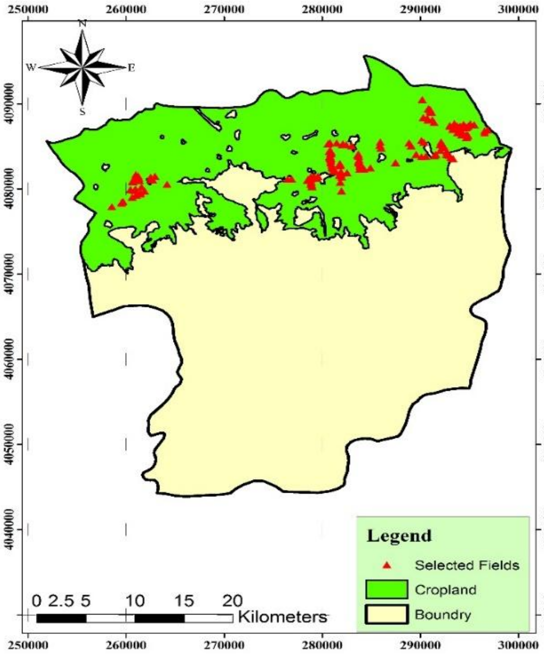

Figure 2. The location of the selected fields in Gorgan county, Golestan province, Iran.

In this research, climatic data were obtained from one meteorological station located within the study area (Hashem Abad station). N concentration in rainfall, atmospheric background NH_3 concentration, atmospheric background CO_2 concentration and annual increase rate of atmospheric CO_2 concentration were considered as climatic parameters in this model. These parameters were obtained from Golestan Meteorology Organization (2017) and NOAA site (http://www.noaa.gov).

In this research, crop parameters were provided based on a field survey and laboratory works (Table 1). All plant samples were separated and measured based on the dry matter weight in the laboratory of the GUASNR. Finally, the soil properties data were obtained from sampling sites distributed in soybean croplands of Gorgan county, including soil texture, pH, bulk density, SOC, field capacity, soil total N, hydro-conductivity point, wilting point, porosity and clay fraction.

Table 1. Main parameters used in the denitrification/decomposition model (DNDC) for the site simulation type

Type	Details
Climate	Latitude (o) N concentration in rainfall (mg L-1) Atmospheric background NH3concentration (mg kg-1) Atmospheric background CO2 concentration (mg kg-1) Annual increase rate of atmospheric CO2concentration (mg kg-1)
Soil	Texture Bulk density (g cm-3) pH Field capacity Wilting point Clay fraction Hydro-conductivity (m h-1) Porosity SOC (g kg-1) Soil total N (g kg-1)
Crop	Maximum biomass (kg C ha-1) Biomass fraction Biomass C/N ratio Total N demand (kg N ha-1) Thermal degree days Water demand (g water g-1dry matter) Tilling date (month-day) Tilling method
Farming management practice	Planting date/Harvest date (month-day) Straw incorporation Fertilizer date (month-day) Fertilizer applied amount (kg ha-1) Irrigation date (month -day) Irrigation amount (mm)

2.3.3. Model validation

In order to the validation of the DNDC model, some statistics were evaluated. These included correlation coefficients (r), root mean square error (RMSE), mean absolute error (MAE), mean bias error (MBE) and model efficiency (EF). Usually, the correlation coefficient is the correlation degree between the simulated against observed values, and its significance was calculated according to the T-test. Also, the accuracies of the simulations were estimated using the other mentioned statistics. The lower values of RMSE, MAE, and MBE indicate the lower difference between the simulated and observed data. Also, the EF equal with 1 value, indicates a better significant correlation between the predicted and observed data (Webster and Oliver, 2000; Mishra et al., 2010; Wang et al., 2013). The statistics were calculated as follows:

$$\mathrm{RMSE} = \sqrt{\textstyle\sum_{i=1}^{n}[(p_i - O_i)]^2 \,/\, n} \tag{3}$$

$$\mathrm{MAE} = \frac{\sum_{i=1}^{n}|p_i - O_i|}{n} \tag{4}$$

$$\mathrm{MBE} = \frac{\sum_{i=1}^{n}(p_i - O_i)}{n} \tag{5}$$

$$r = \frac{\sum_{i=1}^{n}(P_i - \bar{P}) \times (O_i - \bar{O})}{\sum_{i=1}^{n}\sqrt{(P_i - \bar{P})^2} \times \sum_{i=1}^{n}\sqrt{(O_i - \bar{O})^2}} \tag{6}$$

$$\mathrm{EF} = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \tag{7}$$

$$\mathrm{CV} = \frac{\mathrm{RMSE}}{\bar{O}} \tag{8}$$

Where, P is the mean of the predicted values, P_i is the predicted values, $\overline{O}$ is the mean of the observed values, O_i is the observed values and n is the number of paired values (i=1, 2…, n) (Mishra et al., 2010; Álvaro-Fuentes et al., 2012; Wang et al., 2013).

2.4. GIS procedures

The DNDC model input values for soil properties, daily weather, crop rotations, and agronomic management practices collected from various sources and organized as databases by Geographic Information System (GIS) techniques (Xu et al., 2012). In this study, the spatial distribution of predicted data by DNDC and observed data were interpolated by different geostatistical and classic interpolation procedures such as Inverse Distance Weighted (IDW), Ordinary Kriging (OK), Local Polynomial Interpolation (LPI) and Radial Basis Functions (RBF) in ArcMap software, ver.10.6. For this purpose, we used the geostatistical analyst tools in ArcMap. All layers were georeferenced to UTM (WGS-84) coordinate system. Then, the thematic layers were produced in ArcGIS media.

3. Results and Discussion

3.1. DNDC model validation

The long term data from a metrological station located in Gorgan county was used to validate the DNDC model in this study. For model validation, we used the simulated and measured SOC changes. Results showed that the correlation coefficients between the simulated values and field values for SOC content and carbon stock in Gorgan county were 0.99 and 0.99 for before soybean planting stage, and 0.98 and 0.98 for after harvesting stage, respectively. These values were significant at the 0.01 probability level (Table 2).

Therefore, these results showed that there was correlation between the simulated and measured data of SOC (Figure 3). Also, the values of RMSE for the simulation of the SOC content and stock were as 2.56 and 0.31 in before planting stage and 0.89 and 0.28 for after harvesting stage, respectively. The values of model efficiency (EF) were obtained as 0.88 (SOC) and 0.84 (carbon stoke) (Table 2).

The best agreement between DNDC simulated and observed data was found in SOC stock after harvesting, where RMSE was 0.89 (Table 2). These results indicated that the DNDC model can successfully simulate the values of SOC for the soybean fields of Gorgan County. Previously, some researchers used this model for the estimation of SOC change under farming practices. For example, the results of Wang et al. (2013) showed that there was a strong correlation (R^2=99) between the simulated and measured data of SOC. Also, Yan et al., (2016) conducted validation of the DNDC model against field data sets of SOC from Quzhou Huantai County (China). They achieved high accuracy in the model simulation with the improvement of the model parameters. Based on the above validations, we can confirm that this model has an appropriate performance for the SOC change undercurrent soybean croplands in Golestan province.

Table 2. Values of some statistics for DNDC model validation

Variable	r	RMSE	CV	MBE	MAE	EF
SOC Stock- Before Planting (0-30 cm)	0.99^{**}	2.56	8.33	2.48	2.48	0.73
SOC Stock- After harvesting (0-30 cm)	0.98^{**}	0.89	2.54	0.038	0.620	0.95
OC- Before Planting (0-30 cm)	0.99^{**}	0.31	2.28	0.129	0.265	0.97
OC- After harvesting (0-30 cm)	0.98^{**}	0.28	1.91	0.016	0.14	0.96

Variable	r	RMSE	CV	MBE	MAE	EF
SOC Stock- Before Planting (0-30 cm)	0.99^{**}	2.56	8.33	2.48	2.48	0.73
SOC Stock- After harvesting (0-30 cm)	0.98^{**}	0.89	2.54	0.038	0.620	0.95
OC- Before Planting (0-30 cm)	0.99^{**}	0.31	2.28	0.129	0.265	0.97
OC- After harvesting (0-30 cm)	0.98^{**}	0.28	1.91	0.016	0.14	0.96

**; Significant in 1% probability level

3.2. Distribution of annual SOC change in soybean croplands

The average of SOC stock was increased in the soils under soybean cropping (Table 3). It was simulated from 31.13 to 33.74 Mg ha^{-1} for before planting and after harvesting, respectively. These amounts were observed as 28.27 Mg ha^{-1} for before planting and 32.26 Mg ha^{-1} for after soybean harvesting. These results confirmed that soybean croplands in Gorgan county can be a sink of carbon. Therefore, we can increase the SOC in soybean croplands by performing some methods and systems such as conservation agriculture, intercropping systems, crop residue mulching, ley-farming rotation, and organic farming. In similar research, the DNDC model findings indicated that the annual loss of SOC storage highly varied among the cropping systems. For example, the annual SOC losses in soybean fields (3.46 t C ha^{-1}) were two times higher than soybean-maize rotation fields (1.59 t C ha^{-1}) (Han et al., 2005).

3.3. Spatial distribution of SOC change

The spatial distribution of SOC change (0–30 cm) for soybean fields in Gorgan county was provided using ArcGIS software, var**.** 10.6. These amounts were predicted by the DNDC model.

3.3.1. Observed and simulated SOC; before soybean planting

Some interpolation methods, such as Local Ordinary Kriging, Radial Basis Functions, Polynomial Interpolation, and Inverse Distance Weighted were selected to provide a spatial layer of SOC. Results showed that Ordinary Kriging was the best method for interpolation of observed and simulated SOC. This model had the lowest error and the highest accuracy than other methods.

Based on the map produced by the Ordinary Kriging in ArcGIS software, the highest amount of observed SOC was obtained in the east, southeast and partly northeast of the region (Figure 4). It seems that because of the preservation of previouscrop residues (wheat) and increasing soil organic matter and also, reducing bulk density and increasing soil porosity, the soybean fields in these regions had generally the higher SOC than other regions. Also, the lowest amount of observed SOC was estimated in the central and southwest regions of Gorgan county (Figure 4).

Based on the map generated in ArcGIS software, the highest amount of simulated SOC was observed in the southeastern, central, and south areas of Gorgan county (varied from 30.43 – 33.29 Mg ha^{-1}). Also, the lowest amount of simulated SOC was simulated in the north and west regions (27.55- 30.43 Mg ha^{-1}).

Results of soil analysis showed that content of organic matters in these regions were lower than other areas in before soybean planting stage. The findings by Xu et al. (2012) demonstrated that the Spatio-temporal dynamics of SOC in China can be characterized by relating the DNDC outputs to the soil polygon-based database. Also, Lenka and Lal (2013) demonstrated that crop straw incorporation, animal manure application, and no-/reduced tillage were the most effective measures for increasing the SOC level. For example, straw incorporation can offer a substantial contribution to improve SOC by adding exogenous organic carbon to farmlands (Freibauer et al., 2004; Lugato et al., 2006). In another study, Jin et al., (2010) concluded that the effect of straw incorporation in combination with animal manure on increasing the SOC content was better than a high rate of straw return alone. Overall, the simulation accuracy of SOC was affected by the sensitive factors such as temperature, precipitation, soil bulk density, texture, and fertilization. Also, other factors, including rainfall N and atmosphere background NH_3, had a weak influence on SOC dynamic change. It seems that more precise regional parameters need to be provided to achieve higher simulation accuracy for the SOC through the DNDC model.

3.3.2. Observed and simulated SOC; after soybean harvest

Results showed that Ordinary Kriging was the best method for interpolation of observed and simulated SOC. This model had the lowest value of RMSE than other interpolation methods. After soybean harvesting in Gorgan county, the observed amount of SOC in measured fields was estimated between 32.21-35.95 Mg ha^{-1}. The highest content was observed in the eastern, southeast, and central parts toward the south of the county, which was affected by several factors such as soil bulk density, regional climatic conditions, performance of conservation cropping systems, modern irrigation systems, and fertilization management type (Figure 6). Hua-Jun et al., (2010) indicated that crop biomass production with relevant farming management practices plays an important role in affecting the carbon dynamics for agroecosystems. In this research, results showed that the amount of observed SOC decreases from eastern regions towards west regions of the county. In these regions, the amount of SOC ranged from 27.50-32.21 Mg ha^{-1}(Figure 5).

The model outputs indicated that the highest amount of SOC was simulated in the east, northeastern, and southeast areas of Gorgan county. This amount was estimated as 33.59 - 35.46 Mg ha^{-1}. Also, SOC content reduced from southern regions towards the north and southwest regions (Figure 5). In this regard, Chen et al., (2018) confirmed that the DNDC was an acceptable model for simulating SOC stock in Yucheng County (China).

According to the simulated results reported by Hua-Jun et al., (2010), the total SOC storage in China was 4.7-5.2 Pg C (0-30 cm) in 2003, with an average of 4.95 Pg C. In addition, SOC density in croplands of China ranged from 3.9 to 4.4 kg C m^{-2}, and this amount which was much lower than the world average (12.1 kg C m^{-2}). Principally, a variable may be homogeneous at one scale and heterogeneous at another, and information is often lost as spatial data are considered at small scales (Xu et al., 2013). Accordingly, Han et al., (2005) concluded that SOC values in the cropping systems attributed to either the land-use history or farming management.

Some researchers emphasized that climate change and soil conditions could play a role in the long-term SOC change. For example, Paul et al., (2002) observed that SOC accumulation increases with increasing annual rainfall. Also, the potential carbon sequestration is significantly different across the soil groups (Luo et al., 2010).

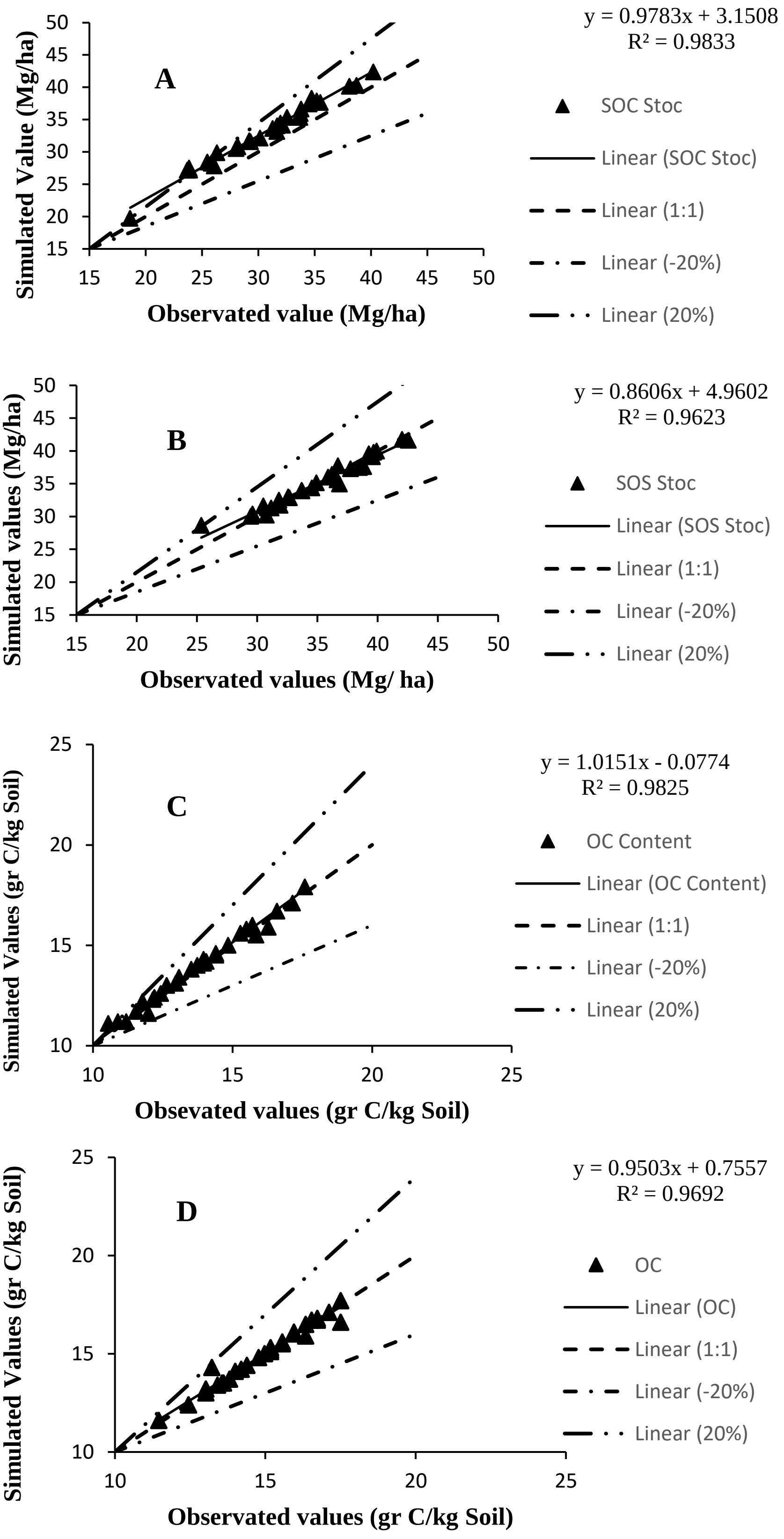

Figure 3. Simulation of SOC contents(0-30cm) in soybean croplands of Gorgan county, Iran; A) SOC stock (Mg ha^{-1}) in before planting, B) SOC stock(Mg ha^{-1}) in after harvesting, C) OC content (gr C kg^{-1} soil)in before planting, D) OC content (gr C kg^{-1} soil) in after harvesting.

Table 3. **Mean of SOC stock and SOC content for before planting and after harvesting stages in soybean fields, Gorgan County, Golestan Province.**

Variable	**Depth(cm)**	**Before planting**		**After harvesting**	
		Simulated	**Observed**	**Simulated**	**Observed**
SOCstock (Mg ha^{-1})	0-30	31.13	28.27	33.74	32.26
SOC content(gr Ckg^{-1}soil)	0-30	12.83	12.55	14.04	13.97

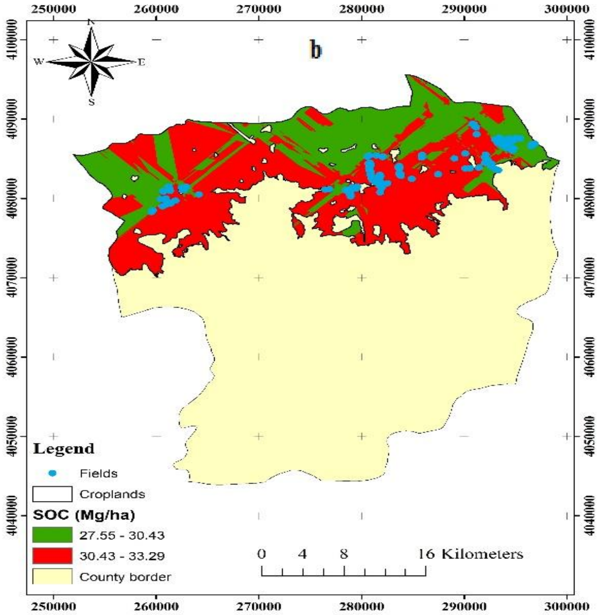

Figure 4. Maps of SOC in croplands of Gorgan county in before soybean planting: a) observed b) simulated values.

Table 4. Mean of CS-SOS and CS-OC in the soil of soybean fields, Gorgan, Iran.

CS- SOC (Mg ha^{-1})		**CS- OC (gr c kg^{-1}soil)**	
Simulated	Observed	Simulated	Observed
2.60	3.97	1.21	1.42

CS- SOC= Carbon Sequestration in Soil total organic C content (Mg ha^{-1}) (depth of 0-30 cm)
CS- OC= Carbon Sequestration in Organic Carbon Content (gr c kg^{-1} soil) (depth of 0-30 cm)

Table 5. Mean of dSOC, DOC and NEE simulated by DNDC model in the soil of soybean fields, Gorgan, Iran.

Stage	**dSOC**	**DOC**	**NEE**
Before planting	-1.18359	157.0035	-13.9894
After harvest	-1.28993	166.2731	-13.8232

dSOC= Daily change in SOC content (kg C ha^{-1} day^{-1}) (depth of 0-30 cm)
DOC= Soil dissolved organic C content (kg C ha^{-1}) (depth of 0-30 cm)
NEE= Net ecosystem C exchange rate (kg C ha^{-1} day^{-1}) (depth of 0-30 cm)

3.4. Carbon sequestration

The average concentration and storage of carbon sequestration in the observed and predicted state were as 3.97, 1.42 and 2.60, 1.42 Mg ha^{-1}, respectively (Table 4). These results demonstrate changes in carbon stock in the observed condition. Xu et al., (2012) demonstrated that Chinese paddy soils sequestered as 5.0 Tg C year^{-1}. Based on our results, in some soybean fields, carbon content decreased. Principally, this means that some soil carbon content was emitted as gas to the atmosphere. This rate depends on the tradeoff between crop residue and organic manure and losses of carbon by predominantly heterotrophic respiration associated with SOC decomposition (Li et al., 1997; Zhang et al., 2007; Gollany et al., 2010). Generally, soils should be managed according to their spatial distribution of carbon sequestration potential under different groups. In this study, the rate of dSOC[†] and NEE[‡] were higher before the sowing stage than after the soybean harvesting stage. Also, the simulated and measured values of these parameters were completely similar (Table 5).

Some researchers reported that due to the complexity of carbon turnover processes and the dynamic response of carbon to environmental conditions, process-based models can extensively use to simulate the dynamics of SOC in agricultural systems (Paustian and Álvaro-Fuentes, 2011;

[†] - Daily change in SOC content

[‡] - Net ecosystem C exchange rate

Gottschalk et al., 2012; Goglio et al., 2014). Hua-jun et al (2010) found that the annual SOC losses in soybean fields (3.46 t C ha^{-1}) were two times higher than those in soybean-maize rotation fields (1.59 t C ha^{-1}). The annual net changes in SOC storage ranged from + 0.19 to -73.6 Tg C yr^{-1} with a mean value of 36.7 Tg C yr^{-1}, or a loss of 0.7%. Approximately 92.6% of the soybean soils sequestrated C, while 5.3% lost C and only 2% kept balance in the soybean growing season.

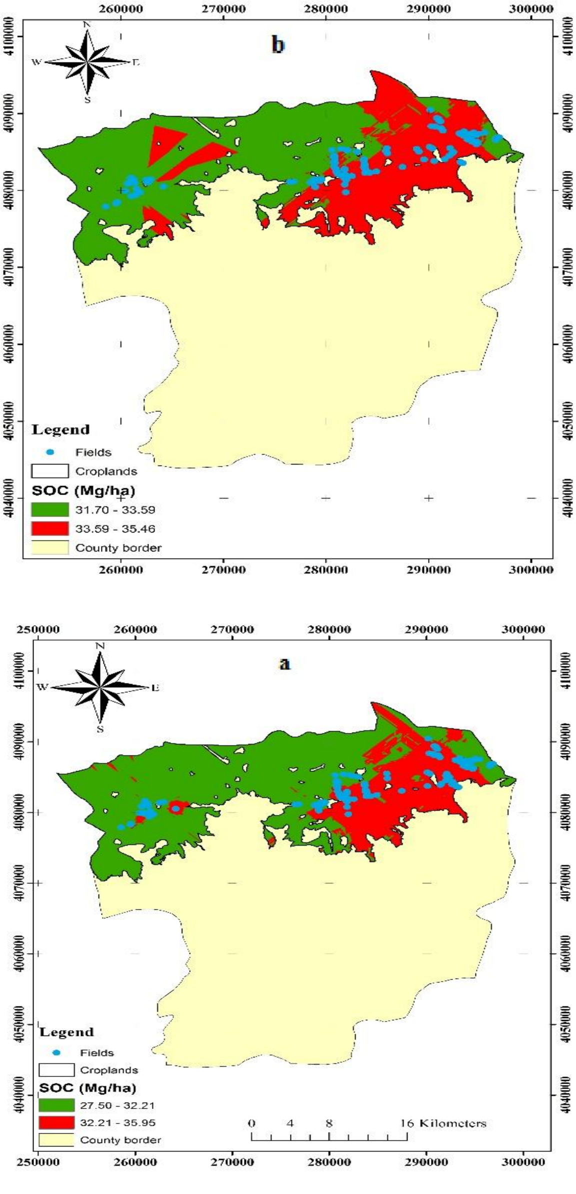

Figure 5. Maps of SOC in cropland of Gorgan county in after soybean harvest: a) observed b) simulated values.

3.4.1. Carbon sequestration; Observed

Some interpolation methods, such as Ordinary Kriging, Radial Basis Functions, Local Polynomial Interpolation, and Inverse Distance Weighted were selected to provide a spatial layer of carbon sequestration in Gorgan County. Results showed that Ordinary Kriging was the best method for interpolation of observed carbon sequestration. The highest carbon sequestration density was observed in the east and southeast of Gorgan county (4.34 – 6.95 Mg ha^{-1}). Also, the lowest carbon sequestration SOC was obtained in the central, west and southwest regions of the county (3.08–4.34 Mg ha^{-1}) (Figure 6). In this regard, the spatial distribution of SOC density in China revealed a sharp contrast between the northern and southern counties due to the differences in climatic conditions and farm management practices (Hua-jun et al., 2010).

Results showed that soybean fields with low soil bulk density and maintaining of residues in the soil surface had the highest carbon sequestration. The results highlighted the importance of crop straw incorporation, organic manure and optimized mineral fertilization on the carbon sequestration in the soybean croplands of Gorgan county.

Follett (2001) found that enhancing nutrient and water use efficiency can improve soil characteristics and microbial activity, following by increasing the carbon sequestration potential in fields.

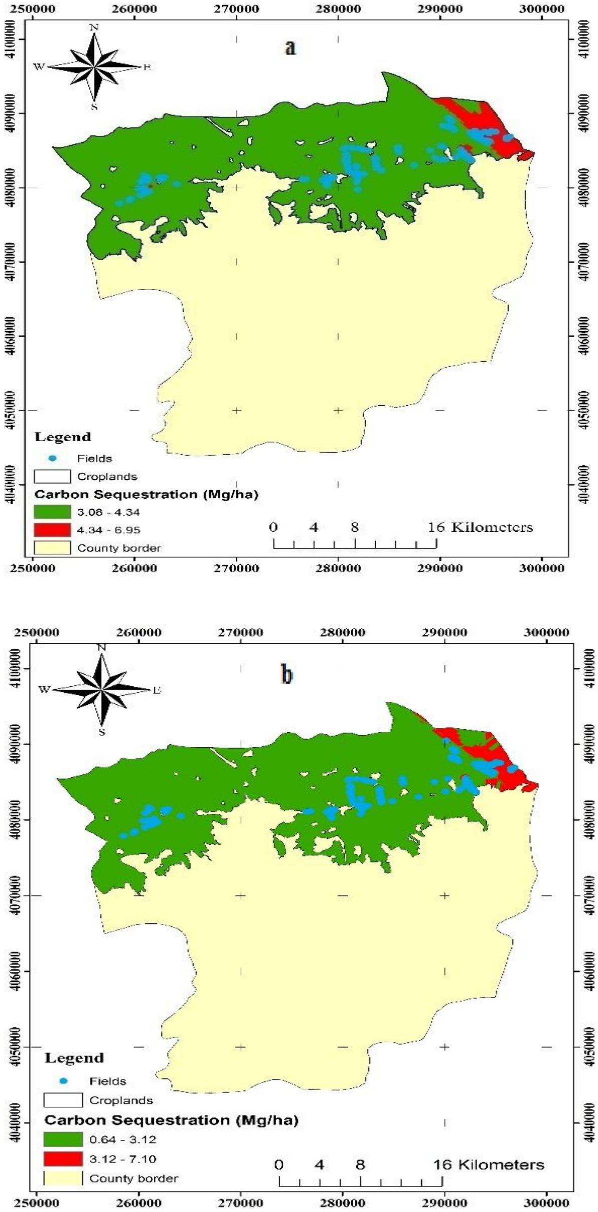

Figure 6. Maps of carbon sequestration in soybean croplands of Gorgan county; a) observed, b) simulated values.

3.4.2. Carbon sequestration; Simulated

Results showed that Ordinary Kriging was the best method for interpolation of simulated carbon sequestration in this study. The model output indicated that the highest amount of carbon sequestration was simulated in the east, northeastern, and north areas of Gorgan county. This amount was estimated as 3.12–7.10 Mg ha^{-1}(Figure 6). In this region, field management was performed very well by farmers than other regions of Gorgan county. Moreover, crop residues maintained in the field surface could increase the carbon sequestration contents in soil. Also, results showed that the carbon sequestration amount was reduced from east regions towards west regions (Figure 6). In the mentioned regions, some farmers usually burned the residues after harvesting the crops. This work can extremely reduce the microbial activity of soil and reduce the biodiversity in the surface soil and subsoil of croplands. The decrease in SOC storage leads to the decline of soil fertility and hence threatens agroecosystem sustainability. The difference between the SOC losses is essentially related to farming management practices (Han et al., 2005).

The study provided new information on how improvements in the process-based DNDC model in Iran. Therefore, it can be utilized to determine SOC change and dynamism and carbon sequestration potential on the regional scale.

4. Conclusion

Most of the information available about carbon sequestration is restricted to farm methods and analysis in Iran. The study reported in this paper provided new information on how improvements in the process-based DNDC model in this country can be utilized to explicitly determine SOC change and carbon sequestration on the regional scale. Results showed that there was a strong correlation between the simulated and measured data of SOC. The average concentration and storage of carbon sequestration in the observed and predicted state were as 3.97, 1.42 and 2.60, 1.42 Mg ha^{-1}, respectively. The highest carbon sequestration density was observed in the east and southeast of Gorgan county. The DNDC simulation results indicated that the SOC content of soybean croplands could be effectively increased when conservation of agricultural system, sewage sludge amendments, organic manure, ley-farming rotation, cover crops, organic farming systems, crop residues mulch, and intercropping systems are involved. Also, some farmers usually burn the residues after harvesting crops in Gorgan croplands and other regions in Iran. We recommend similar studies using different scenarios such as burn/ un-burn of crop residues, different crop rotations, and tillage system types. Based on results, we can confirm that DNDC model has an appropriate performance for the SOC change undercurrent soybean croplands. Also, we suggest preparing some hybrid sub-models with GIS program for the future.

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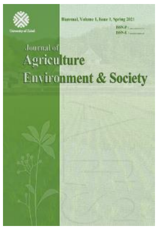

Energy use analyses in Iranian wheat project

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ABSTRACT

The study attempts to analyze the energy input-output relationship during Iranian wheat project from 1990 to 2005. The main sources of evidence for this investigation were obtained from the related companies and different departments of Iran Ministry of Jihad–e–Agriculture including Library. Findings revealed that total energy inputs and output have increased from 26503.5 and 20871.5 MJ ha^{-1} in 1990 to 35466.3 and 30259.8 MJ ha^{-1} in 2005, indicating a 25.27 and 31.03% increase, respectively. Averagely data collection (under both irrigated and dryland conditions), diesel had the highest share, of 37.08%, followed by electricity (21.23%), chemical fertilizers (20.21%), water (8.39%), seed (7.94%), machinery (2.33%) and human labor (2.18%), respectively. There was a significant increase in electricity usage (about 74% increase), and an associated decrease in the diesel usage (about 34% decrease) during 1990-2005 period because electric pumps replaced diesel pumps. Chemical fertilizers rose from 4353.25 to 8659.80 MJ ha^{-1}. In the studied period, the share of nitrogen and potassium in the total fertilizer energy input increased from 72.00 to 84.79% and from 0.00 to 0.65%, respectively, while the share of phosphorus shrunk from 28.31 to 14.56%. There were not significant changes regarding the human labor and machinery annually and seedbed preparation required the maximum energy, followed by harvesting. Pesticides increased extensively in the last year under study, particularly in case of herbicides, and of which 2,4-D/MCPA and Clodinafop-propargyl had the highest share. Values of energy use efficiency (0.70-1.00), specific energy (14.70-21.04 MJ kg^{-1}) and energy productivity (0.05-0.07 kg MJ^{-1}) showed an intensive use of inputs not accompanied by increase in output during wheat project. Most of the total energy inputs were supplied in the non-renewable and direct forms. Also, regression analysis indicated the impact of indirect and non-renewable energy on output was statistically significant.

Highlights

- Total energy inputs and outputs for Iranian wheat production rose significantly between 1990 and 2005.
- Diesel fuel consumption decreased, while electricity usage increased due to the replacement of diesel pumps for irrigation.
- Pesticide use, particularly herbicides, increased substantially in the last year of the study.
- Despite increased energy inputs, output growth did not keep pace, indicating inefficient energy use in the Iranian wheat project.

1. Introduction

Wheat is a strategic crop that has always been the focus of farmers and governments due to its importance in providing food security worldwide as well as Iran. Wheat (total production~ 0.8 billion tons) ranks second after maize (total production~1.16 billion tons) in the world cereal output and it is a staple food for billions of people of the world (FAO, 2023). It is also the most important winter

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cereal grown in Iran (Zand et al., 2007) which contains significant amounts of important nutrients including carbohydrates, proteins, fiber, and minor components including lipids, vitamins, minerals, and phytochemicals which may contribute to a healthy diet (Shewry and Hey, 2015). Wheat is grown under both irrigated and dryland conditions throughout Iran which had higher share of cultivated area than other species (field crops and trees). In general, climate of Iran is mainly dry and warm (Deihimfard et al., 2023). Temperature and precipitation vary with elevation, as winds bring heavy moisture from the Persian Gulf. The Caspian region receives over 40 in. (102 cm) of rain annually. Precipitation occurs mainly in the winter and decreases from northwest to southeast; much of the precipitation in the mountains is in the form of snow. Meltwater is vital for Iran's water supply. The central portion of the plateau and the southern coastal plain receive less than 5 in. (12.7 cm) of rain annually. The country is divided into 31 provinces and 6 regions including arid, semi-arid, Mediterranean, semi-humid, humid, and very humid (Fathi Taperasht et al., 2022). Cultivars of wheat commonly grown in different regions of Iran are listed in alphabetical order as follows: Adl, Alamoot, Alborz, Alvand, Aqua, Argentin, Arvand, Ataei, Atrak, Azadi, Azar, Bakanora, Barekat, Bayat, Bezostaya, Bistoon, Bulani, Chamran, Chenab, C–V3–5, Darab, Dastjerdi, Dehqan, Deihim, Derakhshan, Dez, Falat, Faravan, Firoozeh, Gaskugen, Gaspard, Golestan, Hirmand, Inia, Italyai, Javanjani, Jolgeh, Kalar, Karaj, Kaveh, Kavir, Khalij, Khazar1, Kouhrang, Kouhsar, Mahdavi, Maroon, Marvdasht, Molqani, Moqan, MV–17, Navid, Naz, Niknejad, Omid, Panjamou, Pastour, Pishtaz, Qermezak–e–Varamin, Quds, Rashid, Rasoul, Reihani, Roshan, Saba, Sabalan, Sardari, Sefidak, Shahi, Shahpasand, Shiraz, Shiroodi, Sholeh, Simineh, Star, Tabasi, Taban, Tajan, Tobari, Yavarous, Zarandi, Zarrin.

A national project on wheat production was launched in 1990, the main aim of which was to increase wheat production in Iran in order to be able to cover local demand and minimize imports. In 2002, authorities introduced a new law to facilitate the domestic production of wheat. According to this law, self–sufficiency should be reached during the next 10 years and demand and supply should become equal. Under this law, increasing the yield per area is the main tool to reach self–sufficiency (Deihimfard et al., 2007).

The analysis of energy flows provides us with very relevant information for understanding the type of relationship that each society has established with the natural environment that sustains it. It also provides useful information in understanding the ways in which the land is used and the capacity to satisfy their inhabitants needs (Imran and Ozcatalbas, 2021). Moreover, analyzing energy input flows into agricultural systems can improve energy use efficiency by knowing more details about each input and their contribution in the total energy input entering the farm. Energy use in agricultural production has been increasing faster than that in many other sectors of the world economy because agricultural production has become more mechanized, and use of substitutes for land, such as commercial fertilizers, has increased (Karkacier and Goktolga, 2005; Amiri et al., 2019; Eyni-Nargeseh et al., 2023). Energy use can be divided into direct and indirect. Direct energy use is energy input used in production when such input can be directly converted into energy units (e.g. diesel–fuel, lubricants and electricity for irrigation and drying). Indirect energy use is energy used in the production of inputs used in production when such inputs cannot be converted directly into energy units (e.g. machinery, fertilizers, and pesticides) (Soni et al., 2018; Htwe et al., 2021; Soltanzadeh and Ahmadpour Borazjani, 2022).

The current policy within agriculture seeks to develop crop production systems that minimize energy input mainly fossil fuels for a high level of output. In this respect, the energy balance is important. Energy balance is the numerical comparison of the relationship between input and output of a system or agricultural business in terms of energy units. The main objective of this study was to investigate the energy use patterns and to analyze energy input–output in Iranian wheat project from 1990 to 2005, as overall energy savings and energy efficiency are main factors in agricultural production.

2. Materials and methods

The data used in this study were based on annual data for the period 1990–2005 and were obtained from numerous sources. The main sources of evidence for this investigation were obtained from the related companies and different departments of Iran Ministry of Jihad–e–Agriculture including Library, Deputy of Planning & Economic Affairs, Bureau of Statistics & Information Technology, Deputy of Industries & Infrastructural Affairs, Bureau of Irrigation Networks Development, Bureau of wheat project, Agricultural Mechanization Development Center, Plant Protection Organization, and Agricultural Support Services Company.

Data concerning the amount of electricity, water and fuel used and wells information were obtained from the two companies of Iran's Ministry of Energy, Tavanir Holding Company, and Iran Water Resources Management Specialized Mother Company and from National Iranian Oil Refining & Distribution Company. Further data were come from personal contacts, oral interviews and statistical yearbooks. The study has also benefited from previous researches and studies conducted on energy analysis for different crops in Iran.

First, all inputs and outputs for wheat production under both irrigated and dryland conditions were determined, quantified and entered into Excel spreadsheets, and then, transformed into energy units and expressed in MJ ha^{-1}. The energy equivalents of the inputs and output are shown in Table 1. Data in Table 1 were derived from several sources. Owing to the fact that their respective data were not available, the input from animal labor and from the sun, and output from the straw yield was not included.

Data on total fuel consumption for wheat production were available, but their use in different operations was not clear. Thus, the results of the previous researches conducted in Iran (Hassan–Zadeh–Ghorttapeh et al., 2001; Roozbeh et al., 2002; Haidar–Gholi–Nezhad–Kenari and Hassan–Zadeh–Ghorttapeh, 2003; Sharifi–Ashorabadi et al., 2004; Valdiani et al., 2005; Kohansal and Yazdani, 2006; Komarizade, 2007) were used for the estimation of the duration of tractor and combine usage and diesel requirements. Based on these studies, the values of aforementioned parameters for land preparation, sowing, cultural practices, and harvesting–threshing were 6.1 h and 46.5 l, 0.2 h and 0.5 l, 0.5 h and 1.6 l, and 0.6 h and 20 l, all on ha basis, respectively. Thereafter, total hours and diesel requirements were calculated separately by multiplying percentage of land–area subjected to these mechanical operations by their corresponding values. In their study on energy input–output analysis for crop production in Iran, Gholami and Sharafi (2006) showed that annual energy spent for tractor manufacturing and repair was around 150 MJ ha^{-1}. In the present study, this value was calculated as a part of fuel consumption using conversion factor (52.055 MJ = 1 l diesel ha^{-1}). Gholami and Sharafi (2006) used methodology of Ozkan et al. (2004). The fuel requirements of water pumps (diesel engines) were calculated as total fuel consumption minus fuel consumption in all the above-mentioned mechanical operations.

The assessment of the amount of electricity (all electricity are posited to come from fossil energy sources) used per ha was computed by dividing total electricity power used in agriculture by total cultivated land–area. Almost all electricity power is used by electrical engines for irrigation.

The energy required to manufacture the majority of the pesticides applied were not available directly, although Green (1987) provides values for 24 herbicides, 4 fungicides and 11 insecticides. In accordance with Tzilivakis et al. (2005), the values provided by Green (1987) for specific pesticides were assigned to their chemical group (Table 2). Where there was more than one value for a group, the mean was taken. Those herbicides that did not belong to one of the chemical groups in Green's study were assigned based on value of herbicides from Table 1.

Energy use efficiency was computed by dividing energy output (MJ ha^{-1}) by energy input (MJ ha^{-1}), specific energy was calculated by dividing energy input (MJ ha^{-1}) by grain output (kg ha^{-1}), and energy productivity was obtained by dividing grain output (kg ha^{-1}) by energy input (MJ ha^{-1}) (Mandal et al., 2002).

The input energy was divided into direct, indirect, renewable and nonrenewable forms (Hatirli et al., 2005; Yilmaz et al., 2005; Erdal et al., 2007). Indirect energy consists of the seeds, pesticides, chemical fertilizers, farmyard manure, machinery and direct energy including human labor, diesel and electricity energy used in the wheat production process. On the other hand, non–renewable energy includes diesel, electricity, pesticides, chemical fertilizers, machinery and renewable energy consists of human labor, seeds and farmyard manure.

Due to the fact that wheat is grown under both irrigated and dryland conditions throughout Iran and some energy sources such as insecticides were inseparable between these two conditions and also to avoid a long article and in order that results can be presented as precisely as possible, weights were assigned for each energy source type and weighted averages between the two conditions were calculated according to the area cultivated by each farming system. Multiple regression analysis was performed with 15 years data using PROC REG, Maximum R–Square Improvement Selection Method, in SAS program (SAS version 9.00, SAS Institute Inc., Cary, NC, USA). In the regression analysis, seed yield (kg ha^{-1}) was the dependent variable and other energy sources (MJ ha^{-1}) were considered as independent variables.

3. Results and discussion

3.1. Changes in energy inputs over time

Based on information presented by various sources e.g. (Fathi Taperasht et al., 2022), due to the climatic diversities in Iran, agricultural practices including soil tillage, seedbed preparations, sowing, cultural practices, and harvest during wheat production are applied throughout year. In general, sowing and harvest performed from September until February, and from April to September, respectively in different provinces of Iran. Seeds of different cultivars mentioned in part of introduction are supplied by the related companies and different departments of Iran Ministry of Jihad–e–Agriculture such as Agricultural Support Services Company (ASSC), and Seed and Plant Improvement Institute (SPII), and planting is realized under the supervision of them.

Energy consumption (MJ ha^{-1}) for each item and energy input–output relationships during Iranian wheat project are illustrated in Table 3.

The averages of 1990–2005 for inputs used in wheat production, output and energy equivalences are illustrated in Table 4.

Throughout the period 1990–2005, Iranian wheat project has experienced significant changes in terms of chemical fertilizers (particularly nitrogen), farmyard manure, pesticides, diesel, and electricity usage (Table 3). Table 4 shows that diesel had the highest share, of 37.08%, followed by electricity (21.23%), chemical fertilizers (20.21%), water for irrigation (8.39%), seed sown (7.94%), machinery (2.33%) and human labor (2.18%), respectively. The energy inputs of farmyard manure and pesticides were found to be quite low compared to the other inputs used in production. Singh et al. (2002; 2003; 2004) concluded the major share of source–wise total energy input for cultivating the wheat is contributed through electricity, diesel and fertilizers as 0.3–26.0%, 22.6–26.0%, and 22.5–50.6%, respectively. In their research, the electricity and diesel contribute about 50% of the total energy consumed and the shares of seeds, farmyard manure, human and machinery energy of the total energy were 9.9–12.9%, 3.2–8.6%, 4.5–6.2% and 2.1–2.4%, respectively. Pervanchon et al. (2002) reported the share of fertilizers, pesticides, seeds and machinery production considered for the indirect energy in wheat crop were 31–81%, 3–4%, 6–7% and 12–69%, respectively.

3.2. Energy Sources Contribution

In Iran, an average 213.72 l ha^{-1} diesel was used in wheat production (Table 4) which was about 64 l ha^{-1} higher than value reported by Sayin et al. (2005) for wheat production in Turkey. The energy use in irrigated wheat is heavily dependent on diesel fuel, since most pumps used for irrigation are powered by diesel engines in Iran. Therefore, most diesel fuel consumption is for irrigation (about 54%). Singh et al. (2003) found that the diesel energy was mainly utilized for operating tractors for performing various farm operations.

One of the particularly remarkable findings, presented in Table 3, was a strong and significant increase in electricity usage (about 74% increase), and an associated decrease in the diesel usage (about 34% decrease) in 2005 compared with 1990. The increase in electricity energy use (especially from 1998 onwards) mainly resulted from an annual increment of 6900 in the number of electrified wells and from increment in the wells' depth (Figure 3). Groundwater is estimated to constitute more than 70% of the total volume of irrigation water used in Iran for wheat production and other crops (of which about 70% is from semi–deep and the remaining 30% from deep wells).

Due to national benefits, there was a shift in policies from 1998 toward increasing the number of electrified wells, so that number of these wells reached 124984 in Iran in 2004–2005 which used about 20320530940 kWh (162585.06 kWh per each well). This electricity usage in provinces of Iran which have light precipitations such as Semnan, Khorasan (Mashhad) and Kerman (Figure 1) (2593443.20, 464488.21 and 402497.25 kWh per each well, respectively) was higher. In Iran, particularly in above-mentioned provinces, due to decrease in aquifer water–capacity and decline in groundwater table at an average rate of 1 m every year, farmers attempted to deepen their wells with the expectation that well–water yield would increase and as a result energy usage and costs would be increased. As can be seen in Figure 3, a huge gap exists between total number of wells (with diesel and non–diesel engines) and of electrified wells that must be narrowed.

There is a large range of positive outcomes from electricity rather than diesel use for pumping water. This would save energy, reduce waste and pollution, and reduce costs. Other benefits are reducing groundwater use by identifying and forbidding the wells activity without license as electricity amount can be measured and controlled. In a research by Feiz Bakhsh et al. (2019), they stated that substituting electricity instead of fossil fuel for irrigation reduces energy consumption in farms, and irrigation is performed more easily.

Annual water quantity used during Iranian wheat project was about 4000 m^3 ha^{-1} (Table 4). Gül et al. (2005) by a case study in Syria found values of water consumption for wheat production varied from 3800 to 8300 m^3 ha^{-1}. The volume of water consumption increased until 1999–2000, and from it time onwards decreased (Table 3).

The main factors responsible for this upward and downward trend are increasing the cultivated area (Figure 1) which have caused a decreasing proportion of water consumption per ha (due to water restriction resulted from aquifer depletion in water–scarce areas), and growth of optimized irrigation systems such as sprinkler, center–pivot and wheel move irrigation systems from 108.00 in 1990 to 20853.17 ha in 2005 which showed an improvement in yield and efficiency with the smaller amounts of water that can be applied using these irrigation systems.

Results of Ines et al. (2006) showed that under limited water condition, regional wheat yield could improve further if water and crop management practices are considered simultaneously and not independently. Unfortunately, increasing the cultivated area for wheat production especially from 2003–2004 (roughly coincident with the beginnings of new facilities and other supporting policies which were geared towards expanding wheat production) onwards (Figure 2), unlike general aims of sustainable agriculture (including sufficient food and fiber production, environmental stewardship, economic viability and social justice), has destroyed natural or semi–natural ecosystems such as rangeland, woodland, hedges, etc. so on that can harbor a great number of different plant and animal species. While there is a need to expand the supply of wheat output in general, to feed a growing population in Iran, as much as it, stewardship of natural and semi–natural ecosystems is essential.

The total chemical fertilizers rose from 4353.25 to 8659.80 MJ ha^{-1}, or by nearly 50%. Nitrogen is the most significant fertilizer and its consumption increased around 2.35–fold in the studied period, with an annual average of 84.98 kg ha^{-1}. Nitrogen is followed by potassium and phosphorus and the annual average consumption of phosphorus and potassium was realized as 79.11 and 2.71 kg ha^{-1}, respectively (Table 4).

For the same period, the share of nitrogen and potassium in the total fertilizer energy input increased from 72.00 to 84.79% and from 0.00 to 0.65%, respectively, while the share of phosphorus shrunk from 28.31 to 14.56%. Nitrogen is one of the important inputs entering farms and plays a significant role in the emission of greenhouse gases (Shrestha et al., 2020).

In previous research, Sayin et al. (2005) indicated in the last decade, nitrogen fertilizers account for more than 60% in total fertilizer consumption for wheat production in Turkey. In a Dutch study, total nutrient energy requirement for wheat production was reported to be about 12.5 GJ ha^{-1} (Brehmer et al., 2008).

The application of small volumes of farmyard manure comprised an insignificant portion of the energy input to wheat grown in Iran (Table 4). The large energy required for the manufacture of fertilizer, in particular nitrogen, or the application of small volumes of farmyard manure reduces the overall sustainability of the system; while manure and organic fertilizers are a suitable alternative to chemical fertilizers and can significantly reduce energy consumption in agricultural systems and have positive effects on the agroecosystems (Mc Laughlin et al., 1997). In this regard, Jiang et al. (2021) concluded that applying organic fertilizers such as compost and biochar had lower environmental effects compared to chemical fertilizers.

In general, there were not significant changes regarding the human labor and machinery year by year. In Iran, number of various machines such as tractors and combine harvesters has increased for wheat production in recent years, but due to increasing the cultivated area, the share of mechanical power per area unit stayed almost constant. However, as can be resulted from Table 3, relatively negative relationships existed between human labor and machinery (r = –0.36) which is consistent with findings of Ozkan et al. (2004b) and Hatirli et al. (2005).

Based on the evaluation of data collected, average human labor required in wheat project was 303.20 h ha^{-1}, and machine power was 11.17 h ha^{-1}. Approximately 94.54% of total machine power was consumed for land preparation consists of plowing, disc operating and leveling, 0.54% was for sowing, 0.90% was for other cultural practices mainly including fertilizer application and spraying, and 3.94% was for harvesting–threshing (Table 4). Canakci et al. (2005) stated that out of all the farm operations for wheat production, seedbed preparation required the maximum energy (65.1%), followed by harvesting (22.9%).

Energy from seed was calculated on average 2383.05 MJ ha^{-1} (Table 4) and increased almost 9.50% in the examined period (Table 3).

Figure 1. Different provinces of Iran for wheat production.

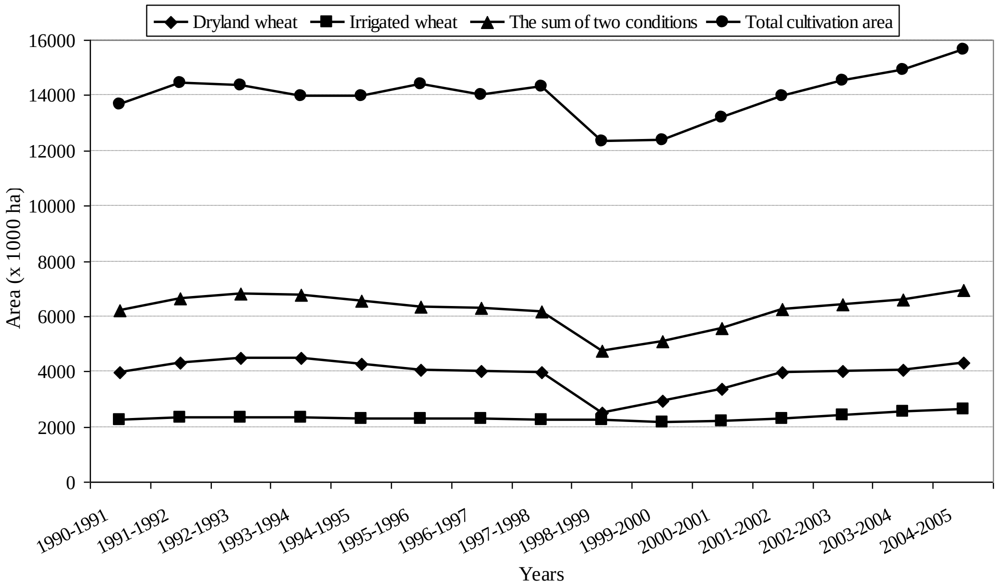

Figure 2. Total cultivation area, and farm area for dryland and irrigated wheat during Iranian wheat project (1990–2005).

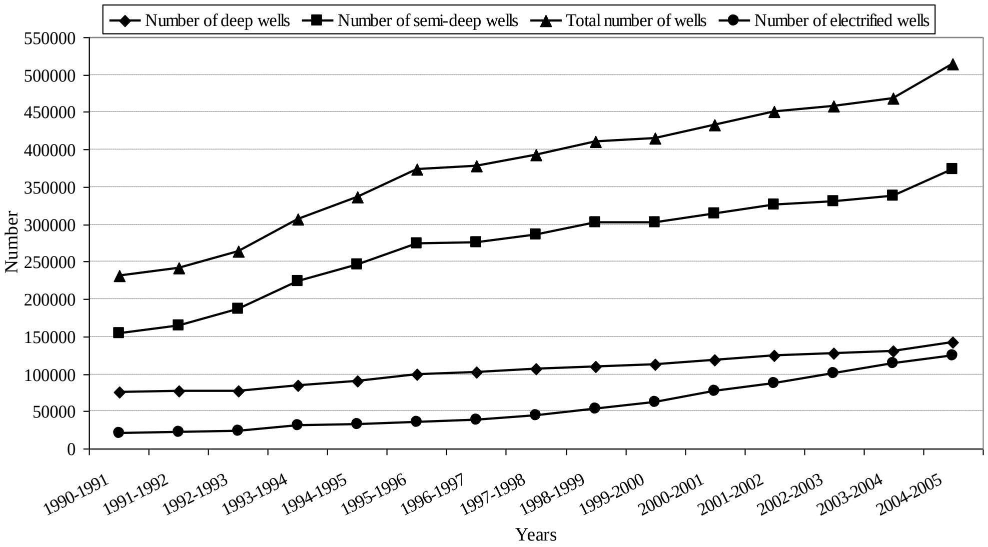

Figure 3. Number of deep, semi–deep and electrified wells during Iranian wheat project (1990–2005).

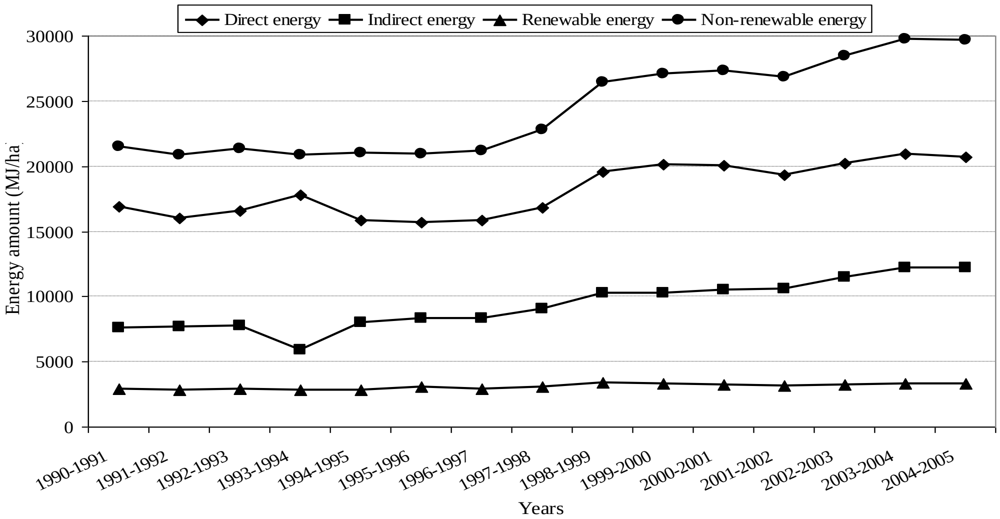

Figure 4. Direct, indirect, renewable and non–renewable energy during Iranian wheat project (1990–2005).

Table 1. Energy equivalences of inputs and output

Energy source	Unit	MJ unit^{-1}	References and remarks
Inputs			
Human labor	h	2.153	The mean of values was presented by Hatirli et al. (2005), Erdal et al. (2007), Strapatsa et al. (2006)
Machinery	h	62.700	Erdal et al. (2007)
Diesel	l	52.055	The mean of values was presented by Erdal et al. (2007), Canakci et al. (2005)
Electricity	kWh	10.590	Canakci and Akinci (2006)
Fertilizers	kg		
Nitrogen (N)		58.106	The mean of values was presented by Hatirli et al. (2005), Erdal et al. (2007), Canakci et al. (2005), Strapatsa et al. (2006), Canakci and Akinci (2006), Sartori et al. (2005), Deike et al. (2008)
Phosphorus (P_2O_5)		13.971	The mean of values was presented by Hatirli et al. (2005), Erdal et al. (2007), Canakci et al. (2005), Strapatsa et al. (2006), Canakci and Akinci (2006), Sartori et al. (2005), Deike et al. (2008)
Potassium (K_2O)		7.947	The mean of values was presented by Hatirli et al. (2005), Erdal et al. (2007), Canakci et al. (2005), Strapatsa et al. (2006), Canakci and Akinci (2006), Sartori et al. (2005), Deike et al. (2008)
Farmyard manure (FYM)	tons	303.100	Erdal et al. (2007)
Pesticides	kg		
Insecticides		199.733	The mean of values was presented by Erdal et al. (2007), Sartori et al. (2005), Deike et al. (2008)
Fungicides		206.000	The mean of values was presented by Erdal et al. (2007), Deike et al. (2008)
Herbicides		267.667	The mean of values was presented by Erdal et al. (2007), Sartori et al. (2005), Deike et al. (2008)
Others		120.000	Canakci and Akinci (2006)
Water	m^3	0.630	Erdal et al. (2007)
Wheat seed sown	kg	15.700	Canakci et al. (2005)
Output			
Wheat grain yield	kg	14.700	Canakci et al. (2005)

Table 2. Energy (MJ kg^{-1}) required for the manufacture of pesticides (based on values from Green, 1987)

Pesticide	Group	Energy
Insectcides		
Fenitrothion	Organophosphate	[a]229
Deltamethrin	Pyrethroid	[a]580
Fenthion	Organophosphate	[a]229
Trichlorfon	Organophosphate	[a]229
Herbicides		
Broadleaf herbicides		
Bromoxynil/MCPA	Hydroxybenzonitrile/Phenoxy	[d]199
2,4–D/MCPA	Aryloxyphenoxy alkanoic acid	[b]108
2,4–D	Aryloxyphenoxy alkanoic acid	85
Tribenuron–methyl	Sulfonyl urea	[a]365
Bromoxynil	Hydroxybenzonitrile	[e]268
Dichlorprop–P/Mecoprop–P/MCPA (DMM)	Aryloxyphenoxy alkanoic acid	[b]108
Triasulfuron/terbutryne	Sulfonyl urea/Triazinone	[c]278
Grass herbicides		
Diclofop–methyl	Aryloxyphenoxy alkanoic acid	[b]108
Fenoxaprop–P–ethyl	Aryloxyphenoxy propionic acid	[b]108
Clodinafop–propargyl	Oxyphenoxy acid	[e]268
Tralkoxydim	Oxime	[e]268
Difenzoquat	Amide	[e]268
Flamprop–M–isopropyl	Arylalanine	[e]268
Dual–purpose herbicides		
Mesosulfuron–methyl/iodosulfuron–methyl (MI)	Sulfonyl urea	[a]365
Sulfosulfuron	Sulfonyl urea	[a]365
Imazamethabenz–methyl	Imidazolinone	[e]268

[a] The values were assigned to their chemical group.
[b] The mean of values of 2,4–D and MCPA.
[c] The mean of values of Chlorsulfuron and Atrazine.
[d] The mean of values of Bromoxynil and MCPA.
[e] The value of herbicides is given in Table 1.

3.3. Energy Use Efficiency

On the other hand, energy use efficiency varied from 0.70 in 1999–2000 to 1.00 in 1997–1998, specific energy (MJ kg^{-1}) from 14.70 in 1997–1998 to 21.04 in 1999–2000, and energy productivity (kg MJ^{-1}) from 0.05 to 0.07 (Table 3). As seen in previous researches, energy use efficiency, specific energy (MJ kg^{-1}) and energy productivity (kg MJ^{-}

^{1}) varied from 1.00 to 7.50, from 2.74 to 11.40 and from 0.00 to 0.15, respectively (Mandal et al., 2002; Singh et al., 2002; Singh et al., 2003; Singh et al., 2004; Canakci et al., 2005; Singh et al., 1999; Singh et al., 2007; Venturi and Venturi, 2003; Ramachandra, T.V., Nagarathna, 2001; Ozkan et al., 2004a; Christersson, 2008). It can be seen from the presented values that the output did not increase as much as in energy input use during Iranian wheat project and wheat productivity in Iran is still lagging behind the world's average. The Food and Agricultural Organization of the United Nations (FAO) reported that in many countries average wheat yields for the period 1996–2000 were below the agro–ecologically attainable yield levels. For example, in India, Argentina, Brazil, Ethiopia, Tanzania and Turkey, wheat yields were calculated to be 45%, 57%, 54%, 30%, 50% and 44%, respectively, of the attainable yield. Several industrialized regions also had yields that were below the agro–ecologically attainable yield levels, such as Australia and the USA, where the average wheat yields were 48% and 47% of the attainable yield, respectively (Smeets et al., 2007).

In order to understand better the direction of agricultural energy use, it is important to investigate the tendency of energy forms. For this purpose, energy input as direct, indirect, renewable and non–renewable forms used during Iranian wheat project were also examined. As can be seen from cure 4, for wheat production most of the total energy inputs were supplied in the non–renewable and direct forms in the period examined. Furthermore, this Figure showed upward trends and the use of all energy forms were realized as 27.31%, 18.48%, 38.14% and 11.98% increase in non–renewable, direct, indirect and renewable energy forms, respectively. Singh et al. (2003) indicated 80.9% of total energy input for wheat production resulted from non–renewable and 18.1% from renewable energy and 58.1% from direct energy and 41.9% indirect energy.

The results of regression analysis of the effects of energy consumption on grain yield are presented in Table 5. The results of the regression indicate that there is a strong relationship between energy use and yield. The values of the coefficient of determination (R^2) showed the impact of electricity, indirect and non–renewable energy on output was statistically significant. Hence, 69 and 15% of the total variation in grain yield could be expected by variation in electricity and other energy input parameters, respectively. The unexplained variation, 16% of the total, may be due to variation in the energy components under consideration and aborted grain formation due to environmental conditions, etc. It is clear from Table 5 that yield and thus energy output are greatly influenced by subtle shifts in, for example, human labor, machinery, pesticides and seed sown. Hence, it should be noticed the timing, method, rate and type of applications of inputs in each region. Mäder et al. (2002) from a 21–year study of agronomic and ecological performance of biodynamic, bioorganic, and conventional farming systems in Central Europe found wheat yields to be 20% lower in the organic systems, although input of fertilizer and energy was reduced by 34 to 53% and pesticide input by 97% and they expressed these systems were less dependent on external inputs.

During the years 1990–2005, the variation in pesticides application with respect to their types has been found considerably high and increased extensively in the last year under study, particularly in case of herbicides. Among the different herbicides, 2,4–D/MCPA and Clodinafop–propargyl (Topic) had larger crop protection energy costs than others (Table 3). Approximately 51.06% of total pesticides were devoted to herbicides, 31.91% to insecticides, 14.89% to fungicides, and 2.13% to other pesticides (Table 4). In pervious researches, when considering the energy inputs for producing a hectare of wheat, pesticides represent about 0.4–3% of the total energy inputs (Singh et al., 2003; Singh et al., 2004; Ferraro, 2003). Although the energy input of pesticides was found to be quite low compared to the other inputs used in production, results of Deihimfard et al. (2007) showed increase in pesticides, particularly in case of herbicides, has not led to a similar increase in wheat yield, which could be attributed in part to the negative impact of high herbicide consumption in wheat fields of Iran and subsequent threat to the long–term sustainability of these agro–ecosystems.

During the investigation period, although some fluctuations were observed, total energy inputs and output during wheat project (Table 3) increased gradually from 26503.5 and 20871.5 MJ ha^{-1} in 1990 to 35466.3 and 30259.8 MJ ha^{-1} in 2005, indicating a 25.27 and 31.03% increase, respectively. The annual average total energy equivalent of inputs was calculated as 30007.82 MJ ha^{-1}. The average grain yield was found 1761.91 kg ha^{-1} and its energy equivalent was calculated to be 25900.02 MJ ha^{-1} (Table 4). In previous reports, energy use for wheat production was between 8496 and 30000 MJ ha^{-1} (Dalgaard et al., 2001; Mandal et al., 2002; Singh et al., 2002; Singh et al., 2003; Singh et al., 2004; Canakci et al., 2005; Singh et al., 1999; Singh et al., 2007; Venturi and Venturi, 2003). The results of Mandal et al. (2002) indicated that the total energy requirement was the greatest for wheat, followed by soybean, mustard and chickpea. As Table 3 shows, a sudden decrease in grain yield in 1999–2000 had taken place mainly due to extreme drought conditions.

4. Conclusions

The study concludes that diesel, electricity and application of chemical fertilizers share the major portion of total energy inputs consumed for wheat crop production during Iranian wheat project. Most diesel fuel consumption was for irrigation and the share of diesel decreased, but electricity showed an increase in the total energy use over the examined period because of increasing the number of electrified wells and depths. Due to mainly increasing the cultivated area and growth of suitable irrigation systems, the volume of water consumption increased until 1999–2000, and from it time onwards decreased. Among the chemical fertilizers' types, nitrogen had a very significant role in wheat production and its consumption increased around 2.35–fold in the studied period, with an annual average of 84.98 kg/ha. In general, there were not significant changes regarding the human labor and machinery year by year and out of all the farm operations, seedbed preparation required the maximum energy, followed by harvesting. Pesticides increased extensively in the last year under study, particularly in case of herbicides, and among the different herbicides, 2,4–D/MCPA and Clodinafop–propargyl (Topic) had higher share than others. During the investigation period, total energy inputs and output increased 25.27 and 31.03%, respectively. Values of energy use efficiency (energy output–input ratio), specific energy and energy productivity showed that the output did not increase as much as in energy input use during Iranian wheat project. During this project most of the total energy inputs were supplied in the non–renewable and direct forms and all energy forms have risen. Also, the results of regression analysis indicated the impact of indirect and non–renewable energy on output was statistically significant.

All findings presented here indicate that energy use during Iranian wheat project has significantly increased over the last 15 years and these results can serve as a basis for developing sustainable wheat production systems. For development, yield growth, poverty alleviation, and environmental sustainability, agreed standards and effective approaches to certification will be essential to protect society from the potential adverse effects of inappropriate policies.

Table 3. Energy consumption (MJ ha^{-1}) and energy input–output relationships for wheat production in Iran between 1990 and 2005

Inputs\Years	90–91	91–92	92–93	93–94	94–95	95–96	96–97	97–98	98–99	99–00	00–01	01–02	02–03	03–04	04–05
Human labor	546.64	663.10	657.47	628.42	576.61	701.99	629.07	637.08	737.99	723.32	715.58	689.92	585.93	656.14	642.53
Machinery	746.67	684.03	706.09	690.87	720.26	649.94	640.70	743.06	712.57	682.78	701.61	704.24	697.21	706.17	716.58
Land preparation	694.43	655.93	677.52	661.60	684.90	622.30	611.62	711.09	676.78	644.35	658.71	658.87	649.55	657.99	670.47
Sowing	0.68	0.85	1.18	2.16	3.03	3.44	3.84	4.17	4.12	4.36	4.68	5.44	5.56	5.41	6.05
Cultural practices	9.16	4.57	5.02	5.17	6.89	4.66	4.26	6.62	5.44	6.12	6.10	8.04	8.52	8.21	8.64
Harvesting	42.40	22.67	22.38	21.94	25.44	19.54	20.99	21.18	26.22	27.95	32.11	31.89	33.57	34.56	31.41
Chemical fertilizers	4353.25	4710.66	4633.02	2845.78	4956.71	5227.30	5235.91	5746.97	6782.67	6835.81	7170.21	7273.19	7937.31	8605.15	8659.80
Nitrogen (N)	3121.00	3481.70	3505.21	2196.58	3865.79	4122.90	4188.95	4744.71	5675.86	5672.61	6031.04	6120.83	6682.82	7318.64	7342.25
Phosphorus (P_2O_5)	1232.24	1228.60	1120.04	647.59	1083.93	1100.29	1034.18	981.67	1075.56	1126.73	1107.51	1123.90	1213.00	1243.12	1261.00
Potassium (K_2O)	0.00	0.36	7.77	1.61	6.99	4.10	12.78	20.59	31.25	36.48	31.66	28.46	41.49	43.39	56.55
Farmyard manure	40.41	10.75	9.30	11.70	12.44	23.36	23.84	30.44	112.51	85.44	69.98	53.93	62.94	96.26	96.42
Pesticides	127.63	156.20	148.84	152.34	86.50	83.76	141.66	116.84	122.45	141.94	135.50	169.41	153.06	163.27	218.77
Insecticides	41.19	41.01	39.44	34.48	37.14	43.32	50.78	35.47	46.74	54.35	48.11	42.96	55.26	55.03	41.00
Fenitrothion	41.19	41.01	39.44	34.48	37.14	43.32	50.78	35.47	38.66	36.28	35.33	34.47	36.92	24.08	15.24
Deltamethrin	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.08	9.54	7.83	7.85	13.84	30.39	25.76
Fenthion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.53	4.95	0.53	4.47	0.45	0.00
Trichlorfon	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.04	0.12	0.00
Herbicides	86.44	115.19	99.40	110.60	41.11	40.44	90.88	58.46	36.82	57.05	56.46	49.49	58.81	67.58	96.68
Bromoxynil/MCPA	–[a]	–	–	–	0.00	0.00	–	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.90
2,4–D/MCPA	–	–	–	–	23.17	0.00	–	36.37	21.92	30.52	23.59	19.24	21.26	23.77	28.59
2,4–D	–	–	–	–	0.00	17.74	–	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Tribenuron–methyl	–	–	–	–	0.07	0.08	–	0.46	0.47	0.70	0.87	0.94	1.19	1.27	1.49
Bromoxynil	–	–	–	–	1.58	1.30	–	2.65	1.09	1.13	0.92	0.63	0.00	0.00	0.00
(DMM)	–	–	–	–	0.00	0.00	–	0.00	0.00	0.00	0.53	0.49	0.33	0.79	1.96
Triasulfuron/terbutryne	–	–	–	–	0.00	0.00	–	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.52
Diclofop–methyl	–	–	–	–	6.70	4.10	–	2.28	1.81	1.58	1.03	1.34	1.09	0.93	2.45
Fenoxaprop–P–ethyl	–	–	–	–	1.05	1.14	–	2.85	2.70	4.86	7.19	8.94	5.47	5.86	3.74
Clodinafop–propargyl	–	–	–	–	1.25	2.43	–	7.27	6.22	12.60	15.42	11.07	26.12	33.00	44.93
Tralkoxydim	–	–	–	–	6.58	7.04	–	2.01	0.00	0.00	0.62	0.72	0.64	0.13	0.27
Difenzoquat	–	–	–	–	0.73	6.61	–	1.32	2.60	4.52	4.48	3.84	1.51	0.60	0.61
Flamprop–M–isopropyl	–	–	–	–	0.00	0.00	–	3.25	0.00	0.00	1.10	1.40	0.43	0.72	0.27
(MI)	–	–	–	–	0.00	0.00	–	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
(*continued on next page*)															
Sulfosulfuron	–	–	–	–	0.00	0.00	–	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.94
Imazamethabenz–methyl	–	–	–	–	0.00	0.00	–	0.00	0.00	1.13	0.71	0.87	0.77	0.29	0.00
Fungicides	0.00	0.00	10.00	7.26	8.25	0.00	0.00	22.91	38.89	30.54	30.93	59.53	28.38	29.45	69.66
Others	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	17.43	10.61	11.21	11.43
Diesel	13385.3	12707.0	12918.9	13217.8	11159.7	10752.9	10646.8	11137.2	11910.1	11567.5	10467.1	9260.07	9553.01	9298.72	8898.99
Electricity	2933.63	2622.29	2962.20	3921.59	4096.04	4216.87	4544.96	5021.61	6889.52	7838.46	8887.70	9412.91	10088.8	10996.3	11147.1
Water	2072.11	2214.97	2224.06	2338.39	2378.81	2496.77	2539.11	2592.18	2894.78	2968.59	2700.27	2682.51	2606.01	2528.09	2547.64
Seed sown	2297.88	2121.45	2225.30	2204.76	2249.08	2327.48	2275.48	2410.19	2534.51	2518.95	2463.73	2380.01	2596.25	2602.19	2538.50
Sum	26503.5	25890.4	26485.2	26011.6	26236.2	26480.3	26677.6	28435.5	32697.1	33362.8	33311.7	32626.2	34280.5	35652.3	35466.3
Output															
Grain yield	20871.5	22534.8	23172.8	23564.2	25131.3	23264.9	23442.1	28436.7	26903.0	23307.9	25040.0	29325.9	30823.7	32421.9	30259.8
Energy use efficiency	0.79	0.87	0.87	0.91	0.96	0.88	0.88	1.00	0.82	0.70	0.75	0.90	0.90	0.91	0.85
Specific energy (MJkg^{-1})	18.70	16.89	16.80	16.23	15.35	16.73	16.73	14.70	17.87	21.04	19.56	16.35	16.35	16.16	17.23
Energy productivity (kgMJ^{-1})	0.05	0.06	0.06	0.06	0.07	0.06	0.06	0.07	0.06	0.05	0.05	0.06	0.06	0.06	0.06

[a] Data not available.

Table 4. Quantities and energy values for wheat production in Iran (the average of 15 yr)

Inputs	Quantity per ha	Energy equivalent (MJunit^{-1})	Total energy equivalent (MJ)	percent
Human labor (h)	303.20	2.153	652.79	2.18
Machinery (h)	11.17	62.700	700.19	2.33
Land preparation	10.56		662.41	2.21
Sowing	0.06		3.66	0.01
Cultural practices	0.10		6.49	0.02
Harvesting	0.44		27.62	0.09
Chemical fertilizers (kg)			6064.92	20.21
Nitrogen (N)	84.98	58.106	4938.06	16.46
Phosphorus (P_2O_5)	79.11	13.971	1105.29	3.68
Potassium (K_2O)	2.71	7.947	21.57	0.07
Farmyard manure (tons)	0.163	303.100	49.31	0.16
Pesticides (kg)			141.21	0.47
Insecticides	0.18	^{a}252.703	44.42	0.15
Herbicides	0.38	^{a}186.764	71.03	0.24
Fungicides	0.11	206.000	22.39	0.07
Others	0.03	120.000	3.38	0.01
Diesel (l)	213.72	52.055	11125.41	37.08
Land preparation	80.50		4190.43	13.96
Sowing	0.15		7.81	0.03
Cultural practices	0.32		16.66	0.06
Harvesting	14.67		763.65	2.54
Tractor manufacturing and repair	3.00		156.17	0.52
Irrigation	^{b}115.08		5990.49	19.96
Electricity (kW h)	601.70	10.590	6372.00	21.23
Water (m^3)	3998.34	0.630	2518.95	8.39
Seed sown (kg)	151.79	15.700	2383.05	7.94
Sum			30007.82	100.00
Output				
Grain yield (kg)	1761.91	14.700	25900.02	

[a] Weighted mean value.
[b] The fuel requirements of water pumps.

Table 5. Summary of multiple regression analysis of grain yield (GY) and various energy input parameters for wheat production

Regression equations	Coefficient of determination
GY = 1350.42 + 0.06 E^{a}	0.69***
GY = 2191.87 – 0.06 D^{b} + 0.04 E	0.73
GY = 1224.87 + 2.96 M^{c} – 0.14 D	0.78
GY = 916.28 + 2.45 M – 0.09 D + 0.03 E	0.81
GY = 732.03 + 2.46 M – 0.85 FYM^{d} – 0.08 D + 0.04 E	0.81
GY = –179.08 + 2.31 M – 1.95 FYM – 0.07 D + 0.03 E + 0.43 SS^{e}	0.82
GY = –791.16 + 2.28 M – 2.06 FYM + 1.35 P^{f} – 0.09 D + 0.81 SS	0.83
GY = –1418.12 + 0.36 HL^{g} + 2.59 M – 2.70 FYM + 1.48 P – 0.09 D + 0.89 SS	0.83
GY = –1451.07 + 0.46 HL + 2.81 M – 0.04 CF^{h} – 2.24 FYM + 1.70 P – 0.12 D +1.00 SS	0.84
GY = –1468.05 + 0.70 HL + 2.79 M – 0.05 CF – 2.11 FYM + 1.63 P – 0.13 D – 0.10 W^{i} + 1.11 SS	0.84
GY = –1452.56 + 0.70 HL + 2.78 M – 0.05 CF – 2.12 FYM + 1.60 P – 0.12 D + 0.001 E – 0.10 W + 1.10 SS	0.84
GY = 795.93 + 0.10 Indirect energy	0.66***
GY = 798.23 – 0.0002 Direct energy + 0.10 Indirect energy	0.66
GY = 479.80 + 0.05 Non–renewable energy	0.60***
GY = 1022.46 – 0.30 Renewable energy + 0.07 Non–renewable energy	0.62

*** Significant at the 0.001 probability level.
[a] E – Electricity.
[b] D – Diesel.
[c] M – Machinery.
[d] FYM – Farmyard manure.
[e] SS – Seed sown.
[f] P – Pesticides.
[g] HL – Human labor.
[h] CF – Chemical fertilizers.
[I] W – Water.

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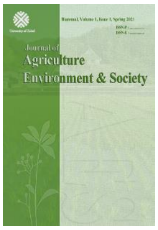

Assessing the educational needs of rapeseed growers in Lorestan province for integrated weed management

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ABSTRACT

In the area of integrated weed management, the objective of this study is to identify and assess the educational requirements of farmers in the province of Lorestan. The research's statistical population comprises all rapeseed growers in Lorestan Province. A stratified sampling method was employed to select 137 respondents from the population using Cochran's formula. As the research instrument, a questionnaire was developed by the researcher. The findings of the study suggest that the participants possess a moderate to limited understanding of integrated weed management as it pertains to rapeseed products. The findings suggest that the knowledge-education modules address the greatest number of educational requirements pertaining to “the impact of weed presence on the farm” and “the competition between weeds and crops on the farm”. The findings revealed that sixteen categories of the knowledge-education needs are at an exceptionally high level. Among these, the categories of “plow preparation”, “reduction in crop yield”, and “manual weeding” are among the most critical. Furthermore, an examination of each module reveals that when it comes to modules that promote the efficient reduction of herbicide usage and the implementation of hygienic and preventive measures, a significant emphasis should be placed on these aspects. According to the correlation results, there is a significant and negative relationship between the number of educational programs participated in by respondents and the frequency with which farmers visit agricultural extension service offices and their educational needs. A positive correlation exists between the needs and the distance between the village and the city. It is suggested that in this region, farmers be informed through the use of mass media such as local radio and television, as well as posters. Additionally, educational workshops and extension visits can serve as influential means to enhance individuals' skill sets.

Highlights

- Lorestan province farmers have a moderate to limited understanding of IWM for rapeseed crops.
- Farmers need training to effectively reduce herbicide use and implement preventive measures.
- Fewer program participations and less frequent visits to extension offices correlate with higher educational needs in IWM.
- Utilizing local radio, television, and posters can effectively reach farmers for IWM education.
- Organizing workshops and extension visits can further enhance farmers' IWM skills.

1. Introduction

Throughout history, crop infestations caused by insects, fungi, weeds, and other potentially detrimental organisms have posed a significant risk to agricultural production on a global scale (Ruttan, 2006). Significant crop losses may result from these detrimental organisms, whereas a severe deterioration in product quality frequently transpires when the product itself is compromised. Pest infestations can result in losses ranging from less than 50% for certain crops (e.g., barley) to over 80% for others (e.g., sugar beet and

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cotton) (Oerke and Dehne, 2004). Therefore, it is unattainable to increase crop production to meet the growing demand for food by merely increasing productivity per unit area; this cannot be achieved without an equivalent increase in pest management (Oerke, 2006).

Elevated potential loss rates in crop production coupled with achievable yields render effective pest management a critical determinant of high productivity. Thus, implementing a targeted pest management program to safeguard plants against agricultural pests will perpetually constitute an essential component of any agricultural system. Underpinned by an understanding of agroecosystem biology, integrated weed management (IWM) strategies integrate multiple methods of weed prevention, avoidance, monitoring, and suppression. The establishment of IWM was driven by the objective of offering farmers methodical strategies to decrease their dependence on herbicides (Swanton and Weise, 1991), as well as to impede the emergence of herbicide-resistant (HR) biotypes (Powles et al., 1997). Despite promotion by university extension personnel (Czapar et al., 1995; Hammond et al., 2006), farmers have been comparatively less inclined to adopt IWM in comparison to integrated approaches for insect or disease pests.

It is not well understood why farmers have been slow to adopt IWM. There are those who argue that the implementation of agrichemical marketing strategies, such as performance guarantees on herbicide products, diminished the perceived necessity for alternative weed control methods (Owen, 1998; Llewellyn et al., 2007). Pest management program decisions are often highly subjective and influenced by a variety of farmer characteristics, such as personal beliefs, perceptions, and objectives (Ajayi, 2000; Atreya, 2000). As a result, technologies frequently fail to gain traction or experience adverse social repercussions due to research that neglected to adequately involve farmers and paid insufficient attention to their own knowledge, practices, needs, and desires (Trautmann et al., 1996; Meerman et al., 1997; Prudent et al., 2007). In order to effectively manage pests, farmers must possess a specific collection of information and knowledge, including technical and conceptual expertise, as well as the “know-how” to implement particular procedures.

Typically, a disparity exists between the information at the disposal of farmers and the information they require to make informed decisions. Despite the dissemination of information to the farmers, their potential for effective utilization may be hindered due to their insufficient foundational knowledge. Involved in this situation is an increased emphasis on farmer education. Training programs can significantly influence decisions regarding pest management by equipping farmers with the technical expertise required to select suitable pest control methods and to utilize pesticides safely and effectively (Norvell and Hammig, 1999; Prudent et al., 2007) (Norvell and Hammig, 1999; Prudent et al., 2007). The primary aim of this study was to investigate the effects of extension workshops on the level of assurance that farmers possessed regarding pest management practices, as well as to ascertain the training requirements of farmers in this area.

2. Material and methods

This applied research is structured as a descriptive investigation. The Statistical population consisted of Rapeseed farmers in Lorestan Province, Iran (N=1012) and 131 respondents were selected as samples based on the Cochran's formula by proportional stratified sampling method. A research-made questionnaire, whose validity was verified by a panel and whose reliability was assessed using Cronbach's alpha (0.996), served as the primary instrument for this study. A questionnaire employing structured five-point Likert scales from 1 (extremely low) to 5 (extremely low) was utilized to gather the necessary data. When analyzing data in terms of mean rank and standard deviation, the correlation coefficient was applied. The data that was gathered were analyzed using SPSS20. The questionnaire comprises two sets of items: 1. A demographic item that is pertinent to farmers; and 2. A needs assessment regarding IWM, which comprises 76 items**.**

3. Results and discussion

It became apparent subsequent to the study that the median and mean for the education of the respondents are both at the primary school level. Furthermore, the mean age of the respondents is approximately 47, suggesting that the age of operators is relatively high. Additionally, with regard to the rate of referrals to agriculture propagation and agriculture Jihad services in the region, the average number of family members is four. The frequency of such referrals is described in Table 1 and provides an overview of the statistical universe's study situation.

Table 1. Distribution of farmers Characteristics

	Farmers characteristics	Age	Family Size	Dry land (ha^{-1})	Wetland(ha)	Training courses	Visiting the Extension office in year
Mean	10.64	46.96	4.07	1.86	3.70	1.28	10.64
Median	10	48	4	1	3	1	10
Mode	10	48	4	0	2	0	10
LSD	8.12	12.48	1.81	2.16	3.09	1.34	8.12

3.1. Need assessment of the total module

The intent of the training module is to provide an overview of pertinent topics within a particular field. The foundation of a structured on-the-job training (OJT) program (Prudent et al., 2007) consists of training modules. The research subject was divided into fourteen modules (Table 2), with the integration of weed management, which was informed by case studies and local experts. With an average rate exceeding four out of five, it can be asserted that the maximal rate of training requirements is pertinent to the training modular, “the impact of weed existence on farms", and the competition between weeds and crops on farms. The instructional modules on "the significance of influential factors in managing weed resistance to pesticides", "effective steps to reduce the use of pesticides", and "the significance of effective steps to reduce the use of pesticides" address the training requirements of the modules and the influential factors in the competitive ability of weeds, as well as the efficiency and importance of physical factors that influence the management of weed resistance to pesticides" at the intermediate to advanced level. The respondents' prioritization of educational needs with regard to general items (specifically educational modules) pertinent to integrated weed management is depicted in Table 2.

The fourteen multiple-choice questions in each module assess the farmers' expertise in the respective field. This field involved evaluation and categorization. The "The impact of weeds on the farm" module: The two concepts that require the most attention in this module are "reduced crop yields" and "reduced agricultural product quality", with mean scores of 4.38 and 4.22 out of 5, respectively.

Table 2. Priority of educational modules in IWM

Knowledge modules required in IWM	Mean	SD	Priority
Despite the impact of weeds on the farm	4.10	0.71	1
Weeds compete with the crop on the farm	4.08	0.78	2
Factors affecting the ability of competitors weeds	3.86	0.69	3
The importance and effectiveness of physical strategies effective in reducing weed	3.85	0.60	4
The importance of agricultural strategies IWM	3.74	0.67	5
The effective implementation of the IWM	3.69	0.74	6
Factors affecting the performance of herbicides	3.67	0.83	7
Plowing operations affecting performance IWM	3.65	0.82	8
The importance of the principles to improve IWM	3.57	0.73	9
IWM role	3.44	0.73	10
The importance of programs IWM	3.41	0.87	11
Important factors in the management of weeds Herbicides resistant	3.29	0.74	12
Effective steps to reduce herbicide use	3.24	0.62	13
The importance of effective IWM	3.12	0.84	14

3.2. Training needs of farmers based on detailed modules

Module "weed competition with the crop on the farm": "water absorption of plants" (mean = 4.18), "absorb of chemical fertilizer" (mean = 4.09), and "mixed with seed crops" (mean = 4.08) are the most critical requirements for this module.

Module "role IWM": "Preventing weed invasion", "Reducing the environmental impact of toxins and chemicals", and "Quickly identifying weed outbreaks" are the three most important requirements of this module, with respective average scores of 3.73, 3.68, and 3.53.

Module "IWM Importance": "Reduce weed resistance" and "Avoid weed dispersion" are ranked highest on this module with mean scores of 3.57 and 3.54, respectively. "Prevent uncontrolled weed growth" is ranked third with mean scores of 3.43.

Module "Factors Affecting the Efficacy of Herbicides": "Considering the Appropriate Mitigation Time" (mean = 3.91), "Weed Age in the Time of Mitigation (mean = 3.82), and "Weed Number in the Time of Mitigation (mean = 3.84)" are the sections of this module that require the most improvement.

Module "Full and Inclusive Application for Mitigation": "Planting certified seeds" (4:18), "Utilizing completely rotted manure" (4.01), and "Managing weeds at the margins of fields, streams, and roadways" (3.68) are the areas that require the most attention from this module.

Effective plowing efficacy of modules on IWM: "Buried up full plant weed" (mean = 3.94), "Embest underground organs in cold and dry weeds" (mean = 3.73), and "evacuate nutrition supplies in the underground organs of reproduction" (mean = 3.28) comprised the greatest need for this module.

Module "The Importance and Efficacy of Effective Physical Strategies for Weed Control": "Plowing" (mean = 4.47), "Manual weeding (4/8), and "Grazing livestock" (mean = 3.91) are the areas with the greatest need according to this module.

Module "Farming strategies in IWM": "farm rotation" (mean = 4.11), "competition with the crop plant" (mean = 3.61), and "standing with crops" (mean = 3.25) are the areas with the highest demand, respectively.

The module titled "Factors Affecting the Capability of Competitors' Weeds" reveals that the areas with the highest average scores are "preparing seed bed" (4.18), "observing the planting date" (4.08), and "appropriate quantity of seed crops" (3.91).

The modules "Importance of factors influencing the management of weed resistance to herbicides": "Crop rotation based on the use of different herbicides" (mean = 3.51), "Herbicide mixing (mean = 3.50), and "Utilizing herbicide alternation with varying yields" (mean = 3.22) are the most in need.

The module titled "Effective Reducing Steps on Herbicide Use" primarily addresses three areas: "Utilizing herbicides during the growth stage of weed scattering", which received an average score of 3.89; "Utilizing herbicides under suitable soil and weather conditions", which received an average score of 3.87; and "Application of tape herbicide in conjunction with cultivators", which received an average score of 2.87.

Module "application of essential principles to improve the IWM": "farmer participation" (mean = 3.72), "instructing and learning about weed control" (mean = 3.67), and "use of appropriate technology" (mean = 3.64) are the aspects of this module that require the most improvement. The results of evaluating all educational needs associated with IWM without detailed modules would comprise 76 items, which are arranged in the following three categories by mean order: “very high need”, “high need”, and “low need”, in that order.

There are sixteen items in the category of “very high need”, with “plow operation”, “reduce crop yields”, and “manual weeding” having the greatest demand. There are 56 categories of educational needs, the most significant of which are high-level categories such as “Buried-up full plant weed”, “Attendance to weed control time”, “Adequate quantity of seed crops”, and “Grazing livestock. “The educational requirements of low-need categories, such as “Utilize Flamethrowers”, “Utilize Specific Herbicides in Conjunction with the Cultivator”, “Mulch”, and “Utilize Cover Crops. “The comprehensive educational requirements of the participants:

The respondents' general training requirements range from unknown to average. (The mean is 3.60 and the standard deviation is 5.7.) In contrast, its mode and median both equal four. Its minimum rate in this domain is 2 (knowing) and its maximum rate is nearly 5 (completely unsure) (Table 3).

Table 3. The situation of training needs about IWM

The situation of training need	Frequency	Valid percent	cumulative percentage
Average	22	16.06	16.1
low	85	62.04	78.1
very low	30	21.90	100
total	137	100	-

Mean: 4 SD: 0.57 Minimum: 2Maximum: 4.88 Range: 2.88

3.3. Correlation Analysis

The Spearman correlation analysis was employed to examine and ascertain the relationship between the primary variables and the variable representing the rate of educational needs, taking into account the ranked nature of the need variable. It can be deduced from table 3 that the critical research variable, “general educational (scientific) need”, has a positive and significant correlation with the village's distance from the nearest city (r=0.286, p=0.0000). Furthermore, the stated variable has a positive and meaningful correlation with the research variable. (p=0.011, r=0.216) In contrast, a significant inverse correlation was found between the total training requirement and both the monthly travel rate (r=-0.181, p=0.034) and the annual referral rate to the Center for Agricultural and Propagation Services (r=-0.249, p=0.003). Furthermore, a significant and negative correlation (r=-0.373, p=0.0000) was found between the aforementioned critical variable and the quantity of educational sessions or periods an individual has attended. There was an absence of significant correlation identified between the age of respondents and the variable of educational need.

4. Discussion

The findings of the research suggest that the participants possess an intermediate to low level of scientific knowledge and expertise regarding IWM in relation to rapeseed (Mean=3.6 out of 5, SD=0.57). Furthermore, the findings from the frequency distribution regarding the overall training requirements of the participants reveal that the “Low-level Category” training needs occur most frequently (16.06 percent), while the “Intermediate level” training needs occur least frequently (62.04 percent). The findings revealed that the training needs items with the greatest magnitude are “the impact of weed presence on the farm” and “the competition between weeds and crops on the farm” (with a mean score exceeding four out of five). The training requirement of the sections that cover “the influential factors in the competitive ability of weeds” together with “efficiency of physical strategies in reduction of weeds” are classified as “intermediate to high level”. The training requirements of the module titled “Weed Resistance Management to Pesticides” assigns an intermediate to low level of importance to IWM. In relation to the training requirements, the findings revealed that sixteen categories are deemed “extremely high level”, with “manual weeding”, “plow operation”, and “reduction of yields” constituting the categories with the greatest demand. There are 56 categories with “very high level” training needs. Among these, “complete burying of weed bushes”, “considering the proper time in the struggling day”, “proper amount of crop seeds”, and “grazing the livestock” have the highest training needs. Conversely, four categories, including “using flamethrowers”, “stripped application of herbicides in addition to operating the cultivator”, and “mulching the crops”, have “low level” (less necessary) training needs.

The correlation coefficient results suggest that there is a significant negative correlation (r=-0.181, p=0.034) between the number of visits to the county agricultural extension office (AEO) by respondents and the number of training courses they have completed, and their training needs. A significant positive correlation is observed between the training needs and the distance of the village from the city center. Consequently, despite the relatively low rate of training course enrollment and the limited number of annual farmers visiting AEO, the initiative may still prove efficacious in augmenting the knowledge of farmers.

4.1. Recommendations

On the basis of the results obtained, the following recommendations can be made: Given that the training needs of the entire respondents (i.e., their knowledge of struggling weed integrated management) range from intermediate to high, it is imperative to employ approaches, informatic methods, and knowledge promotion that are commensurate with the rural community and its operators. In this regard, informational brochures, provincial and national media, agricultural propagation posters, and mass media such as provincial television and radio have the potential to enlighten and pique the interest of operators regarding IWM. The program content should align with the identified priorities and consist of general educational modules that aim to correct operators' perceptions regarding the “influence of weed existence in the farm” and “weed competition with the crop in the farm”, “the impact of following IWM on crop function enhancement”, and “the influence of manual weeding (i.e., mechanical methods) on the improvement of the equality between agricultural product and IWM and the crop”, among others.

In order to enhance the understanding of operators, it is imperative to utilize educational materials such as manuals and photographs, conduct educational-propagation classes, organize tours of propagation for pioneering farmers, establish thematic demonstration farms, and identify and introduce role model farmers who are pertinent to the aforementioned programs in accordance with the priorities determined. The subsequent elements should be duly considered: The competitive ability of weeds is influenced by various factors. This includes the significance and effectiveness of influential physical strategies in weed reduction, as well as specific cases such as “the way livestock are grazed on farms”, “the method and correct steps of weed burial”, and “the proper IWM for plough based on complete observation of weed bushes”. Based on the findings derived from the inferential correlational analysis, the following recommendations can be made: 1. Given the positive and significant correlation between the distance between the village and the nearest city and educational need, and the negative and significant correlation between the monthly travel rate and educational need, it is imperative to establish some foundational strategies for enhancing communications infrastructure.

2. Given the respondents' low attendance at IWM propagation centers (1.28 times) and the negative and significant correlation between educational requirements and educational periods, it follows those organizing educational sessions on knowledge, insight, management skills, and agriculture services will have a significant impact.

3. Given the existence of a significant and negative correlation between the annual referral of clients to the agricultural propagation and services center and their educational requirements, providing hardware and software to these centers in the region that addresses this matter could have a positive impact on the improvement of learners' knowledge and abilities.

4. Furthermore, in-service trainings for personnel training newcomers and active experts in agricultural propagation centers, as well as justification courses for experts from active companies in the region and member experts of the Agriculture and Natural Resources Engineering Organization of Lorestan Province, may indirectly contribute to the enhancement of operators' knowledge and abilities in this field.

5. Taking into account the impact of indigenous or vernacular leaders and native villagers, it is suggested that, in addition to identifying the most enthusiastic and pioneering farmers and the demonstration farms, the Agriculture Jihad Organization of the Province of Lorestan and the managing organization in the townships sponsor and provide service support to these individuals until we are able to maximize the utilization of the pioneer farmers, leaders, and demonstration farms as well.

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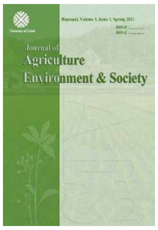

Simulating spring wheat growth under simultaneous salinity and water stress using the AquaCrop model

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ABSTRACT

Crop growth simulation models are developed to predict the effects of different factors, including water and salinity on grain, biomass yields, and water efficiency of various crops. These models are typically calibrated and validated for specific regions based on the availability of measured field data. In this research, spring wheat growth under simultaneous salinity and water stress was Simulated using the AquaCrop model. Calibration and validation were conducted using data from 2010 and 2011, respectively. Results indicate that AquaCrop accurately simulated spring wheat yield, biomass, water use efficiency, and harvest index under salinity and water-limiting conditions. The simulation of harvest index and soil salinity profiles was less precise compared to other characteristics. The mean values of NRMSE, ME, d, CRM, and R2 for grain yield were 13.3%, 36.1%, 0.95, -0.072, and 0.87, respectively in both calibration and verification. For biomass, these measures were 12.59%, 34.46%, 0.92, 0.057, and 0.77, separately. The corresponding values for the soil moisture profile were 11.84%, 25.72%, 0.93, and 0.032, while for the soil salinity profile, they were 26.25%, 58.5%, 0.91, and -0.12, respectively. The most sensitive parameters included the crop transpiration coefficient, normalized crop water productivity, reference harvest index, volumetric water content at field capacity, soil water content at saturation, and temperature.

Highlights

- The AquaCrop model accurately simulated spring wheat yield, biomass, and water use efficiency, under salinity and water stress conditions.
- The model was sensitive to parameters like crop transpiration coefficient, and normalized crop water productivity, at field capacity and saturation.
- The model's simulation of soil salinity was less precise compared to other variables.
- AquaCrop's evaluation was based on two years of field data and demonstrated its applicability for analyzing and forecasting salinity and water stress in spring wheat.
- The model's simplicity requirements make it suitable for evaluating various irrigation scenarios and optimizing water usage in spring wheat cultivation.

1. Introduction

The agricultural sector is the largest consumer of water in arid and semi-arid regions of Iran. As a result, managing water for agriculture is the most important and sensitive aspect of any integrated water conservation project. Implementing deficit irrigation (DI) and using saline water for irrigation are among the most effective strategies for addressing water shortages. However, since both saltiness and drought reduce the availability of soil water for plant roots, yield reduction must be anticipated precisely (Dominguez et al., 2011; Haghverdi et al., 2014). Additionally, salinity is a common outcome of long-term DI action in arid and semi-arid regions. Different researchers have suggested that the solution to the freshwater deficiency issue is deficit irrigation and using of saline water in Iran (e.g., Dehghanisanji et al., 2009;

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Gowing et al., 2009; Kiani and Abbasi 2009). However, there have been few studies focusing on deficit irrigation for spring wheat. Globally, spring wheat with low water requirements is harvested before the high evaporative demand of summer crops. In contrast, its water use efficiency increases since it can take advantage of spring precipitation (Lopez-Urrea et al., 2009).

Agro-hydrology simulation models that assess the influence of water on crop yield at the farm level are valuable tools for making decisions about irrigation management (Pereira et al., 2009; Shafiei et al., 2014). Consequently, to improve management practices, models based on experimental data can be developed to assess crop water requirements (CWR) and enhance irrigation management capabilities under conditions of salinity and water stress. Models allow for the combined assessment of various factors that affect productivity to determine the optimal amounts of water for different situations (Liu et al., 2007). All models should be calibrated and evaluated before use (Nain and Kersebaum 2007). During calibration, model parameters are modified to achieve accurate predictions based on observed data. Conversely, validation involves running the model with independent variables while keeping the parameters consistent (Nain and Kersebaum 2007; Salazar et al., 2009).

In the past few decades, several models such as SOYMOD (Meyer et al., 1981), CERES-Maize (Jones and Kiniry 1986), WOFOST (Todorovic et al., 2009), CropSyst (Stockle et al., 2003), and APSIM (Marinov et al., 2005) have been developed and employed to study irrigation management at the farm level. However, most of these models are quite complex, requiring advanced modeling skills for calibration and numerous input parameters such as Leaf Area Index (LAI). Some models are specific to certain types of plants and are not easily adaptable for general use. However, the newly developed FAO AquaCrop model (Raes et al., 2009a) is designed to be a user-friendly and practical-oriented model (Raes et al., 2009a). It strikes a good balance between accuracy, reliability, and simplicity, requiring only a few input parameters. This model can predict crop yield, water demand, water shortage, and saline water conditions (Raes et al., 2009b). It has been applied and validated for various plants such as maize (Zea mays L.) (Abedinpour et al., 2012; Mebane et al., 2013), cotton (Gossypium hirsutum L.) (Garcia-Vila et al., 2009; Hussein et al., 2011), sunflower (Todorovic et al., 2009), potato (Solanum tuberosum L.) (Vanuytrecht et al., 2011), winter wheat (T. aestivum L.) (Andarzian et al., 2011; Salemi et al., 2011; Mkhabela and Bullock 2012; Kumar et al., 2014), and quinoa (Chenopodium quinoa Willd.) (Geerts et al., 2009) in different places and conditions. All of these research studies have concluded that the model can accurately simulate crop biomass, product yield, and soil water dynamics under both full irrigation and water shortage conditions. Additionally, AquaCrop can simulate soil water content and salinity profiles using basic soil and climate data. The importance of accurately estimating soil water and salinity in agriculture cannot be overemphasized. AquaCrop accounts for various factors in adjusting water for the soil profile investigated by the root system, including evaporation, transpiration, runoff, infiltration, internal drainage, deep percolation, and root uptake (Raes et al., 2009a). Additionally, AquaCrop has been used to determine and optimize irrigation schedules under different levels of salinity and irrigation amounts (Raes et al., 2012).

In most arid and semi-arid regions, the lack of water is associated with reduced water quality, leading to increased salinity. In these areas, plants may be affected by both salinity and water stress simultaneously. The AquaCrop model has not been utilized to simulate spring wheat yield under simultaneous saltiness and water shortage conditions, and sensitivity analysis of the model has not been carried out for spring wheat. Hence, this model (v4.0) assessed synchronous saltiness and water shortage conditions in this study. This version was developed in 2012 to evaluate the impacts of saltiness (Raes et al., 2012). Therefore, the goals of this study were: i) to evaluate the ability of the AquaCrop model (v4.0) to simulate spring wheat yields, biomass, harvest Index (HI), water productivity (WP), soil water content, and saltiness profiles in synchronous saltiness and water stress conditions and ii) to conduct a sensitivity analysis of AquaCrop model for spring wheat in the semi-arid area of Mashhad, Iran.

2. Materials and Methods

2.1. Study area

This study was conducted at the research farm of Ferdowsi University of Mashhad at 36◦16′ N latitude, 59◦38 ′ E longitude in northeastern Iran. It was a two-year cropping study conducted in 2010 and 2011. The spring wheat cultivar (Triticum-aestivum) was planted on the 14th of March 2010 and the 18th of March 2011. Table 1 shows the Physical properties of the soil profile and Table 2 presents the Weather parameters during spring wheat cropping seasons (i.e., from March to July), 2010 and 2011, in the experimental location, Mashhad region of Iran.

Table 1. Soil information in the study area (Haghverdi et al., 2014).

Soil properties	Depth (cm)			
	0-20	20-40	40-70	70-100
Texture	loam	loam	loam	clay loam
θ_{FC} (cm^3cm^{-3})	0.3	0.32	0.32	0.32
θ_{PWP} (cm^3cm^{-3})	0.14	0.15	0.16	0.16
θ_{sat} (cm^3cm^{-3})	0.44	0.40	0.44	0.44
K_{sat} ($cm\ h^{-1}$)	182.6	120.4	81.8	81.8
Bulk density ($g\ cm^{-3}$)	1.35	1.4	1.48	1.48
ECe ($dS\ m^{-1}$)	2	2	2.1	2.1

Table 2. Weather parameters during spring wheat cropping seasons 2010 and 2011

Weather parameters	2010	2011
Average of minimum daily temperature (ºC)	13.57	12.99
Average of maximum daily temperature (ºC)	26.96	26.51
Average of monthly precipitation (mm)	24.93	56.94
Average of minimum daily relative humidity (%)	27.81	35.87
Average of maximum daily relative humidity (%)	64.75	59.90

The typical irrigation interval in this area is 12 days. However, for this study, a 10-day irrigation interval was used throughout the irrigation season to prevent any water stress. The irrigation water (IW) amount was precisely measured using a volumetric water flow meter with a sensitivity of 0.1 L. Two different sources of water with different electrical conductivity (EC) levels, 0.5 and 10 dS m-1, were available for use. The farm had not previously been irrigated with saline water before the experiment in 2010, so there were no issues with saltiness in the first year of the research.

In the second year, the plot area was adjusted so that the plots previously irrigated with saline water were excluded from the experiment. Salinity and DI treatments were applied to all crops after the third leaves had emerged in both cropping seasons. Earlier, all plots were fully irrigated with the same amount of non-saline water. Plant disease and pest management, fertilizer application, and tillage practices were consistent across all plots. The first cropping season was harvested on June 23, 2010, and the second on July 3, 2011.

The harvesting involved hand-harvesting utilizing the center of each plot (i.e., 1 m2) to avoid the possible edge impact of neighboring plots.

2.2. Experimental designs

The information on spring wheat was collected from farm experiments carried out in the study area, as mentioned in Haghverdi et al. (2014). Two different experimental plans were used in the first and second years. In the first year, a four-factor, two-level factorial plan (Myers et al., 2009) was used, while in the second year, a five-factor, five-level central composite plan (CCD; Myers et al., 2009) was employed.

The study examined different levels of available water (IW) at various wheat growth stages: seedling growth-tillering, stem elongation-booting, heading-flowering, and dough stage-ripening. In the first year, the IW levels were 20%, 60%, and 100%, while in the second year, they were 30%, 40%, 65%, 90%, and 100%. The salinity levels were 0.5 and 10 dS m-1 in the first year, and 0.5, 1.8, 5.25, 8.6, and 10 dS m-1 in the second year. Different levels of salinity were achieved by mixing two different water sources with salinity levels of 0.5 and 10 dS m-1 in storage tanks. The growth stages were determined weekly using the Zadoks et al. (1974) growth stages code (Table 3). In the first and second years, there were 36 and 45 plots, each measuring 2 m×2.1 m. These plots were arranged in 4 rows with 2 m spacing between rows and 1 m spacing between plots within each row, except for the side effects.

The detailed information about the first and second years of the experiment is presented in Tables 4 and 5. They include the levels of each treatment applied. During the first year, the Irrigation Water (IW) was calculated using time-domain reflectometry (TDR) readings from TRASE Model 6050X1 probes (Soil Moisture Equipment, Santa Barbara, CA, USA). Before applying treatments, four moisture probes were placed at 20, 40, 70, and 100 cm soil depths in each plot.

The soil moisture from the 100% IW treatment, which was irrigated with non-saline water, was used to calculate the irrigation amounts for all treatments.

Soil moisture was measured the day before irrigation, and the irrigation water (IW) requirement was calculated as the difference between the actual water content and the Field Capacity (FC) in the root zone. Based on previous local observations, the maximum root zone depth for spring wheat was assumed to be 1 m at the last irrigation, approximately two weeks before harvesting, with a linear growth rate during the cropping season.

Because of having many plots and limiting financial and labor resources, TDR probes were not used in the second year. Instead, volumetric sampling was achieved the day before each irrigation event from the main plot, which was fully irrigated with non-saline water to calculate the amount of IW.

The distribution of salt in the root zone was monitored by measuring the salinity of saturated paste from samples collected randomly from different plots at different growth stages in two depths (0–30 cm and 30–60 cm) throughout the second year. Initial random sampling before applying treatments showed that the soil profile salinity level of the entire experimental area was consistent and negligible.

Table 3. Growth stages of spring wheat in Mashhad region and corresponding irrigation water (Haghverdi et al., 2014).

Growth stages	Symbol	Zadoks growth stages	1st year irrigation (mm)[b]	2nd year irrigation (mm)
Beginning	0	Emergence-seedling growth	40, 40	40, 40
Beginning[a]	1	Seedling growth-tillering	36, 52	36, 54
Middle	2	Stem elongation-booting	44, 84	63, 87
Middle	3	Heading-flowering	62, 112	96, 122
End	4	Dough stage-ripening	148	150

[a] Beginning of the deficit and saline treatments.

[b] b Irrigation values belong to the full irrigation treatment applied using both non-saline (0.5 dS m^{-1}) and saline (10 dS m^{-1}) water resources.

Table 4: Detailed information on experimental plots and variable levels during the first cropping season (Haghverdi et al., 2014).

Plot	Variable					Plot	Variable				
	1	2	3	4	EC		1	2	3	4	EC
1	F[a]	0.2F	F	0.2F	0.5	19	0.2F	F	F	F	10
2	0.2F	F	0.2F	0.2F	0.5	20	F	F	F	F	10
3	F	F	0.2F	F	0.5	21	0.2F	0.2F	F	0.2F	10
4	0.6F	0.6F	0.6F	0.6F	0.5	22	0.2F	F	F	0.2F	10
5	0.2F	0.2F	0.2F	F	0.5	23	0.6F	0.6F	0.6F	0.6F	10
6	F	F	F	0.2F	0.5	24	0.2F	0.2F	0.2F	F	10
7	F	0.2F	F	F	0.5	25	0.2F	0.2F	0.2F	0.2F	10
8	0.2F	F	F	F	0.5	26	F	0.2F	F	0.2F	10
9	0.6F	0.6F	0.6F	0.6F	0.5	27	0.2F	F	0.2F	F	10
10	0.2F	F	F	0.2F	0.5	28	F	F	0.2F	F	10
11	0.2F	F	0.2F	F	0.5	29	F	F	0.2F	0.2F	10
12	F	0.2F	0.2F	0.2F	0.5	30	F	F	F	0.2F	10
13	0.2F	0.2F	F	0.2F	0.5	31	0.6F	0.6F	0.6F	0.6F	10
14	F	F	0.2F	0.2F	0.5	32	0.2F	F	0.2F	0.2F	10
15	0.2F	0.2F	0.2F	0.2F	0.5	33	0.2F	0.2F	F	F	10
16	F	F	F	F	0.5	34	F	0.2F	F	F	10
17	F	0.2F	0.2F	F	0.5	35	F	0.2F	0.2F	F	10
18	0.2F	0.2F	F	F	0.5	36	F	0.2F	0.2F	0.2F	10

[a] F: Full irrigation; 1, 2, 3, 4: irrigation water (% of full irrigation treatment) at different growth stages (identical to Table 3), EC: irrigation water salinity (dS m^{-1}).

Table 5. Detailed information on experimental plots and variable levels during the second cropping season (Haghverdi et al., 2014).

	Variable					Plot	Variable				
	1	2	3	4	EC		1	2	3	4	EC
1	F[a]	F	F	F	0.5	24	0.3 F	0.65F	0.65F	0.65F	5.25
2	0.65F	0.65F	0.65F	0.65F	0.5	25	0.65F	0.65F	0.65F	0.3F	5.25
3	0.9F	0.9F	0.9F	0.9F	1.89	26	0.65F	0.3F	0.65F	0.65F	5.25
4	0.9F	0.9F	0.9F	0.4F	1.89	27	0.65F	0.65F	0.3F	0.65F	5.25
5	0.4F	0.9F	0.9F	0.9F	1.89	28	0.9F	0.9F	0.9F	0.9F	8.61
6	0.9F	0.4F	0.9F	0.9F	1.89	29	0.4F	0.9F	0.9F	0.9F	8.61
7	0.4F	0.9F	0.9F	0.4F	1.89	30	0.9F	0.9F	0.9F	0.4F	8.61
8	0.4F	0.4F	0.9F	0.9F	1.89	31	0.9F	0.4F	0.9F	0.9F	8.61
9	0.9F	0.9F	0.4F	0.9F	1.89	32	0.4F	0.9F	0.9F	0.4F	8.61
10	0.9F	0.4F	0.9F	0.4F	1.89	33	0.9F	0.4F	0.9F	0.4F	8.61
11	0.9F	0.9F	0.4F	0.4F	1.89	34	0.9F	0.9F	0.4F	0.9F	8.61
12	0.4F	0.9F	0.4F	0.9F	1.89	35	0.4F	0.4F	0.9F	0.9F	8.61
13	0.4F	0.4F	0.9F	0.4F	1.89	36	0.9F	0.9F	0.4F	0.4F	8.61
14	0.9F	0.4F	0.4F	0.9F	1.89	37	0.4F	0.9F	0.4F	0.9F	8.61
15	0.4F	0.9F	0.4F	0.4F	1.89	38	0.9F	0.4F	0.4F	0.9F	8.61
16	0.9F	0.4F	0.4F	0.4F	1.89	39	0.4F	0.4F	0.9F	0.4F	8.61
17	0.4F	0.4F	0.4F	0.9F	1.89	40	0.4F	0.9F	0.4F	0.4F	8.61
18	0.4F	0.4F	0.4F	0.4F	1.89	41	0.9F	0.4F	0.4F	0.4F	8.61
19	0.65F	0.65F	F	0.65F	5.25	42	0.4F	0.4F	0.4F	0.9F	8.61
20	0.65F	F	0.65F	0.65F	5.25	43	0.4F	0.4F	0.4F	0.4F	8.61
21	F	0.65F	0.65F	0.65F	5.25	44	F	F	F	F	10
22	0.65F	0.65F	0.65F	0.65F	5.25	45	0.65F	0.65F	0.65F	0.65F	10
23	0.65F	0.65F	0.65F	F	5.25						

[a] F: Full irrigation; 1, 2, 3, 4: irrigation water (% of full irrigation treatment) at different growth stages (identical to Table 3), EC: irrigation water salinity (dS m^{-1}).

2.3. Model description

The AquaCrop model needs a few easily accessible parameters grouped into four categories: climatic, crop, soil, and field management data. This model estimates daily water balance, including all incoming and outgoing water fluxes (infiltration, runoff, deep percolation, evaporation, and transpiration) and changes in soil water content. To run AquaCrop, five weather input variables are needed: daily maximum and minimum air temperatures (T), daily rainfall, daily reference evapotranspiration (ETo), and mean annual CO2 concentration in the atmosphere. The first four variables can be obtained from typical agrometeorological stations, while the CO2 concentration data is sourced from records at the Mauna Loa Observatory in Hawaii. AquaCrop simulates the attainable yields of major herbaceous crops based on water consumption under different conditions such as rainfed, extra, shortage, and full irrigation. This is water-driven crop growth model that depends on the conservative behavior of biomass per unit transpiration (Tr) relationship (Raes et al., 2009a). The model calculates transpiration and separates soil evaporation from crop transpiration using canopy ground cover instead of leaf area index (LAI) as a basis. Crop yield depends on above-ground dry biomass and harvest index (HI). The model simulates crop responses to water deficits based on the differing sensitivity to water stress of four key plant processes: canopy expansion, stomatal control of transpiration, canopy senescence, and HI. The harvest index (HI) can be adjusted negatively or positively depending on the level of stress, its timing, and its duration. Soil salinity stress can have an impact on crop production. AquaCrop uses 4 stress coefficients (KsCCx, Ksexp,f, fCDecline, and Kssto, salt) to describe the effect of soil salinity stress on crop development and production. These coefficients account for factors such as maximum canopy cover, canopy expansion, decline coefficient of canopy cover, and stomatal closure. Also, biomass production can be influenced by soil salinity stress, which is quantified using the soil salinity stress coefficient (Kssalt) (Raes et al., 2012). The average electrical conductivity of saturation soil-paste extract (ECe) from the root zone is an important indicator of soil salinity stress. While AquaCrop provides default values for various crop parameters used in simulating different crops like wheat, some of these parameters need to be adjusted to fit local conditions, crop varieties, and management practices.

A method described in BUDGET is utilized to simulate the movement and retention of salt in the soil in AquaCrop (Raes et al., 2006). To represent the movement and retention of soil water and salt, AquaCrop divides the soil profile into multiple compartments (12 by default) with a thickness of Δz. To simulate the movement and diffusion of salts, each soil compartment is further divided into several cells where salts can be stored. The number of cells, ranging from 2 to 11, depends on the soil type of the soil layer. A clayey layer will typically have more cells than a sandy layer due to the strong attachment of salts to clay particles. The electrical conductivity of saturated soil paste extract (ECe) at a specific soil depth (soil compartment) can be estimated using Equations 1 to 3 (Raes et al., 2012):

$$W_{cell} = 1000\frac{\theta_{sat}}{n}\Delta z \quad (1)$$

$$Salt_{cell} = 0.64 W_{cell} EC_{cell} \quad (2)$$

$$EC_e = \frac{\sum_{j=1}^{n} Salt_{cell,j}}{0.64(1000\theta_{sat}\Delta z)} \quad (3)$$

In the equation, $Salt_{cell}$ represents the salt content in grams per square meter of soil surface. The value 0.64 is a conversion factor (1 dS m^{-1} = 0.64 g l^{-1}). W_{cell} stands for the volume of the water in the cell, measured in millimeters. θ_{sat} is the soil water content at saturation (m3 m-3) of the soil horizon. The variable n represents the number of cells, and Δz denotes the thickness of the soil compartment (m).

2.4. Sensitivity analysis

Before applying a model, it's important to understand how it behaves and is sensitive to different input parameters. Sensitivity analysis (SA) helps to identify which parameters have a significant impact on the model's output (Cao and Petzold, 2006). SA, developed in the late 1990s, is a relatively new method for understanding how mathematical and computer models respond to changes in input parameters. If variations in input parameter values only have a minor impact on model predictions, then the input data have an insignificant effect on the results. It means that errors in the field measurements may be negligible. The inputs for SA in the present study are agronomic, soil, meteorological, and irrigation management data. The model was first run with corresponding data of full irrigation treatment with EC equal to 0.5 dS m^{-1}. The results (wheat grain yield, average soil water content, and EC_e) were considered "basic outputs". In subsequent model runs, each step involved modifying one of the inputs while keeping the other inputs constant. The range of variation for the inputs was selected to be between -25% and +25% of their median value (Geerts et al., 2009). After adjusting the input parameters, the model outputs were compared to the "basic outputs" using the sensitivity coefficient (Sc) (Geerts et al., 2009).

$$Sc = \left|\frac{P_m - P_b}{P_b}\right| \times 100 \quad (4)$$

Where Pm represents the output after changing the input value and Pb represents the output before changing the input value. In general, Sc would be used before the calibration stage. Sensitivity classes were categorized as high, moderate, and low, based on the model's response to changes in inputs: greater than 15%, between 15% and 2%, or smaller than 2%, respectively (Geerts et al., 2009).

2.5. Calibration and validation

The model was calibrated using data from the first cropping season field experiment. Initially, the agronomical parameters of spring wheat from Table 6 were used as model inputs for full irrigation non-saline treatment (FI0.5). Then, the maximum canopy cover (CCX), canopy decline coefficient (CDC), normalized water productivity (WP*), and maximum effective rooting depth (Zx) were adjusted through trial and error for this treatment until the lowest relative error (RE) between simulated and measured grain yield and biomass was achieved. The soil moisture data for the first and second years were used to calibrate and validate soil parameters, respectively. During the second year, soil salinity profiles were monitored, and this data was used for validation. The parameters θ_{sat}, θ_{FC}, θ_{PWP}, and K_{sat} were calibrated using trial and error with the soil moisture data from the first year. The calibration process continued until the lowest root mean squared error (RMSE) between simulated and measured soil moisture was achieved. At the same time, efforts were made to minimize the difference between simulated and measured grain yield and biomass. Then, the model was adjusted for the saline full irrigation treatment with an electrical conductivity of 10 dS m^{-1} (FI10). This adjustment used the observed green canopy cover (CC), biomass production, upper threshold for electrical conductivity (p-upper) (dS m^{-1}), lower threshold for electrical conductivity (p-lower) (dS m^{-1}), and the salinity stress curve shape. The reference treatment with no soil salinity stress (FI0.5) and the stressed treatment with soil salinity stress (FI10) were considered according to Raes et al. (2012). The model was calibrated by adjusting the coefficients of water stress and salinity (i.e. soil water depletion threshold for stomatal control (p-upper), shape factor for water stress coefficient for stomatal control, soil water depletion threshold for canopy senescence (p-upper), and shape factor for water stress coefficient for canopy senescence) for 12 treatments in the first year (plots 1, 2, 3, 9, 15, 16, 20, 23, 25, 26, 28, and 32) until the RMSE of the measured and simulated grain yield and biomass were minimized. These 12 treatments were selected from a high number of treatments to represent the range of applied water stresses. The default values from the AquaCrop manual appendix (Raes et al., 2009b) were used for certain parameters like soil water depletion threshold for canopy expansion (p-upper), soil water depletion threshold for canopy expansion (power), and shape factor for water stress coefficient for canopy expansion. These parameters were considered to be broadly applicable and not specific to a particular crop variety (Raes et al., 2009b). After adjusting the model, it was tested with data from the second year to forecast grain yield, biomass, WP, and soil moisture and salinity profiles.

Table 6. Selected non-conservative (cultivar specific) and conservative input for spring wheat (Raes et al., 2009b).

Parameter description	Value	Unit or meaning
Conservative parameters		
Base temperature	0	˚C
Cut-off temperature	26	˚C
Canopy cover per seeding at 90% emergence (CC_0)	2	cm^2
Crop coefficient for transpiration at CC = 100%	1.1	Full canopy transpiration relative to ET_o
Soil water depletion threshold for canopy expansion (*p-upper*)	0.2	As fraction of TAW, above this leaf growth is inhibited
Soil water depletion threshold for canopy expansion (*p-lower*)	0.65	Leaf growth stops completely as this p
Shape factor for water stress coefficient for canopy expansion (f_{shape})	5	Moderately convex curve
Soil water depletion threshold for stomatal control (*p-upper*)	0.65	Above these stomata begin to close
Shape factor for water stress coefficient for stomatal control (f_{shape})	2.5	Highly convex curve
Soil water depletion threshold for canopy senescence (*p-upper*)	0.70	Above this early canopy senescence begins
Shape factor for water stress coefficient for canopy senescence (f_{shape})	2.5	Moderately convex cure
Coefficient inhibition of leaf growth on HI	Small	HI increased by inhibition of leaf growth at anthesis
Coefficient inhibition of stomata on HI	Moderate	HI reduced by inhibition of stomata at anthesis
Non-conservative parameters		
Tim from sowing to emergence	7	day
Time from sowing to start senescence	90	day
Time from sowing to maturity	102	day
Time from sowing to flowering	74	day
Length of flowering stage	10	day
Minimum effective rooting depth, Z_x	0.3	m
Time from sowing to maximum rooting depth	59	day
Reference harvest index, HI_o 40% Common for good condition	39	Common for good condition
Building up of HI, days (CDD)	34	day

2.6. Model evaluation

During the validation process, the simulation results for wheat grain yield, biomass, HI, WP, and soil water content and salinity were compared with the observed/measured values. Various statistical indices such as coefficient of determination (R2), regression line of best agreement, normalized root mean square error (NRMSE, Eq. 5), index of agreement (d, Eq. 6), and coefficient of the residual mass (CRM, Eq. 7) (Willmott 1982) were used to compare the simulated and observed data.

$$\mathrm{NRMSE} = \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}\right]^{0.5} \times \frac{100}{\overline{O_i}} \qquad (5)$$

$$d = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}\left(\left|P_i - \overline{O_i}\right| + \left|O_i - \overline{O_i}\right|\right)^2} \qquad (6)$$

$$\mathrm{CRM} = \frac{\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} O_i} \qquad (7)$$

where Pi and Oi are predicted and observed data, respectively, is the mean value of Oi, and n is the number of observations.

A simulation is considered perfect if the NRMSE is less than 10%, acceptable if it falls between 10% and 20%, fair if it ranges from 20 to 30%, and poor if it exceeds 30% (Jamieson et al., 1991). The value "d" is dimensionless and falls within the range of 0 to 1.0, where 0 and 1.0 represent complete disagreement and complete agreement, respectively. The CRM indicates a model tendency to either overestimate or underestimate measured parameter values.

3. Results and Discussion

3.1. Sensitivity analysis

The model's sensitivity to certain parameters can indicate over-parameterization or high dependence on specific calculation procedures. Sensitivity analysis helps identify which parameters require accurate field measurements and model calibration. In a simulation of soil moisture and salinity profiles, it was found that for simulating soil moisture, *θFC* and *θPWP* had moderate sensitivity, while θsat and Ksat had low sensitivity. For simulating soil salinity, moderate sensitivity was attributed to *θPWP*, *θFC*, and *Ksat*, while *θsat* had low sensitivity. Therefore, precise determination of *θFC*and *θsat* is crucial for modeling.

The sensitivity analysis of AquaCrop input parameters for simulating grain yield is presented in Table 7. The results showed that the crop coefficient for transpiration (KcTr), WP*, and reference harvest index (HIo) were key parameters for the model, as they exhibited high sensitivity to these parameters. The time from sowing to maximum canopy cover is crucial because rapid canopy development leads to higher biomass and yield due to increased transpiration. Additionally, parameters such as soil water depletion threshold for stomatal control (p-upper), shape factor for water stress coefficient for stomatal control (shape), soil water depletion threshold for canopy senescence (p-upper), and shape factor for water stress coefficient for canopy senescence (shape) require attention, as the model is calibrated under deficit irrigation conditions using these parameters. For these parameters, the sensitivity of the model increases for the most stressed treatments (Geerts et al., 2009). The model was not sensitive to plant density, CGC, emergence, length of the flowering stage, upper temperature, K_{sat}, θ_{PWP}, θ_{sat}, initial soil salinity, and rainfall. However, the sensitivity of the model to input parameters may depend on the type of crop and climate of the study region. For instance, Salemi et al. (2011) demonstrated that winter wheat in Ahvaze, Iran, with a hot climate was sensitive to WP* and KcTr, while the maximum temperature was moderate. In contrast, sensitive parameters for quinoa (Chenopodium quinoa Willd) in the Bolivian Altiplano, with an arid climate, were WP*, HIo, θ_{FC}, θ_{PWP}, soil water depletion threshold for canopy senescence (p-upper), soil water depletion threshold for canopy expansion (p-upper), maximum rooting depth, and rainfall (Geerts et al., 2009).

Table 7. Sensitivity coefficient (Sc) of AquaCrop for winter wheat in Mashhad, Iran.

Input parameter		S_c (+25%)	S_c (-25%)	Sensitivity level
		%		
Agronomic parameters	Crop coefficient for transpiration (Kc_{Tr})	0.29	20.33	Moderate
	plant density	1.27	1.7	Low
	CGC	1.80	1.74	Low
	WP^*	23.62	25.26	High
	HI_o	20.05	25.52	High
	emergence	1.97	1.12	Low
	Time from swing to maximum canopy cover	3.04	7.69	Moderate
	Time from swing to flowering	9.6	1.10	Moderate -Low
	Length of flowering stage	0.11	1.07	Low
	Upper temperature	0.0	0.0	Low
	maximum rooting depth (Zr_X)	0.24	1.32	Low
	Soil water depletion threshold for canopy expansion (*p-upper*)	0.33	0.42	Low
	Soil water depletion threshold for canopy expansion (*p-lower*)	0.89	1.67	Low
	Shape factor for water stress coefficient for canopy expansion (f_{shape})	0.40	0.85	Low
	Soil water depletion threshold for stomatal control (*p-upper*)	3.71	4.43	Moderate
	Shape factor for water stress coefficient for stomatal control (f_{shape})	2.02	1.99	Moderate
	Soil water depletion threshold for canopy senescence (*p-upper*)	2.74	2.12	Moderate
	Shape factor for water stress coefficient for canopy senescence (f_{shape})	2.01	2.23	Moderate
Soil parameters	θ_{FC}	17.88	0.63	High- Low
	θ_{sat}	0.33	1.16	Low
	θ_{PWP}	1.90	1.79	Low
	K_{sat}	0.0	0.0	Low
Initial conditions	Soil moisture	0.96	14.73	Low- Moderate
	Soil salinity	0.0	0.0	Low
Climate parameters	Maximum temperature	0.75	2.3	Low- Moderate
	Rainfall	0.63	0.78	Low

3.2. Soil water content and salinity

The soil hydraulic parameters were adjusted to ensure that the simulated soil water content closely matched the observed values (Table 8). Upon reviewing the table, it was noted that all of the adjusted soil hydraulic parameters, except θ_{PWP}, were higher compared to the measured values (Table 2). This indicates that the RETC model may have underestimated these parameters. The model performed well in simulating soil water content and salinity, as shown in Table 9, which demonstrates good agreement with the observed values. Specifically, during the validation phase, the average NRMSE, CRM, and d values for soil water content were 11.27, 0.002, and 0.94, respectively. For soil salinity, the corresponding values were 26.5, -0.12, and 0.91, as shown in Table 9. The evaluation of the model revealed that it underestimated soil water content (positive CRM values) and overestimated soil salinity (negative CRM values), although these discrepancies were relatively minor. Based on Table 9, it was observed that the model exhibited higher accuracy in simulating soil water content compared to simulating soil salinity. It is important to note that as the salinity of irrigation water increases, soil salinity also increases, but the distribution across the soil profile is not uniform. Consequently, simply averaging soil salinity at different soil layers (0-30 and 30-60 cm) for any salinity treatment may not accurately represent the salinity distribution. Therefore, the model may have a greater error in simulating soil salinity compared to simulating soil water content. The statistical metrics used to assess model performance in simulating soil water content during calibration and validation phases exhibited nearly the same. The root mean square error (RMSE) values for soil water content during calibration and validation were recorded as 12.41% and 11.27%, respectively. It is noteworthy that the model was calibrated solely based on soil water content data. Furthermore, the model's ability to accurately simulate soil salinity also supports the claim that it has been effectively calibrated.

Table 8. Calibrated soil hydraulic parameters for simulating soil water content and salinity during spring wheat cultivation.

Depth of soil (cm)	θ_{FC}	θ_{PWP}	θ_{sat}	K_{sat}
		(%)		(Cm h^{-1})
0-20	31	13.8	45.9	185
20-40	30.8	13.4	45.6	140
40-70	32.6	15.7	46.0	87
70-90	32.5	15.7	45.5	86

Table 9. Statistical comparison of observed and predicted soil water content (first-year data for calibration, second-year data for validation) and salinity (second-year data for validation at 0-30 cm and 30-60 cm depths).

Parameter	Method	NRMSE (%)	*d*	CRM
soil water content	calibration	12.41	0.93	0.06
	Validation	11.27	0.94	0.002
soil salinity	Validation	26.25	0.91	-0.12

In Figure 1, both simulated and measured values of soil water content and salinity are presented. The results show significant values (0.77 for soil water content and 0.81 for soil salinity), indicating a strong correlation between the simulated and measured values. These findings align with existing literature. Mkhabela and Bullock (2012) found RMSE, R2, and d values of 49.4 mm, 0.9, and 0.99, respectively, when using AquaCrop to simulate soil water content in a combination of clay and silt loam in Western Canada under dry and humid continental climate conditions for spring wheat. In a study by Mebane et al. (2013), RMSE values ranged from 0.015 to 0.098 m3 when using AquaCrop to simulate soil water content for six different soil depths in a silt loam combination in Pennsylvania with a humid continental climate for rained maize. The model's accuracy in simulating soil water content seems to be influenced by the specific soil type, crop, and regional climate, with variations observed in different soils and climates.

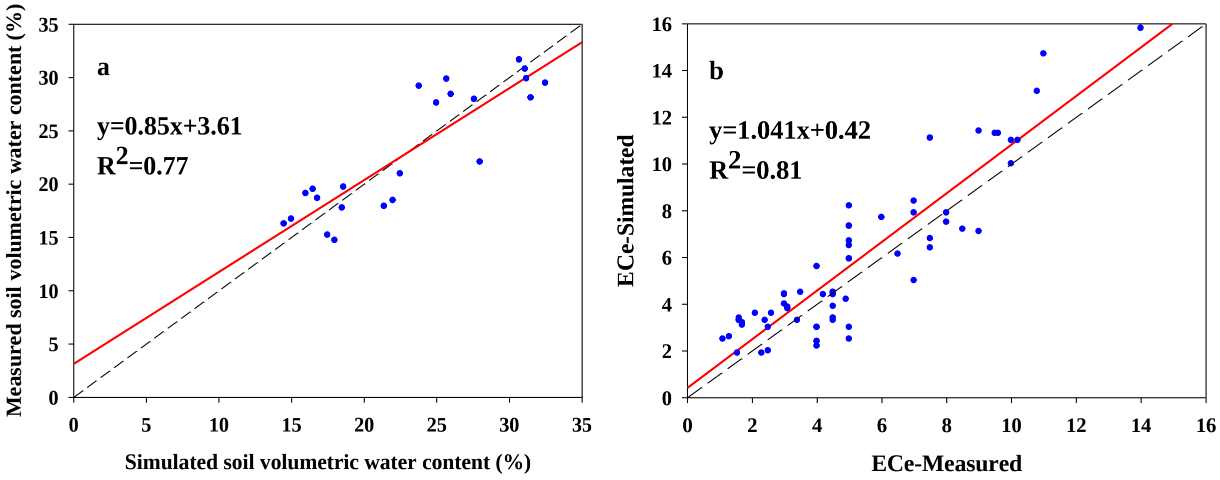

Figure 1. Simulated and measured values of soil water content (a) and salinity (b) during the second growing season.

According to various researches, it has been observed that other models, such as the SWAP model demonstrate a behavior similar to the AquaCrop model. This behavior results in varying soil salinity estimates across different regions. The authorities (Jiang et al., 2011; Kumar et al., 2015; Mohammadi et al., 2016) do not provide a clear explanation for this behavior. The differences in soil characteristics, irrigation methods, and the chemical composition of irrigation water (specifically anions and cations) in different areas are cited as potential reasons for the model's varying behavior. These parameters were found to vary across different sources. Notably, The

AquaCrop model, like the SWAP model, does not consider the dissolution process and sedimentation in the transfer of solutes. In most soils under irrigation, chemical reactions that lead to dissolution or sedimentation (involving anions and cations) may result in salt being added to or removed from the soil solution. Therefore, since these processes are not considered in the model, the calculated salinity may underestimate, accurately estimate, or overestimate the expected salinity. In arid and semi-arid regions, most water resources are saturated with calcium carbonate and some others also contain large amounts of sulfate ions. The presence of this anion in some water sources results in sedimentation as gypsum in the soil. It's important to note that the effects of salinity can be mitigated by water containing high levels of sedimentation anions as well as high concentrations of calcium and magnesium. However, the AquaCrop model does not account for the chemical reactions that lead to solubility in the soil. Therefore, the chemical composition of irrigation water significantly influences the model's behavior across different regions. Additionally, the model's behavior in simulating soil salinity in diverse regions may be influenced by the assumption of a constant diffusion factor. However, in real conditions, the heterogeneity of soil, along with the unsaturation of all soil layers due to seams, cracks, and water courses, can lead to differences between predicted and measured soil salinity values after leaching.

The lower accuracy of the AquaCrop model in simulating salinity could potentially be attributed to the simplification of solute transport equations. The movement of salts in the soil is influenced by a multitude of factors, such as mass transfer, diffusion, water propagation, salt adsorption, salinity degradation, and sedimentation. While the AquaCrop model accounts for mass transfer and diffusion processes in solute transport, it overlooks the influence of other pertinent mechanisms. Notably, studies referenced in the literature (Jiang et al., 2011; Kumar et al., 2015; Mohammadi et al., 2016) have demonstrated that the estimation of soil moisture content varies in different regions. Therefore, it can be concluded that simulating soil moisture content using the AquaCrop model depends not only on different levels of irrigation water but also on the climate and type of soil in the area. The variation in salinity of irrigation water across different regions can be another factor leading to different simulations of soil moisture. The model's underestimation of moisture content may be due to the water balance equation not accounting for certain factors affecting water movement, such as preferential flows and hysteresis. AquaCrop, like most soil water simulation models, assumes that saturated soils drain to field capacity within a short period. Additionally, AquaCrop currently does not have a mechanism to handle input from a rise in the water table, such as a capillary rise from a shallow water table (Raes et al., 2011).

3.3. Grain yield, biomass, HI, and WP

The calibrated crop parameters for spring wheat and water stress coefficients can be found in Table 10. These parameters include Ksto (soil salinity stress coefficient for stomatal closure), EC threshold (p-upper) (dS m^{-1}), EC threshold (p-lower) (dS m^{-1}), and salinity stress curve shape. These parameters were obtained after calibrating the model for salinity conditions. It's worth noting that the water stress coefficients, WP*, and EC thresholds can vary from AquaCrop default values due to factors such as crop type, climate, water stress conditions, and salinity levels of irrigation water. Notably, research has demonstrated that these coefficients and thresholds differ from the default values in various regions and for different crops, such as wheat in New Delhi, India, and rainfed wheat in Western Canada, as well as maize. Kumar et al. (2014) reported that water stress coefficients and EC thresholds under irrigated saline regimes for wheat in New Delhi, India were found to be different than AquaCrop default values. Mkhabela and Bullock (2012) reported water stress coefficients and WP* for rainfed wheat in Western Canada were different than AquaCrop default values. Similar reports were obtained for maize as well (Abedinpour c2012).

Table 10. Calibrated crop-type AquaCrop parameters and water stress coefficients corresponding to the best calibration process for simulating grain yield and biomass of spring wheat.

Parameter	Value	Parameter	Value
CC_X (%)	96	EC threshold (*p- lower*) (dS m^{-1})	4
CDC (%)	9	salinity stress curve shape	2
Zr_X (m)	1.07	Soil water depletion threshold for stomatal control (*p-upper*)	0.44
$K_{sto,salt}$	0.6	Shape factor for water stress coefficient for stomatal control (f_{shape})	1.7
WP^* (g m^{-2})	19	Soil water depletion threshold for canopy senescence (*p-upper*)	0.83
EC threshold (*p-upper*) (dS m^{-1})	13	Shape factor for water stress coefficient for canopy senescence (f_{shape})	2.3

The data in Table 11 shows a comparison between the measured and simulated yield, biomass, harvest index (HI), and water productivity (WP) for spring wheat. The d values were very close to one, except for HI, indicating that the simulated grain yield, biomass, and WP were similar to the measured values. In most cases, the values were sufficiently high, and the CRM values were close to zero, confirming a good correlation between simulated and measured values. The NRMSE values in most cases were lower than 15%, which is considered good. However, the model accuracy for simulating yield and biomass was better than the simulation of WP and HI. It's important to note that Hussein et al. (2011) also reported a less accurate simulation of HI (d=0.66) compared to the simulation of grain yield (d=0.99), biomass (d=0.99), and WP (d=0.99) for cotton Andarzian et al. (2011) conducted a study where they found that the AquaCrop model effectively simulated soil water content in the root zone, as well as crop biomass and grain yield for both fully and deficit-irrigated wheat production in Ahvaz, Iran. Additionally, Mkhabela and Bullock (2012) confirmed the capability of AquaCrop to simulate wheat grain yield accurately. The comparison between the modeled and observed wheat grain yield demonstrated a satisfactory agreement, with statistical indices including R2 of 0.66, d of 0.99, RMSE of 743, and MAE of 611 kg ha−1. Notably, the statistical indices for model calibration and validation were found to be consistent, indicating a well-calibrated model (Table 11).

Table 11. Statistical comparison of measured and simulated yield, biomass, HI, and WP for spring-winter wheat calibration and validation in Mashhad, Iran.

Parameter	Process	NRMSE (%)	*d*	CRM	R^2
Yield	Calibration	11.82	0.98	-0.08	0.94
	Validation	14.79	0.92	-0.064	0.79
Biomass	Calibration	13.28	0.94	0.07	0.84
	Validation	11.91	0.90	0.045	0.69
WP	Calibration	11.93	0.91	-0.08	0.81
	Validation	15.77	0.82	-0.083	0.61
HI	Calibration	21.2	0.70	-0.149	0.51
	Validation	16.77	0.69	-0.135	0.49

The accuracy of the AquaCrop model decreases in high salinity and low irrigation conditions (Figures 2 to 5). Heng et al. (2009) found that the model's accuracy in simulating corn yield under high stress is reduced, but it is acceptable under low and medium stresses. They suggested that the model needs to be reviewed and refined to address this issue. Additionally, Gertz et al. (2009) reported that the model overestimates the yield of Quinoa under full irrigation conditions, as it assumes a fixed amount of normalized water productivity under both full irrigation and deficit irrigation conditions. If the normalized water productivity decreases by 9% and is used for simulation under full irrigation conditions, the results will be improved. Therefore, one reason for reduced model accuracy under both wet and dry conditions is the model's use of a constant value for this parameter. The authors also identified the simulation of the harvest index as a factor contributing to the differences in model accuracy in biomass and yield simulation. They recommended that the model should be adjusted and improved to account for the impact of waterlogging on the harvest index. Todorich et al. (2009) reported that the simplifications adopted in AquaCrop and also in CropSyst could be a limiting factor of both models when severe water stress conditions need to be analyzed. This is particularly due to the lack of a more complex plant physiological submodel to account for water stress's impact on biomass growth and its partitioning into yield. Additionally, Homaei et al. (2002) pointed out that multiplicative models lack a physical basis and cannot differentiate between the various components of soil water energy and their individual effects. Moreover, in the AquaCrop model, the impact of salinity stress on vegetation growth, transpiration, and ultimately crop yield is considered by multiplying it in terms of drought stress (Raes et al., 2012). Therefore, this method is identified as another factor contributing to reduced model accuracy under conditions of salt and drought stress.

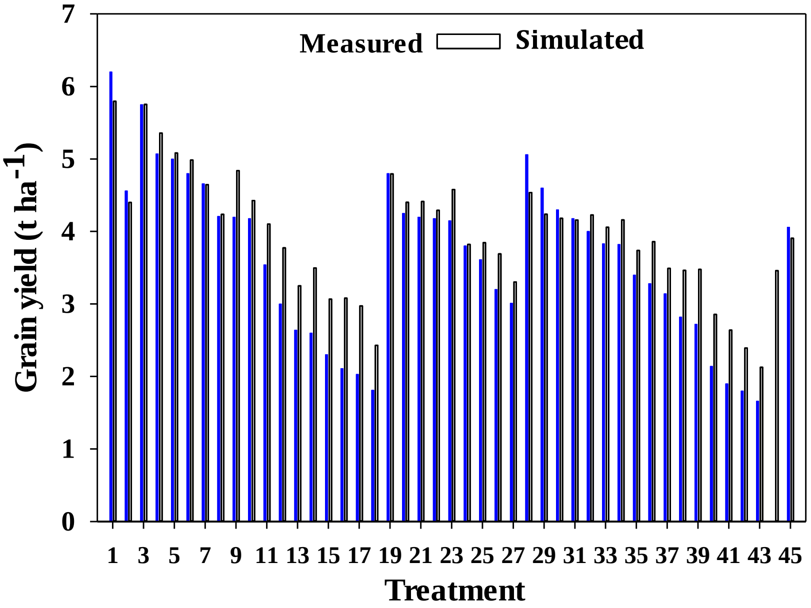

Figure 2. Measured and simulated grain yield of spring wheat in Mashhad. Plot numbers are based on Table 5.

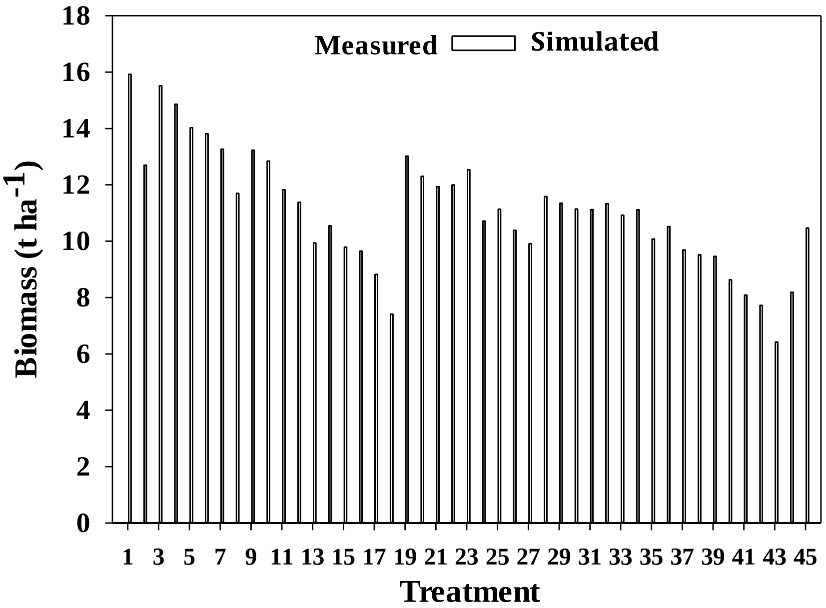

Figure 3. Measured and simulated biomass of spring wheat in Mashhad. Plot numbers are based on Table 5.

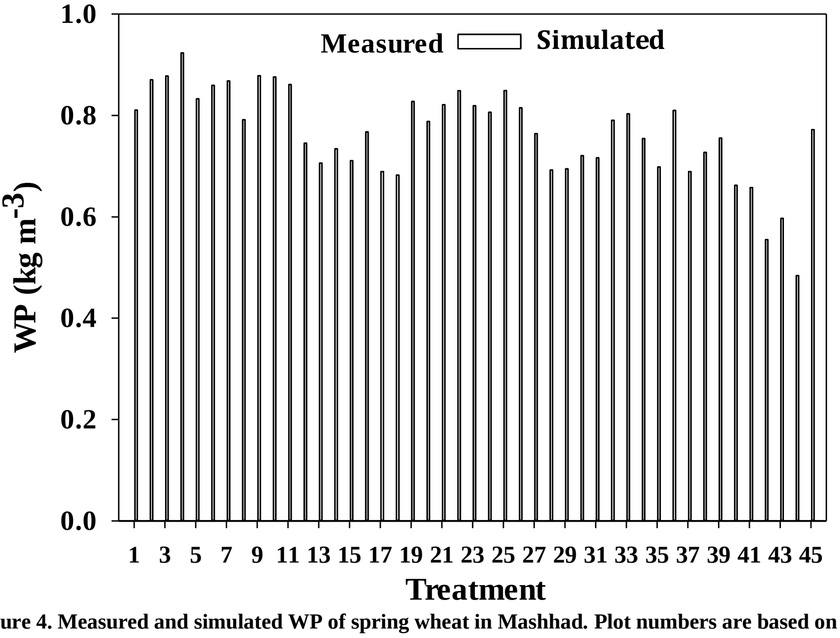

Figure 4. Measured and simulated WP of spring wheat in Mashhad. Plot numbers are based on Table 5.

4. Conclusion

AquaCrop is a simulation model designed to evaluate how water and salinity levels affect crop yield. It uses a basic set of crop parameters and input data, including climate, soil, field, and irrigation management information. Even though it has a simple model structure, AquaCrop is essential for simulating key processes related to crop productivity and how crops respond to water from both physiological and agronomic perspectives. Thus, the evaluation of AquaCrop is especially important for strategic crops such as spring wheat.

In the present study, AquaCrop's efficacy was evaluated based on two years of field-measured data for spring wheat in Mashhad. The primary objective was to ascertain the model's applicability as a tool for analyzing and forecasting salinity and water stress conditions. Sensitivity analysis indicated moderate sensitivity to θ_{FC} and θ_{PWP} for simulating soil water content and moderate sensitivity to θsat for simulating soil salinity. However, for simulating grain yield, the model showed high sensitivity to K_{cTr}, WP*, HIo, and θ_{FC}. AquaCrop was calibrated and validated separately and simultaneously for all salinity treatments. The evaluation of the AquaCrop model showed that it accurately simulated grain yield, biomass, HI, WP, soil water content, and salinity. However, the simulation of HI and soil salinity was less accurate compared to yield and biomass. The model's accuracy in simulating yield and biomass was better than that for WP and HI. The agreement between modeled and observed wheat grain yield, biomass, and WP was satisfactory, with R2 values close to one in most cases, NRMSE values ranging between 10 and 20%, and CRM values close to zero. In the validation phase, the average value of NRMSE, CRM *d*, and R2 for soil water content were 11.27, 0.002 0.94, and 0.77, respectively, and for soil, salinity was 26.5, -0.12, 0.91, and 0.81, respectively.

The AquaCrop model is simple and requires minimal data, making it suitable for use with a wide range of available measurements. As a result, it can be used to evaluate different irrigation scenarios involving varying water qualities, including increased salinity. This application aims to optimize water usage and improve irrigation management for spring wheat cultivation in the Mashhad region.

Data Availability Statement

All data, models, and code generated or used during the study appear in the submitted manuscript.

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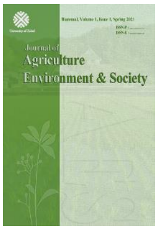

Effects of foliar application of boric acid and nano-chelated boron on characteristics of the dragon's head (*Lallemantia iberica* (MB) Fischer & Meyer)

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ABSTRACT

The seeds of the medicinal plant dragon's head are an excellent source of fiber, oil, and protein, and are used to treat a variety of conditions, including certain nervous disorders, liver diseases, and kidney diseases. This study aimed to determine the effects of foliar application of various nano-chelate and chemical boron fertilizers on morphological indices of the dragon's head *(Lallemantia iberica*). This study employed a completely randomized design with nano-chelate (500, 1000, and 1500 mg/l) and boric acid (1000, 2000, and 3000 mg/l) treatments, in addition to a control group. The results demonstrated that the investigated treatments had a significant effect on the majority of dragon's head indices. The highest inflorescence length (43.66 cm) and number of cycles in the main branch (28.56) were observed in the boric acid treatment with 3000 mg/l of boric acid. The highest number of lateral branche, flower cycle per plant, and seed weight per plant, 1000-seed weight, and seed yields were obtained at 3000 mg/l of boric acid and 1500 mg/l of nano-chelated treatments, respectively. The highest number of seed per plant, plant dry weight, and biological yield were obtained in the treatments of 2000 and 3000 mg/l of boric acid and 1500 mg/l of nano-chelated boron fertilizers, respectively. Application of boron fertilizers significantly increased the nitrogen, phosphorus, potassium, and boron concentrations in the treated plants. In general, foliar application of boron micronutrient increased the yield and improved the indices of dragon's head. Consequently, the application of nano-fertilizers yielded promising results due to their higher absorption efficiencies at lower concentrations than conventional fertilizers.

Highlights

- Dragon's head seeds are high in fiber, oil, and protein and are used to treat nervous disorders, liver, and kidney diseases.
- This study examined the effects of nano-chelate and chemical boron fertilizers on dragon's head morphology.
- 3000 mg/l of boric acid produced the longest inflorescence (43.66 cm) and most main branch cycles (28.56).
- 3000 mg/l boric acid and 1500 mg/l nano-chelated treatments produced the most lateral branches, flower cycles, seed weight per plant, 1000-seed weight, and seed yields.

1. Introduction

Lallemantia sp. is one of the medicinal plants belong to the Lamiaceae family, that has 5 species (*L. peltata, L. oyleana, L. canescens, L. baldshuanica, and L. iberica*). Dragon's head (*L. iberica*) is an annual, herbaceous, and drought-resistant plant that has various usage (Rechinger, 1982). Their seeds are a very good source of fiber (29.66%), oil (20-28%), and protein (18%). Seeds extracted oil widely applicate to traditional medicine, foods industry, and dyeing. Moreover, the seeds of the dragon's head are a rich source of mucilage that is used for the treatment of different disorders, including nervous, liver, and kidney

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diseases (Amanzadeh et al., 2011). In the food industry, the gum and mucilage of dragon’s head usage as ice cream stabilizers, as well as in sweets, dairy, beverages, sauces, edible desserts, and meat products (Sheykhi Sanandaji and Pirzad, 2019).

Plant nutrition is an important factor that affects agricultural products. Nutrition imbalance of plants lead to poor growth and yield reduction (Malakouti and Homaei, 2006). Plants need to low amount of micronutrient elements, but the roles of these elements are very important and efficient. Among the micronutrients, boron has a significant role in plant performance (Alihosinpour et al., 2011). Moreover, Boron has an important role in plant metabolism, the formation of cell wall pectin, cell division, carbohydrate transport, germination, and pollen tube growth (Wojcik and Wojik, 2003).

Foliar application of boron caused to increase in protein contents and oleic fatty acid in Soybean (Bellaloui, 2010), as well as plant yield and seed quality (Dordas, 2006) in alfalfa (*Medicago sativa* L.). Foliar application of boron during the active growth of rapeseed (*Brassica napus* L.) has been shown to enhance its seed yield (Bowyzys and Krauz, 2000). In another study, sesame oil content and seed yield has shown to be elevated with boron foliar application (Pratima et al., 1999).

Considering the low efficiency of chemical fertilizers and the environmental problems caused by their high consumption, the use of nano-fertilizers in agriculture is necessary. They are completely absorbed by plants and obviate the shortage of plant nutrients. The advantages of nano-fertilizers include high effectiveness, high solubility in water, a reasonable price, and greater controllability (Mahajan et al., 2011).

In an investigation, applications of complete nano-fertilizers at a concentration of 1:1,000 have ameliorated the quantitative and qualitative performance of dragon's head (Mafakheri et al., 2016). In research on the quantity and quality of the essential oil of the medicinal plant dragon’s head with the use of conventional chemical fertilizers and nano-fertilizers in rainfed conditions, the results have revealed that the use of macro-nano-fertilizers with 50% chemical fertilizers has increased the amount of the studied traits (Javanmard et al., 2020). Applications of nano-chelated iron and zinc fertilizers in *Lallemantia royleana* Benth. have been seen to enhance the examined traits compared to the control treatment (Moghadam Barati et al., 2017).

In a study on the impacts of different concentrations of micronutrient elements, including chelated and nano-chelated iron fertilizers on basil plant, the results have demonstrated that the use of nano-chelated iron fertilizer has enhanced its growth characteristics and replacement of iron fertilizer prepared with nanotechnology in an appropriate concentration or a concentration of less than that of conventional iron fertilizer has been able to raise its quantitative and qualitative growths (Peyvandi et al., 2011).

The purpose of this research was to investigate and compare the effects of boric acid and nano-chelated boron fertilizers on the quantitative and qualitative characteristics of the dragon's head (*L. iberica*) medicinal plant under greenhouse conditions.

2. Materials and methods

This study was conducted in a completely randomized design with 7 treatments and 3 replications in a greenhouse in the Pakdasht Region of Varamin with the geographical coordinates of 51° and 8' north longitude and 35° and 34' east latitude and an altitude of 1190 m above sea level. The treatments used in this experiment included spraying with boric acid fertilizer at the concentrations of 1000, 2000, and 3000 mg/l, nano-chelated boron at the concentrations of 500, 1000, and 1500 mg/l, and the control treatment (spraying with distilled water).

Dragon's head seeds were procured from Pakan Seed Co., Isfahan, Iran, and cultivated in the plugs. Then seedlings were transplanted in the greenhouse at the 4-leaf stage; the distance of the cultivation row was 25 cm, and the distance between plants in each row was 10 cm. Nano-chelated boron fertilizer used in this experiment was prepared from Sepehr Parmis Company. Foliar application of desired fertilizers was done three times: first when the plant had six leaves, second when the plant stem height reached about 22–25 cm, and third before the plant flowered.

After completing the experiment, the parameters of plant height, flowering branch height, inflorescence length, number of reproductive branches, number of cycles in the main branch, number of flowering cycles per plant, number of nutlets per flowering cycle, number of nutlets per plant, number of seeds per plant, seed weight per plant, and 1000-seed weight were measured.

At the end of the growing season and after fully ripening when the seeds were almost half-brown, the total dry weight of the aerial parts was first measured as a biological yield by using a digital scale and the seed yield was measured after separating the seeds with a sieve. The harvest index was calculated by dividing the seed yield by the biological yield (Goldani and Rezvani, 2006).

The Kjeldahl, spectrophotometric, flame photometer, and atomic absorption methods were employed to determine the amounts of nitrogen, phosphorus, potassium, and boron (Walinga et al., 1989).

The analysis of the obtained data was done using SAS software, version 9.1, and the means were compared by using Tukey HSD test at the 5% probability level.

3. Results and Discussion

The results presented in the data variance analysis table showed that foliar application with boron fertilizers had a significant effect on the traits of inflorescence length, number of lateral branches, number of cycles in the main branch, number of flowering cycles per plant, number of nutlets per plant, number of seeds per plant, seed weight per plant, 1000-seed weight, seed yield, plant dry weight, and biological yield at the probability level of 1%, while it had no significant impact on the traits of plant height, number of nutlets in the flowering cycle, and harvest index (Tables 2).

Table 1. Soil physical and chemical characteristics of experimental location

pH	EC (ds/m)	Organic matter(%)	Clay (%)	Silt (%)	Sand (%)	Nitrogen (%)	Phosphorus (mg/kg)	Potassium (mg/kg)	Boron (mg/kg)
7.5	1.15	0.92	21.37	42.75	35.88	0.39	31.5	295	4.12

Table 2. Analysis of variance for the effect of foliar application of chemical and nano-chelate boron fertilizers on the characteristics of dragon's head

S.O.V.	df	Mean of squares					
		Plant Height	Inflorescence length	Number of lateral branches	Number of cycles in the main branch	Number of flowering cycles per plant	Number of nutlets in the flowering cycle
Foliar application	6	0.56ns	13.95**	8.09**	47.82**	113.77**	0.21ns
Error	14	0.30	0.09	0.62	0.43	1.143	0.28
CV (%)	-	1.32	1.51	6.46	2.85	2.19	11.82

Table 2. Continued

S.O.V.	df	Mean of squares					
		Number of nutlets per plant	Number of seeds per plant	Seed weight per plant	1000-seed weight	Seed yield	Plant dry weight
Foliar application	6	2777.94**	5811.73**	0.23**	0.14**	378.64**	2.24**
Error	14	732.95	30.73	0.009	0.018	14.73	0.16
CV (%)	-	12.42	1.76	3.68	3.77	3.72	3.59

Table 2. Continued

S.O.V.	df	Mean of squares					
		Biological yield	Harvest index	N	P	K	B
Foliar application	6	3580.99**	3.07ns	0.89**	0.036**	0.15**	14.85**
Erorr	14	261.36	2.13	0.139	0.0006	0.014	0.672
CV (%)	-	3.63	6.31	12.35	3.15	8.83	4.86

ns, *, and ** is no significant, significant at 5 and 1% probability level, respectively

Based on the comparison results of the data means, boric acid and nano-chelated boron fertilizer increased the inflorescence length. The highest (23 cm) and lowest (16.8 cm) lengths of inflorescences were related to the boric acid treatment with a concentration of 3000 mg/l and the control treatment, respectively. The results indicated that foliar spraying of boric acid and nano-chelated boron fertilizer at concentrations of 3000 and 1500 mg/l led to 33.72 and 25.77% enhancements in inflorescence length compared to that of the control treatment, respectively (Table 3). If the plant has enough boron, the cell division process will be successful, resulting in increased vegetative growth and plant and flowering stem heights (Marshner, 2012).

Based on the comparison results of the means in this study, foliar applications of boric acid and nano-chelated boron fertilizer had positive effects on the number of lateral branches of each plant. Nevertheless, the nano-chelated boron treatment with a concentration of 500 mg/l had no statistically significant difference from the control treatment in this regard (Table 3). The highest number of lateral branches was observed in the treatment of nano-chelated boron fertilizer at a concentration of 1500 mg/l (14.33 numbers) and boric acid at a concentration of 3000 mg/l (14 numbers), which led to enhancements of 38.72 and 35.52% compared to that of the control treatment, respectively. Our findings revealed no significant differences in the number of lateral branches between the two nano-chelated boron treatments (1000 and 1500 mg/l) and the two boric acid treatments (2000 and 3000 mg/l) on number of lateral branches (respectively). The results of research carried out on olives by Taherian and Bostani (2017) revealed that the applications of nano-chelated boron fertilizer and boric acid caused an increase in lateral branches compared to the control treatment. This finding is consistent with that of this research. In an investigation on the effects of potassium nano-fertilizer treatment on wheat plants (N8019 variety) at concentrations of 1.5, 0.3, and 0.6%, it was reported that the growth of aerial parts and the emergence of lateral branches increased at the concentration of 1.5%. The potassium nano-fertilizer treatment showed a significant increase in the number of reproductive branches and yield compared to those of the control treatment (Tavan et al., 2014).

Based on the comparison results of the means in this research, boric acid and nano-chelated boron fertilizer had positive impacts on the number of cycles in the main branch of dragon’s head. The highest (28.66) and lowest (17.66) numbers of cycles in the main branch were related to the treatments of boric acid at a concentration of 3000 mg/l and the control treatment, respectively (Table 3). Applications of boric acid and nano-chelated boron fertilizer at concentrations of 3000 and 1500 mg/l showed 62.28 and 50.96% enhancements in the number of cycles in the main branch compared to that of the control treatment, respectively.

Boric acid and nano-chelated boron fertilizer had positive effects on the number of flowering cycles per plant. Boric acid and boron nano-chelated treatments with concentrations of 3000 mg/l (55.66) and 1500 mg/l (54.66) led to the highest numbers of flowering cycles per plant, respectively, while the control treatment had the lowest number of flowering cycles per plant (41.33) (Table 3). The results indicated that the effects of boric acid and nano-chelated boron fertilizer at concentrations of 3000 and 1500 mg/l led to enhancements of 34.67 and 32.25% compared to the control treatment, respectively. The application of

1000 and 1500 mg/l boron nanochelated had no significant difference in the number of flowering cycles per plant compared with the 2000 and 3000 mg/l treatments of boric acid.

The results of the research conducted by Khiavi et al. (2010) on rapeseed revealed that the highest numbers of silique per plant and seeds were related to the boron+zinc+sulfur treatment. The results of this research were congruent with those of Yang et al. (2010) and Azizi et al. (2011), who reported that boron foliar application led to an increase in the number of pods per plant, the number of seeds per pod, and the weight of 1000 seeds per plant.

The numbers of clusters, branches, and flowers could be attributed to the role of boron in the transfer of sugar to the active growing parts and formations of young leaves and flowers, which determine the vegetative ratio in plants. If the boron required by the plant is supplied, a larger number of flowers and florets will be produced, and the transfer of sugar to the active growing parts of the plant, including young leaves, will enhance fruit production in the plant (Marschner, 2012). Foliar spraying with boric acid at a probability level of 1% was reported by Mashayekhi et al. (2016) to lead to an increase in the number of clusters in tomato plants (Supra variety).

Foliar spraying of boric acid and nano-chelated boron fertilizer increased the number of nutlets in dragon's head. A nano-chelated boron treatment with a concentration of 1500 mg/l led to the highest number of nutlets per plant (25.33), which showed a 42.64% increase compared to that of the control treatment. There are no significant differences between two treatments of nano-chelated boron (1000 and 1500 mg/l) and two treatments of boric acid (2000 and 3000 mg/l) on the number of nutlets (respectively) (Table 3).

There are no significant differences between two treatments of nano-chelated boron (1000 and 1500 mg/l) and two treatments of boric acid (2000 and 3000 mg/l) on the number of nutlets (respectively).

Boric acid had a positive and significant effect on 1000-seed weight, number of seeds per silique, and number of pods per plant in rapeseed (Pazoki et al., 2013).

Foliar spraying of boric acid and nano-chelated boron fertilizer had positive impacts on the number of seeds in dragon's head. The nano-chelated boron treatment with the concentration of 1500 mg/l (757.66) and the boric acid treatment with the concentrations of 3000 (755) and 2000 mg/l (750) resulted in the highest number of seeds per plant (Table 3).

In their study on the effects of iron and potassium nanochelates on the number of seeds in *Plantago ovata*, Aghazadeh Khalkhali et al. (2015) showed that they significantly raised this trait at the probability level of 5%. The application of boric acid and nano-chelated boron fertilizer resulted in a balance between reproductive and vegetative growth. This could be in part due to the role of boron in regulating growth traits via its contribution to cell division and elongation, nitrogen and carbohydrate metabolism, sugar transport, and the synthesis of indole acetic acid (Shireen et al., 2018).

Boric acid and nano-chelated boron fertilizer had positive effects on the seed weight per plant and seed yield per m^2 in dragon's head. The nano-chelated boron and boric acid treatments with the concentrations of 1500 mg/l (2.95 g) and 3000 mg/l (2.82 g) led to the highest seed weights per plant, which resulted in the enhancements of 47.47 and 34.28% compared to that of the control treatment, respectively (Table 3). Also, they provided the highest seed yields per m^2 at concentrations of 1500 mg/l (118.37 g) and 3000 mg/l (112.82 g), respectively. Our results show that there are no significant differences between two treatments of nano-chelated boron (1000 and 1500 mg/l) and two treatments of boric acid (2000 and 3000 mg/l) on seed weight per plant and seed yield per m^2 (respectively).

Boron foliar application increased the weight of 1000 seeds in dragon's head. The nano-chelated boron and boric acid treatments with concentrations of 1500 mg/l (3.9 g) and 3000 mg/l (3.76 g) led to the highest 1000-seed weights, which resulted in enhancements of 17.47 and 13.25% compared to that of the control treatment, respectively (Table 4).

Table 3. Mean comparison for the effect of foliar application of chemical and nano-chelate boron fertilizers on some characteristics of dragon's head

Foliar application	Inflorescence length (cm)	Number of lateral branches	Number of cycles in the main branch	Number of flowering cycles per plant	Number of nutlets per plant	Number of seeds per plant	Seed weight per plant (g)
Control	17.20d	10.33d	17.66f	41.33d	179c	632.66e	2.1e
Boric acid (1000 mg/l)	19.7c	11.33cd	22d	44c	205.66bc	719.66c	2.496d
Boric acid (2000 mg/l)	19.06c	12bc	25.33c	51.66b	222.66abc	750a	2.56cd
Boric acid (3000 mg/l)	23a	14a	28.66a	55.66a	241ab	755a	2.82ab
nano-chelated boron (500mg/l)	17.50d	10.33d	19.33e	41.66d	180.66c	706.66d	2.4d
nano-chelated boron (1000mg/l)	21.13b	13ab	21.66d	51.66b	241.33ab	738.33b	2.67bc
nano-chelated boron (1500mg/l)	21.66b	14.33a	26.66b	54.66a	255.33a	757.66a	2.95a

Same letters in each column are not significant at the 5% level based on the Tukey HSD test.

Table 4. Mean comparison for the effect of foliar application of chemical and nano-chelate boron fertilizers on some characteristics of dragon's head

Foliar application	1000-seed weight (g)	Seed yield (g/m^2)	Plant dry weight (g)	Biological yield (g/m^2)	N (%)	P (%)	K (%)	B (ppm)
Control	3.32d	84.21e	9.75e	390.13e	1.99c	0.65c	0.91d	12.17c
Boric acid (1000 mg/l)	3.47cd	99.94d	10.92de	436.8de	2.76b	0.68c	1.25c	16.04b
Boric acid (2000 mg/l)	3.39cd	102.67cd	11.65ab	466.13ab	3.05b	0.86a	1.29c	17.42ab
Boric acid (3000 mg/l)	3.76ab	112.82ab	11.64ab	465.34ab	3.31ab	0.89a	1.54ab	18.19a
nano-chelated boron (500mg/l)	3.38cd	96.09d	10.27de	410.93de	3.09b	0.66c	1.36bc	17.48ab
nano-chelated boron (1000mg/l)	3.61bc	106.76bc	11.44bc	457.6bc	3.12b	0.79b	1.44abc	18.10a
nano-chelated boron (1500mg/l)	3.9a	118.37a	12.2a	488.26a	3.77a	0.88a	1.57a	18.59a

Same letters in each column are not significant at the 5% level based on the Tukey HSD test.

Micro-elements play an important role in elevating the activities of some enzymes, amount of photosynthesis, durability of leaf surface, and cell division of meristem tissues besides storing more nutrients and consequently augmenting the 1000-seed weight of plants by affecting absorption of macronutrients, such as nitrogen, phosphorus, and potassium (Pazoki et al., 2013).

Plant yield is mainly related to basic processes, such as the initiation of flower-bud formation, differentiation, growth, and final fruit formation. The increase in yield achieved by applying boron at the stage of bud swelling and before flowering can be explained by its constructive effect on pollen viability and pollen tube elongation. In addition, the increase in yield may be attributed to the positive impact of boron on the improvement of plant nutritional status and assimilate production (Shireen et al., 2018).

This finding is consistent with those of the previous studies, which have shown that nano-fertilizers can be absorbed by plants more efficiently and quickly to meet nutritional needs (Naderi et al., 2011). Davarpanah et al. (2016) gave a similar report, in which the positive effect of nano-boron foliar application on fruit yield was mentioned in the pomegranate tree.

The role of boron in the synthesis of auxin hormone, which is involved in cell division, cell wall strength, and differentiation, has already been documented (Shireen et al., 2018). Boron plays an effective role in source-to-sink transports of sugar and growth regulators (Shireen et al., 2018). Compared to boric acid, the use of lower concentrations of boron in the form of nano-chelate had similar and sometimes more positive effects on the examined traits.

Boron deficiency in plants causes tissues to grow in an abnormal and unusual way, as a result of which vegetative growth decreases. The reduced vegetative growth leads to the reduction of internode length, which will result in a decrease in plant height, flowering branch height, and consequently lowered seed yield in plants (Marschner, 2012). Valenciano et al. (2011) discovered that boron foliar application increased the yield of chickpea plants.

Boric acid and nano-chelated boron foliar applications had positive effects on the dry weight of dragon’s head. Nano-chelated boron treatment with a concentration of 1500 mg/l (12.2 g) and boric acid treatment with concentrations of 2000 mg/l (11.65 g) and 3000 mg/l (11.64 g) produced the highest plant dry weight (Table 4).

Fertilization with nano-chelated boron and boric acid increased the biological yield in dragon’s head. Nano-chelated boron treatment with the concentration of 1500 mg/l (488.26 g) and boric acid treatment with the concentrations of 2000 mg/l (466.13 g) and 3000 mg/l (465.34 g) provided the highest biological yields (Table 4). In a report on *Plantago ovato*, the results revealed that foliar application of micronutrient elements significantly enhanced biological yield compared to the control treatment (Ramroudi et al., 2011). Foliar application of nano-fertilizers and common boron fertilizer in olive plants resulted in enhancements of 16.97% and 11.55% in yield compared to the control treatment, respectively (Taherian and Bostani, 2017).

Boric acid and nano-chelated boron fertilizer increased the amounts of nitrogen, phosphorus, potassium, and boron elements compared to the control treatment. The highest amounts of nitrogen elements were observed in the nano-chelated boron and boric acid treatments, with concentrations of 1500 mg/l (3.77%) and 3000 mg/l (3.31%), respectively. The highest amounts of phosphorus were obtained in the nano-chelated boron treatment with a concentration of 1500 mg/l (0.88%) and the boric acid treatment with concentrations of 2000 mg/l (0.86%) and 3000 mg/l (0.89%). The most potassium element was found in the nano-chelated boron treatment at concentrations of 1500 and 1000 mg/l, as well as in the boric acid treatment at 3000 mg/l. Boron element levels increased in all foliar spraying treatments when compared to the control treatment, but there was no significant difference between the treatments of 2000 and 3000 mg/l boric acid and the nano-chelated boron treatments. The application of 1000 and 1500 mg/l boron nano-chelated had no significant difference in amounts of nitrogen, potassium, and boron elements, respectively, compared with the 2000 and 3000 mg/l treatments of boric acid (Table 4).

The contents of minerals in leaves are measured to identify the nutritional status of plants and are used for fertilizer recommendations (Fernández-Escobar et al., 2009). Boron has been reported to affect the uptake of other plant nutrients, causing an apparent increase in P, N, K, Zn, Fe, and Cu translocations in leaves, buds, and seeds. In the cotton plant, these elements were observed to increase after boron foliar application (Ahmed et al., 2011). In addition, an increase in boron concentration in leaves following boron consumption was reported in olive trees (Perica et al., 2001). Furthermore, foliar application of boron nano-fertilizer improved nutrient status in pomegranate trees (Davarpenah et al., 2016).

In their investigation of the effects of different amounts of boron on the concentrations of micro-elements in radish plants, the results showed that the concentrations of zinc, boron, iron, and copper elements in the leaves underwent a significant increase with the increase in boron amount from 0 to 5 mg/l. Leaf boron concentration was significant at the level of 1% (Tariq et al., 2006).

In comparison with boric acid, the application of lower concentrations of nano-chelated boron has the same positive effects on the mentioned traits. Several properties of nano-fertilizers may be the cause of such results. The specific properties of nanoparticles include their slow release, a large specific surface area, and the provision of a greater reactivity of catalysts that make them better candidates for selective reactivity compared to the equivalent bulk materials (Agrawal and Rathore, 2014).

4. Conclusion

The results of this research indicated that foliar application of boron fertilizer improved the studied traits except plant height, number of nutlets in the flowering cycle, and harvest index. The maximum inflorescence length and number of cycles in the main branch were obtained in the treatment of 3000 mg/l of boric acid. The treatments with 3000 mg/l of boric acid and 1500 mg/l of nano-chelated boron fertilizer had the highest effects on most of the studied traits, including number of lateral branches, number of flowering cycles per plant, number of nutlets per plant, number of seeds per plant, weight of seeds per plant, 1000-seed weight, seed yield, plant dry weight, and biological yield, and these two treatments had no significant differences despite the use of a lower concentration of nano-chelated boron. In general, it could be concluded that foliar application of the micronutrient element of boron ameliorated the characteristics of dragon’s head and elevated its yield. Overall, applications of nanofertilizers can achieve promising results due to their better efficiency at lower concentrations compared to conventional fertilizers. Foliar application of plants with boron nano-fertilizer can reduce production costs, lower fertilizer consumption, help maintain environmental health, and pave the way towards sustainable agriculture.

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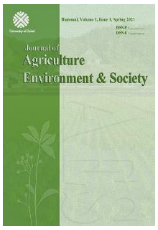

SWAP: a robust planning tool for quantifying the effect of deficit irrigation on the agricultural water productivity indices (case study: wheat farm)

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ABSTRACT

Due to the scarcity of water resources worldwide, it is essential to determine the water productivity indices. In this study, the SWAP model was used to determine the agricultural water productivity indices for three wheat farms in the arid regions of Iran. The model was calibrated and validated for each study farm using a large number of field-measured data. The results showed that the model could satisfactorily predict moisture profiles. SWAP model calculated water productivity. Due to the results of this study, it is possible to increase wheat yield by 14%, if the irrigation scheduling is correctly planed. Deficit irrigation by 30% showed no significant effect on reducing yield. Appropriate irrigation scheduling has increased WP_{ETdp} (yield to crop actual evapotranspiration plus deep percolation ratio) and WP_{Irr} (yield to total applied water ratio) by 48 and 61%, respectively. High evaporation at the initial stages of growth decreases WP_{ET} (yield to crop actual evapotranspiration ratio) by 28% compared to WP_T (yield to crop actual transpiration ratio). Improving agricultural operations such as mulch or soil application using subsurface irrigation methods can improve WP_{ET}. Reducing the applied irrigation depth had a negligible impact on the WP_{ET} and WP_T indices, but the WP_{ETdp} and WP_{Irr} indices exhibited a significant increase.

Highlights

- In this study, the SWAP model was used to determine the agricultural water productivity indices for three wheat farms.
- The paper shows that irrigation scheduling has increased WP_{ETdp} and WP_{Irr} by 48 and 61%, respectively.
- The paper shows that Deficit irrigation has little impact on the WP_T and WP_{ET} indices.

1. Introduction

Wheat is considered the most strategic agricultural crop in Iran**.** Approximately 5 to 6 million hectares, representing 60% of the total cultivated area, are dedicated to wheat cultivation annually. The measurement and analysis of water productivity indices hold a prominent position in Iran's agricultural sector. The issue of water productivity improvement to produce food production is fundamental in many different countries, especially countries like Iran with a low amount of water (Ehsani and Khaledi, 2003). Water productivity, an indicator of the output or benefit generated per unit of water used, encompasses the diverse aspects of water management. Also, water productivity serves as a valuable indicator for evaluating water resources, particularly in arid and semi-arid regions (Molden et al., 2001**,** Singh et al., 2006, Zhao et al., 2020). Field trials to determine and analyze the different irrigation managements are useful but are expensive and time-consuming if the simulation models can be calibrated for the irrigation of different options with low cost and short time (Droogers et al., 2000).

The SWAP (Soil-Water-Atmosphere-Plant) model is a one-dimensional model that, in its new version, can simulate water movement, solute transport, heat transfer, and irrigation scheduling, primarily employed at large scales. The governing equations of this model are solved using the method of finite differences (Van Dam et al., 1997). The applicability of the SWAP model for simulating agricultural water flow, solute transport, and crop performance across diverse geographical regions,

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including Iran, has been evaluated. The model's predictions demonstrated good agreement with field measurements (Singh et al., 2006; Mandare et al., 2008). Akbari et al. (2009) studied the effect of irrigation planning on agricultural water productivity using the SWAP model in networks' cascade. The results showed that irrigation reform programs, barley, and wheat yield significant quantities (15 percent) increase. On the other hand, with improved crop management and reduced 20 percent of water depth, no significant change was obtained. In a study conducted by Vazifedoust et al. (2008), the SWAP model was evaluated and calibrated to simulate water balance components such as transpiration, soil evaporation, and deep infiltration, and to predict crop performance. The results showed that the model is a valuable tool for predicting plant variables such as crop yield and dry weight with high accuracy. The SWAP model in the research farm for two years (2001-2002 and 2002-2003) in the land under wheat cultivation in the north of Gorgan and Homay and Kiani (2007) were evaluated. Statistical analyses revealed that the SWAP model effectively simulated soil moisture, soil salinity, and relative wheat yield under diverse field conditions. In all cases, the coefficient of determination (R^2) exceeded 80%, and the mean squared error (MSE) was consistently lower than the standard deviation (SD) of the data. A study conducted in the Zaragoza region of Spain compared the simulated evapotranspiration (ET) values obtained using the Penman-Monteith and Priestley-Taylor methods with those simulated by the SWAP model developed by Utset et al. (2004). The results showed that the SWAP model, when provided with accurate input data, can effectively predict ET values.

Eitzinger et al. (2004) examined plant performance in three models of Special WOFOST, CERES, and SWAP simulated water content in the soil during the growing season compared. Output models evaluate all three models with experimental data obtained from Lysimeter on different soil types in 2000-2001 crop for the crop of winter wheat and spring barley in the main agricultural region in Australia Marchfld compared. The results showed: 1- CERES and SWAP models unlike WOFOST weight of barley and wheat were well simulated, 2- All three models in soil water content profiles with the same results they bring, 3- none of the models, the total amount of soil profiles did not predict well, 4- CERES and SWAP model of water movement in the depth of 0.3 upper meters of soil, estimates were good. Jiang et al. (2015) investigated the irrigation efficiency and water productivity in the Heihe basin using the SWAP-EPIC model and geographic information system (GIS) on a regional scale. Experiments were conducted during 2012-2013. The results showed that water productivity was low due to excessive irrigation. The average crop evapotranspiration (ETc) was 589 mm, while deep percolation amounted to 125 mm, collectively accounting for an average of 21% of the total irrigation water applied. The results of various scenario analyses showed that improvement in water transfer efficiency and accurate irrigation planning resulted in a 30% reduction in deep percolation and a 15% saving in irrigation water without harming the performance. Ma et al. (2015) estimated the optimal irrigation program and deep percolation using the SWAP model in three experimental sites with wheat and corn plants. The results showed that implementing optimized irrigation scheduling could reduce net irrigation water application by 24.9% to 77.2% compared to conventional irrigation practices in the region. Kumar et al. (2015) used the SWAP model to simulate salt distribution within the soil profile and wheat yield under saline water irrigation conditions. The model calibrated using 2009-2010 trial data and validated using data from 2010-2011. The results showed that model performance is better in predicting the relative performance in salinity tolerant cultivars than unlikely varieties in terms of using saltwater with different qualities. Xue and Ren (2016) investigated plant water productivity under sprinkler irrigation regimes using the SWAP-WOFOST model. The results showed that spring wheat, spring maize, and sunflower seeds improved 16.9%, 8%, and 11.4%, respectively, compared to the surface irrigation scenario, and average water productivity increased by 7.9%, 5%, and 14.1%. Xue and Ren (2017) investigated water productivity using an agro-hydrological model in the Hetao irrigation network. The results showed if the proposed irrigation scenario was applied, it increased the average performance of product and water productivity for wheat, corn, and sunflower plants compared to the baseline scenario. Xu et al. (2019) examined agro-hydrological processes and water use optimization using the SWAP-EPIC model in the Heihe River Basin. The results showed that only 53% of applied water was applied through actual evapotranspiration. While, deep percolation losses and canal conveyance losses accounted for 22% and 25% of the total water consumed, respectively. Also, the results showed that about 15% of the amount of irrigation water was saved with a reasonable allocation of water. A substantial body of research has been conducted in the Neyshabour Plain, encompassing investigations into groundwater level forecasting, water resource management, and watershed studies (Izadi et al., 2007; Farajzadeh et al., 2005). Zhao et al. (2020) modified the SWAP model, and the result showed the yield and water use efficiency respectively 38.9% and 54.3% under mulching conditions improved compared to no mulching field.

Although these studies and hydrologic conditions and groundwater resource management are described in the plains area, the field scale is not the right solution for planning irrigation and agricultural water to increase productivity. This study has two primary objectives. The first stage focuses on simulating water balance components and predicting soil moisture content. Subsequently, the second stage evaluates water productivity under existing conditions, employing an irrigation planning model.

2. Materials and methods

2.1. Study area

Neyshabour Plain, one of the significant plains in Razavi Khorasan Province, was selected as the study area for this research (Figure 1). The Neyshabour plain's water crisis disrupts hydrological balance, with the escalating demand for water resources since 1986 identified as a subsequent contributing factor. The flatland portion of the CalShore basin, situated within the elevation range of northeastern Binalood in Iran's Central Desert, encompasses a significant geographical area. Encompassing a total catchment area of 7,300 square kilometers, the basin comprises 3,900 square kilometers of flatlands, with the remaining portion consisting of mountainous terrain. The basin is characterized by arid and semi-arid climate, with an average annual temperature of 12 degrees Celsius and an average basin-wide precipitation of 292 millimeters. The annual evaporation rate in the Neyshabour Plain is 2335 millimeters. In 1992, groundwater levels in the plain experienced an average annual decline of approximately 0.2 meters. The study area, a plain with a total discharge of 788 million cubic meters, boasts fertile land exceeding 80% suitable for irrigation and cultivation. This characteristic contributes to Neyshabour's status as a leading agricultural center in Khorasan, with over 70% of its crops classified as "blue water" crops, signifying their dependence on freshwater resources. The cultivation of water-intensive grain crops and garden produce is fundamentally incompatible with the prevailing water-scarce conditions in the region (Farajzadeh et al., 2005).

2.2. Essential Data Requirements for the SWAP Model

The SWAP ecohydrological model stands out as a comprehensive tool for simulating water, heat, and solute transport processes in both saturated and unsaturated soil environments. The SWAP model incorporates physically based models to simulate irrigation management practices and plant growth processes. Water movement is simulated using Richards' equation, employing the finite difference numerical method, incorporating imposed boundary conditions, and utilizing soil hydraulic functions. Soil hydraulic functions are defined as mathematical relationships that describe the interplay between hydraulic conductivity, soil moisture content, and soil water pressure head. The SWAP model employs analytical functions based on the equations proposed by Van Genuchten (1980) and Molden (1997) to effectively represent the soil water retention curve. The upper boundary condition is dynamically determined by the interplay of potential evapotranspiration (ET_P, mm/day), irrigation (Ir, mm/day), and precipitation (P, mm/day) fluxes. Potential evapotranspiration (ET_P) is estimated employing the FAO_{56} Penman-Monteith equation, utilizing daily weather data encompassing solar radiation, air temperature, humidity, wind speed, and crop characteristics, including minimum crop resistance, surface albedo, and crop height (Van Dam et al., 1997; Allen et al., 1998).

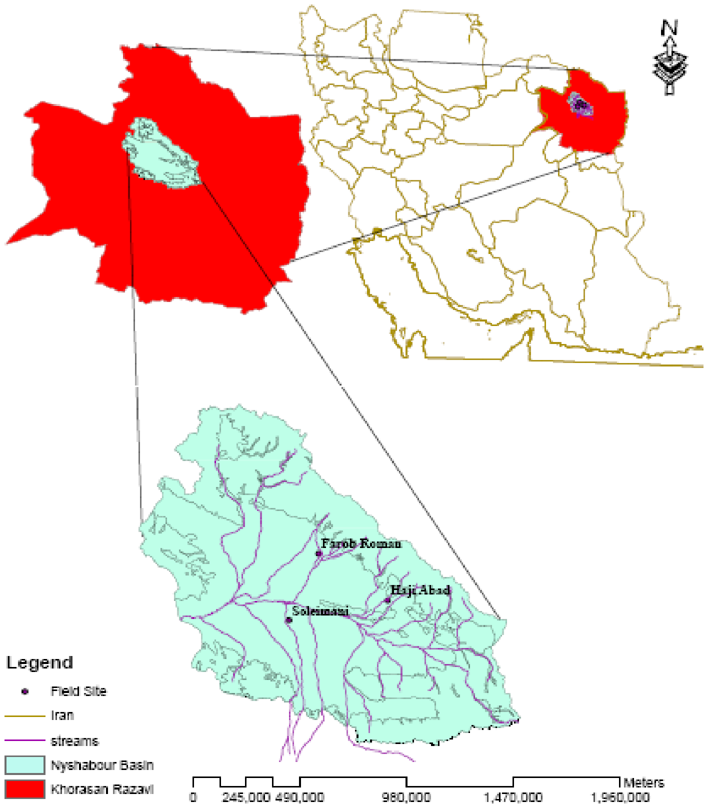

Figure 1. Spatial distribution of selected farms within the Neyshabour Basin

In Neyshabour Plain, wheat cultivation occupies the largest area, with production exceeding 121,000 tons. Consequently, wheat was selected for model evaluation and calibration using the SWAP model. Three wheat farms, namely Farob Roman, HajiAbad, and Soleymani, were chosen to represent the entire plain and collect the data required for the SWAP model (Figure 1). These farms were carefully selected based on their representative agroecological conditions and widespread cultivation of the selected wheat varieties, ensuring that the data collected accurately reflected the agricultural practices and yield potential across the entire region. Daily data from the Neyshabour synoptic station for the 2008-2009 cropping season were used to obtain meteorological data, including solar radiation, precipitation, minimum temperature, maximum temperature, relative humidity, and wind speed at 2 meters height. To acquire the agricultural data required by the model throughout the growing season, irrigation dates, irrigation water volume and salinity, root development depth, leaf area index (LAI), and plant height were measured in the selected fields. Also, at the end of the growing season, harvest date and yield rate were measured and recorded.

The irrigation depth was determined by multiplying the irrigation water flow rate by the irrigation duration and dividing the result by the field area. Furrow irrigation was employed in Farob Roman farm, basin irrigation in HajiAbad farm, and furrow irrigation along contour lines in Soleymani farm. To obtain soil hydraulic parameters, the RETC software package was used so that each layer of soil profile as soil texture, bulk density, and moisture content at the point of field capacity (FC) as the input data model and the equation parameters Van Genuchten including residual moisture θ_{res}, soil saturated moisture content θ_{set}, saturated hydraulic conductivity $K_{sat}(cmd^{-1})$ and soil parameters including $\alpha(cm^{-1})$, $\lambda(-)$, $n(-)$ as output was obtained (Van Genuchten et al., 1997). Some physical and chemical properties of soil in the fields of study are shown in Table 1. Soil moisture directly from the depths of 0-10, 10-20, 20-30, 30- 40, 40-50, 50- 60, 60 -70, and 70- 80 cm during the growing season in all experimental fields using psychrometer TRIME-FM type made in Germany on a two-week interval were measured. The observed soil moisture data were divided into two sets. The first part was used in the calibration procedures, and verification for the second model was used. To assess the performance of the model in simulating soil moisture values, the root mean square error (RMSE) was employed, calculated as follows (Pan et al., 2020):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\{\theta_{obs}(t_i)-\theta_{sim}(t_i)\}^2}{N}} \tag{1}$$

High humidity in the equation and θ_{obs} moisture observations simulated by the model θ_{sim} are.

2.3. The calculation of water productivity

In agricultural production systems, water productivity is determined by dividing the total crop yield by the volume of water consumed (Molden, 1997). Furthermore, water productivity can be defined in different ways. It refers to different types of crop production, i.e. dry matter or grain yield, and amount of water used, i.e. transpiration, evapotranspiration, and irrigation (Molden et al., 2001). Water productivity can be conceptualized and measured in various ways, employing different equations. For instance, crop yield can be quantified as either dry matter or total biomass, while water consumption can be defined as transpiration, evapotranspiration, irrigation, or evapotranspiration plus deep percolation. The flexibility inherent in water productivity definitions allows for the development of insightful indicators to assess water use efficiency. These indicators can guide decisions regarding water conservation strategies and identify opportunities for optimizing water management practices. The specific indicators employed in this study include:

$$WP_T = \frac{Y(kg/ha\ )}{Tr(mm)} \tag{2}$$

$$WP_{ET} = \frac{Y(kg/ha)}{ET_a(mm)} \tag{3}$$

$$WP_{ET_{dp}} = \frac{Y(kg/ha)}{ET_{dp}(mm)} \tag{4}$$

$$WP_{Irr} = \frac{Y(kg/ha\ )}{Ir(mm)} \tag{5}$$

Where: Y is grain yield (kg/ha), Tr is plant transpiration (mm), ET_a is actual evapotranspiration (mm), ET_{dp} is total actual evapotranspiration and deep percolation (mm), Ir is water irrigation (mm), WP_T is ratio of grain yield to plant transpiration, WP_{ET} is ratio of grain yield to actual evapotranspiration, WP_{ETdp} is ratio of grain yield to total actual evapotranspiration and deep percolation, WP_{Irr} is ratio of grain yield to water irrigation.

2.4. Evaluation and calibration model

The application of simulation models necessitates conducting sensitivity analysis, calibration, and validation procedures. In this study, they were used to perform these steps to transfer parts of water and crop growth. Sensitivity analysis of the model was conducted using the method proposed by Lane et al. (1990). This method has also been used in other studies (Akbari et al., 2009). To conduct a sensitivity analysis of the model's response to soil hydraulic parameters, output data from the RETC model for various soil layers and selected fields were utilized as a reference.

To conduct the sensitivity analysis, each input parameter was systematically varied in turn. For each parameter, two perturbations were applied: a positive and a negative change, both of 50% magnitude. The remaining input parameters were held constant during each perturbation. The model was then executed under each new set of conditions to assess its sensitivity to the altered parameter. The results of these two modes with the results compared to the base case sensitive model parameters were determined. To calibrate wheat yield under diverse irrigation regimes, the Soil Water Assessment Tool (SWAP) model was employed. In this study, all measured parameters from various fields, including irrigation dates, irrigation water salinity, plant height, leaf area index, root depth, and harvest date, were utilized. Input data required for the model were prepared and calibrated using information from various fields, as follows: 1- Model performance under different simulated experimental fields, 2- Comparison of measured performance with simulated performance under identical conditions, 3- If the simulated performance did not match the measured performance, the plant yield sensitivity coefficient (K_y) was adjusted. Subsequently, the aforementioned steps were repeated until the simulated results closely matched the measured performance, 4- The calibrated model was employed to investigate the impact of various irrigation scheduling strategies on crop yield.

Table 1. Some soil physical and chemical characteristics of experimental fields (SiL: Silt, L: Loam, S: Sand)

Fields	**Layer**	ρ_d	**Soil**	**Clay**	**Silt**	**Sand**	**Gravimetric Water Content at Field Capacity**	**EC**
		Soil physical properties						
	(cm)	(gr/cm^3)	**Texture**		**(%)**		**(%)**	**(dS/m)**
Farob Roman	0-30	1.51	SiL	18	52	30	20.1	1.06
	30-60	1.57	L	22	44	34	17.1	0.68
	60-90	1.78	L	20	46	34	19.7	0.8
HajiAbad	0-30	1.43	L	18	36	46	15.5	1.56
	30-60	1.49	SL	18	22	60	12.9	2.69
	60-90	1.71	L	16	36	48	11.7	2.02
Soleymani	0-30	1.72	SiL	17	55	28	17	6.96
	30-60	1.70	SiL	16	62	22	23	7.5
	60-90	1.71	SiL	16	60	24	18.2	8.2

3. Results and discussion

3.1. Simulated soil moisture profiles

The sensitivity analysis model to soil hydraulic parameters using the method of Lane et al. (1990), showed the model to α, n and θ_{sat} parameters, the average degree of sensitivity and other parameters for input sensitivity was low. Among the sensitive parameters α and n were moderate and the most sensitive parameters. Thus, phase calibration model parameters were changed; therefore, the best match between observed and simulated moisture was achieved. Calibration parameters and other soil hydraulic parameters (θ_{res}, θ_{set}, K_{sat} and λ) are shown in Table 2. The amount of soil moisture and root mean square error (RMSE) in different fields between 0.02 and 0.039 was fluctuating (Table 3). These results indicate that soil moisture could be modeled at different times and depths for good simulation. Some differences between predicted and measured moisture values may be due to the limitations of inherent models. For example, the phenomenon effects of residual moisture (Hysteresis) and preferential water flow from the large gaps in the model are in order. Another reason may reduce accuracy due to the simple model extracted which is related to some parameters. For example, daily rainfall amounts to the assumption that the model is used to rain all day uniformly distributed, the constant, while may not be accurate both in the model enters (Khaksari et al., 2006). Also, field observations of variability and error may be the difference between observed and simulated values is a fundamental role (Figure 2). RMSE values during calibration and verification procedures in field Farob Roman respectively, 0.035 and 0.020 were calculated. RMSE value observed during both phases is relatively low and acceptable.

Table 2. Soil Hydraulic Properties at Different Depths in Experimental Fields

Fields	**Layer (cm)**	θ_{res} (cm^3/cm^3)	θ_{sat} (cm^3/cm^3)	K_{sat} (cm/day)	α (cm^{-1})	λ $(-)$	n $(-)$
Farob Roman	0-30	0.044	0.353	20.61	0.021	0.5	1.39
	30-60	0.050	0.343	20.44	0.026	0.5	1.13
	60-90	0.041	0.300	9.04	0.037	0.5	1.24
Haji Abad	0-30	0.051	0.381	41.51	0.039	0.5	1.80
	30-60	0.059	0.382	115.41	0.048	0.5	1.10
	60-90	0.042	0.304	41.40	0.062	0.5	1.44
Soleymani	0-30	0.036	0.298	15.95	0.038	0.5	1.27
	30-60	0.040	0.321	11.96	0.008	0.5	1.10
	60-90	0.035	0.302	16.29	0.031	0.5	1.27

3.2. Estimation of Soil Water Balance Components Using the SWAP Model

Using data collected as input soil hydraulic parameters, irrigation depths and other data, water balance components in different fields were simulated by the SWAP model. The accurate simulation of water balance components for the calculation of productivity indices is necessary. Table 4 simulated water balance components in different fields of Neyshabour plains. Rainfall during the growing season is an important source of wheat crop evapotranspiration. The amount of rainfall during the growing season is 280 mm.

With this level of winter precipitation, unnecessary irrigation applications can be eliminated. The water irrigation ranges from 420 to 920 mm. Under actual field conditions, crop evapotranspiration values ranged from 451 to 498 millimeters. The average wheat evapotranspiration was estimated to be 472 mm. Evapotranspiration rates in Haji Abad and Soleymani farms are comparable under identical irrigation volumes. Irrigation management practices at Farob Roman farm are not optimized due to reliance on a surface irrigation system not designed for efficient water distribution. This results in significant water losses through deep percolation and runoff, estimated to be 60% of the total applied irrigation water and precipitation. Due to the improper design of the surface irrigation system in Farob Romen Farm, approximately 60% of the total irrigation and rainfall water is lost from plant access through deep percolation and surface runoff. Therefore, it is shown that while the amount of irrigation in this field is higher than in other fields because the actual evapotranspiration losses inevitable deep percolation and runoff is almost about other fields. Due to heavy irrigation farms in the Farob Roman farm, deep percolation and runoff were higher than in other fields. The SWAP model to separate evapotranspiration plant to evaporation (non-effective water) and transpiration (effective water) using LAI at different plant growth stages. In Figure 3, the amount of daily evaporation and transpiration during the growing season in the field of Farob Roman is shown. As observed in the figure, at the beginning of the growing season, the contribution of evaporation is greater than that of transpiration due to the small size of the plant cover. As the growing season progresses towards its mid-to-late stages, the contribution of evaporation decreases while that of transpiration increases. Consequently, by the end of the growing season, evaporation reaches zero and transpiration reaches its maximum value. This observation highlights the significance of the reduced evaporation component at the beginning of the growing season, which can be considered in farm water management strategies.

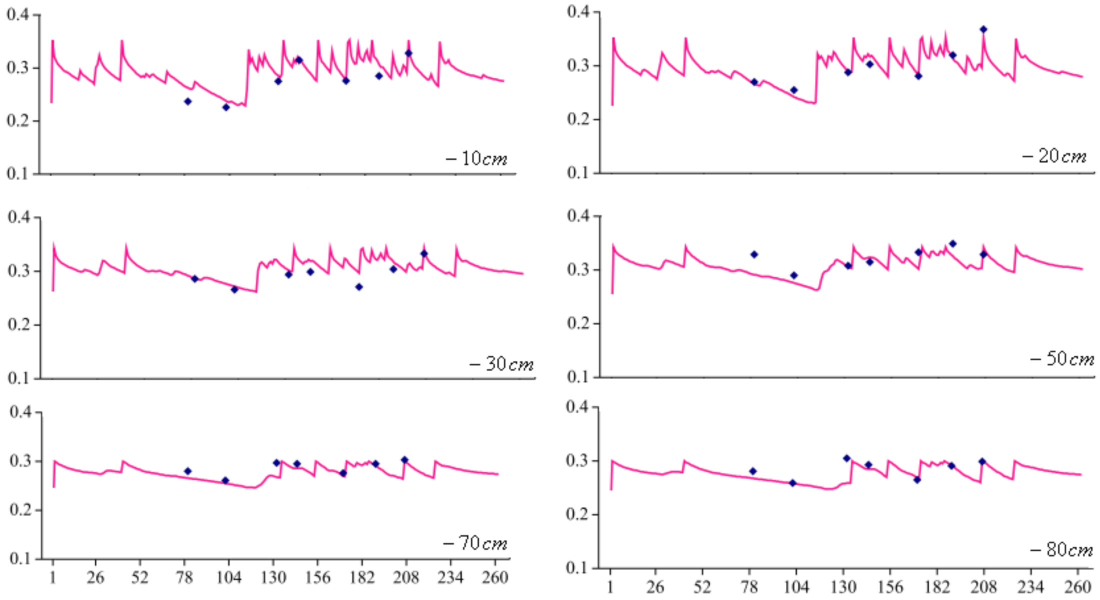

Figure 2. Observed and simulated moisture field in different soil depths Farob Roman

3.3. Water productivity under agriculture management

Water productivity indicators were calculated using water balance components simulated by the SWAP models. These components included irrigation, actual evapotranspiration, crop evapotranspiration, deep percolation, soil moisture storage within the profile, and field-measured yield data. Table 5 shows the values of water productivity indicators in different farms of Neyshabour plain. The WP_T value exhibits variability, ranging from 0.85 to 1.67. The average value of WP_T was calculated to be 1.28. Vazifedoust et al. (2008) estimated the WP_T value for wheat in the Borkhar of Esfahan region 1.18 kg/m^3 which is similar to the value obtained in this study. The intermediate indicators, WP_{ET}, WP_{ETdp} *and* WP_{Irr} in the studied fields were 0.99, 0.6, and 0.88 kg/m^3, respectively. High levels of evaporation in the early period of plant growth due to traditional irrigation methods in the study farms decreased by 28 percent compared WP_{ET} to WP_T. Improving agricultural operations such as mulch or soil application subsurface irrigation can be improved WP_{ET}. In addition and most important reason WP_{Irr} and WP_{ETdp} to WP_{ET} reduce the high amount of deep percolation due to heavy irrigation treatments in the Farob Roman farm. Due to a review of 82 literature sources with results of experiments in the last 25 years, Zwart and Bastiaanssen (2004) established global benchmark values of WP_{ET}, expressed as Y/ET (Kg/m^3), at 1.08 for wheat. The average WP_{ET} for wheat in Neyshabour Plain was calculated to be 0.99. Singh et al. (2006) calculated index values WP_T, WP_{ET}, and WP_{ETdp} for wheat in the Sirsa district, India as 1.88, 1.39, and 1.04 kg/m^3, respectively. These values compared with the indices are higher than can be due to increased crop evapotranspiration and deep percolation to the research done in India. In addition, the demonstrably higher wheat yield in the Sirsa district, averaging 5.4 tons/ha compared to 4.7 tons/ha in Neyshabour, could be another contributing factor. Results of studies show that improved water management, an effective and important step in increasing efficiency and optimal use of water and irrigation water use efficiency (WP_{Irr}) and agricultural products are produced. Zwart and Bastiaanssen (2004) estimated global water use efficiency (WUE) for wheat to range between 0.6 and 1.7 kg/m^3, with an average of 1.09

kg/m^3. The results of this study showed that the index of WUE can largely decrease the amount of irrigation water which increases deficit irrigation practices. Heydari et al. (2005) conducted a study to determine the water use efficiency (WUE) of major agricultural products in five regions of Iran: Kerman, Hamedan, Moghan, Golestan, and Khozestan. Their findings indicate that the average WUE for wheat was 0.75 kg/m^3. Heidari and Haghayeghi Moghaddam (2001) due to the results of two national projects carried out in the field of productivity (efficiency) irrigation experts in the country by the Engineering Research Institute of Agriculture, crop water use efficiency of different methods of surface irrigation management to farmers were calculated. The results showed that these irrigation methods and management of important influence to increase the efficiency of water irrigation and the bulk of issues and problems in irrigation efficiency and water use efficiency (WUE) of irrigation management issues related to the improvement, need little investment and no but an effort to correct management and planning needs. Their irrigation water use efficiency of wheat in Khorasan province, on average 0.57 was calculated. In this study, the amount of irrigation water uses efficiency for wheat in the Neyshabour Plains with average 0.88 kg/m^3. This number compared with the numbers mentioned in previous investigations improved due to practice improvements over the last decade in different parts of the Agricultural Research and Development, so that the value of this index shows an increase at 17% in the country and 54% in Khorasan province.

3.4. Scenario planning irrigation

Due to the field measurements between 2008-2009, the dates and amount of irrigation water applied in the fields Soleymani and HajiAbad optimum level and is suitable for irrigation planning and scenario modeling exercise on wheat yield had no significant effect. The highest water level in the field was the first time Farob Roman was 230 mm, and on other occasions (six times) was estimated at around 115 mm. Runoff and deep percolation of water from the applied field Farob Roman showed that irrigation.

Table 3. Mean square error and number of observations in the calibration and validation stages of moisture

Fields	**Calibration** θ (cm^3cm^{-3})		**Validation** θ (cm^3cm^{-3})	
	N	**RMSE**	**N**	**RMSE**
Farob Roman	18	0.035	13	0.020
HajiAbad	21	0.039	21	0.037
Soleymani	17	0.033	12	0.032

Table 4. Simulated water balance components (mm) in the fields studied (farmer management conditions)

Water balance components	**Fields**		
	Farob Roman	**HajiAbad**	**Soleymani**
P	280	280	280
Ir	920	400	420
E_a	108	109	101
T_a	359	389	350
ET_a	467	498	451
R	188	25	26
ΔW	-20	-3	-19
Q_{bot}	-565	-160	-242
$Y(ton/ha)$	6	5.23	3

Table 5. Water productivity indicators in agriculture management (kg/m^3)

Water productivity indicators	**Fields**		
	Farob Roman	**HajiAbad**	**Soleymani**
WP_T	1.67	1.34	0.85
WP_{ET}	1.28	1.05	0.66
$WP_{ET_{dp}}$	0.58	0.79	0.43
WP_{Irr}	0.65	1.3	0.71

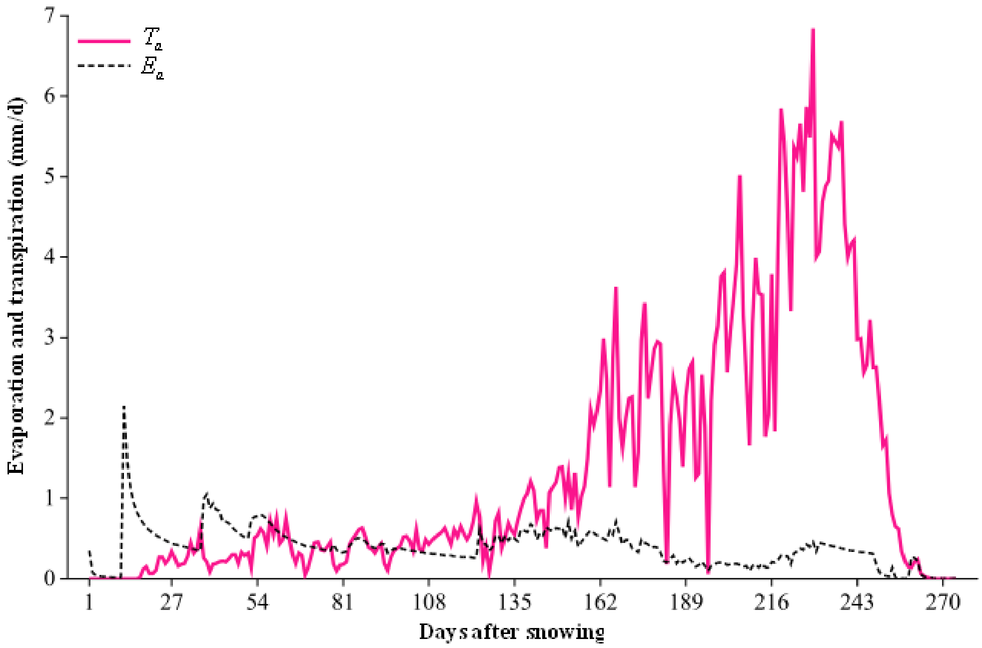

Figure 3. Daily simulated evaporation and transpiration rates for the Farob Roman farm

At this time due to the occurrence of rainfall field season is not adequate for plant growth and irrigation at the right time (the proposed planning model) deep percolation and runoff respectively 42 and 40 percent and 14 percent yield increase.

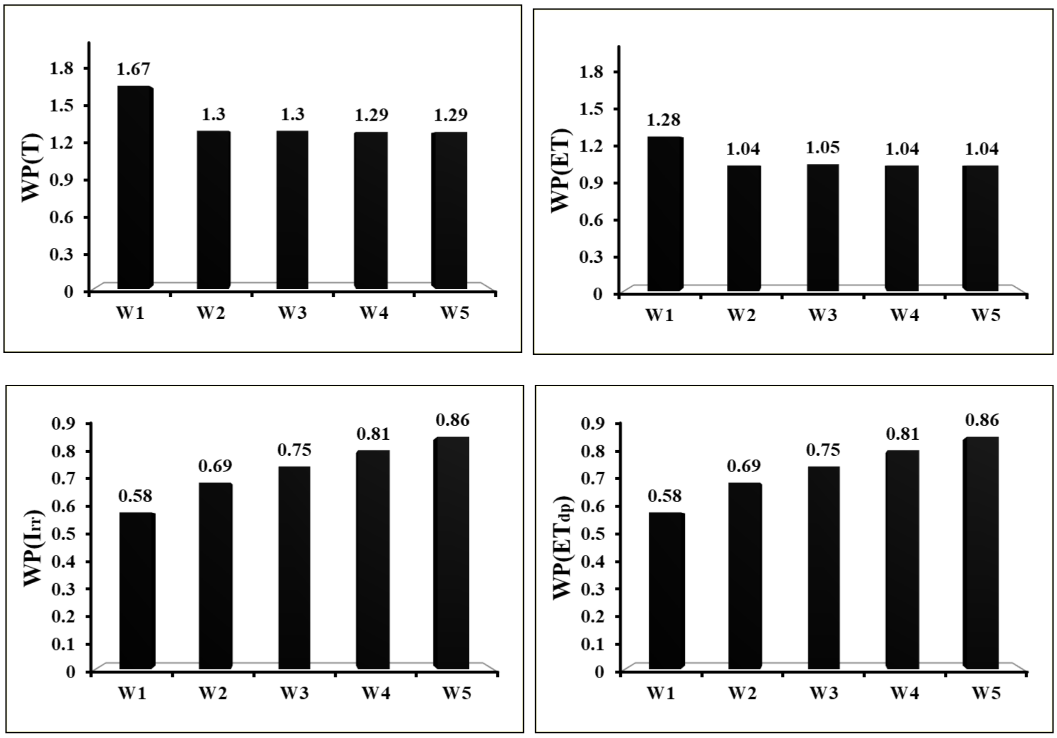

Figure 4. The relationships among the indicators of productivity of water management scenarios in the field of agriculture and Farob Roman (W_1: farmer management conditions, W_2: scenario planning irrigation, W_3, W_4, and W_5, respectively, 10, 20 and 30 percent less irrigation)

The results show the water depth applied due to the soil characteristics and plant characteristics of wheat is higher than the amount required. The simulation results conducted by the SWAP model under different scenarios showed reducing irrigation water depth applied to 30 percent had no significant effect on yield. Although reducing the depth of irrigation reduced the deep percolation and runoff at the farm level, may cause long-term accumulation of minerals and soil salinity. Therefore, reducing the amount of irrigation depth should be a prudent action. The traditional irrigation system and circulatory distribution of water between farmers and water right-holders, reducing irrigation depth and operation very reasonable and seem to be the best option in the present conditions, proper planning of irrigation, and the irrigation amount are at the right time. Figure 4 shows the relationship between water productivity indicators in agriculture and the management of scenarios in, Farob Roman field is shown. As in Figure 4, it is shown in water productivity indices (WP_T and WP_{ET}) independent of deficit irrigation and irrigation planning scenarios, and applying this scenario does not show the effect on these indices. The results by other researchers, including Vazifedoust et al. (2008) have also been confirmed. Deficit irrigation increased significantly in the indices WP_{ETdp} and WP_{Irr} due to deep percolation beeing reduced. For example, applying the correct planning of irrigation and deficit irrigation rate of 30% of indicators WP_{ETdp} and WP_{Irr} were about 48 and 61 percent are growing.

4. Conclusions

The results showed that demonstrated the feasibility of enhancing water management and efficiency through implementing effective irrigation scheduling strategies. Also, some farms with deficit irrigation management practices experienced a substantial decline in water depth (30%), crop yield (14%), and the water productivity indices WP_{ETdp} and WP_{Irr} (48% and 61% decrease, respectively). Conversely, implementing improved irrigation practices resulted in significant promotion of water productivity indices (about 48% and 61% increase, respectively). Deficit irrigation has little impact on the WP_T and WP_{ET} indices. Given the deep groundwater levels in the Neyshabour Plain, the impact of deep percolation on groundwater recharge may take years to manifest. Therefore, it is recommended that deep percolation and surface runoff losses at the field level be minimized to the greatest extent possible by meticulously leveling agricultural lands, employing mechanized surface irrigation methods, or utilizing pressurized irrigation techniques, thereby enhancing water productivity. Given the traditional irrigation system and rotational water distribution among farmers and water rights holders, it is recommended that proper irrigation scheduling practices, enhanced on-farm water management, and fertilizer and other agricultural input management be taught to farmers through extension classes to improve water productivity. It is recommended that this model be further validated and calibrated for other major crops in the Neyshabour Plain, such as forage maize, barley, sugar beet, cotton, and tomato, in subsequent research. The findings should be disseminated to farmers in the form of extension publications.

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