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Assessment of yield gap due to nitrogen management in wheat

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Abstract

To assess effect of N fertilizer on yield gap (the difference between maximum attainable yield and actual yield) on wheat farms, a long-term simulation was performed using the CropSyst model and a farm survey study in 2007 - 2008 in Gorgan, Iran. Therefore, the yield simulation was performed after the different N fertilizer treatments (0 to 300 kg ha^{-1}) under conventional agronomic practices conditions in studied area. The rate of optimum N fertilizer and maximum attainable yield were estimated using a two-segmented regression model as 171 kg N ha^{-1} and 5.6 t ha^{-1}, respectively. The yield gaps between maximum attainable yield and other simulated attainable yields ranged from 0.5 to 3.6 t ha^{-1}. It seems that yield gaps were a consequence of the deficiency of N fertilizer. The higher the yield gap, the lower the applied N fertilizer. The variation range of yield gap between maximum attainable yield and farmers yield under different N fertilizer applications was -0.4 to 3.4 t ha^{-1} and 0 to 2.5 t ha^{-1} for 2007 and 2008, respectively. The assessment of applied N fertilizer on farms indicated that nearly all of the farms had applied N fertilizer the lower than 171 kg ha^{-1}. Therefore, it is expected that there is a yield gap derived N fertilizer on farms. The results showed that in a given level of N fertilizer in both simulation and farm conditions, the yield gaps are different. This can be related to difference between implemented agronomic practices under simulation and farm conditions.

Keywords: N fertilizer; wheat; simulation; field survey; yield gap

Introduction

Nitrogen (N) is often considered as the most important limiting factor for biomass production in natural ecosystems, after water deficit. N fertilization practices can provide a sufficient N supply for plants to achieve the potential yield allowed by the actual climatic conditions (Lemaire et al., 2008). But because of climatic variability, quantities of applied N fertilizer by farmers often are unsuitable for achieving maximum yield. Passioura (2002) showed that for a typical region limited by water availability, poor nitrogen conditions have noticeably limited yield. Therefore, it could be hypothesized that part of the gap between attainable and potential yield might be partially covered by increases in the availability of N, independently of the occurrence of water deficits (Abeledo et al., 2008). It is essential to apply N fertilizers on adequate time and rate. The economically optimum rate of N fertilizer for crops may vary spatially due to variation in soil characteristics and temporally due to the interactions of environmental factors (Mamo et al., 2003; Katsvario et al., 2003; Subedi and Ma, 2007). The rate of applied N fertilizer depends on whether factors influencing soil temperature (Westerman et al., 1999), soil N status, cultivar (Kalra et al., 2007), solar radiation and precipitation (Abeledo et al., 2008). The presence of long-term field experiments to determine optimum N fertilizer and analyze the yield gap under different management and environmental conditions demand great time and cost. Therefore, simulation models for this purpose seem to be helpful. Systems analysis and crop growth simulation have been used in conjunction with surveys of farmer practices, supplemented by measurements of soil properties and crop performance in yield gap analysis (Lobell et al., 2005; Boling et al., 2010a,b; Calvino and Sadras, 2002; Sadras et al., 2002). In recent years, several processes based on dynamic crop simulation models have been developed to predict crop growth, development, and yield using systems approach that integrate knowledge of the underlying processes and interaction of different components of crop production (Boote et al., 1996). The information from long-term simulation experiments is being increasingly used in assessing crop management options and the yield gap analysis by assessing the non-limiting water potential, limiting water potential or limiting nutrient potential yields for a particular region (Aggarwal and Kalra, 1994; Lansigan et al., 1996; Naab et al., 2004; Bhatia et al., 2008). For example, Abeledo et al. (2008) used CERES-Wheat model for assessing yield gap resulted from nitrogen fertilizer. They showed that in the high-yielding potential years, the main restriction for growth was water shortage, and fertilizing only slightly reduced the gap. Conversely, in rainy years characterized by low potential yields and mild water stress, N management may constitute a simple tool for effectively reducing yield gap under rain-fed conditions. Asseng et al. (2008) showed grain yields are often low due to low inputs as results of large uncertainties of rainfall, particularly during the latter part of the season. In addition, they showed soils with higher plant-available water-holding capacity responded more to N applications and thus at high N applications achieved higher yields. Boling et al. (2010a) showed a simulated yield gap of 1.76 t ha^{-1} (41%) currently exists in rainfed rice farmers' fields. Yield gaps could be substantially reduced by 1.48 t ha^{-1} (34%) through improved N-management practices. Also in other study, Boling et al. (2010b) analyzed yield-limiting factors (water, N) on rice yields using data from on-farm experiments. Potential, water-limited, and N-limited yields were simulated

Table 1. The mean long-term simulated yields and estimated yield gaps under different N fertilizer application.

Applied N fertilizer (Kg ha^{-1})	Simulated yield (t ha^{-1})	Yield gap (t ha^{-1})
0	2.1	3.8
50	3.2	2.7
75	3.8	2.1
100	4.3	1.6
150	5.4	0.5
171*	5.9	-
200	5.9	0
250	5.9	0
300	5.9	0

* The rate of estimated optimum N fertilizer by two-segmented model.

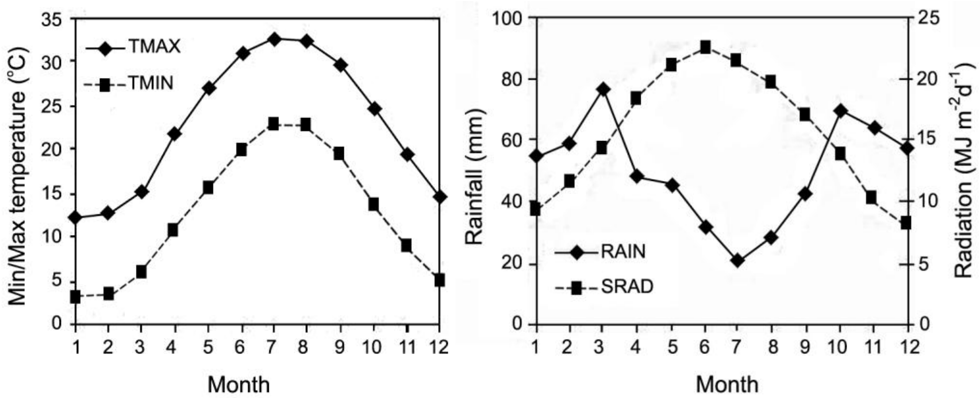

Fig 1. The long-term mean of minimum and maximum temperature (left), rainfall and radiation (right) in Gorgan

using the ORYZA2000 crop growth model. Farmers' fields showed large spatial and temporal variation in hydrology and fertilizer doses. The range of yield gap caused by water limitations was 0–28% and that caused by N limitations was 35–63%. Therefore, the yield gap is estimated as the yield difference between optimum and suboptimal factor(s) conditions. Crop simulation models can be used to estimate crop yields under these conditions. However, with respect to the importance of N nutrition in wheat yield production and unawareness of farmers about quantities of N fertilizer application, the aim of the present study was to (i) determine the optimum N fertilizer rate for achieving maximum attainable yield, (ii) estimate the attainable yields under suboptimal N fertilizer conditions and (iii) assess role of N fertilizer on the yield gap in both simulation and farm conditions.

Results and discussion

Site description

The studied region is in the north of Iran and it has a sub-humid weather with short and intermittent water stress that can impose wheat yield during the crop growth cycle (Soltani et al., 2000). The long-term mean of annual rainfall is 607 mm. Rainfall is not distributed evenly during the year and usually a relatively wet and cold season (autumn, winter, and early spring) is followed by a dry and warm season (Fig. 1). The amount of annual precipitation was fluctuated from 260-668 mm during a period of 45 years. Monthly maximum and minimum rainfall occurs in March (76.5 mm) and July (20.2 mm), respectively (Fig. 1). Based on the long-term means, the maximum (22.4 MJ m^2 day^{-1}) and minimum (8.2 MJ m^2 day^{-1}) solar radiation occur in June and December, respectively (Fig. 1). The soil is usually deep and characterized to have relatively high silt and clay and low sand percentage. The soil has a loess nature. The dominant soil textures are loam, silt loam, silty clay loam, and clay loam.

Assessing yield and applied N fertilizer on farms

The amount of yield on farms ranged from 2.5 to 6.3 t ha^{-1} for 2007 and from 3.4 to 5.9 t ha^{-1} for 2008 (Fig. 2). The mean yields were 4.7 and 4.6 t ha^{-1} for 2007 and 2008, respectively. The cumulative distribution functions showed the yield with 50% probability is 4.7 t ha^{-1} in both years, but the difference in yields between 75 and 25% probability levels was 1.1 and 0.6 t ha^{-1} for 2007 and 2008, respectively. This indicated that yield variations between farms were more in 2007 than 2008 (Fig. 2). One of the reasons for yield variations between farms is due to the variation of N fertilizer management such as splitting, timing, and amount of N fertilizer application. On-farm assessment showed that the amount of N fertilizer application varied between 45 and 172.5 kg ha^{-1} in 2007 and between 65 and 175.5 kg ha^{-1} in 2008 (Fig 3). The mean N fertilizer application was 112 and 94 kg ha^{-1} for 2007 and 2008, respectively. The cumulative probability distribution showed the mean N fertilizer application with 50% probability is 109 and 87.5 kg ha^{-1} for 2007 and 2008 respectively. The difference in N fertilizer application between 75 and 25% probability levels was 43 and 26 kg ha^{-1} in 2007 and 2008, respectively. This indicated N fertilizer application variations between farms were more in 2007 than 2008 (Fig. 3). Variation of N fertilizer application can be explained by the amount of soil's initial N, soil texture, soil

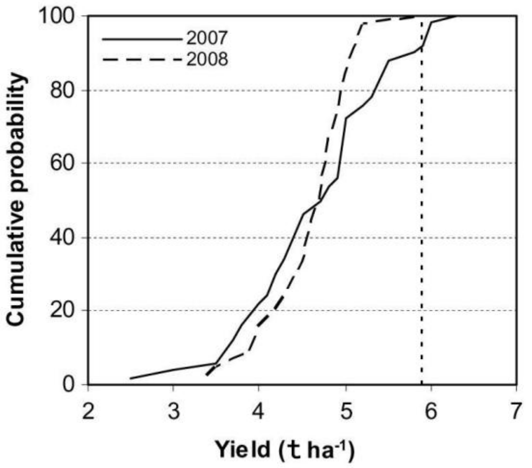

Fig 2. Cumulative probability distribution of yield in different farms in 2007 and 2008 years. The vertical line is maximum attainable yield in long-term simulation

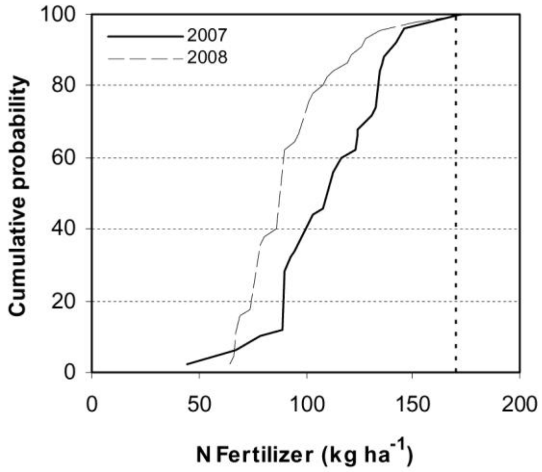

Fig 3. Cumulative probability distribution of N fertilizer application in different farms in 2007 and 2008 years. The vertical line is the measure of optimum N fertilizer long-term simulation.

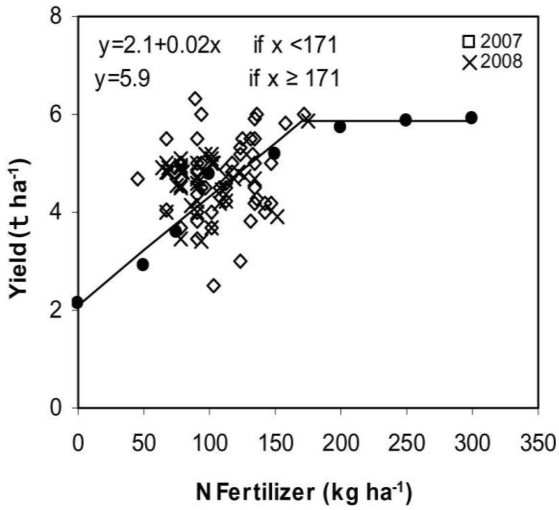

Fig 4. Determining optimum N fertilizer for achieving maximum attainable yield using a two –phase segmented regression model for long-term simulation. The mean attainable yields for different N fertilizers (closed circle) simulation are shown in the figure.

moisture, previous crop and N fertilizer availability for farmers (Kalra et al., 2007).

Simulation analysis

We simulated yield under different N fertilizer application over 1969-2008. The results showed that the mean long-term simulated yield increased between 0 and 200 kg N ha^{-1}. There was no increase in the mean long-term simulated yield over 200 kg N ha^{-1} application (Table 1). The changes of mean yield over long-term simulation versus N fertilizer were describable using a non-linear, segmented regression model. The segmented model consists of two intersecting lines, a sloping line for the linear increase in yield versus N fertilizer application, and a horizontal line, which determines attainable maximum yield. Mathematically, the segmented model may be expressed as (Soltani et al., 2004, 2005; Fig. 4):

$$y = a + bx \quad \text{for} \quad x < x_o,$$
$$y = a + bx_o \quad \text{for} \quad x > x_o$$

where, y is the mean yield over long-term simulation for each N treatment (t ha^{-1}), x is N fertilizer rate (kg ha^{-1}), a is the intercept with the vertical axis, b is the rate of linear increase in grain yield (t per kg N), x_o is the optimum N fertilizer rate for achieving maximum yield. The slope of yield increase was about 0.02 t per kg N fertilizer in hectare. The measure of this slope became zero in 171 kg N ha^{-1} and above it. In other words, N fertilizer application in more than 171 kg ha^{-1} did not increase the yield. Therefore, the rate of optimum N fertilizer for achieving maximum attainable yield was estimated 171 kg ha^{-1}. This amount of optimum N fertilizer calculated during the mean long-term simulation can be a suitable criterion for assessing yield gap. Kalra et al. (2007) showed that the higher N fertilizer application results in increasing N-uptake and LAI, albeit these relations had a quadratic behavior. The gain in LAI results in rapid canopy closure. Positive effects of rapid canopy closure are as reducing soil evaporation, inhibition of weeds, the greater CO_2 fixation per unit of water transpired, high light interception, and consequently yield increase (Soltani et al., 2001; Soltani and Galeshi, 2007).

Assessing the gap between attainable and maximum attainable yield

To measure the gap between maximum attainable yield under optimum N fertilizer and attainable yield under different N fertilizer, the yield simulated under 171 kg N ha^{-1} fertilizer. The mean of maximum attainable yield under condition of 171 kg N ha^{-1} was 5.9 t ha^{-1} over long-term simulation. The yield gap between maximum attainable yield and attainable yield under N0, N50, N75, N100 and N150 was 3.8, 2.7, 2.1, 1.6 and 0.5 t ha^{-1}, respectively (Table 1). The yield gap was zero in 171 kg N ha^{-1} and above it. Therefore, in the lower N fertilizer treatments, the addition of N fertilizer increases the attainable yield and consequently yield gap would be decreased (Table 1). The slope of yield gap decrease against N fertilizer application was about 0.02 t ha^{-1} per kg N fertilizer in hectare (Fig. 5). Yield gap decrease continued until the measure of yield gap became zero in 171 kg N ha^{-1} and above it (Fig. 5). Grassini et al. (2011) showed with a higher N fertilizer rates, N fertilizer efficiency and yield would be increased. Abeldo et al. (2008) showed that increasing N availability declines yield gap in wheat but the rate of N availability depends on rainfall rate. In high rainfall

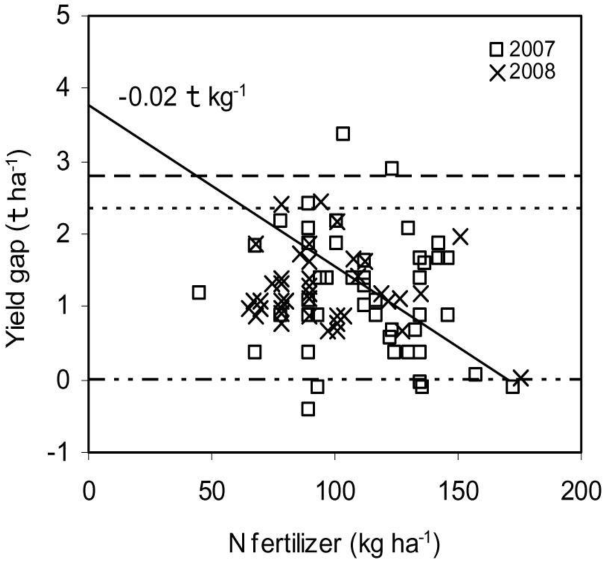

Fig 5. Relationship between yield gap and N fertilizer application. The slope of yield gap decrease is 0.02 t kg^{-1}. The upper horizontal lines are expectable maximum yield gap for 2007 and 2008, respectively. The lower horizontal line is expectable minimum yield gap for both years.

years with removing water stress, the response of yield to fertilization increased.

Assessing yield gap on farms

The results showed that yield gap between maximum attainable yield and farms' yield ranged from -0.4 to 3.4 t ha^{-1} for 2007 and 0 to 2.5 t ha^{-1} for 2008 (Fig. 5). Also, on-farm assessment showed that the amount of N fertilizer application varied between 45 and 172.5 kg ha^{-1} in 2007 and between 65 and 175.5 kg ha^{-1} in 2008 (Fig. 3). With respect to the optimum N fertilizer obtained in long-term simulation, it was identified that in 2007 and 2008 nearly all of the farmers (except one farm for each year) used N fertilizers lower than the optimum N fertilizer (Fig. 3). Therefore, a decrease in yield gap between maximum attainable yield and farms' yield was expected with increasing N fertilizer application on farms. Kalra et al. (2007) showed that the application of nitrogen could explain the variation in grain yield. N fertilization generally improves TE through an increase in green area index and radiation use efficiency (Korentager and Berliner, 1987; Heitholt, 1989, cited by Debaeke and Aboudrare, 2004). Application of fertilizer may be increasing the depth of water extraction, or the amount extracted from specific soil layers or both (Brown, 1971, cited by Debaeke and Aboudrare, 2004). In addition, with respect to linear relation between yield gap and variation range of N fertilizer application on farms, it was expected that: (i) range of yield gap in studied farms to be 0-2.7 and 0-2.3 t ha^{-1} in 2007 and 2008, respectively; (ii) the measure of yield gap in each level of applied N fertilizer on farm to be on regression line. Unlike above points, variation range of yield gap on farms was -0.4 to 3.4 t ha^{-1} for 2007 and 0 to 2.5 t ha^{-1} for 2008 and majority of yield gaps were not on linear regression model. These differences between yield gap of simulation and farms are due to different management condition, such as planting date, variety of wheat, N fertilizer splitting, time of N fertilizer application, soil N status , other fertilizers application, plant density, and soil type of farms (results not shown). Farms yields gap above and below regression line are indicating management condition on farms have been more unsuitable and suitable than it in simulation, respectively. Negative yield gap indicates actual yield on farm has been higher than maximum attainable yield due to the better management condition on farm to simulation. For example, shifting N application from fall to spring or at planting and greater use of split N fertilizer during the growing season, rather than a single large N application, represent options to achieve better congruence (Cassman et al., 2002).

Material and method

On-farm assessment

The on-farm assessment was carried out in five sites namely Jelin, Mohammad Abad, Karim Abad, Varsan and Nodijeh in the eastern part of the coast of the Caspian Sea in Gorgan, Iran, during 2007 and 2008 years. For assessing crop management, 95 farms with different management levels were selected in these sites. In the first year 50 farms and in the second year 45 farms were selected. Data on crop management such as planting date, cultivar, fertilizer, irrigation, harvest date, and incidence of weeds and disease were collected from these farms through interview and phone. For this purpose, a list of all the agronomic operations, from seedbed preparation to harvesting, was prepared. Then farmers were asked questions to find out how they performed the operations. In this list actual yield harvested by farmer was recorded. To ensure the accuracy of farmers' answers, supervisor engineers of these farms reviewed these completed lists. Data associated with N fertilizer application were used to consider influence of N fertilizer on yield in this study. Cumulative distribution functions were used to evaluate variations of actual yield and applied N fertilizer on the studied farms.

Simulation and statistics analysis

CropSyst model (Stockle et al., 2003) was used for crop growth simulation under different management. Evaluation of CropSyst model under Gorgan condition showed that the model predicted growth and yield of wheat reasonably well (Soltani et al., 2010). Four input data series are needed to run CropSyst: weather statistics, physicochemical soil properties, crop properties, and management practices. Weather statistics, including daily temperature, rain, and radiation, were collected over 1969-2008 at closest meteorological station. Soil, crop, and management practices inputs were collected through farms survey in 2007 and 2008 in this study and also in study of Soltani et al. (2010). However, simulations of estimated attainable yield in different levels of N fertilizer (0, 50, 75 100, 150, 200, 250 and 300 kg N ha^{-1}; shown with N0 to N300, respectively) were made for wheat using CropSyst model over 1969-2008 in Gorgan. In this simulation, each level of N fertilizer was used in three stages: 25 kg N ha^{-1} before planting and the rest was divided into 60 and 90 days after planting. In all simulations, irrigation was assumed to be implemented in two stages of growth cycle (at flowering an amount of 60 mm and 20 days after flowering an amount 70 mm) that is a common practice in the area. Simulations were performed at a standard sowing date (10 December) and density (450 plant m^{-2}) which is correct for most of the farms in considerable parts of the area. In addition, Soil texture in these simulations was silty clay loam that its depth was 1.2 meter. There were these properties in the majority of studied area soils.

Yield gap analysis

For considering effect of N fertilizer on yield gap, we estimated optimum N fertilizer in which we obtained maximum attainable yield. Optimum N fertilizer obtained using non-linear regression fitted to mean long-term simulated yield in each level of N fertilizer by NLIN procedure of SAS software (Soltani, 2007). The difference between mean maximum attainable yield and mean attainable yields under suboptimal N fertilizers were calculated as yield gap. In addition, the difference between maximum attainable yield and actual yield in farms was calculated in 2007 and 2008. For assessing yield gap and effect of N fertilizer on yield gap, we compared the variation range of yield gap and applied N fertilizer in both simulation and on-farm conditions.

Conclusion

In generally, in this study optimum N fertilizer for achieving maximum attainable yield was estimated about 171 kg ha^{-1}. Farms survey showed that nearly all of the farmers use N fertilizer less than optimum N fertilizer. It concluded that deficiency of applied N fertilizer can be a yield-limiting factor. Thus, farmers should be using higher rate of N fertilizer. In addition, the results showed that in a given level of applied N fertilizer for both simulation and farm conditions, estimated yield gap was different. This difference is related to other agronomic practices. This study suggests considering influence of these practices on yield in the next studies.

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