Nutrient Availability in the Surface Horizons of Four Tropical Agricultural Soils in Mali

M. Soumaré*, A. Demeyer, F.M.G. Tack & M.G. Verloo

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Summary

Studies of nutrient availability are important for the understanding and the estimation of soil fertility in areas like West Africa, where low nutrient availability is still one of the major constraints for food production. Physico-chemical soil analyses were used to assess the fertility status of the surface horizon samples of four Malian agricultural soils, (Bougouni, Kangaba, Baguinéda and Gao abbreviated as Bgni, Kgba, Bgda and Gao). Soil texture was sandy loam for Bgni and Kgba, sandy clay loam for Bgda and loamy sand for Gao. Soil pH values varied from moderately acid for Bgda to neutral for the other sites. Organic carbon ranged from very low (for Gao) or low (for Bgni and Bgda) to medium (for Kgba). Total N, P and CEC were low for the four soils. Available contents of Fe and Mn in all soils, except Gao, were higher than the critical levels while available Cu and Zn contents (except in Kgba) were below or close to it. Results indicated that Kgba soil had a better macronutrient status for plant growth than the other sites.

Résumé

Disponibilité des éléments nutritifs dans les horizons superficiels de quatre sols tropicaux agricoles du Mali

Les études de la disponibilité des éléments nutritifs sont nécessaires pour la compréhension et l'estimation de la fertilité des sols des régions comme l'Afrique de l'ouest où la baisse de la fertilité des sols constitue une contrainte majeure pour la production alimentaire. Des méthodes d'analyses physico-chimiques ont été utilisées pour évaluer le statut de la fertilité des horizons superficiels de quatre sols agricoles du Mali (Bougouni, Kangaba, Baguinéda et Gao abrégés comme Bgni, Kgba, Bgda et Gao). La texture est limono-sableuse à Bgni et à Kgba, limono-argilo-sableuse à Bgda et sablo-limoneuse à Gao. Le pH des sols varie de moyennement acide pour Bgda à neutre pour les autres sites. Le carbone organique varie de très bas (pour Gao) ou bas (pour Bgni et Bgda) à moyen (pour Kgba). La capacité d'échange cationique et les teneurs totales en azote et en phosphore sont faibles pour les quatre sols. Les teneurs en Fe et Mn disponibles dans tous les sols étudiés exception faite pour celles du Mn dans le sol de Gao, sont supérieures aux valeurs minimales exigées. Quant aux teneurs en Cu et en Zn disponibles, elles sont inférieures ou proches des valeurs critiques dans les sols de Bgni, Bgda et Gao. Les résultats indiquent que le sol de Kgba possède un potentiel en macronutriment plus élevé que les autres sites.

Introduction

Soil fertility in Africa is under pressure as an increasing number of farmers attempt to make a living based on what the soil can offer to growing plants (28). Although many studies on soil fertility in Africa have been carried out by research institutions since the sixties, many agricultural areas are still not studied yet. Most small farmers face to the lack of scientific basis for improving the productivity of their soils. According to the classification of soil nutrient balances for arable land of sub Saharian Africa of Stoorvogel and Smaling (29), Mali is one of the countries where even major fertilizer (N, P, K) application rate is low. Maintenance of soil fertility for sustained soil productivity requires proper knowledge of nutrient availability or soil physicochemical characteristics.

Agricultural soils of Mali have not been sufficiently documented and recent data on fertility status are almost not available. Besides that, there is a need for detailed soil micronutrient status in Mali where most of the studies (for e.g. 2, 37) have been made only on major elements.

Since a first estimation about the fertility status of the soils can be obtained by chemical analyses, analytical procedures described by Pauwels *et al.* (21) were employed to assess the plant availability of some essential nutrients such as Ca, Mg, K, P, Fe, Mn, Zn and Cu in the surface horizon of the four Malian agricultural soils. These procedures were chosen because they are relatively simple and within the

Department of Applied Analytical and Physical Chemistry.
Laboratory of Analytical Chemistry and Applied Ecochemistry, Coupure Links 653, B- 9000 Gent, Belgium.
*Corresponding author M. Soumaré (msoumare@hotmail.com).

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capabilities of many laboratories in the developing countries.

The main objectives of this study were to obtain good information about the nutritional capacity and intensity of major (P, Ca, Mg and K) and micro (Fe, Mn, Zn and Cu) nutrients and about some physical characteristics of the surface horizons of four Malian agricultural soils. These informations are used to give appropriate agronomic and environmental advice.

Methods

Site description and sample collection

Mali is a tropical country located in the Sahelian zone (from 10° to 25° N and 12° W, 4° E). Surface horizon samples were taken from four different cultivated soils that had developed under three different climatic zones (Figure 1).

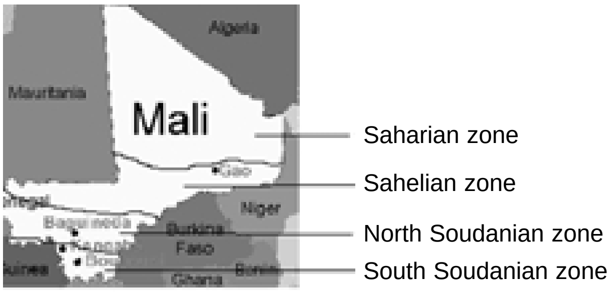

Figure 1: Localisation of the samples areas and the limits of the climatic zones

The Bougouni (Bgni) (11°05' S 7°27'W) and Kangaba (Kgba) (11° 55' S 8°24' W) soils had developed under the southern part of the Sudanian agroecological zone. Annual rainfall in Kgba ranges between 1100 mm to 1500 mm while in Bgni it varies from 1000 to 1300 mm (31). Baguinéda (Bgda) (12°23' S 7°45' W) had developed under the northern part of the Sudanian with annual rainfall varying between 750 mm to 950 mm. Gao (16°18' N 0° GM) is situated in the northern part of Sahelian zone, very closed to the Sahara zone with 150 to 250 mm of rainfall (31). At Bgni site, cotton (*Gossypium hirsutum* L.), maize (*Zea mays* L.), and groundnut (*Arachis hypogaea* L.) are in rotation. For more than 8 years, the Kgba soil is used for the production of maize (*Zea mays* L.). The existence of the system of irrigation at Bgda has made this site usable for rice (*Oryza sativa* L.) production during the raining season and for maize (*Zea mays* L.), groundnut (*Arachis hypogaea* L.) and sometimes vegetables during the dry season. The Gao site is mostly used for sorghum (*Sorghum bicolor* L.), vouandzé and groundnut (*Arachis hypogaea* L.) productions. The corresponding names (from the French classification of 1967) in the American taxonomy are as follows: Ustraptpts, Haplustalfs, Plinthaquepts and Torripsamments for Bgni, Kgba, Bgda and Gao respectively (5). On each site, 20 samples of topsoil (0-10 cm) were taken randomly on an area of about 0.1 ha, mixed to form composite soil samples and air dried by spreading them on a plastic sheet at room temperature.

Analyses

The different analyses were performed according to methods described by Pauwels *et al.* (21). Particle size distribution was performed by dry and wet sieving. Soil pH was measured potentiometrically (Orion model 420A) in a ratio of 1/2.5 soil/water suspension after equilibration for 16 h. Bulk density was determined in the non disturbed samples. Electrical conductivity (EC) and water soluble sulfate were measured in a saturation extract. EC was measured with a Microprocessor Conductivity Meter (LF 537) while the water soluble sulfate by ion chromatography (Dionex 2000i/SP). The organic carbon was analysed by the Walkley and Black method. Total nitrogen was determined using a modified method of Kjeldahl. Cation exchange capacity (CEC) was determined after saturation of the sorption complex with 1M neutral (pH 7) solution of ammonium acetate. Extractable forms of Ca, Mg, Na, K, Fe, Mn, Zn and Cu were extracted with a buffered (pH 4.65) solution of 0.5 M NH_4OAc-0.02 M EDTA with a ratio of 1/5.

Exchangeable Ca, Na, and K were determined with flame emission photometry (Eppendorf Elex 6361). Mg, Fe, Mn, Zn and Cu contained in the different solutions were measured by atomic absorption (Varian SpectrAA 10). Available P was extracted with 0.03 M NH_4F + 0.1 M HCl. Total P was extracted with 18 % $HClO_4$. Total and available P were determined colorimetrically (Spectrophotometer, CE 373) using the Scheel method.

Results and discussions

Physicochemical characteristics

In the four studied soils, the sand fraction dominated (Table 1). Most of the surface horizons of the agricultural soils in west Africa contain more than 50 % of sand (4, 18, 19). This sandy dominance suggests that the soils are quite permeable to air, water and roots, but they have low water holding capacity and poor capacity for storing plant nutrients. According to the soil textural triangle of FAO (8), soils were classified as sandy loam (for Bgni and Kgba), sandy clay loam (for Bgda) and loamy sand for Gao. Clay contents of Bgni and Gao were below the minimum level (12 %) required by Gaucher cited by Horgnies (10). This suggests that these soils are not strong in their structural stability and may be subject to a high erosion. The bulk densities were below the limit level of (1.9 g/cm^3) where root growth is usually stopped (12).

Soil pH varied from moderately acid for Bgda to neutral for the other sites, according to the acidity classes given by Veldkamp (34). This is within an optimal range for growth of maize (*Zea mays* L.), groundnut (*Arachis hypogaea* L.) and rice (*Oryza sativa* L.) (34). According to Sys (30) pH value in Bgda soil (5.67) may indicate P, Ca, Mg, and Mo deficiency while at the other sites (> 5.6) trace elements (such as Fe, Mn, Zn, Cu and Co) deficiency may occur (34). pH values in the four soils indicate that there is no danger from either exchangeable Al or excess of carbonates (15).

The electrical conductivity was below 2 $dS.cm^{-1}$. According to the reference values of the United States

Salinity Laboratory (27), salinity is not expected to affect plant growth. The total N was very low for three soils (Bgni, Bgda and Gao) and low for Kgba. In west and central Africa, levels of 0.125 to 0.2 % of total N are considered as satisfactory (7). Organic matter content was medium for Kgba, very low for Gao and low for Bgni and Bgda (30). Low organic carbon contents in these soils are related to their agricultural use, the very limited organic amendment, and to the fast decomposition of organic matter in the tropical conditions (22, 26). The High C:N ratio (20 - 25.7) confirmed the greater degree of breakdown of organic matter in the studied soils.

According to the reference values of the Laboratory of Soil, Plant and Water of Sotuba (Mali), available phosphorous was from medium (> 5 mg/kg) for Kgba, and very low (5 mg/kg >) for the other three soils (5). Similar results were reported by many authors (23, 24, 33) for tropical ferric and hydromorphous soils. Retention or fixation of P with Fe might be the main reasons of low available P in Bgda (13). Available P in all soils (except Kgba) was below the critical levels (4-29 mg/kg) for rice growth given by Dobermann *et al.* (6). Comparison of total P contents (Table 1) to the data of nine topsoil from the savanna region of Ghana (20) showed high values but according to the Malian reference values (< 200 mg/kg), all soils contained low level of total P (5).

For tropical soils, Kang and Osiname (14) reported a critical extractable sulfate concentration of 8 to 10 g/kg in the surface soil. Using this criterion, all the soils in this study would be considered S deficient (Table 1).

In accordance with the sandy texture and the low organic matter contents, CEC values (Table 2) were low (25).

Table 1
Physicochemical characteristics of the topsoils (0 - 10 cm layer)

Characteristics	Bgni	Kgba	Bgda	Gao
Granulometry				
Sand (%)	74.6	60.8	50.6	81.5
Silt (%)	16.4	26.2	27.4	6.8
Clay (%)	9	13	22	11.7
Texture[a]	sandy loam	sandy loam	sandy clay loam	loamy sand
ρb (mg/m^3)	1.6 ± 0.01	1.6 ± 0.05	1.5 ± 0.01	1.7 ± 0.02
pH_{H_2O}	6.5 ± 0.02	7.0 ± 0.02	5.7 ± 0.01	6.9 ± 0.02
EC[b] (µS/cm)	500 ± 18	488 ± 11	174 ± 11	1843 ± 32
N total (%)	0.042 ± 0.000	0.057 ± 0.004	0.049 ± 0.002	0.019 ± 0.001
Organic C (%)	1.1 ± 0.1	1.5 ± 0.1	1.0 ± 0.2	0.5 ± 0.1
Total P (mg/kg)	131 ± 10	236 ± 32	100 ± 5	114 ± 3
$P_{Available}$ (mg/kg)	1.3 ± 0.2	5.4	0.6 ± 0.1	2.7 ± 0.3
Extractable SO_4[b] (mg/L)	9 ± 0.3	7 ± 0.2	6 ± 2.0	41 ± 4.0

Data are mean ± standard deviation of six replicates. [a]According to the FAO soil textural triangle (Soil Resources, Management and Conservation Service Land and Water Development Division, Rome 1990). [b]Measured in the saturation extract. EC means electrical conductivity.

Table 2
Cation exchangeable capacity (CEC), exchangeable bases (E.B), and exchangeable cation ratios in the topsoils (0 - 10 cm layer)

Characteristics	Bgni	Kgba	Bgda	Gao
CEC (cmol / kg)	2.2 ± 0.40	4.6 ± 0.07	3.1 ± 2	3.0 ± 0.05
E. B. (cmol / kg)				
K^+	0.107 ± 0.00	0.223 ± 0.01	0.07 0 ± 0.01	0.10 ± 0.01
Na^+	< 0.040	< 0.040	< 0.040	0.19 ± 0.01
Ca^{++}	1.24 ± 0.07	2.93 ± 0.07	1.12 ± 0.05	1.80 ± 0.08
Mg^{++}	0.55 ± 0.01	1.39 ± 0.01	0.65 ± 0.01	1.06 ± 0.07
Ca/Mg	2.3	2.1	1.7	1.7
Ca/K	11.6	13.1	16.0	18.0
Mg/K	5.1	6.2	9.3	10.6

Data are mean of six replicates ± standard deviation. < 0.040 means below detection limit.

Defoer *et al.* (4) reported similar results for three major soil types in the southern Mali. Low CEC could be explained by the dominance of kaolinite in the clay fractions and of iron oxides. The dominance of kaolinite and iron oxides of the surface horizon of some Malian soils was reported by N'Diaye *et al.* (18) and Traoré (32). Low CEC values indicate that the studied soils may have a limited capacity to retain nutrients, specially cations and may be subject of a high risk of leaching (26).

Exchangeable Ca, Mg, K and Na

Exchangeable cations followed the normal order (Ca> Mg> K> Na) for all agricultural soils (17). The relative high exchangeable Ca content is in agreement with Veldkamp (34) and may indicate a near neutral pH which is desirable for most plants, microorganisms and good for soil structure. According to the norm of interpretation given by Gaucher cited in Hincourt (9), exchangeable K varied from very low (for Bgda) or low (Bgni and Gao) to medium (Kgba) (Table 2). Veldkamp *et al.* (35) and IER (11) reported similar results. However, exchangeable K in all soils (except Bgda) were within the critical levels (0.1 – 0.4 cmol/kg) given by Wopereis *et al.* (37) for rice growth (*Oryza sativa* L.). The Bgni, Bgda and Gao soils were low in exchangeable Ca and Mg while Kgba was medium (Gaucher cited in Hincourt (9)). Low exchangeable Ca, Mg and K in Bgda is not surprising since it is an acid soil and submitted to double cropping system. Low exchangeable Ca, Mg and K at Bgni could be explained by the low input of organic fertilizers as compared to Kgba which received every year farm compost as fertilizer. Medium level of exchangeable Ca and Mg at Gao could be related to the aridity of the climate under which the risk of leaching is very low.

The Ca/Mg ratios of the four soils (Table 2) were within the optimal range of 1.5 to 5 given by Boyer (3). The Ca/K ratios in all soils except Bgni were higher than the upper limit level of 12 given by Boyer (3). This indicates that only the Bgni soil had an optimal Ca/K ratio. According to the optimal range (2- 5) of Mg/K ratio given by Euroconsult (7), only the Bgni soil presented a good equilibrium between Mg and K (Table 2).

In general, the soils have a low natural fertility as indicated by the low content of total N and P, organic matter and exchangeable bases. Since the utilization of mineral fertilizers by the farmers of the different sites is financially prohibitive, the studied soils must be fertilized adequately by-products (crop residues, manure and farm compost) that are available in the different regions in order to complement their inherent fertility so as to supply the necessary nutrients to meet the requirements of field crops such as rice, maize, cotton and sorghum.

Micronutrients availability (Single extraction with NH_4OAc EDTA pH 4.65)

The NH_4OAc EDTA extractable or available trace metal contents were compared to reference values given by Verloo (36) for the same type reagent. In all soils, available Fe were higher than the critical levels given by Verloo (36) and above the minimum amount (> 4.5 mg/kg) required by *Sorghum bicolor* L. (16) (Table 3).

Available Fe followed this order Bgda> Kgba> Bgni> Gao. The highest amount of available Fe in Bgda soil is not surprising because this soil is used for rice (*Oryza sativa* L.) production under irrigation and that condition may create a reduction of Fe^{3+} to Fe^{2+} (13). Available Mn was above the critical level (10 mg/kg) given by Verloo (36) for Bgni, Kgba and Bgda and low for Gao. Netherless, available Mn obtained in Gao was still higher than the critical level proposed by Cox cited in Adriano (1). The amount of available Zn extracted in all soils (except Kgba) were below critical level for plant growth (36). Available Cu was below (for Bgni and Gao) or close (for Kgba and Bgda) to the critical levels given by Verloo (36). The results suggest that Cu deficiency may occur in all soils, Zn deficiency in three soils (Bgni, Bgda and Gao), and Mn in Gao.

Interpretation of data was difficult because of the absence of reference levels for Malian soils and also in the literature there are no static values of interpretation. In order to evaluate the real uptake of nutrient further studies are required.

Conclusions

The particle size distribution revealed that the sand fraction dominated in the four soils studied and that might indicate low water retention capacity. Three of the four (Bgni, Kgba, and Gao) soils studied had neutral reaction while Bgda was acidic. All the four soils selected for the present study were low in total N and P, available S and Cu, and CEC. The CEC values

Table 3

Micronutrients extracted with NH_4OAC-EDTA in mg/kg

Element (mg/kg)	Bgni	Kgba	Bgda	Gao
Fe	36 ± 4	42 ± 3	70 ± 8	30 ± 1
Mn	12 ± 0.4	21 ± 3	17 ± 0.1	6 ± 1
Zn	1.4 ± 0.5	5 ± 1	1.5 ± 0.3	1.1 ± 0.3
Cu	1.3 ± 0.1	2.0 ± 0.2	2.0 ± 0.1	1.6 ± 0.4

Data are mean of six replicates ± standard deviation.

showed also that in the four soils high leaching of nutrients may occur. The total organic carbon, available P and exchangeable Ca, K, and Mg were low for three soils (Bgni, Bgda and Gao) and medium for Kgba. Three of the four soils (Kgba, Bgda and Gao) were also characterised by imbalance between Ca and K and between Mg and K. Mg deficiency might occur in the Gao soil. Considering the different characteristics studied, Kgba showed a better nutrient status than the other soils. The relatively high nutrient level at Kgba might be related to the use of manure and farm compost. An oriented program for the improvement of the productivity of the selected soils must supply N, P, K, Ca, Mg, Cu, S, organic carbon and Mn (for Gao only). Since the utilization of mineral fertilizers by the farmers of the different sites is financially prohibitive, and the low input of organic fertilizers appeared to be a common problem for the four sites, the improvement of the productivity of the studied soils should be done towards the utilization of by-products (crop residues, manure and farm compost) that are available in the different regions. But, prior to the use of farm compost or manure at Bgni, Kgba and Gao sites, the effects of the chosen organic material on the redistribution of the micronutrients (such as Fe, Mn, Zn and Cu) should firstly carefully be examined. In Bgda, more attention should be given on retention of P.

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Literature

1. Adriano D.C., 1986. Trace elements in the terrestrial environment. Springer Verlag, New York, NY.
2. Bacci L., Cantini C., Pierini F., Maracchi G. & Reyniers F.N., 1999. Effects of sowing date and nitrogen fertilization on growth, development and yield of a short day cultivar of millet (*Pennisetum glaucul* L.) in Mali. European J. Agron. 10, 9-21.
3. Boyer J., 1982. Les sols ferrallitiques Tome X: facteurs de fertilité et utilisation des sols. Initiations-Documentations Techniques n° 52, ORSTOM, Paris.
4. Defoer T., De Groote H. , Hilhorst T., Kanté S. & Budelman A., 1998. Participatory action research and quantitative analysis for nutrient management in southern Mali: a fruitful marriage? Agricul. Ecosys. Environ. 71, 215-228.
5. Diallo Y., 1996. Personal Communication. Soil scientist at the BICD (Bureau d'Ingénieurs Conseils pour le Développement à Bamako), Mali.
6. Dobermann A., Cassman K.G., Sta Cruz P.C., Nue H.U., Skogley E.O., Pampolino M.F. & Adviento M.A.A., 1995. Dynamic soil test for rice. In: Fragile Lives in Fragile Ecosystems. Proceedings of the International Rice Research conference, 13-17 February 1995. International Rice Research Institute, Manila, Philippines, pp. 343-365.
7. Euroconsult, 1989. Agricultural compendium for rural development in the tropics and the subtropics. Elsevier, Amsterdam, pp. 91-740.
8. F.A.O., 1990. Food and Agricultural Organization of the United Nations. Guidelines for soil description. 3rd edition. Soil Resources, Management and conservation Service, Land and Water Development Division. Rome, 42-43.
9. Hincourt D., 1990. Diagnostic morphopédologique et évaluation de la fertilité des terres au Fouta Djalon. Travail de fin d'études. Faculté des Sciences Agronomiques de Gembloux, Belgique.
10. Horgnies M., 1983. Contribution à l'étude de la fertilité potentielle des sols alluviaux au Shaba. Périmètre de Mangomba, Zaïre. Travaux de fin d'étude. Faculté des Sciences Agronomiques de Gembloux, pp. 27.
11. IER (Institut d'Economie Rurale), 1996. Rapport analytique, campagne 1995-1996. IER, Bamako, Mali, pp. 243.
12. Jones C. A., 1983. Effect of soil texture on critical bulk densities for root growth. Soil Sci., Am. J. 47, 1208-1211.
13. Kabata-Pendias A. & Pendias H., 1985. Trace elements in soils and plants. Library of Congress Card Number 83-15083, Inc., 2000 Corporate Blvd., N. W., Boca Raton, Florida, 33431.
14. Kang B. & Osiname O., 1976. Sulphur response of maize in western Nigeria. Agron. J. 68, 333-336.
15. Laurent B., 1988. Premier diagnostic des manifestations ponctuelles de la salinité dans le périmètre de mise en valeur du lac Horo au Mali. Travaux de fin d'études. Faculté des Sciences Agronomiques de Gembloux, Belgique.
16. Lindsay W. L. & Norvell W. A., 1978. Development of a DTPA soil test for zinc, iron, manganese and copper. Soil Sci. Soc. Am. J. 42, 421-428.
17. Marcos M.L.F. & Gonzalez A.P., 1994. Cation leaching from two soils located in lysimeters since 1988 to 1990 in a long term experiment. Agrochimica, 38, 341-354.
18. N'Diaye M.K., Guindo D. & Dicko M. K., 1997. Gestion de la fertilité des sols rizicoles de l'Office du Niger. In: Miézan K.M., Wopereis M.C.S., Dingkuhn M., Deckers J., Randolph T.F., (Eds.), Irrigated Rice in the Sahel: Prospects for Sustainable Development. West Africa Rice Development Association, 01 Bouaké, BP 2551, Côte-d'Ivoire, ISBN 92 9113 1091, pp. 201-211.
19. Ouédraogo E., Mando A. & Zombré N.P., 2001. Use of compost to improve soil properties and crop productivity under low input agricultural system in West Africa. Agricul. Ecosys. Environ. 84, 259-266.
20. Owusu-Bennoah E. & Acquaye D.K., 1989. Phosphate sorption characteristics of selected major Ghanaian soils. Soil Sci. 148, 114-123.
21. Pauwels J. M., Van Ranst E., Verloo M. G. & Mvondo Z. A., 1992. Manuel de laboratoire de pédologie. A.G. Building, Place du Champ de mars 5, Boîte 57, 1050 Bruxelles. Publications Agricoles 28, 191-208.
22. Pieri C., 1989. Fertilité des terres de Savanes. Bilan de trente années de recherche et de développement agricole au Sud du Sahara. CIRAD, Ministère français de la coopération et du développement, Montpellier, Paris, France.
23. Poulain J.F., Doumbia A., Franc M., Jenny F., Pieri C., Thibout F. & Traoré M.F., 1975. Amélioration de la fertilité des sols agricoles du Mali. Bilan de treize années de travaux (1962-1974). Agron. Trop. 31, 401-416.
24. Roche P. & Pichot J., 1972. Phosphore dans les sols tropicaux. Communication présentée au Séminaire conjointement organisé par l'IITA, l'IRAT et la fondation Ford à Ibadan, 22-26 mai 1972. Nigeria.
25. Sanchez P. A., 1976. Properties and management of soils in the tropics. John Wiley, New York, pp. 618.
26. Sanchez P.A., Couto W. & Buol S.W., 1982. The fertility capability soil classification system: interpretation, applicability and modification. Geoderma, 27, 283-309.
27. Seat L.F. & Peterson H.B., 1962. In: Bear, F.E., (Eds), Chemistry of the soil. Reinhold Publishing Corporation, New York, 2nd edition, pp. 292.

28. Smaling E.M.A., Nandwa S.M. & Janssen B.H., 1997. Soil fertility in Africa is at stake. ASA and SSSA, 677 S. Segoe Rd., Madison, WI 53711, USA. Repl. Soil Fert. Africa SSSA 51, 47-61.

29. Stoorvogel J.J. & Smaling E.M.A., 1990. Assessment of soil nutrient depletion in sub-Saharan Africa, 1983-2000. Rep. 28. DLO Winand Staring Ctr. For integrated Land, Soil and Water Res., Wageningen, the Netherlands.

30. Sys C., 1979. Regional pedology. Tropical soils, part II, ITC Ghent, pp. 25-125.

31. Traoré S., 1998. Agro-météorologie au Centre de Recherche Agronomique de Sotuba. Sotuba, Mali.

32. Traoré M.F., 1974. Etude de la fumure minérale azotée intensive des céréales et du rôle spécifique de la matière organique dans la fertilité des sols au Mali. Agron. Trop. 29, 567-586.

33. Traoré M.F., 1972. Evaluation de la fertilité des sols du Mali en phase de végétation. Communication présentée au Séminaire conjointement organisé par l'IITA, l'IRAT et la fondation Ford à Ibadan, 22-26 mai 1972. Nigéria.

34. Veldkamp T., 1992. Fertilité du sol. Agromisa B.P. 41, Wageningen, Pays Bas. Agrodok 2, 2-8.

35. Veldkamp W.J., Traoré A., N'Diaye M.K., Keita B. & Bagayoko M., 1991. Fertilité des sols du Mali, Mali-sud/Office du Niger. Interprétation des données analytiques et des plantes. IER Sotuba, Bamako, Mali, pp. 149.

36. Verloo M.G., 1983. Importance of micronutrients in multiple cropping systems. Food and Agriculture Organization of the United Nations. Rome, Fert. Plant Nutr. 5, 79-83.

37. Wopereis M.C.S., Donovan C., Niébé B., Guindo D. & N'Diaye M.K., 1999. Soil fertility management in irrigated rice systems in the Sahel and Savanna regions of West Africa. Part I. Agronomic analysis. Field Crops Res. 61, 125-145.

M. Soumaré: Malian, Master in soil science, speciality soil chemistry and ecopedology. Master in agronomy, speciality agrochemistry and pedology. Researcher at the Department of Applied Analytical and Physical Chemistry of the University of Ghent since 1997.

Demeyer: Belgian, Doctor, Assistant at the Department of Applied Analytical and Physical Chemistry of Ghent University from October 1994 until February 2001.

F.M.G. Tack: Belgian, Professor at the Department of Applied Analytical and Physical Chemistry of Ghent University since 1998.

M.G. Verloo: Belgian, Professor at the Department of Applied Analytical and Physical Chemistry of Ghent University since 1988.