Field Crops Research 225 (2018) 64–73

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

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

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ARTICLE INFO

Keywords:
Crop management
Food security
Increasing production
Optimum managements
Potential yield

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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https://doi.org/10.1016/j.fcr.2018.06.003
Received 10 May 2017; Received in revised form 27 May 2018; Accepted 4 June 2018
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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

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