Evaluation of Iron Toxicity on Lowland Irrigated Rice in West Africa

M. Chérif[1]*, A. Audebert[2], M. Fofana[3] & M. Zouzou[1]

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Summary

*In tropical areas, lowland rice (*Oryza sativa *L.) cultivation (with or without irrigation) is often hampered by iron toxicity. This edaphic stress is common in West African savanna and forest lowlands. It is a nutrient disorder associated with high iron concentrations in the soil solution. The reducing conditions of waterlogged lowland soils boost iron toxicity through solubilization of almost all iron in its ferrous form (Fe^{2+}). This iron toxicity promoting edaphic features of lowland soils depends on the soil and climatic conditions, thus explaining the high spatiotemporal variability. The high quantity of ferrous ions in the soil solution upsets the mineral element balance in the rice and affects its growth. Ferrous iron (Fe^{2+}) is abundantly taken up by the plant and becomes concentrated in the leaves, causing limb discoloration, reduced tillering, stunted growth, while substantially reducing yields. A survey was conducted to quantify the effects of iron toxicity on rice in three countries (Guinea, Ivory Coast and Ghana) in the West African subregion. It was confirmed that iron toxicity is a major edaphic constraint in cultivated lowlands as it affects more than 50% of lowlands and about 60% of cultivated rice plots on average. About 10% of lowland crop fields were even abandoned due to high iron toxicity stress. Studies have also shown that more than 55% of rice-growing areas are affected by excess iron. There is also a significant impact on yield since affected plots were found to have a mean 54% lower yield as compared to healthy plots.*

Résumé

Evaluation de la toxicité ferreuse en Afrique de l'Ouest

*En zone tropicale, la culture du riz (*Oryza sativa *L.) en condition de bas-fond (avec ou sans contrôle de l'eau) est souvent confrontée au problème de toxicité ferreuse. Cette contrainte de type édaphique est couramment observée, notamment dans les bas-fonds de savane et de forêt ouest africains. C'est un trouble nutritionnel associé à de fortes concentrations de fer dans la solution du sol. Les conditions réductrices que l'on rencontre couramment dans les sols engorgés de bas-fond sont précurseurs de la toxicité ferreuse par la solubilisation dans la solution du sol de la quasi-totalité du fer sous forme ferreux (Fe^{2+}). Ces conditions édaphiques des sols de bas-fond, nécessaires à l'apparition de la toxicité ferreuse sont dépendantes des conditions pédoclimatiques expliquant ainsi la forte variabilité spatio-temporelle de cette contrainte. Cette grande quantité d'ions ferreux en solution entraîne chez le riz un déséquilibre en éléments minéraux. Ce fer ferreux (Fe^{2+}) est absorbé en abondance, se concentre dans les feuilles, entraînant une décoloration des limbes, une réduction du tallage, de la taille des plants, et provoque une baisse importante des rendements. Cette contrainte a fait l'objet d'une étude dans trois pays de la sous région ouest africaine (Guinée, Côte d'Ivoire et Ghana) afin de quantifier ses effets sur la riziculture. L'étude confirme que la toxicité ferreuse est une des contraintes édaphiques majeurs des bas-fonds cultivés puisqu'en moyenne plus de 50% des bas-fonds et environ 60% des parcelles cultivées en riz sont affectés par cette contrainte. Dix pourcent de ces bas-fonds ayant même été abandonnés en raison d'une pression de toxicité ferreuse trop importante. Les études montrent également que plus de 55% des surfaces rizicoles sont affectées par l'excès de fer. L'impact sur le rendement est également significatif puisque les parcelles infectées peuvent perdre en moyenne jusqu'à 54% par rapport aux parcelles saines.*

Introduction

Iron toxicity is one of the most common problems in West African lowland rice cropping systems. Many inland valley swamps and lowlands (rainfed lowlands, irrigated lowlands, mangrove swamps) have soil and water conditions that promote iron toxicity in rice (21). Excessive amounts of iron in the soil and reducing conditions (as generally prevail in lowland soil solutions) upset the nutrient balance in plants. These high iron concentrations are inherent to lowland soil (7), and also result of massive inputs of runoff-borne insoluble iron (Fe-III) derived from land at higher elevations (5, 9). Besides standard symptoms, i.e. browning and yellowing of leaves, iron toxicity can cause a 10-100% crop yield losses, depending on the iron concentration in the soil solution and the cultivar tolerance (1, 2, 14).

Several strategies to overcome this constraint have been evaluated, especially using tolerant cultivars (4, 19), in association with adapted cropping practices, e.g. using suitable fertilizers (5, 17, 19), etc. However, iron toxicity is influenced by multiple factors, thus complicating studies on this cropping constraint (18).

This constraint, which is widespread in West Africa, is presently only assessed qualitatively. Its actual impact on rice growing in West Africa both at the plot and production levels is not clearly known. Quantification of the impact of this constraint would, however, be essential for initiating research and development initiatives adapted to local conditions.

A field survey was conducted during the 2000 and 2001 rice cropping seasons to address this need. The objectives were primarily to evaluate rice cropping areas actually affected by

[1]Laboratoire de Physiologie Végétale, UFR-Biosciences, Université de Cocody-Abidjan, 22, BP 582, Abidjan 22, Côte d'Ivoire.

[2]CIRAD, Centre de Coopération Internationale en Recherche Agronomique pour le Développement, Département CA, TA 70/01, 34398 Montpellier Cedex 5, France.

[3]ADRAO, Association pour le Développement de la Riziculture en Afrique de l'Ouest, 01 BP 2551, Bouaké 01, Côte d'Ivoire.

*Corresponding Author:

Tel.: (225) 22 44 03 07 Fax: (225) 22 44 37 24 E-mail: cherifmamadou@hotmail.com

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iron toxicity, the intensity of visual symptoms and the impact on rice production in the studied zones and, secondly, to create a georeferenced database on the constraint and determine its geographical distribution in the subregion.

Materials and methods

The study took place during the 2000 and 2001 rice cropping seasons in three West African countries (Ivory Coast, Ghana and Guinea). These countries were selected for their high rice production, ecological diversity and accessibility.

In each country, rice production region were identified by the National Agronomic Research System (NARS). Inside each region, the place head of department was selected like base site.hus, a total of 33 base sites distributed in these three countries were selected so as to cover all rice production regions. All accessible lowlands in a radius of 50 km around each base site (study zone) were investigated. In Guinea, 5 base sites were in Guinée forestière, 2 in Guinée Maritime and 1 in Haute Guinée. In Ivory Coast, 13 base sites were covered, 6 in the forest zone, and 7 in the savanna zone (10). The 12 base sites selected in Ghana were all in the forest region. Interviewers were agents of the Centre National de Recherche Agronomique (CNRA) for Ivory Coast, the Institut de Recherche Agronomique de Guinée (IRAG) for Guinea and the Crops Research Institute (CRI) for Ghana. In each country, interviewers underwent training to learn how to identify and score the disease. There was also a training module on the use of global positioning system (GPS) technology.

Each interviewer had to georeference, using GPS, as many lowlands and most plots in the lowlands as possible within the study zone, irrespective of iron intoxication level. With theses spatial data it was possible to draw maps at different scale: Base site scale (1/25.000), Country scale (1/1.500.000) and Sub-region scale (1/4.000.000). However the survey in Ghana was focused mainly on areas that CRI already knew were affected by iron toxicity.

For this exhaustive study, interviewers had to fill in a three-level questionnaire, including: i) the watershed level, questions related to the area, slope and land use, ii) the lowland level, including a description: area, soil type in FAO system (feeling with touched, grounds handle or grounds ribbon), its use (past and present) and characterization of the overall development patterns; iii) at the plot level, information related to areas and cropping practices (variety, preliminary cultivation, sowing type, fertilizer type and dosage), the extent of toxicity (presence and scoring of visual symptoms) and production.

Surveys were conducted in two phases, the first between tillering and ripening onset (60-90 days after transplanting), which is the period when iron toxicity symptoms are more visible, and the second at harvest to estimate production. The constraint intensity, based on leaf symptoms, was defined on a visual scale ranging from 1 to 9, according to the intoxication level. A score of 1 indicated normal tillering and growth, while 9 indicated that most of the plants were dead or withered (11).

Three intensity levels were defined on the basis of the iron toxicity level in each plot. Level 1 for scores between 1 and 3 (low intensity), level 2 for scores between 3 and 6 (intermediate intensity) and level 3 for scores above 6 (high intensity).

The statistical analysis was conducted using the SAS software package (20). The frequency of each intensity level was determined for each lowland and site. The most frequent score was considered as the iron toxicity level for a given lowland or site. Some questionnaire fields could not be filled in for various reasons, so the number of plots or lowlands or even sites sometimes varied according to the parameter being analyzed.

Results and discussion

The survey covered a total of 4,625 irrigated rice plots distributed in 757 distinct lowlands at 33 sites in the three countries. The study covered a total lowland rice cropping area of 3,880 ha. Some 2,145 ha of this area was affected by iron toxicity, i.e. 55.5% of the overall area. In 1987, Abu *et al*. (3) pointed out that the percentage of iron toxicity affected areas in 11 districts of Sierra Leone ranged from 34 to 61%. Thus, contaminated areas in Sierra Leone were in same proportion to those in the three studied countries.

These two studies were conducted more than 10 years apart. This consistency with respect to the proportion of area affected confirms the scope of this edaphic constraint for lowland rice cropping in West Africa.

1. Environmental and ecological characterization

Lowlands were divided into two categories according to the watershed slope: Type 1, where both slopes were less than 5%; and Type 2, with at least one slope greater than 5% (for practical reasons: easy to estimate by the interviewers). Generally, both lowland types were found in all the sites studied, but Type 2 was predominant (64% for the three countries). Three watershed types were distinguished according to the area: small watersheds (areas below or equal to 100 ha), intermediate watersheds (areas between 100 and 200 ha) and large watersheds (areas above 200 ha). In the studied area, most sites (84%) had small watersheds (below 100 ha) whereas only 6% had large watersheds.

The use of the watersheds during the study period is described in table 1. Generally, areas were cultivated (52%), with 87% under various crops and 13% under orchards. The remaining area was used for settlements and infrastructures (5%), or not directly cultivated and left as fallows (17%), or natural vegetation (26%). These proportions varied between countries. In Ivory Coast, less than half (43%) of the watershed areas were used, whereas in Guinea and Ghana cultivated areas represented 56 and 58% of the watershed areas, respectively.

Table 1
Watershed and Lowland use (%) during the years 2000-2001

Countries	Watershed			Lowland					
				Dry season			Rainy season		
	Cultivation (%)	Settle-ments (%)	Non-exploited	Rice	Other crops	Non-exploited	Rice	Others crops	Non-exploited
Ivory Coast	43.18	7.57	49.25	24.86	27.70	47.44	57.31	18.62	24.07
Ghana	57.85	0	42.15	2.04	10.11	87.85	49.05	2.56	48.39
Guinea	55.68	8.72	35.60	19.49	40.86	39.65	80.76	2.68	16.56
Total	52.24	5.43	42.33	15.46	26.22	58.31	62.37	7.96	29.67

Lowlands were also classified in three categories according to the half of watersheds area (each lowland has 2 watersheds): small lowlands (below 50 ha), intermediate lowlands (between 50 and 100 ha) and large lowlands (above 100 ha). Small lowlands predominated overall (12, 13, 15).
The lowlands studied were essentially used for rice cropping in the rainy season and for secondary crops (vegetable) in the dry season (Table 1). In all three countries, 62% of the lowland areas used in the rainy season were cropped with rice. This share reached as high as 80% in Guinea, a renowned rice-producing country. However, in the dry season, secondary crops such as vegetables, fruits and perennials (bananas, palm trees and raffia) were more widely cultivated (26%) than rice (15%). There was also a higher proportion of non-utilized areas in the dry season (58%) than in the rainy season (30%). The reduction in agricultural areas, particularly for rice cropping in the dry season was likely due to the scarcity of water and accrued pressure from biotic and abiotic stresses (rodents, insects, birds, wind, iron toxicity, etc.).
The level of development in cultivated areas was assessed at both the lowland and plot levels and three levels of irrigation in plots were considered: good, intermediate and low irrigation. Good irrigation meant that drains and overflow canals were available, well maintained, and that farmers controlled water level variations in their plots throughout the crop growth period. For low irrigation, the water level on the plot was irregular throughout crop growth (with excesses and shortages) due to a lack of infrastructures or inappropriate use of water. Intermediate irrigation corresponded to situations where infrastructures were more or less available and maintained, with inappropriate water management at the plot level.
Hence, even though the irrigation levels are considered (Table 2), it was noted that plots and lowlands were marked by a lack of infrastructures (low or intermediate irrigation). In fact, irrigation was good, intermediate and low, respectively, in 15, 34 and 51% of the studied plots, but there were marked differences between countries. In Ivory Coast, the proportion of plots with good irrigation was low (8%), whereas in Guinea and Ghana it was 24 and 35%, respectively. In Ivory Coast, after an active investment period that was launched in 1968, the government progressively withdrew from lowland development and maintenance until 1990 (10). Since then, farmers had to handle these tasks, which have been gradually abandoned due to the high costs involved. However, in recent years the government, in Guinea and particularly in Ghana, has been implementing a rice rehabilitation policy based on the modernization of production systems in order to reduce rice imports (16). There was considerable lowland development in these countries (8).

2. Iron toxicity distribution and intensity
There was high spatial variability in iron toxicity at various scales (between the three countries and within each country). For the three countries, the variation coefficient with respect to the visual symptom score is 67% (Table 2). This value was similar in Ivory Coast and Guinea (69 and 64%, respectively) and lower in Ghana (46%) due to the prior selection of lowlands for the study. At each country scale, the stress intensity was not the same at all the studied sites (Figure 1). Hence, two neighboring sites (about 100 km apart) sometimes showed differences in terms of affected rice areas, e.g. Korhogo and Boundiali in Ivory Coast. However, some major zones could be defined. Haute Guinée lowlands were less affected by iron toxicity, whereas the stress was widespread in Guinée forestière.
In Ivory Coast, the Odienné, Bondoukou and Abengourou areas could be considered as not or only slightly intoxicated (most visual scores of 1). Inversely, the other sites seemed to be moderately or highly toxic (score of visual symptoms usually above or equal to 3). At sites like Korhogo and Gagnoa, there was high pressure from this stress (most lowlands had scores above 5). In Guinea, the stress was low in the center (Kissidougou, Guekedou and Kankan) and intermediate in the rest of the country. All sites in Ghana, except Anto-Dompem and Dawadawa, showed moderate or high iron toxicity. For the reasons mentioned above, this country had the greatest share of highly affected lowlands (60%).
The mean coefficient of variation per study zone was 54%. There could thus be substantial differences in stress pressure between two neighboring lowlands (about 10 km apart). This was the case with respect to Kindia and Nzérékoré in Guinea, Gagnoa and Soubré in Ivory Coast and Assin-Akonfudi in Ghana. The results also showed spatial variability at the lowland (mean CV of 50%) or even plot level. Most of the studied sites were only moderately toxic but this did not bar the fact that a few lowlands had high iron toxicity levels.

3. Iron toxicity impact on yield
Mean yields were low at the plot level. For healthy plots with no symptoms (visual score= 1), the mean yield was 1.7 t.ha^{1}. For affected plots (visual score> 1), the mean yield was 1.5 t.ha^{-1}. The mean loss, considering all plots, was 11% relative to the mean yield of the healthy plots. For the overall study, this loss concerned 58% of the plots (2,689 plots).
Yield declined as a function of the intoxication level in plots (Figure 2), as well as the proportion of affected plots. Some 34% of slightly contaminated plots (visual score= 3) had a yield loss of 4% compared to healthy plots. About 19% of the plots had a visual score of 5, corresponding to a yield decrease of 12%. The 6% of remaining plots were highly intoxicated (visual score> 5) and showed a yield decrease of 55%. High iron toxicity stress considerably reduced the mean plot yield. These results corroborate the work of Audebert and Sahrawat (5), Sahrawat and Diatta (18), and Yoshida (22).
In the study zone, nine lowlands were reported to be abandoned by farmers due to iron toxicity. This abandonment occurred long ago for a number of sites (20 years in Ghana for the Dawadawa site and 10 years in Ivory Coast at the Danané site). However, some lowlands were abandoned more recently (less than 5 years earlier), namely at the Danané site.

Table 2
Irrigation levels and variability in iron toxicity visual scores of the selected areas within each country

Country	Irrigation			Iron toxicity visual scores		
	Good	Medium	Bad	Mean	Standard Deviation	C.V. (%)
Ivory Coast	8.29	40.05	51.66	2.61	1.80	69.09
Ghana	35.51	0.94	63.55	5.13	2.35	45.83
Guinea	23.73	27.42	48.82	2.97	1.89	63.54
Total	14.90	34.26	50.84	2.8	1.8	67.4

C.V.: coefficient of variation.

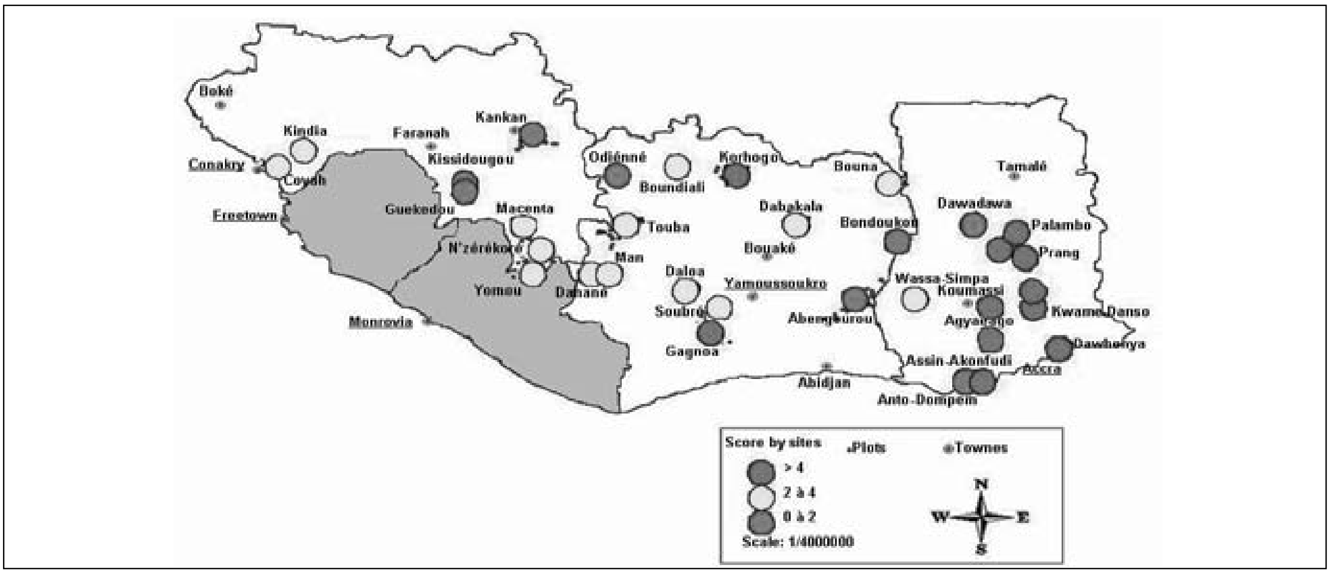

Figure 1: Map of iron toxicity symptoms per survey site. Years 2000-2001.

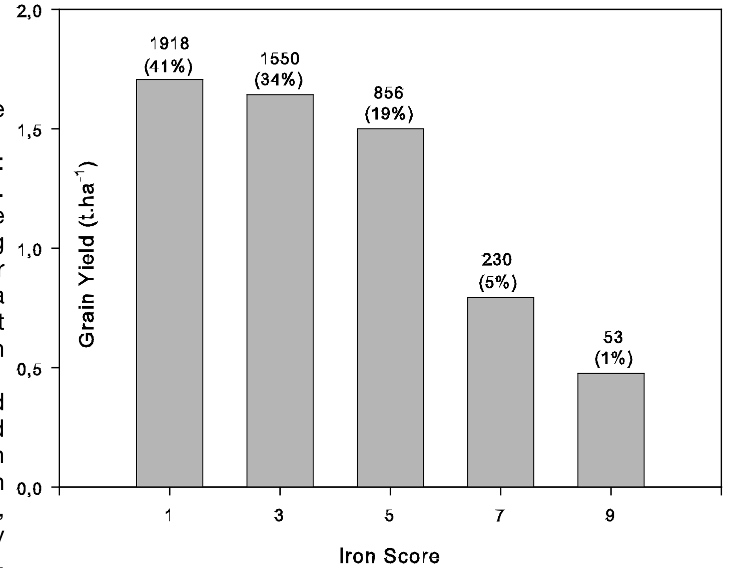

Figure 2: Plot yield and plot frequency according to iron toxicity symptoms. Years 2000-2001.

4. Cropping practices and iron toxicity

Two cropping practices were considered in this study: the type of sowing and irrigation level on the plot.

Three types of sowing were identified in the studied zone: no-till sowing (in rows) transplanting and broadcast sowing. Transplanting was the most commonly used technique in the sub-region (78.5% of plots). No-till and broadcast sowing were used only in 6 and 15.5% of plots, respectively. For each of the countries, no-till sowing was adopted only in a small number of delineated sites. With no-till and broadcast sowing, mean yields were significantly below those with transplanting both in healthy and intoxicated plots (Table 3). In the studied zone, half of the plots (51%), did not have good irrigation. The results showed that better irrigation boosted the mean yields of the plots. In addition, when irrigation was good, there was no significant difference between mean yields in healthy and contaminated plots. Similarly, other cropping practice such as fertilizer input significantly improved grain yield of rice under iron toxicity condition (5, 6, 18). However, there was still a significant difference in the yields between healthy and infected plots.

This analysis also helped to rank cropping practices. This ranking seemed independent of the iron toxicity pressure. Hence, irrigation seemed to be the factor for enhancing yield under the farming conditions encountered (8). Finally, in the farming conditions, the type of sowing could influence production, probably through the impact of sowing type or the initial vigor of the crop (weed competition).

This survey, with the low observed yields, confirmed the fact that lowland rice cropping is not very intensified in West Africa. With such low yields (1.7 $t.ha^{-1}$), iron toxicity, when present, did not have a marked impact at the cropping intensity level in the subregion. This might not be the case with crop yields above 3 t/ha.

Table 3
Effects of iron toxicity on plot yield (t/ha) as a function of cropping practices

	Plot yield (t/ha)					
	Type of sowing			Irrigation		
	Transplanting	Broadcast	No-till	Good	Medium	Bad
Healthy plots	1.87 ax	1.38 bx	0.59 cx	2.65 ax	1.63 bx	1.51 bx
Infected plots	1.62 ay	1.14 by	0.79 cx	2.50 ax	1.35 by	1.31 by
Mean	1.72	1.25	0.69	2.55	1.44	1.42
Toxicity effect		**			**	
Types of sowing effect		**			-	
Irrigation effect		-			**	

**Significant at a the 5% threshold a,b,c= horizontal comparisons x, y= vertical comparisons

5. Factors favoring iron toxicity in lowlands

The results showed that the visibility and extent of the iron toxicity symptoms increased as the watershed slope increased (Table 4). The steepness of slopes directly influenced leaching and transport of mineral elements, including iron, from the upper to the lower part of the watershed. Iron (Fe-II) derived from upstream soil alteration was transported by runoff to the lowlands where it accumulated. The quantity of iron (Fe-II) drained from the upper to the lower parts of the watershed also depended on the slope conditions and the extent of watershed use. The size of the watershed or the total area used did not seem to be correlated with the iron toxicity pressure. However, major use of the soils seemed to promote iron toxicity in the lowlands (8). Table 4 shows that the visual symptoms were more marked in lowland rice plots as the extent of utilized watershed area increased. The continuous use of slopes changed the soil structure and texture, etc., thus causing accrued erosion and Fe-II leaching. Hence, steep slopes associated with high watershed use seemed to increase the iron toxicity risk in lowlands.

Table 4
Iron toxicity intensity in lowlands as a function of the watershed slope and use

Infection	High slopes (> 5%) (%)	Extent of watershed use (%)
Low	60	64
Medium	66	77
High	72	82

Conclusion

This study did not cover the entire West African subregion but it helped to gain insight into the extent of rice-growing areas actually affected by iron toxicity, its intensity in the studied zones and to establish a georeferenced database on the constraint.
In the farming conditions encountered during this study, iron toxicity did not appear to be a major constraint, when only considering yield. However, this constraint deserves greater attention in the light of the number of affected areas. The study highlighted the scope of the phenomenon but also opens research avenues on control methods to implement. There seem to be links with cropping practices at the plot, lowland and even watershed level. Ecologically, improved management of watersheds and tailored cropping practices (same sowing types and dates, good irrigation, same fertilizer types and dosages) in lowlands would probably help to minimize production losses due to iron toxicity. The diversity of varieties cultivated, generally known under local names, makes it difficult to estimate yield losses due to iron toxicity compared to the real potential of the crops. This study revealed links between cropping practices and iron toxicity. These hypotheses pave the way for new potential studies.

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M. Chérif, Ivorian, Doctorant, Etudiant, Laboratoire de Physiologie Végétale UFR-Biosciences Université de Cocody-Abidjan, Côte d'Ivoire.
A. Audebert, French, Docteur, Chercheur, CIRAD, 34398 Montpellier, Cedex 5, France.
M. Fofana, Ivorian, Doctorant, Assistant de recherche, ADRAO, 01 BP 2551, Bouaké 01, Côte d'Ivoire.
M. Zouzou, Ivorian, Maître de conférence, Enseignant chercheur, Laboratoire de Physiologie Végétale UFR-Biosciences Université de Cocody, Abidjan, Côte d'Ivoire.

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