Painting the Rice Red: Iron Toxicity in the Lowlands

IRON TOXICITY is a serious problem affecting lowland rice in West and Central Africa. It is particularly prevalent in inland valleys, where iron can run into the lowland from the upland and slopes. In 1994, the *Centre de coopération internationale en recherche agronomique pour le développement* (CIRAD) seconded a Plant Physiologist to WARDA to look into the problem in detail.

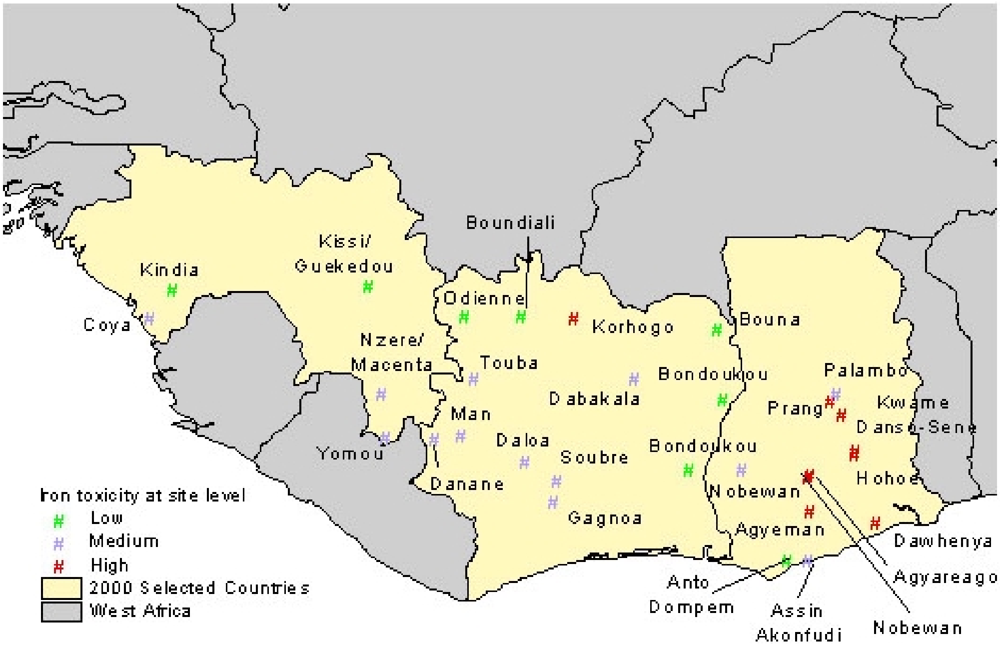
A question of balance

Soil nutrients are essential for plant growth. Plant a crop on a soil that is deficient in nutrients, and watch it struggle and most likely die. However, there is more to plant nutrition than simply adding nitrogen, phosphorus or other fertilizers. There are also the 'trace elements,' like zinc, manganese and iron. These are required in tiny amounts to sustain normal plant growth. The balance is a fine one: too little of the element and the plant will not grow, too much and... Well, this is the story of what happens when there is too much iron in the rice field.

A preliminary survey by WARDA in 2001 suggested that as much as 60% of the lowland rice area in West and Central Africa may be at risk from iron toxicity (*see* map, Figure 4). Average yield loss due to iron toxicity amounts to 50%, and in fact ranges from 10 to 100%. That makes iron toxicity a very serious problem for lowland rice farmers in the region indeed. "Iron toxicity is a typical soil nutrient problem," explains WARDA/CIRAD Plant Physiologist Alain Audebert. "Excess iron in solution is absorbed by the rice plant and accumulates in its tissues. Typical symptoms of iron toxicity are small brown spots, which start appearing at the leaf tips. These spread, merge and result in reddish-colored leaves. In addition, the iron toxicity alters the root structure, plant development, and leads to sterility." (*See* Box 'Iron-toxicity symptom scoring,' page 31.)

"Iron is the most important element in the earth's crust. It is especially concentrated in the lowland soils of the region," explains Audebert, "but many of the upland slopes also have high concentrations of iron." But, just because iron is present in the soil does not necessarily mean that there will be a toxicity problem. WARDA Soil Physicist Sitapha Diatta takes up the story: "In the uplands and on the slopes, iron is typically in what we call the ferric form [Fe^{3+}]. This form is non-soluble, and therefore not available to the plants." In other words, ferric iron is harmless to rice, and iron toxicity is not a problem on the upper slopes. Meanwhile, if the fields are not adequately flushed with fresh water, iron in the lowlands is subjected to an environment depleted of oxygen, and tends to become converted into ferrous [Fe^{2+}] iron. Ferrous iron is soluble in water, and so is available for uptake by the rice plants. "In a typical iron-toxic valley," Diatta continues, "ferric iron is washed down into the valley lowland, either by seepage through the

Figure 4. Map of western Africa showing iron-toxicity risk in three countries



soil (known as interflow), or else by run-off and erosion of the upper slopes into the valley bottom. Either en route (for interflow) or else upon arrival in the valley bottom (for run-off), the ferric iron encounters waterlogged conditions, and becomes ferrous iron" (*see* Figure 5, page 32). Thus, the already high concentrations of ferrous iron in the valley bottom are increased by the iron coming down the slope.

Combating iron toxicity at the field level

"Given what we know about the build-up of iron-toxic conditions, we can propose some field-level management options that may help alleviate the problem," says Audebert. "To do this, we have several possible points of intervention. We might try to block the movement of iron from the uplands, flush fields to wash out excess iron, look for ways of converting ferrous iron to the ferric form, try to minimize plant uptake of iron, or find varieties

Close-up of ground-water resurgence zone at edge of lowland field, where the slope and stationary water meet. Note reddish ferric iron on soil surface becoming paler under the process of reduction

Iron-toxicity symptom scoring

In studies of plant problems, it is always useful for researchers to have a quantitative method of assessing the effect of the constraint (in this case iron toxicity) on the plant. Yield is only one component of this.

For some years, disease, pest and nutrient disorders of rice have been assessed on a numerical scale developed by the International Rice Research Institute (IRRI). This Standard Evaluation Score (SES) uses a nine-point scale, where 1 is given for near-normal growth and development, and 9 is given for a plant that is almost completely dead; a mid-range score of 5 refers to a plant with retarded growth and tillering, and many discolored leaves.

Rice plant with iron-toxicity SES score of 7 as the plants are starting to flower. Note the bronzed flag leaves and small panicles

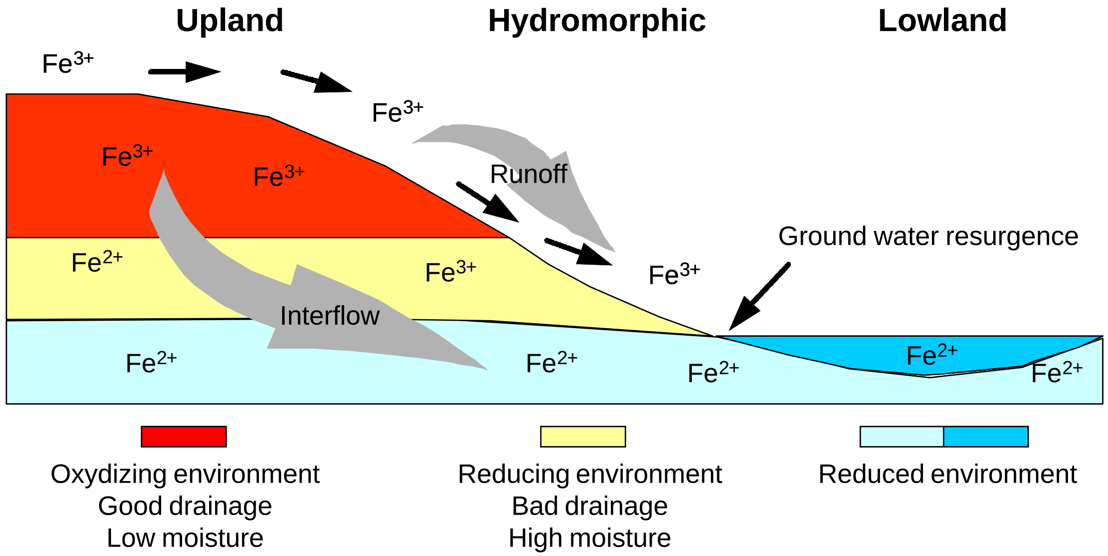
of rice tolerant to high concentrations of iron in the soil." Possible interventions are summarized in Figure 6 (page 32) at the level of the inland valley and in Figure 7 (page 33) for field level.

In many upland situations, farmers leave the soil bare after harvesting of their rice crop. Since sowing is only done after the first rains, dry bare soils are prone to erosion at the start of the rainy season. "We are already promoting the use of legumes in the uplands to diversify rice-based cropping systems, improve soil fertility, reduce soil erosion and alleviate weed pressure," explains WARDA Cropping Systems Agronomist Andreas Oswald. "They also help in the iron-toxicity problem by stabilizing the upland soils, so that they are not washed down the slope in the first rains." In addition, deep-rooted plants used as intercrops between rice plants in the uplands will capture more of the water, thereby reducing interflow. "The next logical step," continues Audebert, "would be to intercept the interflow and runoff in the lower slopes—the hydromorphic zone." However, this latter idea requires a management program for the whole toposequence, and is impractical at the current state of development of the vast majority of inland valleys in the region.

"We know that water in the field becomes increasingly depleted in oxygen the longer it stays there," says Audebert. "One possible solution might be to increase the circulation of water within the field, to keep it aerated, and thereby help to keep iron in the ferric form. Similarly, regular flushing of fresh water through the fields would tend to wash away the iron rather than have it accumulate. The problem here is that the management of many of the valleys is such that there is no available surplus water for doing this."

"It is important for us to view iron toxicity holistically," continues Audebert. "For example, if iron were the only issue, we might easily recommend flushing of fields and thorough draining to below the soil surface. However, one of the basic principles of improved water management in lowlands is the use of standing water to control weeds—a situation that clearly has the potential

Figure 5. Cross-section of toposequence showing movement of iron and reduction process



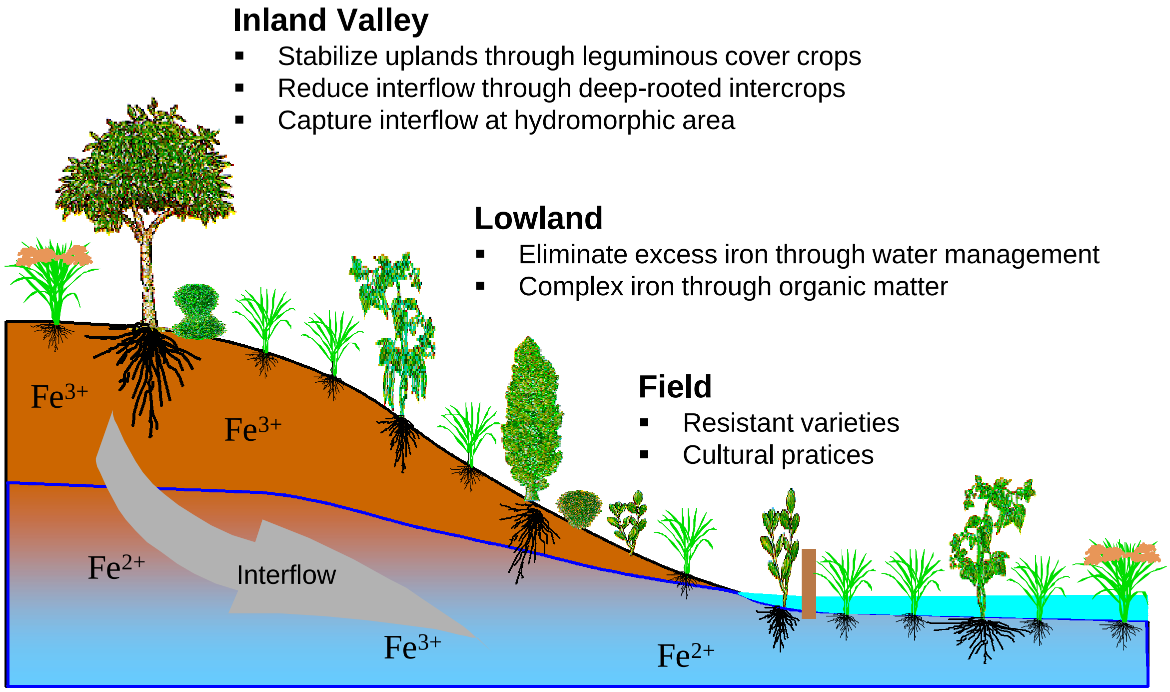


Figure 6. Toposequence diagram showing options for reducing iron movement and toxicity

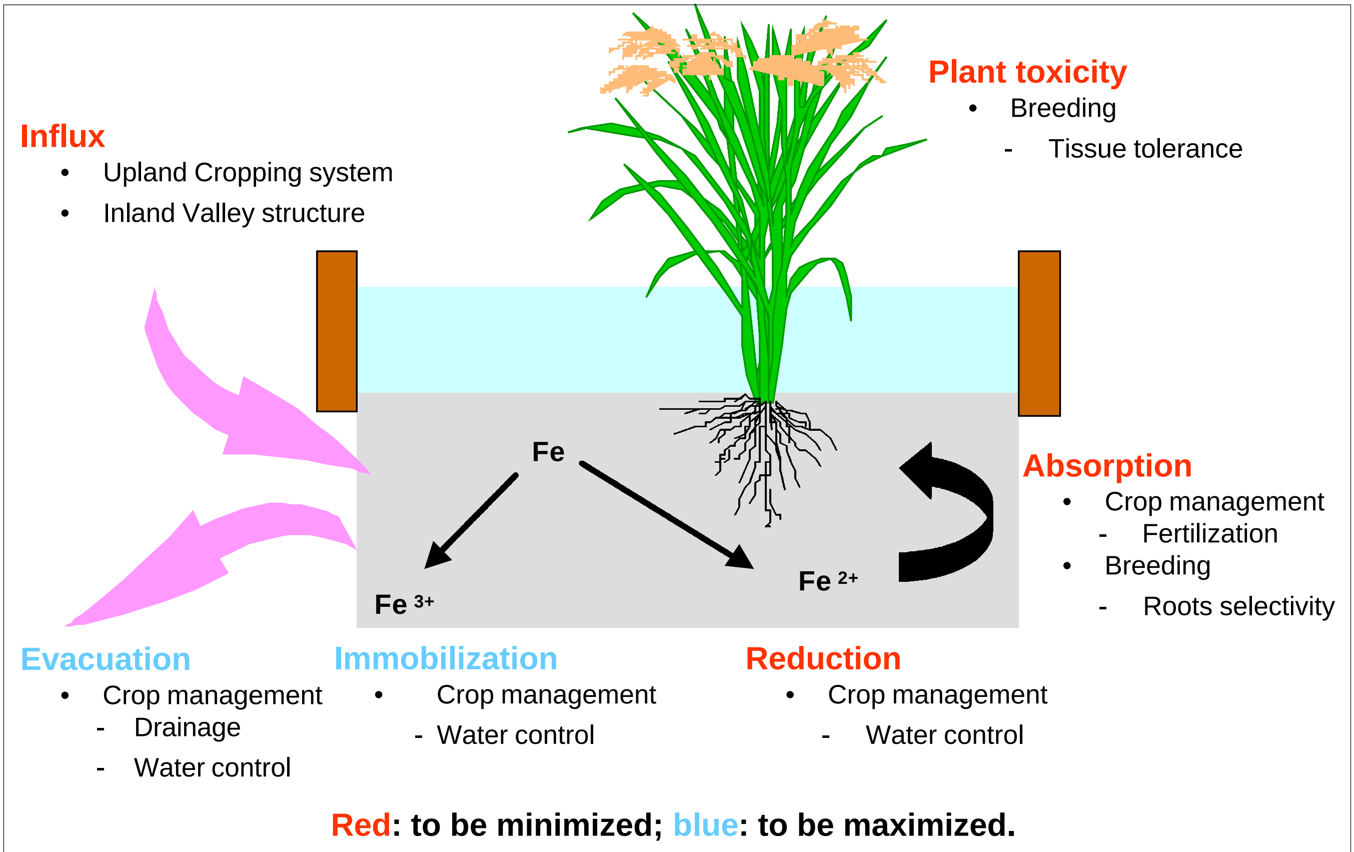


Figure 7. Summary concept of field level processes and sites of intervention to alleviate iron toxicity

to exacerbate iron-toxicity problems." Improved water control in the field would enable better drainage, taking some of the ferrous iron out of the rice root zone, but the infrastructure required for deep drainage is too expensive for most farmers in the region. Audebert and his team have shown that planting on ridges in iron-toxic sites can improve rice yields. This is a result of the rice roots being in an aerobic soil environment above the waterlogged level. In fact, this technique is already used by farmers in Guinea, Guinea Bissau and Senegal to increase yields on iron-toxic fields. Again, however, in those areas where ridge-planting is not a traditional practice, the different field preparation would incur costs (especially labor) that farmers can ill afford.

The team tested the effects of improved water control through bunding at the Korhogo test site. Four varieties tested gave average yield gains of 0.7 t/ha in bunded fields (*see* Table 1). "Since we did not have a non-toxic check plot, we cannot attribute this yield increase to any effect of bunding on iron toxicity itself," explains Audebert. "However, bunding is improving yield at the iron-toxic site by an average of 30%, and that is significant."

Table 1. Effect of variety and bunds on rice yield in iron toxic condition (Korhogo, Côte d'Ivoire, 2001).

Variety	Yield (t/ha)		
	No bunding	Bunding	Difference
TOX 3069	3.28	4.39	1.11
CK4	3.44	4.11	0.67
Bouaké 189	2.55	3.03	0.48
CG14	2.70	3.17	0.47
Mean	2.99 b	3.88 a	0.68

Since iron toxicity is a nutrient disorder, one might reasonably expect some impact of improved soil-fertility management on rice yields at iron-toxic sites. Former WARDA Soil Chemist Kanwar Sahrawat investigated this issue in the 1990s. “It is much easier to add nutrients to the field, than to take something away,” he explains. “Therefore, we looked at the effect of various fertilizer regimes on rice yield of a susceptible variety at the iron-toxic site of Korhogo in northern Côte d’Ivoire.” When the variety was fertilized with a ‘complete’ fertilizer—nitrogen, phosphorus, potassium and zinc—at Korhogo, a yield increase was achieved, but modeling showed that this level is still way below potential (*see* Box ‘Computer simulation of iron toxicity,’ page 35). “Rather better results were obtained from the use of organic matter,” says Sahrawat, “but organic matter (in the form of manure) is not easy to find in many parts of the region, so cost considerations mean that lowland-rice farmers are unlikely to use it.”

What does the plant have to offer?

“It is quite depressing,” sighs Audebert, “to know that there are several ways of reducing the iron problem, while at the same time knowing that few, if any, of the options are currently practical on a typical West African lowland rice farm.” As is so often the case when dealing with resource-poor farmers, much of the burden for finding a solution gets pushed back to breeders. After all, a rice that can cope with a problem like iron toxicity needs only to be distributed to farmers in affected areas, and they can improve their yields almost immediately.

Flooded field with high iron concentration

“The problem is,” explains WARDA Lowland Rice Breeder Howard Gridley, “that breeding takes time. However, some progress has been made, and there are useful varieties out there for the breeding program. For example, ‘traditional’ varieties [that is, varieties that have been grown and selected by farmers for many years—what some call ‘landraces’] tend to have a reasonable level of iron-toxicity tolerance.” The main problem is that some of the initial varieties to come out of breeding and introduction programs, and that are now popular and widespread, are susceptible. For example, Bouaké 189, which is the most widely grown lowland variety in Côte d’Ivoire.

The WARDA lowland breeding program that began in Nigeria had some success. WITAs 1, 3 and 4 are all considered moderately tolerant of iron toxicity, or it may be more accurate to say that they are adapted to sites with moderate iron toxicity. They have each been released

Computer simulation of iron toxicity: what can it teach us?

In the early 1990s, members of the then Problem Soils Task Force (now part of the expanded Natural Resource Management Task Force of ROCARIZ) identified iron toxicity as one of the major soil problems in rice throughout the region. “Despite the unanimous vote by Task Force members to include iron toxicity among the regional research priorities,” explains WARDA/CIRAD Plant Physiologist Alain Audebert, “there were no available data on the impact of the problem, or its effect on rice yields.”

At that time, WARDA already had experience of adapting the crop model Oryza, which predicts potential yield of a variety from climatic data and variety-specific photothermal constants. Consequently, Oryza was adapted for variety Bouaké 189 and simulations run with climatic data for the two test sites in Côte d’Ivoire—Korhogo (iron toxic) and M’bé (non iron toxic)—to predict potential yield from sowing in each month of the year. The iron-toxicity effects were *not* built into the adapted model, which predicted that potential yields for the two normal growing seasons (sowing in February and July) were similar at the two sites. Subsequently, Bouaké 189 was itself grown in the field at the two sites for four seasons.

It can be seen from the graph (Fig. 8) that actual yield at M’bé was in fact 1.7 tonnes per hectare less than full potential. If we take this as a standard difference between potential and farm-realizable yields, and apply the same to the results from Korhogo, we discover a further yield gap of 3.3 t/ha, which can mainly be attributed to the effect of iron toxicity at the Korhogo site.

“These simulations were made using optimal fertilization,” explains Audebert. “When he altered the fertilizer doses in the field, Sahrawat noted a significant increase in yield with full fertilization (*see* main text), but the final yield was still a long way below potential as demonstrated by the simulation of optimum fertilizer application at M’bé (*see* Fig. 9). In fact, the fertilizer is acting as a yield-enhancer *despite* the presence of iron toxicity. In this way, it operates like the improved water management through bunding (*see* main text).”

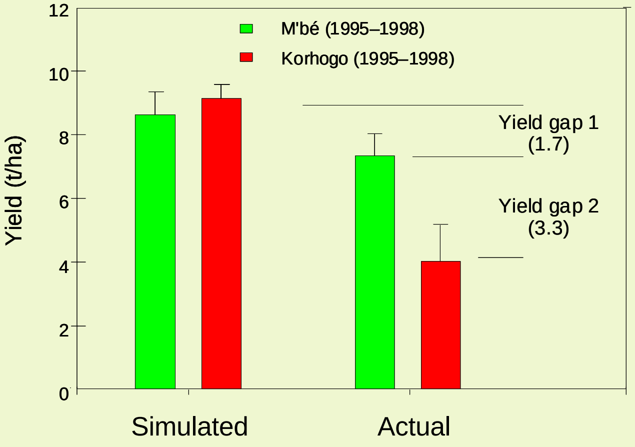


Figure 8. Yield losses due to farm practice (modelled) and iron toxicity (actual)

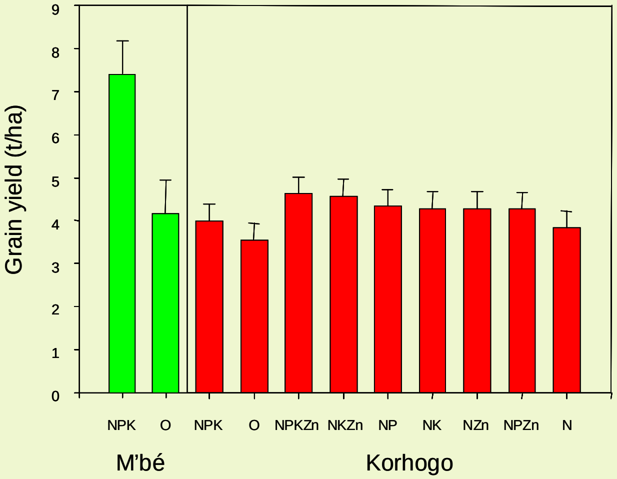


Figure 9. Actual yield of fertilized plots under iron toxicity (Korhogo) compared to potential yield without toxicity (M’bé)

in one or more of the countries of the region for such situations. “Even better,” says Gridley, “is WITA 12, which is undergoing advanced trials in several sites in Côte d’Ivoire.”

Meanwhile, characterization of the *Oryza glaberrima* genepool used in the NERICA program has shown that CG14 is highly resistant to iron toxicity. “Initial screening of NERICAs has revealed several that are iron-toxicity tolerant,” says Gridley, “but iron-toxicity will be a more important target for the ongoing development of lowland NERICAs from *indica* (lowland) varieties of *Oryza sativa*.”

What is going on inside the plant?

As modern plant breeding becomes increasingly complex, researchers want to know exactly how resistance or tolerance to a stress works. Finding out the mechanism behind a variety’s resistance is the first step in working out which combinations of plants should produce high levels of resistance by blending their mechanisms. It is for this reason that iron-toxicity research was given its own project back in 1997, and one of the main foci of Alain Audebert’s eight years at WARDA.

“If two plants can produce different yields in the same iron-toxic field,” says Audebert, “we hypothesized that the tolerant/resistant plant may be preventing the entry of ferrous iron at the roots, it may be distributing the iron among its own parts differently, or else is expressing some tolerance mechanism at the tissue level. So, these are the approaches we have adopted: uptake, partitioning and tissue tolerance.” For breeders who want to combine resistance mechanisms, the ideal situation would be that all three types of mechanism occur in different varieties. “We have discovered that some varieties ‘create’ oxidizing conditions around their roots,” says Audebert. “This causes some of the ferrous iron to be converted into ferric iron. Consequently, such plants may show a crust of insoluble ferric iron in the root zone.” Varieties with this characteristic are the subject of on-going studies into genetic variability of this trait.

To investigate the role of distribution of iron among plant parts, a tolerant variety (CK4), a susceptible variety (Bouaké 189) and a very susceptible one (TOX 3069) were grown in adjacent plots in an iron-toxic field. Results were consistent over three years of study. “The total uptake of iron did not differ significantly among the cultivars,” says Audebert, “showing that for this particular tolerant variety there was no barrier to absorption at the roots. However, there were significant differences in the partitioning among the plant organs.” While the varieties had similar iron concentration in their roots, the tolerant variety partitioned more iron into its stem and dead leaves, leaving the green leaves significantly freer of iron than those of either the susceptible or the very susceptible varieties (*see* Figure 10). What is more, a direct correlation was evident between iron concentration in green leaves and final grain yield.

“Iron is an important component of a plant’s energy-powerhouse chlorophyll,” says Audebert, “it also interacts with all the major enzymes and proteins that make up a plant’s biochemistry. We should therefore expect iron toxicity to affect photosynthesis and other biochemical processes one way or another.” The same experiments that showed the differential partitioning of iron among plant organs, also revealed that the green leaves of the susceptible variety became thinner at higher green-leaf concentrations of iron, whereas those of the tolerant variety did not. This leaf-thinning may result from, or in, reduced photosynthesis, and therefore reduced plant growth. Audebert again: “We are currently working on a hypothesis that an excess of iron in the green leaves disrupts photosynthesis. This may be via disruption of chlorophyll synthesis, or by direct action of the process of photosynthesis itself.” This is the work of PhD student Chérif Madougou from the University of Cocody (Abidjan, Côte d’Ivoire), who started working with the WARDA physiology team in 2001.

Audebert continues: “We are also looking at the form that iron takes within tolerant varieties. What we call ‘tissue tolerance’ may well be related to the tissues’ and

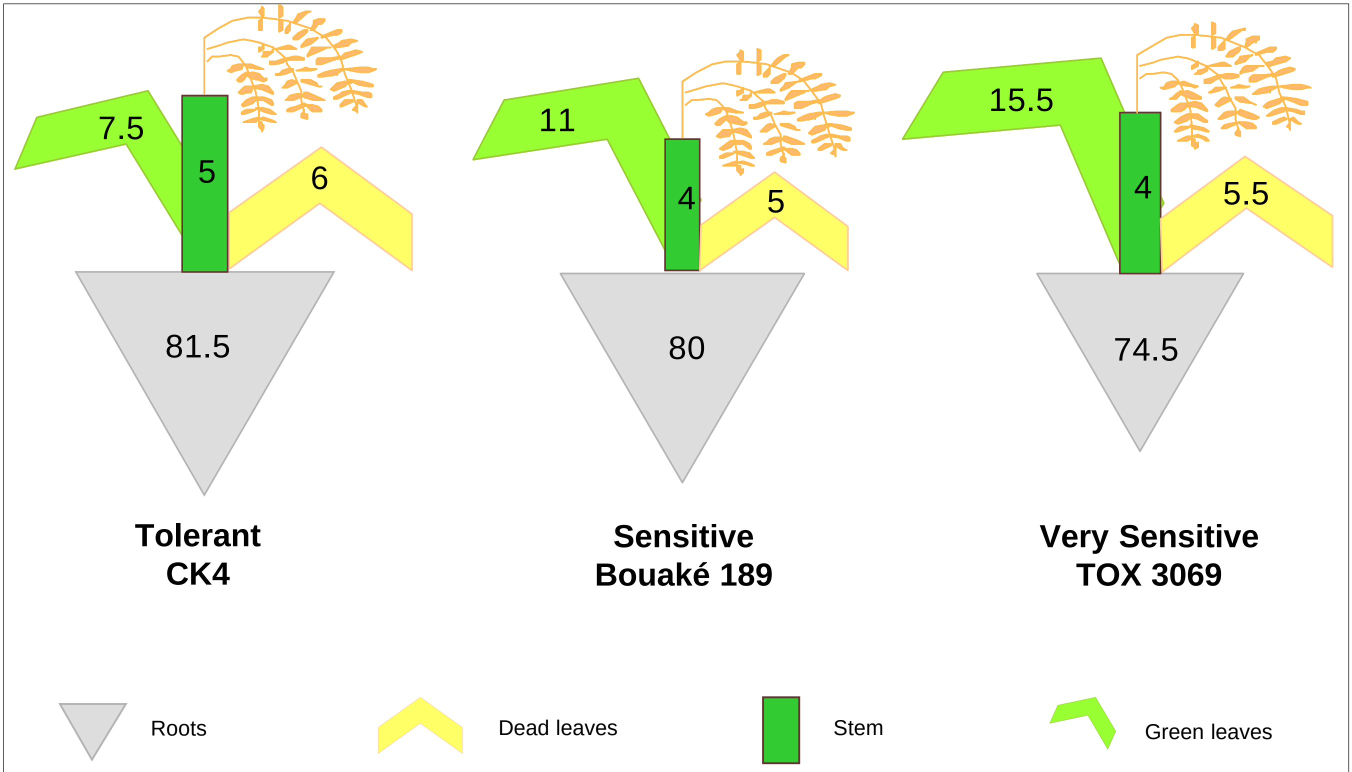


Figure 10. Differences in iron partitioning in different varieties (% total iron content in each organ)

cells' abilities to immobilize the ferrous iron through, for example, chelation—that is, binding of the metal molecule (in this case iron) to an organic compound, thereby rendering the metal unreactive."

"The work of Drs Audebert, Sahrawat and others over the past eight years or so has been crucial to our understanding of iron toxicity," says WARDA Director General Kanayo F. Nwanze. With the upcoming departure of Audebert in 2002, we will be closing a significant chapter on basic research into this issue."

"Given the weight placed on research into this issue by our national partners through the ROCARIZ Task Forces, we plan to wrap-up this phase of the work with a workshop in the second half of 2002," says Audebert. The workshop will be hosted by WARDA at its headquarters in Bouaké, and should result in a detailed state-of-the-art summary of iron toxicity in rice in West Africa.

"From 2003, it is likely that our emphasis on iron-toxicity research will move from strategic to adaptive," explains WARDA Director of Research Günther Hahne. "In practical terms for WARDA, this will mean moving the work from its own special project into the broader projects on lowlands and watersheds."