Upland (aerobic) rice breeding for the harsh environment of the High Plateau of Madagascar

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Abstract

Rice is the staple crop and food in Madagascar, where further expansion of new irrigated lowland rice fields is almost impossible. The challenge is to intensify lowland rice cultivation and to develop new efficient and sustainable rice-based production systems for upland conditions. Blast populations have overcome the resistance of the first set of released varieties causing heavy losses, especially within intensified rice cropping systems. The cold and humid conditions of the High Plateau increase the risk of panicle sterility and favor blast epidemics. The breeding program has therefore focused on widening the genetic base with emphasis on blast tolerance through introduction of new genetic resources, as well as further investigation of the local genetic diversity. Nepalese traditional lowland landraces well adapted to cold environments and altitude, such as Jumli Marshi or Chhomrong Dhan, with the latter performing particularly well in upland conditions, have been used as parents. A mixture of breeding strategies — bi-parental crosses, recurrent population improvement and marker-assisted backcrosses to introgress the three blast-resistance genes (*Pi1*, *Pi2*, *Pi33*) into susceptible varieties FOFIFA 154 and FOFIFA 152 — is being implemented with the objective of creating new adapted, blast-resistant varieties. No-tillage cropping systems on mulches from crop residue and integrated pest management strategies for upland rice cultivation are also under investigation for sustainability in this extreme and fragile ecosystem. Upland lines developed in Madagascar have already been successfully evaluated in the highlands of Andean areas of Colombia and Bolivia.

Introduction

The Vakinankaratra region of the Madagascar central High Plateau is the most densely populated (more than 80 inhabitants/km^2) area of the country. Smallholders (with an average of 0.6 ha of irrigated fields and 0.7 ha of upland fields) traditionally grow irrigated or rainfed lowland rice, mostly landraces, wherever possible, in inland valleys and terraces on hillsides. But there are almost no further possibilities for expanding lowland rice cultivation. Thus, the challenge to meet the growing demand for rice relies on the intensification of lowland rice cultivation and on the development of new rice-based production systems. In the mid-1980s, Centre de coopération internationale en recherche agronomique pour le développement (CIRAD) and Centre National de Recherche Appliquée au Développement Rural (FOFIFA) launched a research program for the highlands with the aim of pushing forward the frontier of upland rice growing in high-elevation areas. This led to the release, in the early 1990s, of new upland rice varieties suitable for cultivation at high altitude on the hillsides ('Tanety') where farmers used to grow maize, beans and cassava. As early as 4 years after the nomination of the first new varieties, a survey showed that more than 1500 ha were already cultivated with upland rice at altitudes above 1250 m, as a result of a vast network of on-farm trials and participatory evaluation. The same survey indicated that more than 9000 farmers (about 10% of the total in the target area) had adopted upland rice cultivation (Galtier and Guimera, 2000). Upland rice is now part of the Madagascar highland's landscape and creates new breeding challenges.

During the first phase of the breeding program (1988–1995), more than 200 crosses were performed drawing extensively on a local population of temperate *japonica* (the Latsika family) as the cold-tolerance donor. Progenies of these crosses were selected by pedigree method at 1500 m altitude (Déchanet *et al.*, 1997; Dzido *et al.*, 2004). This first set of varieties adapted to the climatic conditions of the High Plateau had a fairly good yield potential (over 6 t/ha) but a narrow genetic base. Therefore, populations of *Magnaporthe oryzae*, the fungus causing blast disease, rapidly adapted to these varieties, which were highly susceptible to infection. Moreover, the cool and humid conditions of the High Plateau, beside their consequences on panicle sterility, favor blast epidemics. Blast, particularly neck blast, provokes heavy losses by preventing grain filling, especially when inorganic nitrogen is applied. Unfortunately, the poor economic situation of farmers in Madagascar prevents them from using pesticides.

In 2003, a new breeding program was launched to develop varieties that combine cold tolerance and blast resistance. Since then, more than 200 new crosses have been made and improved materials are expected. In this

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paper, we present the state of the upland rice extension in the Vakinankaratra region of Madagascar and the work of the FOFIFA breeding program.

Conditions of the High Plateau

Climatic constraints

The High Plateau is characterized by the alternation of a hot rainy season from November to April and a cold dry season from May to October.

Altitude has a strong effect on mean temperatures, which decrease by 0.6°C every 100 m. Mean temperatures at 1650 m in Antsirabe, the main town of Vakinankaratra (Fig. 1 and 3) range from 17.9°C in October, at the beginning of the rice-sowing period, to close to 20°C during the reproductive stage. Minimum temperatures can fall below 10°C during early vegetative stage and are below 15°C during the reproductive stage and grain filling. The night–day thermal amplitude is high (10–12 degrees) during the whole rice-growing season. Low temperatures slow rice growth at almost all stages: panicle initiation is delayed and grain-filling and maturation stages are lengthened (Table 1; Ramanantsoanirina *et al.*, 2009). Cold during the reproductive stage may provoke high sterility rate (Chabanne and Razakamiaramanana, 1997).

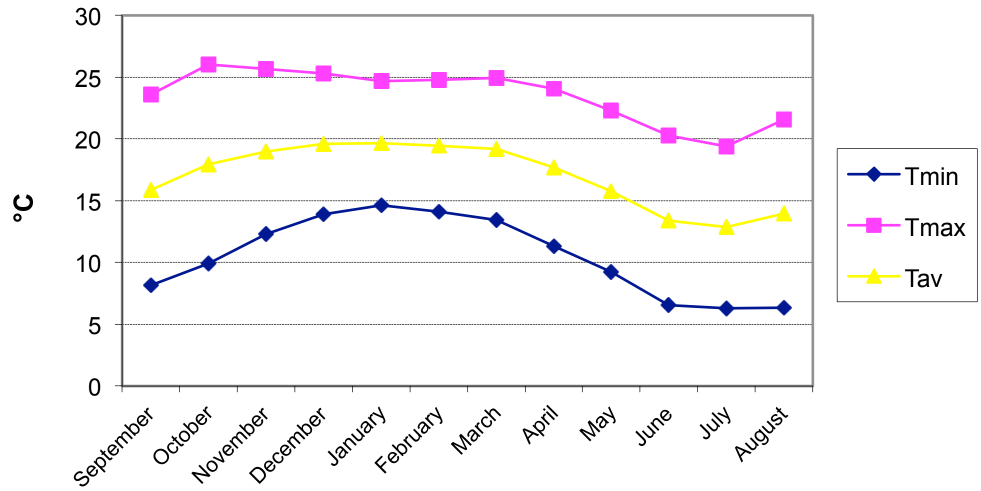

Figure 1. Average temperatures per month over the period 2002–2009 in Antsirabe (1650 m)

Table 1. Effect of altitude on the crop duration (days to flowering) of three upland rice varieties released in Madagascar

Variety	Ivory (900 m)	Antsirabe (1650 m)
Chhomrong Dhan	89.1	118.5
FOFIFA 161	86.9	111.9
FOFIFA 172	81.7	109.7

Annual rainfall ranges from 1300 to 2000 mm depending on year and altitude. In our main breeding station close to Antsirabe at 1650 m altitude asl (above sea level), the average annual rainfall is 1460 mm over the period 2002–2009 (Fig. 2). The rainiest months at this altitude are December and January. Hailstorms are frequent in the High Plateau and can cause severe losses at harvest time. The often erratic beginning of the rainy season may prevent or put at risk the early establishment of the crop.

Blast disease

Rice blast, caused by *Magnaporthe oryzae*, is the fungus disease that causes the most damage to rice production in the world. Blast pressure is particularly high in the upland conditions of the High Plateau. Most of the early released upland varieties became highly susceptible to blast. The two varieties that contributed to the fast development of upland rice in the Vakinankaratra region, FOFIFA 152 and FOFIFA 154, have been withdrawn from the seed production because of their susceptibility that can sometimes cause almost complete yield loss. The resistance patterns of differential varieties (with known resistance genes) to the blast populations present in

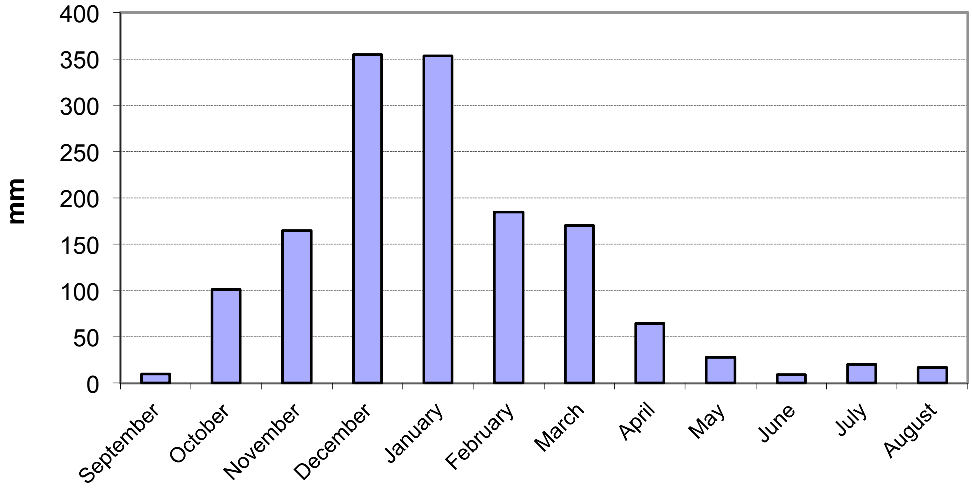

Figure 2. Average rainfall per month over the period 2002–2009 in Antsirabe (1650 m)

the two main breeding sites in Vakinankaratra region are presented (Table 2). The two patterns are very similar and reveal a set of efficient resistance genes that are not yet overcome and thus could be worth using.

Table 2. Resistance patterns to blast disease of differential varieties in two FOFIFA rice-breeding stations in Vakinankaratra region

Variety	R gene	Ansirabe (1600 m)†	Ivory (900 m)†
75-1-127	*9*	1	1
C 101 A51	*2=z5*	2	1–2
C 101 lac	*1+1b+33*	2	2
C 104 lac	*1*	6	6
Co 39	—	6	6
CT 13432-3R	*1+2+33*	1	1
Fujisaka No. 5	*1+ks*	6	3–4
Fukunishiki	*sh+z*	5	3
IR 1529	*33*	2	1
K1	*ta*	3	4–5
K2	*kp+a*	6	5–6
K3	*kh*	6	5–6
K59	*t*	4	4
K60	*kp*	4	3
Kanto 51	*k*	6	5
Pi no. 4	*ta2*	2	1
Toride 1	*zt*	2	1
Zenith	*a+z*	4	5–6

† Lesion types on rice leaves were scored 1 (no symptoms) to 6 (typical susceptible lesions) according to the standard reference scale (Silué *et al.*, 1992).

Where we stand

Released varieties

Since 1994, fifteen upland rice varieties adapted for high altitude have been sequentially released (Table 3). Among these varieties, FOFIFA 152 and 154 became particularly popular at the country level. However, their cultivation is no longer recommended in the High Plateau, due to the emergence of new blast strains that have overcome their resistance, but they are still widely cultivated in other areas of the country (Table 4). The last released variety, FOFIFA 172, has a yield potential of 7 t/ha and is resistant to all blast strains currently prevailing in the region. As one of the parents of this variety is an offspring of IRAT 13 — a variety known for its high level of partial resistance to blast — we expect it to have a more durable resistance. The durability of its resistance will be carefully monitored in the seed production chain and in farmers' fields. Another variety gaining momentum is Chhomrong Dhan, a Nepalese variety selected from a landrace well adapted to the cold conditions of high altitude in Nepal. This irrigated variety is well adapted to upland conditions, as drought

Table 3. Upland rice varieties released by FOFIFA–CIRAD for the High Plateau region of Madagascar, 1994–2006

Name	Released	Blast resistance	Female parent	Origin of female parent	Male parent	Origin of male parent	Diffusion
FOFIFA 133	1994	Highly susceptible	Latsidahy	'Latsika' high-altitude irrigated landrace	FOFIFA 62	Daniela (Brazil) × IAC 25 (Brazil)	Abandoned
FOFIFA 134	1994	Highly susceptible	Latsidahy	'Latsika' high-altitude irrigated landrace	FOFIFA 62	Daniela (Brazil) × IAC 25 (Brazil)	Abandoned
FOFIFA 151	1995	Tolerant	Latsidahy	'Latsika' high-altitude irrigated landrace	Shin Ei	Japan	Abandoned
FOFIFA 152†	1995	Highly susceptible	Latsidahy	'Latsika' high-altitude irrigated landrace	FOFIFA 62	Daniela (Brazil) × IAC 25 (Brazil)	Abandoned
FOFIFA 153	1995	Highly susceptible	Latsibavy	'Latsika' high-altitude irrigated landrace	Daniela	Upland variety from Brazil	Abandoned
FOFIFA 154†	1995	Highly susceptible	Latsibavy	'Latsika' high-altitude irrigated landrace	FOFIFA 62	Daniela (Brazil) × IAC 25 (Brazil)	Abandoned
FOFIFA 157	2000	Susceptible	Latsidahy	'Latsika' high-altitude irrigated landrace	FOFIFA 62	Daniela (Brazil) × IAC 25 (Brazil)	Abandoned
FOFIFA 158	2000	Highly susceptible	FOFIFA 62	Daniela (Brazil) × IAC 25 (Brazil)	Shin Ei	Japan	Abandoned
FOFIFA 159	2000	Susceptible	IRAT 114	Upland variety from Côte d'Ivoire	FOFIFA 133		Wide
FOFIFA 161	2003	Susceptible	IRAT 114	Upland variety from Côte d'Ivoire	FOFIFA 133		Wide
FOFIFA 167	2005	Tolerant	CA 148		Shin Ei	Japan	Limited
FOFIFA 168	2005	Susceptible	Latsidahy	'Latsika' high-altitude irrigated landrace	FOFIFA 62	Daniela (Brazil) × IAC 25 (Brazil)	Limited
FOFIFA 169	2005	Highly susceptible	Pratao Precoce	Upland variety from Brazil	Daniela	Upland variety from Brazil	Abandoned
FOFIFA 171	2006	Tolerant	Chhomrong Dhan	Selected in Nepal from a landrace of Indian origin	SLIP 48-M-1‡[b]	Chokoto (Taiwan) × IDSA 85 (Côte d'Ivoire)	Starting
FOFIFA 172	2006	Resistant	IRAT 265	IRAT 112 × IRAT 13 (upland, Côte d'Ivoire)	Jumli Marshi	Nepal	Starting
Chhomrong Dhan	2006	Tolerant	Selected in Nepal from a high-altitude irrigated landrace of Indian origin (Sthapit *et al.*, 1996)				Spontaneous and fast

[a] Still cultivated, especially in blast-free areas; good varieties with long grains.
[b] SLIP selected line from former IDESSA phytopathology department.

Table 4. Characteristics and agronomic performances of some varieties over 5 years in varietal trials conducted at 1650 m altitude

Name	Grain shape & pericarp color	Blast resist†	Inoculated blast strains										Main varietal trial at 1650 masl					Max. yield observed (t/ha)
			MD824	MD908	MD978	MD983	MD1032	MD1098	MD909	MD979	MD971		2009	2008	2007	2006	2005	
Chhomrong Dhan	Medium Red	4.5	S	S	S	MS	R	MS	MR	MR	MS	Yield (t/ha)	4.9	2.3				7.5
												DTF	121	122				
												Ht (cm)	106	93				
FOFIFA 172	Medium Red	0	R	R	R	R	R	R	MR	R	R	Yield (t/ha)	4.5		2.7	3.25		7.5
												DTF	112		107	125		
												Ht (cm)	76		70	71		
FOFIFA 171	Medium Red	2.5	S	S	MS	S	R	S				Yield (t/ha)					4.1	6.1
												DTF					119	
												Ht (cm)					94	
FOFIFA 167	Medium White	3.5	S	S	S	S	R	S				Yield (t/ha)			2.5	2.77	4.4	6.1
												DTF			122	134	119	
												Ht (cm)			81	93	108	
FOFIFA 161	Medium White	12.5	MS	MS	S	S	R	S				Yield (t/ha)		1.1	2.5	2.53	4.0	6.6
												DTF		117	112	125	109	
												Ht (cm)		74	67	76	81	
FOFIFA 154	Slender White	27.5						S	S	MS	S	Yield (t/ha)				0.3‡	0.5‡	9
												DTF				125	104	
												Ht (cm)				71	65	

† Blast evaluation: percentage of leaf service covered by blast lesions (field evaluation, 2007).
‡ High sterility rate caused by panicle blast.
DTF, days to Flowering Ht, plant height.

stress is not a major constraint. While the variety was still undergoing on-station evaluation trials, it aroused the interest of neighboring farmers who started cultivating it before its official release in 2006. Chhomrong Dhan outperforms most other released varieties when grown above 1500 m altitude, except for FOFIFA 172 (Table 4). It is spreading very fast in Vakinankara region.

The upland varieties developed in Madagascar have already been successfully evaluated in the highland areas of the Andeas in Colombia and Bolivia at altitudes up to 1600 m asl. These materials should also be of interest for many mountainous countries of the east African rift valley. Like in Madagascar, upland rice may represent an interesting diversification strategy to address the increasing demand for rice.

Diffusion of upland rice cultivation in Vakinankaratra region

Before the release of the first FOFIFA varieties especially developed for the High Plateau, upland rice was almost absent in the high-elevation area of Vakinankaratra region. Farmers occasionally practised upland rice cultivation using a lowland Japanese variety Kagoshima Hakamuri or traditional tropical *japonica* varieties such as Botramaintso and improved tropical *japonica* varieties adapted to altitudes below 1000 m, with very poor results (Vales *et al.*, 1997). The release of the new cold-tolerant upland rice varieties lived up to farmers expectations of rice varieties suited for altitudes above 1250 m. As a consequence, the development of upland rice cultivation was fast and successful among farmers, especially in Vakinankaratra area where most of the research and extension efforts were carried out.

A survey in 2000 (Galtier and Guimera, 2000) revealed that at least 10% of farmers in Vakinankaratra region had started cultivating upland rice. A second survey carried out during the 2005/06 crop season showed that upland rice cultivation was present in 62% (16) of the 26 villages surveyed at altitudes above 1250 m. Likewise, 36% of farmers in those 26 villages (301 farmers out of 843 surveyed) cultivated upland rice (Fig. 3). The spatial distribution of the villages practising upland rice cropping is heterogeneous. No upland rice-growing village was recorded in the north of the region. The most frequently cultivated variety was FOFIFA 154 (cultivated on 155 farms out of 301), followed by FOFIFA 133 (66 farms), FOFIFA 134 (31 farms) and FOFIFA 152 (20 farms).

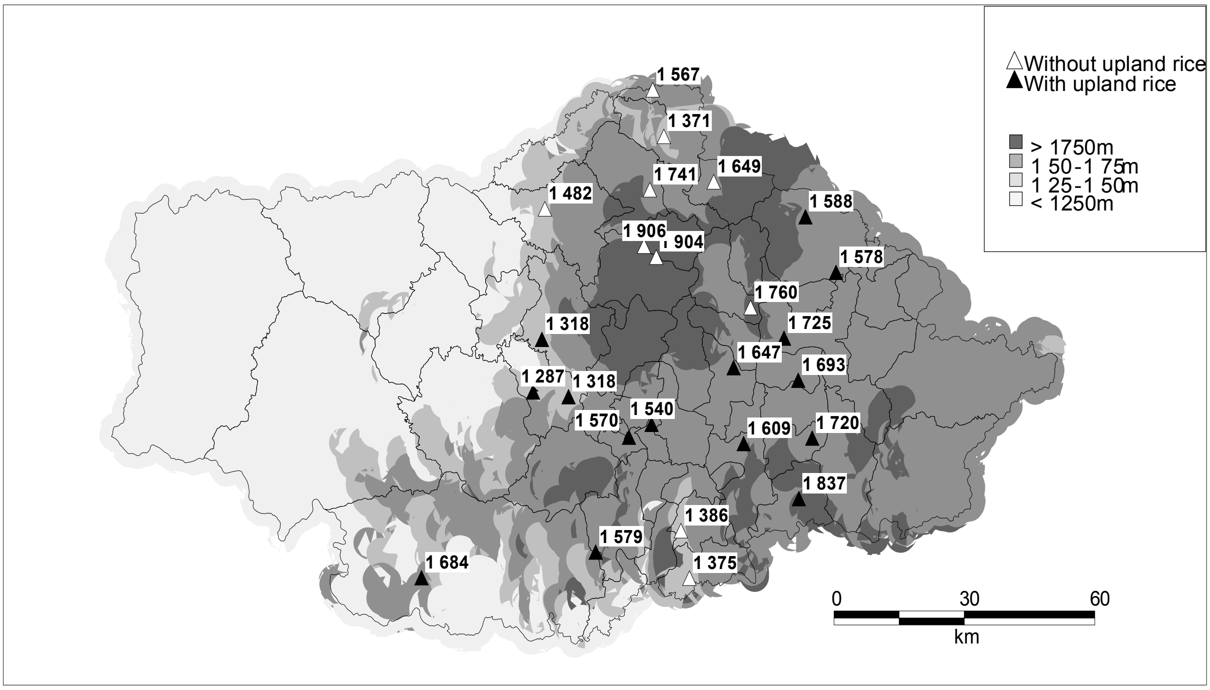

Figure 3. Presence or absence of upland rice in 26 villages of Vakinankaratra region (altitude >1250 m) during the 2005/06 crop season (Radanielina, 2010)

The circle represents Antsirabe zone where most of the breeding work is carried out.

However, these numbers are probably already out-dated. Blast pressure and the release of new varieties may have decreased the share of the old varieties throughout the region (as we have observed in the villages near our 1650-m altitude research station). In particular, Chhomrong Dhan has been spreading fast and spontaneously since 2007. Fifteen years after the release of the first 'high altitude' varieties, upland rice was 'everywhere' in the landscape, but (unfortunately) no reliable data exist on the exact area covered by this new rice cropping system.

Upland rice breeding program for high-altitude areas

Pedigree breeding

Since 2003, more than 200 crosses have been made. The most frequently used parents are listed (Table 5). Although the main objectives are tolerance to low temperatures at altitudes above 1250 m and durable resistance to blast, crosses have also been made for the improvement of grain quality. Indeed, except for FOFIFA 154 and FOFIFA 152, all varieties released for high elevation have intermediate-shaped grains. FOFIFA 171, FOFIFA 172 and Chhomrong Dhan have red pericarp. The program relies on a rather narrow genetic base for altitude adaptation, with the recurrent use of high-altitude FOFIFA varieties or the frequent use of two Nepalese varieties (Chhomrong Dhan and Jumli Marshi).

We are working to enlarge this genetic base through the introduction of new material, but very few are adapted to high-altitude conditions. For example, NERICA 1 to 6 all presented high sterility rates above 85% when evaluated at 1650 m asl. Likewise, among 160 lines introduced from International Rice Research Institute (IRRI), International Center for Tropical Agriculture (CIAT) and the Yunnan Academy of Agricultural Sciences (China) in 2006, only one line had good spikelet fertility. This line, IRBLZ5-CA from IRRI's 31st blast nursery, carrying the *Pi2* blast-resistance gene, yielded 4.7 t/ha at 1650 m altitude (92% of Chhomrong Dhan control) and has a short duration — 109 days to 50% flowering compared to 129 days for Chhomrong Dhan. Subsequently, new varieties were introduced from Nepal, including Palung 2, Chandannath 3 and Macchapuchhre 3 that are released varieties for high hill areas of Nepal (>1500 m). Moreover, an extensive prospection and collection carried out in Vakinankaratra region identified, in three villages above 1700 m, a group of landraces ('Rojokirina') distinct from the Latsika population that could therefore constitute a new source of diversification for high-altitude adaptation (Radanielina, 2010).

The breeding scheme is a classic pedigree selection scheme (Fig. 4). Every year, 30 crosses are made in the greenhouse. During the rainy season, F_1 plants are grown in an irrigated field (where we also conduct our germplasm collections) at 1500 m altitude. At the end of the rainy season in May, after harvesting of F_2 seeds, F_1 plants are transferred (vegetative multiplication through tiller separation and transplantation) to a mid-altitude station (900 m) for an off-season crop cycle that allows us to produce additional F_2 seeds for the most interesting combinations.

Every year, 50 000 F_2 plants are evaluated in our main breeding station at 1650 m. An additional 25 000 F_2 plants from crosses targeting low-elevation areas are also evaluated in our mid-altitude breeding station at 900 m. Given the importance of the blast problem, as early as F_2 generation, selection is performed under high blast pressure created by a combination of inoculum spreader rows of three susceptible varieties (FOFIFA 152, FOFIFA 154 and Rojofotsy) according to a modified DITER design described by Notteghem *et al.* (1980). The most promising lines are evaluated for cold tolerance (moderate increase of duration and spikelet fertility) at our very-high-altitude trial site at 1800 m.

As soon as possible, the breeding material is evaluated under the agronomic practices guided by the conservation-agriculture approach that FOFIFA's agronomists developed and promote. At 900 m, the breeding scheme is performed entirely under a no-tillage cropping system (direct seeding under the mulch of the rotation crops: maize associated with *Vigna*). By contrast, at 1650 m, where the direct-seeding approach is much more difficult to manage, only promising fixed lines (F_6 or F_7) are evaluated for adaptation to different cropping systems. In this case, the performance of the breeding lines under conventional tillage is compared with that under a no-till system with direct seeding on the mulch of the previous crop residues. The progress of the breeding program is formally presented to official extension services, NGOs and farmers' organizations during an annual meeting. Likewise, the nomination of a new variety and the decision to officially release it are made in close dialogue with those partners.

Population improvement through recurrent selection

Recurrent population improvement allows the management of wide variability through the simultaneous recombination of many genotypes. It is a long-term strategy that progressively increases the frequency of favorable alleles for one or more target traits (Châtel and Guimarães, 1997). We are currently developing a new recombinant population for adaptation to high altitude. A population from CIAT (PCT 11) segregating for a recessive male-sterility gene has been crossed with six donors (Chhomrong Dhan, FOFIFA 172, FOFIFA 167, FOFIFA 154, EXP 206, EXP 304) for adaptation to high altitude and with one Brazilian variety (Primavera) that performs well at mid-altitude and has potentially useful grain characteristics. These crosses were conducted in the field in 2007. Crossing plots were isolated with a 5-m maize border. Rows of the pollinator variety were interspersed with rows of the population PCT11 (source of male sterility). Only male-sterile plants of PCT 11 were allowed to flower and were harvested. The pollinator varieties were sown at different dates in order to encompass the flowering period of the population. In 2008, all seven hybrid seeds obtained were selfed. A first

Table 5. Most frequently used parents in 'high-altitude targeted' crosses of FOFIFA–CIRAD breeding program since 2003

Variety	No. times crossed	Origin	Expected characteristics
Chhomrong Dhan	40	Nepal	Adaptation to high altitude and blast tolerance
FOFIFA 154	36	Madagascar breeding program	Adaptation to high altitude and grain character
FOFIFA 152	34	Madagascar breeding program	Adaptation to high altitude and grain character
FOFIFA 169	24	Madagascar breeding program	Adaptation to high altitude
FOFIFA 161	22	Madagascar breeding program	Adaptation to high altitude
FOFIFA 167	21	Madagascar breeding program	Adaptation to high altitude and blast tolerance
FOFIFA 172	20	Madagascar breeding program	Adaptation to high altitude and blast tolerance
Jumli Marshi	16	Nepal landrace	Adaptation to high altitude
Sucupira	15	Bouzinac *et al.* (2009)	Grain character and blast resistance
CT 134/32	14	CIAT (Correa-Victoria and Martinez, 2009)	Blast resistance (*Pi1*, *Pi2*, *Pi33*)
Sebota 330	13	Bouzinac *et al.* (2009)	Grain character and blast resistance
Moroberekan	11	West African upland cultivar	Durable blast resistance due to a complex of partial and complete resistance genes (Wang *et al.*, 1994)
FOFIFA 133	11	Madagascar breeding program	Adaptation to high altitude
FOFIFA 157	11	Madagascar breeding program	Adaptation to high altitude
PRA C630-38	11	Madagascar breeding program	Grain character
Sebota 281	8	Bouzinac *et al.* (2009)	Grain character and blast resistance
FOFIFA 159	8	Madagascar breeding program	Adaptation to high altitude
Sebota 36	8	Bouzinac *et al.* (2009)	Grain character and blast resistance
Espadon	7	Unknown	Grain character
Rojokirina mena	8	Madagascar irrigated landrace	New parent for high-altitude adaptation
IRBLZ5-CA	6	31st IRRI blast nursery	New parent adapted for high-altitude and upland conditions; blast resistant; LTH†/C101A51/3*LTH
Palung 2		Nepal	New parent for high-altitude adaptation
Chandannath		Nepal	New parent for high-altitude adaptation
Machhapuchhare 3		Nepal	New parent for high-altitude adaptation

† LTH, Li-Juang-Xin-Tuan-Hei-Gu.

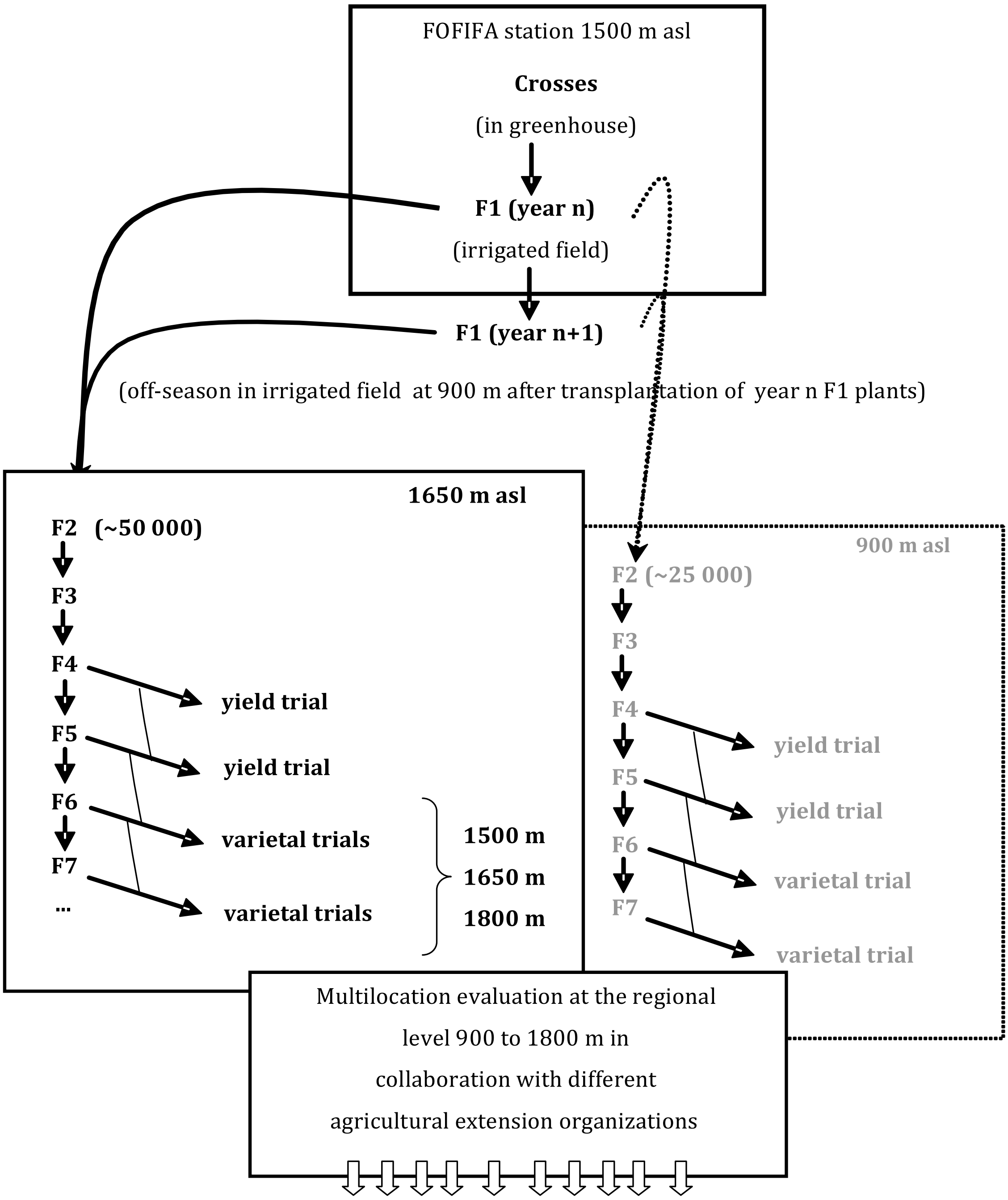

Figure 4. Pedigree selection scheme used

recombination cycle was ongoing during the 2009/10 rice-growing season using a balanced mixture of 'F_2' seeds from the seven initial crosses.

Marker-assisted pyramiding of blast-resistance genes

The combination of the blast resistance genes (*Pi1*, *Pi2*, *Pi33*) confers stable blast resistance after several years of testing under high blast pressure in the field and greenhouse inoculations in Colombia and Latin America (Correa Victoria and Martinez, 2009). In Madagascar, this combination of resistance genes is efficient (Table 2). With the aim of developing durably resistant upland rice cultivars for the High Plateau, we initiated marker-assisted pyramiding of these three blast-resistance genes into two highly susceptible cultivars that used to be popular among farmers (FOFIFA 154, FOFIFA 152). Field evaluation, in 2008, of lines segregating for the different gene combinations indicated that the *Pi1* gene alone is overcome, while *Pi2* gene alone, *Pi33* alone and all combinations of two and three genes are still efficient against the prevailing blast strains. The BC_4F_3 lines homozygous for the resistance allele of the three genes are undergoing field evaluation. Additional backcrosses may be needed to fully recover the phenotype of the recurrent parents.

Conclusions

In Vakinankaratra region, the rice production system has been completely reshaped at altitudes between 1250 and 1800 m, due to the improved upland rice varieties released by the FOFIFA–CIRAD joint program. As upland rice cultivation is gaining momentum, new breeding challenges and new constraints have to be faced. These new constraints include soil insects, weeds, soil fertility and erosion, and drought, which cannot be overcome through genetic improvement alone. Upland rice is often cultivated on the fragile steep slopes of Vakinankatratra hills. Most farmers cannot afford pesticides or organic fertilizers. Thus, the sustainable development of upland rice also depends on the development of new cropping systems based on conservation agriculture: no tillage, semi-permanent organic soil cover consisting of a growing crop or mulch of crop residues, biodiversity-based management of pests and diseases, as well as soil fertility management through crop rotations or associations. Our multidisciplinary team in Madagascar also addresses these issues (Dusserre *et al.*, 2011).

The breeding program has broadened the genetic base of the material and will continue this effort. Durable resistance to blast remains a major objective and we will implement all available innovative strategies to address this issue, including gene pyramiding or the exploitation of long-lasting partial resistance genes such as *Pi21* present in various *japonica* lines (Fukuoka *et al.*, 2009). We have also initiated research activities aimed at better understanding the physiological and genetic bases of adaptation to low temperatures and other altitude-related abiotic stress. Likewise, we have broadened our target environment to mid-altitude areas and are now looking for the establishment of a regional (east Africa and Madagascar) upland-rice breeding and germplasm evaluation network.

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