Large scale assessment of the production process and rice yield gap analysis by comparative performance analysis and boundary-line analysis methods

Ahmad Gorjizad,[1] Salman Dastan,[2] Afshin Soltani,[3] Hosein Ajam Norouzi[1]

[1]Department of Agronomy, Gorgan Branch, Islamic Azad University, Gorgan; [2]Agricultural Biotechnology Research Institute of Iran, Karaj; [3]Department of Agronomy, Gorgan University of Agricultural Sciences and Natural Resources, Gorgan, Iran

Abstract

To reduce the yield gap, specifying yield constraints in a particular area is necessary. A complete yield gap assessment method must provide information regarding potential yield, actual yield, and causes of the gap and their importance. Therefore, documenting the production process to explain crop management factors in each area is very important. The objective of the study was to perform a rice yield gap analysis by using comparative performance analysis (CPA) and boundary-line analysis (BLA). Data were gathered from about 100 paddy fields in Neka, eastern Mazandaran province, one of the major rice producing regions in Iran, in 2015 and 2016. All agricultural practices from nursery preparation to harvest have been recorded for improved rice cultivars. CPA focuses on the ability to estimate potential yield and the reason for a yield gap. Boundary lines were fitted to the edge of the data cloud of crop yield *versus* management variables in data from paddy fields monitoring. The documenting analysis shows that the range of paddy yield in 100 fields varied from 6100 to 8200 kg ha^{-1}. Potential yields were 9241 kg ha^{-1} for CPA method, and 7999 kg ha^{-1} for BLA method. Furthermore, yield gap predicted 2047 kg ha^{-1} for CPA method and 874 kg ha^{-1} for BLA method. In BLA, the average relative yield and relative yield gap of the 13 investigated variables were 89.75% and 10.25% respectively. These results show the importance of each management factor in yield gap. It was concluded that CPA and BLA as applied in the study is a cheap and simple method that, without the need for expensive experimentation, is able to detect yield gap and its causes in a district. From these results, it can be said that the calculated yield gap is close to the definition given for the utilised yield gap and shows the difference between the actual yield and attainable yield in relation to the environmental conditions of the region.

Correspondence: Salman Dastan, Agricultural Biotechnology Research Institute of Iran (ABRII), Karaj, Iran.
Tel.: +98.9111552587.
E-mail: dastan@abrii.ac.ir

Key words: Actual yield; attainable yield; crop management; potential yield; relative yield.

Received for publication: 22 December 2017.
Revision received: 31 July 2018.
Accepted for publication: 13 September 2018.

Italian Journal of Agronomy 2019; 14:1174
doi:10.4081/ija.2019.1174

Introduction

Rice (*Oryza sativa* L.), the most important cereal in the world, fulfils one-third of the food requirement of the world population. It provides about 700 calories per person, and is consumed mostly by people, residing in developing countries (Farooq *et al.,* 2009). Rice is an important crop in Iran, ranking second to wheat as a staple food. Rice has gradually begun to occupy a predominant position in the agricultural economy of the Mazandaran province in Iran. Based on global statistics, rice production is about 750 million tons in the world (FAO, 2016). Presently, the rice cultivation area in Iran was about 550 thousand hectares. In Iran, the Mazandaran province ranks first in terms of rice cultivation area (230 thousand hectares) and rice production. Moreover, the rice cultivation area in the Neka region is about 10,000 hectares equivalent to 4.5% of the total paddy field area in the Mazandaran province (Ministry of Jihad-e-Agriculture of Iran, 2016).

The problems and challenges of the rapidly increasing world population, global climate change, shortages of water suitable for irrigation and degradation of agricultural land are leading to an increase in the demand to improve grain production from rain-fed arable lands. Specific challenges include the estimation of the size and thus the value of the yield gap, identification of the factors limiting current average production, and designing of profitable remedial strategies for a range of agro-ecological regions. One promising way to increase crop production is by closing the gap between yield achieved on the farmer's field and that, which can be achieved by using the best-adapted crop varieties, and best crop and land management practices for a given environment (van Ittersum *et al.,* 2013). Other researchers, through a revision study of completed research works worldwide, also carried out the analysis of cropping systems for increasing resistance (Reidsma and Jeuffroy, 2017). Moreover, yield gap analysis in agricultural plants are vastly investigated in the world, they can be situated into worldwide level (van Ittersum *et al.,* 2013); national level (Hochman *et al.,* 2013) and regional level (Liu *et al.,* 2016). Also, more research is conducted on three main cereals like wheat, rice and corn, which are focused on providing the main component of human food (Beza *et al.,* 2017). Some other studies have been conducted for rice yield gap analysis in conventional and organic cropping systems in the Mediterranean (Delmotte *et al.,* 2011) to determine the effective factors on yield variation of flooded rice in southern-central Benin (Tanaka *et al.,* 2013), define rice yield recession factors in flooded planting systems in the Senegal river valley (Tanaka *et al.,* 2015), simulate rice yield gap in the world (Mueller *et al.,* 2012), and determine yield gap in rice flooding system in China (Xu *et al.,* 2016) and rice yield gap analysis by making models in Philippines (Silva *et al.,* 2017).

Exploitable rice yield gaps are often caused by various factors, which may be classified as physical, biological, agronomic, socio-economic and institutional constraints. These can be effectively improved through participatory approach in action. The narrowing of the yield gap is not static but dynamic with the technological developments in rice production, as the gaps tend to become enlarged with increase in potential yield due to the use of improved cultivars. The narrowing of rice yield gap requires integrated and holistic approaches, including appropriate concept, policy intervention, understanding of the farmers' actual constraints in achieving high yield, deployment of new technologies and integrated crop management promotion, adequate input supplies and field credit, and strengthening of research and extension and the linkages between them. If even one of these components is missing or weak, the narrowing of the yield gap in a particular rice production area cannot reach its full potential. Due to its complexity, there are different points of view regarding the possibility of narrowing yield gaps as a tool for increasing rice production. In fact, the causes of rice yield gaps differ widely from season to season, country to country and/or even from location to location within a country or region. It is therefore essential to consider the yield gap of rice in the local climate and ecosystem. Therefore, the aim of this study was to document the production process and estimate the yield gap in paddy fields in the north of Iran by CPA (Hocking, 1976), and BLA (Webb, 1972; Makowski *et al.,* 2007).

Materials and methods

Description of the site

This experiment was carried out in the Neka area, east of the Mazandaran province. Neka city is located in the northern part of the Alborz Mountains range and the south of the Caspian Sea in northern Iran. The experimental region is geographically situated at 36° 39' N (707702 m E) and 53° 19' E (4058571 m N).

Based on the temperature, rain, and topography of the region, this province is divided into two climate Caspian mild weather and mountain weather. This research covers both climates. Local weather data during the rice-growing period were collected daily from the synoptic meteorological station nearest to the paddy fields (Table 1). *Srad_calc* and *PP_calc* programs can also be downloaded from https://sites.google.com/site/cropmodeling/home.

Data collection

All the agricultural practices in this research, from the primary plough and nursery preparation to harvest, were recorded by paddy field monitoring. For estimating yield gap, all agricultural practices were recorded, from nursery preparation to the harvesting stage, in 100 paddy fields in the Neka region situated in the Mazandaran province via paddy field monitoring in 2015 and 2016. All paddy fields cases pertain to improved rice cultivars. The characteristics of rice cultivars are shown in Table 2. The method of each agricultural practice in the paddy fields was determined for each of the phases of preparing soil, transplanting, cultivating, and harvesting. For each crop, the detected information were frequency and time of tillage operations (*e.g.* plough and disk cultivation), sowing date,

Table 1. Climatic parameters in the survey (2015-2016) and in the long-term period (2001-2016) in Neka region.

Month	Average min. Temp. (°C)		Average max. Temp. (°C)		Evaporation (mm/month)		Rain (mm/month)		Mean relative. humidity (%)		Mean sunshine hours		Solar radiation (MJ m^{-2} d^{-1})	
	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016
April	9.5	10.8	19.5	18.6	71.8	63.2	98.7	99.3	76	77	157.7	123.6	14.7	13.5
May	15.8	16.4	25.2	24.8	115.9	85.9	27.0	41.4	77	78	168.8	140.9	17.0	15.9
June	19.2	19.9	28.6	27.8	154.4	121.8	23.7	24.6	76	80	252.2	232.8	22.2	21.1
July	22.2	22.3	31.4	30.7	169.4	130.2	59.4	39.6	75	79	238.0	203.0	21.3	19.7
August	22.6	22.5	33.5	33.1	193.9	142.3	6.7	11.4	73	76	269.5	232.5	21.9	20.2
September	21.2	21.6	32.0	31.0	156.6	113.9	99.3	88.5	71	65	240.5	193.0	18.6	16.5
Mean 15 years	18.3	18.5	25.2	25.2	147.6	147.6	89.0	89.0	73.5	73.5	208.8	208.8	19.5	19.5

Table 2. Description of name, origin and other characteristics of rice cultivars in the experiment.

Cultivar*	Maturity condition	Paddy yield potential	Baking quality
Shiroodi	Late maturity	High yield	Low
Neda	Late maturity	High yield	Medium
Fajr	Late maturity	High yield	Low
Ghaem	Late maturity	High yield	Low
Khazar	Medium maturity	Medium yield	Medium
Nemat	Late maturity	High yield	Low

*Investigated Iranian improved rice cultivars were semi-dwarf, tolerant to stress.

seeding date, transplanting date, seeding rate, seedling age, plant density, frequency and the amount of nitrogen fertiliser, the amount of phosphorus (P_2O_5) and potassium (K_2O) fertilisers, irrigation frequency and regimes, time and frequency of weed, disease and pest controls and harvesting date. Time of operations (*e.g.* transplanting date) was considered as day since 23 April.

The paddy fields were selected with the help of local experts to represent a wide range of situations. All the management practices/inputs (variables) were monitored and recorded without interfere with farmer operations. The manner of identifying farms covers all main production methods. Then, information pertaining to farm management was collected. For data collecting, all agricultural variables were first separated. In total, paddy fields were different with respect to field area, production operations, inputs used and crop yield were evaluated over the growing seasons from nursery preparation to harvest. At the end of the growing season, the actual yield was registered.

Estimation of yield gap

Comparative performance analysis

Multiple using stepwise regression (Hocking, 1976) was employed to identify factors that explained variation in rice yields from the 150 independent variables. In order to determine the yield model (production model), the relationships between all variables were measured and the yield was evaluated using the regression method. The average paddy yield was calculated by placing the observed average variables (Xs) in the fields under study in the yield model. Thereafter, by putting the best-observed value of the variables in the yield model, the maximum obtainable yield was calculated. The difference between these two is considered as the yield gap. The difference between the products of the average observed value of each variable with its coefficient and the product of the best observed value for the same variable with the coefficient of the same variable presents yield gap value for that variable. The ratio of yield gap for each variable to the total yield gap shows its contribution in creating the yield gap and is presented in percentage. The analysis has been performed by SAS software, version 9.1, were used for the analysis (Hocking, 1976; SAS, 2008).

Boundary line analysis

The main steps adopted for the yield gap assessment using BLA in a specific region/area were: i) selection of farms in the study area. If the study area is large (as it is in the present research) it can be divided to several rather homogenous sub-areas based on climate, soil and/or management system differences. To obtain satisfactory results, a wide range of farms/fields with very different practices/inputs for each of sub-areas, is required; ii) gathering information on management and inputs as the farmers apply them. Only the practices that are under control of the farmers are included. As many as possible agricultural practices need to be included; iii) application of BLA to the gathered data and interpret the results. There is no agreed protocol for application of BLA. 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 under the influence of different levels of a certain variable.

Three general steps can be considered to obtain the boundary line as below (Shatar and McBratney, 2004; Makowski *et al.,* 2007; Patrignani *et al.,* 2014): i) 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.* transplanting date or number of seedling per hill) as independent variable. This step visualises the data cloud and facilitates selecting a proper function to be fitted to the edge of data cloud; ii) selection of the data points from the edge of data cloud to be used in curve fitting: this can be done simply by eye or by one of the advanced statistical methods. There are some statistical methods to objectively choose the outer points for curve fitting or directly fit a line to the outer edge of the data cloud (*e.g.* Milne *et al.,* 2006). For more information in this regards, readers can refer to: Schnug *et al.* (1996); Kitchen *et al.* (2003); Shatar and McBratney (2004); Makowski *et al.* (2007); Huang *et al.* (2008); Riffel (2012); Tasistro (2012); Banneheka *et al.* (2013); and Patrignani *et al.* (2014). For simplicity, in the present study is the selection of the data points from the outer edge of the data by eye and then fitting appropriate function to the points. Such simple methods are also helpful and effective as demonstrated by French and Schultz (1984); iii) the final step is to fit a function to the data points obtained from the second stage. This stage results in a model that explained the response of maximum yield to different levels of the independent variable under examination.

In the BLA method, yield gap (Yg) is calculated as the difference between potential yield (Yp) and average farmers yield (actual yield) (Ya). The relative yield is estimated as:

$$[Ya/Yp \times 100] \quad (1)$$

which indicates how far or close farmers' yields are to Yp. Relative yield gap is obtained as:

$$[Yg/Yp \times 100] \quad (2)$$

as per Soltani *et al*. (2016). SAS software was used to fit the selected functions (SAS, 2008).

Results

Estimating yield gap by comparative performance analysis

Production model

The results of step-by-step regression are presented in Table 3 to determine the most important management variables affecting the yield and production model. In this regression model, the paddy yield per unit area is considered as a dependent variable and other variables such as rapeseed pre-sowing, crop rotation (previous crop), certified seed, seeding date in nursery, N top-dressing usage, K_2O usage, N usage after flowering, and micronutrient foliar application are considered as independent variables, resulting in the final equation. Finally, by using this production equation, the actual yield, the attainable yield, and the share of each variable on yield reduction were determined. Thus, by considering about 150 variables, the model (final regression equation) was selected by stepwise regression with eight independent variables (Table 3). The final yield equation is as follows:

$$Y\ (kg/ha) = 6440 - 425\ X_1 + 307\ X_2 + 256\ X_3 - 9\ X_4 + 495\ X_5 + 10\ X_6 + 146\ X_7 + 314\ X_8 \quad (3)$$

where Y: paddy yield (kg ha^{-1}), X_1: rapeseed pre-sowing, X_2: crop rotation, X_3: certified seed, X_4: seeding date in nursery, X_5: N top-dressing, X_6: K_2O usage per hectare, X_7: N usage after flowering, and X_8: micronutrient foliar application. In this method, Dummy variable approach is adopted.

Yield limiting factors and estimation of yield gap

Table 3 shows the independent variables entered in the regression model with their observed statistics. The best model for some variables, including crop rotation, certified seed, N top-dressing usage, K_2O usage, N usage after flowering, and micronutrient foliar application with positive effect, was selected. Rapeseed pre-sowing and seeding dates in nursery variables had a negative effect and small amount of these variables were selected for best amount. Therefore, the optimal value of these two variables was equivalent to the minimum (Table 3). The increase in yield resulting from the difference between the best and the medium state of rapeseed pre-sowing and seeding dates in nursery was 34 and 223 kg ha^{-1}, respectively, equal to two and 11%. The increase in paddy yield due to the effect of the crop rotation was 111 kg ha^{-1} equivalent to 5% of the total yield increase. The increase in paddy yield related to the effect of using certified seeds and top dressing was 141 and 327 kg ha^{-1} respectively, equivalent to 7% and 16% of total change in paddy yield. The increase in yield related to the effect of K_2O usage per hectare and N usage after flowering was 674 and 324 kg ha^{-1} respectively, 33% and 16% of total yield increase. The yield gap level of micronutrient foliar application was 214 kg per hectare or 10% (Table 1). Among the eight variables introduced in the model, the effect of N top-dressing, K_2O usage per hectare and N usage after flowering is remarkable, and a significant part of yield gap in farmers' fields can be compensated by managing these three variables.

Table 3 shows the total yield gap and contribution of each factor in limiting yield. In the yield model, the mean and maximum yields were estimated to be 7194 and 9241 kg ha^{-1} respectively, comparable with the average and maximum observed yields (7178 and 8200 kg ha^{-1}) respectively. The total estimated yield gap was 2047 kg ha^{-1}. This means that there is a gap of 2047 kg ha^{-1} between the farmer's actual yields and what they can harvest, which can be eliminated or reduced with better management (Table 3). Figure 1A shows the contribution of each variable in the yield gap, along with the actual and potential yields. The actual yield, the calculated potential yield and the yield gap were estimated suggesting that this gap can be compensated. The findings given in

Table 3. Quantifying the rice yield gap and the contribution of each independent variable of the production equation in the comparative performance analysis method.

Variable	Units	Coefficients	Variable in model Min.	Mean	Max.	Best	Predicted yield Mean	Best	Yield gap (kg ha^{-1})	Yield gap %
Intercept	-	6440**	-	-	-	-	6440	6440	-	-
Canola pre-sowing (X_1)	-	–425**	0	-	1	0	-	425	34	2
Crop rotation (X_2)	-	307*	0	-	1	1	-	307	111	5
Certified seed (X_3)	-	256**	0	-	1	1	-	256	141	7
Seeding date in the nursery (X_4)	days since 21	–9**	0	26.11	58	1	–232	–9	223	11
N top dressing (X_5)	number	495**	0	-	1	1	-	495	327	16
K usage (X_6)	kg K_2O ha^{-1}	10**	0	32.60	100	100	326	1000	674	33
N after flowering (X_7)	number	146*	0	0.78	3	3	114	438	324	16
Foliar application (X_8)	number	314**	0	-	1	1	-	314	214	10
Paddy yield	kg ha^{-1}	-	6100	7178	8200	-	7194	9241	2047	100

* and ** show the probability at 5 and 1 percent level, respectively.

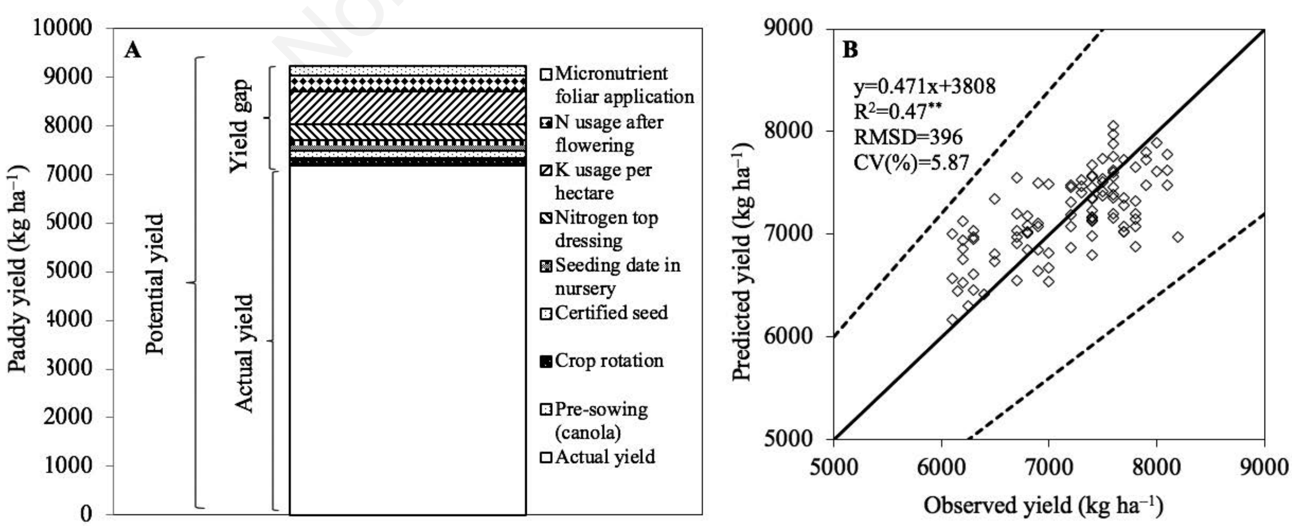

Figure 1. A) The amount of the main constraints of yield gap; B) the relationship between observed and predicted yields. Twenty percent of the differences between predicted and observed yields are shown by segmented lines.

Figure 1B show the relationship between the actual (observed) yield and the predicted yield. This statistic shows that the accuracy of the model (R^2=0.47**) is appropriate and can be used to estimate the yield gap and determine the contribution of each limiting variable (Figure 1B).

Estimating yield gap by BLA method

In BLA method, a relationship is established between maximum achieved yields (*y*) and a target variable (*x*) while other variables are also changing - other variables are not kept constant or optimal. In this method, a line is fitted to the outer edge of the data cloud. This boundary specifies the highest attainable yield (yield potential) or the best yield under the influence of different levels of a certain variable. 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.

By fitting a line on the upper edge of the data, it was determined that the yield response (dependent variable) follows the independent variables, including seedling number per hill, while K_2O usage per hectare follows a positive two-piecewise function. Most variables, including seeding date in nursery, seed usage, planting date, seedling age, plant density, N usage per hectare, and P_2O_5 usage per hectare, follow a negative two-piecewise function. However, the variable, which covers pest and diseases problems, follows a linear function with a negative slope and the variable covering plant lodging and weed problems follows a positive linear gradient function. The findings of these variables indicate that the function of the points below the boundary line is limited by other factors. For some management practices/input, it was not possible to fit a boundary line because there was no relationship between the variables and the maximum yields. Therefore, it has been concluded that crop yield is not limited by the variables as they are currently practiced. Variables that we were able to find relationships for them were: seed rate, seeding date in the nursery, transplanting date, seedling age, seedling per hill, planting density, the amount of applied nitrogen (as N), phosphorous (as P_2O_5) and potassium (as K_2O) fertilisers and the problem of lodging, pests, diseases and weed (Table 4; Figures 2A-D and 3A-D). These variables are causes of the yield gap and should be considered for the improvement under the current conditions. Figures 2 and 3 present scatter plots of rice yield *versus* target management variables. Fitted lines in the figures specify 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 mean crop yield has been limited by other variables else the variable under examination (Kitchen *et al*., 2003).

The average yield in 100 paddy fields was 7178 kg ha^{-1} (Table 4). A two-piecewise regression model was fitted as BLA applied to seed rate, seeding date, seedling age and transplanting date (Figure 2A-D). Seed rate varied between 30 and 120 kg ha^{-1} across the rice production situations in the province. BLA analysis showed that minimum seed rate of 55 kg ha^{-1} was optimal rate for improved rice cultivars in the region and could help farmers to reach potential yield of 7991 kg ha^{-1} (Figure 2A). BLA indicated also that 63% of farmers suffered from yield penalty due to non-optimal seed rate. Regarding the average farmers yield, relative yield gap and yield gap were 10.17% and 7.61% of the total for seed rate variable. Thus, farmers reached 90% of the potential yields by seed usage variable (Table 4). These results indicate that by consuming 55 kg of seed per hectare, optimal paddy yield is obtained and higher seed consumption results in reduced yield.

A negative two-piecewise function was fitted as BLA applied to seeding date in the nursery (as days since 21 March) (Figure 2B). BLA showed that yield potential and yield gap were 8952 and 774 kg ha^{-1} (7.25%) for this variable. Therefore, farmers reached 80% of the potential yields (Table 4). BLF indicated that to reach these potential yields seeding date in the nursery should be undertaken since 4 May (Table 4). Findings regarding seeding date in nursery show that 25% of the fields were outside the optimal level. Relative yield gap and a relative yield for seeding date variables was obtained at 9.73% of 90.27% respectively (Table 4 and Figure 2A).

The boundary line analysis of transplanting date showed that 12% of the paddy fields were outside the optimal level.

Table 4. Estimation of potential yield and yield gap of rice with the boundary-line analysis method.

Variable	Unit	Minimum optimal level	Out of optimal (%)	Yield based on optimal level (kg ha^{-1})	Relative yield (%)	Yield gap (kg ha^{-1})	Relative yield gap (%)	Yield gap (%)
Seed rate	kg ha^{-1}	55	63	7991	90	813	10	8
Seeding date in nursery	from 21 March	25	45	8952	90	774	10	7
Transplanting date	from 21 March	77	12	7894	91	716	9	7
Seedling age	day	40	14	7927	91	749	9	7
Seedling	n/hill	4	12	8000	90	822	10	8
Planting density	n/m^2	22	51	8025	89	847	11	8
Nitrogen	kg N ha^{-1}	116.30	24	8151	88	973	12	9
Potassium	kg K_2O ha^{-1}	20	16	8040	89	862	11	8
Lodging problem	number	1	19	7990	90	812	10	8
Pests problem	number	1	89	8190	88	1012	12	9
Diseases problem	number	1	84	8050	89	872	11	8
Weed problem	number	1	6	7700	93	522	7	5
Mean	-	-	-	8076	90	815	10	100

The average yield in 100 paddy fields was 7178 kg ha^{-1}.

Transplanting outside of the intervals was result in yield penalty for the farmers. The harvested yield of the farmers is suffered from non-optimal sowing date. The minimum optimal value for this variable was June 5 (Table 4). The yield at the optimum level for this variable was 7894 kg ha^{-1} with a yield gap of 716 kg ha^{-1} (6.71% of total). Thus, farmers reached 91% of the potential yield. Relative yield and relative yield gap under the effect of transplanting date were 90.93% and 9.07% respectively (Table 4 and Figure 2C).

The minimum optimal rate for seedling age was 40 days. This variable fallowed a positive two-piecewise function, which shows that seedling-aging time of 20-40 days had no negative effect on the yield while the use of seedlings older than 40 days decreased paddy yield (Figure 2D). BLA analysis indicated that 14% of the farmers suffered from yield penalty due to non-optimal seedling age. Yield potential was 7927 kg ha^{-1}, with a yield gap of 749 kg ha^{-1} (7.02% of the total) (Figure 2D). Thus, farmers reached 90% of the potential yields. Moreover, the relative yield and relative yield gap of seedling age were 90.55% and 9.45%, respectively (Table 4). Findings of seedling frequency per hill showed that a minimum of four seedlings per hill was required to reach a potential yield of 8000 kg ha^{-1}, for which yield gap was 822 kg ha^{-1} (7.70%) and the relative yield was 89.73%. But 12% of the farmers under the production situation did not apply this number of hill (Figure 3A and Table 4). BLA showed that it was possible for the farmers to reach 90% of the potential yield with three seedlings per hill (Figure 3A). The results of BLA for planting density variable indicate that the minimum optimal planting density was 22 plants per m^2 and 51% of the fields were outside the optimal level (Table 4). The yield based on the optimal level under this variable effect was 8025 kg ha^{-1} with a yield gap of 847 kg ha^{-1} (7.33% of total) (Figure 3B). Thus, farmers achieved 89% of the potential yield. Furthermore, the relative yield and relative yield gap for planting density were 89.44% and 10.55% respectively (Table 4).

Using data of paddy yield *vs* total N fertiliser, BLA estimated potential yields of 8151 kg ha^{-1} and that a minimum N fertiliser of 116.3 kg ha^{-1} was required to reach the potentials (Figure 3C; Table 4). The analysis also revealed that application of N fertiliser at rates higher than 116.3 kg ha^{-1} resulted in yield losses for improved rice cultivars in the region. An average of 24% of farmers did not use the optimal range. A yield gap estimate from application of BLA to N related variable was 973 kg ha^{-1} (9.11% of total). Relative yield and relative yield gap for this variable were 88.06% and 11.94%, respectively (Table 4).

When applied to potassium fertilisation, BLA demonstrated that potential yields of 8040 kg ha^{-1} was obtainable, corresponding to yield gaps of 862 kg ha^{-1} equals 8.45% (Figure 3D; Table 4). According to the finding, farmers reached 89% of the potential yield by potassium consumption. The minimum potassium fertiliser required to obtain the potential yields was 20 kg K_2 ha^{-1}. However, 16% of farmers did not apply the minimum levels; furthermore,

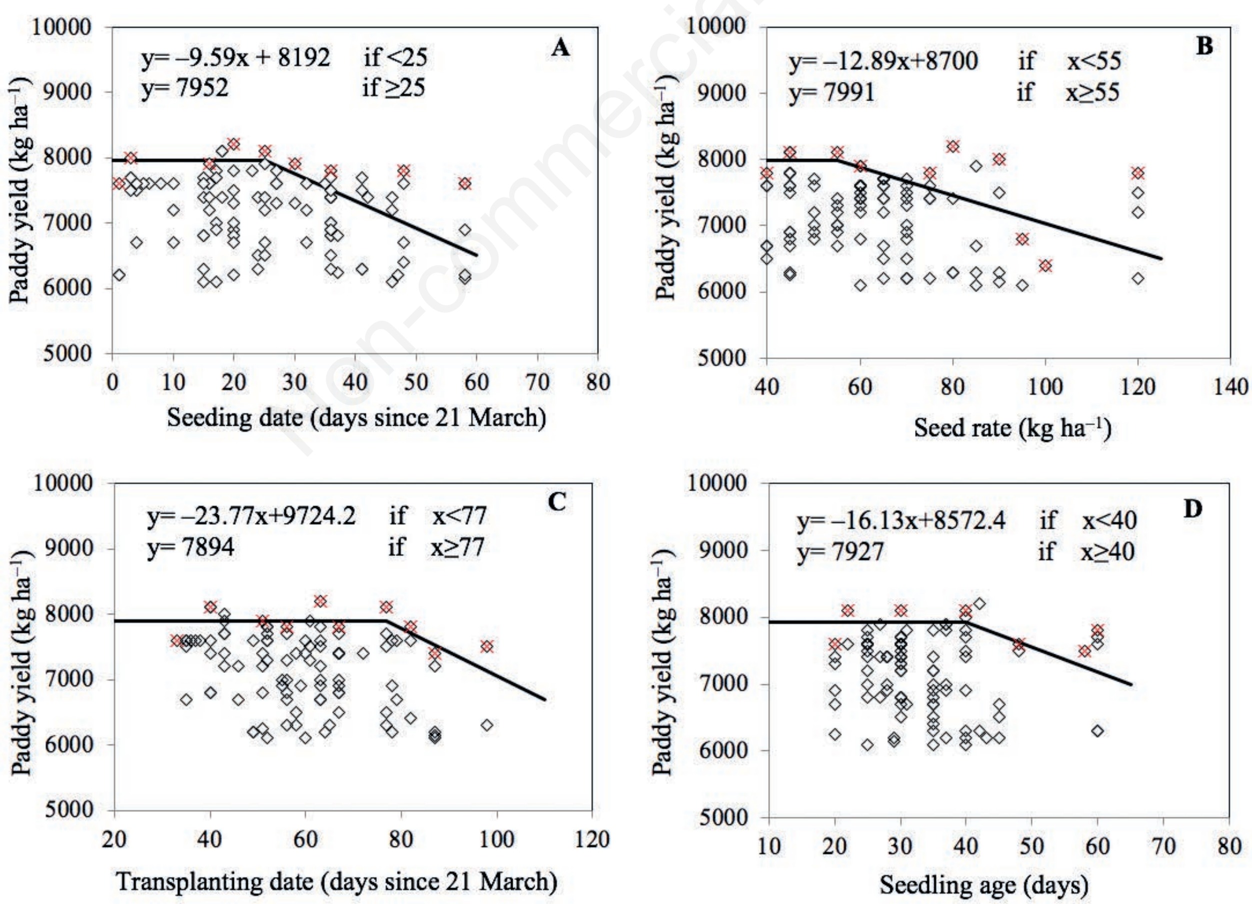

Figure 2. Scatter plots of paddy yield data *vs.* A) seeding date, B) seed rate, C) transplanting date, and D) seedling age along with the fitted boundary line. In green vertical line highest paddy yield will be produced.

yield loss due to not using potassium fertiliser was 8%. For this variable, relative yield and relative yield gap were estimated to be 89 and 11% respectively (Table 4).

The results of BLA for plant lodging, pests, diseases, and weeds problem were ranked as none (0), low (1), medium (2), high (3), and very high (4). The results show that the minimum optimal level for these four variables was equal to one. The percentage value of paddy fields outside the optimal range for these four variables were 19%, 89%, 84%, and 6%, respectively (Table 4). The optimum yield value for these four variables was 7990, 8190, 8050, and 7700 kg ha^{-1} respectively. Farmers reached 90%, 88, 89 and 93% of the potential yield. Regarding the average farmers yield, the yield gaps were equal to 7.61%, 9.48%, 8.17%, and 4.89%. The relative yield value of plant lodging, pest, disease, and weed problems were 89.84%, 87.64%, 89.17%, and 93.22% respectively. Furthermore, the relative yield gaps of these four variables were 10.16%, 12.36%, 10.83%, and 6.78% respectively. According to the boundary line analysis, the average yield based on the optimal level of 13 studied varieties was 7999 kg ha^{-1} with a yield gap of 874 kg ha^{-1}. The average relative yield and relative yield gap of the 13 investigated variables were 89.75% and 10.25% respectively (Table 4).

Discussion

The effort to quantify yield gap requires appropriate methods. To reduce the yield gap in a given area, detection of involved management operations is necessary (van Ittersum *et al.,* 2013). One another important implication of yield gap removal via optimising crop management practice is 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). Paoki *et al.* (2017) revealed that, in wheat and in the same region, a better crop management scenario needed lower nitrogen fertiliser, lower total NPK fertiliser and less input energy, resulted in greater crop yield.

According to the findings of CPA method, the high level of yield gap and the contribution of each factor affecting it show that with proper management, a significant portion of this gap can be offset. The potential yield is rarely achieved in crops, and in practice only part of it is taken as a real crop from the field. Although the purpose of this study was to estimate the rice yield gap in the eastern Mazandaran province, and the reasons for the occurrence

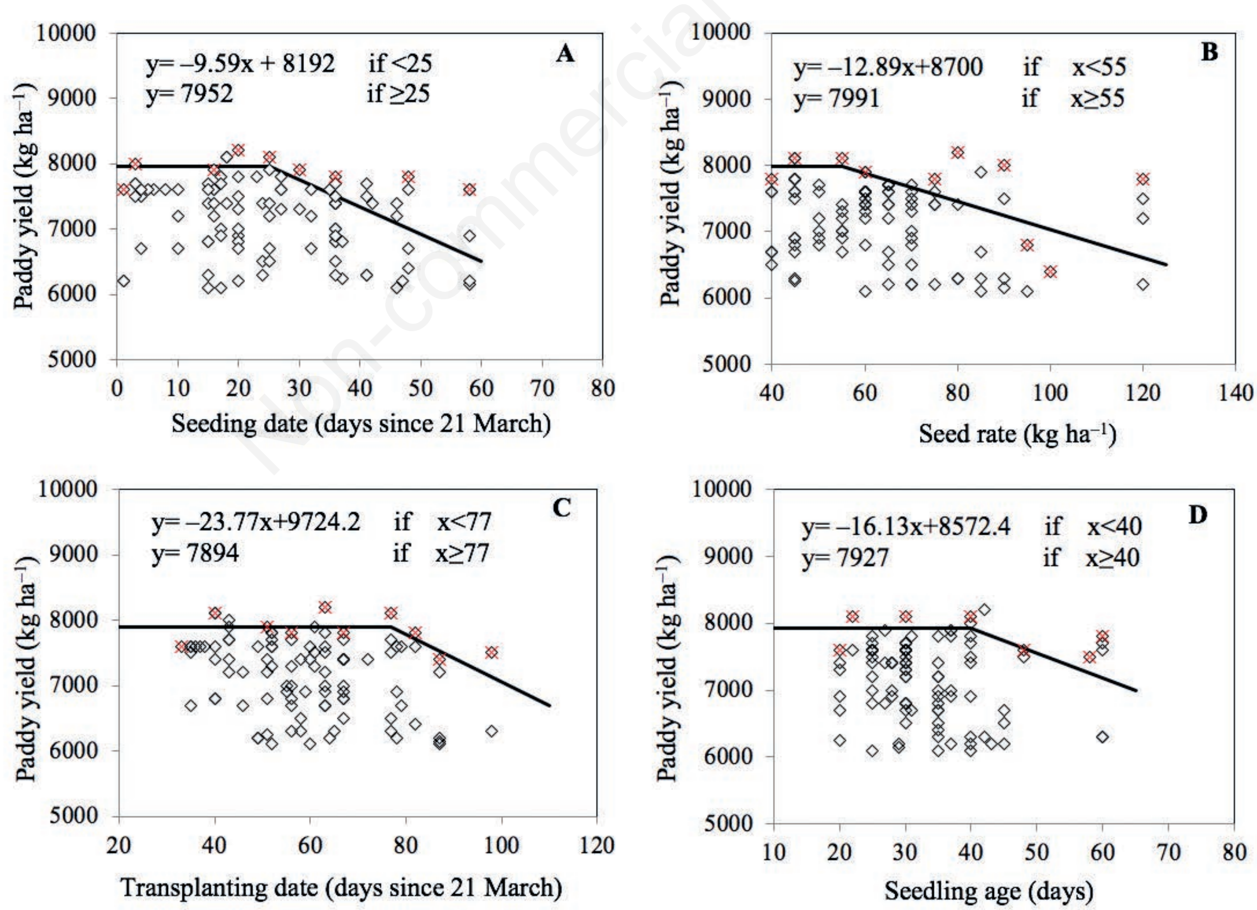

Figure 3. Scatter plots of paddy yield data *vs.* A) seedling frequency per hill, B) planting density, C) total applied nitrogen (kg N.ha^{-1}), and D) applied potassium (kg K_2O.ha^{-1}) along with the fitted boundary line.

of this gap requires further study, the most likely solution that can lead to increased yields and reduced yield gap is by improving crop management in the farmers' fields.

Using BLA method in yield gap studies can clearly show yield responses to agricultural practices and estimate potentials. The interpretation of the results of BLA is simple and it is recommended that a dataset be treated with several analytical methods, along with which boundary line analysis can be used as an applied analysis. It also seems that this analysis can reduce the need for conventional field experiments and provide the investigator with the ability to design new field experiments. If such field surveys are carried out extensively over several years for important crops, it is possible to use more than the ability of such analyses to find ways to increase production. With all these interpretations, it can be said that the calculated yield gap in this study is close to the definition of the yield gap being utilised and shows the difference between the actual and attainable yield values in relation to the environmental conditions of the area. One of the limitations of this research is the number of years covered; the more years taken to complete a study, the more accurate is the estimation of the impact of climate and climate changes. To reduce the yield gap, specifying the yield limits in a particular area is necessary (van Ittersum *et al.,* 2013). The boundary line analysis used in this study in addition to estimating the yield gap indicates the reasons for this yield limitation. The fact that the potential yield calculated in this analysis is obtained from actual data shows that potential yield is dependent on the region; it can be said that this potential yield is attainable. In fact, multi-regional studies impose the effects of planting date, harvesting date, climate and different soil conditions on the plant (van Ittersum *et al.,* 2013). However, there are no such limitations on the potential yield at a research station or in the simulation of potential yield with plant models. Generally, the results of this study indicate that the use CPA and BLA methods in yield gap estimation can properly illustrate the responses of yield to managerial factors by identifying the share of each agricultural variable. Using these responses, researchers can determine the best management and planning to achieve the highest yield. Of course, the use of BLA method has a disadvantage the interaction of variables affecting yield is considered non-significant and only analyses the impact of a variable on yield, while in reality, the yield is the result of the interaction of a set of factors (Kitchen *et al.,* 2003). It is important to note that the use of other methods for estimating potential yield such as the use of plant models along with boundary line analysis can reveal important points of production constraints in a region.

Experiments by various researchers reveal that potential yield is highly sensitive to planting date and cultivar selection in terms of maturity, which together determine the timing of key growth stages and crop-growing season length (Cassman *et al.,* 2010). By estimating yield potential in temperate high-yielding direct-seeded US rice production systems, Epse *et al.* (2016a) reveal that ORYZA rice crop model simulates potential yield well, with most top yields falling within 85% of potential yield for both M-206 and CXL_{745} cultivars. Also, by yield gap analysis of US rice production systems show that there are opportunities for improvement and that potential yield ranged from 11.5 to 14.5 t ha^{-1}, while actual yields varied from 7.4 to 9.6 t ha^{-1}, or 58-76% of potential yield (Epse *et al.,* 2016b). From all these interpretations, it can be said that the yield gap calculated in this research is close to the definition presented by Connor *et al.* (2011) regarding about exploitable yield gap and shows the difference between actual yield and attainable yield in regard to regional environmental conditions. One limitation of this research was the number of years of its implementation. A simulation study done globally for main crops such as corn, wheat, and rice showed a rice yield gap of about 29% internationally; however, the calculated yield gap was estimated to be 11.07-14.73% (Mueller *et al.,* 2012). Further, van Ittersum *et al.* (2013) state that although environmental condition and management (G´E´M) are beneficial for calculating attainable yield in one specific region and by considering the best combination of genotypes, it is impossible to be sure of non-existent live or dead tension throughout plant growing period. Thus, this yield is not sufficiently suitable for the estimation of region potential regarding climatic and earth conditions in most regions. Specific climatic parameters in the region can also be restricting factors of maximum yield in this study for instance; the amount of seasonal radiation in each region causes the increase or decrease in potential yield.

Conclusions

The findings show that farmers in the region are unaware of the importance of seedling age, crop rotation, nitrogen splitting (especially in the flowering stage), K_2O usage by splitting, micronutrient application, and manures usage, which indicates a need to promote and extend scientific findings. In this research, among all the agricultural management practices of the farmers, the cases that have a greater impact on the yield gap and the need for improvement in the first phase are mentioned. Therefore, the advisory recommendation of this study is complementary to other recommended and commonly used management practices.

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