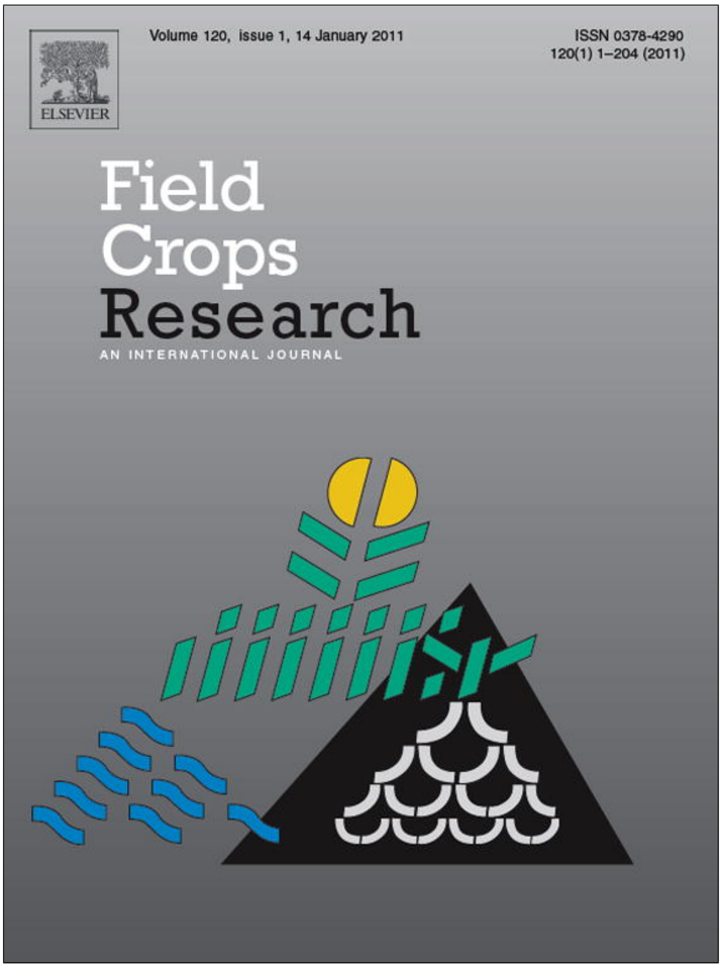

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Comparing decentralized participatory breeding with on-station conventional sorghum breeding in Nicaragua: II. Farmer acceptance and index of global value

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ABSTRACT

Participation of farmers in the genetic improvement of staple crops in vulnerable environments is now widely accepted as a necessary approach for enhancing the acceptance of improved varieties. Our study set out to assess the genetic gains achieved by collaborative decentralized participatory breeding programmes in comparison with those obtained by conventional breeding. The gains were estimated on farmer acceptance and combination of agronomic and quality-related traits, from three breeding programmes on *tortillero* sorghum for low-input cropping systems in northern Nicaragua. In each programme, three selection modes were compared: selection by the farmers on-farm (FoF), by the breeder on-station (BoS), and by the breeder on-farm (BoF). Our results showed that the lines produced by FoF selection were more praised by the farming community, compared to BoS and BoF selection. Comparative advantage of FoF selection was to develop higher proportion of lines with an adequate balance between agronomic traits, and with better quality traits related to grain appearance and plant type. A composite selection index, ISFA, was computed for each line as a combination of agronomic performance in the target environment, and *ex post* farmer appraisal. Based on this index, FoF selection proved again to be more efficient than BoS and BoF selection. We propose that such a selection index be used in participatory breeding programmes to improve their efficiency.

1. Introduction

For low-input agriculture in vulnerable environments whose products are generally earmarked for family consumption, the success of a new variety depends on its agronomic performance in the existing cropping systems and a combination of traits related to plant type and product quality. Farmer preferences for specific plant types, e.g. associated with adaptation to certain cropping systems or local environmental constraints, vary depending on the local production systems. Likewise, if grains or tubers are concerned, quality is a multi-component trait, including appearance (colour, shape and size), conservation and processability, and the culinary value for various local dishes. These components are often influenced by local features. This makes farmer preferences for these quality traits and, even more so for trait combinations, difficult to assess and to integrate in a formal breeding programme. Thus, under these conditions, intense participation of farmers in the selection process is now widely considered as essential for developing appropriate varieties (Morris and Bellon, 2004; Witcombe et al., 2005; Ceccarelli and Grando, 2007).

In this respect, decentralized participatory variety selection (PVS) has proved to be highly effective for providing enhanced varieties which combine superior agronomic performance and adequate quality traits, in a shorter time and at low cost (Joshi and Witcombe, 1996; Tiwari et al., 2009; Trouche et al., 2009). However, few studies have measured the real effectiveness of decentralized breeding programmes managed by farmers from early selection generations, compared with centralized conventional breeding. In a review of twelve participatory plant breeding (PPB) programmes, Witcombe et al. (2006) concluded that collaboration with farmers at the selection stage globally showed favourable results. In comparison with formal programmes managed on-station by professional breeders, the PPB programmes seldom produced genotypes with significant higher yield, but more often with an improved balance between earliness and yield, or between yield and grain quality.

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In general, a major key to the success of a plant breeding work lies in a combination of relevant quantitative traits such as yield, cycle duration, disease and pest resistance, which contribute to agronomic performance, and farmers' criteria regarding specific quality traits, which guarantee ultimate acceptance of the variety. This issue may be addressed through the elaboration of a selection index, attributing appropriate weights to the various key traits. Such an approach has been more extensively explored for animal breeding than for plant breeding. It was first proposed by Smith (1936) and then generalized in plant breeding programmes from the eighties onwards, especially for perennial plant improvement. Selection indices are often used in single trait selection, integrating data from related traits to increase selection effectiveness for the target trait. However, when selecting for multiple traits, significant difficulties arise in assigning economic weights to the various traits (Sölkner et al., 2008). In a comparative review of selection for multiple traits in plant and animal breeding, Sölkner et al. (2008) observed that plant breeders often use non-formalized ways of combining selection pressure on various traits. For these authors, this is because it is generally difficult to estimate the economic value of each trait, as well as the genetic variances and co-variances of the traits considered. Nevertheless, empirical weighting, if judiciously applied, has also proved to be effective for meeting the selection objectives. In one of the few papers linking a selection index and farmer preferences, Sharma and Duveiller (2006) reported that a selection index, when applied in a wheat breeding programme managed on-station, based on resistance to a major disease, early maturing and high kernel weight, could simultaneously improve yields and farmer acceptance under on-farm conditions.

Beginning in 2003, several participatory sorghum breeding programmes were initiated in Nicaragua under a CIRAD-CIAT project managed in collaboration with Nicaraguan partners (Trouche et al., 2009). They set out to develop more suitable sorghum varieties for the low-input farming systems of the Northern Region, which is characterised by a semi-arid climate with highly variable rainfall, and poor soil fertility (Trouche et al., 2011). This research was conducted between professional breeders, agronomists and local farmer groups. Three of the breeding schemes were designed and implemented simultaneously by way of three selection modes: selection by a professional breeder on-station (BoS), by a professional breeder on-farm (BoF) and by farmer–breeders on-farm (FoF). In a previous paper, the agronomic performance of lines derived from these three selection modes was compared and discussed (Trouche et al., 2011). This paper first looks at *ex post* acceptance by farmers of the lines developed from each selection mode with two central questions: (i) are the lines created by FoF selection also those that are preferred by a larger community of farmers in the same region? and (ii) which agronomic and quality traits might help to explain these possible preferences? It then proposes the use of a composite selection index, combining agronomic performance and farmer acceptance, for defining the global value of the lines derived from each selection mode, and finally discusses the advantages of such an index.

2. Materials and methods

This study considered three breeding schemes implemented to improve white-grain, non photoperiodic *tortillero* sorghum, each developed from a distinct segregating population, called PCR-1, PCR-2 and CIR-6. For simplicity, the three breeding schemes will be identified hereafter by their respective population names. Each of them was implemented by way of the three selection modes, FoF, BoS and BoF, as described above.

2.1. Partners

The participants in the sorghum breeding programmes included a professional sorghum breeder from CIRAD, two agronomists from the Cipres NGO, and three farmer–breeder groups, members of local farmer organizations, who had also participated in the PVS phase of the research project.

2.2. Breeding objectives

An iterative interaction process between the local farmer groups and the research team led to the identification of breeding goals and a ranking of the selection criteria, as described in a previous publication (Trouche et al., 2009). At each on-farm site, selection criteria were refined through discussions between the local farmer–breeders and the research team. For the breeding schemes involving the PCR-1 and PCR-2 populations, the selection criteria were detailed in a previous paper (Trouche et al., 2011). Table 1 summarizes the breeding goals defined for the target ecosystems, the sites of selection and the main selection criteria of the three breeding schemes considered in this study.

2.3. Description of the breeding schemes

A complete description of the two breeding schemes developed from the PCR-1 and PCR-2 populations was given by Trouche et al. (2011). The third breeding scheme, identified as CIR-6, was developed from a single cross made between a well-adapted local cultivar, Sorgo Ligero, and an improved inbred line developed in Burkina Faso, BF 94-6/11-1K-1K, selected for giving short plant type and enhanced fodder quality, as well as midge resistance (Dakouo et al., 2005). Table 2 summarizes the history and the general design of all three breeding scheme studied. In each scheme, the same quantity of seed and similar plot area were used both on-station and on-farm. At the on-farm selection sites, three to four farmers, previously involved in the PVS phase of the project, were invited to participate in the breeding programme. In Totogalpa, the selection activities of the CIR-6 and PCR-1 schemes were managed in two districts of the village with two distinct farmer groups. Before

Table 1
Breeding goals, target ecosystems, sites of selection and main selection criteria of the three breeding schemes considered in this study.

Breeding goal and target ecosystem	Schemes	Sites of selection	Selection criteria of higher priority
Grain production under low inputs cropping systems in dry areas	CIR-6 and PCR-1	CNIA station + Totogalpa	Early cycle (90 days to maturity) with drought tolerance Adaptation to low soil fertility Grain yield up to 2 t ha^{-1} Grain quality for auto-consumption (Tortillas and others)
Grain + fodder under intermediate intensification in more favourable areas	PCR-2	CNIA station + Pueblo Nuevo	Intermediate cycle (100–110 days to maturity) Good response to semi-intensified cropping systems Plant height = 1.5–1.8 m High fodder production with improved quality (high leaf/stem ratio) Grain yield up to 3 t ha^{-1} Grain quality for auto-consumption and sale

Table 2
History and design of the three breeding schemes PCR-1, PCR-2 and CIR-6.

Scheme	Source of genetic variability	Number of parents	Selection modes in comparison	Cycles of selection achieved per mode
CIR-6	Single cross	2	BoS, BoF, FoF	3: F_2 to F_5
PCR-1	Synthetic population	6	BoS, BoF, FoF	2: S_0 to S_{2-4}
PCR-2	Synthetic population	6	BoS, FoF	2: S_0 to S_{2-3}

BoS = breeder on-station; FoF = farmers on-farm, BoF = breeder on-farm.

starting the first selection cycle, the farmer–breeders (FB) followed a training course on the basic principles of plant breeding, as well as indications of the heritability of the main traits under selection. At the same time the FBs were also invited, in a group discussion, to define precisely the selection criteria and preferred plant types for the selection work considered. In the following cycles, these criteria were reminded in order to maintain coherence throughout the selection process. Based on these criteria, the FBs carried out their own selection along with but independently from the professional breeder (PB), who applied his own criteria defined from his knowledge of what sorghum growers need and prefer in this region. On-station, the PB used the same selection criteria and applied a similar selection intensity to that used at the on-farm sites.

2.4. Evaluation for agronomic traits of the lines derived from the three selection modes

For the three breeding schemes CIR-6, PCR-1 and PRC-2, yield trials were set up during the *postrera* season on-station and on-farm to assess the agronomic performance and farmer acceptance of the lines derived from each selection mode. In 2006 and 2007, these trials included all the progenies derived from the breeding scheme involved, or a large sample of them (up to 50%); they were planted at the CNIA station and at their respective on-farm breeding locations (Totogalpa for PCR-1 and CIR-6, and Pueblo Nuevo for PCR-2). Based on the 2007 evaluations, the 20% top lines for each selection mode were identified according to a selection index integrating agronomic performance and farmer (for on-farm selection) or breeder acceptance (for on-station selection). Only these top lines and three variety controls were included in the 2008 on-farm yield trials. For each breeding scheme, those trials were established at two sites but two of them were lost because of livestock damages. Table 3 gives a summary of the number of lines and the localization of all the on-farm yield trials managed for this study during the period 2006–2008.

The yield trials were planted in alpha-lattice designs with three replications. The harvested plots measured 4–9 m^2 per genotype, i.e. two 4–5-m long rows in 2007, three or four 5–6-m long rows in 2008, at the farmers' spacing.

The research team measured the following agro-morphological traits in the trials: days to 50% flowering (DF), plant height (PHT), disease and pest resistance, stay-green trait, panicle type (compact, semi-compact, loose), panicle number and panicle weight per plot, grain humidity at harvest stage and 1000-kernel weight (TKW). Grain yield (GRY) was calculated from the panicle weight per plot, applying a standard 0.80 coefficient (Paul, 1990), and were assessed at 14% moisture.

2.5. Farmer evaluation and selection among lines in the yield trials

At the maturity phase, male and female farmers with recognized knowledge in sorghum production and ability to conduct careful lines evaluations were picked from the same locality and neighbouring villages as Farmer–Assessors (FA). In the first year (2007), respectively three, five and four *expert* FAs evaluate individually the complete set of lines derived from the CIR-6, PCR-1 and PCR-2 programmes included in the respective on-farm yield trials. In the second year (2008), 29 FAs participated in the lines evaluation in the field and 13 FAs (11 females and 2 males) evaluated grain quality aspects at post-harvest stage. The FBs accounted for half of the FAs in 2007, but they were a small minority in 2008. At maturity phase, the FA groups were invited to evaluate all the lines included in the trial. For this purpose, it was used a scoring method based on farmers' selection criteria as previously described by Trouche et al. (2009). In the 2007 evaluation exercises, because of the large number of lines to be assessed, the research team proposed that the FAs should only assess quality-related traits, i.e. plant type, grain appearance and forage quality. In addition they were invited to assess the overall appreciation of each line. Each line was thus scored for each of these traits on a scale of 1 (bad) to 4 (excellent), by each FA. In 2008, as fewer lines were included in the yield trials, their evaluation was carried out by small groups of 3–4 FAs. Immediately after completing the evaluation, FAs were asked to select their preferred lines. During these evaluation exercises, they had, of course, no information on the origin of the lines in assessment.

2.6. Elaboration of a composite selection index

A composite selection index, called the Index of agronomic Suitability and Farmer Acceptance (ISFA), was defined and tested in this study. It combined four quantitative agronomic traits (DF, PHT, TKW and GRY) which were quoted as most important by small sorghum growers for the target environments (Trouche et al., 2009). It also included two key qualitative variables based on farmer assessments of the lines in the yield trials: farmers' scores for the first sorghum quality trait, grain appearance in the Totogalpa area and fodder quality in the Pueblo Nuevo area as the first variable, and

Table 3
Summary of the on-farm yield trials evaluating the lines derived of the selection modes in comparison in each breeding scheme.

Scheme	Year	Generation	Number of lines per mode	Sites of evaluation
CIR-6	2006	F_4	18–42–22[a]	CNIA station[b]
	2007	F_5	10–17–12[a]	Totogalpa
	2008	F_5	4	San Lucas
PCR-1	2007	S_{2-4}	30	Totogalpa + CNIA station
	2008	S_{2-5}	6	CECOOP
PCR-2	2007	S_{2-3}	60	Pueblo Nuevo + CNIA station
	2008	S_{2-4}	12	Unile + Palacagüina

[a] For BoS, FoF and BoF, respectively.
[b] Only on-station trial used in our study because the same trial managed on-farm failed because of drought.

Table 4
Respective weights defined for the agronomic and quality-related traits included in the calculation of the ISFAe (Totogalpa area) and ISFAm (Pueblo Nuevo) selection indices.

Index	DF	PHT	TKW	GRY	FSF	GQS	FQS
ISFAe	−3	−2	3	5	4	4	0
ISFAm	−2	−3	2	5	4	0	2

DF, days to flowering; PHT, plant height (m); TKW, thousand kernel weight (g); GRY, grain yield (t ha^{-1}); FSF, farmer selection frequency (%); GQS, grain quality score (1–4 scale) evaluated by FAs; FQS, fodder quality score (1–4 scale) evaluated by FAs; ISFA, Index of agronomic suitability and farmer acceptance.

as the second variable the frequency with which farmers selected a specific line (FSF). This index was computed as:

$$\text{ISFA}_i = \sum\nolimits_j a_j * \left[\frac{x_{ij} - m_j}{s_j}\right]$$

where i was the line number, x_{ij} the phenotypic value of line i for trait j, m_j the mean performance and s_j the standard deviation of all lines for trait j, a_j is the relative weighting of trait j in the index, where j = 1–6 with 1 = DF, 2 = PHT, 3 = TKW, 4 = GRY, 5 = grain quality score (GQS, Totogalpa area) or fodder quality score (FQS, Pueblo Nuevo area) and 6 = FSF.

The weights allocated to each trait were firstly defined based on their relative importance for the adaptation to the target ecosystems and their relative importance for farmer acceptance assessed in previous studies (e.g. earliness gets a higher weight for the dry ecosystem of Totagalpa area, compared to that of Pueblo Nuevo). In the case of Pueblo Nuevo ecosystem, because of the negative correlations between the plant height preferred by farmers and the yield performance and the high positive correlation between PHT and FQS, we had to adjust the weights of GRY, PHT and FQS traits by iterative tests in order to maximize the correlation of the ISFA index with all the constitutive traits. Ultimately the final weights allocated to each trait have been arbitrated by the professional breeder. Table 4 presents the final weights defined for each agronomic and quality trait included in the ISFAe and ISFAm indices respectively, defined for the Totogalpa and Pueblo Nuevo environments.

2.7. Statistical analyses

ANOVAs based on a fixed effects model were performed with the SAS Statistical Software Package using the GLM procedure to calculate the adjusted means of the agronomic variables measured for the yield trials.

The differences between the selection modes in the proportion of the most preferred lines by farmer–assessors were tested using the Rao-Scott Chi-2 test, with the SURVEYFREQ procedure of the SAS program.

A correlation analysis was performed between the agronomic traits measured and the quality-related traits assessed by FAs, and calculated ISFA indices from the results of the 2007 yield trials evaluating the PCR-1 and PCR-2 lines, in order to verify the relationships between these variables in each target area.

The *t*-test of Student was used to test quantitative differences between mean values of the farmers' preferred lines and those of the BoS and FoF lines for the DF, PHT and TKW traits. The Tukey-test was used to perform mean comparisons of the 10% superior lines selected on the basis of the three selection criteria tested, GRY, FSF and ISFA, regarding performance for grain yield. For performing the correlation analyses as well as the *t*-test and Tukey-test, we have used the Xlstat statistical software, version 2009 6.02.

3. Results

3.1. Farmer evaluation of the lines derived from three different selection modes in on-farm yield trials

In the on-farm yield trials evaluating the lines created in each breeding scheme, the lines with high farmer selection frequency (FSF) scores were identified by their selection mode (Table 5).

The preferences displayed by the farmer–assessors (FAs) were globally consistent with the selection work carried out by the farmer–breeders (FBs). In six out of seven trials subjected to field evaluation, the FAs chose a larger proportion of lines derived from FoF selection (Table 5). In only one case, the CECOOP_2008 trial, did they select more lines of BoS origin. Analysing together the CIR-6 and PCR-1 trials and PCR-2 trials for all sites, significant differences were detected between the selection modes according to the results of the Rao-Scott Chi-2 test. BoS selection provided an average 23% of the CIR-6 and PCR-1 lines selected by farmers in the yield trials. It also provided 42% of the PCR-2 selected lines (resulting from only two selection modes). Based on the appraisals of CIR-6 and PCR-1 lines only, BoF selection obtained similar results to BoS selection.

In the post-harvest evaluations of threshed grains, we did not observe any difference between FoF and BoS lines for grain quality,

Table 5
Origin of the lines preferred by farmer–assessors, for their overall value in the field at maturity and for their grain appearance at the post-harvest stage, in the on-farm yield trials (2007–2008).

Breeding scheme	Trial	Stage of farmer evaluation	Number of lines evaluated	Number of most preferred lines[a]	Origin of most preferred lines (%)		
					BoS	FoF	BoF
CIR-6	Totogalpa_2007	Field	39	8	25	62.5	12.5
	San Lucas_2008	Field	12	3	0	66	33
PCR-1	Totogalpa_2007	Field	90	18	28	44	28
	CECOOP_2008	Field	18	5	40	20	40
Average on CIR-6 and PCR-1 schemes				34	26.5	47*	26.5
PCR-2	Pueblo Nuevo_2007	Field	120	24	42	58	NA
	Unile_2008	Field	24	6	33	67	NA
	Palacaguina_ 2008	Field	24	6	50	50	NA
Average on PCR-2 scheme				36	42	58*	–
PCR-1	Totogalpa_2008	Post-harvest	18	5	40	40	20
PCR-2	Unile_2008	Post-harvest	24	6	50	50	NA

BoS, breeder on-station; FoF, farmers on-farm; BoF, breeder on-farm; NA, not applicable.
[a] 20% and 25% most preferred lines by farmer–assessors, for the 2007 and 2008 trials respectively.
* Significant differences between the compared selection modes detected according the Rao-Scott Chi-2 test

Table 6
Mean values and standard deviation of the 20% most preferred lines by farmer–assessors for three phenotypic traits, compared with the average BoS and FoF lines, in the yield trials evaluating the F_4 CIR-6, S_{2-4} PCR-1 and S_{2-3} PCR-2 lines derived from these three breeding schemes.

Breeding scheme and year	Category	DF		PHT		TKW	
		Mean ± sd	Δ[a]	Mean ± sd	Δ[a]	Mean ± sd	Δ[a]
CIR-6 (2006)	Most preferred	61.7 ± 1.4		2.04 ± 0.22		34.1 ± 3.2	
	BoS	61.9 ± 1.6	ns	2.08 ± 0.24	ns	32.8 ± 1.9	ns
	FoF	62.8 ± 1.9	ns	2.03 ± 0.26	ns	34.7 ± 2.9	ns
PCR-1 (2007)	Most preferred	63.9 ± 1.6		1.39 ± 0.17		28.6 ± 2.5	
	BoS	65.6 ± 2.4	**	1.56 ± 0.12	**	27.8 ± 2.6	ns
	FoF	64.3 ± 1.8	ns	1.52 ± 0.18	*	28.3 ± 2.5	ns
PCR-2 (2007)	Most preferred	64.1 ± 3.2		1.79 ± 0.22		31.4 ± 3.9	
	BoS	65.4 ± 3.1	ns	1.96 ± 0.21	**	31.1 ± 3.3	ns
	FoF	63.7 ± 3.0	ns	1.86 ± 0.19	ns	32.3 ± 3.6	ns

DF, days to flowering (days); PHT, plant height (m); TKW, thousand kernel weight (g); BoS, breeder on-station; FoF, farmers on-farm; BoF, breeder on-farm.
[a] Comparison of the mean of most preferred lines with the mean of BoS and FoF selection modes based on *t*-test for samples of unequal size.
* $p < 0.05$.
** $p < 0.01$.

which was assessed by a group of female and male farmers through five criteria of grain appearance and hardness (Table 5).

3.2. Quantitative traits explaining farmer preferences

Table 6 compares the performance of the 20% most preferred lines (i.e. 20% top FSF lines) to the average BoS and FoF lines at the F_4 or S_2 generation stage.

Highly significant differences were observed between the mean values of 20% most preferred lines and BoS lines on DF and PHT traits and on PHT trait, respectively for the PCR-1 and PCR-2 programmes (Table 6). Significant differences between the mean values of 20% preferred lines and FoF lines were only recorded for PHT trait in the PCR-1 programme. The three categories of lines did not deviate significantly for the TKW trait. These results show that, on average, farmer–assessors, farmer–breeders and the professional breeder did not diverge much in prioritizing selection and evaluating the criteria that affected each of these quantitative traits.

Nevertheless, as regards all three breeding schemes, FAs tended to select earlier lines with reduced plant height, compared to the average phenotypes produced by BoS selection. All traits combined, the lines most appreciated by FAs looked phenotypically closer to those produced by FoF selection.

3.3. Qualitative traits related with farmer preferences

For the three breeding schemes, FoF lines were given the highest proportion of good or excellent scores for most of the qualitative traits evaluated (Table 7). Compared to BoS selection, this advantage of FoF selection was more obvious for more defined traits such as grain appearance and plant type than it was for the complex overall appreciation trait (Table 7).

FoF lines were favoured by FAs for different reasons depending on the breeding scheme. In CIR-6, FoF lines were most praised for their grain appearance, as well as their fodder aspect (not shown). In PCR-1, FoF lines were preferred for their grain appearance (mainly size, colour and glume openness) and the combination of earliness, grain aspect and grain yield, which mainly determined the overall appreciation score. In PCR-2, the preference in favour of FoF lines was mainly due to a superior plant type and a better balance between agronomic and quality-related traits, as expressed by the overall appreciation score.

3.4. Combining quantitative and quality traits in a selection index

In order to combine agronomic performance and farmer preferences on quality-related traits in a single parameter, we computed the ISFA selection index as described in Section 2.

The correlation analysis performed for the variables measured in the 2007 PCR-1 and PCR-2 yield traits indicated that the farmer preference score for a line, expressed by FSF, was not correlated with the measured grain yield (Table 8). FSF was correlated with plant height (PHT) and with the farmers' appreciation scores for grain and fodder quality in both PCR-1 and PCR-2, and with the cycle to flowering (DF) for PCR-1 only. For both PCR-1 and PCR-2, the ISFA indices were closely linked with all the agronomic and quality traits, except with PHT for PCR-1 and thousand kernel weight (TKW) for PCR-2. This was consistent with previous observations which identified PHT and TKW as secondary selection criteria for the Totogalpa and Pueblo Nuevo areas respectively.

Table 9 compares the average grain yield and the proportion of the 10% most preferred lines, depending on the use of three selection variables: grain yield, FSF and the ISFA index. These data were obtained from the 2007 on-farm yield trials and combined

Table 7
Proportion of lines with a score equal to or over 3, on a scale of 1–4, for four qualitative criteria assessed in the 2007 farmer evaluations in the on-farm trials.

Qualitative trait	Population source	Site/year	Number of lines tested per mode	Origin of lines (%)		
				BoS	FoF	BoF
Grain appearance	CIR-6	Totogalpa-2007	10–16	65	86	76
	PCR-1	Totogalpa-2007	30	42	48	39
	PCR-2	Pueblo Nuevo-2007	60	48	60	NA
	Together			51	65	–
Plant type	PCR-2	Pueblo Nuevo-2007	60	35	47	NA
Fodder quality	PCR-2	Pueblo Nuevo 2007	60	52	53	NA
Overall appreciation	CIR-6	Totogalpa-2007	10–16	43	35	38
	PCR-1	Totogalpa-2007	30	26	33	29
	PCR-2	Pueblo Nuevo-2007	60	17	23	NA
	Together			29	30	–

BoS, breeder on-station; FoF, farmers on-farm; BoF, breeder on-farm; NA, not applicable.

Table 8
Phenotypic correlations between three candidate selection variables, GRY, FSF and ISFA index and seven quantitative and qualitative traits measured in the 2007 on-farm yield trials evaluating the PCR-1 and PCR-2 lines.

Selection variable	DF	PHT	TKW	GRY	FSF	GQS	FQS
GRY	ns\ns	ns\0.47**	ns\ns	1	ns\ns	ns\ns	no\ns
FSF	−0.39**\ns	−0.32**\−0.28**	ns\ns	ns\ns	1	0.52**\0.49**	no\0.36**
ISFA index	−0.60**\0.22*	ns\−0.39	0.43**\ns	0.46**\0.36**	0.72**\0.67**	0.76**\0.50**	no\0.49**

Correlations on the left correspond to PCR-1 lines and correlations on the right correspond to PCR-2 lines. no = trait not observed, ns = correlation not significant. DF, days to flowering; PHT, plant height (m); TKW, thousand kernel weight (g); GRY, grain yield (t ha^{-1}); FSF, farmer selection frequency (%); GQS, grain quality score (1–4 scale) evaluated by FAs; FQS, fodder quality score (1–4 scale) evaluated by FAs; ISFA, Index of agronomic suitability and farmer acceptance.
* $p < 0.05$.
** $p < 0.01$.

the various selection modes in each breeding scheme. Using grain yield as the selection variable would lead to yield improvement but it would not capture most of the farmers' preferred lines, i.e. none of the 10% most appreciated lines from PCR-1 programme and only one out of five and two out of twelve in the case of the CIR-6 and PCR-2 programmes. Conversely, using only FSF to select lines would cause a significant yield reduction in the selected lines in two of the three breeding schemes, compared to the grain yield variable (average 22% loss). On the other hand, the ISFA variable would limit the yield reduction to about 10% while retaining 50–60% of the farmers' preferred lines.Finally, based on the relevance of the ISFA selection index demonstrated by the preceding correlation results, we found that FoF selection gave persistently the higher proportion of the 10% top-ISFA lines in the three breeding schemes (Fig. 1).

4. Discussion

In a previous paper, which dealt with a comparison of the agronomic performance of lines developed on-farm by farmer–breeders (FBs) versus lines developed, both on-station and on-farm, by a professional breeder, Trouche et al. (2011) concluded about the breeding schemes managed from both the PCR-1 and PCR-2 populations that: (1) the breeder's selection on-station produced lines with higher grain yield even in the target environments, (2) the farmers' selection on-farm produced lines with a combination of earliness, plant height, grain size and grain yield corresponding more to the farmers' expectations for coping with local constraints, (3) the breeder's selection on-farm did not perform as well as the farmers' selection, for either grain yield alone or for agronomic trait combination.

The discussion of this paper focuses on two more relevant results based on *ex post* evaluation of the lines by farmer–assessors (FAs) and a final combination of agronomic and quality-related traits, for the three breeding schemes analyzed: (1) the concordance of selection criteria used by FAs and FBs and (2) the effectiveness of on-farm FB selection for combining the relevant quantitative agronomic traits and quality related traits.

Table 9
Average grain yield and percentage of the 10% most preferred lines identified on the basis of (i) grain yield, (ii) FSF, or (iii) ISFA selection variables (calculated from the 2007 on-farm yield trials evaluating the CIR-6, PCR-1 and PCR-2 lines).

Breeding programme	Selection variable for identifying the 10% superior lines	GRY (t ha^{-1})	% Lines among the 10% most preferred
CIR-6	Grain yield	1.90 a*	1/5
	FSF	1.61 a	5/5
	ISFAe	1.69 a	3/5
PCR-1	Yield	2.45 a	0/9
	FSF	1.86 b	9/9
	ISFAe	2.12 b	5/9
PCR-2	Yield	6.10 a	2/12
	FSF	4.56 b	12/12
	ISFAm	5.51 a	6/12

GRY, grain yield (t ha^{-1}); FSF, farmer selection frequency (%); ISFA, index of agronomic suitability and farmer acceptance.
* Means with the same letter are not significantly different based on Tukey test ($p < 0.05$).

4.1. Coherence of farmer–breeders' selection with farmer–assessors' preferences

The FAs chose more lines from those derived from FB selection than those derived from the professional breeder's selection. Thus, the selection performed on-farm by small groups of experienced FBs was more coherent with the preferences expressed by FAs, which represented a larger number of male and female farmers representative of the target regions. vom Brocke et al. (2010) reached the same conclusion in another PPB sorghum programme developed in Burkina-Faso: they found that FAs clearly preferred the progenies selected by FBs on-farm in the preceding cycle, compared to the progenies selected by a professional breeder on-station. The authors attributed it to divergent selection preferences for plant and panicle types as well as grain appearance between the professional breeder and farmers.

However, in one situation of our study, the PCR-1 CECOOP_2008 trial, FAs mostly selected lines which did not derive from FB selection. Such a divergence may have been due to high environmental differences between the evaluation and selection sites, the Totogalpa area (selection site) being drier and less fertile than the Pueblo Nuevo area (evaluation site) and the hierarchy of criteria also being fairly different between the two sites. On the other hand, despite these global trends, BoS or BoF selection should not be considered any less, as they both provided superior lines for grain yield and some of the lines most preferred by the farmers.

In the case of Burkina Faso, vom Brocke et al. (2010) described sorghum grain quality as complex, variable and difficult to assess by scientists and emphasized that the usual traits formal breeders observe do not fully correspond to farmers' perceptions of grain quality. In our study, FA assessment of grain quality revealed differences in the field evaluations but did not show any difference in the post-harvest evaluations between the BoS and FoF lines. However, the second evaluation, while being more complete, only concerned the few best lines derived from each selection mode, which probably explains this absence of differences. Moreover, the professional breeder in this study had long-standing interactions with farmers and had thus the opportunity to obtain good knowledge of farmer preferences, which favoured the development of lines presenting an adequate grain quality.

4.2. Effectiveness of farmer–breeders in selecting for the expected combination of quantitative agronomic and quality-related traits

For both the PCR-1 and PCR-2 schemes, FoF selection proved to be more efficient than BoS selection in developing the specific sorghum morphotypes expected by farmers (Trouche et al., 2011). Such phenotypes need to combine adequate earliness to mitigate drought risk, moderate plant height to ease harvest and prevent

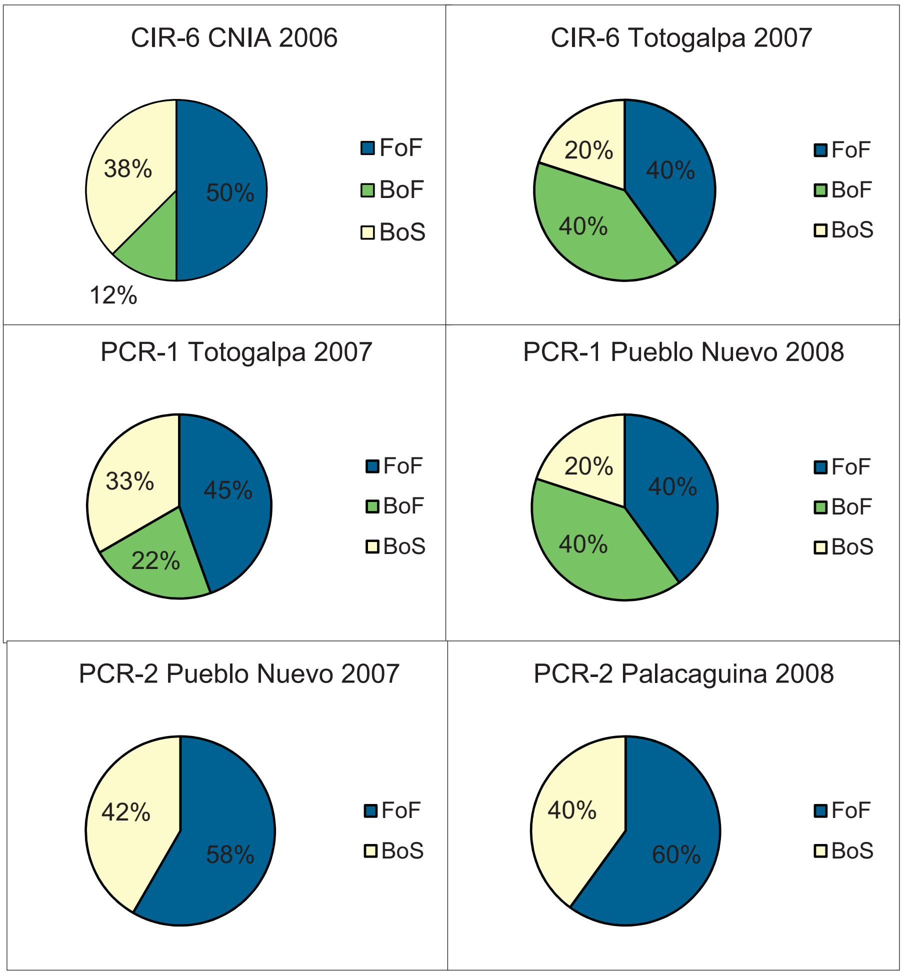

Fig. 1. Origin of the 10% top lines considering the ISFA selection index, computed from the results of the yield trials evaluating the lines derived from the CIR-6, PCR-1 and PCR-2 breeding schemes. BoS, breeder on-station; FoF, farmers on-farm; BoF, breeder on-farm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

lodging, and good yield potential. Even when applying the same selection objectives, differences between the PB and the farmers remain, in particular for the release threshold that is set for their respective selections. The PB hesitates to discard plants or progenies which are higher or which are later than the target phenotype, especially when they show excellent productivity, whereas the farmer has less qualms about discarding progenies. Our paper adds that FoF selection was also the most efficient for taking into account grain appearance as a whole at field level. Preferred grains have a good size (up to 30 g for TKW), a white or cream colour, little grain discoloration, good openness of glumes with low adherence with grains, and no "aguate" dust as described by Trouche et al. (2009). Preferred plant traits for use as fodder include stems of intermediate thickness, high leaf/stem ratio with dense foliage. For the professional breeder, even after several years with a close collaboration with farmers, some of these traits, e.g. the last two components of grain aspect, were difficult to assess on a single plant basis. This might explain the superiority of farmer selection for these traits. Finally, for each of the three breeding schemes considered in our study, FoF selection produced a higher proportion of lines with high ISFA values, i.e. adequately combining agronomic traits and farmers' final acceptance.

Our study is in line with several others. Kornegay et al. (1996) reported that farmer selection in early segregating generations produced bean lines with a superior combination of productivity and quality for the market. In a participatory breeding scheme conducted on-farm from the F_3 generation onwards, Araya-Villalobos and Hernández-Fonseca (2006) reported that farmers obtained a bean line with improved plant architecture, better adapted to humid conditions and cultural practises, an earlier cycle, better grain appearance for market requirements and slightly higher yield than the local cultivar Sacapobre, from which it was derived. Manu-Aduening et al. (2006) noticed also that farmer selection in half-sib families of cassava was equal or better than the breeder's selection for yield and quality components. Contrary to the present study, Ceccarelli et al. (2001) found in Syria that selection for yield was more efficiently done on-farm by farmers than on-station by professional breeders. We think that this result could be attributed to much greater divergence between on-station and on-farm growing conditions than in our case.

4.3. Advantages of a composite selection index for balancing agronomic performance and farmer acceptance

The elaboration and use of selection indices in plant breeding are increasingly common. Based on key physiology, phenology and/or resistance traits which are low susceptible to genotype-by-environment interactions, such selection indices can make selection more efficient for enhancing yield under stressful environments (Chandra et al., 2003; Sharma and Duveiller, 2006; Iqbal et al., 2007). Nevertheless, in stress prone marginal environments, farmers' cropping systems and production goals are diverse and, as a consequence, their preferences for quality traits are also diverse. Despite all the care taken to understand farmers' preferences in such environments, a professional breeder may experience more difficulties than expert farmers in evaluating specific traits related to grain quality or plant type. In fact, it is a true challenge for a professional breeder to integrate into a conventional breeding programme the diversity of quality-related traits that may arise from various cropping systems and production goals. Decentralized and participatory breeding can be very helpful in addressing this diversity. With such an approach, the use of a selection index combining agronomic performance and farmer preferences for key qualitative traits could considerably improve the accuracy of lines selection, especially at the stage of preliminary yield trials managed on-farm. Indeed, those often evaluated a high number of lines on small plots under relatively heterogeneous soil conditions, which can lead to inaccurate yield estimation. In this project, we have observed that, in these heterogeneous conditions, local farmers identify quite well, and probably better than the breeder, what is the effect of the microenvironment and what is the effect of the genotype for achieving yield performance. By rebalancing the measurements of yield and other quantitative traits, by farmer appreciation, we think that ISFA index could also help to identify more accurately the best materials at this stage. This emphasizes again the virtue of collaboration between scientists and farmers. Both mobilize different kinds of knowledge and they take advantage to share it for producing better cultivars than either group cannot produce alone.

4.4. Lessons of these experiences and implications for future participatory breeding programmes managed on-farm

Several lessons can be drawn from these decentralized PPB experiences conducted on sorghum as a food-feed crop in Nicaragua.

In our opinion, a key factor explaining the success of the PPB programmes in Nicaragua was the quality and more the stability of a close collaboration between the local farmer groups, the NGO agronomists, and the professional breeders, supported by stable funding. In that case this collaboration lasted about eight years, exceeding the usual term of most research projects in this area. Furthermore all partners showed high continuous motivation for conducting this research. The initial choice made by the scientists to implement this project with farmer groups previously organized and presenting strong experience in agronomic experimentation probably explain their capacity to appropriate the issues of the programme and thus their permanent motivation. The permanent support of the INTA national sorghum programme, through agreements with both the CIAT-CIRAD project and CIPRES institution, for the on-station breeding activities as well as in the formal process of variety registration was determinant for both scientific and impact issues.

Until to date few professional breeders (PB) of the public institutions are involved in PPB programmes. The majority of these breeders still consider the decentralized PVS approach, using advanced lines or varieties developed on-station under controlled conditions, to be more efficient and cost-effective than the on-farm PPB approach. The latter represents, in their view, situations with excessive vulnerability respect to risks of various kinds (e.g. climatic accident, animal damages or human error), as well as selection environments with low heritability, what would always limit the expected genetic gains on complex trait such as yield. We hope that our results, as well as those of other recent documented PPB programmes, will help change these views and the image of PPB approach in general. Other reasons why PBs are less likely to be involved in PPB programmes may be that managing PPB programmes with farmers requires more time and sometimes more funds, at least at the beginning, than the equivalent on-station breeding programmes, e.g. for travels to the on-farm sites, meetings and training sessions with the farmer–breeders. Furthermore, PBs engaged in PPB research often face difficulties in getting their original scientific papers published as well as lesser opportunities for fund-raisings, which are currently mainly geared towards molecular biology and genomics. It is hoped that these two last constraints will be exceeded in the near future.

5. Conclusion

The selection work carried out on-farm by small groups of farmer–breeders (FoF) in three *tortillero* sorghum breeding programmes, focused on well-defined breeding goals, has been evaluated by analysing the ultimate acceptance by farmers and the combination of agronomic and qualitative traits. Three major results deserve attention. The lines developed by FoF received better acceptance from a wider group of farmers compared to those developed by the breeder on-station and on-farm. These lines generally showed a better combination of major agronomic traits, depending on environmental constraints and production priorities, and also specific quality traits related to grain appearance and plant type. Lastly, they also performed better for the ISFA selection index, which combined agronomic performance in the targeted cropping conditions with the farmers' ultimate acceptance.

In breeding for marginal stress prone environments, as was the case in our study, the use of such a composite selection index should help in identifying genetic material responding both to agronomic gains and farmer acceptance. The individual traits included in the index should reflect the range of sometimes contradictory breeding goals, such as productivity, adaptation to environmental or cropping constraints, and typical quality requirements. The weights given to the traits should take into account their agronomic, cultural and economic value.

Finally, it should be remembered that PPB programmes need long-term institutional commitment and continuous dialogue between scientists, NGOs and farmers in order to achieve successful results and a positive impact as shown by Vaughan and Lançon (2010), for example. This is particularly difficult to achieve with very poor communities, as their contribution in labour, land or inputs during the research process might be very limited. In this case, external resources will have to be found to ensure their long-term commitment.

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