Optimizing Wheat Water Productivity as Affected by Irrigation and Fertilizer-nitrogen Regimes in an Arid Environment

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Abstract

The present study evaluated the applicability of the CropSyst model under variable climatic, irrigation, and fertilizer-nitrogen regimes. The objective was to analyze wheat productivity responses to water and N-application for optimizing water productivity in an arid irrigated environment. Evaluation analysis showed that the model provided very satisfactory estimates for the emergence, flowering and physiological maturity dates. The performance of the model was reasonable as demonstrated by the close correspondence between simulated grain yield, biomass accumulation, seasonal ET, and irrigation water productivity (WP_I) with measured data. The normalized root mean square error ranged between 5 and 10% for most of the parameters. Overall, the Willmott index of agreement between simulated and observed values of grain yield, biomass and seasonal ET were 0.99, 0.98 and 0.97, respectively. The validated model was employed to assess interactive effects of irrigation and fertilizer N on grain yield and water productivity indices. Scenario analyses indicated that WP_I and WP_{ET} (ET water productivity) ranged from 0.16 to 2.07 kg m^{-3}, and from 0.07 to 1.49 kg m^{-3}, respectively. For predicting the best N and water application practices for maximization of water productivity, the best option found by the model was application of water and nitrogenous fertilizer in 70% and 90% of the required values, respectively, for WP_I, and equal to the required values (100%) for WP_{ET}. The simulations demonstrated that the current wheat productivity of 5.0 Mg ha^{-1} obtained by the local farmers can be achieved at 140 kg ha^{-1} fertilizer N and 30% deficit irrigation regime with a WP_I of 1.73 kg m^{-3}. The CropSyst model can be applied to derive best management options in terms of N and irrigation application of wheat under arid conditions.

Keywords: Arid environment, CropSyst, Nitrogen, Optimization, Water productivity, Wheat

1. Introduction

Wheat (*Triticum aestivum* L.) is one of the most important cereals both in Iran and globally. In Iran, irrigated wheat occupies 35% of the total wheat lands. It grows mainly during dry seasons, where irrigation is necessary because precipitation in the growing season is far less than the crop water requirement. However, water resources are usually limited. Hence, irrigation scheduling is used to allocate irrigation water rationally in crop growing stages in order to maximize crop yield, water productivity and profit under the limited conditions. In addition, there is a synergy between fertilizer-nitrogen and water for their effects on wheat productivity more so in arid and semi-arid regions that generally experience N deficiency. However, both water and nitrogen are subjected to losses by many pathways if not managed properly. Consequently, there is a considerable interest in technologies that enhance nitrogen use efficiency and productive use of applied irrigation water leading to increased productivity.

Crop simulation models are nowadays widely applied in agriculture to make predictions about the agronomical, environmental and economic consequences of the complex interactions between crop weather, soil properties, and management factors (water and N) that influence crop productivity (Lewis *et al*., 2003; Gömann *et al*., 2005; Wise and Cacho, 2005). There are many possible applications of growth and water balance models to water and other input management (Hoogenboom 2000). Many of the models currently applied in precision agriculture have complex input requirements and are more detailed than necessary for certain applications. Using a simulation model, one can develop appropriate crop production strategies to increase yields, and to understand the links between climate variability, water availability and use, and agricultural management such as the amount and timing of N application, optimal sowing date, early and late flowering cultivar types, effect of pre-sown stored soil water and the interactive effects of all these factors on yield would require long and expensive field experiments.

Process-based crop models, such as CERES (Jones and Kiniry 1986), EPIC (Thomson *et al*., 2002), and WOFOST (Vandiepen *et al*., 1989) offer the option to estimate crop water use from simplified climate input, irrigation design, and initial soil water condition. The ability to simulate wheat yield by CERES-Wheat has been evaluated in a wide range of environments across the world under different management conditions (Kovács et al. 1995, Timsina et al. 1998, Pathak *et al*., 2006).

CropSyst (Cropping Systems Simulation Model) is a multiyear, multi-crop, daily time step crop growth simulation model, developed with emphasis on a friendly user interface, and with a link to GIS software and a weather generator (Stöckle and Nelson 1999; Stöckle *et al*., 2003). Despite the fact that wheat crop simulation models are now widely applied in monitoring and planning agricultural resources, CropSyst parameters for wheat are limited in the sense that they refer to older model versions (Giardini *et al*., 1998), to specific pedoclimatic environments (Pannkuk *et al*., 1998), and sometimes lack the complete list of crop parameters. The model has been widely applied to cereals and other cropping systems (Stöckle *et al*., 1994; Pala *et al*., 1996; Donatelli *et al*., 1997; Giardini *et al*., 1998; Pannkuk *et al*., 1998; Confalonieri and Bechini 2004; Wang *et al*., 2006; Benli *et al*., 2007; Singh *et al*., 2008).

However, reports on the validation of the CropSyst model under different water and N availability conditions in arid and semi-arid regions are very few (Pathak *et al*., 2006; Singh *et al*., 2008). Evaluations under different N management conditions, and water-nitrogen interactions in wheat crop have been done by Roberto et al. (2006) and Singh *et al*. (2008), respectively. Reports on the validation of CropSyst for crop growth and yield under Iranian conditions are scanty. Hence, a need was felt to validate the CropSyst model under various management situations. This paper provides an evaluation and application of the CropSyst model under variable irrigation and fertilizer N regimes in an arid region. The objective was to simulate winter wheat yield production responses to water- and N-applications for optimizing water productivity under water limitations in an arid sub-tropical irrigated environment. The study emphasizes strategies to maximize water productivity of wheat with the irrigation water and N application scenarios.

2. Materials and methods

2.1 Field experiments

The data used for model calibration and validation was obtained from a field experiment conducted at the Research Farm of Campus of Abouriahan (RFCA) (33°28´N; 50°58´E; elevation: 1180 m) during the 2001/02, 2002/03 and 2007/08 seasons. The climate of the study area is arid and subtropical with a mean annual temperature of 16.9 ^{o}C, and mean annual rainfall of 164 mm with more than 90% falling in the period from October to the next June. Winter wheat grows mainly in this period.

The soil at the experiment site was silty loam, with the bulk density of about 2620 kgm^{-3}. Soil characteristics referring to five genetic horizons selected from the soil survey are presented in Table 1. Soil pH ranged between 7.6 and 7.9, its sodium absorption rate between 1.4 to 1.8, and its electric conductivity was from 2.7 to 5.6 dS m^{-1}.

The experiment was designed as a randomized complete block (RCB) with four replications during three growing seasons. The experimental design incorporates, *Pishtaz,* a bread wheat cultivar which is widely adopted by farmers in the study area tested under four water regimes as the main plot treatments and three nitrogen levels as subplot treatments within each main plot. The water regime (water use) treatments included full irrigation (100% of crop water requirement-W3), and three levels providing 60% (W1), 80% (W2), and 120% (W4) of full irrigation. N management treatments were: the required nitrogen in the study area (N2), and 70% (N1) and 120% (N3) of the required nitrogen. The recommended N dose in this area is 140 kg ha^{-1}. Fertilizer N as urea was applied at 40 kg ha^{-1} at around three months after sowing (middle of March), 50 kg ha^{-1} at tillering and 40 kg ha^{-1} at booting stages (for N2 treatment). The soil residual mineralized nitrogen (NO3 and NH4) was considered as 66.2, 75.5, and 77.6 kg ha^{-1} for the three growing seasons, respectively. The source of the irrigation water was groundwater with a good quality (pH: 7.6; EC: 1.1 dS m^{-1}; SAR: 1.3). Also, harvesting was generally carried out around the beginning of June in the study seasons.

Daily rainfall was measured by a rain gauge in a weather station located in the experimental station. All other meteorological data include air temperature, relative humidity, and wind speed were measured at the weather station located in center of the experimental field (2001/02, and 2002/03) and at distance of 1.0 km from the plots (2007/08). The actual crop evapotranspiration (ET) or seasonal water use (SET) was estimated by water balance equation as follows (Allen et al., 1998):

$$ET=P + I \pm \Delta\theta \quad (1)$$

where P (mm) is the precipitation, $\Delta\theta$ the change in water storage (mm) in the soil profile, and I the irrigation water applied (mm). Other components of soil water balance, such as capillary rising, deep percolation, and surface runoff were ignored.

Soil water content was measured gravimetrically in the depth range of 0–200 and 200-400 mm and with a TDR-probe (Moisture Point MP-917 with a 150 mm, two-rod, single-diode probe) from 400 to 1000 mm depth at an interval of 200 mm on the before and one day after water application. Hydraulic conductivity was estimated by constant head permeameter (Jackson 1973).

Dates of important phenological events (emergence, panicle initiation, flowering and physiological maturity) were observed and thermal time for those stages was calculated as growing degree-days. Observations were taken for leaf area index (LAI); dry weight of stem, leaf and grain; number of tillers and leaves at four different crop growth stages. Also, organic carbon was determined by wet acid digestion method (Walkley and Black 1934).

2.2 Model description and calibration

CropSyst was designed as a management-oriented cropping system model able to simulate a range of weather/management scenarios (Stöckle and Nelson 1999; Stöckle *et al.,* 1994, 2003). The model simulates the soil water budget, soil-plant nitrogen budget, crop canopy and root growth, dry matter production, yield, residue production and decomposition, and soil erosion. Management options include: cultivar selection, crop rotation (including fallow years), irrigation, nitrogen fertilization, tillage operations and residue management (Confalonieri and Bechini 2004). The most important model inputs are: daily weather data, dates and amounts of products applied for each fertilization and irrigation event, sowing date, hydraulic characteristics of the soil profile, crop parameters, and initial conditions of the soil profile (crop residues, water content, mineral nitrogen and organic matter).

In this study, grass reference evapotranspiration was calculated with the Priestley-Taylor equation. Soil water redistribution was simulated with the cascade sub-model. For parameterization of the model, thermal time accumulation for different phenological stage (emergence, peak LAI, flowering, grain filling and physiological maturity) were estimated from the base temperature, cutoff temperature and daily mean air temperature (Stöckle and Nelson 1996). Other crop parameters were derived manually by changing 5% of the default value of each crop parameter till a satisfactory level of agreement between predicted and observed value of grain yield, and biomass was achieved. A few parameters accounting for cultivar-specific differences were calibrated based on outputs of growth characteristics, patterns of water use, and minimization of differences between actual and simulated yields for a limited number of simulation trials, using available field measurements, and they were adjusted within a reasonable range as provided by the manual. Weather, soil, management, and initialization parameters as observed in the experiment were input. For calibration of the model, the N2 and W3 treatment was considered, and the rest of data were used for model validation.

2.3 Validation and statistical analysis

The model was subsequently validated for the site conditions using other treatment data and using the crop model parameter values calibrated as mentioned above with associated water management. Soil characteristics, initial conditions of available soil water, nitrogen and organic matter and daily weather data were model input data for CropSyst as observed in the experiments.

Model evaluation and validation was conventionally made by comparing simulation outputs with observed and simulated data. Two different groups of test criteria, called summary measures and difference measures have been used to evaluate the performance evaluation of the model. While summary measures describe the quality of simulation, difference measures try to locate and quantify errors. Summary measures include the mean of observed and predicted values. The difference measures include the mean absolute error (*MAE*), the root mean square error (*RMSE*), and the Wilmot (1982) index of agreement (*IoA*) were used to evaluate the model.

2.4 Model application

After promising results from the model calibration and validation on the 3-year experimental period, we decided to apply different scenarios for predicting the best water and N application practices for maximization of wheat grain yield and water productivity. Scenarios included various options of 30% to 130% of the required crop water and 0% to 130% of the required nitrogenous fertilizer.

3. Results

3.1 Weather conditions during the crop growing period

For all experimental seasons, there was inadequate rainfall for seed germination in October, following sowing, with a total annual amount of 79.5, 156.4 and 106.8 mm for 2001/02, 2002/03 and 2007/08, respectively (Table 2). Mean maximum and minimum air temperatures were slightly higher than the long-term average (35.7 and 12.8 ^oC) during the 3 years of study (35.8 and 19.2 ^oC during the first season; 35.9 and 19.9 ^oC during the second season; and 36.7 and 20.3 ^oC during the third season). The coolest months were January and February. In the 2007/08, minimum air temperature reached to -9.0 ^oC during January, which was the coolest month in the experimental seasons.

3.2 Model calibration

Crop coefficients required for CropSyst model are presented in Table 4. With a base temperature of 1°C and cutoff temperature of 20°C, the leaf duration was found to be 1200 °C day. Thermal time for peak leaf area index was found to be 1300 °C day that for physiological maturity was 1700 °C day. Specific leaf area was fixed at 22 $m^2 kg^{-1}$, a stem to leaf partitioning coefficient of 3 used and the unstressed harvest index was fixed at 0.42. The model provided very satisfactory estimates for flowering, for example, 109 days after sowing (DAS) as against observed date of 111 DAS during 2007-08. The physiological maturing date (165 DAS) was the same as the observed date. For all crop growing seasons, prediction of dates were good. Similar results were reported by Singh *et al*. (2008) for the New Delhi area. The calibrated crop model parameters are shown in Table 3. The results indicated that grain yield, biomass and maximum LAI prediction was satisfactory.

3.3 Validation of model

The validation results of the model are described under the following sub-headings:

3.3.1 Seasonal ET

The simulated seasonal ET closely corresponded with the measured values for most of the water and fertilizer N regimes in different seasons. For example, the RMSE value of 33.7, 19.5, 17.9, and 56.3 mm and MAE of 26.0, 18.9, 17.9, and 51.9 mm were observed in the predictions of seasonal ET across the three N treatments for W1, W2, W3, and W4 water regimes in 2007-08, respectively (Table 5). The simulated response of ET to irrigation and N regimes had a trend similar to the measured response. Prediction of seasonal ET by the model was satisfactory for each of the four water regimes with significant R^2 (>0.84) and *IoA* values (>0.97) (Table 5). The normalized *RMSE* was 7.5% under variable irrigation and fertilizer N regimes in different cropping seasons.

The highest seasonal ET was recorded in W4 water regime while the least seasonal ET was recorded in W1 water regime during all seasons. This was expected since the W4 had regularly a full irrigated while the W1 experienced limited water supply. The measured seasonal ET varied between 263.2 and 598.5 mm for treatments during the seasons. The highest seasonal ET was recorded in treatment of W4, during 2002/03 while the least seasonal ET was recorded in treatments of W1 during 2001/02 (263.2 mm).

3.3.2 Grain yield

Grain yield simulation results showed that predictions using CropSyst were satisfactory for each of the four water regimes and combined water regimes in the growing seasons with high R^2 (>0.84; pooled) and *IoA* (>0.92; pooled) (Table 6). The results demonstrated that model responded well to the measured N application rates (Fig. 1). Predicted grain yields under all N application rates during different seasons followed the same trend as measured except for the W1 water regime. For example, N1, N2, and N3 in W1 water regime in 2001/02 deviated from the measured trend by 15.30, 33.60 and 37.20%, respectively (Table 7). Consequently, predictions of grain yield tended to be quite accurate in general, though under severe water deficits precision was lower.

Departure of predictions from observed values were 6.0, 4.4, 5.0% for the N1, N2, and N3 experiments, respectively, in W4 water regime during this season (Table 7). Grain yields in W2 water regime were also well predicted by the model in this season, except for the N3 treatment, falling within one standard deviation of the observations (Fig. 1). The deviations of simulations from the observations in this water regime were 7.10, 3.90, and 15.50% for the N1, N2, and N3 treatments, respectively (Table 7). Model predictions for W3 water regime were also accurate except with a slight underestimation in N2 treatments during 2007-08 (Fig. 1). Predictions departed from the observations in this water regime by 2.5, 13.0, and 6.8% for the N1, N2, and N3 treatments, respectively. *RMSE* value of 0.41, 0.33, and 0.34 Mg ha^{-1} and *MAE* of 0.29, 0.27, and 0.33 Mg ha^{-1} were observed in the predictions of grain yields across the three N treatments and four water regimes during the first, second, and third growing season, respectively (Table 6). The normalized *RMSE* was 9.0% under variable irrigation and fertilizer N regimes in different cropping seasons.

3.3.3 Biomass

Prediction of biomass by the model was satisfactory with significant R^2 (>0.84; pooled) and IoA values (> 0.94; pooled) for each of the four water regimes and combined water regimes in the growing seasons (Table 8). Biomass simulation results also showed that it responded well to measured N application rates (Fig. 2). Model predictions of biomass also followed a similar trend as grain yield discussed above. Deviations were 3.4, 2.9, and 2.3% for the N1, N2, and N3 experiments, respectively, in W3 water regime during 2001-02 (Table 9). Deviations of predicted biomass from observed for W1 water regime were 16.1, 18.2, and 17.0% for the N1, N2, and N3 treatments, respectively, during this season. Model predictions for W1 water regime were less accurate in all N treatments during 2007-08. Similar grain yield and biomass predictions tended to be quite accurate in general, though under severe water deficits precision was lower.

Predictions departed from the observations in this water regime by 9.8, 8.3, and 16.2% for the N1, N2, and N3 treatments, respectively (Table 9). In general, biomass predictions by the model were in the same agreement with the observed values in all seasons (*IoA* = 0.97). A *RMSE* of 0.79, 1.14, and 0.76 Mg ha^{-1} and *MAE* of 0.63, 0.86, and 0.54 Mg ha^{-1} were observed in the predictions of biomass across the three N treatments and four water regimes during the first, second, and third growing season, respectively. The normalized *RMSE* was 8.0% under variable irrigation and fertilizer N regimes in different cropping seasons.

In this model, the water and nitrogen budgets interact to produce a simulation of N transport within the soil (Stöckle *et al*., 1994) and thus predict N transport correctly. Correct N uptake resulted in good prediction of N response to grain yield and biomass. Stöckle *et al*. (1994) also found good agreement between simulated and observed biomass and yield of winter wheat and spring wheat grown in two locations with a total of 77 data points.

4. Discussion

4.1 Water productivity indices

Water productivity may be calculated as follows:

$$WP_{ET}=Y / ET \quad (2)$$

$$WP_{I}=Y / I \quad (3)$$

where WP_{ET} is the ET water productivity, Y is the grain yield (kg ha^{-1}), and WP_I is the irrigation water productivity. Both WP_I and WP_{ET} are also considered as productivity of irrigation water and water use efficiency, respectively.

The results indicated that WP_I was influenced by irrigation and nitrogen fertilizer strategies (Table 10). Deficit irrigation effectively boosted irrigation water productivity. Generally, water productivity decreases with increase in irrigation as grain yield is less than proportional increase in ET. The highest WP_I, 2.15 kg m^{-3}, was achieved under deficit irrigation (W1) and N2 strategies in 2002-03, indicating that the irrigation water and nitrogen were most efficiency used in this treatment. Similar results were reported by earlier researchers working with deficit irrigation of wheat and other crops (Oweis et al., 2000; Zhang et al., 2004; Ali et al. 2007). The lowest WP_I, 0.79 kg m^{-3}, was obtained under the greatest irrigation amount (W4) and lowest N1 strategy in 2007-08. Thus, it may be concluded that a high level of applied water and low N rate effectively decreases the productivity of wheat.

Table 11 shows the observed and predicted values of WP_I and WP_{ET} across the three N regimes and water regimes during the third season. As a result, predictions of WP_I were more appropriate than WP_{ET}. The mean absolute deviations of predicted from observed were 6.7% and 11.1% for WP_I and WP_{ET}, respectively. A good agreement and the similar trend were found between simulated and observed water productivity indices of winter wheat in the others seasons data (Fig. 3). The mean predicted and observed WP_I were determined as 1.50 and 1.48 kg m^{-3}, respectively. The highest WP_I (2.15 kg m^{-3}) was predicted under W3 regime during 2002-03. Under the climate condition in this growing season, a medium water status, and irrigation water regime (i.e., 294 mm), a field water balance status was suitably provided. However, crop yield and water productivity were strongly influenced by the climate variability and irrigation scenario under nitrogen management during the season.

4.2 Model application scenarios

Fig. 4 and 5 show the simulation results of different options tried for predicting the best water and N application practices for maximization of grain yield and water productivity, respectively. The predicted grain yield, WP_I and WP_{ET} as functions of applied water and N scenarios (percent of the required water and N) were presented. The scenarios of 30% to 130% of required water and 0% to 130% of required nitrogenous fertilizer were considered. The best options were application of water and nitrogenous fertilizer in 100% and 110% of the demand values, respectively, for maximization grain yield (8.29 Mg ha^{-1}). Also, the best options were application of water and nitrogenous fertilizer in 70% and 90% of the required values, respectively, for WP_I, and equal to the required values (100%) for WP_{ET}. The highest WP_I and WP_{ET} were predicted 2.07 and 1.49 kg m^{-3}, respectively (Fig. 5).

For the proposed scenarios, WP_I and WP_{ET} ranged from 0.16 to 2.07 kg m^{-3}, and from 0.07 to 1.49 kg m^{-3}, respectively. A large range of the indices was due to the interactions effects of irrigation and fertilizer N management on grain yield and water productivity, which influenced by soil water and mineral-N status. It is interesting to note that the WP_I value in the full irrigation and N option (100% for both), 1.95 kg m^{-3}, was equal to the full N and deficit irrigation as 25% of full irrigation option. Generally, WP_I had an increased sensitivity to N and irrigation regimes than $WP_{ET.}$

Maximum WP_I and WP_{ET} values as affected by irrigation and fertilizer-nitrogen management scenarios

In arid and semi-arid regions where water is limited, small amounts of irrigation water can make up for the deficits in seasonal rain and produce satisfactory and sustainable yields. The findings of the research indicate that use efficiency for water and nitrogen was greatly increased by deficit irrigation. Consequently, when limited supplemental irrigation is combined with N fertilizer appropriate management, wheat water productivity may be substantially and consistently increased in the region.

The most dramatic implication from this study is the saving in irrigation water with little loss in yield. The crop yield increases with applied N are expected, given the long established relationship between N and soil moisture (Ramig and Rhoades 1962). The response of WP_{ET} to total ET is similar to the relationship derived in Liu *et al*. (2005) and Chen *et al*. (2009).

The data generated here indicated that under no applied N fertilizer (N=0%), wheat productivity increases with increase in applied water but not more than a grain yield of 3.2 Mg ha^{-1}. It was shown that at 112 kg ha^{-1} fertilizer N (N=80%) with deficit irrigation as 50% of full irrigation option, this grain yield value may be achieved. The highest grain yield was predicted 8.17 Mg ha^{-1} at 182 kg ha^{-1} fertilizer N (N=130%) with over irrigation as 10% of full irrigation regime.

A currently wheat productivity of 5.0 Mg ha^{-1} is obtained with the local farmers. The simulations demonstrated that this production can be achieved at 140 kg ha^{-1} fertilizer N (N=100%) and 30% deficit irrigation regime. For this scenario, a WP_I of 1.73 kg m^{-3} was estimated. The results demonstrated that in the deficit irrigation regimes, the applied water value had a significant impact on the wheat productivity, more than N fertilizer (see zones of I and II in Fig. 4). While, in the full or over of the required water, N fertilizer value had a significant impact on the grain yield, more to than applied water (see zones of III and IV in Fig. 4).

Irrigation and N fertilizer management as shown in this study improves efficiency in water use, and thus reduces the impact of limited water. The results of the study provide an information base for making irrigation and N management decisions in the study area. It may be concluded that with fewer input parameters and less complex calibration procedures, CropSyst can be applied for simulating effect of N and water management on growth, yield and water productivity of wheat under Iranian subtropical conditions. It was also demonstrated that the model can be used to derive best management options in terms of N and irrigation application.

5. Conclusions

Water deficit is an important constraint for wheat yield generation under arid environments. Also, nitrogen availability could limit yield in a more important way than poor water conditions. In this study, the CropSyst crop simulation model was calibrated, validated, and used as a tool to provide estimates of climatically-driven potential yield, yield production, water balance components, and WP_I and WP_{ET} of wheat under a range of N fertilizer and water regimes in an arid region of Iran. Predictions of grain yield and biomass tended to be quite accurate in general, although under severe water deficits precision was lower. Consequently, it may be concluded that a high level of applied water and low N rate effectively decreases the productivity of wheat. Predictions of WP_I were more appropriate than WP_{ET}. The results indicated that the WP_I and WP_{ET} indices were strongly influenced by irrigation and nitrogen fertilizer strategies. Generally, water productivity decreases with increase in irrigation as grain yield is less than proportional increase in ET. The mean absolute deviations of predicted from observed were 6.7% and 11.1% for WP_I and WP_{ET}, respectively, across the N treatments and water regimes during the growing seasons. The highest WP_I, 2.15 kg m^{-3}, was predicted under W3 regime during 2002/03.

Among different options tried for predicting the best N and water application practices for maximization of water productivity, the best option found by the model was application of water and nitrogenous fertilizer in 70% and 90% of the required values, respectively, for WP_I, and equal to the demand values (100%) for WP_{ET} (Table 12). For the proposed scenarios, WP_I and WP_{ET} ranged from 0.16 to 2.07 kg m^{-3}, and from 0.07 to 1.49 kg m^{-3}, respectively. The wide range in the indices was due to the interactions effects of irrigation and fertilizer N management on grain yield and water productivity, which influenced by soil water and mineral-N status. It is interesting to note that the WP_I value in the full irrigation and N practice (100% for both), 1.95 kg m^{-3}, was equal to the full N and deficit irrigation as 25% of full irrigation practice (Table 12). Generally, WP_I had increased sensitivity to N and irrigation regimes compared to $WP_{ET.}$ Simulations demonstrated that the current wheat productivity of 5.0 Mg ha^{-1} obtained by the local farmers can be achieved using 140 kg ha^{-1} fertilizer N (N=100%) and 30% deficit irrigation regime. For this scenario, a WP_I of 1.73 kg m^{-3} was estimated. This analysis has implications for improving wheat water productivity under dry-land and limited water scenarios. It may be concluded that with fewer input parameters and less complex calibration procedures, CropSyst can be applied for simulating the effect of N and water management on growth, yield and water productivity of wheat under Iranian subtropical conditions. It was also demonstrated that the model can be used to derive best management options in terms of N and irrigation application.

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Table 1. Soil characteristics of the study site

Soil parameters	Soil depth				
Genetic horizon (mm)	0-200	200-400	400-600	600-800	800-1000
Texture	Silty loam	Silty loam	Silty loam	Silty loam	Silty loam
Sand (%)	20.2	34.1	36.2	27.2	26.0
Silt (%)	74.8	60.9	58.8	65.8	67.0
Clay (%)	5.0	5.0	5.0	5.0	5.0
pH	7.9	7.7	7.6	7.6	7.6
EC (dSm^{-1})	2.74	4.15	5.61	4.09	4.70
Bulk density (kg m^{-3})	2600	2620	2640	2640	2630
Cation exchange capacity (meq/1000g)	10.4	9.2	9.0	8.0	8.0
Organic matter (%)	1.35	0.75	0.15	0.15	0.6
Organic C (%)	3.09	1.64	0.34	0.34	1.37

Table 2. Weather data for the three study seasons and for the long term

Season	2001/2002				2002/2003				2007/2008				Long-term [a]			
	P (mm)	Tmax (°C)	Tmin (°C)	RH (%)	P (mm)	Tmax (°C)	Tmin (°C)	RH (%)	P (mm)	Tmax (°C)	Tmin (°C)	RH (%)	P (mm)	Tmax (°C)	Tmin (°C)	RH (%)
October	0	27.4	12.3	40.9	21.5	30.1	16.0	35.2	0.3	30.3	0	33.3	9.6	26.2	6.0	49.7
November	2.5	18.2	5.4	46.2	8.0	18.6	7.0	50.8	6.7	21.6	6.6	43.9	9.3	17.6	-1.8	59.1
December	0	13.6	3.3	64.0	25.5	9.0	0.4	63.0	0.0	11.2	1.1	69.0	15.0	11.9	-4.7	67.1
January	13	10.4	0.9	61.5	15.0	11.9	0.2	55.7	3.4	1.0	-9.0	71.2	19.6	10.2	-6.7	65.4
February	0	15.6	1.6	45.7	20.7	12.3	2.0	56.4	13.3	10.0	0.3	63.6	19.5	12.9	-5.4	58.2
March	15	20.7	6.5	38.1	41.5	16.4	4.5	48.9	0.1	23.5	9.2	33.2	32.6	16.3	-2.8	52.4
April	49	21.6	10.3	50.9	45.5	22.5	11.2	52.7	2.2	26.0	12.4	34.0	22.4	23.9	2.7	46.8
May	5	29.6	14.4	33.0	8.6	28.4	13.4	37.6	1.6	30.0	14.4	31.9	10.5	29.5	7.1	42.1
June	0	35.8	19.2	22.1	0.0	35.9	19.9	27.3	0.0	36.7	20.3	31.7	0.8	35.7	12.8	36.3

[a] Average parameters for long-term (1978–2007)

Table 3. Genetic coefficients derived using CropSyst for wheat variety *Pishtaz*

Variable	Value	Units
Base temperature	1	°C
Cutoff temperature	20	°C
Leaf duration	1200	°Cday
Begin flowering	120	°Cday
Peak LAI	1300	°Cday
Begin grain filling	1400	°Cday
Physiological maturity	1700	°Cday
Maximum rooting depth	1.2	m
Maximum water uptake	10	$mmday^{-1}$
Maximum expected leaf area index (LAI)	4.12	m^2m^{-2}
Fraction of max. LAI at physiological maturity	0.6	0-1
Specific leaf area	22	m^2kg^{-1}
Stem/leaf partition coefficient	3	-
Above ground biomass transpiration coefficient	6.1	kPa kgm^{-3}
Light to above ground biomass conversion	3.1	gMJ^{-1}
Optimum mean daily temperature for growth	25	°C
Leaf water potential at the onset of stomata closure	-1400	$-Jkg^{-1}$
Wilting leaf water potential	-2100	$-Jkg^{-1}$
Extinction coefficient for solar radiation	0.51	-
Unstressed harvest index	0.42	-

Table 4. Calibration results of CropSyst model

Parameters	2001/02		2002/03		2007/08	
	Predicted	Observed	Predicted	Observed	Predicted	Observed
Flowering date (DAS)	110	113	112	113	109	111
Grain filling date (DAS)	122	123	128	128	124	124
Physiological maturing date (DAS)	164	164	168	168	165	165
Grain yield (Mg ha^{-1})	6.71	6.58	7.07	6.89	6.76	6.65
Biomass at harvest (Mg ha^{-1})	16.98	16.87	17.13	16.94	17.01	16.87
Maximum LAI ($m^2 m^{-2}$)	3.93	4.00	3.97	4.05	3.91	4.03

Table 5. Statistical indices derived for evaluating the performance of the model in predicting seasonal ET (2007-08)

Treatment	P_{mean} (mm)	O_{mean} (mm)	n	*RMSE* (mm)	*MAE* (mm)	*IoA*	R^2
W1	259.6	270.9	3	33.7	26.0	0.99	0.84
W2	365.9	384.8	3	19.5	18.9	0.98	0.88
W3	488.0	483.2	3	17.9	17.9	0.97	0.93
W4	633.4	581.5	3	56.4	51.9	0.97	0.97
Combined	436.7	430.1	12	28.3	28.3	0.99	0.99

P_{mean}: mean of predicted value, O_{mean}: mean of observed value, n: number of observations, R^2: coefficient of determination.

Table 6. Statistical indices derived for evaluating the performance of the model in predicting grain yield

Treatment	Season	P_{mean} (Mg ha^{-1})	O_{mean} (Mg ha^{-1})	n	*RMSE* (Mg ha^{-1})	*MAE* (Mg ha^{-1})	*IOA*	R^2
W1	2001-02	1.91	2.66	3	0.75	0.81	0.96	0.86
W2		3.81	3.85	3	0.33	0.36	0.92	0.88
W3		5.79	5.46	3	0.34	0.35	0.99	0.99
W4		5.09	5.03	3	0.25	0.25	0.99	0.99
W1	2002-03	3.81	3.35	3	0.71	0.74	0.97	0.97
W2		4.50	4.69	3	0.37	0.37	0.95	0.85
W3		7.10	6.67	3	0.44	0.43	0.98	0.99
W4		6.21	6.18	3	0.25	0.24	0.99	0.96
W1	2007-08	3.60	2.86	3	0.75	0.74	0.94	0.84
W2		3.57	4.06	3	0.50	0.49	0.94	0.86
W3		6.17	5.77	3	0.54	0.46	0.98	0.93
W4		5.94	5.35	3	0.62	0.59	0.96	0.85
Combined	2001-02	4.15	4.25	12	0.41	0.29	0.97	0.90
	2002-03	5.4	5.22	12	0.33	0.27	0.98	0.94
	2007-08	4.57	4.51	12	0.34	0.33	0.98	0.87

P_{mean}: mean of predicted value, O_{mean}: mean of observed value, n: number of observations, R^2: coefficient of determination.

Table 7. Absolute percent deviation between observed and predicted grain yield

Water regime		N-levels		
		N1	N2	N3
W1	2001-02	15.3	33.6	37.2
	2002-03	23.9	21.7	19.0
	2007-08	27.0	18.9	36.8
W2	2001-02	7.2	3.9	15.5
	2002-03	6.1	8.1	9.0
	2007-08	14.8	7.6	15.2
W3	2001-02	6.0	8.0	4.8
	2002-03	7.0	8.0	5.0
	2007-08	2.5	13.0	6.8
W4	2001-02	6.0	4.4	5.0
	2002-03	4.4	2.7	5.1
	2007-08	9.6	11.9	10.8

Table 8. Statistical indices derived for evaluating the performance of the model in predicting Biomass

Treatment	Season	P_{mean} (Mg ha^{-1})	O_{mean} (Mg ha^{-1})	n	*RMSE* (Mg ha^{-1})	*MAE* (Mg ha^{-1})	*IoA*	R^2
W1	2001-02	9.95	8.5	3	1.48	1.45	0.95	0.99
W2		10.56	11.04	3	1.02	0.98	0.94	0.97
W3		15.30	14.88	3	1.24	1.22	0.99	0.99
W4		14.81	14.62	3	1.21	1.29	0.97	0.90
W1	2002-03	12.74	10.77	3	1.99	1.97	0.95	0.99
W2		14.02	13.99	3	0.99	0.89	0.94	0.86
W3		19.14	18.77	3	1.24	1.22	0.97	0.90
W4		19.43	18.34	3	1.13	1.09	0.98	0.99
W1	2007-08	9.50	9.26	3	1.00	0.99	0.99	0.87
W2		11.88	12.03	3	0.50	0.49	0.98	0.84
W3		15.92	16.22	3	1.35	1.33	0.96	0.92
W4		16.22	15.92	3	1.66	1.47	0.96	0.88
Combined	2001-02	12.65	12.26	12	0.79	0.63	0.97	0.89
	2002-03	16.33	15.47	12	1.14	0.86	0.97	0.94
	2007-08	13.67	13.36	12	0.76	0.54	0.98	0.97

P_{mean}: mean of predicted value, O_{mean}: mean of observed value, n: number of observations, R^2: coefficient of determination.

Table 9. Absolute percent deviation between observed and predicted biomass

Water regime		N-levels		
		N1	N2	N3
W1	2001-02	16.1	18.2	17.0
	2002-03	18.0	18.0	19.0
	2007-08	9.8	8.3	16.2
W2	2001-02	8.2	6.3	13.6
	2002-03	2.3	6.4	11.0
	2007-08	5.1	2.7	4.7
W3	2001-02	3.4	2.9	2.3
	2002-03	9.0	7.2	4.0
	2007-08	7.0	10.0	7.5
W4	2001-02	5.0	9.7	9.0
	2002-03	7.1	4.0	7.2
	2007-08	7.9	14.9	5.3

Table 10. Water productivity,WP_I, by treatments (kg m^{-3})

Water regime		N-levels		
		N1	N2	N3
W1	2001-02	1.35	1.69	0.98
	2002-03	1.72	2.15	1.21
	2007-08	1.23	1.47	0.86
W2	2001-02	1.34	1.69	1.34
	2002-03	1.61	2.07	1.65
	2007-08	1.15	1.48	1.18
W3	2001-02	1.18	1.71	2.15
	2002-03	1.45	2.11	2.50
	2007-08	1.04	1.51	1.77
W4	2001-02	0.91	1.59	1.29
	2002-03	1.11	1.97	1.60
	2007-08	0.79	1.41	1.14

Table 11. Observed and predicted values of WP_I and WP_{ET} during 2007-08

Water regimes	WP_I (kg ha^{-1})		WP_{ET} (kg ha^{-1})	
	Predicted	Observed	Predicted	Observed
W1	1.12	1.19	0.52	0.71
W2	1.38	1.27	0.45	0.81
W3	1.54	1.44	1.18	1.2
W4	1.17	1.11	0.88	0.95

Table 12. Maximum WP_I and WP_{ET} values as affected by irrigation and fertilizer-nitrogen management practices

<table>
<tr><th>Nitrogen practice</th><th colspan="2">Irrigation practice</th><th colspan="2">Irrigation practice</th></tr>
<tr><th>Percentage of the required N fertilizer</th><th>Percentage of the required water</th><th>Max. WP_I (kg m^{-3})</th><th>Percentage of the required water</th><th>Max. WP_{ET} (kg m^{-3})</th></tr>
<tr><td>0</td><td rowspan="7">80</td><td>0.84</td><td rowspan="10">80</td><td>0.85</td></tr>
<tr><td>5</td><td>0.92</td><td>0.92</td></tr>
<tr><td>10</td><td>1.02</td><td>0.98</td></tr>
<tr><td>15</td><td>1.03</td><td>0.99</td></tr>
<tr><td>20</td><td>1.12</td><td>1.04</td></tr>
<tr><td>25</td><td>1.18</td><td>1.07</td></tr>
<tr><td>30</td><td>1.24</td><td>1.11</td></tr>
<tr><td>35</td><td rowspan="4">70</td><td>1.29</td><td>1.12</td></tr>
<tr><td>40</td><td>1.35</td><td>1.14</td></tr>
<tr><td>45</td><td>1.43</td><td>1.35</td></tr>
<tr><td>50</td><td>1.51</td><td>70</td><td>1.16</td></tr>
<tr><td>55</td><td rowspan="3">75</td><td>1.54</td><td rowspan="3">75</td><td>1.20</td></tr>
<tr><td>60</td><td>1.53</td><td>1.17</td></tr>
<tr><td>65</td><td>1.52</td><td>1.14</td></tr>
<tr><td>70</td><td rowspan="2">80</td><td>1.50</td><td>90</td><td>1.13</td></tr>
<tr><td>75</td><td>1.59</td><td rowspan="4">80</td><td>1.19</td></tr>
<tr><td>80</td><td rowspan="2">75</td><td>1.57</td><td>1.16</td></tr>
<tr><td>85</td><td>1.72</td><td>1.23</td></tr>
<tr><td>90</td><td>70</td><td>2.07</td><td>1.27</td></tr>
<tr><td>95</td><td>75</td><td>1.95</td><td>90</td><td>1.39</td></tr>
<tr><td>100</td><td rowspan="2">85</td><td>2.05</td><td rowspan="4">100</td><td>1.49</td></tr>
<tr><td>105</td><td>2.03</td><td>1.54</td></tr>
<tr><td>110</td><td rowspan="2">100</td><td>2.05</td><td>1.55</td></tr>
<tr><td>115</td><td>2.00</td><td>1.47</td></tr>
<tr><td>120</td><td>90</td><td>2.00</td><td>105</td><td>1.41</td></tr>
<tr><td>125</td><td>95</td><td>2.03</td><td>100</td><td>1.44</td></tr>
<tr><td>130</td><td>100</td><td>1.97</td><td>105</td><td>1.42</td></tr>
</table>

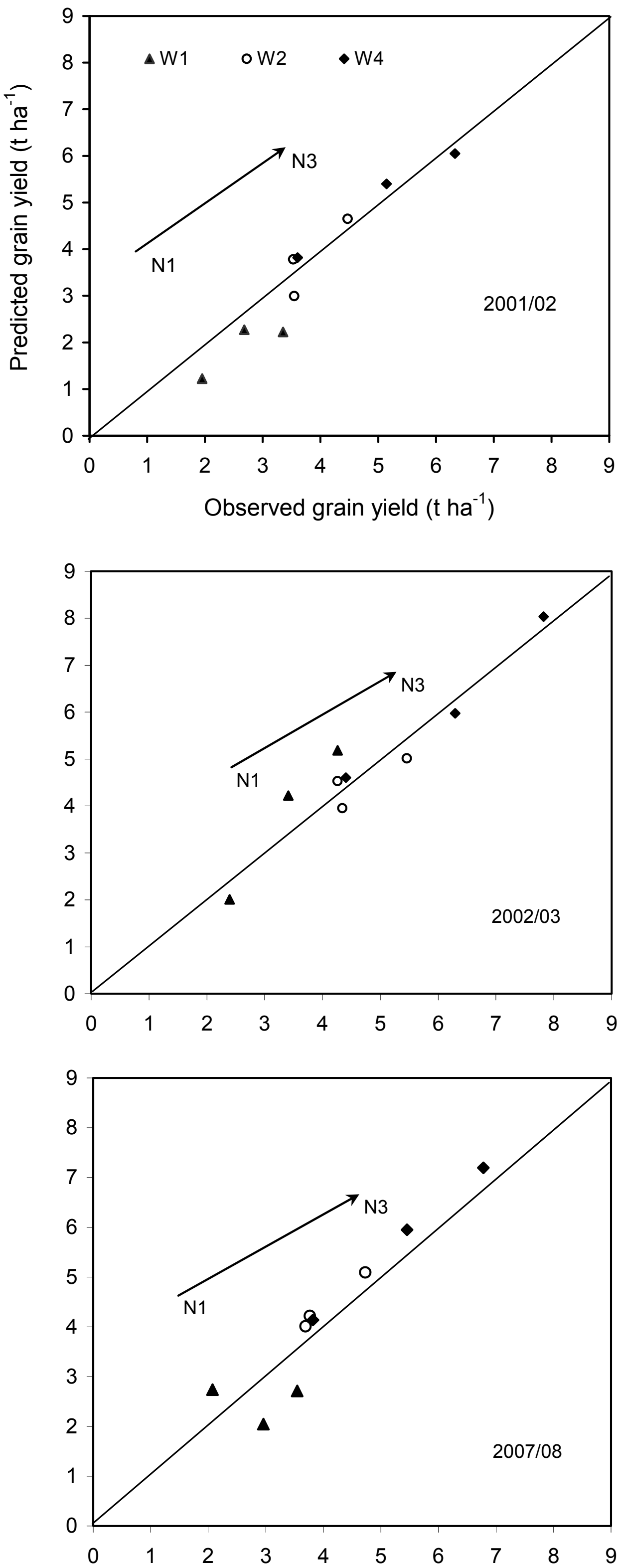

Figure 1. Validation of model for grain yield under different water regimes and N treatments in growing seasons

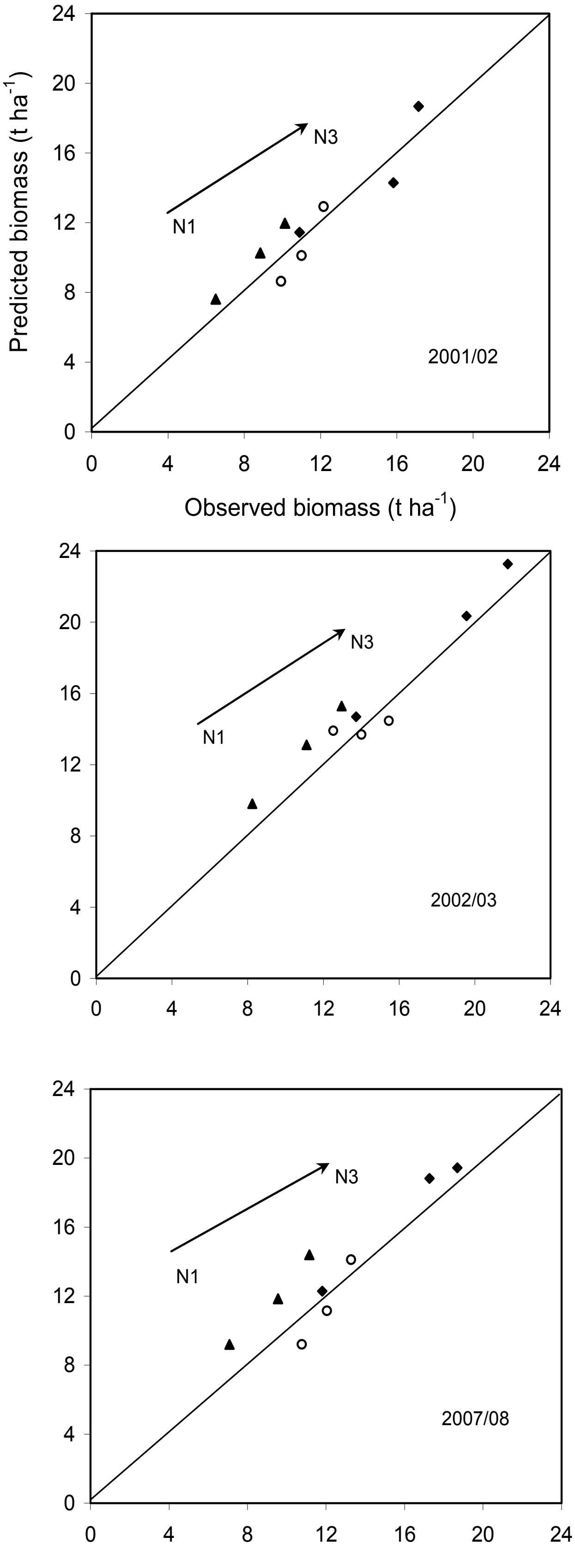

Figure 2. Validation of model for biomass under different water regimes and N treatments in growing seasons

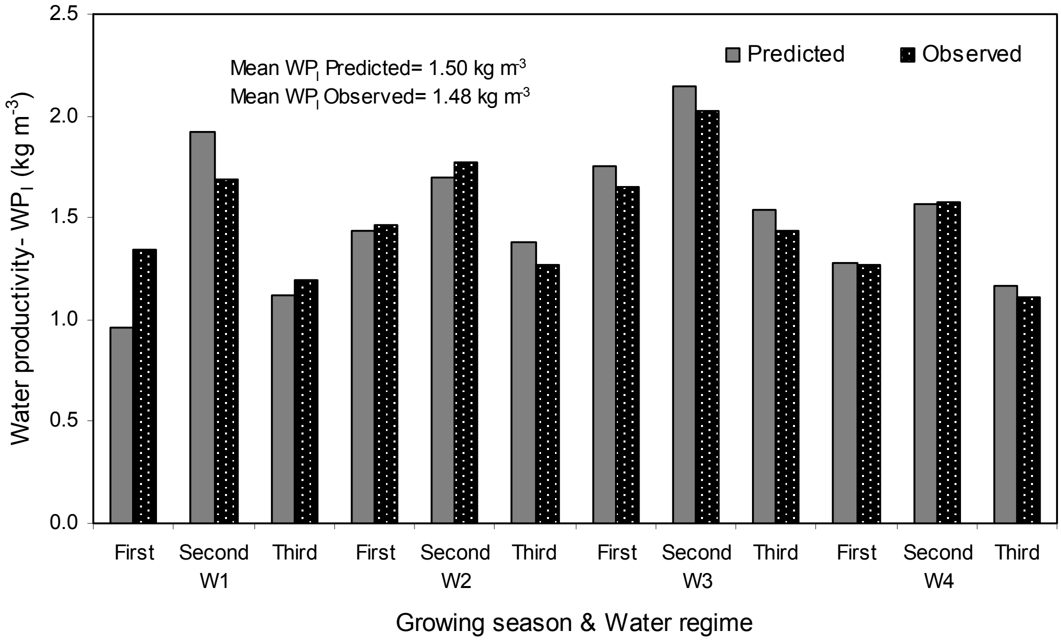

Figure 3. Predicted and measured water productivity of wheat for the growing seasons and water regimes

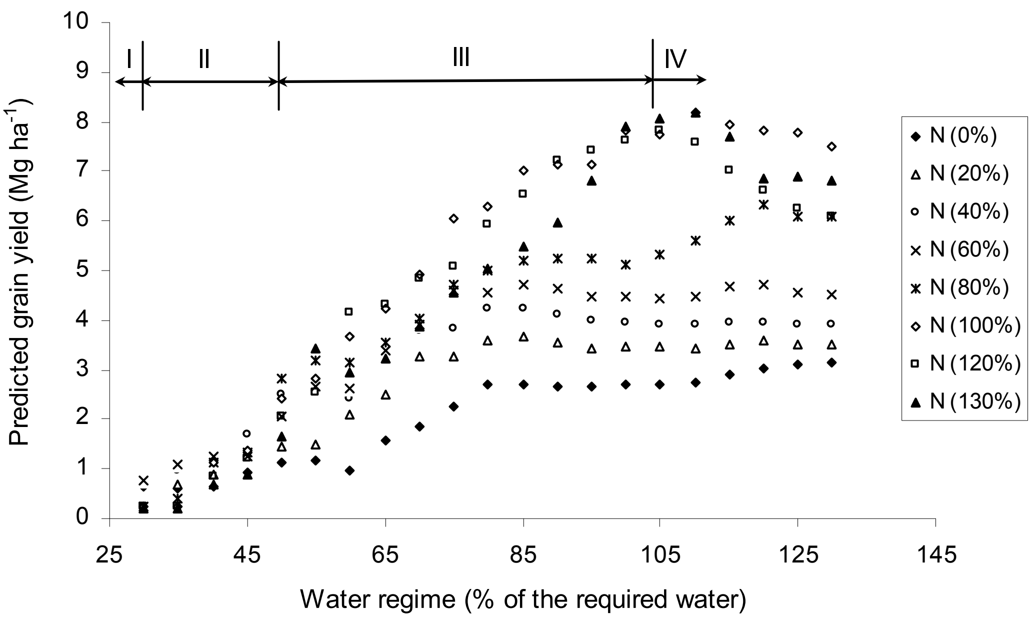

Figure 4. Simulated grain yield of wheat under various water regime and N management situations

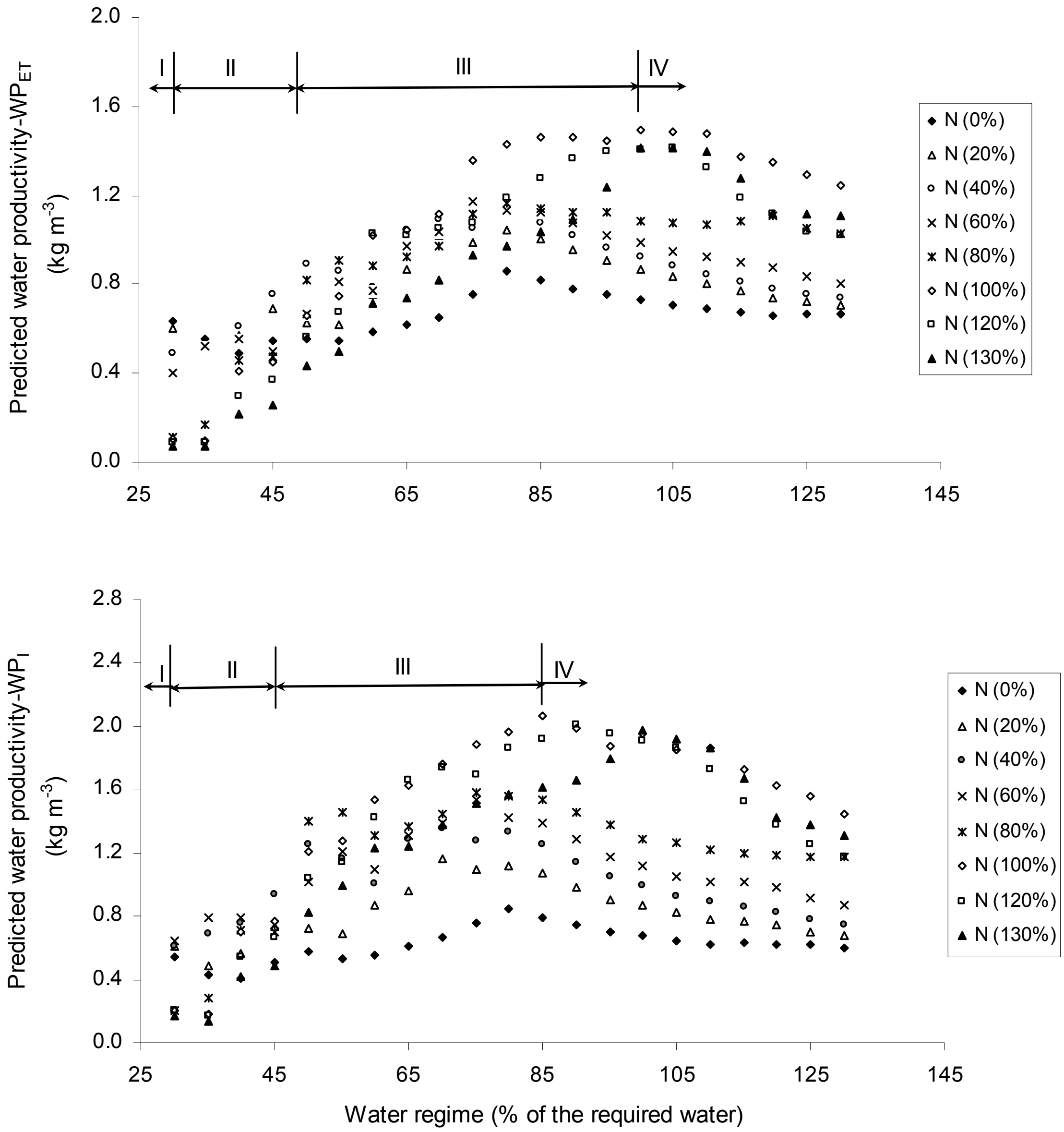

Figure 5. Simulated WP_I and WP_{ET} of wheat under various water regime and N management situations