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SOIL PROPERTIES AND RICE YIELD IN HIGHLAND MARSHES OF BURUNDI

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ABSTRACT

To identify the factors influencing rice (*Oryza sativa* L., cv "Yunnan 3") yield, 37 highland (1,300 - 1,700 m asl) marsh soils previously cultivated with or without water control, were sampled. Physical soil characteristics were related to organic carbon (C) content which ranged between 8.5 and 360 g C kg^{-1}. When the soils were flooded, the redox potential (pE) decreased from 9.5 to 3.5, pH increased (from 4.6 to 6) and Fe^{2+} dominated the exchangeable cations (48% of the ECEC). Exchangeable Fe^{2+} and iron saturation ratio Fe^{2+}/ECEC increased with pH and C content. The shift between exchangeable cations was better seen when concentration per unit volume rather than mass was used. Yields were greater (up to 6,000 kg ha^{-1}) in waterlogged eutrophic mineral soils belonging to the USDA Soil Great Groups: Tropaquent, Tropaquept, Hydraquent. Acid peat soils (Tropohemist, Troposaprist) were less suitable, and were suspected to induce iron toxicity. Potential yields were computed from climatic data and observed data recorded during the rice cycle. Mean grain yield (2,800 kg ha^{-1}) was 27% of the potential yield. Irrespective of diseases, the marshes seemed to have the same climatic yield potential. Though yield losses due to diseases averaged 16% of the potential yield, soil water control and nutrient availability were the main limiting factors of rice yield under farmer's practice in the marshes of Burundi.

Key Words: Exchangeable Iron, flooding, oligotrophy, peat, wetlands

RÉSUMÉ

Pour identifier les facteurs influençant les rendements du riz (*Oryza sativa* L., cv "Yunnan 3"), 37 sols de marais d'altitude (1300-1700 m) précédemment cultivé en riz avec ou sans contrôle de l'eau ont été échantillonnés. Les caractéristiques physiques des sols sont corrélées au taux de carbone organique (C) (entre 8.5 et 360 g C kg^{-1}). Quand les sols sont submergés, le potentiel redox diminue (de pE=9, 5 jusqu'à pE=3,5), le pH augmente (de 4, 6 à 6) et Fe^{2+}domine les cations échangeables (moyenne 48% de la CEC). Les changements entre cations sont plus visibles si les concentrations par volume sont utilisée plutôt que par masse. Le Fe^{2+} échangeable et le taux de saturation en fer Fe^{2+}/CECE augmente avec le pH et le C. Les rendements sont les plus élevés (jusqu'à 6000 kg ha^{-1}) en sols submergés d'eutrophes minéraux appartenant aux Grands Groupes de la classification américaine suivants: Tropaquent, Tropaquept, Hydraquent. Les sols tourbeux acides (Tropohemist, Troposaprist) sont moins favorables, et pourraient induire une toxicité ferreuse. Des rendements potentiels ont été calculés à partir de données climatiques et des longueurs de cycle. Le rendement moyen (2800 kg ha^{-1}) représente 27% du rendement potentiel. Les marais semblent avoir le même potentiel climatique. Comme les pertes de rendement dûes aux maladies représentent 16% du rendement potentiel, le contrôle de l'eau et la disponibilité des éléments nutritifs sont les facteurs limitants principaux pour le riz dans les conditions de culture actuelles dans les marais du Burundi.

Mots Clés: Fer échangeable, oligotrophie, tourbe, submersion, marais

INTRODUCTION

Highland swamps in Burundi (112,000 ha) are increasingly important for food production especially since the introduction, in 1982, of a cold-tolerant rice cultivar (Loevinsohn and Wang'ati, 1992). The wetlands are seasonaly slightly waterlogged and drained, the amplitude of the water table being about 0.5 m. The wetlands were traditionally cultivated for maize and beans only during the dry season (July-September). Large areas of wetlands at an altitude of 1,300 - 1,700 m, are now cultivated with rice without water control during the second part of season (January-June) (Hennebert, 1991). Rice yields vary widely from 100 to 6,000 kg ha^{-1}. Obvious sources of yield variation are diseases, soil nutrient supply, and water regime plus the interaction of these factors. Diseases have been intensively studied and surveyed by phytopathologists and breeders (Detry *et al.*, 1989). The most important are pyriculariosis and bacteriosis. Breeders have attempted to obtain resistant varieties.

The physical and chemical properties of wetland soils are not well known. They vary widely. Texture, for example, can be clayey, sandy or peaty. Buried peat horizons frequently occur at 0.2-0.5 m. According to the water regime, the soils are alternately chemically reduced and oxidised. Reduction occurs along a defined chemical pathway. Microorganisms need electron acceptors to complete the oxidation of organic matter and obtain energy. Under drained soil conditions, the electron acceptor is gaseous oxygen. When submerged, however, the rate of diffusion of 0_2 from the atmosphere becomes too low. The environment becomes more reduced and the redox potential decreases. Other electron acceptors are used; namely, nitrate, manganese oxide, and iron oxide (Table 1). Soluble Mn^{2+} and Fe^{2+} may then accumulate up to toxic level (Ponnamperuma, 1972).

In Burundi, water tables are not yet controlled by farmers. Extension services are not familiar with the management of consecutive irrigation for rice and drainage for beans or potatoes. In peat soils, permeability is so high that it is hardly possible to keep the water table above the soil surface. The objective of this study was to improve, by a survey in the farmers' fields, the knowledge of the wetland soils used for rice production in the highlands of Burundi, and identify the soil characteristics influencing the paddy yields.

TABLE 1. Theoretical reduction sequence in flooded soils, e^-/H^+ ratio, and comparison with observed pE/pH relationships

Half-reaction of reduction	e^-/H^+	pE/pH
Theoretical		
$0_{2g} + 4H^+ + 4e^- \longleftrightarrow 2H_20$	1/1	pE + pH = 15.2
$2N0_3^- + 12H^+ + 10e^- \longleftrightarrow N_2 + 6H_20$	1/1.2	pE + 1.2 pH = 19.9
$Mn0_2 + 4H^+ + 2e^- \longleftrightarrow Mn^{2+} + 2H_20$	1/2	pE + 2 pH = 24.0
$Fe(0H)_3 + 3H^+ + e^- \longleftrightarrow Fe^{2+} + 3H_20$	1/3	pE + 3 pH = 22.6
$Fe_3(0H)_8 + 8H^+ + 2e^- \longleftrightarrow 3Fe^{2+} + 8H_20$	1/4	pE + 4 pH = 30.9
Observed		
oxidised soils (pE>6)		pE + 1.43 pH = 16.05
reduced soils (pE>6)		pE + 2.81 pH = 20.35
all data		pE + 3.87 pH = 27.08

Theoretical pE/pH relationships calculated from Lindsay (1979) [activities of solid phases = 1, pN_2 = 78 kPa, $(NO_3^-) = (Mn^{2+}) = (Fe^{2+}) = 10^{-6}$ M].

MATERIALS AND METHODS

Soil sampling and water regime. Two groups of soil samples were collected in the Ap horizon. The first group comprised of 15 samples collected from plots of 2 m by 3 m in sites of the 1989 cultivar trial of the "Highland Rice Improvement Programme" (Detry *et al.*, 1989), in the Kirimiro, Buyenzi, Bugesera and Bweru region (Fig. 1). The plots were irrigated and lightly fertilised with 30 kg N, 30 P_2O_5 and 30 K_2O ha^{-1}. Samples from two waterlogged marshes with either lower C content (9 g kg^{-1}, intense hill erosion deposit) or very high C content (360 g kg^{-1}, peat) in the Kirimiro and the Buyogoma region were also included. Soil samples were collected at harvesting and stored in plastic containers at their initial water content until analysis.

The second group comprised of 20 composite soil samples collected from 15 marshes of the Buyenzi and Bweru region in october 1989. One composite sample for a given marsh was prepared from subsamples (20 subsamples ha^{-1}). A total of 960 subsamples were collected. The water level at sampling was between 0.2 and 0.6 m below the surface. The samples were kept in plastic containers at their initial water content prior to analysis. A sample of a drained histic marsh from the Kirimiro was included in this group. These soils were Tropaquent, Tropaquept, Hydraquent, Tropohemist and Troposaprist (Soil Survey Staff, 1990).

Soil analysis. Bulk density and porosity were measured on an undisturbed cylinder core of 0.1 dm^3, dried at 40 °C. Particle density was determined using an air pycnometer (Eijkelkamp), organic C by wet oxidation (Nelson and Summers, 1982) and total N by the Kjeldahl method (Bremner and

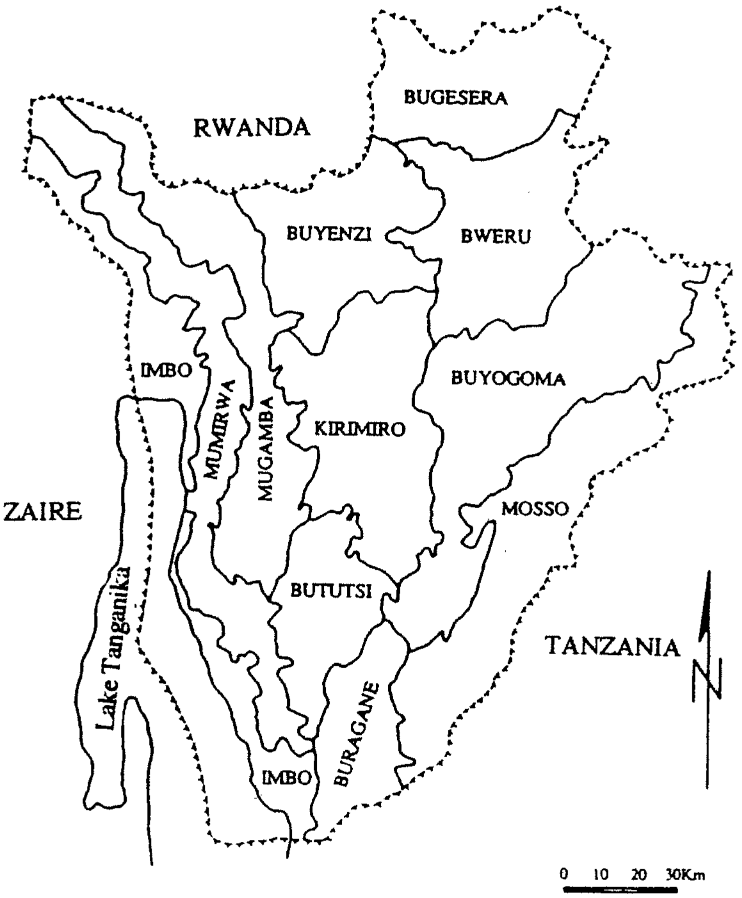

Figure 1. Map of Burundi showing Administration Divisions

Mulvaney, 1982). Redox potential and pH were measured differently depending on whether the soil was waterlogged at sampling or not. The electrodes used were platinum/calomel and PE 50 WTW. For samples saturated with water, the electrodes were placed at 0.1 m below the surface of the soil in the plastic containers. For unsaturated samples, a suspension of undried soils in distilled water was used, basing on a solid/water ratio of 1:5, in narrow tubes to minimise contact with air. The electrodes were placed in the bottom of the tubes for one hour. Redox potential (Eh) was calculated and expressed as $pE = Eh/59.2$ at 25 °C (Lindsay, 1979). Like $pH = - \log (H^+)$, $pE = - \log (e^-)$, where (e^-) is the activity of electrons in the solution relative to the activity of electrons in the H_2/H^+ redox reference reaction. pE is, therefore, a relative expression of the concentration of electrons in a solution. pE decreases as (e^-) increases, i.e., as the environment becomes more reduced.

Free iron from oxyhydroxide was extracted by the dithionite-citrate-bicarbonate (DCB) method (Olson and Ellis, 1982), and measured by atomic absorption spectrophotometry. Exchangeable Ca^{2+}, Mg^{2+}, Na^+ and K^+ were extracted from dried samples by ammonium acetate solution 1 M of pH 7, and exchangeable acidity by unbuffered 1 M KCl solution. Exchangeable Fe^{2+} was extracted by shaking 5 g (dry weight basis) fresh samples of the soil with 100 ml of 1 M KCl solution for one hour in capped tubes. The headspace was previously purged with butane to avoid reoxydation. The soil suspension was then rapidly filtered under vacuum in a Buchner funnel filled with 10 ml of 0.05 M reductant $SnCl_2$. Exchangeable bases and Fe^{2+} were measured by atomic absorption spectrophotometry. The 1 M KCl extracted acidity was titrated with 0.005 M NaOH. Effective CEC was calculated at the reduced state ($pE<6$) as the sum of Ca^{2+}, Mg^{2+}, K^+, Na^+ and Fe^{2+}, and at the oxidised state ($pE>6$) as the sum of Ca^{2+}, Mg^{2+}, K^+, Na^+, Al^{3+} and H^+. Olsen P was extracted with 0.5 M Na_2CO_3 solution at pH 8.5, and measured by the ammonium vanado-molybdate photometry method (Olsen *et al.*, 1954).

Yield and diseases. Only rice cultivar "Yunnan 3" was used in this study. For the first group of soils, paddy yields and disease impacts were measured using Detry *et al.* (1989) method. Zero yield (due to extreme water stress at transplanting) were excluded during data analysis. Overall, 9 yield data were excluded.

For the second group of soils, paddy rice yields in the farmers' fields were estimated from surveys (Bagambake *et al.*, 1989). Twenty samples per ha^{-1} were taken along grids in the farmers' fields. Each sample consisted of five rice plants. To compute yield, a density of 35 plants per metre was used. Yields greater than 7.5 Mg ha^{-1} were considered extreme values and were excluded from the analyses. A total of 16 yield data were analysed.

Disease incidence (percentage of panicles showing symptoms) and severity (weight loss of diseased panicles compared with healthy ones) were measured for pyriculariosis and bacteriosis in the first sample group, and for pyriculariosis in the second group. Sterility (number of empty grain divided by the total number of grains per panicle) was also measured in the first group. Incidence, severity and sterility enable calculation of the proportion of loss due to each disease (Detry *et al.*, 1989).

Potential yield. The climatic potential yield, in the absence of any limiting factor like soil, water, disease, insect damage and weeds, was calculated by a very general net biomass production model based on climatic data, group of photosynthesis response to temperature, and duration of the growing cycle (FAO, 1979). Temperature and insulation of 21 sites were recorded and extrapolated with corrections for altitude from available year-book records (Tessens, 1989). The length of the cycle of "Yunnan 3" observed in each sites (mean = 225 days) was used, substracting 20 days for the maturation period. Harvest index (grain yield/biomass) was fixed at 40%, and relative humidity of the paddy at 14% using data collected in a low altitude and high yield area of the country, in the Imbo region (Fig. 1) (Schaelbroeck, 1989). The model output is an approximation of potential rice production in highland valleys. Correlation, regression and factor analysis were executed with Statistical Package for Social Sciences/PC (1990) software.

RESULTS

Soil properties. Compared with upland soils, soil bulk densities were low, and porosities were high (Table 2). A flooded peat showed porosity of 0.88 $m^3 m^{-3}$ and water content of 5.88 g g^{-1} on dry basis. Particle density of the most mineral soils reached the classical value of 2,650 kg m^{-3} (Sanchez, 1976). Bulk density, particle density, porosity, ash content, C and N content were all correlated with each other (Table 3). Carbon content varied widely among the soils (Table 2). Carbon to N ratio averaged 14, a classical value for alternately flooded and drained soils (Sanchez, 1976).

At the oxidised state (chosen from pE histogram as pE>6), mean pH was 4.6, indicating the soil to be acidic. Mean pE+pH was 14.1, wich is typical of oxidised soils, having been flooded or not (Lindsay, 1979). In reduced state (pE<6), mean pH significantly shifted upward to 6 and mean pE+pH downward to 9.5 (Table 2, Fig. 2). pE and

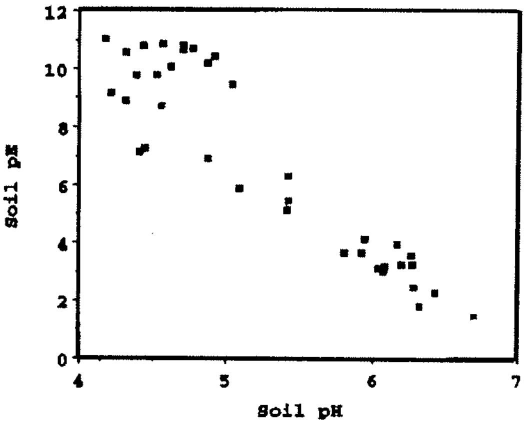

Figure 2. Soil pE versus soil pH

TABLE 2. Selected chemidal and physical charateristics of the study soils

Group		Density (kg m^{-3})		Porosity	Ash	C	Kjeldah N	C/N	DCB Fe
		Bulk	Particle	($m^3 m^{-3}$)	(g g^{-1})	(g kg^{-1})	(g kg^{-1})		(g kg^{-1})
all dry	mean	545	2030	75	64	151	10.0	14	37
	min	140	1165	54	27	9	7	7	12
	max	1182	2728	88	92	360	20.7	28	81

		Exchangeable							
		Ca^{2+}	Mg^{2+}	K^+	N^{a+} (mmol kg^{-1})	Al^{3+}	H^+	ECEC(dry)	P (mg kg^{-1})
all dry	mean	37	9	2	2	22	6	78	108
	min	6	1	0	0	0	0	16	15
	max	181	35	4	7	59	16	220	530

Group		pE	pH	pE+pH	Exch. Fe^{2+}	ECEC wet	Fe^{2+}/ ECEC
					mmol$_c$ kg^{-1}		
1(pE<6)	mean	3.5	6.0	9.5	86	153	48
wet	min	1.4	5.1	8.1	0	18	0
	max	5.9	6.7	11.0	217	414	0.87
2(pE>6)	mean	9.5	4.6	14.1	7	n/a	n/a
dry	min	6.3	4.2	11.5	0		
	max	11.0	5.4	15.5	3.4		

n/a: not applicable

pH were inversely correlated, but the correlation was not significant among the oxidised groups with pE>6 (Table 3).

Soil content of exchangeable Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+} varied widely among the soils (Table 2). The Ca^{2+}/Mg^{2+} ratio increased with C content (Table 3). The contents of exchangeable Al^{3+} and H^{+} in drained wetland soils were similar to those of the ferralitic acid soils of the surrounding hills (calculated from Tessens, 1993).

All the soils contained DCB reducible iron from oxyhydroxides. There was no correlation between this value and other soil variable investigated. Exchangeable iron appeared at pE<6, when the soils were waterlogged. Equilibrium calculations indicated that this exchangeable Fe was Fe^{2+} (constants from Lindsay, 1979). As pE decreased below 6, and pH correspondingly increased, Fe^{2+} became the dominating cation of the exchange complex (Table 2). Exchangeable iron decreased as pE decreased and pH increased (Table 3, Fig. 3). Iron saturation ratio Fe^{2+}/ECEC followed the same trend, ,and increased with C content. Under flooding, Fe^{2+} displaced the other cations from the exchange complex. Cation dynamics under flooding and drainage was best expressed by the correlation cycle obtained by a factor analysis (Fig. 4). This view was improved

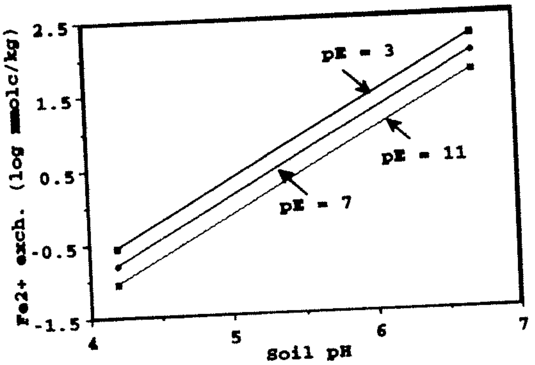

Figure 3. Exchangeable Fe^{2+} versus soil pE and soil pH

TABLE 3. Relationships between soil characteristics and yields

						n	p	r
Bulk density	=	-2.32	C	+	896	37	0.000	0.857
Solid density	=	-3.88	C	+	2.62E+3	37	0.000	0.883
Porosity	=	6.53E-4	C	+	0.647	37	0.000	0.804
Ash	=	-1.86E-3	C	+	0.914	37	0.000	0.972
Nitrogen	=	0.558	C	+	1.53	37	0.000	0.950
C/N	=	0.0217	C	+	11.20	37	0.000	0.549
pE	=	-2.81	pH	+	20.35	17	0.000	0.931
pE	=	-1.43	pH	+	16.05	20	0.204 NS	0.296
pE	=	-3.87	pH	+	27.08	37	0.000	0.924
log (Fe^{2+} exch)	=	1.10 -0.06	pH pE	+ -	5.00	37	0.000	0.807
Fe^{2+}/ECEC wet	=	-0.148	pE	+	0.989	17	0.009	0.615
Fe^{2+}/ECEC wet	=	0.620 1.25E-3	pH C	+ -	3.45	17	0.001	0.812
ECEC wet	=	0.793 137	C pH	+ -	792	17	0.000	0.852
Ca^{2+}/Mg^{2+}	=	0.0100	C	+	2.89	37	0.000	0.615
P	=	262	Al%	+	22.31	37	0.002	0.503
Yield (Group[1])	=	-9.07E-3	C	+	3.42	9	0.047	0.671
Yield (All)	=	-7.76E3	C	+	4.32	25	0.011	0.501

Units of variables: see Table 2. Al%:Al^{3+}/ECEC dry. Yield: Mg ha^{-1}

when the mole of charge per unit volume (Fig. 4a) rather than per unit mass (Fig. 4b) was used. In Fig. 4a, factor 1 (39% total variation) is the cationic distribution of oxidised soils shared in basic and acidic cations. Factor 2 (26%) is the oxidation status factor. Iron dominated at low pE. The three groups are inversely related. If the concentrations per unit mass were used, the oxidation status would be represented by the third factor.

The ECEC of the soils, as defined above, significantly increased with waterlogging (Table 2), and was influenced by the pH and the C content (Table 3). Olsen P values were positively

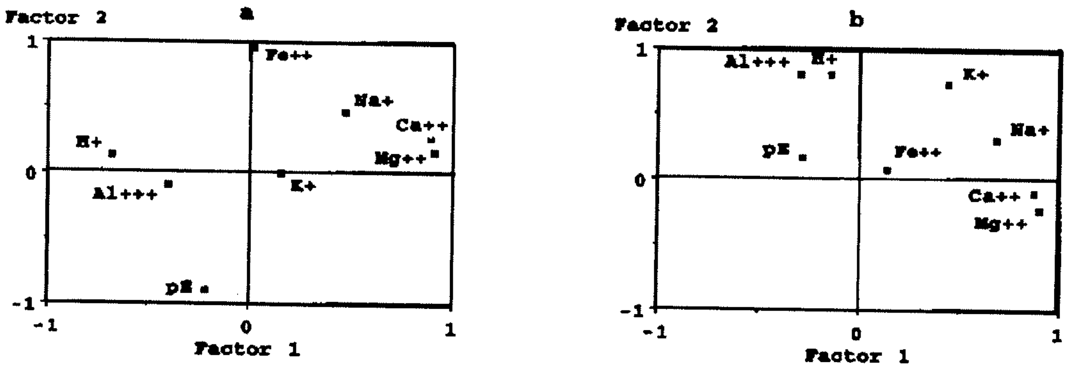

Figure 4. Cation dynamics of the exchange complex (factor analysis). (a) mol$_c$ per volume, (b) mol$_c$ per mass

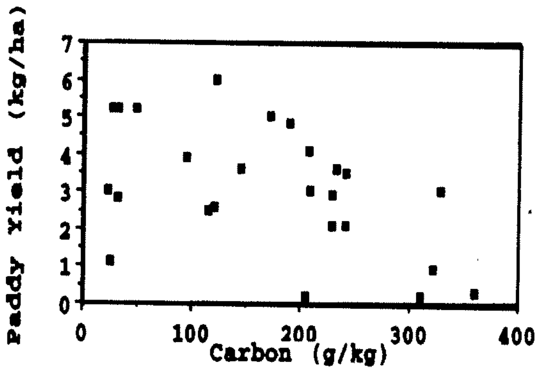

Figure 5. Yield versus soil carbon

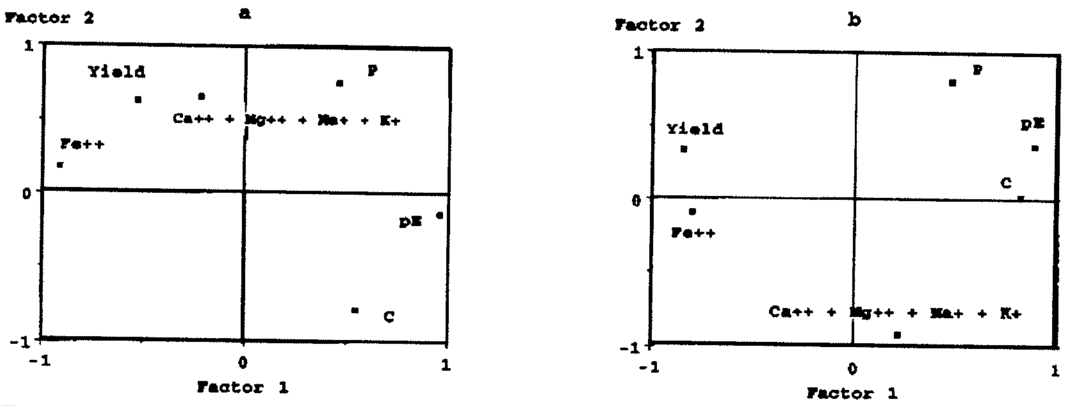

Figure 6. Yield and soil characteristicsat harvest (factor analysis). a: mol$_c$ per volume, b: mol$_c$ per mass

correlated with the aluminum saturation ratio (Al^{3+}/ECEC) but not with the C or exchangeable Fe^{2+} concentration.

Soil-diseases relationships. A positive correlation was obtained between exchangeable Ca^{2+} concentration, or exchangeable Ca^{2+}/Mg^{2+} ratio, and the loss of yield due to pyriculariosis (result not shown). This suggests that eutrophic marshes were conducive to this disease, as has been previously reported (Maraite, 1990). The sterility (number of empty grain divided by the total number of grain per panicle) is influenced by the content of DCB extractable iron of the soil, but those correlations were largely due to 2 and 1 singular points, respectively.

Yields decreased significantly as soil C increased (Fig. 5), but the relationship was rather weak (r^2= 0.5; Table 3). The simultaneous influence of different soil characteristics on yield at harvest (first group of data) is seen in Fig. 6. The soil characteristics used in this factor analysis were found to be uncorrelated. Again, the relationships were more obvious when soil cations concentrations were compared on a volume basis (Fig. 6a). Factor 1 (43% of the total variation) was the oxidation status and 2 (38%) was the cationic and organic status, with a negative relationship between the basic cations and the C content. Yields were highest in reduced eutrophic mineral soils.

The influence of uncorrelated soil characteristics from dried samples, on yield (first and second group of data) is presented in Fig.7. The relationships were stronger when the concentrations were expressed on volume basis. Factor 1 (43% of the total variation) was the cationic distribution and 2 (38%) the C content and the yield. Yields were negatively influenced by the C content; mineral soils resulted in greater yields than their organic matter counterparts (Table 3). The same conclusion is valid if effective saturation ratios were used rather than the cations per unit volume.

Observed yield data, yield corrected for diseases and sterility, and potential yield of 21 sites are presented in Table 4.

DISCUSSION

Yields were greatest in waterlogged eutrophic mineral soils (reduced, rich in exchangeable

TABLE 4. Rice yields and limiting factors

Yield	Mean (Mg ha^{-1})	Range (Mg ha^{-1})	%
Observed (n = 25)	2.8	0.2 - 6.0	27
Corrected for pathology	4.5	0.5 - 9.0	43
Potential (computed)	10.4	8.5 - 11.5	100

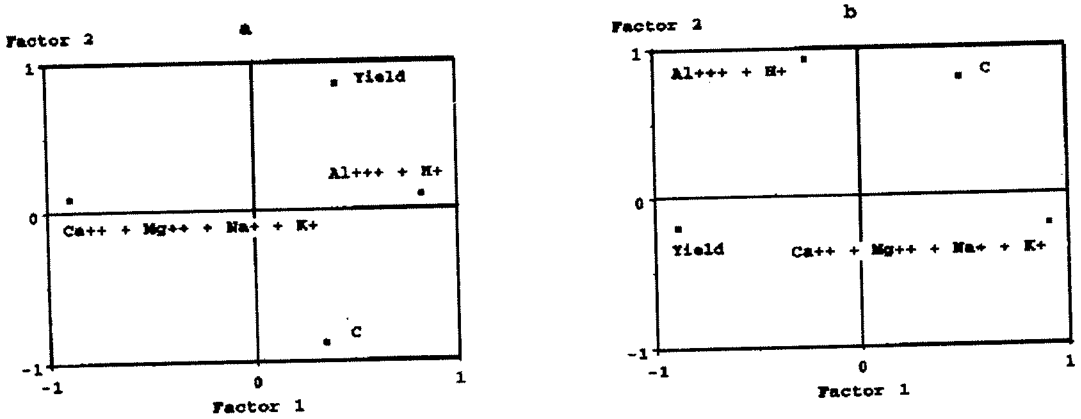

Figure 7. Yields and soil characteristics from dried samples (factor analysis). (a) = mol_c per volume, (b) = mol_c per mass

bases and poor in C), i.e., Tropaquent, Tropaquept, and Hydraquent. Acid peat soils, namely, Tropohemist and Troposaprist were less suitable. The discussion that follow is in terms of soil chemistry, including the iron toxicity to rice, and in terms of land and crop management technology.

Factors affecting soil chemistry

pE and pH buffer in wetland soils. A theoretical reduction sequence is presented in Table 1. Each reaction has an equilibrium constant at 25 °C. If numerical values are attributed to the activities of the ions in solution, simple pE/pH relationships would be obtained. The pE/pH data are included in Table 1. The observed pE/pH relationship at pE>6 was not significant, but was fairly similar to the theoretical one during the reduction of a mixture of 0_2 and $N0_3^-$. On the other hand, the pE/pH relationship in reduced soils (pE<6) approached the theoretical one for the reduction of $Fe(OH)_3$. Overall data were closer to the pE/pH relationship obtained with mixed Fe^{2+}/Fe^{3+} amorphous ferrosic oxide $Fe_3(OH)_8$. Since these wetland soils were seasonnally drained and waterlogged by a fluctuating water table, and since top soil was never dry, iron oxide could easily form in the soil.

The pE and pH relationship of all the soils would be ruled by the same redox buffers, iron hydroxide when submerged, and 0_2 when drained. Differences among soils would be primarily due to the amount of acidity present. It seemed that most soils were subjected to acidification by seasonal ferrolysis (Van Breemen *et al.*, 1983). Organic and peaty soils were the most affected.

Control of exchangeable Fe^{2+} in submerged soils. Higher pH under flooding induced variable charges, exchangeable Al^{3+} to precipitate, and H^+ to vanish. The resulting negative sites were occupied by Fe^{2+}, which became the dominant cation. It was observed that exchangeable Fe^{2+} and Fe^{2+} saturation ratio Fe^{2+}/ECEC increased with pH. However, according to the hydroxide solubility equations (Table 1), the activity of Fe^{2+} in solution in equilibrium with a solid phase decreases, as the pH increases. This divergent evolution is nevertheless, consistent with previous findings on acid sulfate soils, demonstrating a negative relationship between Fe^{2+} activity in solution and exchangeable Fe^{2+} (Moore and Patrick, 1989). It was concluded that the exchange reactions interfered with the solution equilibrium. The present study suggest that the significant increase in the sum of the cations (ECEC) during flooding could also partly explain the divergent evolution of Fe^{2+} in solution and on the exchange surfaces.

Factors limiting rice yield

Iron toxicity to rice. There was no significant correlation between Fe^{2+} saturation ratio and the paddy rice yield. However, yield decreased with C, while the Fe^{2+} saturation ratio increased with C (Table 3). Yield reduction due to Fe toxicity occurs when Fe^{2+}/ECEC reaches 75% or more (Moore and Patrick, 1989; Genon *et al.*, 1993).

Diseases, water and nutrient. The limiting factors for rice production can be evaluated based on the results shown in Table 4. The variability of potential yield was low. Longer cycles partly compensated for colder temperatures. Therefore, the marshes at altitudes 1,300-1,700 m seemed to have similar climatic potential. Mean yield was about 27% of the maximum. This agrees with the general estimation of yield in traditional farmer's fields of about 25% of the maximum yield (FAO, 1979).

Losses in yields due to diseases and sterility were assessed. The yields multiplied by a correction factor cancelling those losses reached 43% of the potential yield. The main limiting factors are, therefore, water and nutrient availability. Further study in controlled sites showed that oligotrophy was widespread and very severe in peat soils (Genon *et al.*, 1993; Hennebert, 1993).

Agrotechnology. Nutrient availability can be improved by organic matter transfer, liming and fertilizers application. Organic matter is lacking, and is used largely in upland food crops. Lime and fertilizers are considered by farmers to be too expensive, especially when the demand for rice on the local market is low. They are sometimes unavailable. So, the first proposal to farmers for paddy soil management in rice production should be to control the water level on mineral soils. The second is the use of lime and fertilizers. Peat soils should be devoted to acid tolerant crops, with a moderate drainage.

CONCLUSIONS

Carbon content of the soil influences physical properties, iron dynamics and paddy rice yield in the marshes of Burundi under uncontrolled water regime. One possible mechanism of the action of carbon on yield could be the promotion of increased exchangeable Fe^{2+} (absolute and relative to the other cations) in organic soils.

The highest yields were obtained on reduced (water saturated) eutrophic mineral soils. Peats were less suitable. The yields (mean 2,800 kg ha^{-1}) were much lower than the computed potential. Therefore, water and nutrient availability during the entire rice crop growth are the main limiting factors of rice production in the swamps of Burundi. It is recommended that the first step in paddy soil management should be to control the water level on mineral soils. Peat soils should be devoted to acid tolerant crops.

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