5 A Continent-wide, Product-oriented Approach to Rice Breeding in Africa

Takashi Kumashiro,* Koichi Futakuchi, Moussa Sié, Marie-Noëlle Ndjiondjop and Marco C.S. Wopereis
Africa Rice Center (AfricaRice), Cotonou, Benin

Introduction

Urbanization, changes in employment patterns, rising income levels, shifts in consumer preferences, and rapid population growth have contributed significantly to the widening gap between rice supply and demand in sub-Saharan Africa (SSA) (Seck *et al.*, 2012). In 2008, Africa imported about 10 million tonnes (Mt) of milled rice, at a cost of US$3.6 billion. Continued reliance on imports is unsustainable and potentially dangerous, as it may affect food security and civil stability on the continent. Rice is one crop for which SSA can become self-sufficient given the continent's available land and water resources.

Rice is grown across a large diversity of growth environments in Africa, from the salty delta of the Senegal River to the highlands of Madagascar. The Africa Rice Center's (AfricaRice) gene bank alone contains about 17,000 African rice germplasm accessions (Sanni *et al.*, Chapter 7, this volume). Rice environments are generally divided into rainfed upland, rainfed lowland, irrigated lowland, deep-water/floating and mangrove-swamp production systems (for details, see Saito *et al.*, Chapter 15, this volume). In addition to this tremendous diversity of rice-growing environments, there are also large differences in terms of consumer preferences for rice, both between and within countries. For example, surveys in Benin showed large differences between consumer preferences in urban and rural areas (see Futakuchi *et al.*, Chapter 25, this volume).

The challenge to develop new rice varieties for such diversity is huge and compounded by the fact that training and recruitment of rice breeders has been neglected across the continent since the 1990s. There are very few rice breeders left, and those remaining are mostly over 50 years of age, often with additional managerial responsibilities.

In response to this tremendous lack of research capacity, in 1991 AfricaRice established rice-breeding Task Forces (collective research and development efforts by national and AfricaRice breeders, based on the principles of sustainability and build up of critical mass at the national and regional levels) catering to the different rice environments in West and Central Africa. These Task Forces were later merged into a regional rice research and development network in West and Central Africa (ROCARIZ). Funding for ROCARIZ ceased in 2005 and this has severely disrupted AfricaRice's ability to collaborate and plan activities with national agricultural research system (NARS) partners.

AfricaRice established a new, continent-wide Rice Breeding Task Force in 2010, aiming

* Corresponding author: t.kumashiro@cgiar.org

to accelerate rice varietal development through continent-wide varietal evaluation of nominated elite lines from AfricaRice and its international and NARS partners.

Despite the difficulties, AfricaRice and partners have contributed to the release of many new rice varieties since 1960 (Sanni *et al.*, Chapter 6, this volume). However, many rice farmers still do not have access to new varieties that are better adapted to their farming environment and likely to sell well on the market. This is partly related to cumbersome, non-functional or non-existent varietal release procedures (Sanni *et al.*, Chapter 6, this volume) or non-functional seed systems (Bèye *et al.*, chapter 14, this volume). However, there is also a clear need to develop rice varieties better targeted to rice environments and market segments.

This chapter reviews the continent-wide, product-oriented breeding approach promoted by AfricaRice within the framework of the Global Rice Science Partnership (GRiSP). GRiSP is a CGIAR research programme for rice, led globally by the International Rice Research Institute (IRRI) and for Africa by AfricaRice (IRRI *et al.*, 2010).

A Systematic, Continent-wide Product-oriented Approach to Rice Breeding

The systematic, continent-wide product-oriented approach to rice breeding pursues varietal development in different phases, with feedback loops as schematically represented in Fig. 5.1. These phases feed into 'varietal development pipelines' tailored to different growth environments and market segments. The important phases in this breeding approach are: (i) definition of breeding goals; (ii) pre-breeding activities; (iii) breeding activities; and (iv) multi-environment testing (MET). These phases are discussed in more detail below.

Definition of breeding goals

Rice breeding in Africa aims to develop improved cultivars with high and stable grain yield – varieties that are able to resist environmental stresses that reduce or limit productivity, and that respond well to nutrient inputs. Traditional varieties usually have good yield stability, but often low yield potential. In addition to these two general requirements, grain quality has become important in meeting the demands of consumers for healthy, high-quality food. Grain quality is essential for marketability of locally produced rice in SSA. Long slender grain and aromatic rice is preferred by urban consumers; rice of medium amylose content (20–25%) is widely acceptable, but rice with high amylose content (>25%) is preferred in Nigeria.

Breeding goals must, therefore, address the most important challenges of the target rice-growing environment (e.g. iron-toxicity in some rainfed lowlands, salinity in mangrove-swamp areas), the level of input use (low-, medium- or high-input system) and specific desired traits of the variety (e.g. grain quality, growth duration and plant height). The breeding goals must also respond to the needs of the various stakeholders in the rice value chain (with due consideration of gender issues), including rice farmers, millers, traders and consumers. For example, a varietal development pipeline for rice grown in irrigated Sahelian systems and tailored to the urban market may have as breeding goals: high and stable yield potential, tolerance to salinity, resistance to *Rice yellow mottle virus* (RYMV) and bacterial leaf blight, short duration, medium height, and aromatic, long and slender grains.

Pre-breeding

Activities in the pre-breeding phase aim to accelerate and facilitate the varietal development process in the different varietal development pipelines. This includes: (i) *ex-situ* conservation and characterization of different *Oryza* species germplasm in AfricaRice's gene bank; (ii) development of novel populations through enhanced recombination of cultivated and wild gene pools; (iii) phenotyping for key agronomic traits, resistance to diseases and responses to major stresses, including those of importance to adapt to climate change (e.g. tolerance to drought, high temperatures, salinity); and (iv) identification of genes responsible for these traits through quantitative trait loci (QTLs) mapping or association analysis, then fine mapping.

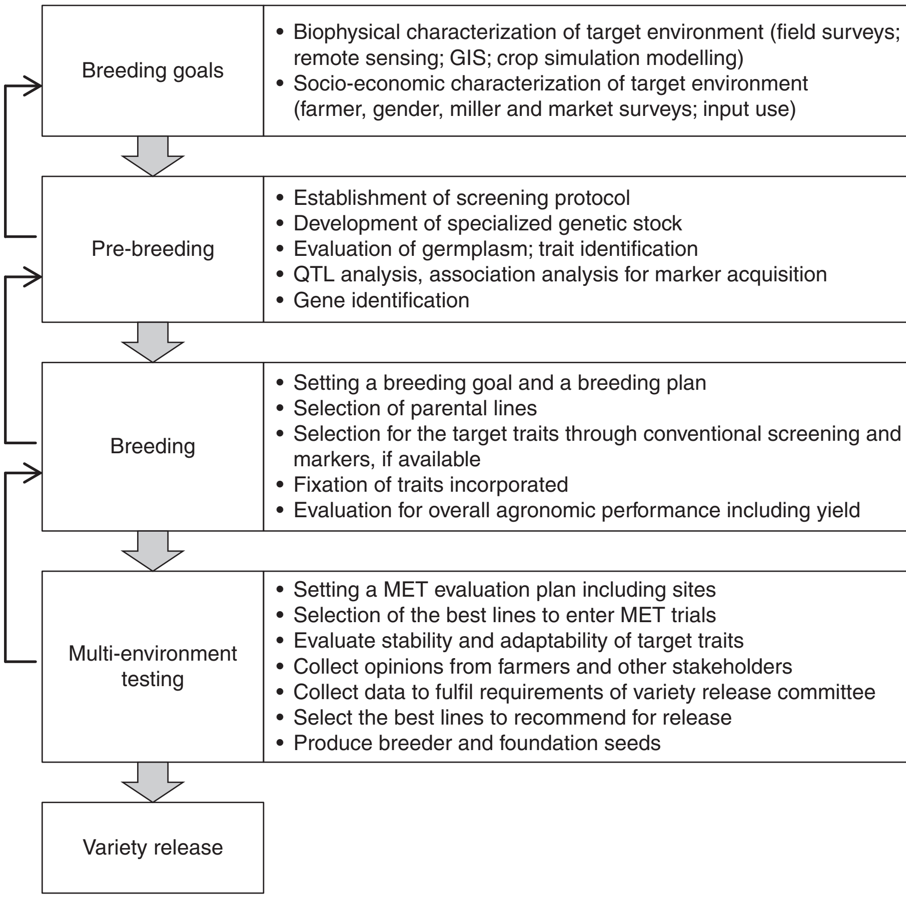

Fig. 5.1. Stages of a varietal development pipeline: definition of breeding goals, pre-breeding activities, breeding activities and multi-environment testing (MET).

AfricaRice and partners have focused in particular on gene discovery related to tolerance to abiotic stresses such as drought, different types of submergence, salinity, cold, heat, iron-toxicity and phosphorus deficiency (Dramé *et al.*, Chapter 11, this volume), and resistance to biotic stresses including blast, bacterial blight and RYMV (Séré *et al.*, Chapter 17, this volume) and African rice gall midge (AfRGM) (Nwilene *et al.*, Chapter 18, this volume; see also Lorieux *et al.*, Chapter 10, this volume). Among these target traits, novel resistant or tolerant germplasm has been successfully identified for salinity (unpublished), cold (unpublished), RYMV (Albar *et al.*, 2006) and AfRGM (Nwilene *et al.*, 2009).

Institut de recherche pour le développement (IRD, France) has been a collaborator of AfricaRice in studies on RYMV, and a new resistance gene (*RYMV2*) has been identified in *O. glaberrima* (Thiémélé *et al.*, 2010). The International Center for Tropical Agriculture (CIAT) and IRD have developed novel populations based on chromosome segment substitution (chromosome segment substitution lines, CSSL) that have *O. glaberrima* segments introgressed in different genetic backgrounds. These populations are used by collaborators for the localization of genes/QTLs for important traits such as drought tolerance, panicle architecture, root development, iron-toxicity tolerance and bacterial leaf blight resistance.

Through the IRD–CIAT–AfricaRice collaboration, efforts have been made to overcome the sterility barrier in the interspecific breeding of the two cultivated rice species to make greater use of useful traits of *O. glaberrima*; one of the project outputs is the development of 'interspecific bridge lines', which possess a high content of the *O. glaberrima* genome and produce fertile hybrids with *O. sativa* (Lorieux *et al.*, Chapter 10, this volume).

Japan International Research Center for Agricultural Sciences (JIRCAS) has worked with AfricaRice on drought research, focusing on deep rooting. Screening of 654 rice accessions identified 17 with deep-rooting capabilities; efforts to identify associated QTLs are under way (Tsunematsu and Samejima, 2011). AfricaRice and JIRCAS are also collaborating on tolerance to phosphorus deficiency and resistance to blast. Diversity analysis of blast isolates in Africa is conducted using 'differential varieties', each of which carries one resistance gene in the same genetic background (these varieties were developed under long-term collaboration between Japan and IRRI). To develop a variety with durable blast resistance, DNA markers linked with field resistance (Fukuoka *et al.*, 2009; Hayashi *et al.*, 2010) identified by the National Institute of Agrobiological Sciences (NIAS), Japan, are being used. For the development of rice cultivars capable of using a greater portion of phosphorus from the soils, markers for the *Pup1* (Heuer *et al.*, 2009) gene were introduced from JIRCAS and are being used to detect donors among upland varieties in Africa.

Breeding

The most suitable parents and breeding methods are selected on the basis of the breeding target. The availability of a reliable phenotyping method to identify desirable individuals or lines giving adequate performance for each trait of interest, especially for quantitative traits such as drought tolerance and yield potential, is crucial for the success of any breeding programme.

In principle, 'hot spots' with regular occurrence of a particular abiotic or biotic constraint offer the breeder a natural screening platform. However, spatial and temporal variability of the constraint may be large. For instance, iron-toxicity in the AfricaRice breeding hot spot in Burkina Faso is unevenly distributed in the field. For diseases and insects, prevailing strains and constraint severity may vary from year to year. Therefore, hot-spot screening should be coupled with screening in a controlled environment, to ensure more reliable evaluation of phenotypic performance.

AfricaRice will benefit from the global phenotyping platform that is being established within GRiSP, focusing mainly on tolerance to abiotic stresses and yield potential. AfricaRice is developing additional facilities for phenotyping for major abiotic stresses (e.g. drought, cold, Fe-toxicity) and the most important diseases (i.e. blast, bacterial leaf blight, RYMV) under controlled conditions, where stress intensity is managed to mimic the target environment and artificial inoculation is carried out using the prevalent strains.

Use of molecular markers

Marker-assisted selection (MAS) improves the efficiency of the breeding process when molecular markers tightly linked to the trait of interest are available and when phenotypic performance for the trait cannot be evaluated reliably or in a timely fashion on a routine basis. Loci or genes responsible for important agronomic traits in rice (e.g. disease resistance, abiotic-stress tolerance, grain quality) have been identified through QTL analyses and association analyses. The Q-TARO ('QTL annotation rice online', http://qtaro.abr.affrc.go.jp) (Yonemaru *et al.*, 2010) and Gramene (http://www.gramene.org/) databases summarize and update important QTLs for rice.

AfricaRice is using MAS on a routine basis to incorporate resistance to biotic and abiotic stresses in different rice varietal development pipelines (Table 5.1). For example, MAS was used to incorporate the resistance allele, *rymv1-2*, of the *RYMV1* gene into a number of major varieties grown in Africa, such as IR64. Near-isogenic lines (NILs) of IR64 bearing the resistance allele were developed and evaluated in Burkina Faso, Côte d'Ivoire, Mali and Nigeria (Ndjiondjop *et al.*, Chapter 12, this volume). Likewise, markers linked to genes/QTLs for tolerance to abiotic stresses are also routinely used in MAS. For instance, the *Sub1* gene (Septiningsih *et al.*, 2009) is being introgressed into major African varieties such as WITA 4 and NERICA-L 19 to increase tolerance to flash floods during the early vegetative stage.

Table 5.1. Ongoing marker-assisted selection (MAS) at AfricaRice, 2012.

Trait	Locus	Reference(s)
RYMV1 resistance	*rymv1-2*	Ndjiondjop *et al*. (1999); Thiémélé *et al*. (2010)
RYMV2 resistance	*rymv2*	Thiémélé *et al*. (2010)
Bacterial blight resistance	*Xa4*	Sun *et al*. (2003)
	xa5	Jiang *et al*. (2006)
	Xa7	Chen *et al*. (2008)
Blast resistance (field)	*Pb1*	Hayashi *et al*. (2010)
	pi21	Fukuoka *et al*. (2009)
Salt tolerance	*saltol*	Thompson *et al*. (2010)
Submergence tolerance	*sub1*	Xu *et al*. (2006)
Drought tolerance (upland)	*DTY12.1*	Bernier *et al*. (2007)
Drought tolerance (lowland)	*DTY 3.1*	Venuprasad *et al*. (2009)
Cold tolerance	*Ctb1, Ctb2*	Saito *et al*. (2010)
	qRCT6b	Negussie (2011 unpublished)

In addition to using MAS to target a single gene or major QTL, AfricaRice is also using a more advanced MAS scheme where QTLs for target traits are detected within the segregating progenies of elite lines crossed for their complementarities. This marker–phenotype information serves to guide the breeding process towards the ideal mosaic of QTLs or favourable chromosomal segments from the two parents. Such a breeding scheme, involving several successive generations of crossing of progenies bearing complementary QTLs, is referred to as marker-assisted recurrent selection (MARS) or genotype construction (Stam, 1995; Peleman and van der Voort, 2003). AfricaRice, Centre de coopération internationale en recherche agronomique pour le développement (CIRAD) and partners are implementing a MARS scheme to increase drought tolerance in lowland rice. Bi-parental populations are being developed for mapping QTLs involved in drought tolerance and yield potential; the breeding scheme (directed recombination between specific individuals carrying the favourable allele of the detected QTLs) is designed to produce or approach the ideal genotype accumulating favourable alleles for as many QTLs as possible.

Breeding for high yield

Most varietal development pipelines in Africa address the incorporation of resistance or tolerance to various stresses, because there are so many constraints that hinder the expression of the full potential of a variety in farmers' fields (see Dramé *et al.*, Chapter 11, this volume). However, more emphasis is now being placed on raising yield potential in different growth environments. This is important because high-yielding varieties that have been bred and do well in environments without major yield-reducing or yield-limiting factors will usually also out-perform in environments where a particular stress interferes, unless the stress becomes too severe (e.g. Bänziger *et al.*, 1997, for soil fertility status in maize; Kumar *et al.*, 2008, for drought tolerance in rice; Saito, 2010, for rice competitiveness against weeds). Several approaches are used to increase yield potential.

The first approach is to validate and incorporate yield-component QTLs detected elsewhere (Ando *et al.*, 2008; Obara *et al.*, 2010; Ookawa *et al.*, 2010) into popular varieties in Africa.

The second approach is to apply recurrent selection, a multi-parental scheme designed to facilitate the accumulation of favourable alleles for complex traits such as yield through successive cycles of recombinations and phenotypic selection (Gallais, 1990; Guimaraes, 2005). Such a scheme was used successfully in Brazil to achieve rapid gains in grain yield for upland rice (e.g. Breseghello *et al.*, 2009, 2011). The third approach is to develop F_1 hybrid varieties adapted to African rice environments. Hybrid rice has been very successful in Asia, especially in China and India. AfricaRice started work on hybrids in 2009, evaluating hybrids from China and developing an in-house hybrid-rice breeding programme for the irrigated environment at the AfricaRice Sahel station in Senegal. Some parental lines, including male sterile lines and restorer lines, were introduced from IRRI, Egypt and China, and are being tested (El-Namaky and Demont, Chapter 13, this volume).

Grain quality

Given the importance of grain quality in enabling locally produced rice to compete with imported rice (Fofana *et al.*, 2010; Futakuchi *et al.*, Chapter 25, this volume), it is important to assess grain quality when choosing the parental lines and then during the breeding process. Since grain quality is easily affected by many factors (e.g. timing of harvest, moisture content, storage condition of harvested grain), repeated evaluation of properly prepared grain samples is necessary. At AfricaRice, all elite lines entering the multi-environment testing phase are evaluated for quality traits, including basic parameters directly related to farmers' income, such as chalkiness, grain colour and milling properties. Attention is also paid to the needs of the various stakeholders. For instance, among the three aromatic varieties released in Senegal in 2009, Sahel 177 has the highest yield potential, Sahel 328 the shortest growth duration and Sahel 329 is the most appreciated for its taste.

Multi-environment Testing (MET) Network, the Africa-wide Rice Breeding Task Force

In 2010, the Africa-wide Rice Breeding Task Force was launched by AfricaRice involving NARS from 25 countries (Plate 1). The objectives of the MET network are to evaluate the stability of traits incorporated in breeding processes and to identify varieties that best fit the growth conditions in target regions and the markets. The Task Force also accumulates data on the performance of new elite lines, thereby facilitating varietal release procedures. Furthermore, by exposing scientists from NARS and farmers to these elite lines during the testing phase, dissemination will be facilitated (Table 5.2). Moreover, the Task Force is also building the capacity of rice breeders, by enabling experienced and younger breeders to work together on evaluation trials.

The MET conducted by the Africa-wide Rice Breeding Task Force consists of a series of three consecutive trials. Promising breeding lines developed by AfricaRice, national or international partners (e.g. IRRI and CIAT) are nominated for evaluation in one or several rice-cultivation environments: lowland, irrigated, upland, high elevation and mangrove (Plate 1). All nominated lines should be fixed and accompanied by supporting data on traits incorporated during the breeding process and with information on yield performance. These characteristics are checked at AfricaRice before incorporation into the MET network.

The first phase (MET-1) consists of an initial evaluation of about 100 lines selected from the nominated lines. Each national partner evaluates these lines at sites in its country. Such sites may be at an experimental station under optimal management to evaluate yield potential, or may be a 'hot spot' to check the performance of the nominations in a stressed growth environment. Trials are replicated three times and include common and local checks. Data collected at all sites are analysed centrally at AfricaRice, including comprehensive genotype-by-environment (G×E) analysis. Based on the results of these analyses and breeders' observations, about 30 lines are advanced to the next phase.

The second phase (MET-2) serves to evaluate and confirm the performance of the selected lines. These lines are cultivated at the same sites as MET-1 using the same experimental design with three replications. An important feature of MET-2 is that farmers and other stakeholders (e.g. millers and traders) are invited to participate in varietal selection and their opinions on the performance of all entries are collected through a participatory varietal selection (PVS) procedure (Sié *et al.*, 2010). Members of national varietal release committees are also invited. Using the data collected, observations by the breeders and the opinions of stakeholder groups, NARS partners select up to ten lines.

In the third phase (MET-3), the ten lines selected during MET-2 are evaluated in at least three sites per country during one or more growing seasons, depending on varietal release requirements. Entries are arranged in an alpha-lattice

Table 5.2. Principles of multi-environment testing (MET) conducted by the Africa-wide Rice Breeding Task Force.

Trial phase	Name of trial	Characteristics of trials	Sites/ country	No. lines in trial	Exp design	No. lines to advance	Evaluator(s)
MET-1	MET (multi-environment trial)	Evaluation of lines nominated by breeders	1	About 100 lines	Alpha-lattice with 3 replications	About 30	NARS breeders
MET-2	PET (participatory evaluation trial)	Evaluation of lines selected in MET	1	About 30	Alpha-lattice with 3 replications	About 10	NARS breeders Farmers VRC members Other stakeholders
MET-3	PAT (participatory advanced trial)	Evaluation of lines selected in PET by NARS breeders	3	About 10 best lines	RCBD with 4 replications	1–3 lines recom-mended for release	NARS breeders Farmers VRC members Other stakeholders
	FAT (farmers' adoption trial)	Evaluation of a few lines selected in PET by farmer	50	3 lines among 10 for each farmer	No replication		

Exp = experimental; NARS = national agricultural research system; RCBD = randomized complete block design; VRC = varietal release committee.

design (Patterson and Williams, 1976) with at least four replications. All stakeholders are again invited to familiarize them with the new lines and voice their opinions to help select lines for further advancement. Among the ten lines, farmers are invited to select three lines and cultivate these in their own fields, together with a common check and their own variety (Sié *et al.*, 2010).

The ultimate decision to nominate a particular variety for release in a country will be made by the country's rice breeder involved in the Task Force, based on evaluation of all data acquired before and during the MET phase.

In 2011, AfricaRice and partners decided to assign a new name to particularly promising breeding lines that result from Task Force activities: 'ARICA', which stands for 'Advanced RICes for Africa'.

ARICA varieties can be considered as the next generation of rice varieties for Africa, after the success of the 'NEw RICes for Africa' (NERICAs) developed in the 1990s and the first decade of this century. For a breeding line to be nominated as an ARICA line it must have a clear advantage over the best check varieties in a region, backed by quality data over at least three seasons. Moreover, at least one country should show interest in nominating the line for varietal release. Unlike the NERICA varieties, they are not restricted to interspecific crosses. Any line that shows promise, regardless of its origin, can become an ARICA line as long as the data collected are convincing. The ultimate decision on naming an ARICA line is taken by AfricaRice, and is based on data gathered in the Task Force trials, and any other data gathered during the breeding process.

During the 2013 Task Force meeting, five nominations for ARICA naming were examined and accepted to become the first ARICA lines. ARICA1, 2 and 3 are suited for the rainfed lowland growth environment and are proposed for varietal release in Mali (ARICA1, ARICA2 and ARICA3) and Nigeria (ARICA2 and ARICA3). ARICA4 and 5 are suited for the upland growth environment and have just been released in Uganda. All these ARICAs out-yielded local checks including NERICA-L 19 in the rainfed lowland environment and NERICA 4 in the upland environment. In addition, ARICA3 has better grain quality, higher milling recovery, lower chalkiness and shorter cooking time than NERICA-L 19.

Data management

Rapid access to information on germplasm, including advanced breeding lines and varieties, is essential to the use and deployment of breeding lines for further research and evaluation. Data management plays a central role starting from germplasm stored in a gene bank up to information on performance of elite breeding lines about to be released – high-quality data needs to be available for all the fixed breeding lines generated.

Data acquired by NARS in the MET trials are collected and sent to AfricaRice for central analyses and archiving, following the standards of the International Rice Information System (McLaren *et al.*, 2005). These data can be used to facilitate varietal release in a particular country or new varietal development activities.

Conclusions

Setting correct breeding goals is essential in any breeding process. Each region, country or market niche will have specific requirements in terms of traits that ideally need to be incorporated in a new variety. However, in general, very little knowledge is available about the target environment, both in terms of biophysical settings and preferences of farmers, millers and rice consumers. Much greater and more precise information with respect to such requirements is needed. AfricaRice is gathering such information through focused field surveys and trials and increasing use of crop simulation modelling to deal with spatial and temporal variability of growth conditions, in collaboration with partners such as CIRAD, IRRI and Wageningen University. AfricaRice and partners are also conducting surveys in key rice-growing regions across Africa, interviewing farmers, millers, traders and consumers. This information will allow more precise definition of breeding goals and a greater variety of varietal development pipelines. It will also allow collaborating NARS to specify in greater detail their requirements for their growth and market conditions, enabling more targeted selection of germplasm entering the MET-1 trials of the Africa-wide Rice Breeding Task Force. Greater breeding precision and a larger diversity of varietal development pipelines will only be possible by strengthening national rice-breeding capacity in Africa.

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