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Properties and management of gravelly soils developed on ferruginous cuirass in Mali

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In Mali, different types of gravelly soils on Cuirass were identified in association with a native vegetation including many species of tree, shrub and herbaceous. All these soils are developed by degradation of ferruginous cuirass, a material largely observed in West Africa Sudanian and Sudano-Guinean zones. Gravelly soils of Mali have a variable depth (< 10 to 95 cm depth) and gavel content (15 to 60%) and are ranged in three textural classes (silty, sandy loam and clayey loam). Their marginal status for agriculture are always justified by pedologists but they are used both for cropping and breeding (when annual rainfall ≥ 800 mm) or only for breeding (when annual rainfall < 800 mm). In manual cultivation system, many farmers prefer gravelly soils where weed control is easy. In mechanized agriculture, the gravelly soils on cuirass are used when deep soils of lowlands are not available. Agriculture use of cuirass lands favours deforestation, increase runoff, soil erosion and inundation risk at watershed scale. So, better management systems are needed and research programs must identify techniques for harvesting runoff from cuirass table and its stockage for complementary irrigation. However, the field experimentations must identify ways to improve fodder production and conservation.

Key words: Ferruginous cuirass, gravelly soils, land use, landscape degradation, West Africa contrasted climate zones.

INTRODUCTION

In the Sudanese zones of West Africa, there are large areas where the ferruginous Cuirass is present, covered or not with a shallow or moderate depth gravelly material. Studies of this landscape had permitted production of a relatively abundant literature (Maignien, 1958; Tricart and Cailleux, 1974; Michel, 1973; Leprun, 1977, 1979; Boeglin, 1990; Bantsimba, 2001). The genesis of Cuirass materials, their mineralogical and geochemical characteristics, as well as their influence on the current dynamic of reliefs have been studied with special attention in regional geology and geomorphologic research programs, and mineral exploration. Moreover, the description and evaluation of soils located on cuirassed reliefs were made during pedological surveys (Anonyme, 2001). These soils have generally been recognized marginally for agriculture and native vegetation development (Anonyme, 2001; PIRT, 1983). Gravely soils on Cuirass deserve to be reviewed in order to develop new strategies for land management in the current context of general degradation and reduced

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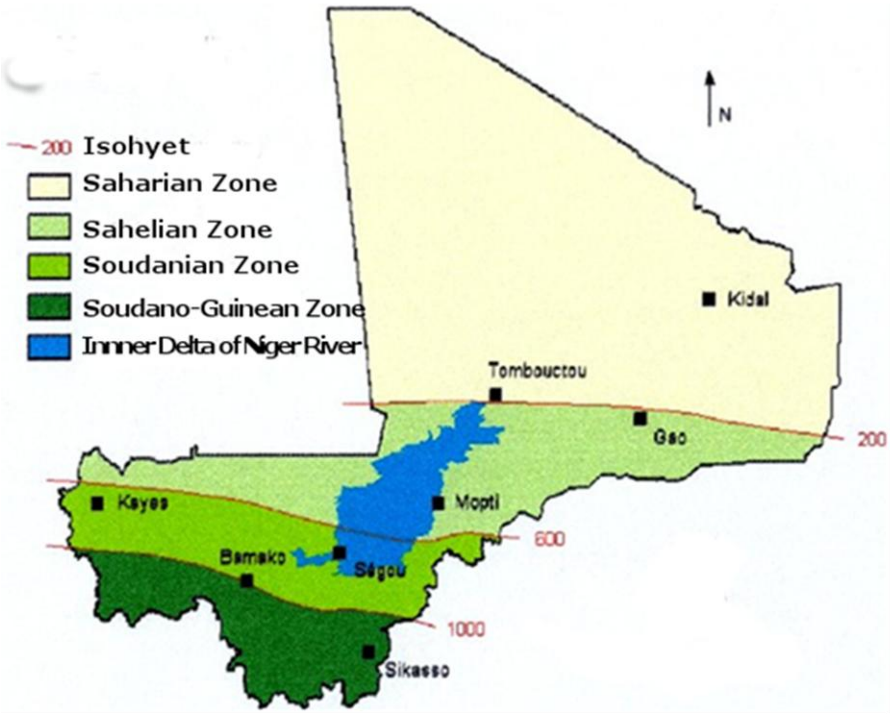

Figure 1. Agroecological map of Mali according Labo SEP, quoted by Coulibaly (2003).

Figure 2. Gravelly soil profile observed in Bagoe watershed, Sikasso region (Photo I: Kassogué).

productivity of Sudano-Sahelian ecosystems. The present paper aims to underline the pedological properties of shallow and moderate depth gravelly soils), their capability and current uses and a discussion about research needs for new strategies to manage this landscape.

STUDY AREA

Localisation of the study area

Gravelly soils developed on ferruginous Cuirass in Mali are mainly surveyed in Sudanian and Sudano-Guinean zones (Figures 1 and 2), which are largely represented in West Africa.

Climate context

The current climate of Sudanian and Sudano-Guinean zones where cuirass materials are observed in West Africa, is characterized by a high variability of parameters as annual rainfall: more than 1300 mm (in south) to 600 - 550 mm (in north). Some current climatic characteristics measured at Sikasso station, located at 5°6'W and 11°3'N are shown in Tables 1 and 2 according to Malian Meteorological Service (Sangaré, 2011). In the Sudano-Gunean zone, maximum temperature is over 30° all the year. Air humidity is very low from January to March (43 to 50% for maximum value and 13 to 17% for minimum value), in relation with Harmattan (a dry wind) presence. When Monsoon come in the Sudanian zones (around April and May) air humidity increases and get its most high values (more than 90% for maximum value and around 60% for minimum value) during the period July to October. The mean annual rainfall, for the period 1980 to 2008 was 1105.4±16 mm; only in four months (June to

Table 1. Means of temperature and air humidity at Sikasso Station from 1980 to 2009 (Sangaré, 2011).

Parameter		J	F	M	A	M	J	J	A	S	O	N	D
Temperature (°C)	Min	18	21	24	26	25	23	22	22	22	22	20	17
	Max	33	35	37	37	35	33	30	30	31	33	34	33
Air humidity (%)	Min	15	13	17	29	40	52	60	64	59	46	25	17
	Max	48	43	50	70	81	89	94	95	95	91	79	61

Table 2. Means of rainfall and evaporation at Sikasso Station from 1980 to 2009 (Sangaré, 2011).

Parameter	J	F	M	A	M	J	J	A	S	O	N	D
Rainfall (mm)	1.3±0.0	5.0±1.6	9.6±12.4	48.4±8.2	99.1±39.6	155.1±17.3	221.2±53.1	285.1±37.7	198.0±19.0	76.2±101.2	6.6±3.5	0.0±0.0
Evaporation Piche (mm)	269.5±33	282.7±34	303.6±48	218.8±37	164.6±34	103.4±18	70.9±12	54.8±8	59.4±8	96.1±24	175.6±27	232.8±29

Table 3. Geochemistry and mineralogy of Cuirass and gravel in Kangaba sector (Mali) according to DNGM, ORSTOM, CNRS (1986).

Element	Cuirass (%)	Gravels (%)
SiO_2	33.04	58.76
Al_2O_3	19.02	17.01
Fe_2O_3	43.9	18.74
TiO_2	0.89	1.34
MgO	0.2	0.23
K_2O	0.37	0. 38
MnO	0.03	0.02
Quartz	17.5	38.74
Gibbsite	11.98	0.02
Kaolinite	1.74	43.04
Goethite	45.27	7.67
Hematite	14.67	11.84

September), rainfall was superior to evaporation.

Paleoclimatic considerations are usually mentioned when talking about cuirass materials currently observed in West Africa and other tropical regions. Cuirass materials and reliefs are the result of a long evolution, more than 100 Ma (Tardy, 1991), influenced by alternating humid and arid climates in the past, during geological times. These considerations allowed scientists to consider Cuirass materials as an important paleoclimatic marker in the tropics (Gunnell, 1996). Most Cuirass land in West Africa are actually located in very contrasted climate conditions (wet from May-June to October and severely dry the rest of the year).

Geological context

Cuirass reliefs and the associated soils in West Africa are formed from different rock types, granite, shale, sandstone, greenstone (Boeglin, 1990; Bantsimba, 2001). According to their mineralogical characteristics, different types of cuirass are distinguished: bauxite or aluminous cuirass, alumino-ferruginous cuirass and ferruginous cuirass (Boeglin, 1990). Ferruginous cuirass, on which are located shallow and moderate depth gravelly soils, which is subject of the present paper, is characterized by the preponderance of goethite, Fe_2O_3 and SiO_2 (Table 3). The associate gravel (≥ 2 mm) is rich in goethite, SiO_2 and kaolinite. Geomorphologic studies showed the important role of cuirass in the organization of actual relief in the Sudanese zones of West Africa, where different categories of surface covered by cuirass are observed (Michel, 1973). Among these surfaces, there are glacis which are quaternary reliefs characterized by the presence of ferruginous cuirass and gravelly soils (Michel, 1973).

The formation process of cuirassed materials has been described by many researchers (for example, Tricart and

Cailleux, 1974; NcFarlane, 1976; Tardy, 1991). It is widely known today that cuirassed materials (or laterite) are the result of enrichment of superficial geological material in iron or alumina, or a mixture of both, and their induration. It should be noted, that the enrichment in iron, for example, can be the result of one of the two following process:

i) A relative accumulation by departure of other elements;
ii) An absolute accumulation as result of migration in the cuirass development site.

About current evolution of old ferruginous cuirass materials (mainly formed during the old and middle Quaternary), ubiquitous in West Africa, Leprun (1977) explained the process running on a toposequence in Thion (Burkina Faso), located on biotite and amphibole migmatite. This evolution is characterized by:

i) Old soil profile internal degradation by geochemical weathering;
ii) Surface degradation by mechanical process.

So, the cuirass is attacked in its mass and basics by hydrodynamic and geochemical mechanisms which magnitude increases with the degree of slope; the result is lithosols transformation in gravelly soils. At the landscape scale, relief formation process will be strongly influenced by current destruction of old cuirassed material and will differ, depending on the climate zone, the anterior cuirassed relief and the original rock.

METHODOLOGY

This article is based on a synthesis of accumulated data on Cuirassed reliefs and soils identified in Mali during studies for rural development program. These data were supplemented by detail soil descriptions, indigenous knowledge and agricultural surveys.

Extracting data from Malian Atlas of land resources

The inventory project of Mali land resources led from 1975 to 1981 provided important data on the major soils of the country and the state of land use and management. Some data from these studies are synthesized in this work.

Soil profile description and soil sampling

Some supplementary soil profiles (about 50) have been described in Malian Sudanian and Sudano-Guinean zones. The main criteria for describing soils *in situ* were the tickness of the profile, horizons colour, texture and porosity, the behavior of roots and the traces left by water saturation above hardpan (cuirass). Soil samples were taken in representative soil profiles.

Laboratory analysis

These analyses mainly concern the determination of particle size distribution with the international method (Baize, 1984), measurements of pH by electrometric method in the ration 1/2.5 and carbon by Anne method (Baize, 1984).

Agricultural practices surveying

Surveys were conducted with 51 farmers distributed in 17 villages. The questions focused on indigeneous knowledge of soil resources, land use practices, actual agricultural techniques application to gravelly soils and crops grown on the gravelly soils.

CHARACTERISTICS AND ALTERNATIVE MANAGEMENT OPTIONS OF GRAVELLY SOILS ON CUIRASS

Characteristics of gravelly soils on Cuirass

Typology and morphologic characteristics

Soil surveys in Mali led to the distinction of seven soil-vegetation units under the name of Cuirass land (*Terrains cuirassés*, TC), noted TC1 to TC7 (PIRT, 1983). These units are spatially distributed in annual rainfall context range from 250 to over 1100 mm/yr. Only soil profiles of units TC2 (formed on alluvial material) and TC7 (formed in colluvial and often alluvial material) are not gravelly, except at the lower layers of the profile, the contact between alluvium or colluviums and Cuirass. Soils of the other units (Table 4), subjects of the present article, are mainly gravelly, derived from the degradation of ferruginous cuirass. They occupy different topographic positions (upland and slope of different gradients) and are different types of soil, according to PIRT (1983): Cambic Cuirorthids, Cuirustalfs aridic, Typic Cuirustalf, mollic Cuirorthents.

Morphological descriptions of these soils are depicted as follows:

i) The thickness of the soil profile (always less than 100 cm above ferruginous cuirass); profile depth is usually variable in each soil type and from a soil type to another (Table 4);
ii) Ferruginous gravels on the surface, but also in the soil profile;
iii) Ferruginous blocks on the surface;
iv) the hue of topsoil (0 to 10 cm) colour is variable according to Revised Standard Soil colour Charts (10YR in flat position and 7.5YR on slope); it is generally 7.5YR or 5YR under surface.

Texture, pH and organic matter status

Soils content in gravel is variable (15 to 60%) and three textural classes are distinguished: silty, sandy loam, clayey loam. All these soils have an acidic pH (5.1 to 6.0), and organic matter content generally close to 2%.

Table 4. Some characteristics of gravelly soils on ferruginous cuirass in Mali.

Characteristic		Soil vegetation units				
		TC1	TC3	TC4	TC5	TC6
Annual rainfall (mm) of reference station		250 – 550	550 -800	800-1150	> 800	>1100
Typical soil		Cambic Cuirorthids	Cuirustalf aridic	Typic Cuirustalf	Mollic Cuirorthents	Typic Cuirustalfs
Soil depth (cm)		20 to 70	25 to 85	60	< 10 to 35	< 10 to 35
Presence of ferruginous block and gravel		+	+	+	+	+
Vegetation species	Total number of species observed with high frequency	21	29	46	34	45
	3 main woody species	(1) (2) (3)	(1) (3) (4)	(4) (5) (6)	(4) (6) (7)	(8) (9) (10)
	3 main herbaceous species	(a) (b) (c)	(d) (e) (f)	(f) (g) (h)	(f) (i) (g)	(g) (j) (k)

(1) Pterocarpus lucens (2) Boscia senegalensis (3) Combretum micranthum (4) *Combretum glutinosum ;* (5) *Bombax costatum* (6) *Pterocarpus erinaceus* (7) *Lanea microcarpa* (8) *Isoberlinia doka* (9) *Detarium microcarpum,* (10) *Anona senegalensis;* a)*Schoenefeldia gracilis* (b) *Aristia SPP* (c) *Cenchrus biflorus* (d) *Loudetia togoensis* (e) *Diheteropogon ragerupii (f) Andropogon pseudapricus* (g) *Andropogon gayanus* (h) *Pennisetum pedicellatum* (i) *Ctenium SPP* (j) *Cochlospermum glutinosum.;* (+) means Yes. NB: Soil typology refers to Malian Land Resources Atlas (PIRT, 1983).

Soil-Water relationship

Gravelly soils on Cuirass have low water storage capacity when they are located on slope (4 to 6%). The average annual runoff coefficient is high enough: 41.2% in Djitiko watershed, according to measurements on experimental plot (Diallo et al., 2004). Due to runoff process, water volume lost on a surface bearing shallow gravelly soil (<40 cm) can reach 504,000 to 307,500 m^3/ ha/yr in Sudanian zone, depending on the isohyets and land use (Diallo and Roose, 2008).

Associated native vegetation

Vegetation installed on gravelly soils includes trees and shrubs in the woody stratum, and mainly grasses in the herbaceous layer. Many plant species are observed (Table 4). This biodiversity is mainly a function of the rainfall range. Only in the case of TC5, where the thickness of the soil is very low (usually less than 30 cm), soil material has more impact, than rainfall (greater than 800 mm/yr), on native vegetation. Woody vegetation of this unit occurs generally as groves scattered in abundant herbaceous stratum (PIRT, 1983). A site of unit TC5 is shown in Figure 3.

Alternative management options of soils

The characteristics of gravelly soils on cuirass, especially thin profile and high content in gravel were always arguments for soil scientists who drew attention to the marginal status of these soils. All these constraints are well known by farmers who practice mechanization. The current uses of these soils (Table 5) are linked to climatic factors agricultural techniques evolution and land availability in each agricultural village.

Climatic factors and land use

In situation where annual rainfall is 800 mm and plus, gravelly soils are used both for cropping and breeding. In this climate context TC4, TC5 and TC6 are observed as indicated in Table 5. The units TC4 and TC6 have the same assignments: sorghum, millet, maize, peanut and often cotton. The unit TC5 which occupies a flat topography, favorable to stagnation of rainwater, is managed as a garden and assigned to a wide range of crops (sorghum, maize, peanut, yam, sweet potatoes and various vegetable crops) in a general context of female and manual agriculture. In this case, crops are generally installed on boards or mounds (around 30 cm high), made to increase the volume of soil exploited by the roots of crops and also to mitigate the negative effects of any excess standing water (Figure 4).

When annual rainfall is less than 800 mm, gravelly soils on cuirass are exclusively used for breeding (units TC1 and TC3).

Agricultural techniques evolution and land use

Agricultural techniques evolution has an impact on gravelly soils use. In manual cultivation system, many farmers prefer gravelly soils where weed control, is relatively easy. In rural areas where mechanization with animal traction is widespread, the peasants are not interested in gravelly shallow soils and are driven to the plains and lowlands with deep soils, where they can easily practice conventional tillage (Figure 5). So, according to photographs interpretation, in Bélékoni watershed (120 km^2) for example, gravelly soils on

Figure 3. Groves scattered in herbaceous stratum in TC5 sites observed during the rainy season in Bagoé watershed, Sikasso region (a) I. Kassogué (b) T. Diallo.

Table 5. Current use of gravelly soils on Cuirass.

Rainfall and land use	Soil vegetation units				
	TC1	TC3	TC4	TC5	TC6
Annual rainfall (mm) of the reference station	250 – 550	550 - 800	800 - 1150	> 800	>1100
Breeding	(+)	(+)	(+)	(+)	(+)
So, Mi, Ma, Pe	(-)	(-)	(+)	(+)	(+)
Ri	(-)	(-)	(-)	(+)	(-)
Co	(-)	(-)	(+)	(-)	(+)

So = sorghum; Mi= millet; Ma = maize; Pe= peanut; Ri = rice; Co = cotton. (+) means Yes and (–) means No.

cuirass represented 62% of the cultivated area before 1960. Today this percentage is very low (inferior to 20%). With the development of mechanized agriculture, many village communities look gravelly soils as women landscapes. Indeed, these soils are occupied by many small plots, manually owned by women.

Environmental impacts of agricultural use of gravelly soils on cuirass

Problems arising from the cultivation of gravelly soils depend on topographic position, land use and agriculture techniques. Concerning soils of TC5, the problems are not perceptible enough. But after heavy rains, runoff and fine particles lost by erosion are possible. Cultivation of gravelly soils located on slope (TC4 and TC6), especially with the mechanization, can quickly lead to the disappearance of the dense tree cover. That is a major problem, because the presence of cuirass (not far of surface) and gravel does not allow recovery after cultural abandonment. Moreover, the slope (> 4%) is favorable to high runoff in Sudanian zone of West Africa and erosion of fine particles (clay and organic matter); it is a mass of sterile gravel that will be left on site. Many farmers give evidence of this rapid depletion of fine particles of gravelly soils.

DISCUSSION

Gravelly soils fundamental properties

Ferruginous gravels and blocks presence can be explained by the current degradation process affecting cuirass materials (parental materials of these soils), as described by Leprun (1977). The dominance of red in soil colour is due to the presence of iron oxides and the acidity seems a consequence of the large amounts of silica in the parental material.

The low agricultural quality of gravelly soils on cuirass is mainly explained by the low thickness of soil profile, its

Figure 4. Mounds confectioned on TC5 for cropping in Bagoé watershed, Sikasso région (a) peanut plantation (photo T. Diallo); (b) sorghum and earth peas (photo I. Kassogué).

Figure 5. Conventional tillage on a deep soil in Bagoé watershed, Sikasso region (photo H.Sangaré).

high content in ferruginous gravel and the low water storage capacity.

Current land use and sensibility to degradation

In Mali, the widespread use of gravelly soils for breeding is justified by the existence of high forage availability. The cultivation of these soils in some situations is explained by low availability of land resources and strong pressure on the better one (deep soils). In a climate context characterized by an annual rainfall inferior to 800 mm, it is very likely that gravelly soils are cultivated in general, because growing of crops is highly uncertain (low rainfall and low water storage capacity of soils are serious constraints).

The high sensibility of gravel soils to degradation can be explained by:

i) the thickness of the soil over hardpan which is favourable to runoff;
ii) the low levels of stable macro-aggregates measured in these soils (Diallo et al., 2004). These authors reported that stable macro-aggregates rate is variable from 147 to 225 g/kg of gravelly soil against 560 to 630 g/kg of brown vertic soil located below.

Concerning soils of unit TC5, the physical degradation is not perceptible enough according to the flat topography; it is also not conductive to runoff.

RESEARCH NEEDS FOR A BETTER UTILIZATION OF CUIRASS ENVIRONMENT

Better utilization of ferruginous cuirass environment, occupying large areas in the Sudanian and Sahelian zones of Mali and elsewhere in West Africa, is necessary in the current context:

i) Generalization of land and ecosystems degradation;
ii) Necessity to improve food production for a growing population.

So, studies must be thorough in order to better enhance their impluvium function and their potential fodder.

Research needs for improving impluvium function of cuirass table

Today it is necessary to develop research in two directions:

i) Development of runoff harvesting from cuirass table and its stockage techniques on the landscape in upstream of rivers;
ii) Development of micro irrigation systems with the stocked water on the landscape.

Research needs for improving potential fodder of gravelly soils

Improvement of the potential fodder requires field experimentations in order to:

i) identify better herbaceous species according to their biomass productivity and their agrostological quality;
ii) identify better production and conservation techniques of fodder.

Conclusion

Agricultural use of cuirass lands faces real physical constraints (mainly thin material, heavy duty gravel and low water storage capacity) and has been identified by pedologists since long time. The techniques developed by some farmers (construction of boards and mounds) appear to be a significant alternative to improve soil depth and profitability of rainwater. However, pastoral potential of these lands appear significant. Globally, current management practices for cropping on gravelly soils are poor and contribute to acceleration of degradation process (particularly runoff) affecting all the toposequence. Better management systems have to be developed for better use of gravelly soils on cuirass and the concerned landscape in upstream of rivers. In this order, development of runoff harvesting from cuirass table and its stockage for complementary irrigation can be experimented in the local context. In other words, field experimentations are necessary to improve biomass (from herbaceous species) production and conservation for livestock use.

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