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Explaining yield and gross margin gaps for sustainable intensification of the wheat-based systems in a Mediterranean climate

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ABSTRACT

Closing the attainable yield and gross margin gaps are important for improving food security and reducing poverty in developing world. Closing these gaps requires quantifying them, identifying major factors constraining the attainable yield and gross margins, and developing mitigation measures. Past literature predominantly focused only on quantification of yield gaps, using yields from experimental stations as the potentially attainable yields. This body of literature overlooked the gaps in gross margins, and more importantly, factors responsible for these gaps – thereby failing to provide sufficient policy guidance to increase productivity. We used a random sample of 2296 fields in 21 major wheat-growing provinces of Morocco as a case study to carry analysis of both yield and gross margin gaps. We used the random forest model to identify factors responsible for variations in yield and gross margins. Our results show that average yield in rainfed areas was 0.9 t ha^{-1} with yield and gross margin gaps of 41% and 75%, respectively. In irrigated areas, average yield stands at 4.0 t ha^{-1} with yield and gross margin gaps of 29% and 34%, respectively – indicating that there is substantial scope for increasing yields and gross margins in both environments. In the rainfed environment, tillage method was the most important variable in determining yield, followed by quantity of phosphorus and nitrogen fertilizer, seed quality, and type of preceding crop. In the irrigated environment, preceding crop was the most important variable in explaining yield gap, followed by variety, seed quality, and quantities of nitrogen and phosphorus fertilizers. Grain yield and grain price were the most important variables explaining gross margins. Top performer farmers in both environments had applied higher quantities of inputs and hence incurred higher costs but still had higher nitrogen and phosphorus use efficiencies and higher gross margins than the rest as the yield gains more-than offset the increases in costs. Policy and institutional implications of these results are: 1) The irrigated environments should be targeted with efforts and incentives to motivate wider adoption of legume-based rotations; 2) Incentive mechanisms should be created to encourage farmers in the rainfed environments to adopt no-tillage, use more phosphorus and nitrogen fertilizers, and buy certified seeds; 3) Legume-based rotations reduce need for nitrogen and enhance phosphorus use efficiency in subsequent crop, targeting rainfed environments also with rotation can be used as a strategy to enhance sustainability of the production system and reducing financial burden of higher doses of chemical inputs.

1. Introduction

To meet the growing food demand for the world population, crop production levels should increase by 70% above current production levels by 2050 (Hunter et al., 2017). Production can be increased either through the expansion of the crop area or increasing yield per unit area or both (Alexandratos and Bruinsma, 2012). Increases in yield per unit area can be achieved through an increase in yield potential and or by narrowing the attainable yield gaps (Fischer et al., 2014).

Estimation of the attainable yield gap and identification of its causal factors provide important information on the potential options for intensification on existing crop production systems (Lobell et al., 2009). Attainable yield gap is generally defined as the difference between a potential yield (under no-limitation of water and nutrient and no other biotic stresses) and the mean farm yield achieved by farmers over a specified temporal and spatial scale of interest (Lobell et al., 2009; Sumberg, 2012; Van Ittersum et al., 2013). However, estimates of yield gap by themselves may not be sufficient to inform decision makers on whether the introduction of technologies and practices that can help in narrowing the gap will be well received by farmers. This is because, the

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technologies and practices required to narrow the yield gap may be costly - thereby making the changes financially infeasible. In this paper, while we borrow a concept from the frontier production function approach and apply it to the standard yield gap analysis (Fischer, 2015) to classify the farmers in different yield categories in the estimation of the yield gap across different agro-ecologies in Morocco, we don't claim to make a methodological contribution to the literature. However, we do introduce for the first time what we termed as the “gross margin gap” the computation of which, accounts not only the gap in yield but also the additional quantities of inputs that are needed to close the gap, the input and output prices, and costs of new technologies and practices introduced. Farmers are unlikely to adopt a technology which is not economically viable (with few exceptions involving natural resource management). Hence, we believe that gross margin gaps would help decision makers in making better predictions on the potential adoption by farmers of the interventions that are needed for and hence the feasibility of closing the yield gap.

There are several methods to estimate and explain yield gaps considering different yield benchmarks including crop simulation (Hochman and Horan, 2018; van Rees et al., 2014); field experiment with no yield constraint (Pala et al., 2011; Peake et al., 2014); 80% of potential yield (Van Ittersum et al., 2013); the mean of the upper decile of farmers' yields (Laborte et al., 2012); the maximum observed yield from a sample of farmer's fields (Waddington et al., 2010); and attainable farm yield (the mean of the top decile) with the population mean (Devkota et al., 2019; Stuart et al., 2016). Each estimation method has its own strengths and limitations, which pose a major challenge in making yield gap estimation consistent, comparable, and clear for the end user (Stuart et al., 2016).

Wheat is the major food crop in Morocco, cultivated on an average area of about 2.96 M ha in the last ten years (FAOSTAT, 2020), where about 83% are located in arid or semi-arid rainfed areas and only 17% of the wheat area is irrigated (Yigezu et al., 2019a). With the increasing population and changing food habits in favor of wheat-based products such as bread and couscous, local production is unable to meet the local demand and hence the country's wheat imports have been increasing over the years. In 2017, domestic production covered only 58% of domestic demand, while the remaining 42% was fulfilled by imports (Bishaw et al., 2019), suggesting considerable need for the enhancement of productivity and hence current domestic production.

Compared to the base period of 1991–2000, average wheat yield in Morocco during 2009–2018 is higher by 29 kg ha^{-1} year^{-1} showing that only little yield gain was achieved over the last 28 years with 41% annual variability (coefficient of variation) in productivity (FAOSTAT, 2020). Based on comparison of simulated potential, yield data from experimental stations, and nearby farmers' fields, wheat yields in rainfed and irrigated areas can be increased by 160% to 250% in different regions of Morocco, by 150%–300% in Turkey, and by 170% to 200% in Syria (Pala et al., 2011). The study also reported a higher yield gap (89%–250%) in the rainfed than in the irrigated (46%–82%) production environments in Morocco. However, the study compares experimental station yields and yields from farmers' fields and takes the difference as the yield gap which may not be realizable as we cannot convert all farmers into scientists and it is difficult to compare the yields of closely monitored small experimental station plots with large wheat fields under real farmers' management condition. They also don't provide quantification of the causal factors for closing the yield gap. More importantly, the study does not take into consideration the gross margin gaps and their causal factors for rainfed and irrigated conditions.

Attainable yield gaps and the major causal factors may vary under irrigated and rainfed environments (Fischer et al., 2014; Pala et al., 2011). Yield gap can be closed through supplemental irrigation, and increased efficiency of irrigated and rainfall water use, along with high-yielding varieties and improved agronomic management in the Middle East and North Africa (MENA) region (Pala et al., 2011). “Agronomic deficiencies” such as seeding time, insufficient nitrogen and phosphorus nutrition, tillage practices, lack of control of pests and diseases, and cropping sequences are the major causes for yield gap in water-limited conditions of Australia (Hochman and Horan, 2018).

The MENA region is characterized by frequent droughts, high fluctuations of rainfall and irrigation water and generally high input prices (Pala et al., 2011). Therefore, analysis is needed not only of yield gap but also in terms of the gap in profits that can be bridged. Also, optimal crop production strategies to increase yield and profit needs to be risk efficient. High yield, low risk (risk efficient) options with economic profitability could lead the production system towards sustainability (Peake et al., 2016). However, comparative biophysical, socio-economic and crop management analysis of alternative crop management practices for rainfed and irrigated wheat production environments is lacking for the MENA region in general and Morocco in particular.

Understanding farmers' current crop management practices, average current and potential grain yields and gross margins, are important for targeting and for guiding research, investment, policies and institutional objectives including extension and input service delivery systems and ultimately to close the gaps in yield and gross margins. Wheat yields in farmers' fields are not only affected by agricultural practices but also largely determined by the resource endowment, input use, and cropping system, which varies across location and individual farmers, and hence the need for site-specific recommendations (Elias et al., 2019). It is important to study why crops in some fields are not performing as well as the crops in other fields cultivated by the same or different farmers, and why some farmers are not obtaining the maximum attainable gross margin under their own conditions and the determinants for improvement.

Recommendations based on field-level information and/or by applying machine learning techniques to big data can help in increasing the precision of recommendations and in saving time and resources (Jeong et al., 2016). Random forest (RF) and partial dependent plots (PDPs) are among such tools for better understanding the causal factors for yield and profit gaps and for generating recommendations for an optimal use of inputs and resources. Thus, the objectives of this study are: (1) to use large field-level data and robust estimation methods and generate credible estimates of the yield gaps and hence the potential for increasing wheat productivity and income among low performing farmers in the rainfed and irrigated environments of Morocco and the Mediterranean region at large; (2) to identify the major factors which explain the variation in the yield and gross margin gaps; (3) to make specific recommendations for closing the yield and gross margin gaps in the rainfed and irrigated environments of Morocco.

2. Methodology

2.1. Study site description

Morocco has a total area of nearly 711,000 km^2 including 2934 km of coasts on the Atlantic Ocean on the West, and 512 km of coast on the Mediterranean Sea to the North. It borders Algeria to the East and South-East and Mauritania to the South-West. The country is characterized by a wide variety of topographies ranging from mountains and plateaus to plains, oasis and Saharan dunes. The country faces irregular rain patterns, extended periods of dry spells and wet periods with a regime of irregular precipitation, cold spells and heat waves (Lahlou et al., 2016). These conditions - typical of the Mediterranean climate, are increasingly resulting in droughts, which significantly affect agriculture. The country's long-term (2000–2019) average annual rainfall is 308 mm with 25% variation and average annual temperature of 29.7 °C. In the crop growing season of the study year (2013), the weather condition can be considered average with national average rainfall of 282 mm which was only 8.5% lower than the long-term average (Fig. 1).

In Morocco, agriculture exhibits a dichotomy between traditional

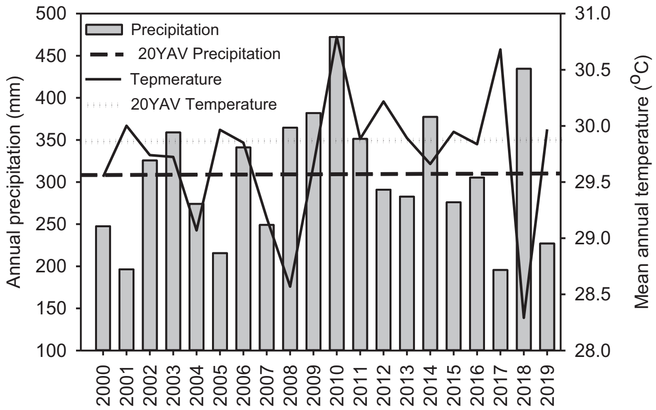

Fig. 1. Long-term rainfall (mm) and temperature (°C) in Morocco. Short dotted line is 20 years average (20YAV) temperature and long-dotted line 20 years average rainfall.

subsistence-oriented production and market-oriented production. The traditional subsistence sector consists of small farms in rainfed areas involved predominantly in cereal, legume, and livestock production. Rural population that represents nearly 44% of Moroccan inhabitants is mostly composed of small subsistence farmers whose production depends almost entirely on rainfall. The gross annual agricultural product is therefore strongly correlated to the annual rainfall and, due to the economic weight of the agricultural sector, each rainfall deficit impacts the whole economy of the country. Market-oriented agriculture is concentrated in irrigated areas and although representing only 15% of agricultural lands, contributes to 45% of the GDP and 75% of agricultural exports (Lahlou et al., 2016).

Morocco is divided in to 13 administrative regions (16 regions before 2015, i.e., during study time). Cereal production in Saharan region is essentially limited to barley and represents only about 2% of Morocco's rainfed cereals for which this zone has been excluded from our study. The study was conducted in nine out of the 16 regions which are concentrated in the central parts of Western Morocco (Fig. 2). Those regions consist of market-oriented wheat production areas with irrigation facilities to traditional, rainfed and subsistence-oriented wheat production covering over 83% of the total national wheat area. Although there are some agro-ecological differences, the wheat varieties and agronomic practices used in the studied region are similar (Yigezu et al., 2019a). Therefore, given the homogeneity within and substantial heterogeneity across the rainfed and irrigated environments, all the analysis that follows is carried based on the broad classification of the country into irrigated and rainfed wheat production systems. Given the substantial yield difference between irrigated and rainfed environments even within a given province, the classification based on water source becomes more sensible for yield gap analysis.

2.2. Data collection

This study is based on data collected through a nationally representative survey of 2296 wheat fields cultivated by 1230 households in the wheat-based production systems of Morocco. This sample size ensure 95% confidence and 3% precision levels on the estimates of adoption of improved wheat varieties. The survey was carried out in the 2013 growing season covering both irrigated and rainfed environments of the 21 major wheat-growing provinces that account for 73% of the total national wheat production. The Directorate of Strategy and Statistics (DSS) at the Ministry of Agriculture and Marine Fisheries (MoA) of Morocco has established a national sample of 20,000 farm households for its regular annual agricultural surveys on crop production. The sample was based on the "area frame" approach using the following steps:

- To create more homogeneous groups of farms, five strata representing different farm sizes were established for the survey
- With high resolution maps drawn from satellite images acquired by the MoA, and other available maps, very accurate stratification of the land was done. The stratification was done on topographic maps where sampling is based on a GIS application, which gives the global positioning system (GPS) coordinates of the sample households
- Validation was done using maps and actual interviews on the ground by enumerators from the DSS
- Data was consolidated and verified in the office
- Strata were identified, and boundaries delineated digitally
- A GIS application was used to build area frames for the different strata from which the samples were drawn randomly
- A total of 20,000 farm households were selected from the selected

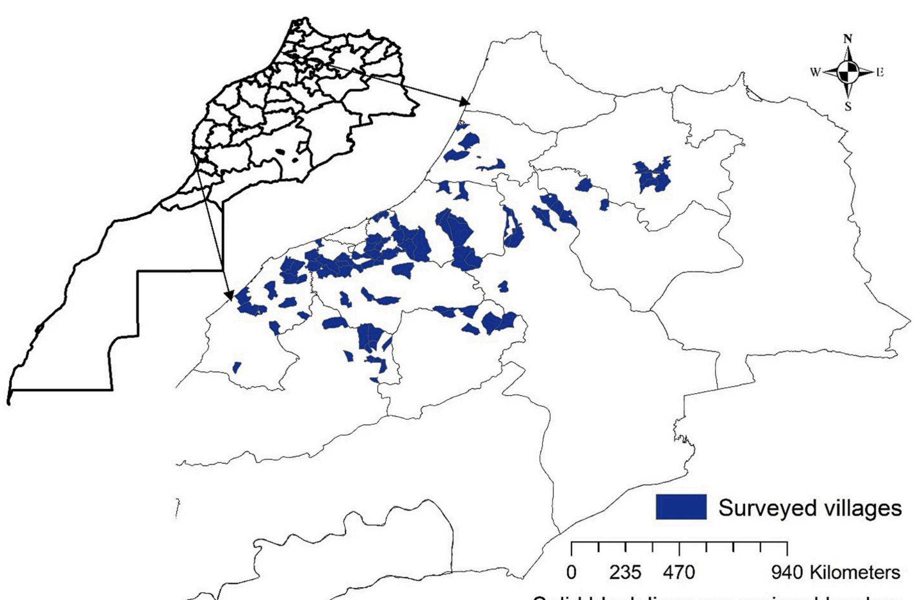

Fig. 2. Study sites in Morocco showing the surveyed villages within the nine study regions.
Note: Regional boundaries in this study are based on the classifications before 2015.

Table 1
Wheat area, number of farmers and distribution of sample households across the 21 major wheat-producing provinces.

Region	Province	Area (,000 ha), average for 2002-2011			Total no. of wheat growers (,000) in 2011	Sample statistics		
		Bread wheat	Durum wheat	Total		No. of districts	No. of villages	Total HH
Chaouia-Ouardigha	Benslimane	54.96	25.41	80.37	13.92	3	10	27
	Berrechid	131.96	133.9	90.39	20.70	2	13	43
	Settat			175.47	40.19	3	33	82
Doukkala-Abda	El Jadida	95.98	79.46	92.98	64.08	3	16	76
	Sidi Bennour			82.46	56.82	2	17	68
	Safi	74.74	73.59	148.33	63.25	3	19	130
Fes-Boulemane	Fes	69.79	29.72	12.94	3.64	1	1	8
	Moulay Yacoub			86.57	24.34	2	7	52
Gharb-Chrarda-Bni Hces	Kenitra	94.03	13.36	85.97	30.66	3	17	59
	Sidi Slimane			21.42	7.67	1	8	18
	Sidi Kacem	144.94	32.59	177.53	44.40	5	22	67
Marrakech-Tensift-Alhaouz	El Kelaa	155.36	67.91	73.68	20.33	2	12	38
	Rehamna			149.59	41.27	2	12	77
Meknès-Tafilalet	El Hajeb	48.95	9.88	58.83	9.02	3	7	22
	Khenifra	67.09	37.25	104.34	28.05	2	11	58
	Meknes	71.78	4.49	76.27	13.73	1	11	29
Rabat-Salé	Khemisset	127.62	29.58	157.2	32.67	4	25	67
Tadla-Azilal	Beni Mellal	153.68	37	190.68	46.06	3	7	90
Taza-Alhoceima-Taounate	Taounate	103.26	80	183.26	61.16	4	24	124
	Taza	32.83	70.34	82.54	39.24	5	14	75
	Guercif			20.63	9.81	2	6	20
Total Sample		**1,426.97**	**724.48**	**2,151.45**	**671.01**	**56**	**292**	**1230**
Total National		**1930.07**	**979.90**	**2,909.97**	**Not available**			
Sample as % National Total				**73.9%**				

segments; these became the master sample for the annual national agricultural surveys.

The area frame sampling technique is used for many purposes including the estimation of crop areas, yield, and the use of fertilizers, seeds. So, in the initial design, existing estimates of coefficients of variation for many variables were collected and the largest estimate was used to cover all issues. The master sample that was generated now supports all studies and surveys conducted by the DSS. Consequently, the master sample for cereal crops was used as the sampling frame for this study from which the sample of 2,296 wheat fields was taken. A multi-stage stratified random sampling procedure was used for drawing the sample where provinces, districts and villages were sequentially used as units of stratification at the level of each geographic unit. Sample provinces, districts and villages were randomly selected and then farmers were selected from the roaster of the bigger sample of farmers that is maintained by DSS. The total sample was distributed across provinces, districts and villages in proportion to their cereal farmer population sizes (Table 1). A structured survey questionnaire was developed and used to collect data from each of the 1,230 sample households. The first part of the questionnaire comprised of several household-level questions including demography, different forms of capitals (human, social, financial, physical, and natural resources), the farmer's knowledge of the different wheat varieties and recommended agricultural practices, and location. The second part of the questionnaire contained detailed field-level questions including field size, soil type, previous crop, wheat variety used in the current year, tillage number, seed source, seed rate, access to irrigation, quantities and prices of inputs used (labor, different kinds of fertilizers, pesticides, and herbicides) and prices received for the outputs.

2.3. Data analysis

2.3.1. Yield and gross margin gaps

Based on grain yield, farmers were classified into three categories: top (10th decile), majority (between 2ndand 9th deciles), and bottom (1st decile). As mentioned in the introductory section, while different approaches exist for the measurement of yield gap, in some recent studies (Devkota et al., 2019; Fischer, 2015; Stuart et al., 2016), the attainable yield gap is computed as the difference between the yield of the top-performing farmers (e.g., yield of the farmers in the top decile) and the population mean yield. Borrowing the conceptual framework from productive efficiency analysis using the frontier production function approach, where the farmers in the frontier are compared with everybody else (Battese et al., 1989), we argue that the population mean is not the correct reference as it includes those who have already achieved the highest possible yield under farmers' current management. By using the population mean yield as the reference, some past studies have inadvertently underestimated the yield gap. Therefore, in this paper, we computed yield gap as the difference between the mean yield of the top (10th) decile and the mean yield of all other farmers who are not in the top decile. The percentage yield gap is then computed by dividing the yield gap by the mean yield of the rest of the farmers which are in the 1st-9th deciles.

2.3.1.1. Determination of gross margin. Gross margin was computed as the difference between revenue and cost per hectare (excluding the costs of land and environmental externalities). Total revenue is calculated as the sum of the products of the grain and straw yields with their respective market prices while total cost is calculated as the sum of costs of all inputs including labor, machinery hire, seed, fertilizer, irrigation, pesticide, tillage, and other farm operations.

In Morocco, bread wheat is subject to a support price set by the government every year. Bread wheat farmers get the support price when they deliver their produce to the grain mills provided that the shipment meets the minimum quality standards set by flour mills. About 61% of bread wheat producers in the country deliver their grain to the mills while the rest sell in the market at the going price which varies according to the law of supply and demand. Durum wheat is not subject to price support and hence its price is determined according to market conditions. The price variations in our grain price data obtained from the farmer interview reflects that farmers received different prices for their produce. During our survey, we inadvertently didn't collect data on residue prices for which we solicited for a single estimate for a national average residue price from experts and the literature. Therefore, considering the market situation in the country, we used in our analysis the wheat grain prices reported by each farmer and a single average wheat residue price of $110 per ton without regard to how much of it is used for the farm households' own human consumption and animal feed, respectively. By so doing, we have implicitly assumed that the value of own consumption is represented by the market price. While this assumption will make our gross margin gap analysis in this paper more realistic, in the face of highly subsidized bread that is sold in the market, it will not be valid for impact assessment as own consumption has higher opportunity cost. The average producer price of wheat for 2012/2013 was $ 305 ton^{-1} which is slightly higher than the 10-year average of $ 279 per ton.

Even though some of the inputs are subsidized, prices of inputs including seed vary across provinces, districts and even villages within the same district because, farmers can source their inputs from different establishments including some public and private agro-vet businesses. Depending on their objectives, cost structure, transaction costs and individual profit margins, the prices charged by the different input dealers vary substantially. On the other hand, we have applied the real price received by faremrs for wheat grain they sold based on their own reporting. This we believe makes the gross margin gap analysis more useful as it reflects the reality on the ground and hence may have important policy implications. For example, if there is disproportionately higher gross margin gap than there is yield gap, it might possibly be because the more productive farmers are receiving higher prices and/or paying relatively lower input prices and hence standardizing input and output prices (preferably at the higher and lower levels, respectively) may provide an incentive to bridge the yield gap and the gross margin gaps.

2.3.2. *Analysis of variables of importance*

Several approaches including principal component analysis (PCA), hierarchical ascendant classification (HAC) and the random forest (RF) model can be used for groupwise comparisons of means. However, these groupwise comparisons fail to capture the impacts of variations in several other factors. Therefore, regression analysis which enables the analysis of the impacts of changes in one variable holding the values of all other variables constant at the sample mean values of each variables are preferred for such comparisons. RF, which is a binary tree-based machine-learning method (Breiman, 2001; Cutler et al., 2012), can be used for both classification and regression purposes. In RF, source data for model training are bootstrapped to make various subsets to randomly generate a large number of trees. RFs are composed of multiple independent decision trees that are trained independently on a random subset of data. To classify a new instance, each decision tree provides a classification for input data. RF collects the classifications and chooses the most voted prediction as the result. The input of each tree is sampled data from the original dataset. In addition, a subset of features is randomly selected from the optional features to grow the tree at each node. Each tree is grown without pruning. RF enables a large number of weak or weakly-correlated classifiers to form a strong classifier (Mao and Wang, 2013). Predictor variables are evaluated by how much they decreased node impurity and for how often they make successful predictions when selected. Node impurity is measured in terms of the mean square error (MSE) at the node in the RF (Breiman, 2001).

In this paper, the RF model was applied to field-level data on crop management practices, soil, and weather information, which is augmented with household level data on selected socio-economic variables to analyze the major determinants of variations in yield and farm gross margins under farmers' management practices for the rainfed and irrigated environments of Morocco (Table 2). The RF was also used to analyze variables of importance and partial dependence plots (PDPs) for grain yield and gross margins for wheat. We used the 'randomForest' package of the statistical program R (R CoreTeam, 2016) and followed Liaw and Wiener (2002) to set the values of parameters for estimation of the model (mtry = 5, ntree = 1000, and nodesize = 10). Two variable analysis tools available from the package were used for analyzing the importance of variables and to generate PDPs (Breiman, 2001). First, mean decrease accuracy the percentage increase in mean square error (%IncMSE) was used as a measure of variable importance. The %IncMSE plot shows the average increase of MSE in nodes that use a predictor in the model when values of the predictor are randomly permuted. To assess the performance of the model, we used R^2, root mean square error (RMSE), and slope which we also visualized by making an observed vs. predicted plot. The second analysis tool, PDP, shows how the RF model predictions are influenced by each predictor when all of the other predictors in the model are controlled for. The Y-axis values of a partial dependence plot are determined by the average of all of the possible model predictions using the dataset for every value X of the objective predictor. Further, for those categorical variables which could not be visualized by PDP, a boxplot diagram was presented.

2.3.3. *Risk/return trade-off for different management practices*

To understand the risk/return trade-off and to identify the optimum or risk-efficient farm management strategies, we used a variant of the mean-variance approach (Barah et al., 1981; Caberry et al., 1993; Hammer et al., 1996; Peake et al., 2016). This approach involves plotting mean gross margin vs. standard deviation of the mean for each farm-management practice. In this paper we have analyzed the risk/return trade-off for the frequency of tillage operation, fertilizer (nitrogen and phosphorus) management, crop rotation practiced. The line of indifference frontier was used to understand risk/return trade-off analysis. This line represents the 1:2 ratio between gross margin and standard deviation that has been found to represent the intermediate level of risk/return trade-off preferred by the majority of growers in multiple cultures (Barah et al., 1981; Peake et al., 2016) and has previously been used in conjunction with the risk frontier (Caberry et al., 1993; Peake et al., 2016).

2.3.4. *Trade-off among input use and efficiency indicators*

Nitrogen (N)- and phosphorus (P)- use efficiencies (NUE and PUE expressed in kg grain kg^{-1} elemental N and P, respectively) were computed by dividing the total grain yield harvested by the total elemental N and P applied. Radar/spider diagrams were used to analyze the tradeoffs between input use, input use efficiency, cost of production, yield and gross margins among the three yield categories across the irrigated and rainfed environments for the continuous variables which fits on a linear scale. Some key factors such as tillage, previous crop and use of certified seed have not been incorporated as they don't fit on a linear scale, hence are resented in a box plot. For the ease of visual comparison, the values of all variables were normalized by percentage share of each yield category.

3. Results

3.1. *Characterization of the production environment*

As described in Section 2.2, data for only one year (2013) was collected. Therefore, all the results that are presented below the year 2013 or can be generalized for a typical year in Morocco. The average grain yield of wheat under farmers' management was 897 kg ha^{-1} in rainfed and 3994 kg ha^{-1} in the irrigated environments. Yield variability was higher in the rainfed environments with a coefficient of variation (CV) of 28% which is double of what is in the irrigated environment (Table 3). The average landholding size was 12 ha and 14 ha, respectively, in the rainfed and irrigated environments with greater variation in the irrigated areas. In irrigated environment, the average landholding of top decile farmer was lower than the average landholdings. With an average of 250 kg ha^{-1} average seed rate in the irrigated environments was higher relative to the 157 kg ha^{-1} in the rainfed environments. The top decile (10th) farmers used comparatively high seed rate in rainfed and low seed rate in irrigated

Table 2
List of variables used as predictors for random forest model.

Variable group	Specific variables included
Variables used for grain yield gap (21 variables)	
General information	study village, total land holding, area under wheat, whether the household received government incentive, whether the household head is leader farmer, and whether credit was available
Soil tillage and planting material	tillage passes before seeding (no-tillage, single tillage, two tillage passes, three or more tillage passes), whether improved variety was used (improve variety: released after 1993), source of seed (own or purchased), seed treatment weather seed treated before seeding, Y/N), age of variety (year of variety release), seed rate (how much seed used kg ha^{-1}), and distance of the seed source (distance of seed source from household to purchase seed, km)
Fertility management	nitrogen application rate (amount of elemental N applied kg ha^{-1}) and phosphorus application rate (amount of P_2O_5 applied kg ha^{-1})
Weed and pest control	herbicide application and insecticide application (amount applied L ha^{-1} during wheat growing season).
Edaphic and climatic	rainfall amount, previous crop (categorized in four groups, i.e., cereal (wheat and barley in both rainfed and irrigated); legume (in irrigated only fababean and in rainfed: fababean and lentil; vegetables (in irrigated); fallow (not any crop grown- in rainfed), percent of previous crop residue retention, soil fertility status (farmers reported: good, medium and poor), and irrigation amount.
Variables used for gross margin gaps (21 variables)	
General information	study village, whether the household received government incentives, whether credit was available, land holding size, whether improved variety was used, age of variety, rainfall amount
Amount of input used	number of labor used, irrigation amount, tillage times, cost of seed, amount of input used in kg ha^{-1} (seed rate, nitrogen fertilizer, phosphorus fertilizer, pesticide, and herbicide), previous crop (crop planted before wheat), and percent previous crop residue retention
Income and price	grain yield (kg ha^{-1}), price per kg of grain, and straw yield (kg $ha^{-1)}$

environment than the average seed rate. The mean fertilizer application rate for nitrogen (N) and phosphorus (P_2O_5) was 13 kg ha^{-1} (CV-69%) and 9 kg ha^{-1} (CV-55%), respectively in the rainfed environment and 78 kg ha^{-1} N (CV-13%), 36 kg ha^{-1} P_2O_5 (CV-27%) in the irrigated environments. In terms of the average N and P rates, top decile farmers used comparatively high N and P fertilizer rates. The average production cost was \$ 216 ha^{-1} (CV-22%) for rainfed and \$ 499 ha^{-1} (CV-10%) for the irrigated environments. The average gross margins were \$ 224 ha^{-1} (CV- 51%) for the rainfed and \$ 1435 ha^{-1} (CV- 19%) for the irrigated environments. For most variables, CV was higher in rainfed environments than in irrigated environments (Table 3). The average grain price was \$ 0.37 kg^{-1} with 13% variation. and the grain prices are higher for the top 10th decile than the rest of the farmers in both the irrigated and rainfed environments. Estimate of the national average straw price was \$ 0.11 kg^{-1} (Table 3).

TAverage yield and gross margin were higher under the irrigated system than in the rainfed system. The average wheat yield under farmers' management in the rainfed environment was 897 kg ha^{-1}, where yield ranged between 0.51 and 1.73 t ha^{-1}. The mean yield of the top (10th) decile is 1.41 t ha^{-1} while the mean yield for the rest of the farmers is 0.84 t ha^{-1} showing an attainable yield gap of 0.57 t ha^{-1} (Fig. 3). Similarly, in the irrigated production systems, the average wheat yield stands at 3.99 t ha^{-1} while the average yield for the top (10th) decile was 5.38 t ha^{-1} and the mean yield for the rest of the farmers was 3.84 t ha^{-1} with large variation in yield ranging from 2.77 to 5.98 t ha^{-1} and attainable yield gap of 1.54 t ha^{-1}. The relative attainable yield gap (40%) under rainfed environments was larger than that in the irrigated environments (29%) (Fig. 3).

Gross margin under current farmers' management in the rainfed environments also showed substantial variation where it ranged between \$ -72 and 745 ha^{-1} with an average of \$ 224 ha^{-1}. The attainable gap in gross margins for rainfed production systems was \$ 223 ha^{-1} or 57% (Fig. 3). Similarly, in the irrigated production systems farm gross margins had large variation ranging from \$ 777 to

Table 3
Characterization of wheat production in the rainfed and irrigated environments in Morocco. Values shown under different category is mean ± SD.

Variables	Average for the entire sample		Average for the top 10th decile		Average for the 1st -9th deciles	
	Rainfed (N = 1901)	Irrigated (N = 395)	Rainfed (N = 188)	Irrigated (N = 40)	Rainfed (N = 1713)	Irrigated (N = 355)
Grain yield (kg ha^{-1})	897 ± 237 (26)	3994 ± 559 (14)	1411 ± 113	5379 ± 460	840 ± 171	3838 ± 289
Straw yield (kg ha^{-1})	1528 ± 476 (31)	6582 + 874 (13)	2189 ± 651	9103 ± 813(9)	1448 ± 623	6228 ± 702
Land holding (ha)	12 ± 29	14 ± 48	12 ± 29	10 ± 16	12.8 ± 32	17.7 ± 67
Seed rate (kg ha^{-1})	157 ± 44 (28)	250 ± 43 (17)	175 ± 43	243 ± 45	152 ± 43	252 ± 46
Nitrogen (kg ha^{-1})	17 ± 8(47)	78 ± 10 (13)	21 ± 9	90 ± 11	16 ± 7	76 ± 9
P_2O_5 (kg ha^{-1})	12 ± 3.4 (28)	36 ± 10 (27)	12.5 ± 4.4	44.7 ± 10.9	10.6 ± 3.4	35.7 ± 10.5
Total pesticide (kg ha^{-1})	1.48 ± 0.6 (40)	1.25 ± 0.32 (25)	1.69 ± 0.67	1.23 ± 0.31	1.5 ± 0.64	1.2 ± 0.32
Production cost (\$ ha^{-1})	216 ± 48 (22)	499 ± 49 (10)	211 ± 40	558 ± 45	216 ± 48	492 ± 43
Gross margin (US \$ ha^{-1})	224 ± 116 (51)	1435 ± 275(19)	4254 ± 92	1962 ± 293	202 ± 96	1375 ± 200
Tillage (% farmer)	No-tillage = 6% 1 pass = 10% 2 pass = 49% 3 pass = 35%	3 pass = 100%	No-tillage = 41% 1 pass = 12% 2 pass = 47% 3 pass = none	3 pass = 100%	No-tillage = 2% 1 pass = 10% 2 pass = 49% 3 pass = 39%	3 pass = 100%

Previous crop (% farmers)	*Legume = 33%
	€Cereal = 66%
	Fallow = 1%
		#Legume = 49%
		Cereal = 38%
		Vegetable = 13%
			Legume = 68%
			Cereal = 32%
				Legume = 100%	*Legume = 29%
					€Cereal = 70%
					Fallow = 1%
						*Legume = 43%
						€Cereal = 42%
						Fallow = 14%

Grain price (\$ kg^{-1})^	0.374 + 0.046	0.371 ± 0.047	0.408 ± 0.063	0.433 ± 0.073	0.371 ± 0.042	0.364 ± 0.038
Straw price (\$ kg^{-1})$^{\alpha}$	0.11					

*Notes: Values in brackets denote coefficients of variation (CV); Exchange rate in 2013: 1 US \$ = 8.62 Moroccan Dirham (MAD); *legume in rainfed = fababean and lentil; #legume in irrigated = fababean only;* €cereal = wheat and barley.

^ The grain prices received by farmers are higher than the producer prices set by the government because they include the reimbursement for transportation costs for delivering to the mills which varies based on the distance between the farm and the mill. $^{\alpha}$ straw price is an estimate of the national average from secondary sources.

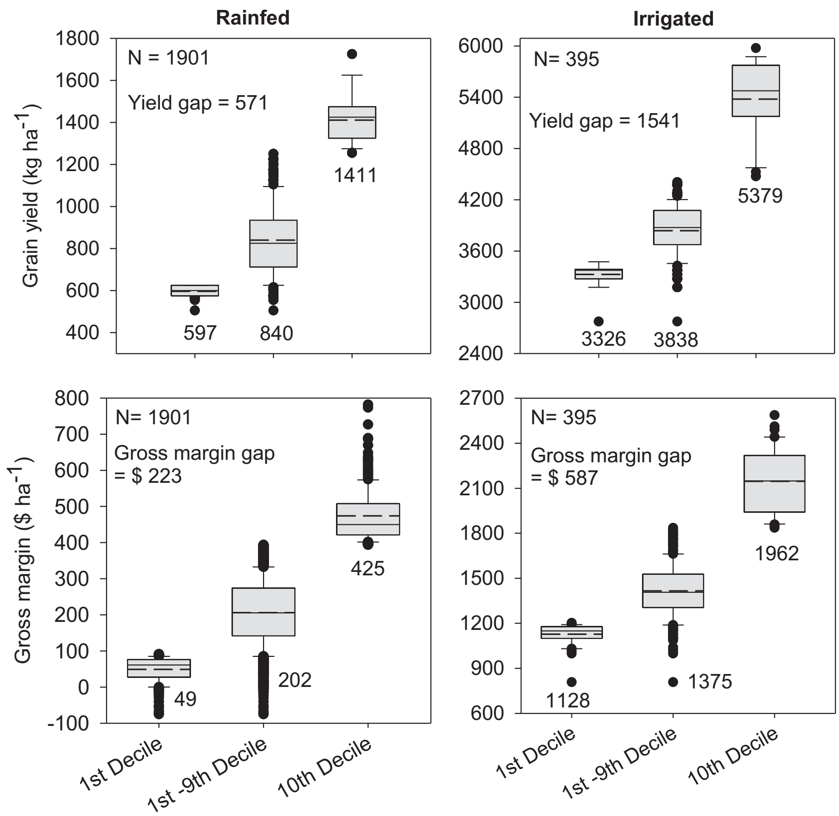

Fig. 3. Wheat yields and yield gaps in kg ha^{-1} (*Upper row*) and gross margin in US \$ ha^{-1} (*Lower row*) between the top (10th) decile the rest of the farmers in the rainfed and irrigated environments.
Note: Dotted lines inside the boxes are the mean and the black solid lines are the median. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2491 ha^{-1} with an average of \$ 1435 ha^{-1}. The average attainable gap in gross margins in the irrigated environments was \$ 587 ha^{-1} or 34% (Fig. 3). The average gross margin of top 10 performing farmers was \$ 425 and 1962 ha^{-1} under rainfed and irrigated environments, respectively. The relative attainable gross margin gap (57%) under rainfed environments was larger than that in the irrigated environments (34%) (Fig. 3).

In the rainfed environment, only 6% farmers practiced no-tillage and 49% farmers tilled their land two times and 35% tilled their land three times. In the irrigated environment on the other hand, all farmers tilled their land three times before seeding. Similarly, 41% of the farmers in the 10th decile (top performers) in the rainfed environment, practiced no-tillage (Table 3).

In the rainfed environment, 33% farmers planted legumes (fababean and lentil) before wheat, 66% planted cereal and only 1% kept the land fallow. In the irrigated environments, 49%, 38%, and 13% farmers planted respectively legume (fababean), cereal and vegetable crops, respectively, before wheat. Similarly, 66% in rainfed and 100% in irrigated farmers in the 10th decile (top performers) planted legumes prior to wheat crop (Table 3).

3.2. Prediction and causal factors of wheat yield and gross margin gaps for rainfed and irrigated systems

Random forest successfully predicted yield and gross margin for wheat when compared against the test data that had been included in model training for both rainfed and irrigated environments (Fig. 4). The RF model explained 88% yield variance in rainfed and 87% yield variance in irrigated systems and with good agreement between the predicted and observed values in the test data. The RMSE of the model was 81 kg ha^{-1}, which is 9% of the average observed yield for rainfed and 293 kg ha^{-1}, which is 7% of the average observed yield for irrigated environment (Fig. 4). Similarly, the model explained gross margin variance by 93% for rainfed and 97% for irrigated production systems with good agreement between the predicted and observed values. The RMSE of the model was \$ 33 ha^{-1}, which is 14% of the average observed gross margin for rainfed and RMSE of \$ 119 ha^{-1}, which is 8% of the average observed gross margin for irrigated environment (Fig. 4). By applying the RF model to twenty-one different factors for yield gap and gross margin gap (see Table 2), model results showed that there are differences in the relative importance of the variables in explaining yield and gross margin gaps in rainfed and irrigated wheat production environments (Fig. 5). These results do not come by surprise as farmers in the two production environments face different challenges and have different opportunities. In the rainfed environment, that tillage method that was used was the most important factor for explaining variation in wheat yield, followed by application rate of phosphorus, the quality of seed (i.e., whether seed is certified), level of application of nitrogen fertilizer, whether or not the preceding crop was legume, seed rate, amount of previous crop residue retained, variety, and amount of rainfall in the order of their importance (Fig. 5). Similarly, in the irrigated environment, the previous crop and variety used were the most influential variables for explaining variation in wheat yield, followed by quality of seed, level of application of nitrogen and phosphorus fertilizer, distance from seed source, location, and rainfall amount in order of their importance (Fig. 5).

In the analysis of gross margin gap in wheat production, grain yield was the most influential variable for explaining variation in gross margin in the rainfed environment, followed by gain price, number of labor days used, tillage method, straw yield, amount of herbicide, amount of P fertilizer, previous crop, and variety in order of their importance (Fig. 5). On the other hand, grain price was the most influential variable for explaining variation in gross margin from wheat production in the irrigated environment, followed by grain yield, type previous crop, variety, straw yield, amount of N and P fertilizers, location, and rainfall amount in order of their importance (Fig. 5).

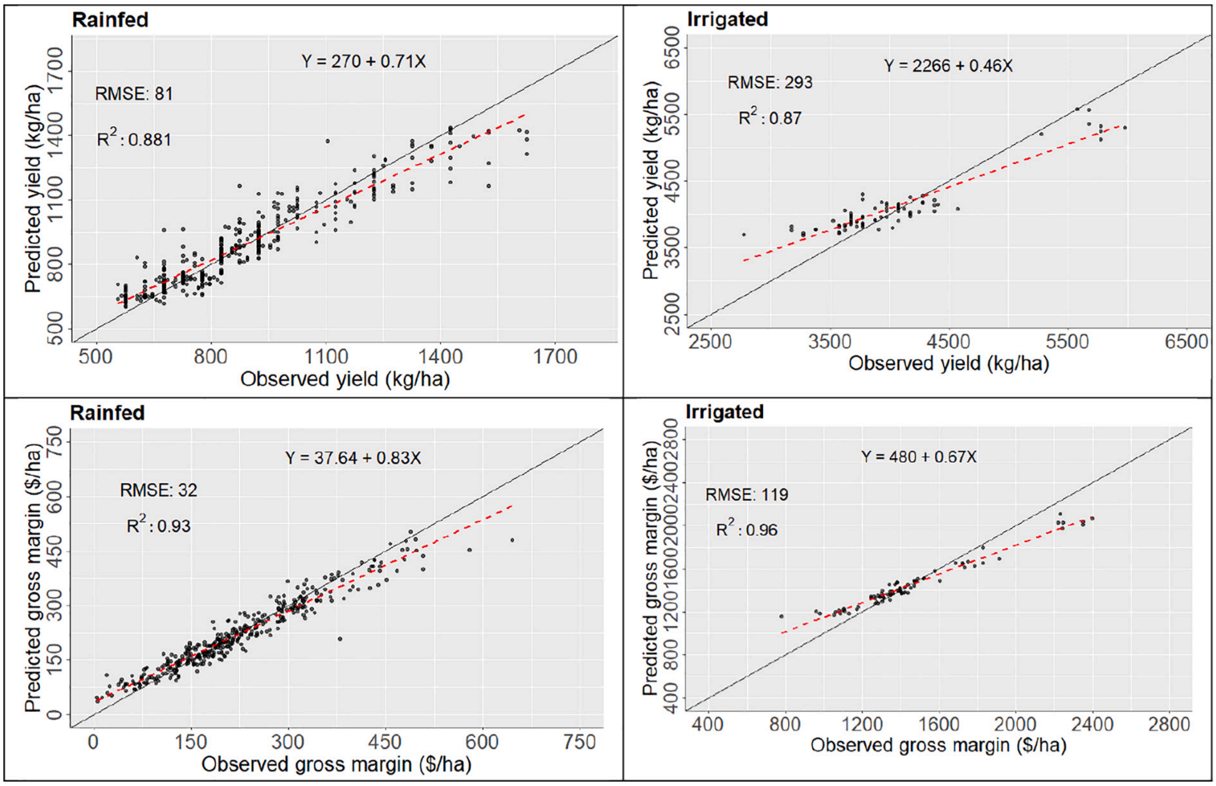

Fig. 4. Performance test for the Random Forests model for grain yield (*Upper row*) and gross margin (*Lower row*). Black dots are the observed data, red dotted line represents the Ordinary Least Square (OLS) regression of the RF predictions on the observed for which RMSE is also reported and the gross margin. Black solid line is the 45-degree line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

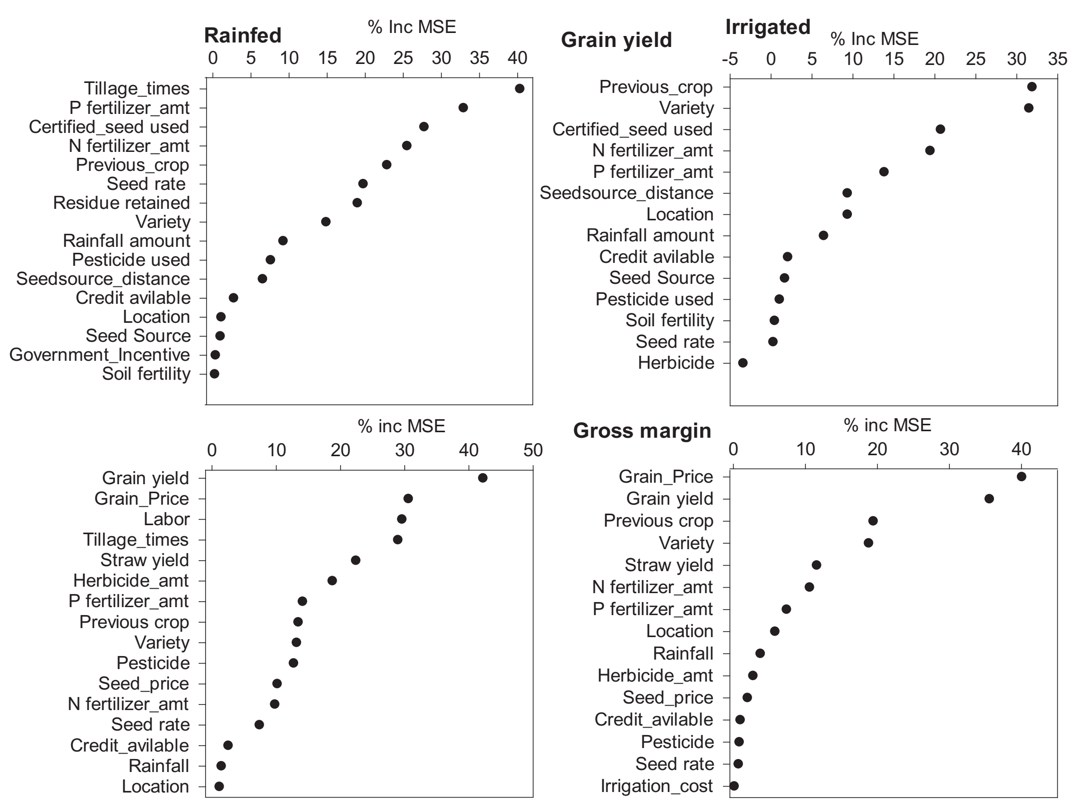

Fig. 5. Importance of different variables in explaining variation in yield (upper row) and gross margin (lower row) in rainfed and irrigated environments, results from the random forest (RF) models.

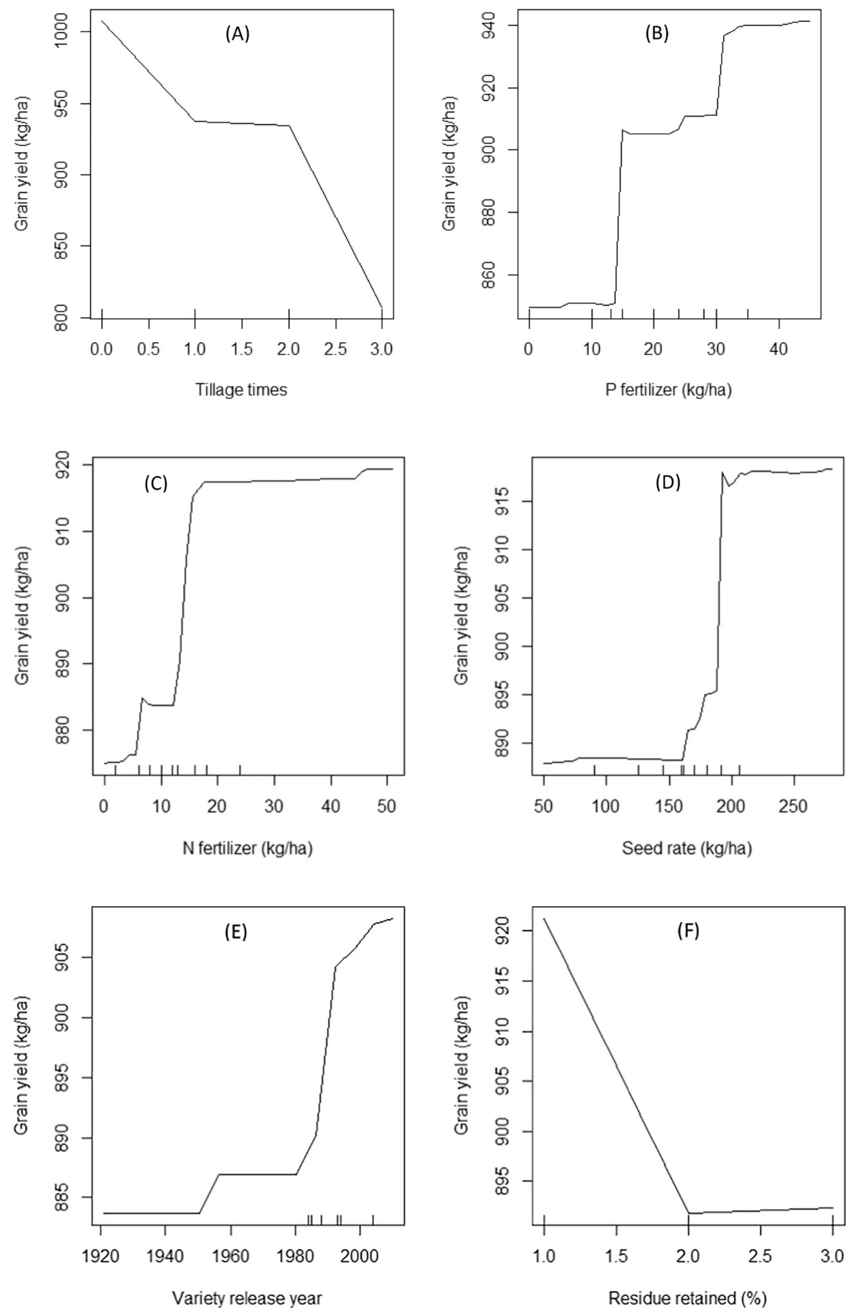

Fig. 6. Partial dependence plots for the top-ranked predictor variables from variable importance measures of Random Forests models in the rainfed production environment. (A) tillage times, (B) phosphorus fertilizer level, (C) nitrogen fertilizer level, (D) seed rate, (E) year of variety released, and (F) amount of previous crop residue retention.

Note: The Y-axis of each plot indicates the average of all of the possible model predictions for the X predictor value. The hash marks other than the X-axis labels indicate deciles.

3.3. Response of wheat grain yield to changes in individual variables

3.3.1. The rainfed environment

The partial dependence plot for yield showed that excluding the effect of all other variables, grain yield of wheat increased by 200 kg ha^{-1} (25%) with no-tillage practice and increased by 140 kg ha^{-1} (16%) with minimum tillage (1–2 tillage passage before seeding) compared to the farmers who have practiced three tillage passages before seeding (Fig. 6A).

Similarly, excluding the effect of all other variables, wheat grain yield increased by 5 kg ha^{-1} with each kg of P_2O_5 fertilizer application and by 3 kg ha^{-1} with each kg of N fertilizer application up to a level of 20 kg of each P_2O_5 and N fertilizer ha^{-1} (Fig. 6B and C). The partial dependence plot for seed rate revealed that the increase in seed from 100 to 150 kg ha^{-1} is accompanied by no gain in wheat grain yield. However, yield gain of 45 kg ha^{-1} was observed when seed rate increased from 150 to 200 kg ha^{-1} and no yield advantage when seed rate increased beyond 200 kg ha^{-1} (Fig. 6D).

There was clear trend of yield increase by using the varieties released after 1990 (Fig. 6E). Excluding the individual and synergistic effects of other variables, the yield gain from using varieties released after 2000 compared to the use of varieties released before 1980 was 25 kg ha^{-1} (Fig. 6E). Similarly, excluding the effect of other variables, the yield gain from retaining 60% previous crop residue on the

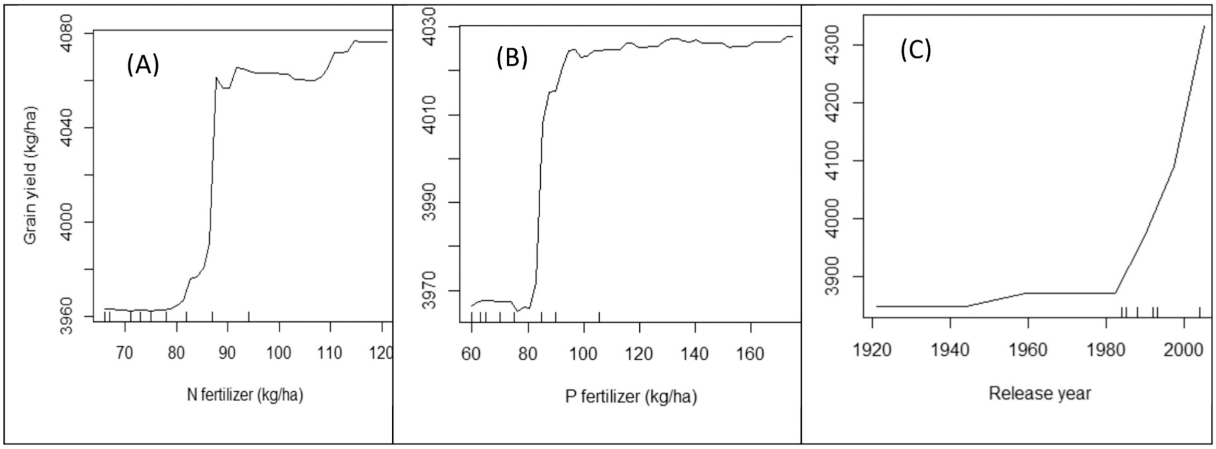

Fig. 7. Partial dependence plots for the top-ranked predictor variables for yield in the irrigated production environment based on results of the Random Forests models. (A) nitrogen fertilizer level, (B) phosphorus fertilizer level (C) year of variety released.
Note: The Y-axis of each plot indicates the average of all of the possible model predictions for the X predictor value. The hash marks on the X-axis indicates deciles.

following wheat crop was 25 kg ha^{-1} compared to residue removal (Fig. 6F).

3.3.2. Irrigated production environment

In the irrigated environment, each sample farmers applied above 70 kg N ha^{-1} and 30 kg phosphorus fertilizer. Each additional kg of N fertilizer above 70 kg N ha^{-1} increased wheat yield by 3.3 kg ha^{-1} up to an application level of 100 kg N per hectare, when the effects of other variables were excluded (Fig. 7A). Similarly, farmers had on the average harvested 3972 kg ha^{-1} with the application of 30 kg of P_2O_5 ha^{-1}. After this level, each additional kg of P_2O_5 ha^{-1} fertilizer increased wheat yield by 2 kg ha^{-1} up to the level 50 kg of P_2O_5 ha^{-1} when the effects of other variables were excluded (Fig. 7B). The partial dependence plot for the age of variety illustrates a clear trend of yield increase by using the varieties released after 1990 (Fig. 7C). Excluding the individual and combined effects of all other factors, using varieties released after 2000 alone led to yield gain of 350 kg ha^{-1} relative to the use of varieties released before 1980.

3.4. Response of wheat farm gross margins to changes in different variables in rainfed and irrigated environments

In both rainfed and irrigated environment, as expected, grain yield, price of grain and straw yield were positively associated with farm gross margin (Figs. 8 and 9). Excluding the individual and combined effects of all other factors, an additional one kg ha^{-1} grain yield is associated with an increase in farm gross margin of \$ 0.175 in the rainfed environments (Fig. 8A) and with an increase in farm gross margin of \$ 0.205 in irrigated environments (Fig. 9A). Similarly, a \$ 0.08 kg^{-1} (10%) increase in grain price (i.e., an increase from \$ 0.37 kg^{-1} to \$ 0.44 kg^{-1} grain) is associated with a \$ 21 ha^{-1} (9.7%) increase in wheat farm gross margin in the rainfed environments (Fig. 8B) a \$ 150 ha^{-1} (10%) in the irrigated environment (Fig. 9B).

In the rainfed environment, adoption of no-tillage and minimum tillage (1–2 tillage passages) practice increased gross margin by \$ 54.2 ha^{-1} and \$ 36 ha^{-1}, respectively, compared to the practice of tillage operation ≥3 times before seeding (Fig. 8C). Similarly, in the rainfed environment, number of labor days used was inversely related to farm gross margin. Without the synergies obtained from other variables, an increase in total labor from 10 to 25 person days ha^{-1} reduced farm gross margin by \$ 36 ha^{-1} (Fig. 8D). Each kg ha^{-1} increase in straw yield gross margin is also associated with \$ 0.06 increase in wheat farm gross margin ha^{-1} in the rainfed environment (data not shown) and a \$ 0.08 increase in wheat farm gross margin ha^{-1} in the irrigated environment (Fig. 9C). The partial dependence plot for the age of variety illustrates a clearly increasing trend in gross margin for farmers using varieties released after 1990 in both rainfed and irrigated environments (Fig. 9D). The gross margin gain was \$ 7.23 ha^{-1} for rainfed and \$ 60.24 ha^{-1} for irrigated environment by using the variety released after 1990 compared to the use of variety released before 1980 (Fig. 9D). Increase in application level for nitrogen and phosphorus fertilizers associated with increase in farm gross margin in both the rainfed and irrigated environments (data not shown).

In the rainfed environment, farmers who have practiced no-tillage produced 35% higher yield than those who practiced one or two tillage passages and by 87% relative to those who practiced three tillage passes (Fig. 10A). Farmers who had used the certified seed on the average produced at least 218 kg (31%) more yield per hectare in rainfed (Fig. 10B) and 455 kg (12%) more yield in irrigated (Fig. 10C) than those who did not use certified seed, which in the face of only 48% farmers in rainfed, and 54% farmers in irrigated environment using certified seed. Similarly, farmers who had planted a legume in the previous season produced 147 kg ha^{-1} (17%) and 659 kg ha^{-1} (18%) higher yield in the rainfed and irrigated environments, respectively, than those who practiced cereal monocropping (Fig. 9D and E).

3.5. Assessing the risk efficiency of farm management practices

Using the average price of \$ 0.36 kg^{-1} reported by farmers, our analysis showed that in the rainfed environment, gross margin was < \$ 240 ha^{-1}. On the other hand, farmers in the rainfed environment can achieve gross margin of > \$ 350 kg^{-1} if prices were to increase to > \$ 0.45 kg^{-1} (Fig. 11A). Similarly, in rainfed production environment, the practice of no-till was more profitable and risk efficient than practices involving tillage before seeding (Fig. 11B).

In rainfed environment, application of more than 15 kg N and P fertilizer ha^{-1} is more profitable than no or low N and P fertilizer application, with similar risk efficiency (Fig. 11C and E). This indicated that application of N and P fertilizer is more profitable and risk efficient than low or no application. Similarly, in irrigated environment, N and P application ranged from 65 to 120 kg N ha^{-1} and 28–80 kg P (60–170 kg DAP) ha^{-1}. High application rate (> 100 kg N ha^{-1} and > 90 kg P fertilizer application) had highest partial gross revenue with more risk than the application rate of 75–100 kg N and 60–90 kg DAP fertilizer per hectare (Fig. 11D and F). In both rainfed and irrigated environment, inclusion of legume in wheat-based crop rotation system was more profitable and comparatively high risk than other rotation systems (Fig. 11G and H)). In rainfed environment, wheat after fallow and barley crops found less profitable and risk efficient than wheat-fababean, and wheat-wheat rotation (Fig. 11G).

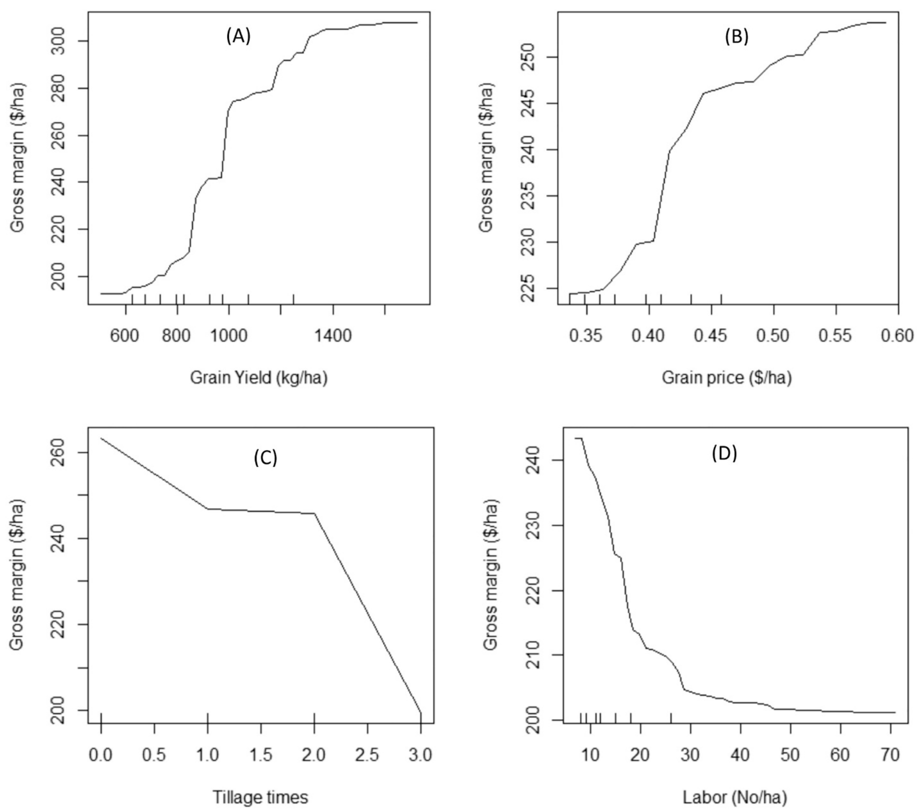

Fig. 8. Partial dependence plots for the top-ranked predictor variables for wheat farm gross margin in the rainfed production environment – results from the Random Forests model. (A) grain yield, (B) grain price, (C) times of tillage, and (D) number of labors used.
Note: The Y-axis of each plot indicates the average of all of the possible model predictions for the X predictor value. The hash marks on the X-axis indicates deciles.

3.6. *Trade-off among input use and efficiency indicators in rainfed and irrigated environments*

The analyses highlight the trade-offs between production inputs and outputs and how these variables varied within and across production environments and between different categories of farmers classified based on their grain yield performance (Fig. 12). Large differences in the input application rates and quantities of outputs were evident between the rainfed and irrigated production systems. Grain and biomass yield and application rates of most of the inputs included in this analysis were higher in the irrigated environments than in the rainfed environments. The only exception to this is the amount of pesticide

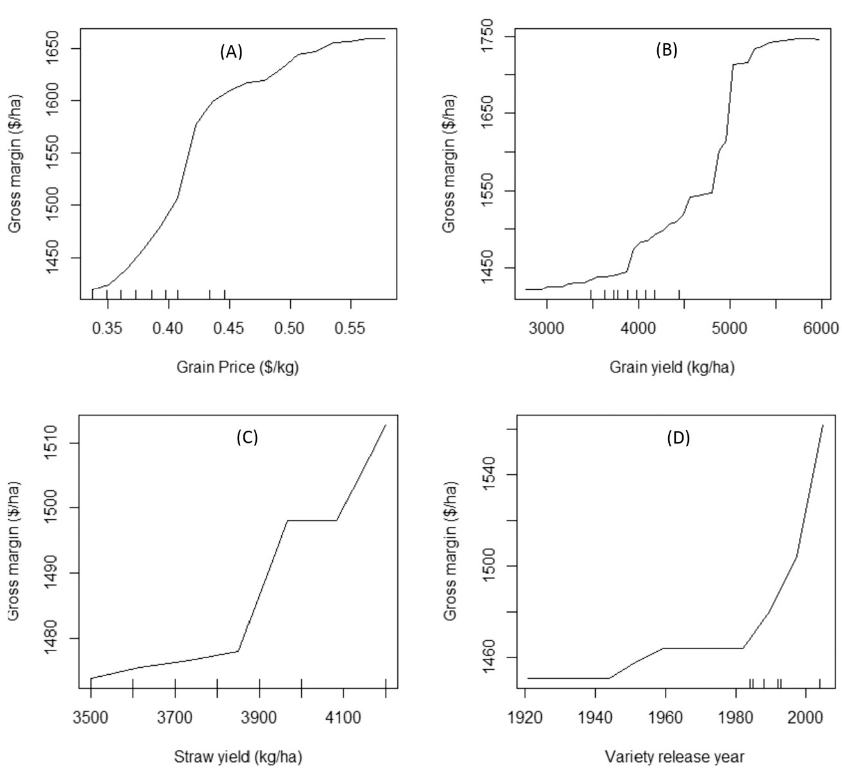

Fig. 9. Partial dependence plots for the top-ranked predictor variables for wheat farm gross margin in the irrigated production environment – results from random forests models. (A) grain price, (B) grain yield, (C) straw yield, and (D) year of variety released.
Note: The Y-axis of each plot indicates the average of all of the possible model predictions for the X predictor value. The hash marks on the X-axis indicates deciles.

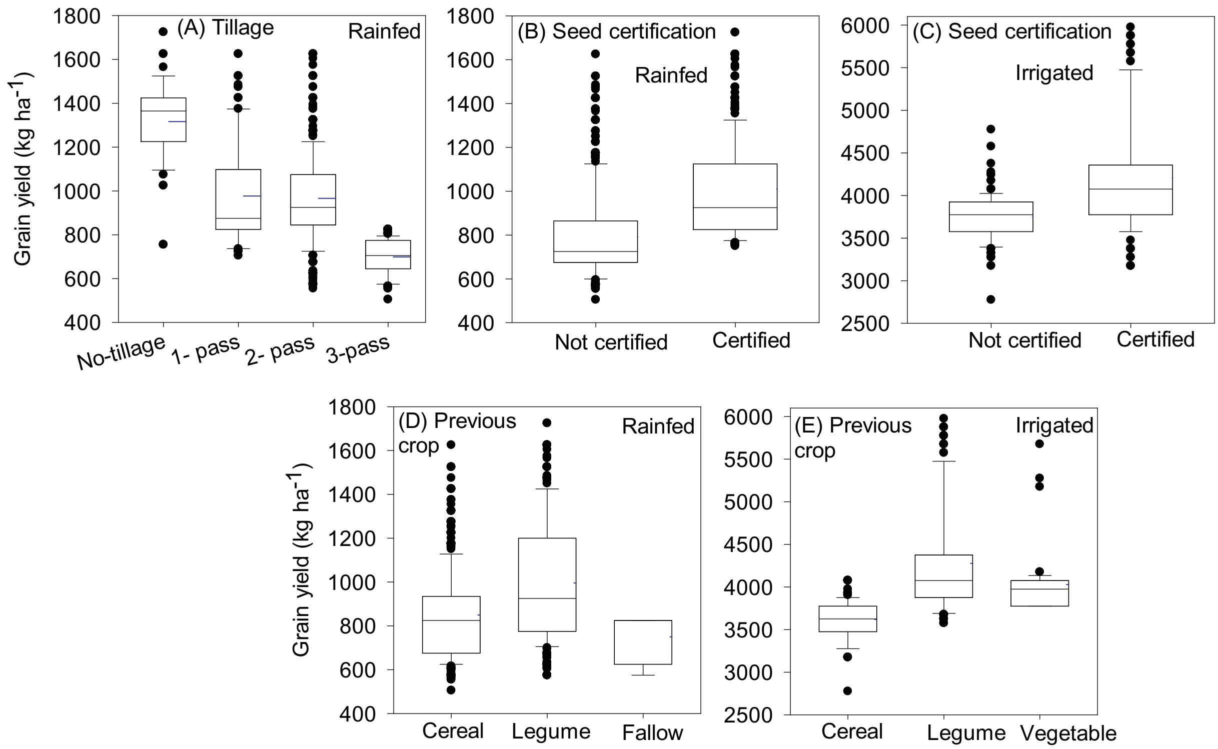

Fig. 10. Grain yield of wheat (kg ha^{-1}) (A) with different tillage passes in rainfed; (B and C) with the use of certified and non-certified seed used (B) in rainfed and (C) in irrigated environments; and (D and E) with different previous crop used before wheat (D) in rainfed and (E) in irrigated environment in Morocco.

application and nitrogen use efficiency (NUE) both of which were higher under the rainfed environment (Fig. 12A).

In the rainfed environment, the farmers categorized as having the top (10th) decile yield had higher production cost, gross margin, and had higher N and P fertilizers, seed and pesticide application rates, higher average NUE and PUE and lower use of labor than the averages for the farmers in the 1st to 9th deciles and the bottom (1st) decile. An interesting observation in these results is that landholding size was the smallest among farmers with the top (10th) decile yields and gross margins (Fig. 12 B). In the irrigated environments, farmers in the top (10th) decile used higher N and P fertilizer with high NUE and PUE. Costs and gross margins were also higher. However, seed rates were lower than that of the farmers in the bottom (1st) and 1st to 9th deciles. Landholding size was also smaller among the farmers in the top (10th) decile (Fig. 12C).

4. Discussion

The high R^2 and low RMSE and SD values, and the good agreement between observed and predicted values indicate that the predictor variables we chose well explain the variation in the dependent variables (yield and gross margins) for both rainfed and irrigated environments. The RF model was found to be effective and versatile for predicting the yield variability of wheat, maize and potato in a global review (Jeong et al., 2016), in rice in West Africa (Niang et al., 2017). The ranking of variables that led to higher yield and gross margin varied between rainfed and irrigated environments (Fig. 5).

The higher yields with no or minimum number of tillage especially in the rainfed environment indicated that there is great opportunity to reduce the gaps in yield and gross margins through the adoption of conservation tillage practices in the rainfed systems of Morocco where intensive tillage and mono-cropping are predominantly practiced (Table 3). The no tillage method is found to be the most important variable determining wheat yield and gross margin in the rainfed environment. Several previous on-station research (Kassam et al., 2012; Moussadek et al., 2014; Mrabet et al., 2012, 2001) and on farmers' fields (El-Shater et al., 2015) documented that the adoption of zero tillage in wheat-based systems can help to enhance grain yield, soil quality, and water use efficiency while reducing the production cost in the Middle East and North African (MENA) region.. Conservation agriculture technology is also recognized as an alternative technology to stabilize crop yield under climate change and variable rainfall (Michler et al., 2019). Despite several benefits of conservation tillage, less than 2% area is under conservation agriculture practices in the MENA region (Kassam et al., 2019). Therefore, efforts on scaling out the conservation tillage technology is important for risk efficient and sustainable intensification of wheat-based systems in rainfed environments in the MENA region. None of the sample farmers have adopted no-tillage technology in irrigated areas. The yield and gross margins are significantly higher under irrigated condition than under rainfed. Thus, under variable rainfall condition, adoption of conservation agriculture practice (no-tillage, residue retention and crop rotation) with supplementary irrigation can be the alternative agriculture practice for sustainably increasing yield, water productivity and energy use efficiency as suggested by Jat et al. (2019) and Nasseri (2019).

Type of crop planted in the previous season was identified to be the most important variable influencing wheat yield and gross margin in the irrigated and rainfed wheat production environments. This indicates the importance of legume crops in wheat-based production systems in both irrigated and rainfed environments. In this study, only 33% and 49% of farmers in the rainfed and irrigated environments, respectively, practiced legume-based rotation -implying that there are still opportunities to reduce the gaps in yield and gross margins in the rainfed and irrigated systems through the inclusion of legumes as rotation crops in the predominantly cereal mono-cropping production systems. In agreement with this result, a recent study by Yigezu et al., 2019b found that the inclusion of a legume crop (fababean) as a rotation crop in the wheat-based systems of Morocco increased the two-year gross margin by 48% relative to wheat mono-cropping. This result further justifies that 70% and 100% of the farmers in the 10th decile

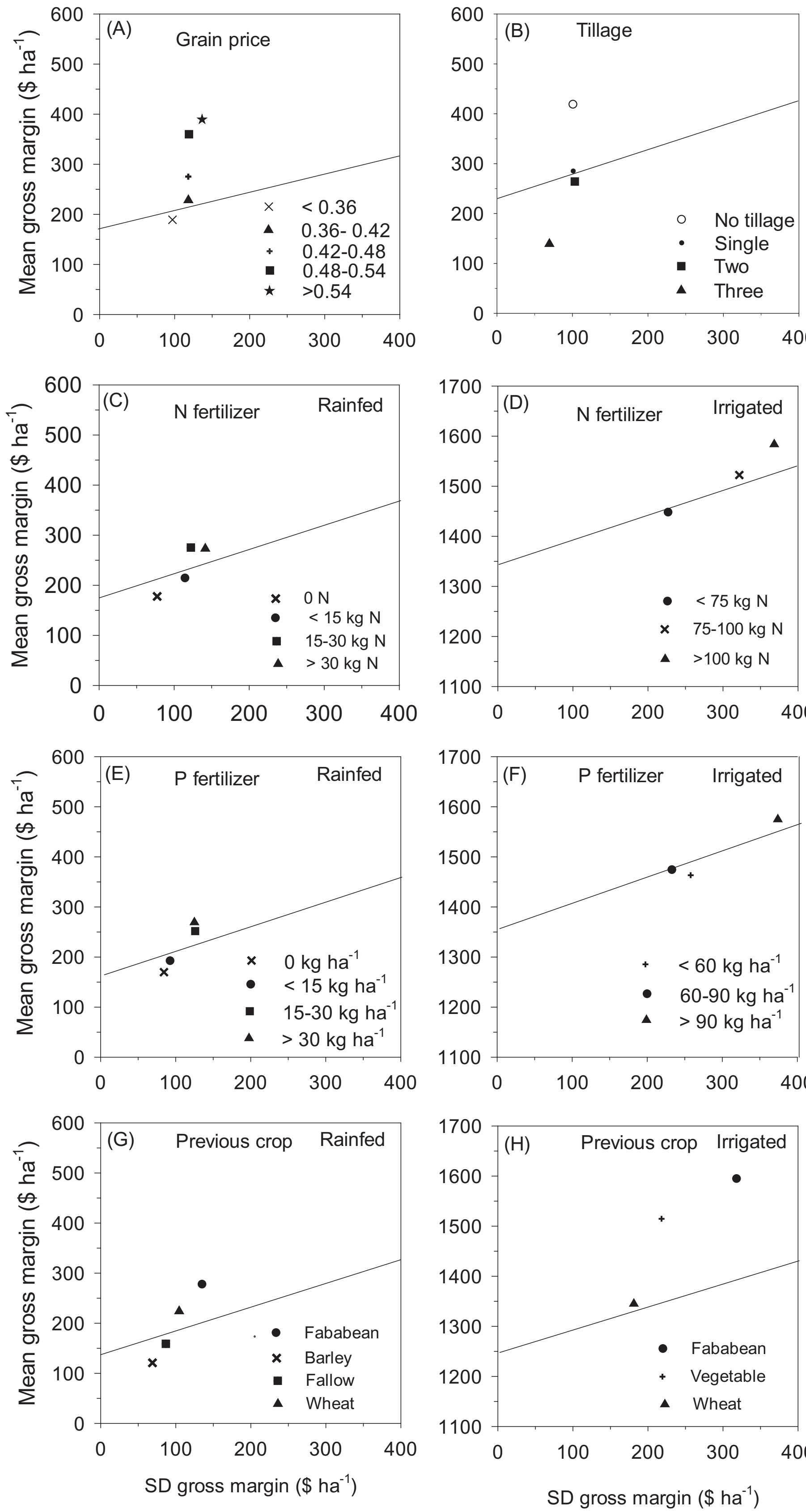

Fig. 11. Mean gross margin vs. standard deviation (SD) of the mean for different crop management practices for (A) grain price (US \$ kg^{-1} grain); (B) number of tillage passage before seeding in rainfed; (C and D) N fertilizer rate (kg ha^{-1}) in rainfed (C) and in irrigated (D); (E and F) P fertilizer (DAP; 46% P_2O_5) rate (kg ha^{-1}) in rainfed (E) and in irrigated (F); (G and H) type of previous crop used in rainfed (G) and in irrigated (H) environment; in 1:2 mean: SD line of indifference. Points below the line less profitable. SD = standard deviation.

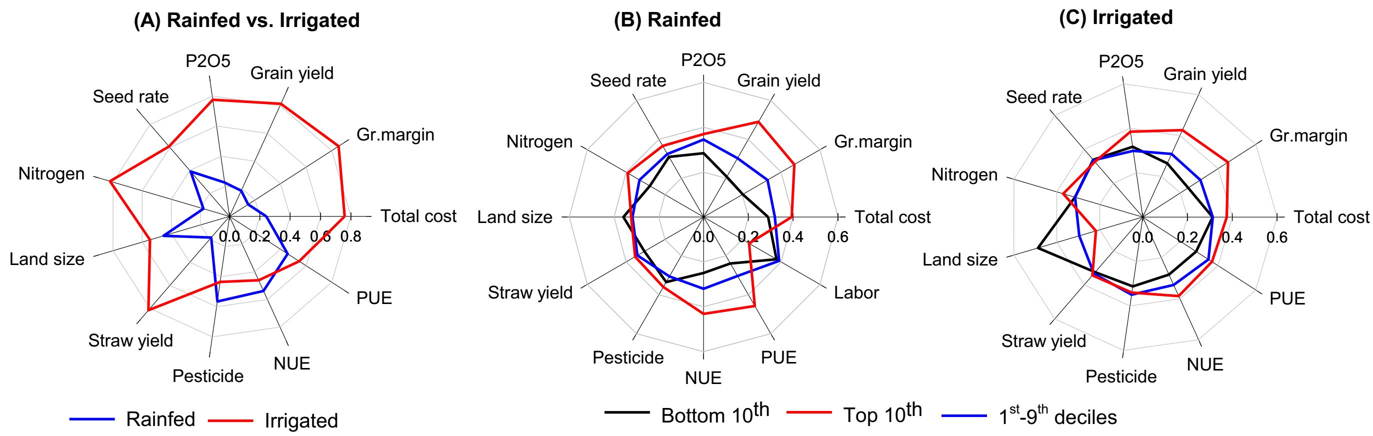

Fig. 12. Trade-offs between inputs and outputs under (A) irrigated and rainfed production environments; and among three categories of farmers (delineated by grain yield performance percentile category) (B) in rainfed and (C) in irrigated environments.
Notes: Symbols and units for the parameter used: Grain yield (kg ha^{-1}); Straw yield: amount of straw weight (kg ha^{-1}); Seed = seed rate to seed rate (kg ha^{-1}); Nitrogen = nitrogen fertilizer input (elemental N kg ha^{-1}); P_2O_5 = phosphorus fertilizer (P_2O_5, kg ha^{-1}); Land size (total land holding size, ha); Total Cost = total production cost (US $ ha^{-1}); Gr. margin = gross margin (US $ ha^{-1}); pesticide = total amount of herbicide + insecticide applied kg ha^{-1}).

(top performers) in the rainfed and irrigated production environments, respectively included legumes as rotation crops. Despite several benefits to legume-based rotations, cereal mono-cropping is the dominant production system in the Middle East and North African (MENA) region with continued reduction in the area under legumes (FAOSTAT, 2020). Therefore, the inclusion of legumes as rotation is important for sustainable intensification of wheat-based systems in both the rainfed and irrigated environments.

Average application rates of N and P fertilizers under both irrigated and rainfed environment are considerably lower than the averages of the national recommendations in Morocco (80:60:60 NPK kg ha^{-1} for rainfed and 120: 80: 80 NPK kg ha^{-1} for irrigated system). A closer look at the data showed that about 15% of sample farmers did not apply any fertilizer, and about 80% of farmers had applied less than 20 kg nitrogen and phosphorus fertilizer per hectare in the rainfed areas. Our model results showed that P is a limiting nutrient in rainfed systems, as both application rate and PUE are low. Phosphorus deficiency is associated with a low P-reserve or a high soil P-adsorption capacity (Nziguheba et al., 2016). Similarly, in the irrigated areas, more than 60% of farmers had applied less than 75 kg N and 35 kg P_2O_5 fertilizer per hectare. We believe the application of sufficient NPK fertilizer emerged as an important agronomic practice in the region for the following reasons: (a) the cultural practices of removal/ over-grazing the straw from the field prevents the return of nutrients from straw to the soil (Zhao et al., 2019); (b) most of the soils in the region are low in organic matter (Moussadek et al., 2014) and hence low nutrient supply capacity could be related to continuous cereal mono-cropping (Woźniak, 2019), intensive soil tillage (Moussadek et al., 2014) and the associated loss of topsoil due to soil erosion. Low or no use of chemical fertilizers in a cereal monocropping in such poor soils leads nutrient mining and decrease the soil quality (Singh and Ryan, 2015). The top-performing farmers in both rainfed and irrigated environments not only applied more N and P fertilizers than the rest, but also that each additional kg of fertilizer is more effective for increasing yield and income indicating that even the top-performing farmers are producing at input levels which are below the marginal product and marginal profit-maximizing levels. The higher NUE and PUE in rainfed condition in trade-off analysis is due to low application of these nutrients by the farmers, which might be leading wheat farming towards nutrient mining under rainfed condition.

Though they computed yield gap as the difference between research stations and a farmers field, Pala et al. (2011) also identified low fertilizer application as the main reason for yield gaps. All these results indicate that gaps in yield and gross margins can be narrowed with improving fertilizer application rates and their use efficiencies. Using time series data, further studies will also need to assess how environmental stress, such as rainfall variability influence nutrient management practices, in minimizing the gaps in yield and gross margins and production risks especially in the rainfed areas.

The top decile farmers are more efficient, getting higher grain price, higher profit with low production cost than rest of the farmers in rainfed environment is related to adoption of low cost technology for example optimum seed rate, use of certified seed, no-tillage practice and legume crop in rotation. This indicates the possibility of enhancing grain yield and profit from rainfed wheat production.

Grain price was identified major variables determining variance in gross margin in both production environments. Our analysis of long-term (1991–2018) grain price data from FAOSAT showed that wheat price in Morocco is static where in 30 years it increased by $ 12.8 per ton ($ 276 in 1991 and $ 289 per ton in 2018) (FAOSTAT, 2020). In the same period, in Australia which has similar agro-climatic conditions, wheat price increased by $ 92.4 t^{-1} i. The static grain price in Morocco might have been influenced by the price support for bread wheat by the government. Also, the grain price is determined by the quality standards of flourmill. Hence, increasing profit will require increasing grain yield while maintaining the grain quality. to enhance net profit from wheat production.

Similarly, low-cost technologies, i.e., use of certified seed and use of recent varieties, were also identified as important causal factor for increasing wheat yield and gross margin in both rainfed and irrigated environments. However, only 48% farmers in rainfed and 54% in irrigated production environments were using certified seed showing that the Moroccan government might need to consider these options as recommendation for closing the yield gaps (Fig. 10B and C). The amount of labor used was also identified as a major determinant of gross margins in the rainfed environment (Fig. 5) and is inversely related to gross margins in rainfed wheat production (Fig. 8D). The 10th decile (top performers) in the rainfed systems used a smaller number of labor days per hectare (Fig. 10B). This indicates the importance of enhancing mechanization services for different crop management practices to reduce the amount of labor use, which leads to higher yield and gross margins from wheat production. The fact that landholding among the top performers was small indicates that the increased land fragmentation induced by high population growth and the inability of the non-agricultural sector to absorb the excess labor in agriculture will have a positive effect on wheat farm productivity and profit growth. The lower seed rates among the farmers in the top (10th) decile than the rest indicates that the least performing farmers were unnecessarily using higher seed rates than required – a possible signal for a gap in agricultural extension education in the country.

All the above results indicate that a large scope exists to increase yields and economic benefits to a large portion of the Moroccan wheat-growing farmers. For example, the average wheat yield ranged from 0.51 to 1.73 t ha^{-1} with attainable yield gap of 0.571 t ha^{-1} (67%) under the rainfed system. These results are much lower than the figures reported by which indicated the possibility of increasing wheat yields in Morocco by 160%–250%. Likewise, yield ranged from 2.78 to 5.98 t ha^{-1} with attainable yield gap of 1.38 t ha^{-1} in the irrigated system. Yield and total production in the country greatly vary due to rainfall amounts and its distribution. Therefore, given that 85% of the total quantity of local wheat is produced under rainfed conditions, improving productivity and achieving yield stability in the rainfed environments deserves high priority. Based on five years (2010–2015) average data, Morocco produced only 61% of the domestic supply, while 39% (an annual average of 3.68 million MT) is supplied through imports from different countries (FAOSTAT, 2020). If Morocco succeeds to fully close the yield gaps within the rainfed and irrigated environments, it can substitute two-thirds of its current level of imports making the country to depend on imports for only 10% of its total wheat demand. However, considering the current production and imports using from FAOSTAT (2020) for Morocco to become self-sufficient in wheat production, in addition to closing the existing yield gap, the country will need to expand its irrigated area to 21% of total wheat area. While this is a very ambitious goal, it is not impossible as Pala et al. (2011) argue that when water resources are available, supplemental irrigation in rainfed areas can boost wheat productivity by 3 to 4 times. Several analyses in this study including the trade-off analysis indicated enhanced facility of irrigation or supplementary irrigation or efficient utilization of rainfall water is key.

5. Conclusions

This study carried analysis of data obtained from 2296 wheat fields using a multi-stage stratified sampling procedure from 21 major wheat-producing provinces of Morocco that account for about 73% of total wheat production. The paper not only applied a slightly different concept to determine the gaps in yields and gross margins but also applied the random forests (RF) model to identify the main determinants of the gaps. The results show that there exist substantial gaps in both yield (40% and 29%) and gross margins (56% and 34%) respectively in the rainfed and irrigated environments – signaling that there is a great opportunity for increasing wheat yield and gross margins in both the irrigated and rainfed production environments. In the rainfed environment, tillage method was identified as the most important factor for increasing wheat yield and gross margins. Better fertilizer management, use of improved wheat varieties and high-quality seeds, and inclusion of legumes as rotation crops in the predominantly cereal monocropping system provide complementary options for increasing on-farm wheat yields and gross margins in both rainfed and irrigated environments. Therefore, understanding the reason for why the vast majority of farmers do not apply better practices and the recommended levels of inputs and using the results to devise strategies to support the majority of farmers to achieve the full potential of their wheat fields is crucial if Morocco and other countries with similar production environments to reduce their wheat imports which, in the face of a growing populations and rising per-capita demand, are expected to increase in the future.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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