Excessive iron uptake (iron toxicity) by wetland rice (Oryza Sativa L.) on an acid sulphate soil in the Casamance/Senegal

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1 Summary

In order to evaluate the impact of the nutritional status of rice plants (in particular with respect to K, P and Ca) on the uptake of iron, a fields trial (with IR8) on a typical acid sulphate soil was carried out in South Casamance in cooperation with the Institut Sénégalais des Recherches Agricoles (ISRA) at Djibelor. In the experiment the effect of fertilization (N, N+P, N+K, N+Ca) on nutrient uptake (leaf analyses), the symptoms of Fe toxicity and the development of pH, Eh and Fe(II) concentrations in the soil solution of the rhizosphere were measured periodically throughout the vegetation period. The experimental site and other rice fields with severe Fe toxicity symptoms were characterized physico-chemically. In the untreated control, two peaks of intensive Fe(II) formation and -uptake occurred, one during the first week after transplanting (primary iron toxicity) and the second between heading and flowering (secondary IT). Fertilization (particularly P application) decreased Fe(II) uptake, which seemed to be governed neither by soil pH or redox potential nor by the Fe concentration in the soil solution. The phosphorus and potassium status of the plants, however, significantly affected the Fe contents of the leaves. Primary iron toxicity is explained by an apparent sensitivity of freshly transplanted rice seedlings to high amounts of Fe(II) accumulated just after flooding, while secondary IT may be ascribed to the excessive Fe(II) uptake caused by an increased root permeability (K deficiency) and enhanced microbial iron reduction in the rizosphere (intensive exudation) during the physiological active phase between heading and flowering. In terms of managament, rice seedlings should be transplanted only 5-20 days after flooding and well fertilized afterwards (particularly with P and K), if iron toxicity is to be eliminated.

Résumé

Afin d'évaluer l'impact de l'état de nutrition (particulièrement avec K, P et Ca) des plantules de riz sur l'absorption du fer, des essais au champ (avec IR8) ont été mis en place sur les sols sulfaté-acides typiques du sud de la Casamance. Ces essais ont été effectués avec la collaboration de l'Institut Sénégalais de Recherches Agricoles (ISRA) à Djibélor.

L'effet de la fertilisation (N, N+P, N+K, N+P+K, N+Ca) sur l'absorption d'éléments nutritifs (analyse des feuilles) ainsi que l'effet de la toxicité ferreuse sur le développement du pH, du Eh et du Fe(II) dans la rhizosphère, ont été évalués pendant toute la durée du cycle végétatif.

Le site expérimental, de même que d'autres rizières où l'on avait relevé des graves symptômes de toxicité ferreuse, ont été caractérisés du point de vue physico-chimique.

Dans le cas du témoin non traité, deux périodes de pointe ont été observées dans la formation et l'absorption du Fe(II). Une, survenue au cours de la première semaine après le repiquage (toxicité ferreuse primaire) et la seconde, entre l'épiaison et la floraison (toxicité ferreuse secondaire). La fertilisation et particulièrement celle avec du phosphore, a diminuée l'absorption du Fe(II), qui semble n'être pas dirigé par le pH du sol ou le potentiel redox, et non plus par la concentration du fer dans la solution de sol. Pourtant, les quantités de phosphore et de potasium présentés dans les plantes, affectent d'une manière significative la teneur en fer des feuilles.

On explique la toxicité ferreuse primaire par une sensibilité apparente des plantules de riz fraîchement repiquées aux quantités élevées de Fe(II) accumulés immédiatement après l'inondation, tandis que la toxicité ferreuse secondaire, peut être attribuée à l'absorption excessive du Fe(II) provoquée par une plus grande perméabilité des racines (déficience en K) et une augmentation de la réduction microbiennes du fer dans la rhizosphere (intense exudation) pendant la phase de grande activité physiologique qui se situe entre l'épiaison et la floraison.

Dans la pratique, les effets nocifs de la toxicité ferreuse primaire peuvent être facilement evités par repiquage des plantules seulement 5 à 20 jours après la submersion. Cet interval varie d'un sol à l'autre, et dépend surtout de la vitesse de réduction microbienne du fer, qui est généralement directement proportionelle à la teneur en matière organique facilement décomposable. La toxicité ferreuse secondaire, peut être allégé par fertilisation, soit avec d'engrais minéraux (particulièrement phosphore et potassium), soit par incorporation de restes organiques, fumure et/ou cendre. Une fertilisation à niveau satisfaisant et répété, est nécessaire surtout sur les sols sulfaté-acides lessivés (qui commencent à s'oxyder dès qu'ils sont sechés et désalinisés après un lessivage intensif) ainsi que sur les Histosols oligotrophes fortement altérés. En fait, la toxicité ferreuse secondaire, peut être considérée comme 'une maladie de mise en culture' qui disparaît aussitôt que les sols sont régulièrement fertilisés (Japon).

2 Introduction

Disorders of wetland rice due to high iron uptake ('bronzing') may be encountered in nearly all rice producing areas of the world. In south Senegal this stress limits rice yields increasingly, particularly on the mangrove-derived soils (IRAT 1969). Farmers in these regions claim iron toxicity to be responsible for major yield losses during the past 15 years.

In the last decades several views have been discussed to explain the mechanism(s) of excessive Fe(II) uptake. Special attention, however, was paid to the role of low soil pH and/or high Fe(II) concentration in the soil solution (Howeler 1973; Ponnamperuma 1977; van Breemen and Moormann 1978). Other authors (Sahu 1968; Tanaka and Tadano 1972; Trolldenier 1977) considered potassium to be involved in the problem. Based on physico-chemical analyses of various iron-toxic soils (Ottow et al. 1982; Ottow et al. 1983) and pot experiments (Benckiser et al. 1984) iron toxicity was explained by a multiple nutrient stress in which deficiencies of P, K and other elements (Ca, Zn?) were considered to trigger the breakdown of the root oxidizing capacity by an increased exudation resulting in high iron influx. This hypothesis was tested in a field experiment on a typical acid sulphate soil in the Casamance.

3 Material and methods

3.1 Characterization of soils

Amongst the sites under rice cultivation in the Basse Casamance various soils were sampled and characterized physico-chemically (Schlichting und Blume 1966). Profiles which showed net jarosite mottling at less than 50 cm depth or residual sulfidic material at less than 100 cm depth were considered to be acid sulphate soils. Their properties (0-20 cm layer) are listed in Table 1.

Table 1. Analytical parameters (0-20) of rice soils derived from acid sulfate soils

Soil	pH H_2O/KCl	mS/cm 1/2,5	$P_{av.}$ ppm	CEC*	K	Na	Ca	Mg	Fe	Al	Fe-toxicity**
				meq/100g at pH pH 8,1							
L.O	3,8/3,6	3,2***	3,7	11,6	0,13	0,76	1,16	0,99	0,80	0,45	+++
E 6	4,2/3,7	0,29	9,9	11,5	0,05	0,11	2,35	0,19	0,93	0,73	++
1	3,4/3,3	1,9	83,6	8,1	0,03	0,08	0,35	0,13	0,70	0,59	+++
3	3,4/3,3	0,75	52,0	7,4	0,03	0,40	0,31	0,25	0,92	1,14	+++
4	3,7/3,6	0,5	6,2	10,1	0,01	0,05	0,20	0,31	0,50	2,13	+++
6	3,2/3,2	3,6***	n.d.	10,0	0,03	0,49	0,26	0,17	1,38	1,07	+++
7	4,1/3,8	1,9***	1,5	19,0	0,16	1,57	2,52	2,27	1,75	1,09	+
9	5,0/4,8	0,77	n.d.	28,0	0,06	0,41	16,25	2,33	1,54	0,51	++
15	3,7/3,5	0,55	2,5	9,1	0,03	0,19	0,68	0,30	1,12	1,37	++
KA 2	3,7/3,6	0,63	n.d.	9,2	0,03	0,27	0,42	0,20	0,39	1,85	+++
KA 5	4,3/3,9	1,65***	2,1	11,2	0,39	2,36	1,23	0,90	0,25	n.d.	+
DD 3	3,4/3,3	0,89	6,5	9,8	0,03	0,09	0,83	0,18	1,24	1.68	++
DD 4	3,3/3,3	0,66	n.d.	7,9	n.d.	0,46	0,68	0,08	1,34	2,32	+

* CEC in saline soils after desalination
** Iron-toxicity symptoms: + leaf symptoms, ++ beginning mortality, +++ severe mortality
*** Dry season values,
$P_{av.}$: available P, extracted with 0,5m $NaHCO_3$ (Olsen)
n.d.: not detected

3.2 Field experiment

A typical site located near Loudia Ouolof was chosen as experimental site (L.O. in Table 1). At 20-50 cm depth the profile revealed appreciable jarosite mottling and mangrove root residues. Occasionally residual sulfidic material was observed between 50 and 100 cm depth. The original Avicennia-mangrove was cleared in the early sixties and the soil used ever since for wetland rice. Seven treatments (unplanted, planted+N,

– +N+P, – +N+K, – +N+P+K, – +N+Ca and – +N with P+K application only in the nursery) in 5 replications were randomized and arranged in blocs. Plot size was 5 x 4 m with 27 seedlings/m² planted on small levees according to the system of the local Diola farmers.

All plots received N (11.25 g N/m² as urea) and Zn (0.23 g/m² as $ZnSO^4$) while P (6.75 g P/m² as ammonium phosphate), K (15 g/m² as KCl) and Ca (7 g/m_2 as $CaCl_2$) were only given in the corresponding plots. Fertilization was splitted: 2/3 were applied before transplanting and 1/3 at maximum tillering. The seedling nurseries received 8 g N/m² or 8g N + 8g P + 22g K/m², respectively.

Three or five weeks old seedlings (R8) were transplanted 1 or 21 days after flooding. The experimental site was guarded by the farmer's wife to chase away the birds.

3.3 Measurements

From transplanting to harvesting pH and Eh in situ as well as the concentration of Fe(II) in the soil solution (= Fe(II)-sol) were measured periodically in each plot. At the same time samples of leaves (2nd and 3rd leaf from top) were taken and analyzed afterwards.

For electrochemical measurements (WTW pH meter 191, with Ingold combined pH-Eh-electrode Pt 405-85) undisturbed soil columns (0-50 cm) were sampled with handaugers (Eijkelkamp, Ø 7 cm) and pH- and redox values recorded in the 0-10 cm, 10-20 cm and 40-50 cm layers of each plot. The results obtained are averages of three to four measurements per layer and were related to the standard hydrogen electrode by addition of 208 mV (30 °C).

For measurement of F(II)-sol a soil/soil-solution mixture was aspired by means of a plexiglass tube (50 cm long, Ø 1 cm, inserted in 15 cm depth at proximity of the rice root systems) and a hand vacuum pump (Soil moisture Cat. Nr. 2005G1). Care was taken to prevent surface water from entering into the tube, especially during the insertion and extraction of the tube. As soon as the aspired soil/soil-solution mixture appeared in the upper part of the tube, the system was withdrawn from the soil and its content passed immediately through a paper filter (S+S Nr. 311609) into a 10 ml volumetric flask containing 7 ml of specific reagent solution. This solution contained 5 ml orthophenanthroline solution (in concentrations depending on the Fe(II) content) and 2 ml mono-sodium citrate buffer (0.5 m) of pH 3.3. The contents of the flasks were homogenized and the extinctions measured at 508 nm (Perkin and Elmer spectral photometer 550 s) after appropriate dilution. Blanks without orthophenanthroline were run as control (Sandell 1959). Results are averages of 2-4 samples per plot.

3.4 Leaf analyses

Sampled leaves (5-10 g fresh weight per plot) were rinsed in tap and deionized water before drying (105 °C). Ashing (at 420 °C), ash digestion and analysis of element content were done with methods described by Fassbender und Ahrens (1977).

4 Results and discussion

4.1 IR8 performance in the field

The first IR8 seedlings were transplanted immediately after field inundation and a nearly total loss of plants occurred within a few days due to heavy iron toxicity. This damage was recorded irrespectively of fertilization. The iron contents of the leaves increased in one week from 156 to 3780 ppm. This period of iron intoxication (= primary iron toxicity) coincided with a very high Fe(II)-sol.

Transplantation was repeated 3 weeks later when Fe(II)-sol had decreased. These plants again suffered heavily from 'bronzing' as revealed by symptoms and increased Fe content of the leaves. However, losses were limited and dead plants were replaced 10 days later.

Only fertilization with P (in the treatments N+P and N+P+K) visually improved rice growth, diminished 'bronzing' and reduced Fe uptake. This effect was maintained throughout the whole vegetation period and resulted in significant (at 5% level) yield differences between P-fertilized and non-P-fertilized treatments. However, factors other than iron toxicity (rice borer attack, consumption of paddy by weaver birds and asynchronous ripening) affected grain yields considerably.

Highest mean paddy yield was obtained with N+P+K application (1100 kg/ha) while the treatment +N (with P+K only into the nursery) gave lowest results (160 kg/ha). Several plots had to be excluded from evaluation because they virtually yielded no rice. Although plants recovered quite well from primary iron intoxication, a second increase in 'bronzing' was observed beginning at heading.

4.2 Development of pH, Eh and Fe(II)-sol

The developments of pH and redox potential in situ (in 0-10 cm layer) are shown in Figure 1. The rapid decrease of the redox potential is accompanied by an increase of pH. No real differences between the treatments could be observed except that non-planted plots revealed less intensive microbial reduction processes as judged from lower pH- and higher Eh-values. Correspondingly, the Fe(II)-sol reached a higher level in planted plots over a long period (Figure 2). Immediately after inundation, the Fe(II)-sol increased up to 4700 ppm but diminished rapidly during the vegetation period. A second peak of Fe(II)-sol was observed in the planted plots during flowering. No clear difference in iron reduction between the different treatments could be detected.

These results indicate that the presence of rice roots in the soils favour microbial processes, especially iron reduction. This can be explained by an improved energy supply (root debris and/or exudation of carbohydrates) that stimulate microbial activity in general and anaerobic respiration (denitrification and/or ferric iron reduction) in particular.

The occurrence of a pronounced peak of Fe(II)-sol immediately after flooding, also reported previously by Ponnamperuma (1977b), was confirmed for other examined acid sulphate soils in the area. This intensive microbial iron reduction should be considered responsible for the high mortality of seedlings transplanted too soon after

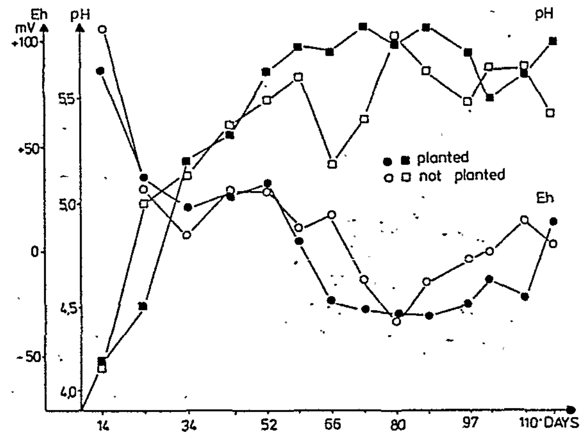

Figure 1 Development of pH and redoxpotential on an acid sulfate soil during the growth period. Experiment 'Loudia Ouolof'

reflooding an oxidized soil. No significant correlation between Fe(II)-sol (or pH, or Eh) and leaf iron content could be established at any sampling time.

4.3 Plant nutrient and Fe uptake

The effects of phosphorus fertilization were not only visible in plant development and yield, but were also reflected in the P contents of rice leaves (Figure 3). P-fertilized plants had higher P contents than those without P. The same leaves showed also higher K contents than all other treatments (Figure 4). However, leaf analysis failed to reveal any effect of K fertilization on K uptake. The positive effect of P on K uptake may be explained by its significant role in root growth (Jones et al. 1982). A well developed root system facilitates the uptake of all soil nutrients that become available by diffusion and interception (K, P).

A comparison of the total Fe content of leaves from P-fertilized and non-P-supplied plots suggests (Figure 5) that plants well supplied with P (and consequently with K) can recover more rapidly from an initial Fe stress after transplantation than those without P fertilization.

From Figure 5 a second slight increase in the leave iron content is observed at flowering. The correlation between leave iron content at the beginning of heading and the grain yield finally obtained in the corresponding plots is presented in Figure 6. This Figure supports the significance of an excessive iron uptake in this phase for the productivity of the site. Nearly identical results were obtained by Leihner (1975). High

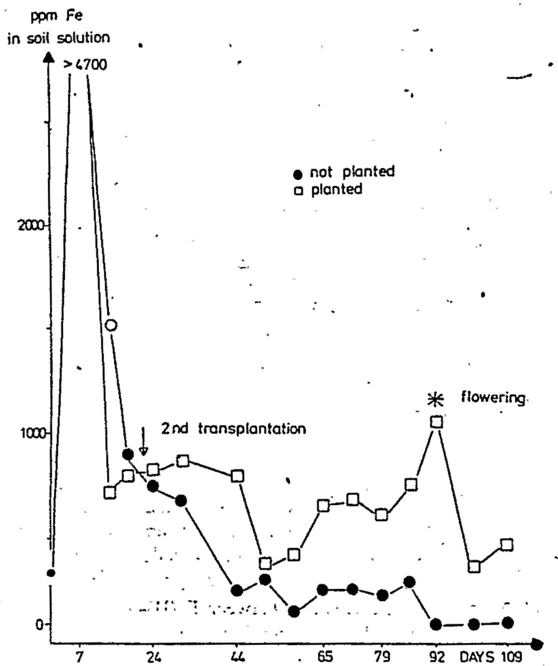

Figure 2 Development of Fe(++)-concentrations in the soil solution in planted and not planted plots throughout the growth period at Loudia Ouolof

iron contents in leaves at this stage indicate that tillering as well as spikelet formation might have been hampered by high iron influx.

A highly significant correlation between iron and potassium content of the leaves at the early heading stage is shown in Figure 7. At this physiologically active phase of the vegetation, iron uptake seems to depend highly on the potassium status of the plant. The better the K supply, the lower is the uptake of Fe. This result supports findings of Tanaka and Tadano (1972), Trolldenier (1977) and Benckiser et al. (1984) who stressed the importance of K deficiency for iron toxicity. Based on the experiments performed, the positive effect of P application should be explained at least partly by an improved K nutrition of the plant and, in consequence, by a more effective Fe(II)-excluding and oxidizing mechanism.

If phosphorus itself affects the plant metabolism in a way similar to potassium, such a feature was not detected by the results presented. This may be due to the fact that the relatively high P content in the Fe-oxide fraction of the soil permitted simultaneous P uptake of those plants who took up high amounts of iron after reductive

dissolution of P-rich Fe oxides. But at present the involvement of potassium in the iron intoxication process seems to be more evident.

The chemical analysis of some other acid sulphate rice soils in Basse Casamance (Table 1) revealed to a large extent low nutrient availability, especially for P and K. In the same area we frequently witnessed well developed rice populations suffering heavily from iron toxicity at the heading stage, finally resulting in very low grain yields. These findings are in agreement with those of Ottow et al. (1982) who noticed the congruency of low nutrient availability and iron toxicity on various soils.

4.4 Management and alleviation

The excessive uptake of Fe(II) by wetland rice seems to be most pronounced shortly after the beginning of submergence (primary iron toxicity) as well as during growth phases of high physiological activity between maximum tillering and flowering (secondary iron toxicity). In terms of management, primary iron toxicity should be easily excluded by transplanting the seedlings not until 5-20 days after the onset of flooding. This delay in planting may vary from soil to soil and depends largely on the rate of

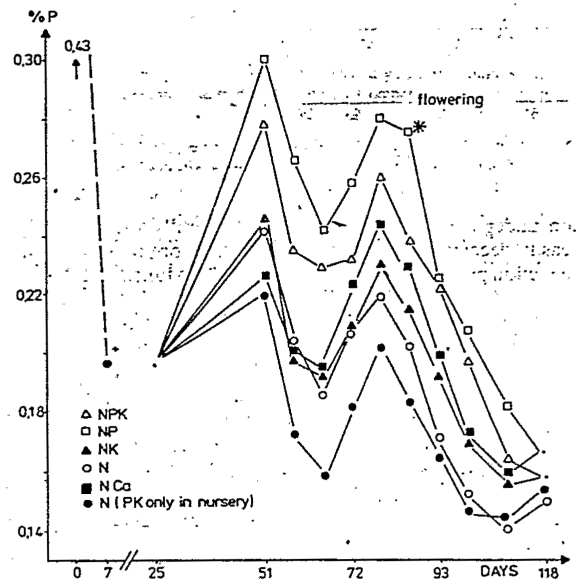

Figure 3 Development of P-contents in the leaf dry matter throughout the growth period (% total phosphorus in the second and third leaf from top)

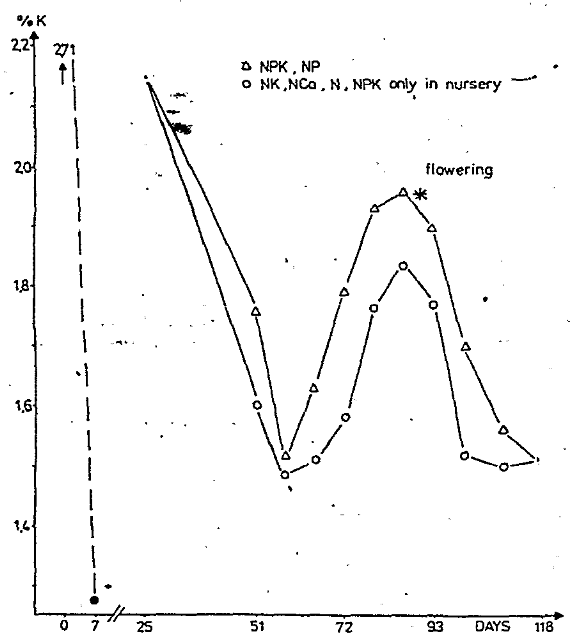

Figure 4 Development of K-contents in the leaf dry matter throughout the growth period (% total potassium in the second and third leaf from top). Compared are treatments with or without P-application

microbial iron reduction under the soil conditions given. Generally speaking, the higher the amount of easily decomposable organic matter, the more intensive and rapid are the bacterial reduction processes (Ottow and Glathe 1973; Munch and Ottow 1983).

Under field conditions, re-precipitation of dissolved ferrous iron as ferrous sulphide usually indicates the end of mineralization with Fe(II) oxides as an electron acceptor. This situation may also be indicated by the formation of a red scum on the flood water and/or on the soil surface. In southern Senegal, we ascribe a major part of rice crop losses to primary iron toxicity because presently most farmers tend to transplant their seedlings immediately after flooding and salt removal. This is a change of customs caused by a significant shortening of the rainy season during the last 15 years.

While primary iron toxicity may be explained by a high sensitivity of the rice plant to Fe(II) stress immediately after transplanting (caused by death and replacement of the primary root system), secondary IT should be considered as a physiological disorder induced by an insufficient supply of essential nutrients involved directly (K, possibly also Ca and Zn) or indirectly (P) (see also Benckiser et al. 1984a, b). An insufficient supply of K, Ca and Zn (in relation to the uptake of N) probably increases root permeability, carbohydrate exudation and iron reduction, which are a pre-

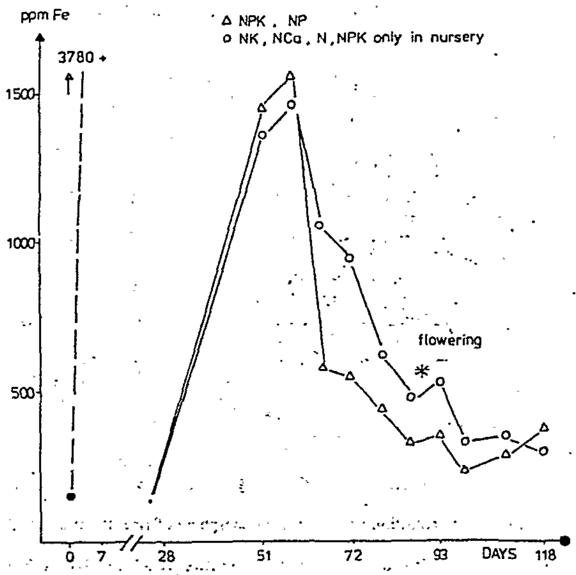

Figure 5 Development of Fe-contents in the leaf dry matter throughout the growth period (ppm total iron in the second and third leaf from top). Compared are treatments with or without P-application

requisite for the breakdown of the effective iron-oxidizing and excluding mechanism, particularly during the most active phase of plant metabolism. This secondary iron toxicity may be alleviated only by fertilization, either in mineral form or by the incorporation of organic remains that are rich in at least P, K, Ca and Zn such as manure and/or ashes. To be effective, intensive, repeated nutrient supply is necessary, particularly on leached acid sulphate soils (which become oxidized upon drying and desalinized by intensive leaching) or on highly weathered Ulti-, Oxi- or oligotrophic Histosols. In fact, secondary iron toxicity can be considered as a 'reclamation disease', which disappears as soon as the soils are regularly fertilized (Japan).

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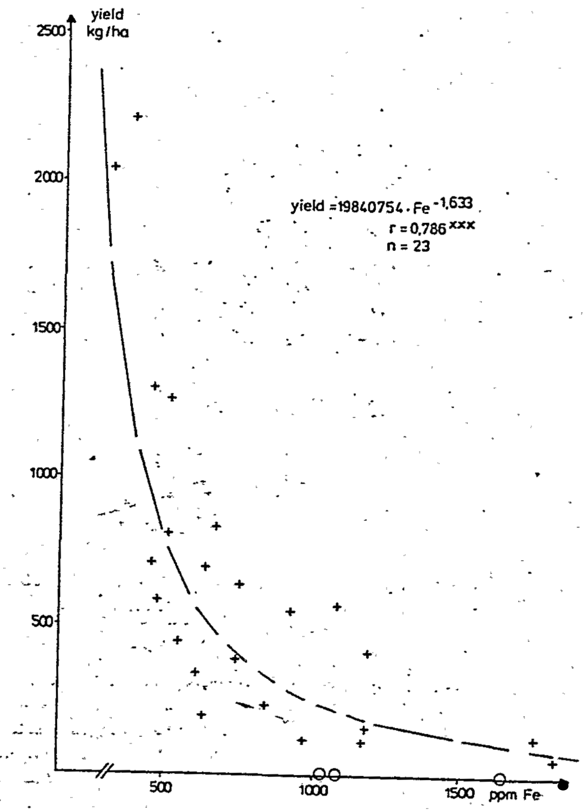

Figure 6 Correlation between Fe-content of leaves at the beginning of the heading stage and subsequent yield in the corresponding plots

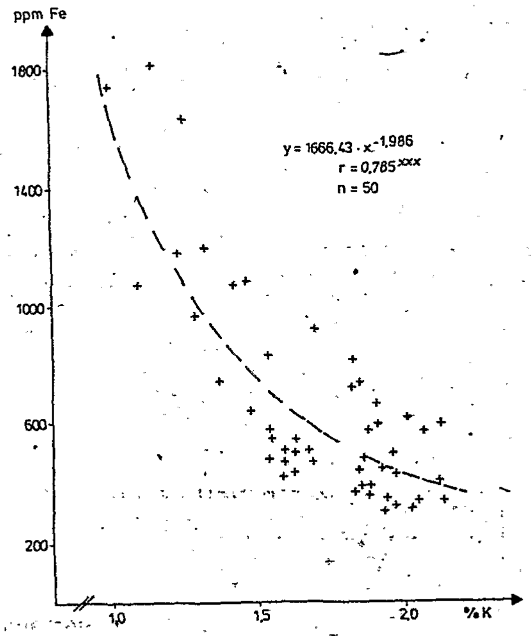

Figure 7 Correlation between K- and Fe-content of the leaves at the beginning of the heading stage

Rice improvement in the mangrove swamps of West Africa

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1 Summary

In West Africa more than 200,000 ha of mangrove swamp, with predominantly acid sulphate soils are being cropped for rice. Rainfall regimes, tidal movement, fresh water supply from river and rainfall, and environmental stress of the mangrove swamp differ from area to area and the need for varieties and farming practices differ accordingly. Constraints of mangrove swamp rice farmers have been identified and research strategies to solve the problems are developed by West Africa Rice Development Association at Rokupr. Results of the research work on Varietal Improvement, Soil and Crop Management, Pest Management, Technology Assessment and Transfer Training are discussed.

Résumé

Le régime de précipitations, le mouvement tidal, l'apport de l'eau douce des rivières et précipitations, ainsi que les stress de l'environnement des mangroves, différent d'une place à l'autre. C'est pour cela que les pratiques d'aménagements doivent être différentes, comme différentes doivent être aussi, les variétés de riz cultivées.

L'association pour le Développement de la Riziculture en Afrique Occidentale de Rokpur, a étudié les contraintes des 'rizières profondes' et a élaborée des stratégies de recherches pour l'amélioration.

L'article discute les résultats concernant l'aménagement du sol et des cultures, la tolérance des variétés, la lutte contre les maladies, la vulgarisation des connaissances et technologies.

Un monitoring du pH et de la teneur en sels a été réalisé durant plusieurs années, en vue de connaître l'acidité et la salinité des sols, et d'expériences à divers doses de fertilisants (NPK) ont été conduites, afin de pouvoir determiner les meilleurs reponses de plantes.

Au Sierra Leone, l'application de l'azote par injection d'une solution aqueuse d'urée à 20 cm de profondeur a donné d'excelents résultats. De même, l'application de 20 kg P/ha sous forme de superphosphate a augmenté l'efficacité de l'azote et a apporté d'importants surplus de récolte. Par contre, en Gambie, seul le phosphore a été l'élément nutritif déffîcitaire et l'application de l'azote n'a pas apporté d'augmentation de récolte.

La potassium, seul ou en différentes combinaisons, n'a pas apporté non plus d'augmentation de récolte.

En 8 années, environs 3000 variétés/lignées de riz ont été introduites et triées pour des conditions de mangroves à influence tidale et non-tidale.

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