Article

Participatory Farmers-Weighted Selection (PWS) Indices to Raise Adoption of Durum Cultivars

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ABSTRACT

The adoption of new cultivars depends largely on the extent to which the breeding objectives set to identify the new cultivars align with the farmers' preferences. There is documented potential of improved cultivars to enhance productivity and income in the developing world, but their adoption among smallholders remains low. Here, we attempt to understand if in the case of Morocco the low level of adoption of new durum wheat (*Triticum durum* Desf.) cultivars can be partially explained by a misalignment of breeders objectives. Factorial analysis was applied to data obtained through a set of interviews with 90 wheat breeders from 49 countries and a case study of 861 durum wheat growers in Morocco, to reveal the existence of five breeders and four farmers classes based on relative importance assigned to five mega-traits: grain yield potential, yield stability, abiotic stress tolerance, biotic stress resistance, industrial quality, and household use. Weighted indexes were derived based on the average rate of preference shown by each interviewee belonging to that specific class, and hierarchically clustered to reveal poor matching between North African breeders and Moroccan farmers. Further, these indexes were applied to the actual performances of 23 durum wheat elite lines to reveal 71% to 87% matching. However, breeders' and farmers' classes had preferences for different genotypes. Together, these results indicate that a certain degree of misalignment exist between farmers and breeders' objectives, and that the use of participatory farmers-weighted indexes could help raise the level of adoption.

KEYWORDS: breeding objectives; breeding goals; socio-economic weights; farmers survey; Morocco

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ABBREVIATIONS

PSW, participatory farmers-weighted selection indices; G, genotype; G × E, genotype by environment interaction; BLUE, best linear unbiased estimation; AMMI, additive main effects and multiplicative interaction; AWAI, AMMI-wide adaptation index; SDS protocol, sodium dodecyl sulfate protocol; TKW, thousand kernel weight; PCA, principal component analysis; BRD, breeder; hclust, hierarchical clustering

INTRODUCTION

Accounting for a fifth of humanity's food, wheat (*Triticum* ssp) is second only to rice (*Oryza sativa* L.) as source of calories for consumers living in developing countries, and it ranks first as a source of protein [1]. In North Africa, wheat production has quadrupled during the past five decades, while the total wheat area has increased by less than 20% during the same period [2]. This dramatic increase in productivity was achieved mostly due to the replacement of ancient landraces with modern cultivars capable of better utilizing fertilization and irrigation inputs. However, for a large part of this region, the cultivars replacement campaign has substantially stop in the early 1990s, and most of the cultivars currently grown were released over 30 years ago [3]. Breeding programs have continued to regularly release better yielding cultivars that are tolerant to both biotic and abiotic stresses, but their uptake by farmers thus far has been extremely low.

Morocco is no exception to this general trend. A 2012 survey by Yigezu et al. [4] revealed that of the 40 wheat varieties cultivated by local farmers, only 8 (20%) were released in the last decade and these occupied less than 10% of the total surface, while the remaining area was dominated by varieties released between the late 1980 and early 1990. At the same time, 60% of the annually sown seeds are certified, indicating that Moroccan farmers recognizes the importance of using seeds of improved varieties and are willing to invest in their purchase. Several issues have been identified to justify the situation, including a national variety system that releases only germplasm that perform averagely well across very different agro-ecologies (spanning from the snow-covered Atlas Mountains to the irrigated hot-steppes of the plateau of Marrakech), a national seed market which is substantially controlled by a single actor, and a public extension program that cannot reach enough farmers. Yet, recent advancements made by the Green Morocco Plan have addressed many of these concerns, but the adoption rate continues to be slow. This paradox has pushed several national and international organizations to analyze the issue.

In this sense, one primary concern has been to determine why the new cultivars have not achieve the same appreciation by farmers as the one released in the past [5–8]. The desirability of a cultivar is derived by a combination of its traits, including yield, resistance to specific stresses, but also the market price that it fetches, which in turn is dependent on the cultivar consumption and its food processing qualities. Hence, the duty of breeders is to develop new improved crop cultivars that possess all or most of the traits desired by farmers, but also by its end-users that purchase the harvest, such as consumers and food processing industries. Further, seed companies also play a pivotal role in diffusing the cultivars, hence their appreciation also needs to be targeted.

Depending on the socio-ecological contexts, the number and type of desired traits can vary. To this effect, breeders prioritize traits through the painstaking and lengthy process of selection to identify the best possible cultivars. Often, there are tradeoffs between some of the traits, where the improvement of one comes only at the expense of another. Therefore, the breeders balance among the different competing objectives and try to come up with cultivars that are acceptable by all stakeholders. One tool that breeders often use for prioritization is called "selection index". A selection index is a linear combination of different criteria for selection, where each criterion is given certain weights [9–11]. The weights are determined either by the breeder, the market, the end-users, or a combination. The extent of diversity of socio-ecological conditions and interests in a given country determines the ease or difficulty of developing a "national" selection index that satisfies the interest of all actors along the entire value chain. Therefore, well-developed selection indexes can be instrumental in guiding research and enhancing the ability of breeding programs to produce successful crop cultivars. Consequently, many approaches have been proposed to maximize the efficiency of selection indices [12].

Here, a set of interviews with wheat breeders and wheat growers drawn from 21 provinces of Morocco, were used to derive weights of mega-traits. Their comparison revealed scarce overlap between the two, providing a possible explanation for the prevailing low adoption levels of recently released improved cultivars. This article builds on these results to propose the use of participatory farmers weighted selection (PWS) indices as a mean to better align breeders' objectives to farmers' needs, and as a more scalable alternative to the costly use of participatory variety selections (PVS).

MATERIALS AND METHODS

Analysis of Breeders' Profiles and Breeding Objectives

The analyses presented here were based on three existing datasets. The first dataset was originally developed for conducting a broad appraisal of the global wheat breeding objectives. The data were collected in 2014 through an online survey of 90 wheat breeders [3] based on a short questionnaire. In this dataset, each country was treated as one observation, where the person in charge of the public wheat breeding program provides the answers on behalf of her/his whole team, and hence counted as one respondent. The only exceptions were China, Turkey, and India, for which 8–13 respondents covering different regional programs responded to the survey and other 11 countries for which 2–3 respondents were considered per country. The final set used here covers 49 countries: 6 in the European Union, 10 least developed countries mainly from East Africa and South Asia, and 6 net food importing developing countries mainly from North Africa. The main question asked in the survey was: "What are your most critical breeding objectives in order of importance?" This was an open-ended question, so for homogenization before statistical analysis, the breeders' responses were converted into five broad categories of mega-traits (**Supplementary Table S1**).

Because breeders responded freely, each provided different numbers of responses, from a minimum of three to a maximum of seven. In total, 26% of the interviewed breeders indicated four criteria, whereas only 1% indicated five or more. In this study, only the first three responses were considered the most critical and used for analysis. Following [13], this study used the factorial analysis method to linearly transform the original set of breeding objectives into a substantially smaller set of uncorrelated clusters that represent most of the information in the original set. A factorial design in multiple components was derived to define profiles of *breeders' objectives*, using the Xlstat software [14]. Within each cluster, the weighted importance of each broader category was determined as the number of positive responses divided by the total number of responses within the cluster. This value was considered the *breeders' weighted index*.

Analysis of Moroccan Farmers' Profiles and Objectives

The second dataset used in this study was obtained from a household survey of a nationally representative random sample of 861 Moroccan durum wheat farmers from 21 wheat-growing regions ([4]; Supplementary Dataset 1) and four agro-ecological zones: *i.* "favorable" (*bour favorable*) representing areas with annual moisture in excess of 400 mm, *ii.* "intermediate" with moisture not exceeding 400 mm, *iii.* "unfavorable" with annual moisture not exceeding 300 mm, and *iv.* "mountains" located above 900m a.s.l.. During the survey, farmers were asked to use values between 1 and 10 to rate the importance of 28 suggested wheat traits, based on how much each trait influenced their adoption decisions, where 10 and 1, represented the most and the least important traits that the farmer would prefer to have in an ideal durum cultivar, respectively. Following the same procedures that were used for the data collected from breeders, the 28 criteria of farmers were converted into five broad categories following the guidelines provided in **Supplementary Table S2**. Ten priorities identified in the farmers' survey were not mentioned by any of the interviewed breeders. These mostly referred to the adaptation of the cultivar to the family farm system, notably those linked with: (1) the livestock system (biomass production, particularly straw yield, ease of threshing, or palatability of straw); (2) family consumption (e.g., taste for different dishes, amount of time to cook, etc.); and (3) postharvest loss (e.g., storability). For analytical convenience, these criteria were aggregated into a sixth category called "household use".

As for breeders, a factorial design in multiple components was conducted and then a clustering analysis using the Ward method was carried out to define profiles of *farmers' objectives* based on their preferences for specific traits using the Xlstat software [14]. Within each cluster, the importance of each broad category was determined as the weighted average of the scores for each of the multiple traits within a cluster. These weighted scores were then converted into ratios overall (%) and defined as *farmers' weighted index*.

Estimation of Field Performance of a Set of ICARDA Durum Wheat Elite Lines

The third dataset used in this study was the actual field performance of a set of 23 ICARDA durum wheat elite lines that were field-tested at 27 stations in 18 countries, including two stations in Morocco and additional five in North Africa. This dataset was selected because the full information on the elite lines was recently published with full details already available [15]. To convert the field data into the six broad criteria, the steps listed below were used (**Table 1**).

Table 1. Conversion of field measurements into broad criteria.

Broad criteria	**Field measurements used to score**		
Yield potential	r^2 value of Freely Wilkinson index	BLUE $^{\alpha}$ calculated across all test sites	Grain yield at the top yielding site
Yield stability	AWAI $^{\beta}$	b' value of Finlay $^{\gamma}$ Wilkinson index	Ratio of worst to top yielding sites
Biotic resistance	Leaf rust score	Hessian fly score	Tan spot score
Abiotic tolerance	Yield at a heat affected station	Yield at a drought affected station	TKW $^{\delta}$ at a worst yielding site
Industrial quality	Gluten strength	Grain protein content	Colorimeter score for b* $^{\varepsilon}$
Household use	Biomass yield	Plant height across sites	TKW ^{4} across all sites

$^{\alpha}$ BLUE: Best linear unbiased estimation; $^{\beta}$ AMMI wide adaptation index as per Bassi and Sanchez-Garcia (2017); $^{\gamma}$ Stability value b' as per [16]; $^{\delta}$ 1000-kernel weight (TKW); $^{\varepsilon}$ b* is the yellow color channel expressed by Konica Colorimeter.

The broad criterion of "yield potential" was interpreted as the ability of a genotype to maximize its productivity via a combination of genotype (G) and genotype × environment (G × E) effects. The value of r^2 in the Finlay Wilkinson index was considered a good indicator of response to the inputs, and therefore of yield potential, as it measured the increase in yield as compared with the average yield of each site [16]. In addition, the best linear unbiased estimation (BLUE) for grain yield across all sites was used to measure the G component of yield. A final criterion used for this dataset was the yield performance at the highest yielding station, which in the case of this dataset was Sids, Egypt.

The broad criterion of "yield stability" was considered the capacity of a cultivar to minimize G × E effects and maintain stable performance across sites. This was assessed by the additive main effects and multiplicative interaction (AMMI)-wide adaptation index (AWAI), which measures the capacity of a cultivar to reduce the G × E effect (for details, see [15,17]). The b' value of the Finlay Wilkinson stability index [16] was also included, and finally the ratio between the performance at the lowest-yielding site (Swift Current, Canada in the case of this dataset) and performance at the highest-yielding site (Sids, Egypt in the case of this dataset) was computed and used as a measure of stability.

The broad criterion of improving the "biotic resistance" was measured as the response to three major wheat pests: leaf rust (*Puccinia trticina)*, Hessian fly (*Mayerovora destructora)*, and tan spot (*Pyrenophora tritici repentis*). The broad criterion of "abiotic tolerance" encompasses many stresses. However, the majority of the interviewed breeders and farmers primarily focused on tolerance to heat and drought stress. Hence, only these two criteria were assessed among the ICARDA lines, using the yield performances at the most heat-affected station (Fanaye, Senegal in the case of this dataset; [18]), drought-affected station (Kfardan, Lebanon in the case of this dataset), and kernel size at the worst yielding station overall as a measure of both stresses combined.

The broad criterion of "industrial quality" mostly refers to the possibility in certain countries to get premium prices when selling grains that are of high value for the processing industry. These traits in the case of durum wheat include gluten strength measured via the sodium dodecyl sulfate (SDS) protocol, grain protein content, and colorimeter yellow scale of the milled flour by the b* value measured by a chroma meter Konica Minolta CR-400 [19].

The broad criterion of "household-use" determines the capacity of a cultivar to meet the requirements of a farming system, where the harvest is partly or entirely consumed in the household, and the by-products (mainly straw and stubble) are used as feed for livestock. This last characteristic can be measured in the experimental trials as the biomass and plant height. For the household consumed food, it refers mostly to the cooking of traditional (non-industrial) dishes, such as *burghul* and *frikhe* in the case of Morocco. These types of dishes are prepared by boiling cracked wheat grains and the suitability of a cultivar for this use is mainly controlled by the size of its grains, which can be measured in the field via the weight of 1000-kernels (thousand-kernel weight or TKW) averaged (BLUE) across all test sites. Additional measurements should probably be considered to target the requirements expressed by farmers for palatability of the straw, grains, and storability, but these types of values are hard to measure and not available for the specific set of lines used here.

The individual field-measured traits differ in units of measurement and scale. Therefore, to homogenize each value for use in the calculation of a selection index, the value was converted first into a ratio between the genotype and the highest recorded value expressed by the best genotype for that specific trait. This ratio was then considered for each group of traits constituting a specific criterion. The average of these percentages was then used to express the relative performance of each line for each broad criterion.

Analysis of Convergence between Breeders' and Farmers' Preferences for Candidate Cultivars

The initial test was based on the direct comparison between weighted indices of breeders' and farmers' objectives, for each of the identified clusters. Ideally, Moroccan breeders' and Moroccan farmers' preferences should have been compared. In Morocco, a single public durum wheat breeder was active in 2014 and was responsible for nearly the total of public releases. The situation is only mildly different today. Hence, to avoid assessing the bias of a single individual, the whole cluster, to which this Moroccan breeder belonged, was used as comparison to farmers preferences. As before, factorial regression analysis was carried out for each of the *breeders'* and *farmers' class*. In addition, a correlation matrix was generated between all weighted indexes, which was then represented as a dendrogram by calculating the Ward's hierarchical distances via the *hclust* algorithm of the Xlstat software [14,20]. However, since cultivars that meet both farmers' and breeders' preferences can occasionally be generated, a second comparison was done by applying the weighted indexes of farmers' and breeders' preferences for each class to the set of 23 elite lines, to see if different weights could in anyway result in the identification of the same cultivar following the use of value computed via this simple formula:

$$\sum w_{ni} \times x_{nv} \tag{1}$$

where w is the weight in percentage assigned by the specific class (farmers or breeders) i to criterion n, and x is the field-measured value for the cultivar v for criterion n. In this formula, a perfect matching cultivar would get a score of 100%, and 0% if there is no match at all. The results for all indexes were represented using a box plot distribution graphic generated using the function boxplot [21].

RESULTS & DISCUSSIONS

Clustering of Breeders' Profiles

A total of 90 breeders from 49 countries responded to the on-line questionnaire [3]. **Figure 1** represents a summary of the overall preferences of breeders by region. "Yield potential" was the most sought-after trait (64% globally), followed by "abiotic tolerance" (18%), "biotic resistance" (8%), and "yield stability" (6%). As might be expected, "industrial quality" was a trait of low interest globally (4%), but it found appreciation in countries where premium prices were paid for high quality grains, such as West (29%) and East (13%) Europe. The latter was the region that gave the least importance to "yield potential" (25%) in favor of abiotic stress tolerance (38%). Central and West Asia also shared preference for abiotic tolerance (40% and 38%, respectively) and a more moderate focus on "yield potential" (54% and 40%, respectively). Breeders from South and East Asia, and Africa mostly focused on increasing "yield potential" (100% to 61%). In South Asia and East Africa, some attention was also given to "biotic resistance" (11% and 10%, respectively). Yield potential (80%) was the most important criterion in North Africa, followed by "abiotic tolerance" (20%).

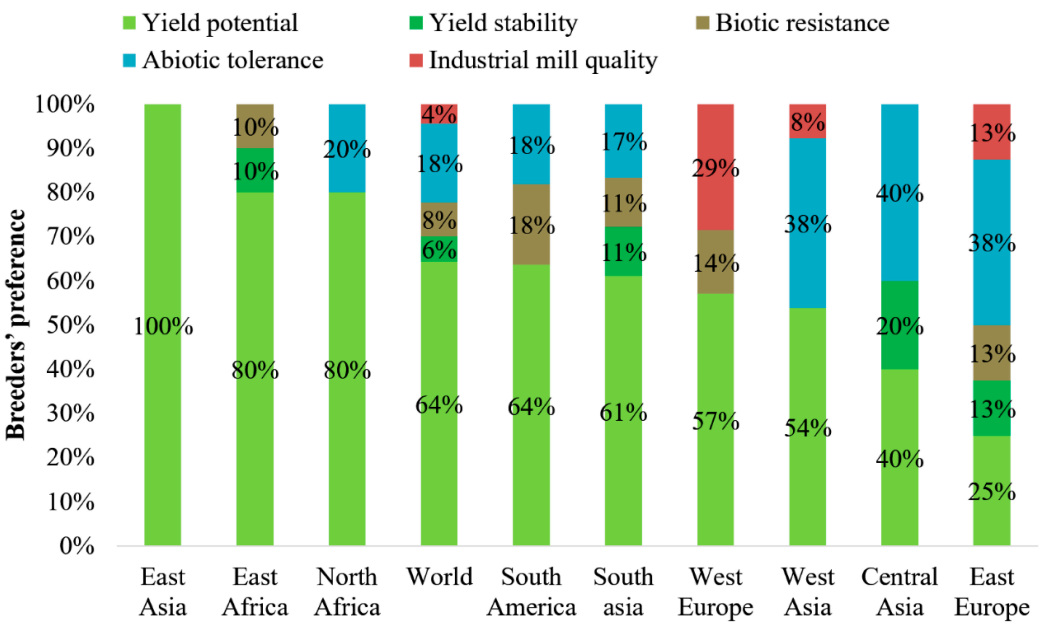

Figure 1. Objectives of breeders by region (in % for each region). Source: [3].

To better define specific groups of breeders, a clustering analysis was carried out to cluster breeders' objectives into five profiles (**Figure 2**). The five categories captured 65.1% of total variation, whereas the more simplistic classification provided above based on geographical origin alone explained only 34.5% of the variation, indicating a comparative advantage in using factorial analysis (**Table 2**). The categories were determined based on two main factors: i) the weight of the criterion "industrial quality", which differentiated between developed and developing countries, and ii) the importance attributed to "yield stability" and "abiotic resistance" (**Figure 2**). The second factor differentiated mostly according to the degree of vulnerability of the breeders' target environment, notably between European countries and North African/West Asian countries. North African breeders were grouped together into class 1, with a common focus on resistance to "biotic" and "abiotic" stresses, whereas West European breeders were clustered in class 3, with the shared aim of increasing "yield potential" and "yield stability" (**Table 3**). All other regions occurred in two or more classes, such as South and West Asia breeders that were present in both class 1 and class 2, which focused strongly on "abiotic resistance" and "yield stability", respectively. East Asia breeders were grouped in class 4 and class 5, both targeting "yield potential" and "industrial quality", but differentiating in the secondary preference for "abiotic tolerance" vs. "biotic resistance", respectively. To assign a weighted importance to each broad category of criterion, a percentage was calculated for each criterion for each cluster of breeders based on the relative importance assigned by the interviewees belonging to each class. This percentage was then considered a weighted index and used for all subsequent analyses.

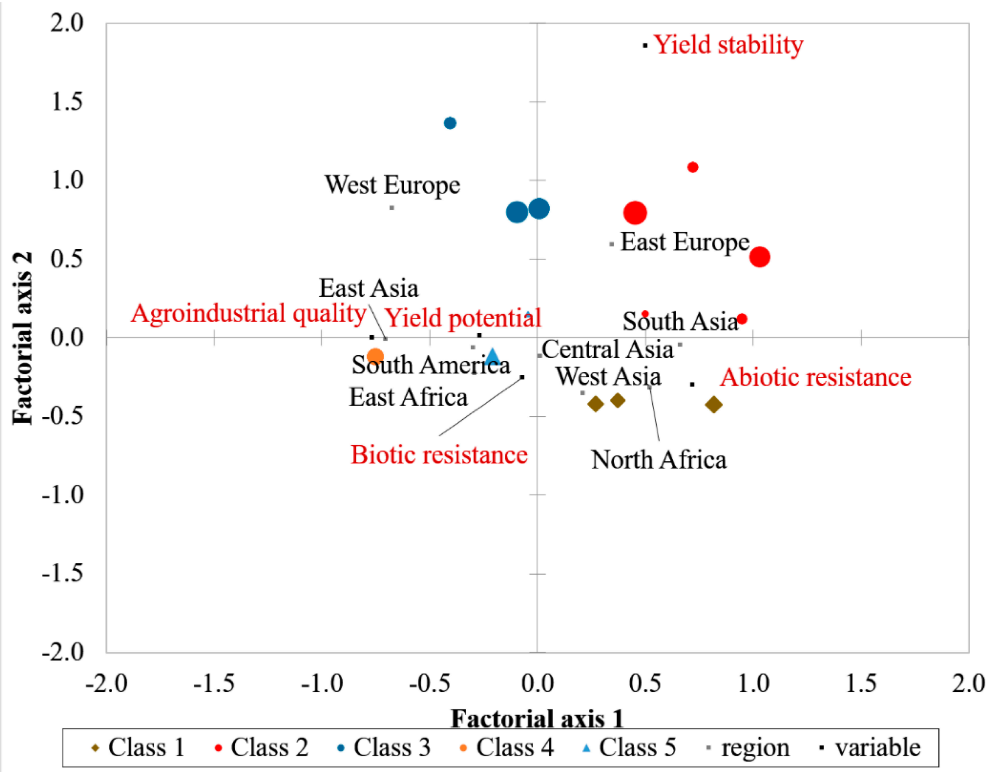

Figure 2. Factorial regression clustering of breeders based on declared preferences for specific objectives. Size of the class indicates the weight of the class. The regions and criteria are projected as supplemental variables.

Table 2. Analysis of variance (ANOVA) to compare the best approach for clustering preferences for specific traits by geographical origin or by principal component analysis (PCA).

Method of clustering	Breeders		Farmers	
	df	% of variation	df	% of variation
by geographical origin	44	34.5 **	251	30.1 **
by PCA	24	65.1 **	111	48.9 **

** Significant at the 0.01 probability level.

Clustering of Farmers' Profiles

A total of 861 farmers from 21 regions of Morocco were asked to score the importance of 27 traits of their wheat cultivars. A principal component (PC) analysis was used to group farmers into clusters of shared preferences and similar ranking of traits. This clustering captured 89.20% of the total interclass variance, allowing the identification of four classes of farmers' preferences (**Figure 3**). As for breeders, analysis of farmers' trait preferences showed that regional classification alone explained only 30.1% of the variation (**Table 2**), while in PC two main factors alone captured 60.39% of the total variance. The farmers' classes were differentiated according to: i) "yield potential" was the main trait for the majority of farmers, while some preferred a combination of traits, including "biotic" and "abiotic resistance" and "household use", and ii) the relative importance assigned to "biotic resistance" and "household use". The second axis is differentiated most farmers according to their degree of diversification of agricultural activities and market strategies.

Table 3. Weighted index of breeders' (BRD) objectives based on five clusters.

Class ID	Descriptive	Regions	Yield potential	Biotic resistance	Abiotic resistance	Industrial quality	Yield stability
BRD1	Class 1 oriented to biotic & abiotic resistance	North Africa, South & West Asia	23%	34%	36%	7%	0%
BRD 2	Class 2 oriented to yield stability & abiotic resistance	South & West Asia	12%	15%	42%	0%	30%
BRD 3	Class 3 oriented to yield potential & stability	South Asia, East & West Europe	30%	22%	0%	15%	33%
BRD 4	Class 4 oriented to yield potential, abiotic stress & industrial quality	East Asia, West Asia, East Europe	33%	7%	30%	30%	0%
BRD 5	Class 5 oriented to yield potential, biotic resistance and agro-industrial quality	East Asia, South America, East Africa	33%	33%	0%	33%	0%

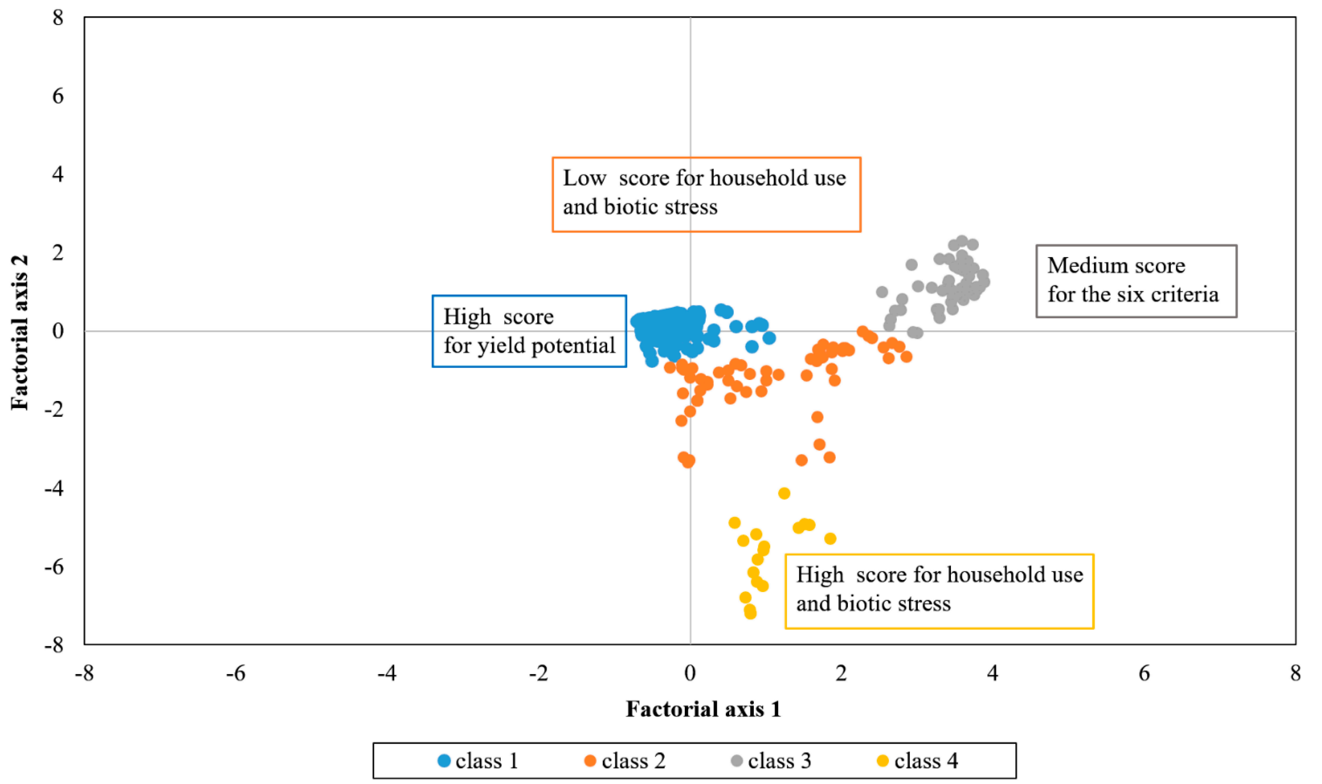

Figure 3. Factorial regression clustering of farmers based on declared preferences. Text explanations are provided for simplicity of interpretation.

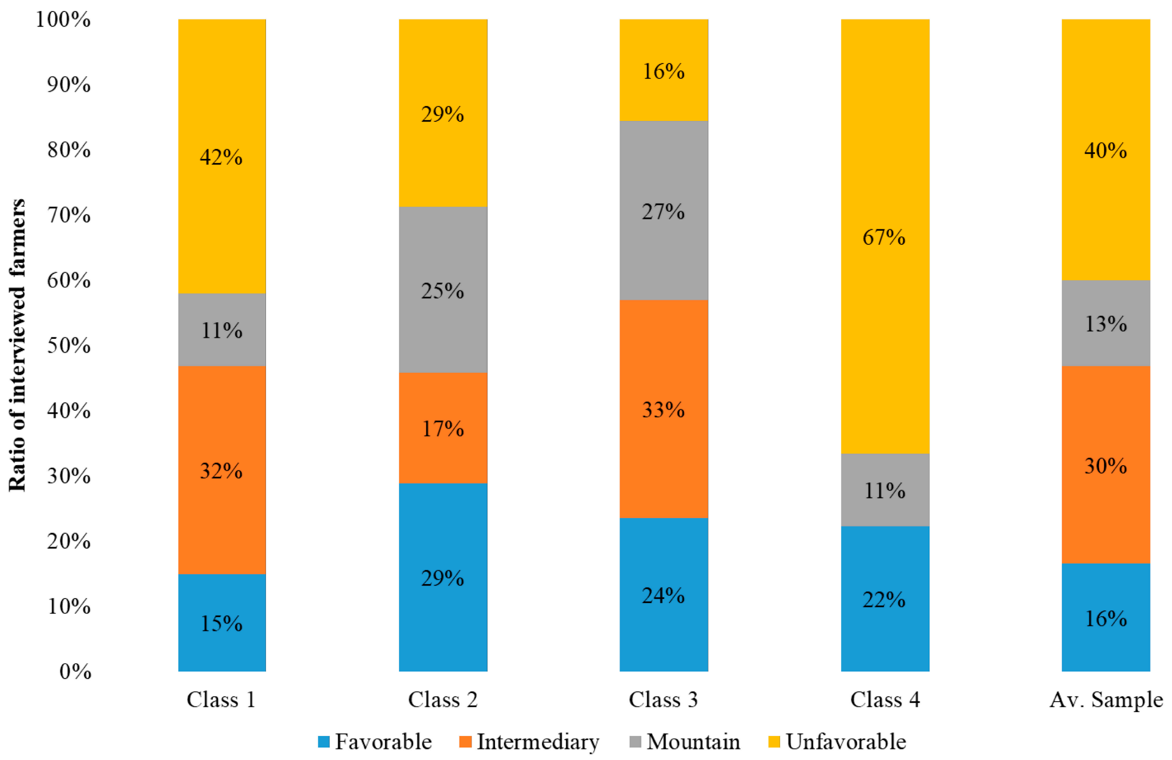

Figure 4. Geographical distribution of farmers' classes. The agro-ecological zones of Morocco are represented by colors and the ratio of farmers from a specific agro-ecology is presented as fraction of the total of that class.

Nearly all interviewed farmers (85%) belonged to class 1, the main preference of which was high "yield potential" (34%), followed by the interest in "industrial quality" (31%) and "household use" (12%). "Yield stability", followed by "abiotic resistance", and then "biotic resistance" remained important for the other classes. "Abiotic resistance" had the highest score in class 2, which placed more than one third of the farmers located in favorable zones like Meknès-Tafilalet and Rabat-Salé regions (**Figure 4**). These two were among the most industrialized regions and farmers' class 2, with a marked preference (19%) for "industrial quality", showed a clear target of selling their produce to food processors. On the opposite spectrum, farmers' class 3, from which 22% were located in mountain areas like Tensift-Alhaouz, showed preference for "yield stability" and "household use", traits that are typically preferred by smallholders practicing subsistence farming. Farmers' class 4 represented just 2% of the Moroccan farmers interviewed and was interested, nearly equally, in all traits, with priority given to "biotic resistance", "abiotic resistance" and "yield stability". The majority of them lived in the Taza-Alhoceima-Taounate region, which represents an extremely poor rural area, disconnected from the main markets, and with recurrent droughts and diseases epidemics. Hence, the farmer classes' preferences are well aligned with the issues of their production areas. **Figure 4** represents the geographical distribution of the farmers' classes into four agro-ecological zones according to their respective annual precipitation. Note that farmers' class 3 was present in all agro-ecological zones, contrary to the other classes where two thirds of farmers were in favorable or intermediate zones. This explains the heavy weight given to the criterion "household use" in this class as it would be expected for smallholder farmers. In class 2, 25% of farmers originated from the mountainous zones, which might explain the weight given to "biotic" and "abiotic" criteria, compared to class 1. The distributed weight given to the six criteria by farmers' class 4 can be partially explained by their location in favorable environments, where optimal production can be expected.

The classes of farmers and relative preferences are presented in **Table 4**. The scores provided by each farmer belonging to a farmers' class were converted into a percentage of preference for each broad category of criteria. This percentage was thus considered a weighted preference and used as a selection index for all downstream analyses. Based on the results, it is evident that "yield potential" was really the one critical trait for all farmers, followed by different preferences for the other traits depending on the specific farming systems. The average weight given to "industrial quality" (17%) reflected the shared objective of farmers to satisfy the household use, but also the market demand. Apparently, the basic need to produce for "household use" would be satisfied with the available amount of seeds in the market. This explains why the "industrial quality" would be determinant in the seed choice of this farmers' class. This can be put in relation with the geographical repartition of the sample with 71% in favorable and intermediary zones, which favors productions exceeding their household needs. Furthermore, the traits of "baking quality", "bread making quality", and "flour making quality" had been categorized in the broader criteria of "industrial quality". Yet, these traits could also be interpreted as "household use", since all rural households prepare their own couscous and other durum foods. Still, the industrial-made and home-made foods abide to substantially the same quality requirements, making it hard to discern what the exact intention of the farmers was when answering the interviews. This complexity is also somewhat true regarding the traits of "yield stability" and "biotic" or "abiotic resistance". For instance, "guaranteed minimum yield" trait can reflect the search for cultivars that resist well usual stresses like diseases or drought in Morocco. Whatever this ambiguity, "stability" was their third preferred trait (15.5%), and the usual stresses (drought and diseases) followed (both around 13%). This showed the relatively high importance of these traits when considered together under the general term "resilience", with an average weight of 41%, ranging from 23% for the class 1 to 51% for the three other classes. However, breeders clearly defined differences between stability and tolerance traits. As such, we also consider splitting farmers' preferences into these three separate criteria to be the correct decision. For the future, interviews conducted with the scope of developing selection indices should limit the type of answers, providing a precise list of traits, keeping in mind the possible confusions listed here.

Table 4. Weighted index of farmers' objectives based on four class clusters and overall preferences.

Criterion	Farmer 1	Farmer 2	Farmer 3	Farmer 4	Average
Yield potential	34.0%	21.3%	17.2%	18.8%	29.9%
Industrial quality	31.3%	18.7%	16.7%	17.5%	17.5%
Household use	12.1%	9.1%	15.9%	12.8%	11.3%
Abiotic resistance	7.6%	19.3%	16.6%	16.5%	12.9%
Biotic resistance	7.6%	17.3%	15.9%	16.9%	12.9%
Yield stability	7.6%	14.2%	17.7%	17.6%	15.5%

Comparison between Breeders' and Farmers' Weighted Indexes

The weighted index of five breeder classes (**Table 3**) was compared with the selection preferences of four classes of Moroccan wheat farmers (**Table 4**) in **Figure 5**. Four broad criteria were distributed evenly in the four quadrants of the principal component graph, with the exception of "yield potential" and "industrial quality", which shared one quadrant, indicating similar preferences across classes. The criterion of "biotic resistance" was not discriminant, while "household use" was removed all together since none of the breeders' groups indicated it. The five groups of breeders' objectives (from BRD1 to BRD5) were also distributed across the four quadrants based on the relative priority given to a trait over the others, with the exception of BRD4 and BRD5, which shared the quadrant containing "yield potential" and "industrial quality". Limited spread was observed for farmers' weighted indexes, which had the tendency to cluster at the center of the graph, suggesting stronger similarities to each other (within farmer ratings) than to breeding indexes. Similar results were also obtained by estimating dissimilarity distances (**Figure 5**), with the breeder objectives divided into five separate clades at the 0.95 level of confidence, while farmers' preferences were grouped together. For BRD3, we observed an overlap of preferences with farmers' classes 2, 3 and 4, whereas BRD4 and BRD5 belonged to the same clade as farmers' class 1. Interestingly, BRD3, which was characterized by preferences for "yield potential" and "stability", was mainly composed of South Asia, East Europe and West Europe breeders. Similarly, BRD4 and BRD5 were composed of East Asian breeders. However, the North African breeders' group (BRD1), including the sole Moroccan breeder that responded to the interview and breeders from Tunisia, Algeria, and Egypt, was quite distant from the Moroccan farmers' preferences. As a note, this is the normal situation in most North African countries where a single public breeder is the main responsible for releases of durum wheat public varieties. Hence, this revealed misalignment between the preferences of the Moroccan farmers and the selection objectives of breeders that aim at serving them. Farmers belonging to class 1 represented 86% of the interviewed farmers located in the favorable and intermediary zones of Morocco, from where the national food processors provision most of their grains for transformation. Their influence on the national breeders' choices should then be evident, leaving eventually the other classes less well served. However, BRD1 selection index highly focused on "abiotic" and "biotic" resistance, two traits that the interviewed farmers did not recognize as critical. Furthermore, this class of breeders did not mention at all any traits related to the "household use" (straw and home cooking), which accounted for 10–15% of the farmers' decision process to adopt new cultivars.

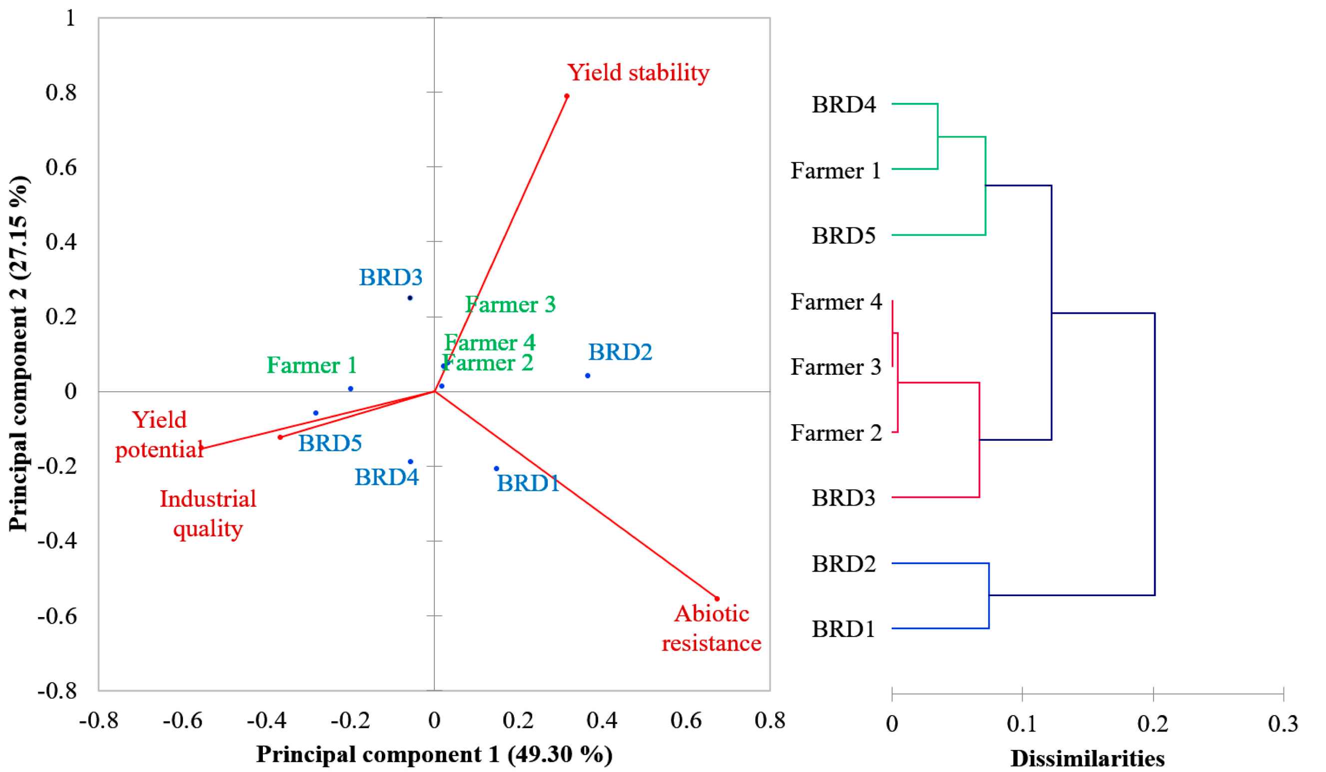

Figure 5. Comparison of weighted indexes of five broad wheat cultivars criteria between five breeders' (BRD) and four farmers' classes (Farmer) and their overall value. Left-Principal component analysis. Right-Dissimilarity hierarchical distances.

Comparison between Breeders' and Farmers' Preferences for Candidate Cultivars

The 38th International Durum Wheat Yield Trial (IDYT) is a set of durum wheat international nurseries distributed in 2015 by ICARDA to breeders that requested them. The total distribution reached 64 partners in 32 countries, mostly overlapping with the list of breeders interviewed as part of the work of [3], but only 27 partners from 18 countries returned data for the analysis. Results of this dataset were published in [15] and converted into values for each of the broad criteria (**Supplementary Table S3**). In this sense, "Icaverve" and "Derazejihan" were identified as the candidate cultivars with the highest yield potential (99%), "Derazejihan" as the cultivar with the most stable yield (89%), "Kundermiki" as the most disease resistant (67%), "Zagharin2" as the most tolerant to abiotic stresses (94%), "Bezajihan" as having the best industrial quality (93%), and "Azeghar2", "Icarukus", and "Zagharin2" as the most suitable ones for household use (96%). Altogether, the candidate cultivars used for this study showed a high level of phenotypic variation for all tested criteria, hence providing a good dataset to test the preferences of breeders and farmers.

The weighted indexes of breeders' and farmers' preferences were applied to this set of candidate cultivars (**Figure 6**). The elite named "Derazejihan" was found to meet up to 80% of the preferences of three classes of farmers. As expected, this candidate cultivar also matched the breeding objectives of breeders' class 3, which showed overlapping selection weights with farmers. In addition, the largest farmers class (class 1) matched at 87% the preference for "Zagharin 2", also preferred by BRD4, two classes that were placed in the same clade by hierarchical analysis of their selection weights (**Figure 5**). This indicated that ICARDA's selection of elites fell around 13% to 21% short of fully meeting the preferences of Moroccan farmers.

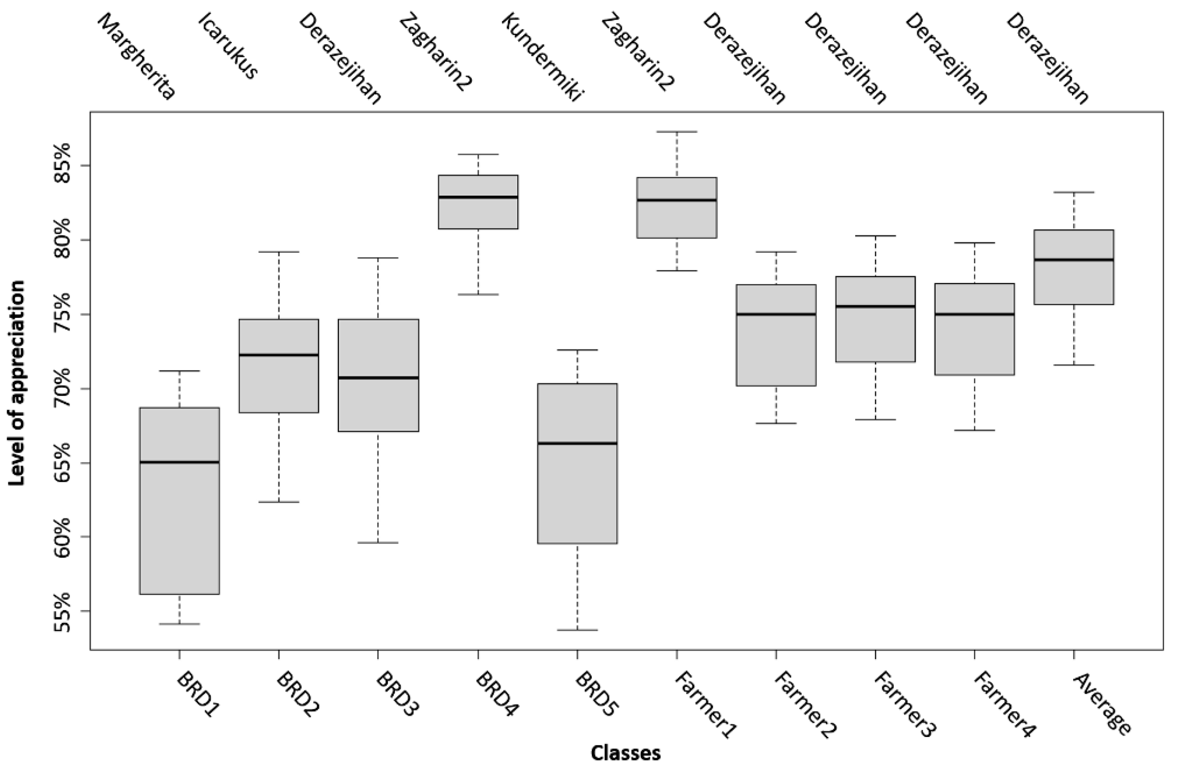

Figure 6. Distribution of matching preference for 23 candidate cultivars as assessed by selection index for five breeders (BRD) and four farmers (Farmer) classes. Percentage of match is presented. The "average" of farmers classes was obtained using as weighted index the "Average" column from Table 4.

Among breeders' classes, the best matching scores reached 71%, 79%, 79%, 86%, and 73% for classes 1 to 5, respectively. Breeders class 1 (BRD1) was overall the least well served among all classes by this set of elite lines, with an average of just 63%. The preference of this class, which includes North African breeders, was the elite "Margherita" because of its combined "abiotic" and "biotic" stress tolerance. In reference to "Derazejihan" and "Zagharin2" (the two most preferred cultivars by Moroccan farmers), BRD1, which is the class that includes the North African breeders, attained a matching of only 69% and 62%, corresponding to the 5th and 14th places of preference, respectively. Similarly, the cultivar "Margherita", the preferred genotype by BRD1, was identified as the 4th or lower preferred cultivar by all farmers' classes (**Supplementary Figure S1**).

The class 2 weighted index identified "Icarukus" as meeting 79% of the criteria, because of its good "abiotic stress tolerance" combined with "yield stability". Class 3 preference was for "Derazejihan", the same elite cultivar appreciated by Moroccan farmers, which combines "yield potential" and "yield stability". Class BRD4 best match was the elite "Zagharin2", as it was the case for farmer class 1, and this preference was because of its combination of "yield potential", top "abiotic stress tolerance", and good "industrial quality". Finally, BRD5 focus on "biotic resistance" was ideally served by "Kundermiki", the most disease resistant of the lines, while still providing good "yield potential" and acceptable "industrial quality".

An additional note can be added about the old cultivar "Omrabi 5", which is currently cultivated on approximately 10% of the area in Morocco under the name of "Tomouh". This line fell 22% to 33% short of meeting farmers' needs, providing a good argument for promoting its replacement with "Zagharin 2" or "Derazejihan". Unfortunately, none of these two candidates were among the top 3 favorites of the North African breeders (BRD1), who actually identified "Margherita" as the most suitable cultivar, which in turn was not among the top 3 preferred by any of the farmer classes. Since breeders typically promote only the top 1 or 2 best genotype each year for variety consideration, the gap identified in weighted indexes between farmers and North African breeders resulted in an actual gap between the farmers' preferences and the breeders' responsibility to deliver them the best fitting cultivars at the national level. The stagnant rate of cultivar replacement observed for Morocco in the last two decades could then be partially pin pointed to the observed differences between breeders objectives and farmers' preferences.

Still, the preferred line by breeders, even though it was not the favorite of farmers, reached nevertheless 86% to 77% approval by Moroccan growers, well above the 78% to 67% shown for the currently grown "Omrabi 5". Hence, other structural issues still exist in the Moroccan variety system that continue to create misfits slowing farmers adoption.

CONCLUSION

Faced by the multiple constraints and risks of the harshening climates, improving grain yield potential, yield stability, resistance/tolerance to biotic and abiotic stresses, end-use and nutritional quality characteristics remain the most critical wheat breeding objectives. However, the weights attributed to each objective varies according to the farming systems, agro-ecological, sociological and market environments and the main actors involved along the value chain. Capturing this complex diversity is extremely difficult, especially in developing countries where it is challenging to gain access to transparent and comprehensive market or social data. Farmers can then become a very valid alternative of information, as they are ideally positioned along the value chain as buyers of varieties and sellers of grains to the food processors. Moreover, they are typically willing to share their opinions and transparent about their needs. Hence, taking advantage of socio-economic surveys of farmers via weighted index can be a simplistic tool to capture part of this complexity, and promote ideal cultivars for national breeding programs. In that sense, this article provides a good guide on how to approach this challenge.

Even though breeders tend to develop long term goals, while farmers preferences are somehow subject to short term issues encountered, a clear gap was identified between North African farmers' (farmer class 1) preferred traits and North African breeders' (BRD1) selection objectives. In fact, *i.* BRD4 ignored the importance of "household use" which accounted for 10–15% of farmers preference, *ii.* gave high priority to "abiotic" and "biotic" stress response (34–36%) while farmers did not (7.6–19.3%), *iii.* and these resulted in a clear gap in germplasm selection in terms of the top 3 entries to be advanced for variety consideration. This was not the case for BRD3 and BRD4, which aligned well with farmers preferences both as weighted objectives and germplasm selection, showing that matching farmers preferences is possible.

Further, a risk exists that without a thorough review of the future priorities, the distance between local farmers and North African breeders could become even wider. In addition, some geographical and social discrimination exist among Moroccan farmers. Even though only a small portion of farmers belong to minority classes, still they represent hundreds of thousands of rural families, often living in severe poverty and growing wheat under the harshest of conditions. Hence, it would be important to target also these minority groups. Even if data of farmers from other countries were not available, we can assume that similar gaps might exist between breeders and smallholder farmers' priorities. Hence, a similar approach to what is described here should be undertaken to measure the existence of misalignments and address them by re-targeting breeding goals. Until this will be possible, the weighted selection indices presented here can be used to provide better targeting in the short term.

Along the same line, some research teams have already applied in the past the concept of farmers' participation in the variety selection process (participatory variety selection, PVS). This approach is now recognized as essential for favoring adoption of new cultivars and providing a feedback to breeders, especially in vulnerable environments as shown by [22–25].

However, this approach is extremely time-consuming and only a limited number of farmers can take part in the selection process. In that sense, the use of participatory farmers-weighted selection indexes (PWS) appears simpler, less costly, and with a larger number of farmers inputs that can be integrated into breeding. In addition, PVS lacks the instruments to link the "food system" at territorial level (including the "household use") to the "value chain" at national level, as it relies only on the immediate knowledge of the participating farmers, without including the futuristic visions of other actors along the value chain. Again, socio-economic weighted selection indices appear as a strategic solution, where farmers' opinions could be integrated with multi-actor considerations. Overall, this challenge calls for more systemic and complex approach to develop the criteria for cultivar selection in developing countries and the clear need for wheat breeders to ensure good farmers alignment in their current approach of priority setting.

SUPPLEMENTARY MATERIALS

The following supplementary materials are available online at https://doi.org/10.20900/cbgg20200014:

Supplementary Figure S1: Distribution of matching preference for 23 candidate cultivars as assessed by selection index for breeders' class 1 (BRD1) composed of North African breeders and the largest Moroccan farmers (Farm) class. Percentage of match is presented,
Supplementary Table S1: Grouping of breeders' open-end responses into five homogeneous categories,
Supplementary Table S2: Grouping of farmers' preferences into six homogeneous categories,
Supplementary Table S3: Estimated performances of 23 durum wheat candidate cultivars by selection criteria converted from field data into ratio to the best genotype (0–100%).

AUTHOR CONTRIBUTIONS

VA, YY, and FMB wrote the article; YY collected the farmers survey data; FMB collected and analyzed field data; VA analyzed all data combined; VA and FMB designed this study; all authors reviewed and approved the final version.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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