African Journal of Biotechnology Vol. 11(23), pp. 6368-6376, 20 March, 2012
Available online at http://www.academicjournals.org/AJB
DOI: 10.5897/AJB11.2820
ISSN 1684–5315 © 2012 Academic Journals

Full Length Research Paper

New approach for regional crop yield gap analysis in the Borujen Plain, Iran

A. Ghanbari[1*] and J. Taei-Semiromi[2]

Department of Agronomy. Faculty of Agriculture, University Of Zabol. Zabol, Iran;

Accepted 17 January, 2012

This study was performed to analyze the regional crop yield gap for potential and water-limited production situations in the cold-semiarid climate at Borujen basin, Iran. Experimental data were used for model calibration and evaluation of WOFOST as a crop growth simulation model. WOFOST divides wheat growth into three key development stages: 1) emergence, 2) flowering and 3) physiological maturity. The length of growth period and phenology was calibrated using the field experiments results. In general, simulated results matched well with the measured parameters in the calibration procedure. Calibrated results of WOFOST model are linked to a geographic information system, in order, to get easier their presentation and also to contribute to identification of hotspots for interventions aimed at yield improvements. Finally, the results of quantitative analysis (yield estimation in different wheat cropping systems) performed on four different agro-ecological zones, include: 1) yield gaps = 4.2 to 6.2 Mg/ha, 2) yield gaps = 3 to 3.6 Mg/ha, 3) yield gaps < 2.4 Mg/ha, and 4) is unsuitable area. This yield gap between potential and rainfed production system is due to rainfall period during spring when temperature is not a limiting factor for wheat growth. Borujen Basin has semiarid climatic conditions with cold winter and winter precipitation. For the sake of it, temperature was a decisive factor during rainfall seasons, limiting the crop growth period. This study demonstrates that WOFOST model can be used to analyze cropping systems and accurately simulate regional wheat yields in cold semi arid climates.

Key words: GIS, yield gaps, wheat**,** suitability, WOFOST.

INTRODUCTION

Yield forecasting, or determining yield in advance of harvest, has been used in many parts of the world to assess national food security and provide early food shortage warning (Bannayan et al., 2003). Crop growth simulation models can provide accurate estimate of the benefits and risks of crop management system with a preliminary knowledge of yield (Amiri and Rezaie, 2009). The difference between the achievable yield estimated by a crop model and a farm or national average are referred to here as the yield gap. Alternatively, it can be estimated as the difference between yields from crops grown under near-perfectly managed conditions, as in variety tests, and the yields of a farm or a national crop grown nearby in the same season (Jaggard et al., 2010).

In most of the recent researches, CGMs was used as a useful tool for yield gap analysis but these models often are limited in that they have been developed for a site-specific simulation and may not be appropriate for regional-scale yield prediction and assessment (Jagtap and Jones, 2002). Applicability of these models can be extended to a much broader spatial scale by combining them with a Geographic Information System (GIS). GIS provides a framework to facilitate the storage,

*Corresponding author. E-mail: ga_agric@yahoo.com. Tel: +98 9131065401.

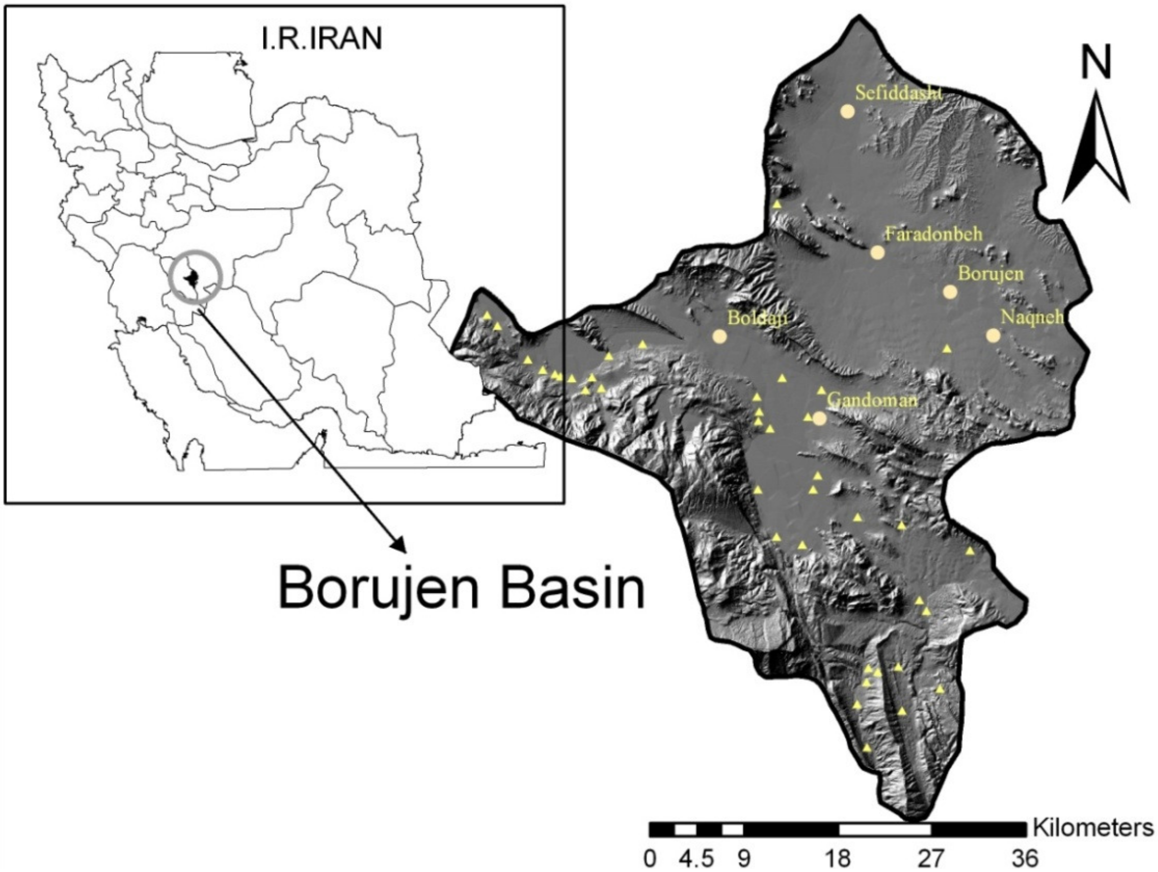


Figure 1. Location of Borujen Basin in Chahar Mahaal and Bakhtiari, Iran.

manipulation, analysis, and visualization of spatial data. Some research have been conducted on its use in assessing crop growth and yield at regional and national levels (Wu et al., 2006; Quiring and Legates, 2008; Sharma et al., 2010). Wu et al. (2006) used a calibrated WOFOST model to quantify wheat yields for potential and water-limited production situations using 40 years of weather data from 32 meteorological stations in the North of China. Simulation results are linked to a Geographic Information System to get easier their presentation and to contribute to the identification of hotspots for interventions aimed at yield improvements. In the northern part of the North China, average simulated potential yields of winter wheat go up to 9.7 Mg ha^{-1}, while average water-limited yields only reach 3 Mg ha^{-1}. In the southern part of the NCP, both average potential and water-limited yields are about 7.5 Mg.ha^{-1}. Rainfall is the limiting factor to winter wheat yields in the northern part of the NCP, while in the southern part, the combination of low radiation and high temperature are the major limiting factors.

Hochman et al. (2009) describe relationships between yield simulations made with a crop-growth model of wheat in Australia and farmers' observations. On average, farmers recorded yields that were 80% of the benchmark value and most of the variation in yield could be accounted for by considering evapotranspiration alone, so the effects of the farmer choosing an insufficient N fertilizer dose or an inappropriate sowing date were small. The objective of this study was to propose a useful approach for suitability evaluation of different crop production systems using yield gap analysis concept at regional scale. In this study, we explore spatial variation of winter wheat yield gap in the potential and water limited situations.

MATERIALS AND METHODS

Description of case study

The Brujen Basin is located in the Chahar Mahaal and Bakhtiari in the western part of Iran. It is geographically located between 31°29'N and 32°13'N latitudes and between 50°47'E and 51°26'E longitudes (Figure 1). The climate in the Brujen Basin is semiarid with moderate summer and cold winter (UNESCO, 1979). The rainfall is characterized by temporal and spatial fluctuation. Average annual rainfall is estimated to be varying from 350 mm in the Brujen station to 600 mm at Imam-Gheis, of which 84% is concentrated in the winter and autumn seasons and 15% in the spring. The catchment area is approximately 2114.3 km^2 of which 18, 66.6 and 0.8% of the total area were respectively covered with agricultural lands, rangelands and forestry lands.

Climate data

Daily weather parameters records from 33 years for the period from 1975 to 2008. Therefore, the complete data sets were retained for the analysis. In nearly all stations vapor pressure, mean wind speed, precipitation, sunshine hours, minimum and maximum air temperatures were available for 18 meteorological stations. The ETo of the stations in the study area was calculated using FAO Penman–Monteith method with ET Calculator software (Allen, et al., 1998; FAO, 2009).

Description of the model

WOFOST is a representative of the models developed in The Netherlands by the school of Professor C.T. de Wit (Bouman et al., 1996). WOFOST has been applied as a tool for the analysis of yield risk and inter-annual yield variability, of differences among cultivars, of sowing strategies, effects of climate change and for other purposes. The model simulates daily crop growth rate, based on soil properties (that is soil depth, water holding capacity and infiltration capacity), climate conditions (that is solar radiation, temperature and distribution of rainfall) and crop characteristics (that is length of growing cycle, photosynthetic characteristics and distribution of dry matter over plant parts). The model is able to simulate two distinct production situations (Bouman et al., 1996). In the potential production situation the crop growth rate is determined by climate conditions only, that is radiation and temperature, given a set of crop characteristics. In the later-limited production situation, the growth rate is limited by the shortage of water during at least a part of the growing period. For the water-limited production situation WOFOST keeps track of a daily water balance taking into account water entering and leaving the rooting zone. Water enters the rooting zone through rainfall, while soil specific non-infiltrating fractions are taken into account. The infiltrated fraction is added to the soil water, while the non-infiltrated fraction is stored on the soil surface and may be subsequently lixiviate, evaporate and/or runoff.

Under sub-optimal water supply the transpiration's rate is reduced. Consequently, it reduces photosynthesis rate proportionally, resulting in reduced growth and yields. Severe drought may result in complete crop failure. In both the potential and water-limited production situation, nutrients are in ample supply while weed, pest and disease control and other crop management are optimal for the simulated yield levels. Historical climate data from 11 weather stations evenly distributed in the wheat suited area of Borujen basin was used. The data included daily maximum and minimum air temperature, sunshine duration, vapor pressure, wind speed and rainfall, which were available for the period 1961 to 2000. Sunshine duration was converted into solar radiation using the Angstrom–Prescott equation (Supit et al., 1994). When applying a simulation model to problems on regional scale, two methods can be used: simulate first and then interpolate results on a grid ('calculate first, interpolate later', CI), or interpolate first inputs on a grid and then calculate model outputs at grid nodes ('interpolate first, calculate later', IC). Some researches showed that CI resulted in smaller mean squared differences between predicted and observed values than IC, mainly because more variables were interpolated in the IC procedure thus increasing the error in model application. In this study, CI method was used (Wu et al., 2006).

Crop data

Field data were obtained from a previous study that has been fully described by Sahragard et al. (2008). Winter wheat ('Alvand') was sown during the autumn of 2001 to 2004, ranged from 5 October to 11 November in the Research Centre of Agriculture of Chahar Mahal-Bakhtiari. Additional site and experimental information, including participations institutions, latitude, longitude, sowing date, descriptions of the soil series, the number of collected samples taken, and climate information are presented in Table 1. The 3-years winter wheat experiment was carried out with five treatments of sowing date. The treatments of sowing date included 22 September, 7 October, 22 October, 6 November and 21 November. In the simulations, we assumed that the same winter wheat variety Alvand was used throughout the study area.

The model evaluation

The performance of WOFOST was evaluated separately for the calibration data set of 2001 to 2003 and for the validation data sets of 2003 to 2004. Repeated and well-documented comparisons between model simulations and reality measurements increase confidence in the suitability of a model for a certain purpose. A combination of graphical presentations and statistical measures were used to evaluate the performance of the model. For model evaluation, the root mean square error (RMSE) and normalized root mean square error ($RMSE_n$) were calculated as proposed by Rinaldy et al. (2003):

$$\text{RMSE} = \left(\sum_{i=1}^{n} (P_i - O_i)^2 / n\right)^{0.5}$$

$$\text{RMSE}_n = 100\left(\sum_{i=1}^{n} (P_i - O_i)^2 / n\right)^{0.5} / O_{mean}$$

Where, P_i is the simulated value; O_i is the observed value; O_{mean} is the mean of observed data and n is the number of observations. Paired *t*-test and linear regression analysis were also used to assess the goodness of fit relationship between the observed and simulated dataset.

A good model reproduces experimental data when: α is 1, β is 0, R^2 is 1, P(t) is larger than 0.05, RMSE is similar to SE and normalized $RMSE_n$ is in the same order of magnitude as the CV of measured values.

RESULTS AND DISCUSSION

Model evaluation

The statistical output was used to evaluate the WOFOST model performance as shown in Table 2. Paired *t*-test showed no significant difference between the observed and simulated yield and total biomass values (P > 0.05). In general, simulated results matched well with the measured parameters in the calibration procedure. Therefore, total biomass was somewhat lower estimated but simulation of grain dry matter showed a relative good fit. As shown in Figure 2, nearly 70% yield and total biomass data points dropped in plus and minus SE lines of observed yield. Agreement between observed and simulated values is also described by the slope and the coefficient of determination (R^2) of the regression lines between simulated and observed values for total biomass

Table 1. Climatic, soil and crop management summary for evaluation experimental site.

Longitude	Latitude	Soil series and description	October-December Temperature (°C) – P(mm)- ETp (mm)	January-March Temperature (°C) – P(mm)-ETp (mm)	April-June Temperature (°C) – P(mm)- ETp (mm)	July - August Temperature (°C) – P(mm)- ETp (mm)
50°-56´ E	32°-18´N	Chramahal series, Sandy clay loam, top soil with 5 to 25% gravel, 25% $CaCO_3$, 140 cm depth.	7.8 - 60.4 - 232	-2.3 - 246.2 -259	13.2 -152.8 - 405	21.6 - 4.5 - 271

Table 2. Evaluation results of WOFOST simulations of yield and final biomass, for the calibration and validation conditions.

Year	Crop variable	N	X_{obs} (SD)	X_{sim} (SD)	α	β	R^2	P(t)	RMSEn (%)	SE	CV (%)
2001-2004	Yield (kg/ha)	15	4044 (825.9)	4276.9 (936.2)	0.962	-74	0.72	0.26	15	513.6	12
2001-2004	Biomass (kg/ha)	15	14615 (3331.7)	14515 (3560)	0.966	593	0.74	0.49	14	1886	12.9

N, Number of observed/simulated data pairs; Xobs, mean of observed values in whole population; Xsim, mean of simulated values in whole population; SD, standard deviation of population; α, slope of linear relation between simulated and observed values; β, intercept of linear relation between simulated and observed values; R^2, adjusted linear correlation coefficient between simulated and observed values; $RMSE_n$ (%), normalized root mean square error. * Means simulated and observed values are the same at 95% confidence level; S.E. = standard error of observed variables; CV = coefficient of variation of observed variables.

and yield. WOFOST divides wheat growth to three key development stages: Emergence, flowering, and physiological maturity. We calibrated the length of growth period and phenology for using the field experiment results are given in Table 3.

Spatial variation in potential and water-limited yields

The suitable areas for wheat were delineated in the Borujen Basin. These land units are composed of the existing and potential agricultural areas. Results show that potential yields vary from 4 to 6.4 Mg ha^{-1} in the Borujen Basin, with an overall mean of 5.7 Mg ha^{-1} for the entire the basin (Figure 3). Generally, potential yields decrease from eastern north to western south, due to lower temperatures in the high lands of western south area. The meteorological station in Borujen has the highest potential yield, thanks to the long growing season. Near Imam-Qeis meteorological station, the lowest potential yields are attained, that is they are often less than 4.50 Mg ha^{-1}. Long-term average water-limited yields in the Borujen Basin vary between 2.4 and 3.7 Mg ha^{-1}, with an overall mean of 3.07 Mg ha^{-1}. Because of the assumption that weather is not homogenous in the basin, the potential production of the crops varies along the basin within a cropping season. A yield gap analysis is a procedure which aims to establish differences in yield level and identify those factors responsible for these differences. Yield gap analysis was carried out based on the results of potential yield and water-limited yields estimations (Figure 3). The yield gap between potential and water-limited yields varies between 0.55 Mg ha^{-1} in the Imam-Qeis station and 5.6 Mg ha^{-1} in the Borujen station (Figure 3). These yield gaps indicate yield loss due to water stress and suggest potentials to increase yields by improving water supply, such as in Faradonbeh lands in the eastern-northern part of the Borujen Basin, where the yield gap is the greatest. For the entire area, the mean yield gap between potential and water-limited yields is 2.7 Mg ha^{-1}.

Finally, the results of quantitative analysis (yield estimation in different wheat cropping systems) performed on four different agro-ecological zones (Table 4). The wheat cropping system suitability classes include of Zone 1: yield gaps = 4.2 to 6.2 Mg/ha, Zone 2: yield gaps = 3 to 3.6 Mg/ha, Zone 3: yield gaps < 2.4 Mg/ha, and Zone 4 is an unsuitable area (Figure 4). In Zone 1, average losses due to water stress are about 90% of the potential yield in the whole plain, but its losses in Zone is 10% of the potential yield of the whole plain. As a result, the map showed (Figure 4 and Table 4) the minimum yield gaps between 3

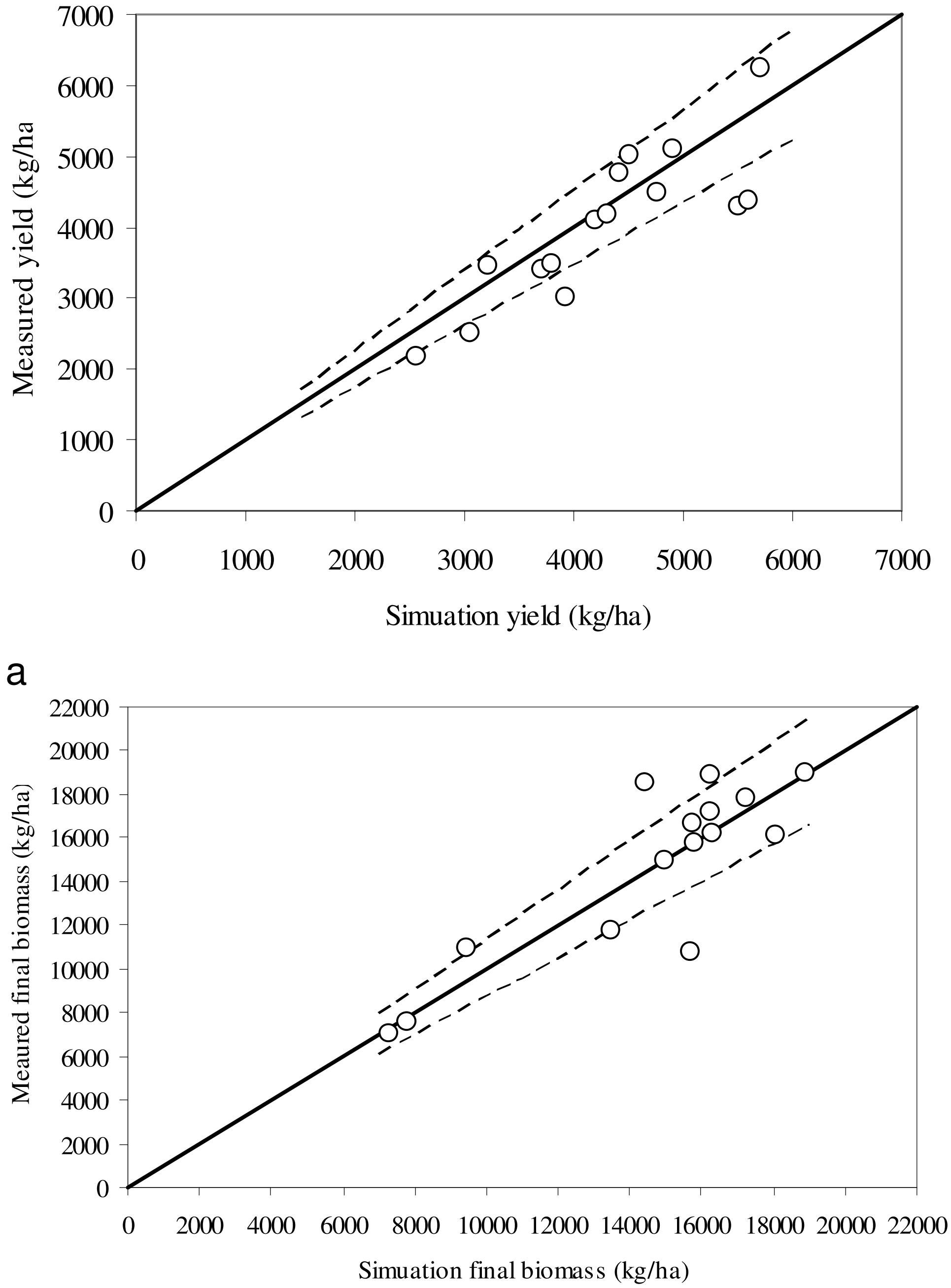


Figure 2. Evaluation results of WOFOST using experimental data from the growing season 2001–2004. a) Simulated results for grain yield and b) simulation results for final biomass.

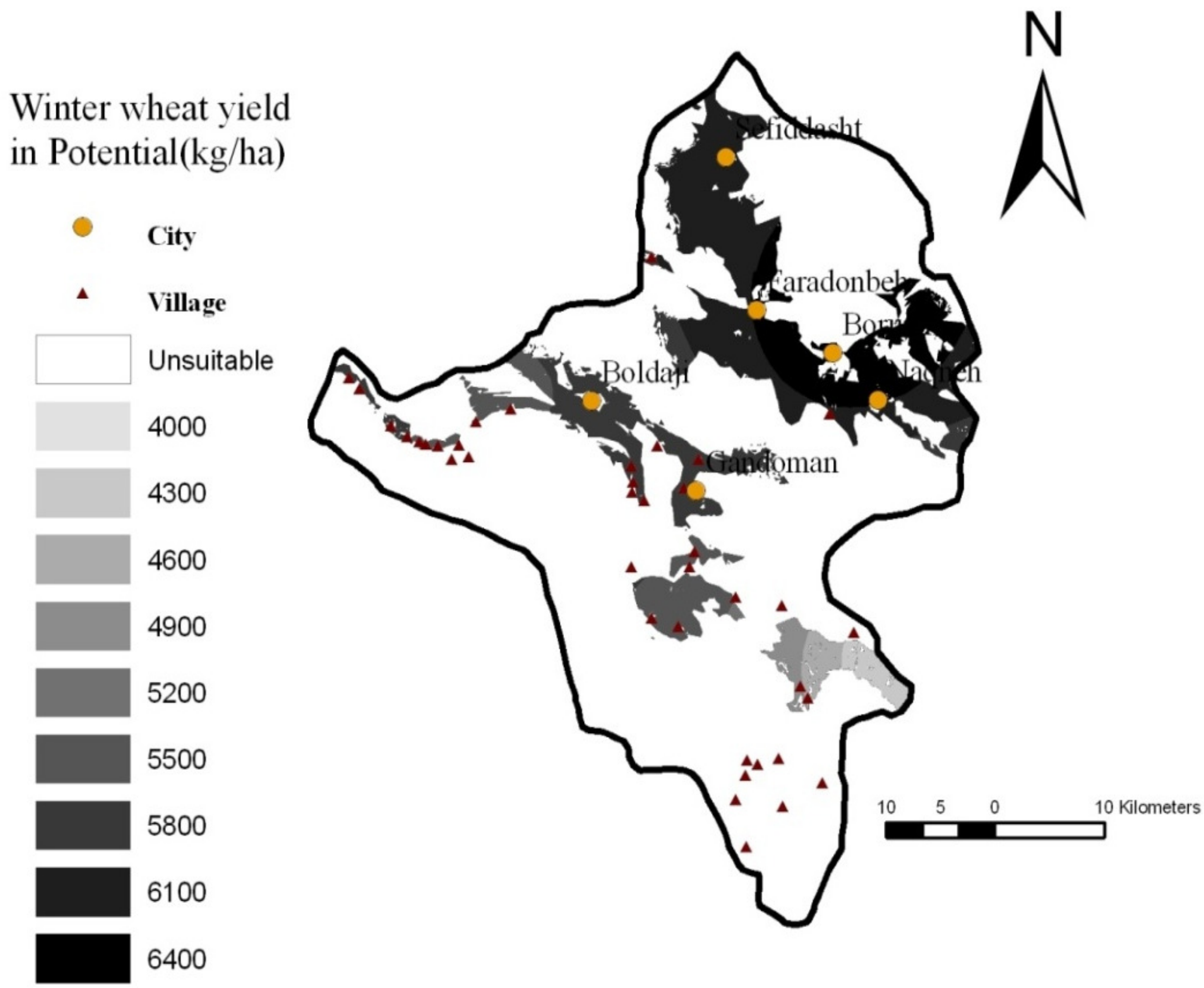
irrigated wheat cropping system and rainfed system occurred in Zone 3 whereas the maximum yield gap occurred in Zone 1. This demonstrates that Zone 1 is not suitable for rainfed wheat production system whereas, it is suitable for irrigated wheat cropping system. Yield gap reduction in Zone 3 is due to increase of yield in water limiting condition (rainfed cropping system). This increase related to its precipitation distribution (Table 4).

Analysis of rainfall pattern (Table 4) showed the mean spring rainfall in the Borujen station (Zone 1) is 91.5 mm but mean spring rainfall in the Imam-Qeis station (Zone 3) is 210 mm. The performance or the productivity of the crops adapted to the local semi-arid environment mainly depends on the duration (in days) of the rainy period in which the reference evapotranspiration is correlated with a given amount of rainfall (Ati et al., 2002). Furthermore,

Table 3. Calibrated parameters in WOFOST for Winter wheat var. Alvand.

Calibrated parameters for winter wheat var. Alvand	Value
*TSUM*1 (°C·d)	1700
*TSUM*2 (°C·d)	1300
DVSI	0
TDWI (kg/ha)	210.00
LAIEM (ha/ha)	0.1365
RGRLAI [ha/(ha·d)]	0.00817

*TSUM*1 is temperature sum from emergence to flowering; *TSUM*2 is temperature sum from flowering to maturity; *DVSI* is development stage at simulation initialization; *TDWI* is total plant dry weight at transplanting; *LAIEM* is leaf area index at transplanting; *RGRLAI* is maximum relative increase in leaf area index.



a

Figure 3. Spatial distribution of winter wheat yield in (a) Potential and (b) Rainfed condition over the Borujen Basin.

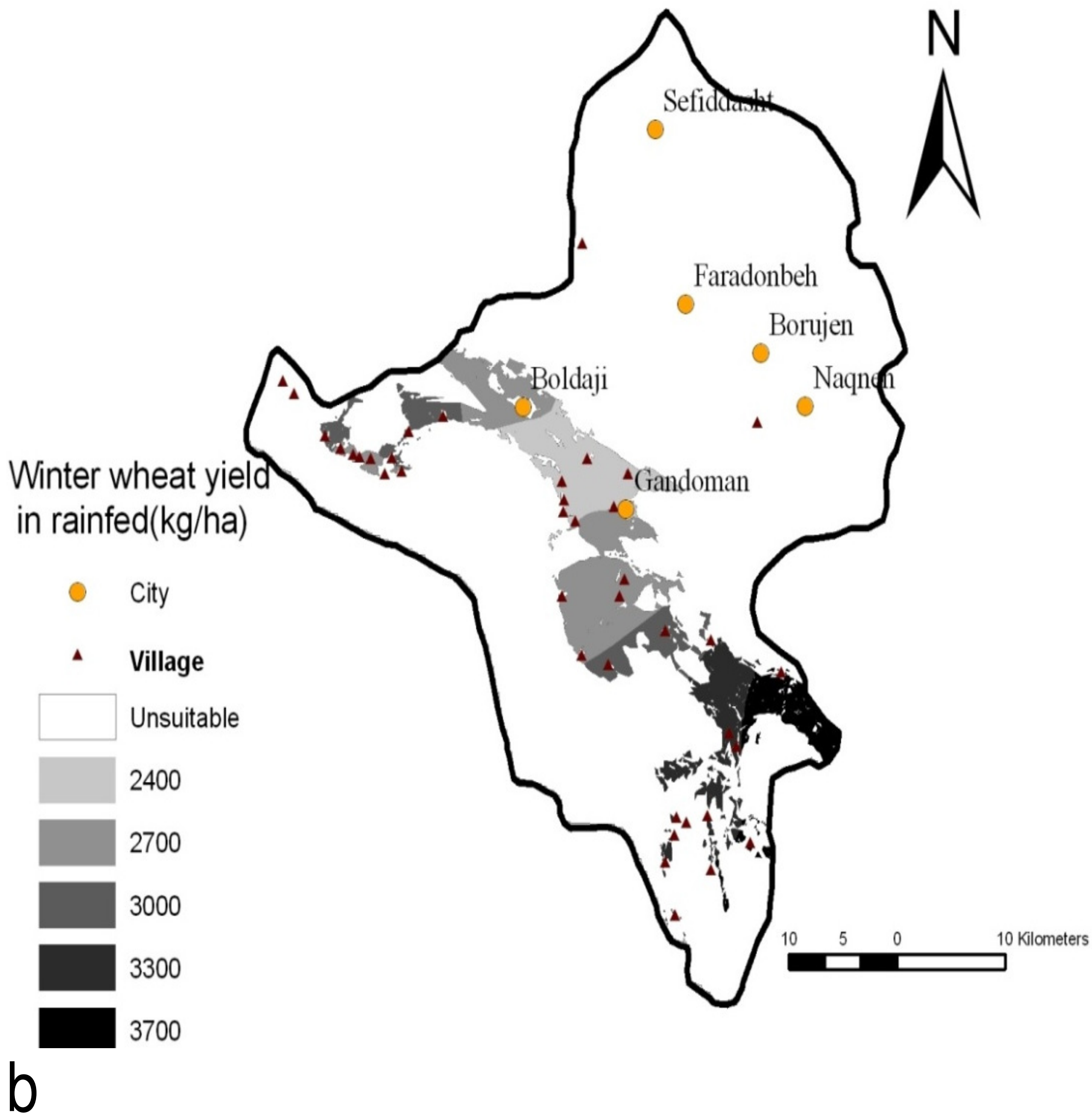


Figure 3. Contd.

it seems that in the cold semi arid climate such as Borujen Basin, during the rainfall period when moisture is not limiting factor to crop growth, temperature will be the most important climatic determinant factor. Some researchers have reported rainfall to be the most important climatic determinant for rainfed crop production conditions (Tilahun, 2006). These researches were carried out in semiarid tropical or subtropical climatic conditions, but the Borujen Basin has semiarid climatic conditions with cold winter and winter precipitation. In this condition, temperature as a determining factor during rainfall season has limited the crop growth period. After rainfall period, only sources of water for the plants for other months of growth period were the soil water storage. The soil water was at its upper limits after flowering stage. Water stress in the critical periods of crop growth drastically affects the level of production. In contrast, water stress in non-critical periods does

Table 4. Wheat yield gaps analysis due to cropping systems over the Borujen Basin

Yield gap zone	Yield gap (Mg/ha)	Area (ha)	Total yield gap (Mg/ha)	October-December[1] [2]Temperature (°C) –P(mm)-ETp (mm)	January-March Temperature (°C) –P(mm)-ETp (mm)	April-June Temperature (°C) –P(mm)-ETp (mm)	July-August Temperature (°C) –P(mm)-ETp (mm)
Zone1	4.2-6.2	29799.8	125159-184758	6.6-30.8-221	0.4-132-247	14.6-91.5-383	22.1-1.9-256
Zone2	3-3.6	9144.3	<41555	6.0-54.3-222	0.9-236.6-259	14.3-124.2-384	21.0-0.8-258
Zone3	<2.4	17314.6	27432-32919	9.5-73.3-229	0.4-319.0-267	14.6-210.7-395	22.1-6.9-265
Unsuitable	-	152865.2	-	-	-	-	-

[1]-Climatological data are base on period from 1975 to 2008. [2]-Season includes the weather data for the entire wheat growing season, starting in October and ending in August.

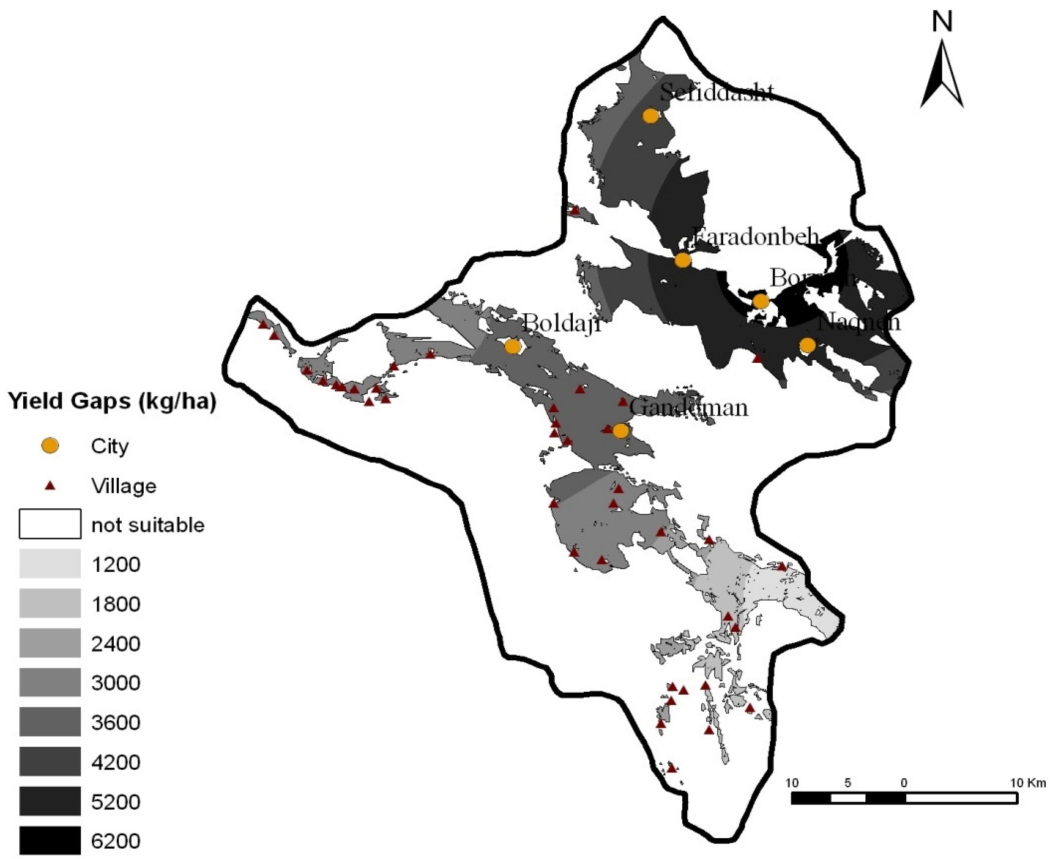


Figure 4. Spatial distribution of winter wheat yield gaps over the Borujen Basin.

not significantly affect the growth process (Sadras and Calderini, 2009). So, the decrease of yield gap between potential and rainfed production system in Zone 3 is due to rainfall period during spring when temperature is not a limiting factor to wheat growth.

Conclusion

In this study, we present a useful approach to analyze yield gaps at a regional scale. This approach was complemented with the use of GIS and simulation models. Combination of these two tools enabled a more effective analysis because the spatial and temporal dimensions are studied at once; hence, broader understanding about the implications of the indices under investigation. The crop level analysis using crop growth models gave a clearer understanding to the interactions of the crop, weather and water (Ines et al., 2003). The spatial differences can be accounted in a GIS, which enables one to see the where and what of the wheat production indices being studied.

We conclude that WOFOST model can be used to accurately simulate regional wheat yields in cold-semi arid climate. However, WOFOST systematically fails to account for yield reductions due to disease outbreaks, pests, and the effect of extreme weather events (that is wind damage). This finding (example, systematic overestimation of regional yields) is not unique to this study. Other studies that have performed crop-model simulations of regional yields report similar findings (Chipanshi et al., 1999; Jagtap and Jones, 2002). Results of this study have various implications for policy makers and researchers concerned with management of winter wheat. The yield gap analysis is useful for identification of where and to what extent yields can be improved when irrigation water is available.

REFERENCES

Allen RG, Periera LS, Raes D, Smith M (1998). Crop evapotranspiration, guidelines for computing crop water requirements. In: FAO Irrigation and Drainage Paper No. 56. FAO, Rome.

Amiri E, Rezaei M (2009). Testing the modeling capability of ORYZA2000 under water-nitrogen limit conditions in Northern Iran. World Appl. Sci. J. 6(8): 1113-1122.

Ati OF, Stigter CJ, Olandipo EO (2002). A comparison of methods to determine the onset of the growing season in northern Nigeria, Int J. Climatol. 22: 732-742.

Bannayan M, Crout NMJ, Hoogenboom G (2003). Application of the CERES-Wheat model for within-season prediction of winter wheat yield in the United Kingdom. Agron. J. 95: 114-125.

Bouman BAM, Van Keulen H, Van Laar HH, Rabbinge R (1996). The 'School of de Wit' crop growth simulation models: a pedigree and historical overview. Agric. Syst. 52: 171-198.

Chipanshi AC, Ripley EA, Lawford RG (1999). Large-scale simulation of wheat yields in a semi-arid environment using a crop-growth model. Agric. Syst. 59: 57-66.

FAO (2009). ETo calculator version 3.1. In: evapotranspiration from Reference Surface, FAO, Land and Water Division, Rome Italy, p. 65.

FAO (2002). World Agriculture: Towards 2015/2030: Summary Report. FAO, Rome, Italy.

Hochman Z, Holzworth D, Hunt I R (2009). Potential to improve on-farm wheat yield and WUE in Australia. Crop Pest. Sci. 60: 708-716. (doi:10.1071/CP09064).

Jaggard KW, Aiming Q, Ericber SO (2010). Possible changes to arable crop yields by 2050, Phil. Trans. R. Soc. B. 365: 2835-285.

Jagtap SS, Jones JW (2002). Adaptation and evaluation of CROPGRO-Soybean model to predict regional yield and crop production. Agric. Ecosyst. Environ. 93: 73-85.

Quiring S, Legates D (2008). Application of CERES-Maize for within-season prediction of rainfed corn yields in Delaware, USA. Agric. Meteorol. 148: 964-975.

Rinaldy Losavio M N, Flagella Z (2003). Evaluation of OILCROP-SUN model for sunflower in southern Italy, Agric Syst. 78: 17-30.

Sadras A, Calderini V (2009). Crop Physiology Application for Genetic Improvement and Agronomy. Academic Press. USA.

Sahragard N, Izadpanahi K, Masumi M, Babaee GH, Afsharifar A (2008). Effect of seed treatment with systemic insecticides and use of three cultivars of wheat on control of virus diseases with natural vectors. P.510 in: Proc. 18th Iran Plant Protec. Cong. University of Bu-Ali Sina Hamedan, Hamedan, Iran Volume 2.

Sahragard N, Masumi M, Yassaee M, Izadpanahi K (2006). Evaluation of resistance in some advanced lines of soft wheat and some cultivars of barley to virus diseases in Shahrekord. P.41. in: Proc. 17th Iran. Plant Protec. Cong. Karaj, Iran.

Sharma A, Bharat R, RaoK KV, Vittal PR, Ramakrishna YS, Amarasinghe U (2010). Estimating the potential of rainfed agriculture in India: Prospects for water productivity improvements. Agric. Water Manage. 97: 23-30.

Supit I, Hooijer AA, Van Diepen CA, (Eds.) (1994). System Description of the WOFOST 6.0 Crop Growth Simulation Model. Joint Research Center, Commission of the European Communities, Brussels, Luxembourg.

Tilahun K (2006). The characterization of rainfall in the arid and semi-arid regions of Ethiopia. Water SA. 32 (3): 429-436.

Wu D, Yu Q, Lua C, Hengsdijk H (2006). Quantifying production potentials of winter wheat in the North China Plain Eur. J. Agron. 24: 226-235.