Genes, Genomes and Genomics ©2012 Global Science Books

Towards a Rational Use of African Rice (*Oryza glaberrima* Steud.) for Breeding in Sub-Saharan Africa

Moussa Sié[1*] • Kayode Sanni[1] • Koichi Futakuchi[1] • Baboucarr Manneh[2] • Semon Mandé[3] • Raymond Vodouhé[4] • Selome Dogbe[1] • Khady-Nani Dramé[1] • Ayoni Ogunbayo[1] • Marie-Noelle Ndjiondjop[1] • Karim Traoré[2]

[1] Africa Rice Center (AfricaRice), 01 BP 2031 Cotonou, Benin
[2] Africa Rice Center (AfricaRice), BP 96 Saint-Louis, Senegal
[3] Africa Rice Center (AfricaRice), c/o International Institute of Tropical Agriculture (IITA), PMB 5320 Ibadan, Nigeria
[4] Bioversity International, c/o IITA/Benin Research Station, 08 BP 0932 Cotonou, Benin

Corresponding author: * **m.sie@cgiar.org**

ABSTRACT

Africa Rice Center (AfricaRice) plays an important role in germplasm enhancement for their adaptation to different ecologies of upland, lowland, irrigated, mangrove and deep water. The genebank of AfricaRice contains over 20,000 rice accessions, notably two cultivated species (*Oryza sativa* and *O. glaberrima*) and wild species (*O. longistaminata*, *O. barthii* and *O. stapfii*), which are being used in breeding programs. In recent years, NERICA rice suitable for upland, lowland and irrigated ecologies were developed from interspecific crosses between *O. sativa* and *O. glaberrima*. For the better utilization of *O. glaberrima*, characterization studies of genetic diversity have been made using both molecular and conventional tools. The screening of this material for biotic and abiotic stresses has allowed us to identify firstly, genes for resistance to major rice diseases such as rice yellow mottle virus, rice blast disease and insect pests, and secondly, new sources of tolerance to drought, salinity and iron toxicity. A thorough exploitation of these resistance/tolerance genes will lead to rice varieties of better performance, under the heterogeneous production conditions in Africa. AfricaRice therefore planned to better exploit *O. glaberrima* and wild species conserved in its genebank through the use of biotechnology tools. Emphasis shall also be on the improvement of grain quality, nutritional values and post harvest techniques; this will greatly enhance the achievement of the objective of producing better quality rice in Africa. The objective of this paper is to propose several ways to better exploit *O. glaberrima* as breeding materials than the current interspecific breeding program through the critical review of published data and new additional data on the performance of NERICA lines.

Keywords: Africa Rice Center, NERICA, *Oryza sativa*, participatory varietal selection, wild rice species

CONTENTS

INTRODUCTION

Oryza glaberrima Steud., which is the cultivated *Oryza* species different from *Oryza sativa* L., was domesticated in West Africa (Jones *et al*. 1997b) and is still cultivated in this sub-region (Singh *et al*. 1997). Since the yield level of *O. glaberrima* is regarded as generally low compared to that of *O. sativa* due to grain shattering and poor resistance to lodging, its growing area has been decreasing (Linares 2002). However, *O. glaberrima* is considered to have resistance to various local constraints in West and Central Africa (WCA) because of its domestication history and be important as genetic resources to develop rice suitable for resource-poor farmers in WCA, who are suffering from low yielding due to multiple stresses in their fields. Therefore, Africa Rice Center (AfricaRice) commenced a new breeding program to use only assets of this species by crossing it to *O. sativa*, although a commercial variety had never been developed from this wide cross before in spite of a number of attempts by many researchers.

In 1990 and 1991, AfricaRice screened 1130 accessions of *O. glaberrima* in upland conditions at the experimental

Received: 8 May, 2010. Accepted: 13 November, 2011

Invited Review

field of its headquarters in M'bé, near Bouaké, Côte d'Ivoire in terms of early maturity, high tillering ability and rapid seedling growth, and nominated eight lines for wide hybridization. These eight *O. glaberrima* lines selected were expected to compete with weeds (high tillering and rapid seedling growth) and escape drought and late-season fungal disease (early maturity). As *O. sativa* parents for the wide crosses, five high yielding elite japonica type upland lines developed by AfricaRice, all of which were officially released in Côte d'Ivoire and/or other WCA countries later on, were nominated. In 1992, interspecific crosses between those lines were made. After two backcrossings to the respective *O. sativa* parents, BC_2F_1 progenies were subjected pedigree selection and the first fixed fertile upland interspecific progenies (WAB450 series) were obtained from the cross of WAB56-106 (*O. sativa*) and CG 14 (*O. glaberrima*) in 1994. The details of the development of the first interspecific progeny are described in Jones *et al*. (1997a). All fixed interspecific lines are now called as NERICA, which was named after New Rice for Africa. The original basic concept of the interspecific breeding was to develop NERICAs possessing the adaptability of *O. glaberrima* to local rice growing conditions in WCA and the characteristics of *O. sativa* associated with high yielding. A number of promising upland NERICA lines were developed under this basic concept and seven NERICA varieties were released in Côte d'Ivoire and/or Guinea in 2000. Eighteen upland NERICA varieties were adopted by several sub-Sahara African (SSA) countries beyond WCA as of 2007 (Futakuchi 2008).

NERICAs for lowland (WAS122, 161 and 191 series) have been developed under the same breeding concept with the upland NERICA. Resistance to rice yellow mottle virus (RYMV), which is a crucial indigenous disease in Africa, is especially an expected trait from *O. glaberrima*, and some of the lowland NERICA lines have been released in Burkina Faso, Cameroon, Gambia, Mali, Niger, Sierra Leone and Togo (Futakuchi 2008). Several prototypes of lowland NERICA lines have also been developed from another cross such as WAB1159 series (Futakuchi *et al*. 2004).

NERICA varieties have already had impacts on farmers' livelihoods and poverty reduction in SSA (Obilana and Okumu 2005; Kijima *et al*. 2008). However, Obilana and Okumu (2005) have also pointed out that there are still gaps in AfricaRice's interspecific breeding program and *O. glaberrima* has not been fully utilized despite the current success of NERICA. The objective of this paper is to propose several ways to better exploit *O. glaberrima* as breeding materials than the current interspecific breeding program through the critical review of published data and new additional data on the performance of NERICA lines, especially upland ones, and *O. glaberrima*.

Rice is one of the crops that are important in the world. It feeds almost half of the world population, particularly in Asia, Africa and Latin America. There are two cultivated rice species: *Oryza sativa* L. (Asian rice) and *Oryza glaberrima* Steud. (African rice). African rice was cultivated long before the arrival of Europeans on the continent. It was domesticated in the Niger River valley, since about 2000-3000 years (Linares 2002).

Although there are still farmers in West Africa which continue to grow *O. glaberrima*, it is being massively replaced by Asian rice varieties because of its low performance related to lodging and shattering. However, having survived with minimal intervention of man, this allowed it to acquire and develop tolerance and resistance against the majority of biotic and abiotic stress affecting rice cultivation in SSA (Jones *et al*. 1994; Jones *et al*. 1997a, 1997b). The interspecific hybridization programs designed to combine the traits of interest for both crops have met with little success because of sterility barriers between the two species. Researchers of AfricaRice during an extensive breeding program managed this challenge by creating fertile interspecific hybrids, by backcrossing and embryo rescue. These new varieties which combine the hardiness of African rice and Asian rice productivity were named NERICA (New Rice for Africa). The creation of the NERICA suitable for upland (Jones *et al*. 1997a) and lowland (Heuer *et al*. 2003) earned the AfricaRice international awards including the World Food Price in 2004 and Koshihikari International Rice Award from Japan in 2006, attributed to the original breeders of these successes. AfricaRice also received the 2006 United Nations Award for South-South Triangular Partnership in recognition of the success of an interspecific hybridization project, where NERICAs have been developed.

Despite this important development, rice production in SSA still cannot meet demand. In this region, rice production is guaranteed to 80% by small farmers whose livelyhoods in terms of equipment and finances are very limited, in addition to the environmental constraints affecting the regular sub-Saharan Africa. To address the shortage, African countries are forced to import rice. According to FAO, these imports cost about 2 billion of dollars per year. This is a significant loss of foreign exchange for those countries already indebted.

To cope with increasing demand for rice in Africa, one of the least expensive alternatives is the development of high yielding varieties adapted to environmental conditions in the region. In this objective, AfricaRice has established a research program on biodiversity and genetic improvement of rice covering the different ecologies of the upland, lowland (rainfed and irrigated), mangroves and deep water. AfricaRice's genebank that contains a little over 20,000 accessions of rice formed including two cultivated (*O. sativa* and *O. glaberrima*) and other wild (*O. longistaminata*, *O. barthii* and *O. stapfii*) species continues to be enriched with new accessions. Their screening has identified new sources of resistance to abiotic stresses such as drought, salinity and iron toxicity and biotic stresses like RYMV, bacterial leaf blight (BLB), African rice gall midge (AfRGM) and blast. Identification of genes for resistance to disease and pests has been made for RYMV (Ndjiondjop *et al*. 1999) and is being conducted for AfRGM and BLB. Useful germplasm and genes identified have been used for Center's varietal improvement programs in both conventional and marker-assisted breeding. Through participatory approaches (farmers' participatory varietal selection: PVS), farmers are involved in the selection process to ensure a faster adoption of new varieties developed and their ownership by the farmers. Through its various partnership networks such as ROCARIZ (West and Central African Rice), INGER-Africa (International Network for Genetic Evaluation of Rice in Africa), and ARI (African Rice Initiative), AfricaRice is heavily involved in the characterization, evaluation, multiplication and distribution of promising germplasm to researchers working on rice in Africa and worldwide. It also contributes to strengthening the capacity of national agricultural research systems (NARS) of member countries. Thus, many NARS scientists are trained each year by the AfricaRice in the management of biodiversity for genetic improvement of rice through the creation and participatory varietal selection. The aim of this paper is to give an overview of the status of rice in Africa, progress in the field of breeding and present challenges to achieve food security in SSA by means of local production in sufficient and good quality.

Africa is the only continent where the two cultivated rice species coexist. African rice despite its low yield continues to be cultivated locally for its hardiness, its taste. Because of its resistance/tolerance to many environmental stresses, it has a wide range of varieties allowing it to adapt to several types of habitat. It is indeed an important gene pool. Rice production in SSA is subject to numerous constraints that significantly reduce yields in all ecologies. Therefore, the use of *O. glaberrima* for improved Asian varieties less adapted to the conditions of the SSA is more than timely and successful NERICA is a proof.

STATE OF RICE IN SSA

AfricaRice publishes a booklet called "Africa Rice Trends", which is updated once every few years. This publication reviews trends of rice in Africa as regards the production, consumption, importation and self-sufficiency. The following information was extracted from the latest version (Africa Rice Center (WARDA) 2008). In 2006, paddy production was estimated at 14.2 million tonnes. From 1961 to 2005, annual growth in production was 3.23%. This growth has been higher than the annual growth rate of the population by 2.9% in the same period. Over 5 years (2001-2005), the output growth reached 5.81%. The West and East Africa were the main rice producing areas in SSA accounting for 95% of the total rice produced in SSA. On average, 7.86 million ha/year were sown to rice during the period 2001-2005, with an annual growth of 3.29% during this period. The expansion of the total area cultivated is the cause of the increase in production since the average annual growth in yields is negative (-1.14%) and continues to 1.51 tonne/ha. The faster growth in area planted compared to performance is consistent with the historical dynamics of the rice sector in SSA rather favorable to non intensification. Among the major cereals of the continent, rice is the staple food crop that grows quickly. Between 1961 and 2005, the annual increase in consumption of rice was 4.52% above that of production in the same period. During 2001-2005, annual growth in consumption of rice was 5.84%. This increase is largely attributed to strong demand from West Africa and South America where rice consumption is believed to be average of 6.55 and 11.58%, respectively. The average consumption per capita was 18.33 kg/year from 2001-2005, although there are large disparities between different subregions (West Africa, East Africa, Central Africa and South Africa).

Between 1961 and 2006, annual growth in rice production, which amounted to 3.18% was above the population growth of 2.9% per year but much lower than the growth in rice consumption of 5.84%. This explains the growing gap that exists in SSA and increased imports to meet this demand. Among the 10 largest importers of the year 2006, include 4 countries in sub-Saharan Africa: Nigeria, Cote d'Ivoire, South Africa and Senegal with respective quantities imported of 1600, 850, 800 and 750 million tons.

Different production ecologies

Rice is characterized by its high plasticity allowing it to develop in very different environments. Five ecologies can be distinguished for rice production on the basis of topography and water supply (Windmeijer *et al*. 1994), i.e. (1) rainfed upland rice in the uplands and slopes; (2) rainfed lowland Rice in the valley bottom and floodplain; (3) irrigated rice with controlled water in the deltas and flood plains; (4) deep water or floating rice along the banks and beds of rivers; and (5) mangrove rice in lagoons and delta of coastal.

In WCA systems, upland rice covers the largest area representing 44% of rice land. rainfed lowland rice systems cover 31% while irrigated rice system covers only 12% of rice land. Floating and swamp rice are very small minority (Defoer *et al*. 2002). Regarding the production from each of these ecologies, production systems are still predominant rainfed and provide more than half of total production. The rainfed lowland contributes up to 36% in production followed by upland with 25%. The irrigated system contributes up to 28% including 22% from the Sahelian zone and the remaining areas of savanna and rainforest (Defoer *et al*. 2002). For all these ecologies, actual yields achieved are well below potential yields.

Most rice production ecologies have similarities such as pressure from weeds, pest pressure and declining soil fertility. In addition, there are interactions between ecologies, i.e., water flow, the flow of nutrients from the upland to the lowland. In response to these effects, AfricaRice has developed a concept of continuum from upland to lowland along the toposequence based on water depth (WARDA 1989).

Genetic diversity studies

Knowledge of genetic diversity (size and distribution) within a population and between populations is very important for breeding and conservation programs. On the one hand, it promotes the achievement of a higher variation in the segregating populations in guiding the choice of genetically distant genotypes. On the other hand, it allows people to choose for conservation programs, representative of the biodiversity of a species in any region.

1. Genetic diversity in O. glaberrima

The genebank of AfricaRice have nearly 3,000 African rice accessions adapted to different ecologies and from different countries of SSA. Very little genetic diversity has been identified in *O. glaberrima* in comparison to *O. sativa* using RFLP markers and isozymes (Second 1982; Wang *et al*. 1992). The use of microsatellite markers (SSRs) has improved this situation. One hundred and ninety eight accessions of *O. glaberrima* the AfricaRice were characterized with 93 SSR markers. The average number of alleles per locus detected in this study was 9.4 alleles per locus ranging from 2 to 27 alleles per locus. Genetic diversity revealed by this set of markers was elevated to a PIC (polymorphism information content) of 0.34 (Semon *et al*. 2005). The analysis also showed that the collection of *O. glaberrima* studied was divided into 5 genetic groups, two of which segregate with the control group *O. sativa* indica and japonica indicating the existence of intermediaries between the two species (Semon *et al*. 2005). *O. glaberrima* and *O. sativa* have cohabited for 300-500 years, gene flow occurred between the two species.

Improving rice resistance to biotic stresses

Most traditional varieties of rice cultivated in the region have a narrow genetic base, making them vulnerable to diseases and pests. Some diseases such as African rice gall midge (AfRGM), *Rice yellow mottle virus* (RYMV) and blast spread rapidly in the region because of the dominance of cultivation of susceptible varieties.

AfRGM: Several accessions of African rice proved highly resistance to the African midge. However, little is known of the genetic resistance to AfRGM in this case. Maji *et al*. (2003) undertook an analysis of Mendelian genetics on intraspecific lines (*O. glaberrima* x *O. glaberrima*) derived from crosses between 3 resistant and 2 susceptible varieties. This study showed that a single pair of recessive genes condition resistance in Tog 7106 and Tog 7206 while 2 pairs of recessive genes would be responsible for resistance in Tog 7442.

RYMV: RYMV is a major problem of lowland rice; it can cause a total production failure and contributing to famine in areas where rice is a predominant food crop. Screening of high yielding varieties which occurs for about 15 years has had some success, resistant or tolerant material was identified in three main types of cultivated rice. Several varieties *O. glaberrima* and *O. sativa* ssp. japonica showed immunity against RYMV but the low yields of rice in Africa and the inadequacy of japonica rice in the irrigated lowland does not permit a direct release. Very recently, screening of a collection of *O. gaberrima* lines lead to the identification of other sources of resistance, some of which carry a gene different from *rymv 1* (Delesse, pers. comm.). In addition to these traditional varieties, the crossing of *O. glaberrima* varieties with popular but susceptible *O. sativa* gave progeny resistant to RYMV in condition of artificial inoculation (Africa Rice Center (WARDA) 2005) and also in real environment (Sié *et al*. 2005).

Blast: Blast is also a rice disease most prevalent in the world. It is found in most ecologies of rice cultivation in

West Africa. It is particularly dangerous for the upland rice but can also cause serious damage in rainfed lowland and irrigated. To develop varieties resistant to this disease, AfricaRice adopted a screening strategy for targeting the durable resistance of varieties (Séré *et al*. 2004). This methodology is to evaluate the horizontal resistance of varieties where vertical resistance has been overcome. In 2001, the analysis of hundreds of interspecific varieties and their parents has led to the identification of 34 varieties with good levels of horizontal resistance that include NERICA 1, 2, 3 and 5 and their *O. sativa* parent (WAB56-104) and the *O. sativa* check variety (Moroberekan). Seventy two accessions including NERICA 6 and NERICA 7 and the *O. glaberrima* parent (CG 14) and the susceptible control were found to have low levels of horizontal resistance (Séré *et al*. 2004). Sié *et al*. (2004) also identified successful interspecific lines derived from crossing IR 64/Tog 5681. Most resistance genes to blast have been characterized and are controlled by alleles located at a single locus and most dominant genes that can be easily used in breeding programs.

Improving rice resistance to abiotic stresses

The climatic conditions of the SSA entail regular environmental stresses, particularly abiotic stress. The erratic rainfall puts upland rice to frequent periods of drought while the major constraint of lowland rice is iron toxicity and that of irrigated systems, salinity. The latter is also in the mangrove rice. These constraints are very likely to increase with climate change currently taking place. The SSA will not be spared and the best prospect before it occurs is to improve the adaptation of varieties.

Drought: Drought tolerance is a major component of research activities AfricaRice given the importance of upland rice in SSA. Research on drought tolerance have focused on identifying sources of tolerance in *O. sativa*, *O. glaberrima*, the intra-and interspecific; on identifying characteristics of tolerance related to performance under stress and identification of QTL associated with these characters. The drought is particularly difficult to address in SSA that: (1) the rainfall is highly variable and the type of drought can vary accordingly, (2) environmental conditions (including soil, availability of nutrients, interactions with pests and weeds, etc.) are very different from one environment to another target which makes difficult the precise definition of drought typical for screening, (3) irrigation, which is likely to mitigate the effects of drought effectively is not always affordable for most farmers in SSA. In *O. glaberrima*, the mechanism of drought tolerance has been attributed to its ability to limit water loss through transpiration by closing its stomata rapidly and leaf curling and possession of a root system well developed (WARDA 2001). Efisue *et al*. (2004) and Audebert (2006b) also showed that *O. glaberrima* had a good capacity for recovery, which is an important feature for survival during long periods of drought. Screening of 11 upland NERICA (NERICA 1-12, except NERICA 11) for drought resistance showed a great diversity in a response to the drought. Six of the 11 NERICA tested (NERICA 3, 5, 7, 8, 9 and 12) were identified as resistant lines judging from yield performance under drought (Manneh and Ndjiondjop 2008). Work on the QTL is underway with the development of backcross populations.

Iron toxicity: Iron toxicity is the major abiotic stress in lowland. Iron is widely present in the lateritic soils of West Africa, but it becomes soluble in anaerobic conditions, when soil is waterlogged. Once released, it remains in solution in water, which carries progressively downwards flowing where it is concentrated in the flooded valley bottoms. Areas where iron toxicity becomes a major cause of yield losses in rice reach around 30 to 40% of the lowlands in West Africa (WARDA 2001). With the help of simulation using the model of growth and yield of rice Oryza-S, it has been shown that iron toxicity could reduce the yield (yield spread) from 10 to 100% with an average of 45%. Yield losses depend on the cultivar, the intensity of iron toxicity and crop management (control of water) (Diatta and Saharawat 2002; Audebert 2006a). Characterization Work on the gene pool of *O. glaberrima* used in the NERICA program showed that CG 14 is highly resistant to iron toxicity. The initial screening of NERICA has revealed that many are resistant to iron toxicity (WARDA 2002).

Salinity tolerance: About 650,000 ha of rice land in West Africa are threatened by salinization, particularly in the Sahel. Salinization of rice comes from other mismanagement of irrigation water and salt water intrusion. At the Ndiaye Station, Saint Louis, Senegal, AfricaRice is selecting rice varieties for Salinity tolerance. Accessions of *O. glaberrima* from Mali, Mali's African Rice (RAM) have proved tolerant to salinity. They are: RAM 62 RAM 88 RAM 100 RAM 163 (Traoré pers. comm.). New screening methods will be used in greenhouses this year to intensify screening against salinity. Under the project on abiotic stresses, a major QTL for salinity tolerance (saltol) identified by IRRI will be introgressed into popular and elite varieties of the countries involved.

Furthermore, it is important to combine resistance to biotic and abiotic stress in the same range for greater adaptability. For example, the RYMV is often associated with iron toxicity in lowland. It is therefore crucial to combine resistance to both stresses in the same variety for the lowland. Similarly drought increases the susceptibility to blast in the uplands. It is therefore important to screen all improved variety for a given stress against other major stress that it may face in ecological adaptation.

NERICA DEVELOPMENT

Design of NERICA

To meet the challenge of food self-sufficiency and helping small producers of rice in the region, AfricaRice has launched an ambitious program of breeding in 1991. The researchers involved have evaluated nearly 1721 accessions (1130 *O. glaberrima* and 591 *O. sativa* accessions) and on the basis of morphological and agronomic characters, selected the best (Jones *et al*. 1997a). One of these accessions *O. glaberrima* (CG 14) and three *O. sativa* ssp. japonica (WAB56-104, WAB56-50 and WAB181-18) were crossed to develop interspecific hybrids. With the selection backcross, the lines derived from these crosses gave birth to 18 varieties adapted to the ecology of the upland. These new varieties of 1 to 18 were named NERICA (New Rice for Africa) (WARDA 2001). The NERICA varieties combine the best characteristics of both parents: the yield potential of Asian parent and the ability to withstand environmental constraints of the African parent in addition to earliness and high protein content (Somado *et al*. 2008).

Encouraged by the success of the upland NERICA, breeders of AfricaRice continued work to improve rainfed lowland rice and irrigated rice also using *O. glaberrima*. Crosses were conducted with eighteen accessions of *O. glaberrima* and twenty *O. sativa* ssp. indica (Heuer *et al*. 2003). The field evaluation of hybrid progeny from the cross IR 64 × Tog 5681 revealed a wide genetic diversity within populations BC_1 and BC_2. Some lines showed superior performance relative to those of *O. sativa*, indicating that the level of heterozygosity and complementary gene action after two backcrosses are sufficient to exert a positive influence on plant vigor (Heuer *et al*. 2003). This work led to the creation of 60 varieties named in 2006 by homology with their "sisters" of the upland, NERICA-L (lowland NERICA). Through the participatory approach, these 60 NERICA-L were evaluated in 8 countries in sub-Saharan Africa and 19 sites (Sié *et al*. 2008). The results showed that compared with the intraspecific evaluated during the same study, the interspecific NERICA emerged as the most interesting group with better adaptability to different stresses. They were sometimes of higher yields (up to 5 tonne/ha) than intraspecific and parents (Sié *et al*. 2008). The NERICA-L series are therefore perfectly suited to intensive rice cultivation in the lowland and irrigated systems.

Interspecific hybridization by backcrossing used in these breeding programs has helped improve the agronomic performance of varieties *O. sativa* ssp. japonica and indica. It also provided access to the genome of *O. glaberrima* in making possible the introgression of minor oligogenic characters of *O. glaberrima* in sativa varieties, which until then had experienced very limited success. From these breeding programs, there are still several hundreds of lines to use for future development of NERICA. Moreover, in the near future new interspecific lines developed from wild species of rice are available (Semon pers. comm.). NERICA varieties offer real hope for improving productivity, profitability and sustainability of rice farming in SSA.

Genetic diversity among NERICA

The analysis of a population of 70 interspecific BC_2 lines developed from a cross between WAB56-104 and CG 14, which are also parents of NERICA 1 to 11, with 130 SSR markers was used to estimate the relative contribution of each parent in the offspring. The average proportion of recurrent parent genome *O. sativa* was 87.4%, while the average proportion of genome *O. glaberrima* was 6.3%. Non-parental alleles were also detected in 83% of lines. They represent an average proportion of the genome of strains of 2.2% (Semagn *et al*. 2007).

In a second study, the genetic distances among the 18 upland NERICA were determined on the basis of molecular data and agromorphological for 7 of 18 NERICA (NERICA 1 to 7). The molecular analysis revealed the existence of 2 distinct groups: the group of NERICA 1 to 7 and the group of NERICA 8 to 18. In this analysis, no genetic difference was found between NERICA 8 and 9 while the biggest difference was detected between NERICA 6 and 17 (Semagn *et al*. 2006).

Gaps between existing NERICA lines and *O. glaberrima*

A weed problem is one of the major constraints for rainfed rice production in WCA; according to a yield gap study conducted by AfricaRice in Côte d'Ivoire, weed competition was the most important yield-reducing factor, followed by nitrogen nutrition and pests (WARDA 1996). *O. glaberrima* is known to be highly weed competitive compared to *O. sativa* due to its growth characteristics at the vegetative stage such as vigorous initial growth, high tillering ability, large leaf area and droopy leaves (Johnson *et al*. 1998; Dingkuhn *et al*. 1999). An ideal plant type of high yielding weed competitive rice was developed according to the basic concept of the interspecific breeding mentioned in the introduction (Jones *et al*. 1997a). The ideal plant type may have the vegetative growth of *O. glaberrima* (vigorous growth, high tillering, large leaf area and droopy leaves) and the reproductive growth of *O. sativa* (erect leaves, no lodging, no grain shattering and large panicles). Current NERICAs had an intermediate value of leaf area between *O. sativa* and *O. glaberrima* and the same tiller number with *O. sativa* at vegetative growth (Dingkuhn *et al*. 1998). On the other hand, NERICA did not lodge and its yield level was higher than *O. glaberrima*'s, especially with fertilizer inputs, and as same as *O. sativa*'s (Jones *et al*. 1997a; Dingkuhn *et al*. 1998). In general, the current NERICA lines were more similar with *O. sativa* than *O. glaberrima* in relation to morphological characteristics in both the vegetative and reproductive growth stages. Judging from their morphology at vegetative growth, therefore, there is a gap between the current NERICAs and *O. glaberrima* in terms of weed competitiveness (Futakuchi and Sié 2009).

Better NERICAs in relation to weed competitiveness should be more similar with *O. glaberrima* than the existing ones so that the less number of backcrossings to *O. sativa* may be desirable during their development (Futakuchi and Sié 2009). Anyway, weed competitiveness comprises various traits such as early vigor, high tillering ability, large leaf area and droopy leaves, etc. and will concern a large number of genes.

Characteristics of *O. glaberrima* which have not yet been focused

O. glaberrima is a rich genetic source to provide resistant genes for growth constraints in WCA, some of which cannot be found easily in the variation of *O. sativa* such as resistance to RYMV. Another noteworthy character of this species, which has not been clearly described, is that a single line can have multiple resistance to various local constraints although certain *O. sativa* varieties with stronger resistance for individual constraints can be found. For example, CG 14, a parent of all upland NERICA varieties released in WCA and other sub-regions of SSA, has weed competitiveness (Jones *et al*. 1997a; Dingkuhn *et al*. 1999), strong resistance to iron toxicity (Sahrawat and Sika 2002), drought resistance (Jones *et al*. 1997a), drought recovery (Audebert 2006b), resistance to nematode (Coyne *et al*. 1995), resistance to water logging (Futakuchi *et al*. 2001), adaptability to acid soil with low phosphorus availability (Tobita *et al*. 2003). Such resistance to multiple constraints is a highly desirable character for rice cultivated by resource-poor farmers in rainfed ecology in WCA, who cannot afford to adopt intensive agronomic measures against such constraints.

Another possibility to develop such a NERICA variety may be backcrossing to an *O. glaberrima* parent. There was no influence of the *O. glaberrima* parent on the yielding type of the existing NERICA lines. The *O. glaberrima* parent, CG 14, showed a much larger number of panicles even than *O. sativa* varieties of the panicle number type, although its individual panicle is smaller (Futakuchi and Jones 2005). The introduction of such an extraordinary trait, which can not be seen in *O. sativa*, may increase yield potential of NERICA lines. Therefore, the additional new concept of the interspecific breeding is to combine the adaptability of *O. glaberrima* to local environments with the optimal conjunction of the best traits of the two species in relation to yield generation. For instance, a higher yielding weed competitive NERICA therefore becomes a promising interspecific progeny that possesses vegetative growth of *O. glaberrima* and reproductive growth of the combination of *O. glaberrima* and *O. sativa*.

Seeking better *O. glaberrima*

O. sativa is one of the major staple food crops and a huge number of basic and applied studies have been made with this species, e.g. its whole base sequence was already determined. On the other hand, *O. glaberrima* is much less explored in a scientific manner. AfricaRice is still seeking better *O. glaberrima* lines for important traits in rainfed rice cultivation in WCA such as drought resistance and short duration, etc. IRCG Accession No. 104038 is one of the examples of such better *O. glaberrima* lines newly identified. The line apparently showed better initial growth than CG 14 (unpublished data) and its growth duration was 19 days and 6 days shorter than CG 14 and NERICA 8 possessing the earliest maturity among the eighteen upland NERICA varieties, respectively, with the same seeding date of 22 May 2006 (unpublished data). When improved screening tools are developed for important traits, re-screening of the germplasm already tested should be made too.

Feasibility of intra-specific breeding of *O. glaberrima*

Intra-specific breeding of *O. glaberrima* will be the best way to exploit its unique assets such as multiple resistance to major constraints in WCA and high protein content etc., because fixed fertile progeny can be obtained without suffering from a sterility barrier always cropping out in interspecific breeding. However, *O. glaberrima* seems to have several drawbacks when we attempt to develop a commercial variety acceptable in WCA. Genetic variation of amylose content is very narrow (Watanabe *et al.* 2002a); most of *O. glaberrima* lines showed amylose content in between 25 and 27%. Amylose content is a major factor to determine rice texture and consequently taste. Preference for texture is ranging in WCA. Different studies were conducted with landraces from Africa and NERICAs lines from NERICA 1 to NERICA 7 (Traoré 2005). Results showed tremendous variability for cooking, sensorial and nutritional values of African germplasm. Different classes of amylose content were found within upland NERICA varieties. NERICA 1 had aroma. Different classes of cooking time, and protein contents were found among interspecific progenies and landraces. Results from the studies conducted by Kishine *et al.* (2008) confirmed the findings of Traoré (2005) and concluded that NERICA varieties with high amylose content (29%) have the gene derived from the *glaberrima* parents while the lower amylose content (22%) varieties had the gene from the sativa parents. Watanabe *et al.* (2002b) studied *O. glaberrima* lines, interspecific progenies and *O. sativa* lines and concluded that the progenies were superior to the *O. glaberrima* parent based on the following traits: husking yield, milling yield, whiteness and translucency of milled rice. Low yield is sometimes listed up as a cause of the decline of *O. glaberrima*'s cultivated area in the sub-region (Linares 2002). Low yield of *O. glaberrima* is caused by grain shattering and lodging enhancing grain shattering; the sink capacity of *O. glaberrima* estimated by the spikelet number is not inferior to that of *O. sativa* (Dingkuhn *et al.* 1998). We obtained yield of more than 5 tonne/ha in irrigated lowland in the dry season cropping at AfricaRice's experimental field in Côte d'Ivoire (Futakuchi and Jones 2005). Yield potential of this species will not become an obstacle to develop acceptable varieties by farmers. To achieve it, however, we should identify *O. glaberrima* lines resistant to lodging and grain shattering. The screening of *O. glaberrima* lines in this regard has already been commenced. However, lines possessing strong resistance to lodging have not yet been identified (Futakuchi *et al.* 2008).

CHALLENGES

Although major advances have been made in improving the rice and transfer of technology to farmers, much remains to be done to achieve food self-sufficiency and for the local African rice to be competitive in world markets. Regarding the responsibility of Program 1 of AfricaRice, particular emphasis will be placed on:

- A more thorough characterization of *O. glaberrima* germplasm to better exploit this reservoir of genes for tolerance / resistance to environmental stresses;
- A better use of rice genetic heritage preserved in the genebank of the Center through the increasing use of local ecotypes of *O. glaberrima* and other wild materials;
- Greater use of molecular tools in breeding programs to reduce the cost of breeding; Better management of the production of quality seeds and distribution to ensure a constant availability;
- The technical capacity of NARS, extension workers and farmers to take over from the breeders in national programs;
- More research efforts on improving post-harvest operations to make available to producers of alternative rice production of better quality; and
- Strengthen work on grain quality through improving the nutritional value of new varieties (protein content, organoleptic and culinary).

The major challenge facing SSA to achieve sustainable food self-sufficiency is to reduce the gap between actual yields and potential yields. And this could be achieved by better exploitation of lowland (rainfed and irrigated), which contain enormous potential of extensification and intensification. Only 10-25% of lowland is currently used for rice (Defoer *et al.* 2002). In addition to the expansion of acreage, improved water management and crop management in this ecology would achieve returns much higher than current yields (Touré *et al.* 2009; Yang and Zhang 2010; Sudhir *et al.* 2011).

CONCLUSION

In the concept of the interspecific breeding of AfricaRice, what was expected from *O. glaberrima* was adaptability to rice growing environments in WCA. However, NERICA was yet to be rivalling with *O. glaberrima* in some traits related to the adaptability such as weed competitiveness. In addition to those traits of *O. glaberrima* which were already focused in varietal development, attention was paid to new characteristics of *O. glaberrima*, introduction of which could improve the performance of existing NERICA varieties; such examples were multiple resistance of a single line to various local constraints in WCA and an extremely large number of panicles compared to *O. sativa*. As seen in the latter example, *O. glaberrima* also possessed advantageous characteristics to yield generation as well as adaptability to local environments in spite of the initial concept of the interspecific breeding at AfricaRice.

Intra-specific breeding of *O. glaberrima* is also a feasible approach to exploit unique and useful characteristics of this species, although a wide cross to *O. sativa* to develop NERICA will still be a strong tool to obtain better varieties. Low yielding ability of *O. glaberrima*, which has sometimes been regarded as the character of this species, will not be an obstacle in the intra-specific breeding since its yield potential estimated from the spikelet number was not inferior to that of *O. sativa*. However, some grain quality characteristics of *O. glaberrima*, especially its narrow genetic variation in amylose content, may hinder the development of commercial varieties in *O. glaberrima*.

REFERENCES

Africa Rice Center (WARDA) (2005) *Annual Report for 2003–2004*, Africa Rice Center WARDA), Cotonou, Benin, 53 pp

Africa Rice Center (WARDA) (2008) *2007 Africa Rice Trends*. Africa Rice Center (WARDA), Cotonou, Benin, 74 pp

Audebert A (2006a) Rice yield gap due to iron toxicity in West Africa. In: Audebert A, Narteh LT, Kiepe P, Millar D, Beks B (Ed) *Iron Toxicity in Rice-based Systems in West Africa*, Africa Rice Center (WARDA). Cotonou, Benin, pp 47-63

Audebert A (2006b) Morpho-physiological characteristics in rice related to drought adaptation mechanisms in *Oryza glaberrima, Oryza sativa* and Nerica. In; *the CIAT Seminar*, 24 January, 2006, CIAT, Cali, Columbia. Available online: http://www.ciat.cgiar.org/training/pdf/060125_morpho_physiological_charact_in_rice.pdf

Coyne D, Plowright R, Jones MP (1995) The African rice *Oryza glaberrima* provides nematode resistance for interspecific hybrids. In: WARDA (Ed) *WARDA Annual Report for 1994*, WARDA, Bouaké, Côte d'Ivoire, pp 66-67

Defoer T, Wopereis MCS, Jones MP, Lançon F, Erenstein O (2002) Challenges, innovation and change: towards rice-based food security in sub-Saharan Africa. In: *Proceedings of the 20th Session of the International Rice Commission*, 23-25 July, 2002, Bangkok, Thailand. Available online: http://www.fao.org/DOCREP/006/Y4751E/y4751e0p.htm

Diatta S, Sahrawat KL (2002) Iron toxicity of rice in West Africa: Screening tolerant varieties and the role of N, P, K and Zn. In: Audebert A, Narteh LT, Kiepe P, Millar D, Beks B (Eds) *Iron Toxicity in Rice-based Systems in West Africa*, Africa Rice Center (WARDA). Cotonou, Benin, pp 75-81

Dingkuhn M, Johnson DE, Sow A, Audebert AY (1999) Relationship between upland rice canopy characteristics and weed competitiveness. *Field Crops Research* **61**, 79-95

Dingkuhn M, Jones MP, Johnson DE, Sow A (1998) Growth and yield potential of *Oryza sativa* and *O. glaberrima* upland rice cultivars and their interspecific progenies. *Field Crops Research* **57**, 57-69

Efisue AA, Gridley HE, Cisse F, De Milliano W (2004) Development of drought tolerant lines for upland rice ecologies in the tropics of Africa: Preliminary results. In: Poland D, Sawkins M, Ribaut JM, Hoisington D (Eds) *Resilient Crops for Water Limited Environments: Proceedings of a CIMMYT/ Drought/Rockefeller Foundation Workshop*, Cuernavaca, Mexico, 24-28 May, 2004, CYMMYT, Mexico City, Mexico, p 94

Futakuchi K (2008) Achievement and outlook in rice research in Africa with special reference to WARDA's activities. *JIRCAS Working Report* **(57)**, 121-135

Futakuchi K, Fofana M, Sié M (2008) Varietal differences in lodging resistance of African rice (*Oryza glaberrima* Steud.). *Asian Journal of Plant Sciences* **7**, 569-573

Futakuchi K, Jones MP (2005) Yield performance of upland interspecific *Oryza sativa*×*O. glaberrima* progenies under different growing ecologies. *Japanese Journal of Crop Science* **74 (Extra Issue 2)**, 34-35

Futakuchi K, Jones MP, Ishii R (2001) Physiological and morphological mechanism of submergence resistance in African rice (*Oryza glaberrima* Steud.). *Japanese Journal of Tropical Agriculture* **45**, 8-14

Futakuchi K, Jones MP, Osiname O (2004) Development of lowland rice from the interspecific cross of *Oryza sativa* and *O. glaberrima*. In: *Proceedings of the 4th International Crop Science Congress*, 26 September – 1 October, 2004, Brisbane, Australia. Available online: http://www.cropscience.org.au/icsc2004/poster/3/4/3/841_futakuchi.htm

Futakuchi K, Sié M (2009) Better exploitation of African rice (*Oryza glaberrima* Steud.) in varietal development for resource-poor farmers in West and Central Africa. *Agricultural Journal* **4**, 96-102

Heuer S, Miézan KM, Sié M, Gaye S (2003) Increasing biodiversity of irrigated rice in Africa by interspecific crossing of *Oryza glaberrima* (Steud.) × *O. sativa indica* (L.). *Euphytica* **132**, 31-40

Johnson DE, Dingkuhn M, Jones MP, Mahaman MC (1998) The influence of rice plant type on the effect of weed competition on *Oryza sativa* and *Oryza glaberrima*. *Weed Research* **38**, 207-216

Jones M, Heinrichs E, Johnson D, Riches C (1994) Characterization and utilization of *Oryza glaberrima* in the upland rice breeding program. In: WARDA (Ed) *WARDA Annual Report for 1993*, WARDA, Bouaké, Côte d'Ivoire, pp 3-13

Jones MP, Dingkuhn M, Aluko GK, Semon M (1997a) Interspecific *Oryza sativa* L.×*O. glaberrima* Steud. progenies in upland rice improvement. *Euphytica* **92**, 237-246

Jones MP, Mande S, Aluko K (1997b) Diversity and potential of *Oryza glaberrima* Steud. in upland rice breeding. *Breeding Science* **47**, 395-398

Kijima Y, Otsuka K, Sserunkuuma D (2008) Assessing the impact of NERICA on income and poverty in central and western Uganda. *Agriculture Economics* **38**, 327-337

Kishine M, Suzuki K, Nakamura S, Ohtsubo K (2008) Grain qualities and their genetic derivation of 7 New Rice for Africa (NERICA) varieties. *Journal of Agriculture and Food Chemistry* **56**, 4605-4610

Linares OF (2002) African rice (*Oryza glaberrima*): History and future potential. *Proceedings of the National Academy of Sciences USA* **99**, 16360-16365

Maji AT, Singh BN, Aken ME, Ova M, Akoroda O, Fawole A (2003) Inheritance of resistance to African rice gall midge in *Oryza glaberrima* Steud. In: Sanyang S, Ajayi A, Sy AA (Eds) *Proceedings of the Second Biennial Regional Rice Research Review (4Rs 2002)*, WARDA, Bouaké, Côte d'Ivoire, pp 87-91

Manneh B, Ndjiondjop MN (2008) Drought screening of upland NERICA varieties. In: Somado EA, Guei RG, Keya SO (Eds) *NERICA®: the New Rice for Africa – a Compendium*, Africa Rice Center (WARDA), Cotonou, Benin; FAO, Rome, Italy; Sasakawa Africa Association, Tokyo, Japan, pp 62-64

Ndjiondjop MN, Albar L, Fargette D, Fauquet CM, Ghesquière A (1999) The genetic basis of high resistance to *Rice yellow mottle virus* (RYMV) in cultivars of two cultivated rice species. *Plant Disease* **83**, 931-935

Ndjiondjop MN, Manneh B, Semon M, Efisue A, Fousseyni C, Futakuchi K, Gridley H, Bocco R, Cissoko M (2007) Gene mining of rice germplasm (*Oryza glaberrima* and *Oryza sativa*) to improve drought resistance in rainfed production systems for resource-poor farmers of Africa. In: *Rockefeller Foundation Meeting on Biotechnology, Breeding and Seed Systems for African Crops: Research and Product Development That Reaches Farmers*, 26-29 March, 2007, Maputo, Mozambique, p 170 (Abstract)

Obilana AB, Okumu BN (2005) *Evaluation Study Report for Interspecific Hybridization between African and Asian Rice Species*, Africa Rice Center (WARDA), Cotonou, Benin, 81 pp. Available online: http://www.warda.org/publications/UNDP%20Report/UNDP%20report.pdf

Sahrawat KL, Sika M (2002) Comparative tolerance of *Oryza sativa* and *O. glaberrima* rice cultivars for iron toxicity in West Africa. *International Rice Research Note* **27**, 30-31

Second G (1982) Origin of the genic diversity of cultivated rice growing environments in West Africa. (*Oryza* spp.): Study of the polymorphism scored at 40 isozyme loci. *Japanese Journal of Genetics* **57**, 25-57

Semagn K, Ndjiondjop MN, Cissoko M (2006) Microsatellites and agronomic traits for assessing genetic relationships among 18 New Rice for Africa (NERICA) varieties. *African Journal of Biotechnology* **5**, 800-810

Semagn K, Ndjiondjop MN, Lorieux M, Cissoko M, Jones M, McCouch S (2007) Molecular profiling of an interspecific rice population derived from a cross between WAB56-104 (*Oryza sativa*) and CG 14 (*Oryza glaberrima*). *African Journal of Biotechnology* **6**, 2014-2022

Semon M, Nielsen R, Jones MP, McCouch SR (2005) The population structure of African cultivated rice *Oryza glaberrima* (Steud): Evidence for elevated levels of linkage disequilibrium caused by admixture with *O. sativa* and ecological adaptation. *Genetics* **169**, 1639-1647

Séré Y, Sy AA, Akator SK, Onasanya A, Zai K (2004) Screening strategy for durable resistance to rice blast disease at WARDA. In: Séré Y, Sreenivasaprasad S, Nutsugah SK (Eds) *Rice Blast in West Africa: Characterization of Pathogen Diversity, Key Screening Sites and Host Resistance*, The Africa Rice Center (WARDA), Bouaké, Côte d'Ivoire, pp 38-43

Sié M, Kaboré B, Sérémé D, Moukoumbi YD (2004) Selection of intra-specific (*Oryza sativa*×*O. sativa*) and inter-specific (*O. sativa*×*O. glaberrima*) lines for their tolerance to blast in Burkina Faso. In: Séré Y, Sreenivasaprasad S, Nutsugah SK (Eds) *Rice Blast in West Africa: Characterization of Pathogen Diversity, Key Screening Sites and Host Resistance*, The Africa Rice Center (WARDA), Bouaké, Côte d'Ivoire, pp 23-37

Sié M, Dogbe SY, Coulibaly M (2005) Selection of interspecific hybrids (*O. sativa*×*O. glaberrima* or lowland NERICAs and intraspecifics adapted to rainfed lowland growing conditions. *International Rice Commission Newsletter* **54**, 47-51

Sié M, Séré Y, Sanyang S, Narteh LT, Dogbe S, Coulibaly MM, Sido A, Cissé F, Drammeh E, Ogunbayo SA, Zadji L, Ndri B, Toulou B (2008) Regional yield evaluation of the interspecific hybrids (*O. glaberrima* × *O. sativa*) and intraspecific (*O. sativa* × *O. sativa*) lowland rice. *Asian Journal of Plant Sciences* **7**, 130-139

Singh BN, Fagade S, Ukwungwu MN, Williams C, Jagtap SS, Oladimeji O, Efisue A, Okhidievbie O (1997) Rice growing environments and biophysical constraints in different agroecological zones of Nigeria. *Meteorology Journal* **2**, 35-44

Somado EA, Guei RG, Nguyen N (2008) Overview: Rice in Africa. In: Somado EA, Guei RG, Keya SO (Ed) *NERICA®: The New Rice for Africa – a Compendium*, Africa Rice Center (WARDA), Cotonou, Benin; FAO, Rome, Italy; Sasakawa Africa Association, Tokyo, Japan, pp 1-9

Sudhir Y, Gurjeet G, Humphreys E, Kukal SS, Walia US (2011) Effect of water management on dry seeded and puddled transplanted rice. Part 1: Crop performance. *Field Crops Research* **120**, 112-122

Tobita S, Sahrawat KL, Diatta S, Jones MP (2003) Response of African rice (*Oryza glaberrima* Steud.) to phosphate application in the upland of a P-deficient soil in the humid forest zone of West Africa. In: *Proceedings of the 2nd International Symposium on Phosphorus Dynamics in the Soil-Plant Continuum*, 21–26 September, 2003, Perth, Western Australia, Australia, pp 70-71

Touré A, Becker M, Johnson DE, Kone B, Kossou DK, Kiepe P (2009) Response of lowland rice to agronomic management under different hydrological regimes in an inland valley of Ivory Coast. *Field Crops Research* **114**, 304-310

Traoré K (2005) Characterization of novel rice germplasm from West Africa and genetic marker associations with rice cooking quality. Ph.D. Dissertation, Texas A&M University, xv + 195 pp

Wang Z, Second G, Tanksley S (1992) Polymorphism and phylogenetic relationship among species in the genus *Oryza* as determined by analysis of nuclear RFLPs. *Theoretical and Applied Genetics* **83**, 565-581

WARDA (1989) *Annual Report for 1988*, West African Rice Development Association, Bouaké, Côte d'Ivoire, 48 pp

WARDA (1996) *Annual Report for 1995*. West African Rice Development Association, Bouaké, Côte d'Ivoire, 69 pp

WARDA (2001) *Rice Interspecific Hybridization Project: Research Highlights 2000*. WARDA, Bouaké, Côte d'Ivoire, 36 pp

WARDA (2002) *Annual Report for 2001–2002*. West African Rice Development Association, Bouaké, Côte d'Ivoire, 103 pp

Watanabe H, Futakuchi K, Jones MP, Teslim I, Sobambo BA (2002a) Brabender Viscogram characteristics of interspecific progenies of *Oryza glaberrima* Steud and *O. sativa* L. *Nippon Shokuhin Kagaku Kogaku Kaishi (Journal of the Japanese Society for Food Science and Technology)* **49**, 155-165

Watanabe H, Futakuchi K, Teslim I, Sobambo BA (2002b) Milling characteristics and grain quality traits of interspecific progenies of Asian rice (*Oryza sativa*) with African rice (*Oryza glaberrima*). *Japanese Journal of Tropical Agriculture* **46**, 47-55

Windmeijer PN, Duivenbooden NV, Andriesse W (1994) *Characterization of Rice-Growing Agro-Ecosystems in West Africa: Semi-Detailed Characterization of Inland Valleys in Côte d'Ivoire*, SC-DLO-Wageningen Agricultural University, Wageningen, The Netherlands, 129 pp

Yang J-C, Zhang J-H (2010) Crop management techniques to enhance harvest index in rice. *Journal of Experimental Botany* **61**, 3177-3189