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3 Long-term collaboration between farmers' organizations and plant breeding programmes

Sorghum and pearl millet in West Africa

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Introduction

Sorghum and pearl millet are cultivated across West Africa in a great many contexts, due both to the differing agro-ecological conditions and the specific, contrasting production objectives of individual farmers, women or men, with more or less access to resources. These contrasting contexts lead to highly differentiated varietal preferences and needs.

The ancestors of todays' farmers in West and Central Africa contributed to domesticating sorghum and pearl millet. Also today, these farmers use and manage varietal diversity of these crops to optimize household productivity and minimize risks (Haussmann *et al.*, 2012). These crops, vital for survival and livelihoods, are closely intertwined with the cultures of the various peoples of West Africa (Weltzien *et al.*, 2006a).

This great diversity of varietal preferences and needs of West African farmers, as well as farmers' deep knowledge of these crops, calls for approaches that can support both the co-creation of contextual knowledge and collaborative farmer–researcher implementation of variety development activities. A farmer–researcher joint network approach, with decentralized collaborative activities, offers many possibilities for significant and tangible genetic gains that can contribute to improving the livelihoods of farm families.

Documentation of experiences of participatory breeding efforts has generally been limited to individual projects or specific research designs. Longer-term experiences have rarely been described. However, the long-term nature of variety development, along with challenges for seed production and dissemination, calls for collaboration between farmers and plant breeders over longer periods.

The joint activities conducted by sorghum and pearl millet breeders together with farmers in West Africa from 1998 onwards represent one case of such long-term collaboration. Activities have included the joint development of experimental varieties, the testing and validation of those varieties in a decentralized manner, and building the seed production and marketing capacities of farmers' organizations.

A wide range of farmers' organizations have been engaged in these collaborative activities – from village-based cooperatives like the Cooperative des Producteurs Semenciers du Mande (COPROSEM) in Siby, Mali, with less than 100 members, to unions of farmer cooperatives, like the Union Locale de Producteurs de Cereales (ULPC) in Mali, and to large farmer federations like MOORIBEN and Fuma Gaskiya in Niger, with several thousand members coming from large geographical regions. Also individual large cooperatives like Association Minim Song Panga (AMSP) and Union des Groupements pour la Commercialisation des Produits Agricoles (UGCPA) in Burkina Faso have been involved in this work.

Participating sorghum and pearl millet breeders have come from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), the French Agricultural Research Centre for International Development (CIRAD), and the national agricultural research organizations in Mali (Institut d'Economie Rurale, IER), Burkina Faso (Institut de l'Environnement et Recherches Agricole, INERA) and Niger (Institut National de Recherche Agricole du Niger, INRAN). Teams of national and international breeders have interacted with the various farmers' organizations in planning and implementing activities.

This chapter documents and discusses the methodologies used, the experiences gained, and some of the achievements of this long-term farmer–breeder collaboration. These collaborative activities have covered the full range of breeding stages (Weltzien and Christinck, 2017) and are here discussed as follows: (a) setting and revising breeding objectives, (b) generating diversity, and continuing through (c) selecting in segregating materials and (d) evaluating experimental varieties, followed by (e) variety registration, seed production and dissemination. Farmer–researcher collaboration for developing hybrid varieties is presented separately, as an overarching engagement through all stages of the breeding cycle. Many of the methods and tools used for facilitating farmer–researcher collaboration are described by Christinck *et al.* (2005).

Collaboration and main achievements

Setting breeding objectives

Translating overarching goals into breeding objectives

The goals of the sorghum and pearl millet breeding programmes in West Africa have been broad, targeting the improvement of food security, income generation, farmer capacity-building and the conservation of agrobiodiversity.

As the research team came to realize that nutritional improvement could be integrated with this collaborative breeding work (Isaacs *et al.*, 2018; Rattunde *et al.*, 2018), that became a deliberate goal, based on the growing understanding of farmers' targeted management and use of varietal diversity and of the nutritional role of these crops, especially for children and women (Bauchspies *et al.*, 2017; Christinck and Weltzien, 2013).

Translating these rather broadly defined goals into breeding objectives has called for continual reflection and revision of priorities. These efforts have been spurred by the limited adoption of varieties from prior breeding work, as has been documented for sorghum (Yapi *et al.*, 2000), and by the researchers' desire to create a range of varietal options in line with farmers' diverse needs and opportunities for improving their overall farming systems.

Priority setting, identifying key traits

Setting priorities in breeding has been pursued through specific studies of farmers' production systems and goals, seed systems and trait preferences, also taking gender roles into account, as well as through continual interaction and discussions between farmers and breeders as part of routine participatory breeding activities conducted both on-farm and on-station. Work that contributed to the formulation of more specific breeding objectives has included studies of farmers' seed system for sorghum in Mali (Siart, 2008), women's roles in sorghum production (Rattunde *et al.*, 2018), the contributions of specific traits to the adaptation of plants to farmers' production contexts, e.g. photo-period sensitivity (Clerget *et al.*, 2008) and adaptation to low soil-phosphorous conditions (Leiser *et al.*, 2012).

The priorities for sorghum breeding in Mali, as determined by this process, were to develop new open-pollinated varieties with higher grain yield and adaptation to the predominant growing conditions. Additionally, the grain quality needs to be appropriate for storage, processing, and food uses, as farmers want to increase the amount of food produced, not just the weight of grain harvested per unit area (Weltzien *et al.*, 2018).

The formulation of general priorities and the breeders' evolving understanding of farmers' objectives and needs resulted in a growing list of specific traits to be targeted in variety development for sorghum. These traits include early maturity, with photo-period sensitivity helping to ensure timely maturity and stability despite variable sowing dates (Haussmann *et al.*, 2012); adaptation to soils with low phosphorous availability, typical of sorghum cultivation, especially by women (Leiser *et al.*, 2018); drooping panicles to reduce damage from insect, bird and grain-mould attacks (Weltzien *et al.*, 2018); open glumes for clean threshing, also under drought conditions (Diallo *et al.*, 2018); ease for women to decorticate the grain, and hard grain to minimize losses during storage and decortication (Isaacs *et al.*, 2018). Further: high food yield (Weltzien *et al.*, 2018); and intermediate plant heights for ease of harvesting – reduced from 4 m but not shorter than 2.5 m, where risks of transhumant cattle grazing become serious.

The traits targeted for pearl millet in the Sahelian zone of West Africa include higher grain yield; yield stability in the unpredictable and variable climate; earlier maturity than prevalent local varieties, to provide grain during the hunger period; plasticity of tillering, to respond to moisture availability; compact panicles that can resist insect attack; resistance to downy mildew (*Sclerospora graminicola* (Sacc.) Schroet.) and the parasitic weed *Striga hermonthica;* and adaptation to poor soil fertility.

Generating diversity

The choice of parental material for producing specific crosses or new populations was carefully considered by the sorghum and millet breeding teams, to assure variability for the farmers' priority traits. The sorghum team emphasized use of local germplasm to provide a strong foundation for the diverse adaptation traits wanted by farmers (Weltzien *et al.*, 2018). Some farmers contributed to the crossing programme specific varieties with which they were familiar (see also below). Exotic germplasm was introgressed approx. 12–25 per cent, to increase variability for traits related to productivity.

Diverse breeding approaches have been used to create new sources of useful diversity for breeders and farmers, to derive new lines and experimental varieties. Approaches for which long-term farmer–breeder collaboration has been of particular importance include the use of introgression with a single backcross generation; population improvement; and dynamic genepool management. These approaches are described briefly in the following sections.

Introgression with a single backcross generation

Efforts to create new varieties by crossing preferred local varieties with exotic donor parents gave unsatisfactory results, as the derived lines approached one or the other parent, with frustratingly few novel, desirable types emerging. A useful alternative was to create backcross-derived sub-populations by using a farmer-preferred variety chosen for improvement as recurrent parent, and conducting a single backcross generation. Multiple exotic donors were used, to generate diversity within the context of the farmer-preferred variety type, based on experiences in Australia (Jordan *et al.*, 2011). The diverse set of lines or sub-populations derived from these backcrosses, with approximately 75 per cent preferred variety background, has provided new variability with acceptable levels for many required adaptation traits. Farmers have shown great interest in selecting within these sub-populations, because of the diversity and acceptable levels of key farmer-preferred panicle, grain and glume traits. This method is seen as effectively creating useful diversity, from the perspective of farmers and breeders alike.

Population improvement through recurrent selection

The improvement of broad-based populations, created by crossing multiple parents to make a population bulk, is a cyclical process that results in new gene combinations from mixing the genetic backgrounds of all the parents. Each cycle involves selecting promising progenies from a population bulk and then inter-mating them to produce the next, improved population bulk. This selection and random mating in rapid cycles is expected to concentrate favourable genes and thus increase the frequency of progenies with superior performance for the targeted traits, while retaining genetic variation for future gains from selection.

This approach was used to create a sorghum population for West Africa based on tall Guinea-race landrace varieties (Rattunde *et al.*, 1997). The retention of genetic diversity for plant height in this tall (plant heights of 3–4 m) population enabled deriving a new shorter Guinea-race population, the 'Population Guinea Naine Diversifié' (Weltzien *et al.*, 2018). This shorter population offers a unique source material for responding to farmers' interest in new dual-purpose grain and fodder varieties that combine good quality Guinea-race grains for food and better stem-digestibility for feeding their livestock during the dry-season. The population has been improved for grain yield as well as panicle form and glume opening, to develop highly productive and short plant types with key farmer-preferred traits. One of the varieties derived from this population, 'NafalenP6', has been top-ranked for grain yield and is superior in both phosphorous uptake and phosphorous use efficiency (Leiser *et al.*, 2014).

Farmers' collaboration with breeders in the various stages of recurrent selection aimed at improving this population has evolved over the years, based on joint learning and inspiration from engagement in diverse activities (Table 3.1). Farmers' engagement in deriving new progenies from the population bulk has been a major contribution here. A few (5–15) farmers with particular expertise and interest opted to grow plots of the population bulk from the most recent random-mating, and conducted single plant selections, which the breeders could then use to derive further progenies (Table 3.1). These farmers, with their eye for the diverse panicle, grain and glume characteristics, frequently detecting differences that breeders fail to notice, helped to retain genetic materials with important traits and trait combinations before the range of variability was narrowed. Their involvement has helped to increase genetic gain: firstly by increasing the scale of operations and the population size; secondly, by helping to focus the limited breeding resources on more acceptable plant types during the later stages of selection and testing. Furthermore, farmers' selections contributed to widening the diversity of progenies, as each person selected using his or her own criteria, and the farmers' selections complemented those of the breeders. The farmers shared half of the seed of each selected panicle with researchers and kept the remainder for their own use.

Table 3.1 Breeding scheme for recurrent selection, random-mating 'Population Guinea Naine Diversifié', Mali

Year	*Material sown/main step*	*Farmer activity*	*Breeder activity*
1	Random-mated S0 population bulk (3–10,000 plants/field) to derive new progenies	Sow bulk in isolated fields, thin to single plants, label male-fertile plants at flowering, select desirable male-fertile panicles to derive S1 lines.	
2	S1 progenies (500–750) for evaluation	On-station scoring of grain desirability, panicle appreciation, and threshability in S1Trial; Contribute to selection of panicles to derive S2 lines. Experienced women farmers score grain quality.	Manage S1 progeny trials, evaluate for maturity, disease resistances, grain yield and overall appreciation, chose progenies for further testing based on index of farmer- and breeder-observations; Conduct S1 Nursery to derive S2 lines.
3	S2 progenies (approx. 125) for stage 2 testing and selection	Score grain and panicle desirability, threshability, label desired progenies in S2 trial; Contribute to selection of panicles to derive S3 lines for on-farm testing.	Manage S2 progeny trials, evaluate for maturity, disease resistances, grain yield and overall appreciation, create selection index of to choose best progenies to recombine; Conduct S2 Nursery to derive S3 lines for line/variety development. Plant remnant S1-seed of the selected progenies in isolation for an initial random mating and increasing the frequency of the male sterility gene. Only seed from sterile plants will be harvested.
4	S1 progenies derived in S0 (approx. 30) for random-mating	Contribute to selection of desirable panicles based on form, grain and glume characteristics.	Sow remnant S1-seed of selected progenies in isolation, I alternating rows with seed harvested from sterile plants from the first random mating, label male-sterile and male-fertile plants, select panicles of desirable sterile-plants and bulk to create next cycle.

Farmers also contributed their skills during on-station progeny evaluation activities (Table 3.1). For example, one or two farmers with special expertise in observing panicle form and free-threshing characteristics scored hundreds of progeny plots prior to harvest. Women farmers recognized for their skill at judging grain quality contributed by visually scoring grain desirability and grain hardness after harvest. These farmers were paid for contributing their special expertise. Farmers participating in annual field days also volunteered to evaluate population progeny trials, attaching labels to more desirable progenies and afterwards discussing the strengths and weaknesses of the new materials they observed. These forms of farmer involvement have helped breeders to gain both quantitative data and qualitative understanding for informing various breeding decisions.

Farmers' collaboration with breeders in population improvement has offered advantages for addressing the large number of plant, panicle and grain traits required for farmer acceptability and adaptation to local conditions. It has also facilitated sharing of the improved and genetically diverse populations with other breeders or farmers interested in selecting for adaption and quality traits for their own conditions and objectives (Weltzien *et al.*, 2018). For example, one farmer-breeder in a zone of Mali more humid than that of the experiment stations conducted multiple years of his own on-farm selection, starting from his population bulk grow-out. He later shared the lines he had developed with the breeders, for further variety development work targeting the more humid regions in Mali and other West African countries.

Dynamic genepool management

Another option for recurrent selection that may rely more heavily on farmers' selection activities in broad-based populations is 'Dynamic Genepool Management'. It aims at simultaneous *in situ* conservation and facilitating adaptation of plant genetic resources to climatic changes, specific site characteristics and evolving farmers' needs. As it is performed in close cooperation with farmers, it increases their access to and use of crop genetic resources, thereby increasing intra-species or intra-varietal genetic diversity, which in turn can contribute to yield stability.

In this approach, a diverse base population is built, through crossing and recombining genetically highly diverse genetic materials (see above for sorghum). After phenotypic (and possibly genetic) characterization of the base population, representative seed lots are distributed to farmers and grown at contrasting sites in a diverse target region. Selection by farmers and breeders, as well as natural selection, lead to the development of locally adapted, farmer-preferred subpopulations with new trait combinations (via re-combination) not previously available. The sum of all subpopulations grown in the contrasting sites can be considered as a 'mass reservoir' of genetic adaptability. This concept has been applied successfully in several ways. A population of pearl millet adapted to the Sahelian agro-ecologies has been significantly improved for *Striga* resistance in Niger and Mali. Several types of *Striga*-resistant experimental varieties have been extracted from it (for example, one with shorter and one with longer panicles) in line with the preferences of various farmers (Kountche *et al.*, 2013). Farmers' seed-cooperatives and breeders in Niger have developed new varieties that combine improved yield with local adaptation. These varieties have been registered on the national variety list of Niger; the seed is disseminated by the farmers' seed cooperatives which selected them.

Selection in segregating materials

Taking selection decisions for complex requirements and needs

Conducting selection within and among segregating progenies or sub-populations is the critical bridge between the newly generated genetic diversity on the one hand, and, on the other, the identification of experimental varieties that are sufficiently uniform to effectively discriminate and test yet retain a degree of intra-varietal variability necessary for yield stability. Selection over several generations in this phase operates like a funnel in narrowing down total genetic diversity, so as to focus on a more limited number of progenies/sub-populations of greatest interest for achieving the breeding objectives. Decisions made during this phase are pivotal. In conducting this selection, the breeding programmes have worked hard to apply their evolving understanding of farmers' needs and preferences and defined breeding objectives. The definition of a variety- or product-profile (Ragot *et al.*, 2018) to guide the selection provides a framework for planning and documenting this approach.

The breeding programmes have experimented with diverse options for involving farmers in this selection process. Farmers' direct evaluation of progenies using various methods, as described for the population improvement activities, has become an integral part of the breeding programmes, contributing to the final selection of progenies to use in developing experimental varieties. Farmers have also sowed nurseries of 30 to 50 early-generation progenies, to select within these segregating materials using their own criteria and growing conditions. However, the breeding programmes have not managed to integrate this approach in their regular activities due to various factors, including farmers' propensity to select within nearly all progenies and their reluctance to eliminate any progenies, and the difficultly of effectively selecting among hundreds of progenies with only subsets, and under highly contrasting conditions with individual farmers.

Although farmers' contributions to selection of progenies for key, farmer-preferred, morphological and phenological traits have been of obvious and high value, it seems less clear whether or how they could contribute to early-generation selection for improving grain yield – the top priority for the breeding programme.

Early generation progeny selection for yield

The selection among early generation progenies for grain yield solely on the basis of on-station testing has been of questionable utility for achieving yield gains in farmers' fields under different, lower-input, conditions (Bänzinger and Cooper, 2001). However, the ability to achieve genetic gains for a complex and environmentally sensitive trait like yield through on-farm testing of early-generation progenies has been uncertain due to the obscuring effects of uncontrolled within-field, site-to-site, and year-to-year heterogeneity (Atlin *et al.*, 2001).

Sorghum breeders and 34 volunteer farmers set out to test the feasibility of large-scale early generation yield testing on-farm. The team tested a set of 150 early-generation progenies (S2/S3) for grain productivity using a trial design with sub-sets of 50 progenies and two common repeated check varieties tested per farmer. The testing of just 50 progenies per farmer and use of single-row plots was intended to make the trial manageable for participating farmers and to help locate the trials in somewhat more homogeneous portions of the farmers' field. Progenies were selected using combined on-farm or on-station results, and their on-farm yield performance was tested in subsequent years in a series of replicated on-farm trials.

Although farmers' management practices and field conditions have differed greatly among the various on-farm selection trials, early generation on-farm yield testing has been found effective (Rattunde *et al.*, 2016). Significant genetic variation and acceptable heritability for grain yield have been obtained in combined analyses of all on-farm yield trials. Moreover, although the genetic gains for yield from on-farm evaluations had been predicted to be greater than those expected from only on-station testing, combining yield results from on-farm and on-station, particularly under low soil-phosphorus conditions, emerged as more effective for selecting for on-farm yield performance than using solely on-farm or on-station results.

Evaluating experimental varieties

Protocols and procedures for variety evaluation

Many farmers have been keen to evaluate new varieties, which led the West African sorghum and pearl millet breeding programmes to develop protocols for variety evaluations by and with farmers. These protocols address two main objectives: achieving a common understanding of the advantages and disadvantages of specific varieties (and traits); and assessing productivity and its stability across a wide range of growing conditions within the priority target-zone for the new varieties (Rattunde *et al.*, 2013; Weltzien *et al.*, 2006a, 2008).

Initial understandings of sorghum farmers' variety and trait preferences were obtained by using standard tools like open-ended evaluations, matrix ranking and occasionally pairwise ranking (Ashby, 1990; Quirós *et al.*, 1991). The team subsequently developed a system where farmers (sometimes assisted by a village facilitator) could score a standard set of priority traits (crop duration, adaptation to the local conditions, panicle appreciation, overall appreciation) (Weltzien *et al.*, 2006a). Researchers, with assistance from farmers, measured grain yields and yield components. All observations were recorded in the field book kept by the farmer who conducted the trial, with researchers entering the data for analysis and keeping a photocopy of the field book.

Gradually, methods developed for ascertaining preferences for traits and specific experimental varieties from a wider base of men and women farmers. Field days were arranged, for visiting and evaluating the trials at harvest in at least ten participating villages (Weltzien *et al.*, 2006a). The procedures for the farmers' evaluations evolved, from scoring a set of fixed criteria across all villages, to having farmers chose the three most important traits for which they observe varietal differences pertinent to their context. Men and women farmers first discussed separately their choice of traits, followed by plenary presentations by both men and women, and joint negotiations to agree which three traits would be evaluated by all participating farmers (vom Brocke *et al.*, 2010). The participants, divided into small groups of women or men farmers, scored all plots for the three chosen traits and for overall appreciation. This approach has facilitated inclusion of gender-specific trait preferences. The technician recording the scores has also noted the reasons mentioned for scoring certain varieties especially high or low. A scoring system of 5 ('much better' than the local check) to 1 ('very poor') was used; farmers could readily relate to this, as it corresponded with the school grading system.

Developing and adapting trial designs

The initial design for the sorghum variety trials in Mali was a single replicate of 32 entries (Weltzien *et al.*, 2006a). Joint discussions of breeders with participating farmers led to a modified design, where 2 separate trials were conducted, each with 16 entries: 1 for taller height entries and the other for shorter entries. A two-replicate alpha-lattice design with sub-blocks of four plots was used to enable repeatability estimates and control error, with trial size maintained constant at 32 plots. The experimental varieties to be tested were contributed by both the Malian IER and the West and Central African ICRISAT sorghum breeding programmes, on the basis of on-station and on-farm progeny trials (as described in Table 3.1), as well as contributions coming directly from farmers. Both trials included a common landrace check variety (Tieblé, initially registered as CSM 335). Both trials were conducted in 10 to 12 villages, with each trial conducted by two farmers per village, as well as in two to three research stations in a single year. Each set of experimental varieties was tested for two years, based on the farmers' and researchers' desire to see varietal performance over years. All experimental varieties were given short vernacular names that could easily be remembered, but without any suggestive connotations, to facilitate farmers' discussions and feedback. The analysis of individual farmers' trials and combined over-environment analyses were conducted by the breeders, and the results were presented to the farmers for discussion and selection of entries for post-harvest grain quality tests and second-stage, fully farmer-managed, on-farm testing. This made it possible to collect robust data on grain yield performance and farmer appreciation of the experimental varieties over a large number of diverse environments (Kante *et al.*, 2017; Rattunde *et al.*, 2013).

Developing post-harvest quality tests

Post-harvest culinary tests of experimental varieties were generally conducted in each of the participating villages. These tests were necessary since grain quality, grain storage, and food-processing attributes are critical for variety adoption, and the breeders lacked capacity to assess these traits on their own. Farmers chose four of the experimental varieties and a local check to include in the tests based on their preferences from field observations and the yield results of both the tall and short variety trials presented in the feedback sessions. Procedures for the culinary tests evolved such that teams of women could provide quantitative and qualitative measurements of varietal differences for grain-quality attributes like the ease and amount of time involved in various processes, decortication losses, flour-to-grit ratios, and swelling potential (the capacity to absorb water) of the stiff porridge *(tô)*, a local staple dish (Isaacs *et al.*, 2018). A village-based panel of men and women taste-testers evaluated the colour, taste and consistency of the prepared *tô*.

Large-scale testing of varieties for adaptation

The second stage on-farm adaptation trials were conducted to give a much larger number of farmers the opportunity to evaluate, under their own field and management conditions, varieties chosen from the first-stage tests (Weltzien *et al.*, 2006a). The testing procedure evolved to include the option of splitting the plots with one-half fertilized, so that farmers could assess the performance of each variety with and without fertilizer. Adaptation trials were conducted in villages where four or more farmers were interested. Farmers had to agree on the specific objective for their trials – like finding varieties with good performance even with *Striga* infestation, late or early sowing, more or less weeding, or in a specific intercropping situation. Demand for these trials was very high, so, for several years, trials were allocated to villages only if also a group of at least four women conducted a variety trial in their own fields. The trials were designed with three, four, five or sometimes six varieties, always including a common local check widely grown in the village. Separate protocols with single-row test plots, intercropped with groundnuts, were developed to facilitate testing by women (Rattunde *et al.*, 2018). Farmers recorded their observations directly or with help of village facilitators, and each group of farmers jointly discussed and documented its choice of varieties. Researchers visited some of the trials, and assisted some groups, particularly women's groups, with harvesting and weighing of plot yields. Yield data from these trials, extracted from the field books, enabled broad assessments of the relative performance, profitability, and risks of not recouping investments in seed of improved open-pollinated varieties and hybrid varieties and fertilizer relative to the farmers' local varieties, over diverse environments for men and women farmers (Weltzien *et al.*, 2018).

Preparing varieties for release and seed production

Some experimental varieties tested during the first stage of evaluation showed superior levels of productivity, but were not sufficiently homogeneous for traits readily noticed by farmers such as panicle form, glume opening, or grain colour. In such cases, one or two farmers known for their expertise grew plots of 100 to 200 single plants per variety and then visually selected desirable panicles that were uniform and conformed to the farmers' standard for those traits. The selected panicles were grown head to row by the breeders; uniform comparable rows were bulked together for initiating seed multiplication.

Variety registration, seed production and dissemination

Variety registration as a step towards official seed marketing

Following the introduction of harmonized seed legislation in all countries of the Economic Community of West African States (ECOWAS) region in 2008, variety registration has become a prerequisite for legal seed marketing in West Africa (for an analysis of the opportunities and barriers created by seed legislation for PPB, see de Jonge *et al.*, this volume). The two-stage procedure for yield testing (explained earlier) provided high-quality data, which, together with farmers' decisions as to which of the selected varieties to disseminate, facilitated the identification of varieties for official release and the preparation of release proposals. In addition, some farmers' varieties included in the trials have been formally released in Mali, such as 'Boboje' and 'Sakoykaba', just as direct selections from germplasm accessions, such as IS 15401 ('Soumalemba') originating from Cameroon or 'Gnossiconi' from Burkina Faso (vom Brocke *et al.*, 2014). Six sorghum varieties derived through population improvement with farmer–researcher collaboration have been released in Mali to date, in addition to releases of varieties selected mostly on-station. One of these, 'Lata3 (Bala Berthe)', is now cultivated by Malian farmers as a variety per se and used as the male-parent for hybrid breeding (Kante *et al.*, 2017; Rattunde *et al.*, 2013). In Burkina Faso and Niger, varieties from these collaborations have also been released, seeds produced and disseminated by farmers' organizations who were involved in variety development earlier on.

Farmer-managed seed production and marketing

Farmers' access to seed of the newly bred varieties was not assured initially, since West Africa's large, state-run seed production and distribution agencies had basically collapsed at the turn of the century (Coulibaly *et al.*, 2008). Sorghum and pearl millet seed of non-traditional varieties was distributed in Mali through one or two remaining sub-centres in low quantities, mostly of older varieties, with even nearby farmers rarely acquiring seed. This is why training in production of certified seed began at this time (starting in 2002), supporting participating farmers' organizations in following through, from variety testing to seed production of newly identified and released varieties. The farmers' organizations proved very capable of producing seed; their members were highly motivated to produce seed, which for them was a new 'cash crop' involving less investment and risk as compared to cotton, for example.

Emerging for-profit seed companies (Dalohoun *et al.*, 2010), with minimal seed production capacities of their own, bought the seed produced by the farmers' organizations. Although the expectation was that these seed companies would sell seed to farmers, years passed, with ever-increasing quantities of seed produced by farmer cooperatives but without detectable seed sales or distribution networks for rural sorghum producers. It became apparent that closer examination of the sorghum seed system was needed to identify entry points for large-scale dissemination surpassing traditional exchanges between neighbours and relatives.

A detailed study of sorghum seed systems in the Sudan Savannah of Mali revealed strong cultural norms regarding sorghum seed (Siart, 2008). 'Good farmers' are expected to produce their own seed; moreover, it is a social obligation to give seed to anyone who asks, in exchange for an equal volume of any cereal grain after harvest – but never for money. Collaborating farmers and farmers' organizations explained that although it is unacceptable for individuals to sell seed and profit from someone else's need, a farmer *group* could sell seed, as the benefit then goes to the group. This understanding motivated efforts aimed at strengthening the capacity of farmer seed-cooperatives to market their seed directly to local farmers.

Seed dissemination in accordance with farmers' values and needs

The marketing of sorghum seed by farmer cooperatives was hampered because the farmers were not familiar with purchasing seed. A breakthrough came when farmer demand for seed-sets from adaptation trials soared, exceeding the breeders' capacity. When single variety seed 'mini-packs' of just 100g were offered for sale by the extension office to interested farmers, this resulted in initial sales of 2,500 seed packets, with minimal advertising. This approach was then pursued with a continually increasing number of farmer cooperatives, until farmer demand for larger seed packages began to develop. A decentralized model of seed dissemination by farmer cooperatives is now emerging in West Africa (Access to Seeds Foundation, 2018; vom Brocke *et al.*, 2014; Christinck *et al.*, 2014): this model is in line with local socio-cultural values, the farmers' need for trust and knowledge of the seed seller, and the provision of diverse varieties to men and women farmers in contrasting agro-ecologies. Opportunities for strengthening the capacities of farmer seed-cooperatives to market seed include linking demonstration plots with local radio coverage, threshing and yield comparisons of new and old varieties, testimonials by locally respected farmers, use of photos and 'farmer friendly' varietal descriptions, and ensuring that seed sellers have experience cultivating the varieties they sell.

Sorghum hybrid varieties – learning and actions across breeding stages

Initially, West African breeders focused on open-pollinated varieties, conscientiously deciding not to breed hybrids due to farmers' desire to have varieties that they could reproduce by means of traditional, culturally rooted practices. Sorghum breeders reconsidered this decision after learning from a 1999 farmer survey that higher grain yield was farmers' top priority for new varieties (Weltzien and Christinck, 2017), and the fact that yield gains with open-pollinated varieties were limited (15 per cent or less) and too small for farmers to notice. A proof-of-concept effort was launched to determine whether hybrid varieties based on Guinea-race germplasm with the required adaptation and grain characteristics could deliver markedly higher yields under farmers' diverse and typically low-input conditions. An initial step was to breed the first Guinea-race cytoplasmic male-sterile seed parents (near-isogenic pairs of a male-sterile seed parent line used as the female for producing hybrid seed and its male-fertile 'maintainer' for multiplying female parent seed). The new hybrid parents, based on Malian farmers' Guinea-race landrace varieties and breeders' Guinea-Caudatum inter-racial materials, were used to produce the first Guinea-race experimental hybrids.

Farmer participatory trials were conducted in three zones of contrasting agricultural intensification over several years to evaluate these experimental hybrids. The yield superiorities of these new hybrids over the popular Malian landrace variety 'Tieblé', averaging over 30 per cent across diverse low- and high-productivity environments (Rattunde *et al.*, 2013), and the farmers' appreciation of the grain qualities of these hybrid varieties (Kante *et al.*, 2017) were very positive results. The hybrid 'Pablo', although not a top choice of the breeders due to its tall height and its yield superiorities under productive conditions being less than those of shorter hybrids, is currently the most popular hybrid in the intensified cotton-production region of Mali, as it closely resembles the local varieties but has significantly higher yields. Thus, the results obtained through a decade-long proof-of-concept effort provided solid justification for pursuing hybrid development as a complement to open-pollinated variety breeding for sorghum in West Africa.

There were, however, substantial concerns about how hybrid seed would be produced and reach the farmers, as there was little commercial sale of seed and no production of hybrid seed of any crop in Mali at that time. Therefore, in 2009, experimentation and training in hybrid seed production of several farmers' organizations already engaged in seed production were initiated, parallel to hybrid variety testing and the release of the first hybrids. Formal training courses were conducted jointly by IER and ICRISAT prior to providing seed and protocols for interested farmers to start up small (e.g. 600 m^2) seed-production plots to gain experience. Training booklets in the local language were developed (Rattunde *et al.*, 2014) and trainings were repeated for at least two years, for each cooperative to absorb new concepts of sowing male and female 'varieties' (hybrid parents) in alternating blocks, managing them so as to obtain simultaneous flowering, and ensuring precision harvest and threshing of each parent separately.

Three years after the initial trainings, farmers began larger-scale hybrid seed production by using plots of one ha or larger, and modifying the planting design (e.g. by increasing the ratio of female- to male-parent rows). Farmers became increasingly interested in producing hybrid seed when they learned that they could 'add a cash crop to their food production plots', as explained by a village facilitator, referring to the female parent being harvested for sale of hybrid seed while the grain of the male parent could be kept for food. Some farmers reported producing as much grain for home consumption with the male-parent in their hybrid seed-production plot as they would have previously achieved on the entire plot thanks to the fertilizer obtained on credit from their cooperative for producing hybrid seed. The amount of hybrid seed produced doubled annually (Kante *et al.*, 2017) as more and more farmers and farmers' organizations started producing hybrid seed.

In fact, disseminating the seed of hybrid varieties proved more challenging than producing hybrid seed. Farmers had no prior contact with hybrid crop varieties; the term *hybride* in French was widely feared as it was associated with genetically modified organisms. Discussions led farmers, already familiar with hybrid chickens, to coin the term '*si woloso*' ('si' means seed, and 'woloso' is a term used to refer to chickens or goats produced by crossing a local breed with an exotic breed) to identify hybrid seed in the local language Bambara. Farmer field days, trainings, radio and video messages were used to communicate the expected advantages, disadvantages and differences of sorghum hybrids relative to open-pollinated varieties. One major topic for farmers was the issue of saving and re-sowing seed harvested from these hybrids: Would it actually germinate and grow? What would it look like? How much yield would it give? Farmers who grew hybrids for several years confirmed the on-station results, indicating that some hybrids could be re-grown for one or two years without noticeable yield disadvantages (both parents of Guinea race origin), whereas others could be re-grown for only one season, and others not at all.

Village-level culinary tests were conducted specifically with hybrids, confirming not only that hybrid grain was edible, but that food quality of several hybrids equalled or surpassed the popular landrace check varieties. Farmers then related their own experiences with these new hybrids to their neighbours. For example, one farmer reported that five measures of grain of the hybrid Pablo (with high test-weight, hard grain and low decortication losses) were sufficient to feed his family, whereas six measures of his own variety would be needed to prepare sufficient food for one day.

That farmers' seed-cooperatives have been doubling the production of hybrid seed annually (Kante *et al.*, 2017) and that farmers are now starting to purchase and cultivate hybrid seed (Smale *et al.*, 2014, 2018) is ultimate proof of farmer acceptance. Such change has been possible only through sustained collaboration and joint learning between farmers and breeders.

Conclusions

The opportunity for breeders and farmers to work together over such a long period, and their shared interest in learning from each other, have been important factors enabling the extent and depth of knowledge increase. The capacities and skills of farmers and breeders alike have further contributed to genetic gains for the objectives targeted. Every joint interaction and project with farmer–researcher collaboration has advanced joint learning and effective farmer-oriented breeding. Closer examination of the long-term farmer–researcher collaboration in sorghum and pearl millet breeding in West Africa reveals crucial advantages for achieving transformational change, including:

- The possibility of follow-through, from understanding of farmer needs and conditions to changing the design and activities in the breeding programme: the long-term collaboration has helped the breeding programmes to evolve, linking lessons learned directly with actions at every stage of the breeding process in order to create new varieties that respond to identified priority needs and emerging opportunities.
- Establishing synergetic roles and sharing responsibilities for breeding: long-term engagement has made it possible to build on the strengths and expertise of farmers as well as scientists in clearly defined procedures, in turn helping to achieve the strong genetic correlation of test results, even with activities conducted at larger scales.
- Increased performance of new varieties for diverse users: the decentralized design of the breeding programmes, combining on-station selection and selection in target environments in an effective manner, has helped to achieve sizeable genetic gains despite limited resources and complex environmental and socio-economic contexts.
- Realizing impact and contributing to high-level development goals: the sustained collaboration of farmers and breeders has resulted in clearly detectable contributions to overarching goals such as:
    - Enhanced food security, with understanding of and breeding for traits required for reduced risk to climate variability (Haussmann *et*

al., 2012; Weltzien *et al.*, 2006b) and yield improvements also under poor soil-fertility and farmers' low-input management systems (Kante *et al.*, 2017; Leiser *et al.*, 2012, 2015; Rattunde *et al.*, 2013), helping to reduce the amounts of sorghum grain to be purchased for food while increasing the portion of harvest that is sold (Smale *et al.*, 2018).

- Improved nutrition, particularly in view of the micronutrient deficiencies widespread among women and children in West Africa (Bauchspies *et al.*, 2017; Christinck and Weltzien, 2013): understanding the women's practice of preparing separate meals for children with the grain they produce, along with selecting for vitreous grain and reducing micronutrient losses during decortication, has provided a pathway to enable the benefits of bio-fortified varieties to reach vulnerable groups, especially children.
- Empowerment of farmers: women and men initiated their own variety and cropping-system experimentation as well as methods of marketing seed and facilitating communication about seed among farmers and farmers' cooperatives, based on their learning and access to new types of varieties (Weltzien *et al.*, 2018), thereby also becoming co-owners of the process of variety development and dissemination.
- Conservation and sustainable use of agro-biodiversity: the extensive use of local germplasm in breeding programmes has resulted in an expanded range of variety types made available to farmers through a decentralized system for variety development, seed production and delivery that involves and responds to various types of farmers within and across differing agro-ecological zones (Weltzien *et al.*, 2018).

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