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Using boundary line analysis to assess the on-farm crop yield gap of wheat

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ABSTRACT

Food security is one of the most important challenges facing human kind. A very promising approach to solve the problem is closing the yield gap, i.e. the difference between farmer's and potential yield. A 'complete yield gap assessment method' must provide information regarding potential yield, actual yield and yield gap, the causes of the gap and their importance. The objective of this study was to indicate how boundary line analysis (BLA) could be applied to such an assessment. BLA was only applied to crop management practices/inputs, e.g. sowing date and rate and fertilizer applications. The data were gathered from about 700 wheat farms in Golestan province, one of the major wheat producing regions in Iran, during two growing seasons of 2013–2014 and 2014–2015. Wheat production in Golestan province can be divided into three production situations according to agro- and geo-climatology criteria: these are 'irrigated or high-rainfall', 'high-yield rainfed', and 'low-yield rainfed'. Boundary lines were fitted to the edge of the data cloud of crop yield versus management variables using data from each of the three wheat production situations in the province. Actual farmers' yields were 3900 kg ha^{-1} for irrigated, 4000 kg ha^{-1} for high-yield rainfed and 2000 kg ha^{-1} for low-yield-rainfed situations; BLA indicated that potential yields (the highest yields obtained by farmers in the sample) were 6900, 5800 and 3900 kg ha^{-1} for each situation, respectively. The corresponding yield gaps were high at 42%, 31% and 50%. Using BLA it was possible to determine the optimal sowing date, seeding rate, frequency and amount of nitrogen fertilizer applied, amount of nitrogen top-dressing, amount of phosphorus and potassium fertilizers and irrigation frequency. The percentage of farmers who cultivated outside of the optimal levels was also identified and was used to determine the importance of each management factor in yield gap. It was concluded that BLA as applied in the study, was a cheap and simple method which, without the need for expensive experimentation, was able to detect yield gaps and their causes in a region. The method can be used effectively in countries/regions where important yield gaps exist.

1. Introduction

Food production needs to increase by 70–110% (Tilman et al., 2011; FAO, 2009; Ray et al., 2013) to feed an expected 9–10 billion people in the world in 2050 (O'Neill et al., 2010). Cassman (2012) stated that ensuring global food security and protecting the environment at the same time is perhaps the single greatest scientific challenge facing humankind. Several options have been proposed to solve this food security challenge (Godfray et al., 2010; Foley et al., 2011; Smith, 2013). One of the most promising options, especially in developing countries, is to bridge the yield gap (Cassman, 2012; van Ittersum et al., 2013).

Yield gap is the difference between farmers' yields and the yields achievable under favorable cultural management (Lobell et al., 2009; van Ittersum et al., 2013). In other words, yield gap, in a certain region, is defined as the difference between the potential yield and the actual yield achieved in farmers' fields in that area (van Ittersum et al., 2013). Yield gap analysis also provides a quantitative estimate of the possible increase in food production capacity for a given area which is critical input for the development of food security strategies at regional, national and global scale (van Wart et al., 2013). Increasing food production via closing the yield gap has less environmental consequences than expanding food production area (van Wart et al., 2013; Soltani et al., 2013, 2014).

In recent years, yield gap analysis has attracted much attention and

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different approaches/methods are being used for the analysis (Lobell et al., 2009; van Ittersum et al., 2013; Wang et al., 2015; Soltani et al., 2016). Boundary line analysis (BLA) is a statistical method that has been used in the analysis of potential limiting factors. In this method, first developed by Webb (1972), a relationship is established between maximum achieved yields (as *y*) and a target variable (as *x*) while other variables are also changing – other variables are not kept constant or optimal (Makowski et al., 2007). In this method, a line is fitted to the outer edge of the data cloud. This boundary therefore specifies the highest yield (yield potential) or the best yield under the influence of different levels of a certain variable used in x-axis. In this way, it is assumed that (with large data sets) these yields are the highest values in the absence of other limiting factors and all points that fall below of the line have been limited by other factors.

BLA has been applied to assess crop yield as a function of soil properties (nutrient concentration, organic matter, pH, etc.) (Casanova et al., 1999; Kitchen et al., 2003; Shatar and McBratney, 2004; Tittonell et al., 2008), rainfall, evapotranspiration, nitrogen use, pests and diseases and plant density (Patrignani et al., 2014; Huang et al., 2008; Tittonell and Giller, 2013; Tasistro, 2012). Recently, Wang et al. (2015) in a survey study of 254 coffee farms in Uganda, attempted to identify the limits of coffee production using BLA. However, while BLA has been used in yield gap analysis (e.g., Tittonell et al., 2008), it has not been used as a complete method, i.e. to identify the magnitude of yield gap, its causes and importance of each factor affecting the yield gap.

Thus, the objective of this study was to use BLA as a complete yield gap analysis. Here, BLA was applied to the analysis of the relationship between crop yield and crop management practices/inputs, i.e. those factors that are under farmers' control. Then, BLA was used to characterize potential yield, optimal level of the management variable under consideration and percentage of farmers that did not practice optimally. Wheat in Golestan province north-eastern Iran was used as a case study. Golestan province is among the top five wheat producing provinces of Iran and is responsible for about 10% of Iran's wheat production. About 1.1 million tons of wheat grain is produced from 380,000 ha of sown land (Iran's Agricultural statistic, 2015). About 60% of the area is cultivated as rainfed and 40% as irrigated wheat.

2. Materials and methods

2.1. Study area

Golestan province covers 20,438 km^2 and lies between 36° 30′ to 38° 8′ N and 53° 51′ to 56° 22′ E in the northern part of Iran. Six of the most important wheat producing counties within the province was selected for the field survey. The selected counties were Gonbad (37.25 °N, 55.16 °E and 37.2 m asl), Aliabad (36.9 °N, 54.86 °E and 184 m asl), and Kordkoy (36.77 °N, 54.12 °E and 140 m asl) for irrigated wheat and Gomishan (36.98 °N, 54.13 °E and -22 m asl), Aqqala (37.01 °N, 54.5 °E and -12 m asl) and Kalaleh (37.36 °N, 55.48 °E and 128.8 m asl) for rainfed wheat. The climate of the selected areas is semi-cold dry for Gonbad, semi-cold humid for Aliabad, semi-cold humid for Kordkoy, semi-cold dry for Gomishan, cold arid for Aqqala and semi-cold humid for Kalaleh according to Emberger climate classification method. Wheat is cultivated mainly in a wide plain in the province surrounded by the Alborz ranges from the south and southeast, by Qaraqum desert of the Central Asia from the north and northeast and by Caspian Sea from the west (Fig. 1).

2.2. Data collection

Wheat farms surveys were conducted during two growing seasons of 2013–2014 and 2014–2015 in each of the selected counties. Diversity of farmers with respect to crop yield is necessary for the success of the analysis (please see next section). Groups of farmers with low to high yields were identified with the help of local experts, and then farmers were randomly selected from each of the groups for the study. In total, there were 335 rainfed farms and 349 irrigated farms with different field area, production operations, inputs used and crop yield. The farms were evaluated over the growing seasons from sowing to harvest. All the management practices/inputs (variables) were monitored and recorded without interfering with farmers operations. Fig. 1 indicates the position of the evaluated farms and the location of weather stations in the province. Some important management measures were frequency and time of tillage operations (e.g. plough and disk cultivation), sowing date, seeding rate, plant density, frequency and amount of nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O) fertilizers, irrigation frequency, time and frequency of weed, disease and pest controls and harvesting date. Time of operations (e.g. sowing date) was considered as day since 23 September, the beginning of autumn.

2.3. Yield gap assessment based on boundary line analysis

Main steps for a complete yield gap assessment using BLA in a specific region/area are proposed as:

(i) Selection of farms in the study area. If the study area is large (as it is in the present research) and environmental factors like rainfall vary significantly, it can be divided into several rather environmentally homogenous sub-areas based on climate, soil and/or management system differences. To obtain satisfactory results, a wide range of farms/fields with regards to practices/inputs needs to be selected in each sub-area.
(ii) Gathering information on management measures and inputs as they are applied by the farmers. Only the practices that are under control of the farmers are included. As many as possible management variables/inputs are needed to be included in the analysis.
(iii) Application of BLA to the gathered data and interpret the results as it is explained below.

There is no agreed protocol for the application of BLA. In some studies, an arbitrary boundary line is fitted to the data (Makowski et al., 2007). In general, some points from the outer edge of the data cloud are chosen and a line is fitted to them. This boundary line specifies the highest attainable yield or the maximum yield (as *y*-axis) under the influence of different levels of a certain variable (as *x*-axis).

Three general steps can be considered to obtain the boundary line (Shatar and McBratney, 2004; Makowski et al., 2007; Patrignani et al., 2014):

1 Examining the scatter plot of data: a scatter plot (XY chart) should be prepared with crop yield as dependent variable and one selected management variable (e.g. sowing date or number of irrigation) as independent variable. This step visualizes the data cloud and facilitates the selection of a proper function to be fitted at the upper edge of data cloud.
2 Selection of the data points from the upper edge of data cloud to be used in the curve fitting: this can be done simply by eye (e.g., French and Schultz, 1984) or by an advanced statistical methods (e.g. Milne et al., 2006). For more information in this regards, readers can refer to Makowski et al.,(2007); Banneheka et al. (2013); Shatar and McBratney (2004); Riffel (2012); Kitchen et al. (2003); Tasistro (2012); Schnug et al. (1996), and Huang et al. (2008). In this study data points from the upper edge of the data cloud were selected by eye and then an appropriate function was fitted to these points.
3 The final step is to fit a function to the data points obtained from the second stage. This stage results in a model that explains the response of the maximum yield to different levels of the independent variable under examination. Parameter estimates of the model can be further used for interpretation.

Further explanation is provided using Fig. 2 which represents

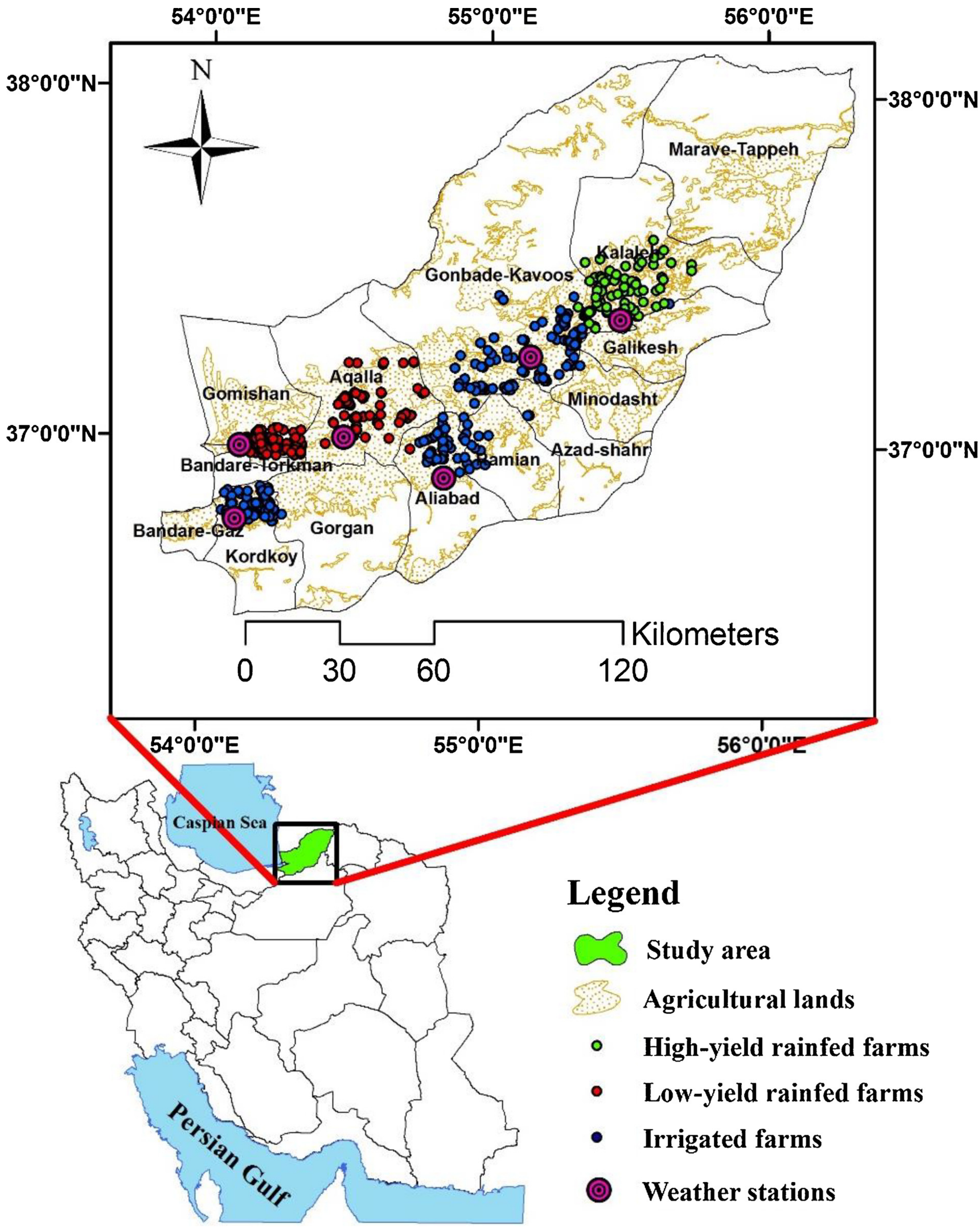

Fig. 1. Location of monitored farms in Golestan Province during over two growing seasons (2014 and 2015).

scatter plots for four managerial variables (x) in a hypothetical study. For some variables, for instance Fig. 2a, BLA resulted in no model, i.e., there was no relationship between maximum yields and levels of the x-variable. In that case, a horizontal line could be fitted to the edge of the data cloud, which meant that maximum yield was obtainable with every level of the x-variable (X_1 in Fig. 2a) within the observed range of the evaluated farms. It is interpreted that such variables cannot be considered as a cause for yield gap. If needed, an estimate of the yield gap (Y_g) can be obtained as the difference between the horizontal line (potential yield; Y_p) and the average farmers yield (actual yield; Y_a – dotted horizontal line in Fig. 2a):

$$Y_g = Y_p - Y_a \quad (1)$$

For other management variables of Fig. 2 (X_2, X_3 and X_4), the data cloud showed a pattern and maximum yields for different levels of x-variable could not be describe by one horizontal line. Instead, two or

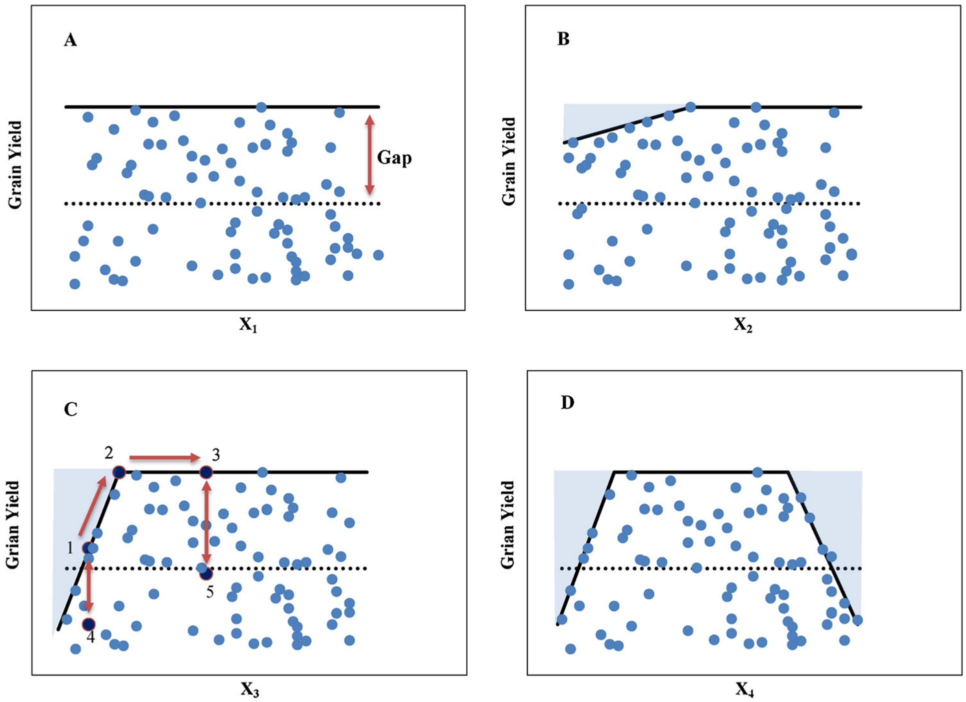

Fig. 2. Scatter plots of the yield data vs managerial practices (X_1-X_4) in a hypothetical study.The fitted bold line to the edge of the data cloud is the boundary line. The dotted horizontal line is the average of farmers yield, the actual yield. The yield gap is the difference between the actual yield and potential yield. The potential yield is indicated by horizontal boundary line. The shaded area indicates 'lost yield area'.

more pieces of straight lines were required to describe the changes of the maximum yield (the edge of data cloud) versus different levels of the *x*-variable (Fig. 2b-d). It could then be concluded that these variables (X_2, X_3 and X_4; Fig. 2b-d) were important and should be considered as causes for yield gap. Therefore, a prime role of BLA in a complete yield gap assessment is to divide the management practices/inputs in two groups of non-important variables and effective variables. However, not all the effective variables have the same importance in yield gap (please see below).

Segmented non-linear regression models with two or three segments, where the horizontal segment of the models represents the maximum yield or potential yield can be used to describe changes in maximum yield (the edge of the data cloud) versus different levels of variables X_2, X_3 and X_4. Two-segmented model can be shown as:

$$\begin{aligned} Y_x &= a + bX \quad if X < X_o \\ Y_x &= a + bX_o \quad if X \geq X_o \end{aligned} \tag{2}$$

where Y_x is the maximum yield for every level of *x*-variable, X_o is the inflection point indicating the minimum optimal level of *x*-variable over the examined fields, and *a* and *b* are regression coefficients. And, three-segmented model can be shown as:

$$\begin{aligned} Y_x &= a + bX && if X < X_{o1} \\ Y_x &= a + bX_{o1} && if X_{o1} \leq X \leq X_{o2} \\ Y_x &= a + bX_{o1} - c(X - X_{o2}) && if X > X_{o2} \end{aligned} \tag{3}$$

where X_{o1} and X_{o2} are two inflection points so that X_{o1} represents the minimum optimal level of *x*-variable and X_{o2} specifies the maximum optimal level of *x*-variable and *a*, *b* and *c* are regression coefficients. *X*-variable levels lower or higher than the optimums result in yield penalty for the farmer. Potential yield (Y_p) over the evaluated farms can be estimated as $Y_p = a + bX_o$ for the two-segmented model and as $Y_p = a + bX_{o1}$ for the three-segmented model. Yield gap (Y_g) can then be obtained as the difference between Y_p and Y_a. It is expected that Y_p estimated using BLA is lower than Y_p estimated using a simulation model (Fig. 3).

Variables X_2, X_3 and X_4 do not have the same importance in yield gap. From the slope(s) of the relationship between Y_x and the *x*-variable and the percentage of the farmers that do not practice optimally in using each of X_2-X_4, one can compare the importance of each variable. The farmers who do not practice optimally are those data points under the sloping line(s) in Fig. 2b-d. Alternatively, the importance can be judged from 'the lost yield area' as indicated in Fig. 2b-d which shows unattainable yields. For example, X3 is more important than X2 in Fig. 2.

In Fig. 2a-d, all the data points below the fitted line(s) were those farms where crop yield had been limited by other managerial practices/inputs. For example, in Fig. 2c, the yield difference between farms 1 and 2 was primarily due to non-optimal level X_3 in farm 1. However, the yield difference between farms 4 and 1 was due to non-optimal management of other variables in farm 4 as both the farms have received equal level of X_3. The same was true for yield difference between farms 5 and 3. BLA for X_3 could not exactly say which management variables were responsible for the yield difference between farms 4 and 1. However, if BLA was applied to as many managerial variables as possible, those variables with a pattern (like X_2-X_4 in this example) are responsible for such differences.

BLA, as described above, was applied to all management variables of the present study. Some variables showed no pattern in BLA (Table 1). To concentrate on management practices rather than the environment and as we did not measure rainfall in each farm, the analysis was done separately for farms within each production situation in the province. According to agro- and geo-climatology of the cultivated lands, wheat production in Golestan province was divided into three production situations (Fig. 1):

(1) Irrigated-wheat (Aliabad and Gonbad) or rainfed wheat in area with high rainfall and/or high water-table level (Kordkoy) including most parts of foothill areas in the south of the province, Long-term total rainfall during the growing season of wheat (November to May) are 486 mm for Aliabad, 340 mm for Gonbad, 492 mm and for Kordkoy (Fig. 3). Due to irrigation in Aliabad and Gonbad and high-level of water table in Kordkoy, rainfall seems not to be important in yield gap in this production situation. Long-term average of maximum and minimum temperatures during the wheat growing season are 17.4 and 7.2 °C for Aliabad, 18.4 and 7.3 °C for Gonbad, 19.6 and 9.2 °C for Kordkoy (Fig. 3).

(2) High-yield-rainfed wheat in the northeast of the province with appropriate rainfall and non-saline soil (Kalaleh). Long-term total rainfall during the growing season of wheat is 455 mm in Kalaleh and

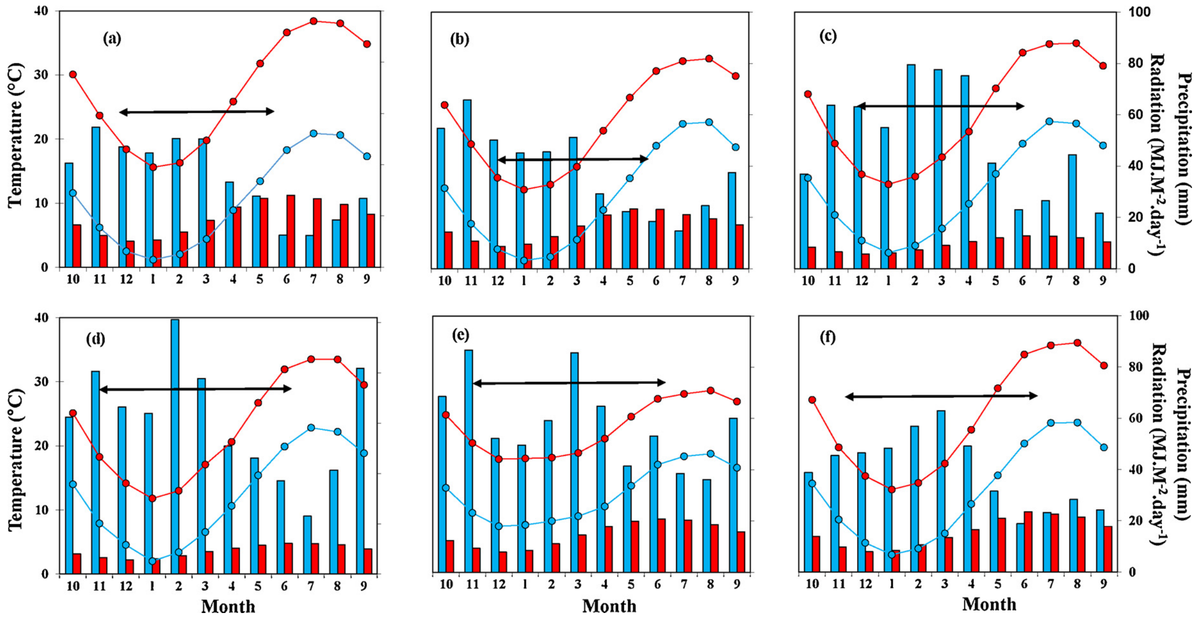

Fig. 3. Long-term average of monthly minimum temperature (blue circles), maximum temperatures (red circles), precipitations (blue bars) and solar insolation (red bars) at Aqqala (a), Gomishan (b), Kalale (c), Aliabad (d), Kordkoy (e), and Gonbad (f). Arrows indicate the growing period of wheat in these areas and x-axes start with October (month 10). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 1
The list of management variables that showed no pattern in BLA.

The frequency of using plough implement
The time of using plough implement
The frequency of disking cultivation
The frequency of using a chisel implement
The number of years from the last legume crop
The number of years from the last leveling
Clod conditions of the seed bed (a score from 1 to 10)
Sowing depth
Plant density
The time of nitrogen fertilizer application after sowing
The time of irrigations
The frequency of application of weedicides
The time of application of each weedicides
The frequency of application of fungicides
The frequency of application of insecticides
weed density at harvest time
Insects damage (a score from 1 to 10)
Disease damage (a score from 1 to 10)
Weeds damage (a score from 1 to 10)
Harvesting date

long-term average of maximum and minimum temperatures during the wheat growing season are 18.4 and 7.1 °C, respectively (Fig. 3).

(3) Low-yield-rainfed wheat in the north of the province with lower rainfall and salt-affected soils (Aqqala, Gomishan). Long-term total rainfall during wheat growing season are 307 mm for Aqqala, and 309 mm for Gomishan and average maximum and minimum temperatures are 21.6 and 5.5 °C for Aqqala, and 17.6 and 5.9 °C for Gomishan (Fig. 3).

Therefore, yield gaps were averaged over the environmental conditions of each production situations. SAS software was used to fit the selected functions (Eqs. (1) or (2)).

3. Results

Average farmers yields (Y_a) for the three production situations were 3900 kg ha^{-1} for irrigated, 4000 kg ha^{-1} for high-yield-rainfed and 2000 kg ha^{-1} for low-yield-rainfed situations (Table 2).

For several management practices/input, it was not possible to fit a boundary line because there was no relationship between the variables and the maximum yields (as depicted in Fig. 2). These variables are listed in Table 1. Therefore, crop yield was not limited by these variables, at the level where they are currently practiced. Variables showing a relationship with yield were: sowing date, seeding rate, frequency and amount of the applied nitrogen, the amount of applied nitrogen top-dressing, the amount of applied phosphorus (as P_2O_5), the amount of applied potassium (as K_2O) and the irrigation frequency (Figs. 4–7). These variables were causes of yield gap and should be considered for the productivity improvement under the current conditions. Figs. 4–7 present scatter plots of wheat yield versus target management variables for the three production situations. Fitted lines in the figures represent the maximum yield (Y_x) for every given level of the variable under consideration and the horizontal line represent potential yield (Y_p). All the data points below the lines represents situation in which the crop yield had been limited by other variables than the variable under examination (Kitchen et al., 2003).

A three-segment non-linear regression model was fitted as BLA applied to sowing date (as days since 23 September) (Fig. 4). The BLA showed a yield potential of 6500 kg ha^{-1} for irrigated conditions, 5800 kg ha^{-1} for high-yield-rainfed conditions, and 3900 kg ha^{-1} for low-yield-rainfed production conditions. Thus, farmers reached 61, 69 and 50% of the potential yields, respectively (Table 2). BLA indicated that to reach these potential yields sowing should be undertaken within the interval of Nov. 5 to Dec. 9 for irrigated conditions, Nov. 12 to Dec. 14 for high-yield-rainfed and Nov. 10 to Dec. 17 for low-yield-rainfed conditions (Table 2). Sowing outside these intervals resulted in yield penalty for the farmers. The analysis further revealed that 34% of farmers under irrigated conditions, 22% of farmers under high-yield-rainfed conditions and 17% of farmers under low-yield-rainfed conditions sow their wheat crops out of the optimal sowing window. The harvested yield of the farmers then suffered from sowing at non-optimal date.

Sowing rate varied between 100 and 300 kg ha^{-1} across the production situations in the province. BLA showed that seed rate of 166 kg ha^{-1} was optimal under irrigated conditions and could help farmers to reach a potential yield of 7000 kg ha^{-1} (Fig. 4). A minimum optimal seed rate of 180 kg ha^{-1} was calculated for both high-yield-rainfed and low-yield-rainfed giving potential yields from the BLA of 6000 and

Table 2
The results of boundary line analysis as well as estimated potential yield and yield gap of wheat in Golestan province.

Management/Input	Min.	Max.	Opt.	Farms out of Optimal (%)	Potential Yield ± SE (kg ha^{-1})	Yield Gap ± SE (kg ha^{-1})	Yield Gap[a] (%)
Irrigated wheat with the average yield of 3900 kg ha^{-1} from 349 fields							
Sowing date (since the first day of growing season)	14	120	45-79	34	6500 ± 161	2600 ± 189	39
Sowing rates (kg ha^{-1})	100	300	166-216	40	7000 ± 55	3100 ± 113	44
N fertilizer (kg N ha^{-1})	0	225	> 95	50	6900 ± 55	3000 ± 113	43
N fertilizer applied after sowing (kg N ha^{-1})	0	193.2	> 94	62	7000 ± 50	3100 ± 98	44
No. splitting N fertilizer	0	6	> 2	8	7000 ± 55	3100 ± 113	44
Phosphate fertilizer (kg P_2O_5.ha^{-1})	0	115	> 50	89	7000 ± 55	3000 ± 113	43
Potassium fertilizer (kg K_2O.ha^{-1})	0	90	> 33	93	7000 ± 50	3100 ± 110	44
Irrigation frequency	0	6	> 2	74	6700 ± 312	2800 ± 327	41
Average					6900 ± 187	2900 ± 187	43
High-yield rainfed wheat with the average yield of 4000 kg ha^{-1} from 119 fields							
Sowing date (since the first day of growing season)	20	110	52-84	22	5800 ± 138	1800 ± 149	31
Sowing rates (kg ha^{-1})	150	300	180-220	45	6000 ± 153	2000 ± 163	33
N fertilizer (kg N ha^{-1})	28	156	> 93.24	61	5700 ± 129	1700 ± 140	30
N fertilizer applied after sowing (kg N ha^{-1})	25.3	144.5	> 91.4	50	5800 ± 203	1800 ± 210	32
No. splitting N fertilizer	1	4	> 2	6	5900 ± 203	1900 ± 210	32
Phosphate fertilizer (kg P_2O_5.ha$_{-1}$)	0	92	> 19.2	16	5900 ± 196	1900 ± 204	32
Potassium fertilizer (kg K_2O.ha^{-1})	0	45	> 30	96	5500 ± 179	1500 ± 188	28
Average					5800 ± 153	1800 ± 153	31
Low-yield rainfed wheat with the average yield of 2000 kg ha $^{-1}$ from 216 fields							
Sowing date (since the first day of growing season)	31	99	50-87	17	4000 ± 48	2000 ± 79	50
Sowing rates (kg ha^{-1})	137	250	180-215	22	4000 ± 23	2000 ± 67	51
N fertilizer (kg N ha^{-1})	0	101.2	23-69	13	3900 ± 38	2000 ± 73	50
N fertilizer applied after sowing (kg N ha^{-1})	0	92	11.5-51	29	4000 ± 38	2000 ± 73	51
No. splitting N fertilizer	0	4	> 1	4	3800 ± 118	1900 ± 133	49
Phosphate fertilizer (kg P_2O_5.ha$_{-1}$)	0	83	> 20.4	40	3900 ± 111	1900 ± 127	49
Potassium fertilizer (kg K_2O.ha^{-1})	0	48	–	–	–	–	–
Average					3900 ± 63	2000 ± 63	50

[a] The percentages do not indicate yield gap due to each management/input variable, but indicate yield gap in the production situation.

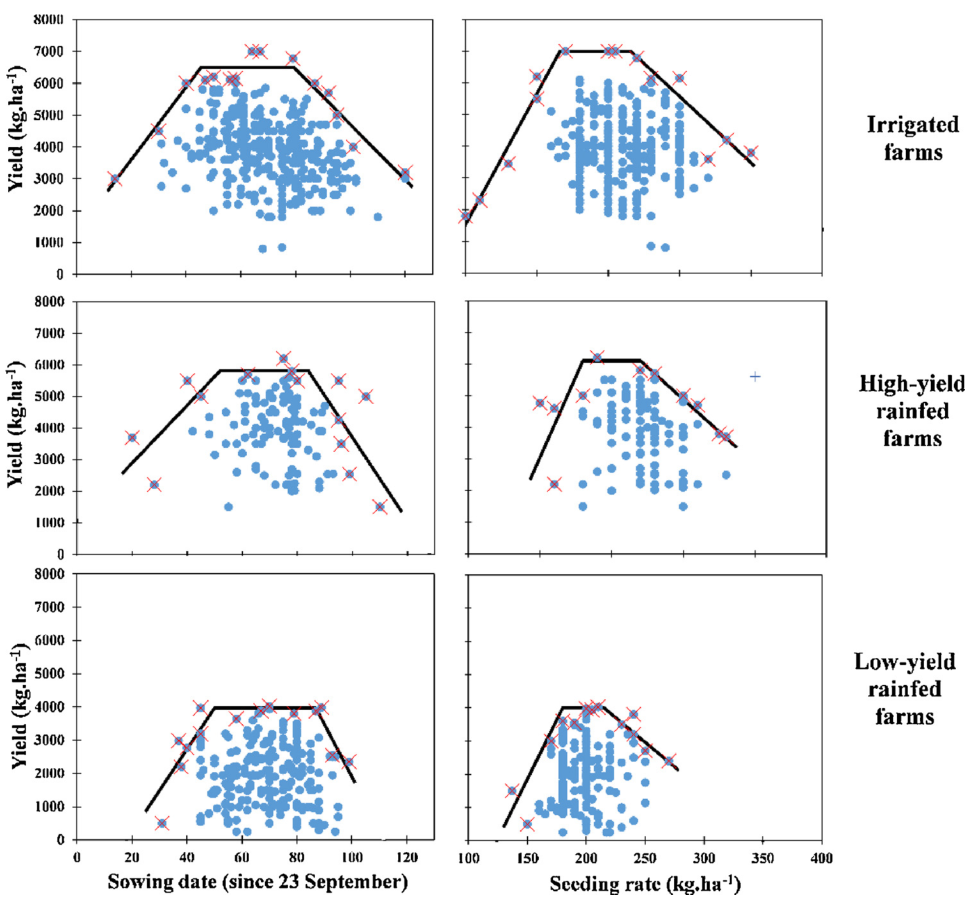

Fig. 4. Scatter plots of the yield data vs sowing date (days since 23 September) and rate (kg.ha^{-1}) along with the fitted boundary line in irrigated, high- and low-yield rainfed situations. Data used for fitting the line are marked with crosses. In high-yield rainfed situations, outlier data of the seed rate has been marked with + and were discarded from the data sets.

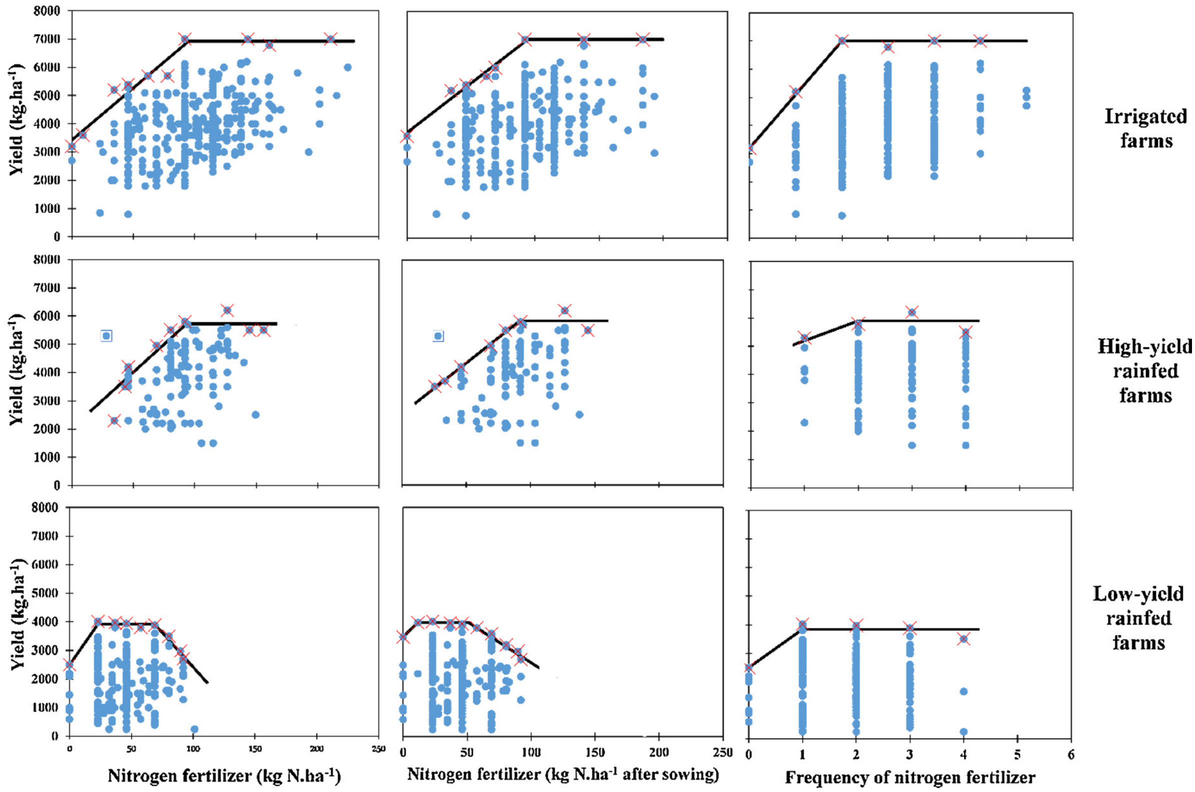

Fig. 5. Scatter plots of the yield data vs N fertilizer (kg N ha^{-1}), N fertilizer applied after sowing (kg N ha^{-1}) and the number of split N fertilizer application (base and top-dressing) along with the fitted boundary line in irrigated, high- and low-yield rainfed situations. Data used for fitting the line are marked with crosses. In high-yield rainfed situations, the data point shown in a square represents a farm where 5 t.ha^{-1} of manure compensates for the low levels of N fertilizer application.

4000 kg ha^{-1}, respectively. In comparison to the average farmers yield, the yield gap was 44% for irrigated, 33% for high-yield-rainfed and 51% for low-yield-rainfed situations (Table 2). BLA analysis then indicated that 40, 45 and 22% of the farmers suffered from yield penalty due to non-optimal sowing rate under irrigated, high-yield rainfed and low-yield rainfed conditions, respectively (Table 2).

Using data of yield vs. total N fertilizer, BLA estimated potential yields of 6900 kg ha^{-1} for irrigated conditions, 5700 kg ha^{-1} for high-yield rainfed conditions and 3900 kg ha^{-1} for low-yield rainfed conditions and that a minimum N fertilizer of 95, 93 and 23 kg ha^{-1} was required to reach these potentials yields for the mentioned conditions, respectively (Fig. 5; Table 2). The analysis also revealed that the application of N fertilizer at rates higher than 69 kg ha^{-1} resulted in yield losses under low-yield rainfed conditions, but such a response was not detectable, within the observed range of applied N, under irrigated conditions and high-yield rainfed conditions. One interesting finding from the application of BLA was that under irrigated and high-yield rainfed conditions almost all of the N fertilizer (94 and 91 kg ha^{-1}; Fig. 5; Table 2) was best applied as top-dressing in two applications at minimum (Fig. 5; Table 2). By contrast, under low-yield rainfed conditions, half of the required N (11.5 out of 23 kg N ha^{-1}) was best applied as a basal application at sowing time and the remaining part as top-dressing. Again, application of more than 51 kg N ha^{-1} fertilizer as top-dressing resulted in yield reduction under low-yield rainfed conditions (Fig. 5; Table 2). An average of 56% of the farmers did not use an optimal N fertilization under the irrigated and high-yield rainfed conditions, while these were 22% in the case of low-yield-rainfed condition. Yield gap estimates from application of BLA to N related variables were 44, 31 and 50% for irrigated, high-yield-rainfed and low-yield-rainfed situations, respectively (Table 2).

When applied to P fertilization, BLA showed potential yields of 7000 kg ha^{-1} for irrigated conditions, 5900 kg ha^{-1} for high-yield rainfed conditions and 3900 kg ha^{-1} for low-yield rainfed conditions, corresponding to yield gaps of 43, 32 and 49% (Fig. 6; Table 2). The minimum P fertilizer required to obtain the potential yields was 50, 19.2 and 20.4 kg P_2O_5 ha^{-1} under irrigated, low-yield rainfed and high-yield rainfed conditions, respectively. However, 89% of farmers under irrigated conditions, 16% under high-yield rainfed, and 40% under low-yield rainfed conditions did not apply the minimum levels, and this led to yield losses of 32% for irrigated, and 23% for both high-yield and low-yield rainfed conditions due to not using an optimal P fertilizer (Table 2).

From a similar analysis for K fertilization (Fig. 6; Table 2) potential yields were determined as 7000 kg ha^{-1} (yield gap = 44%) for irrigated conditions and 5500 kg ha^{-1} (yield gap = 28%) for high-yield rainfed conditions, obtained with an application of a minimum K fertilizer of 30 kg K_2O ha^{-1}. A high percentage of farmers (> 90%) did not use the minimum required K fertilizer. K fertilizer data for low-yield-rainfed conditions did not indicate a specific pattern, so BLA was not applied for this situation (Fig. 6).

Under irrigated conditions, BLA showed that a minimum of 2 irrigations was required to reach a potential yield of 6700 kg ha^{-1}, but 74% of the farmers under the production situation did not apply this number of irrigation (Fig. 7; Table 2). BLA showed that it was possible for the farmers to reach 86% of the potential yield with no irrigation (Fig. 7).

4. Discussion

Sustainable intensification and improvement of the world food security critically need to quantify yield gaps and regions with greatest potential and yield gaps need to be identified to increase food supply (van Ittersum et al., 2013). This is also vital to inform policies and prioritize research to achieve food security without environmental degradation (van Wart et al., 2013). The effort to quantify yield gap requires appropriate methods. BLA is a method that has been used to study limiting factors, but it has not been used as a complete method to

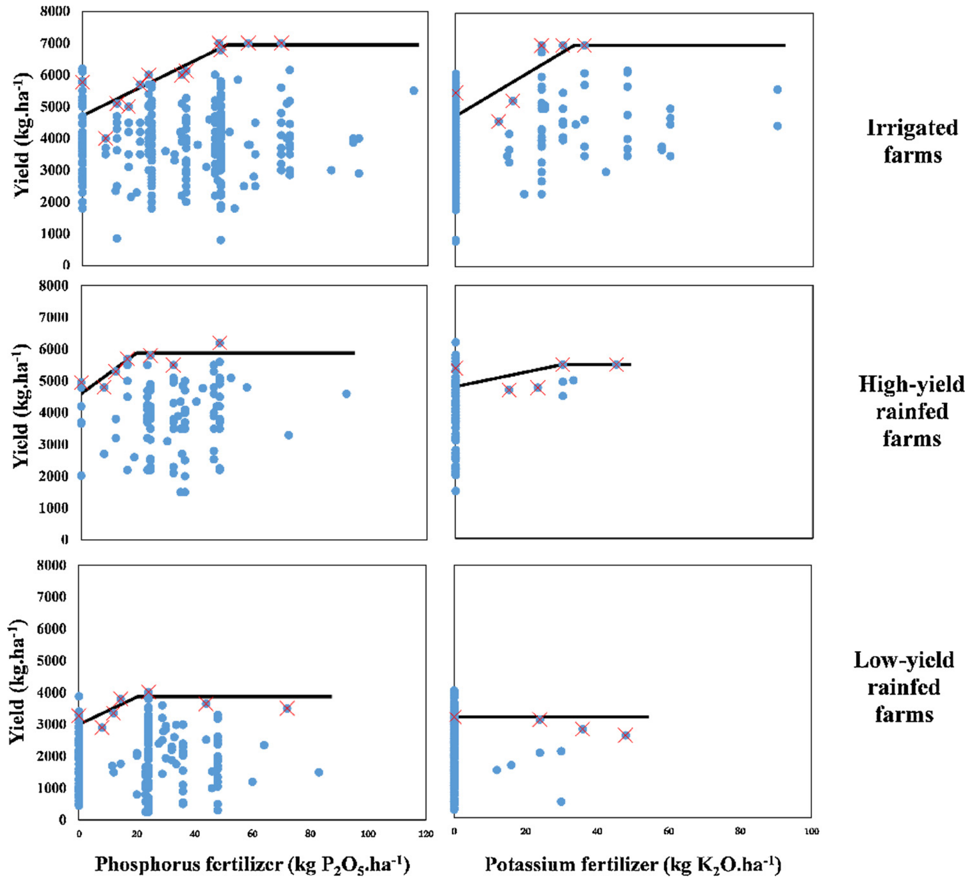

Fig. 6. Scatter plots of the yield data vs applied phosphate (kg P_2O_5.ha^{-1}) and potassium (kg K_2O.ha^{-1}) fertilizers along with the fitted boundary line in irrigated, high- and low-yield rainfed situations. Data used for fitting the line are marked with crosses.

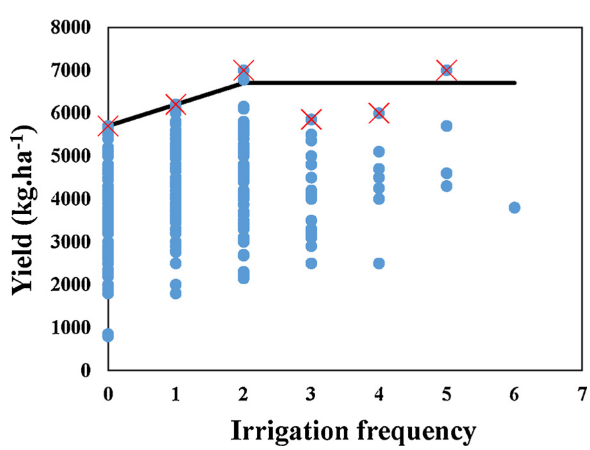

Fig. 7. Scatter plot of yield data vs irrigation frequency along with the fitted boundary line in the irrigated wheat situation. Data used for fitting the line are marked with crosses.

find the causes for yield gap in a given location. A complete yield gap assessment needs to indicate potential yield, actual yield, yield gap, the causes of the gap and the magnitude of their importance.

BLA was applied to wheat crop in Golestan province, one of the top five wheat producing provinces in Iran. It revealed that wheat production in the region suffered from a considerable gap and BLA was also able to indicate which management practices needed to be improved and which ones were not necessary to be considered (listed in Table 1) under current conditions of crop production. Bridging the gap can help food provisioning in the country.

To reduce the yield gap in a given area, detection of involved management operations is necessary (van Ittersum et al., 2013). In the present study, BLA showed that amongst many management practices, sowing date and rate, total N fertilizer applied, the amount of N applied as top-dressing, the number of N top-dressing, the amount of phosphorus and potassium fertilizers and the number of irrigation (only for irrigated wheat) were responsible for yield gap across the three production situations. Among these management variables, total N fertilizer, the amount of N applied as top-dressing, and sowing date and rate were the most important. The number of N top-dressing, the amount of phosphorus and potassium fertilizers and the number of irrigation (for irrigated wheat) had less importance because the lost yield area were smaller for the variables. It should be noted that the slope of the relationship between levels of the variables and the achievable yield is not high although the percentage farmers that did not manage the practices optimally could be high.

Recommended sowing rate by local research centers are 120–150 kg seed ha^{-1} for rainfed and 130–160 kg seeds ha^{-1} for irrigated conditions. However, due to lower seedling establishment under farmers' conditions compared to experimental conditions, the optimal sowing rates found by BLA were higher (Table 2).

Application of BLA to each management factor resulted in an estimation of potential yield and the yield gap. Thus, when applied to several managerial variables, several estimates of potential yield were provided. Average potential yield obtained from application of BLA to different management measures were 6900 kg ha^{-1} for irrigated, 5800 kg ha^{-1} for high-yield rainfed and 3900 kg ha^{-1} for low-yield rainfed production situations. Farmers who managed all the effective management practices within their optimal ranges could reach potential yields (data points on or just below the horizontal lines in Figs. 4–7). Considering average farmers yield of 3900 kg ha^{-1} for irrigated, 4000 kg ha^{-1} for high-yield rainfed and 2000 kg ha^{-1} for low-yield-rainfed situations, average estimated yield gap would be 2900 kg ha^{-1} for irrigated, 1800 kg ha^{-1} for high-yield-rainfed and 2000 kg ha^{-1} for low-yield rainfed situations. These are equal to 43, 31 and 50% yield gap for irrigated, high-yield rainfed and low-yield rainfed situations, respectively. The yield gap estimated for wheat by BLA here is comparable to the figure of 40% for wheat in Iran reported by Mueller et al. (2012). They estimated yield gap of major cereals including maize, wheat and rice in the globe by application of crop simulation models. Similarly, using crop models, Gharine et al. (2012) reported yield gaps of 40 to 65% for wheat in Khuzestan province in the southwest of the country and Nasiri and Koocheki (2009) estimated yield gaps of 58 to 62% for wheat in Khorasan province located in the north-east of the country. It is expected that crop models result in higher estimate of potential yield since yield gap from crop models assume no limitations from pests, diseases, nutrient deficiencies. Hence, yield gaps from crop models are higher.

The calculated yield gap by BLA was close to the definition of exploitable yield gap by Connor et al. (2011) as both potential and actual yields were obtained from farmers' fields. Under farmers' conditions, potential yield was affected by many restrictions. For example, crop rotation imposes sowing and harvesting dates. Sowing date, on the other hand, was also related to other factors such as labor, equipment etc. (van Ittersum et al., 2013). However, potential yield obtained from research stations or from application of simulation models are not influenced by such restrictions.

The highest yield gap belonged to wheat fields under low-yield rainfed conditions. This appeared to be quite normal since such conditions (rainfed farming in salt-affected soils) requires more sophisticated crop management (Debaeke and Aboudrare, 2004).

Application of BLA as describe here is cheap because it does not require expensive measurements as it is only applied to management variables and not to soil or plant related variables. So, the method is suggested for developing countries where yield gaps are higher and the greatest agronomic opportunity exists to increase global food security (van Ittersum et al., 2013; George, 2014). Using BLA, most limiting agronomic measures can be detected and need prompt attention. However, developing countries farmers do not adopt improved agronomic operations unless there is the prospect of making profits with lower risk (George, 2014). Therefore, additional efforts should be made to demonstrate these potential gains experimentally. One important note is that the results from BLA are valid for current conditions and farmers' collection of practices. By changing the production systems (e.g. from conventional tillage to conservation tillage) or climate (change), or after correcting the present limitations of production, other practices/inputs could become important, therefore requiring a new BLA analysis.

Some limitations exist in applying BLA. It was only applicable to quantitative factors and not to qualitative ones such cultivar or type of pesticides. However, the importance of the qualitative variables can be determined using simpler statistical analysis like mean comparison. Also, BLA does not consider the interactions of influential variables in determining crop yield. Indeed, the method only includes the effect of one variable, in spite of the fact that yield is the product of the interactions of a collection of variables (Kitchen et al., 2003). Another limitation was that in the absence of cropping systems under intensive management in the study area, and then maximum yield may not have been indicative of the real potential yield. For example, there may be a specific management or environmental restrictions in the area affecting all farms that could remain hidden in the BLA. Abnormal years in term of weather during the study period or in the presence of an exceptional farmer in the statistical population, could also cause errors in the estimation (van Ittersum et al., 2013; Lobell et al., 2009). Combining BLA with simulation modeling could solve the issue; similar potential yield from both BLA and simulation means that there was no hidden factor in BLA analysis.

One other important implication of yield gap removal via optimizing crop management practice was that optimal crop management may also be significantly cleaner for the environment. Optimal crop management may decrease required input and may lead to less environmental burdens and less pressure on the natural resources (Foley et al., 2011; Smith, 2013; Soltani et al., 2013, 2014). Soltani et al. (2013) showed that, in wheat and in the same region, a better crop management scenario needed 38% lower nitrogen fertilizer, 33% lower total NPK fertilizer and 11% less input energy, but it resulted in 33% greater crop yield. The scenario also had 20% less GHG emissions per unit field area and 40% less GHG emissions per ton of grain.

5. Conclusion

BLA applied to only several management practices/inputs under farmer's control using a large sample of diverse farms was able to quantify a series of yield gaps, their main causes and the magnitude of importance of each of the causes. Irrespective of its limitations, the method can be used easily in countries/regions where the yield gap are high and therefore open to great agronomic opportunities to increase crop production and overall contribute to global food security.

BLA applied to wheat in one of the main wheat producing region of Iran revealed that a substantial yield gap existed, varying from about 2000 to 3000 kg ha^{-1} (31–50% of potential yield). Bridging this gap could help food supply in the country. BLA moreover indicated that total N fertilizer, the amount of N applied as top-dressing, and sowing date and rate were the most important managerial practices/inputs responsible for the gaps, and determined what optimal levels of these variables could be.

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