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Soil Properties Influencing Hydraulic Sealing of the Surface on Alfisols in the Sahel

Justin Wayne Heil

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SOIL PROPERTIES INFLUENCING HYDRAULIC SEALING OF THE SURFACE ON ALFISOLS IN THE SAHEL

A Dissertation

by

JUSTIN WAYNE HEIL

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 1993

Major Subject: Soil Science

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December 1993

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ABSTRACT

Soil Properties Influencing Hydraulic Sealing of the

Surface on Alfisols in the Sahel. (December 1993)

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Surface seals reduce crop yields and increase erosion by decreasing infiltration and increasing runoff. Seals form when intense rainfall breaks aggregates into smaller particles that clog pores. The objectives of this study were to (1) identify sealing soils in selected Alfisols in West Africa and to define the processes of sealing; (2) determine the soil properties which affect sealing.

Six soils at Hamdallaye, Niger, and two soils at the Cinzana Research Station, Mali were studied. Soils in fallow fields at the Cinzana Research Station were actually deeply compacted soils due to structural losses from cultivation or heavy animal traffic. The following results were obtained from the Hamdallaye soils. Infiltration measurements with a disk infiltrometer were > 130 μm/s in the unsealed sites and 3 to 103 μm/s in the sealed sites. Dry unconfined strength was about 36 Mg/m^2 in the sealed sites and 5 Mg/m^2 in the unsealed sites. The seals were structural seals. Thin section analysis showed a dense 0.1 to 1 mm thick continuous

plasmic layer just below a 1 mm thick layer of loose bare sand. All of the 12 sites studied with clay contents greater than five percent were sealed, and all of those below five percent were not. All of the seals were associated with erosion, where the sandy topsoil was eroded to expose an argillic horizon. Amounts of exchangeable aluminum, iron, and pH all correlated with clay content. Low pH (4.9 in sealed sites) causes the soils to flocculate, so that disaggregated clay remains flocculated in silt-size particles and clogs pores. Silt content is often an indicator of sealing in other soils, but because of low silt contents and flocculated clay in these soils, clay content is diagnostic of sealing.

Seals created under artificial rainfall on the Hamdallaye soils consisted of either two- or four-layer seals, depending on clay content. The seals formed quickly and were fully developed after 30 minutes of rainfall. Dispersion of the clays with Na saturation before rainfall prevented seal formation in soils with less than 10% clay due to complete eluviation of the clay.

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I am grateful to many people who have contributed to this work. Thanks to r. Anthony Juo, Dr. Kevin McInnes, and Dr. L. Wilding who shared their wisdom, me, and knowledge, and generously approved this dissertation. In addition to my ommittee members, I am indebted to Dr. Richard Drees and Dr. Norman White, ho both gave me generous amounts of time and advice. Thanks go to Dr. Joe ixon for his suggestions on the electron microscope work. Thanks to Jim Thomas r providing the rainfall simulator and providing information and equipment for any of the analyses. Thanks also go to my friends and fellow graduate students ho have shared their time and abilities. In particular, I would like to thank Clement oulombe for his friendship, and for graciously sharing the fruits of his labors by elping me do the pore size analysis at the last minute. I especially appreciated orking with Mrs. Peggy King because of her generosity, optimism, and ncouragement.

I would also like to thank those in Niger and Mali who provided me ssistance in the field work. These are Mamadou Doumbia, Zoumana Kouyate, umar Niangado, Samba Traore, and Gaston Sangare in Mali, and Mamadou uattara, Andrew Manu, Boucari, Hama, and Kati in Niger.

My family, as always, gave me strength and encouragement throughout this rocess. My parents were especially encouraging. I am deeply grateful for their love

and wisdom. I owe much of my accomplishment to their high expectations and confidence in me.

Thanks to TropSoils, the semi-arid soil management CRSP at Texas A&M University, for providing the funding for this research.

PREFACE

It was a typically sunny and hot afternoon on the West African savannah as I prepared infiltration rings for hydraulic measurements on soils susceptible to sealing. The clouds filling the northern horizon became more reddish as they seemed to compress the sky, diminishing my world and thrilling my eyes. I'd seen sand storms and rain storms on the Sahel, but this looked like a combination of the two. I finished preparing the infiltration rings and went to sit in the "yellow submarine," an affectionate name given to a four-door Toyota pickup by another graduate student. As the storm grew nearer I realized the significance of this event. Having prepared the soil using several treatments for infiltration under a disk infiltrometer, I could now qualitatively compare infiltration under rainfall by watching the six infiltration rings I had set out. This unplanned experiment, as well as other observations, yielded as valuable information as those I'd planned.

It was the daily experiences of curiosity, experimentation, and discovery in the fields of Hamdallaye and Cinzana that gave me an appreciation for the enthusiasm behind successful scientists. The thrill of scientific discovery combined

with the new environment I was experiencing gave me a fascination in my work that ranks among the best experiences I have had. The task of sharing these discoveries, however, is among the most difficult! Nevertheless, I will attempt to do so in a clear and concise way.

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CHAPTER I

INTRODUCTION

Many Alfisols in West Africa form a hydraulic seal at the surface during intense rainstorms. Rainfall breaks down aggregates into smaller particles that clog pores (Figure 1). Often bare sand layers are left at the surface. Surface seals in the Sahel are characterized by slowed infiltration, increased runoff, and increased erosion compared to those soils in which a seal does not form. In a runoff experiment in Niger, Anneke DeRouw and Christian Valentin (personal communication, 1992) found that runoff on laterite plateaus (bare, 0.2% slope) is 95%. On side slopes (grass, few shrubs and patches of erosional crust, 5.2% slope) runoff is 60%, with no runoff below 6 mm rainfall event. On foot slopes (cropped, deep sandy soil, tilled, no crust, 4.5% slope), there is little runoff during most rainfall events and 40% runoff during heavy storms.

In the Sahel, where water availability can limit crop growth, the loss of rain water by runoff may lead to substantially reduced crop yields. Upon drying, this sealed surface layer occasionally forms a hard surface crust, that may inhibit seedling

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This dissertation uses the style of the *Soil Science Society of America Journal.*

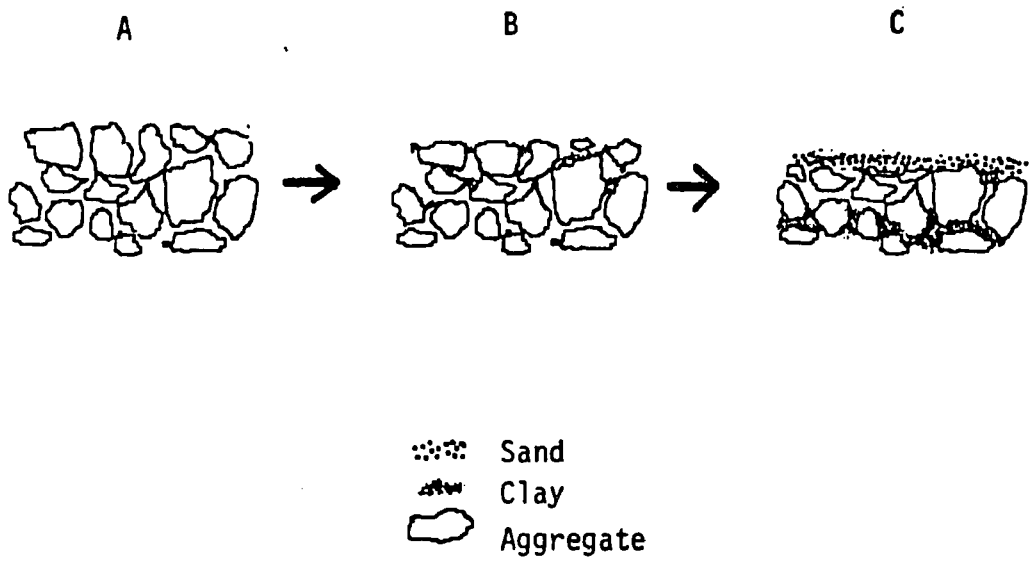
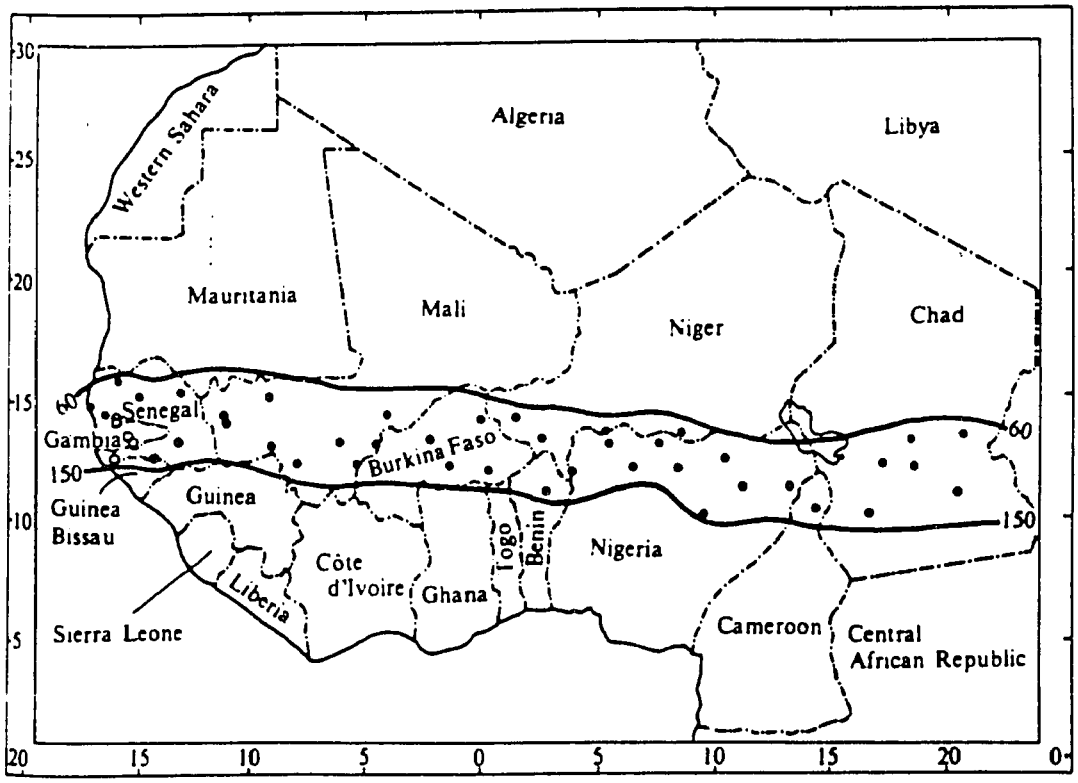


Figure 1. Process of structural seal formation. Aggregates (a) are broken down by rainfall (b). Small particles then clog macropores, leaving a "washed-in" clay layer and a coarse sand layer above it (c).

emergence and crop establishment. The distinction between a crust and a seal is that a soil crust is a broader term for a surface feature that is dense, hard, or restricts infiltration. Seal is a more specific term referring to a surface layer that inhibits infiltration. Desertification has been recognized in West Africa since the 1930's, and measures to protect vegetative cover and to control erosion have been largely unsuccessful. Population pressures demand that current land use be altered to increase yields and decrease risk of crop failure. Ironically, population pressure has also caused degradation of lands through more intense use.

There are still many gaps in the knowledge of processes leading to soil sealing and the soil properties that influence these processes. The purpose of this study is to provide fundamental information on the influence of soil properties on soil sealing processes in Sahelian Alfisols. This in turn will provide a wider knowledge base for relating management practices to their affect on soil sealing and crusting and consequently water infiltration, erosion, and seedling emergence. The study area is the Sahelian zone of West Africa, which is comprised mostly of sandy Alfisols (Figures 2 and 3).



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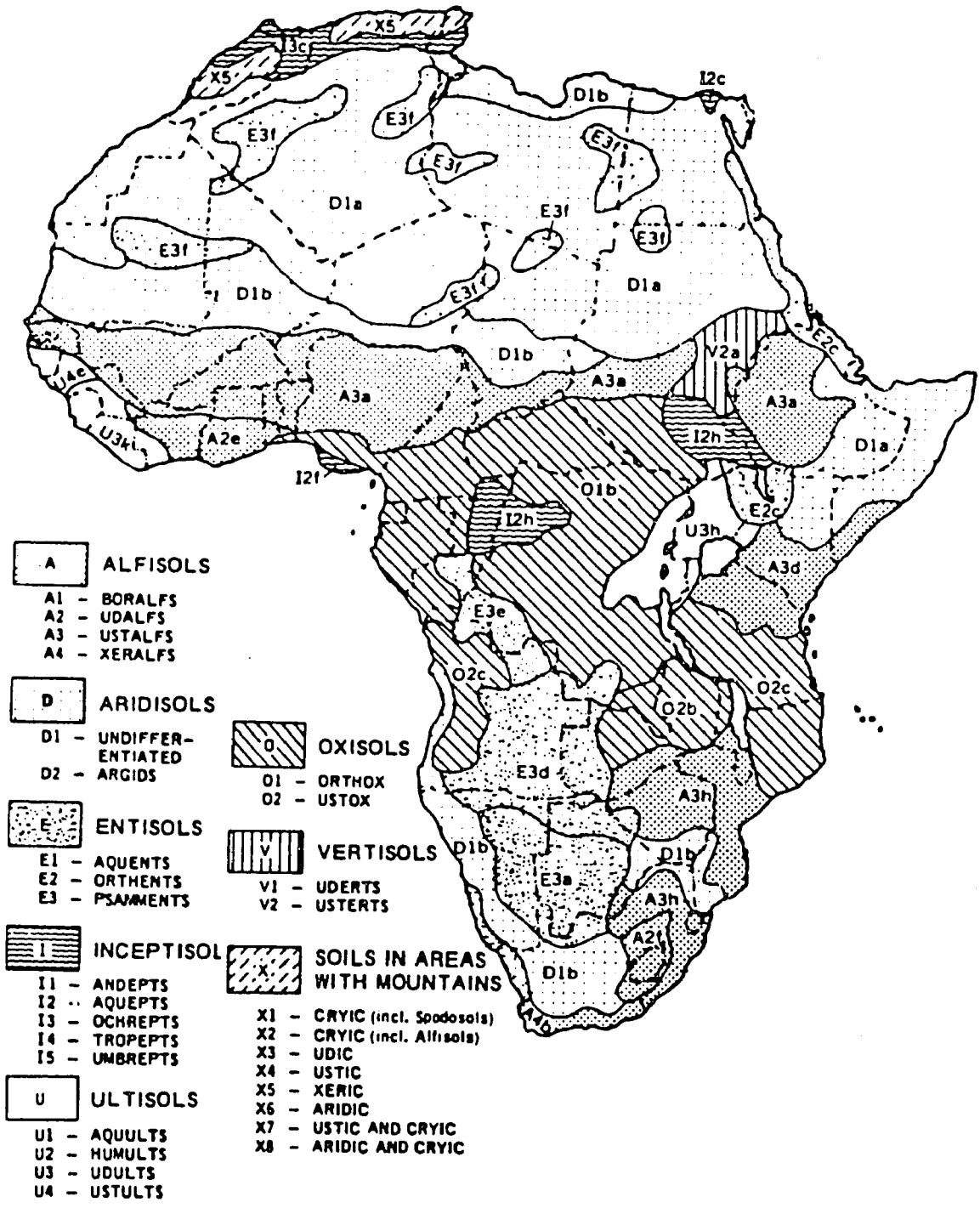

Figure 3. Soil map of Africa. Most of the soils in the Sahel are Alfisols. From USDA-SCS (1972).

CHAPTER II

OBJECTIVES

The overall objective is to determine the soil properties that cause seals to form on some West African Alfisols, while others remain unsealed, and to be able to explain the processes of sealing and crusting.

The laboratory and field studies are designed to achieve the following objectives:

I. Identify sealing and crusting soils in selected Alfisols in West Africa and define the processes and degree of sealing or crusting. The seals will be defined in terms of morphology, genesis, their affect on infiltration and runoff, and in terms of the hardness of the dry crust.

II. Determine the soil properties which affect sealing and crusting. The properties of the sealed layer which affect infiltration are its thickness and pore size distribution. Regardless of the process of seal formation, its affect on infiltration is by decreasing the number and/or continuity of large pores. This is done either by compaction or destruction of aggregates by raindrop impact and redistribution of soil particles or by deposition of fine particles on the surface and filling pores.

The role of soil properties in seal formation lies in the resistance of aggregates to breakdown in aggregated soils or in the potential for close particle

packing arrangements in single grained soils. Therefore, the studies include determining the texture and aggregation of particles along with the dispersion/flocculation properties of the clays. This includes identifying the type of bonding in aggregates. The relative importance of physical and chemical processes on seal formation will be shown by measuring soil properties of sealed soils in the field and comparing them to similar unsealed soils, and by studying seals generated in the laboratory.

CHAPTER III

LITERATURE REVIEW

Despite their coarse textures, Sahelian Alfisols exhibit a tendency towards forming a surface seal which affects infiltration, runoff, and erosion (Valentin, 1985). Upon drying, this surface layer occasionally forms a hard crust, affecting seedling emergence.

Extensive reviews of soil sealing have been done by Mualem, Assouline and Rohdenburg (1990), Bresson and Valentin (1992), and for African soils in particular, van der Watt and Valentin (1992). Soil sealing has been a popular topic for research in the past decade. Previously, confusion and inconsistencies existed in the use of various terms describing the components and genesis of surface seals. Recently a consensus has developed in the literature on a genetic classification.

Perhaps the clearest description of soil sealing processes is by West, et al. (1992). They classified surface seals as structural or sedimentary seals. Structural seals are those formed in place as a direct result of raindrop impact. They often have several microlayers. As aggregates are broken by raindrops and rapid wetting, a thin, dense disruptional layer forms at the surface. Fine material may move as a front into the soil, forming a "washed-in layer," or clay-rich layer. Washed-in layer is most often used to describe a 0.1 to 1 mm thick continuous sheet of fine material

below a "washed out layer," or clay-depleted layer, but is still used by some to describe thicker regions of clay accumulation. As the seal develops, coarse and fine sands are sorted at the surface, leaving a coarse sand layer at the top, a fine sand and silt layer below this, and then the washed-in layer. Later, the coarse layers may be eroded so that the washed-in layer is at the surface. All structural seals seem to fit into this genetic scheme. Since seal formation is dynamic, Mualem et al. (1990) pointed out that the process of crust formation should always be observed as a function of time.

Sedimentary seals form as material is transported and deposited on the soil surface. These are usually easy to distinguish from structural seals because of particle sorting. Particles are sorted vertically with finer material above coarser material in each depositional event, and there are usually several microbeds from successive rainfall events. Clays on the surface are often strongly birefringent in thin section, showing parallel orientation. These often occur in tilled soils between ridges, in low areas, or where slope, and rate of flow of run-on water, decreases. Bresson and Boiffin (1990) suggest that structural seals often follow a pattern in which the surface is first sealed by a structural crust, and then a sedimentary crust is deposited above it.

Both extrinsic and intrinsic factors are involved in determining whether a soil will seal. The extrinsic factors, such as rainfall intensity and duration, topography, plant or mulch cover, and land management all have significant effects on the

development of surface seals (Figure 4). The degree of seal formation can be directly related to the kinetic energy of rainfall, which usually occurs in high-intensity storms (Hoogmoed and Stroosnijder, 1984a). Surface sealing is usually inversely related to slope steepness because as the slope increases, the soil is eroded faster than the seal is formed (Bradford and Huang, 1992). Higher rainfall intensities may even reduce sealing over lower intensities when erosion is faster than seal formation (Gimenez et al., 1992). Plant and mulch cover shield the soil from raindrop impact, and therefore can reduce or eliminate sealing in otherwise susceptible soils. In the Sahel, cultivated soils are bare at the end of the long dry season so they are unprotected during the early part of the rainy season. Depending on the strength of soil aggregates, plowing may be a useful soil management tool. Lal (1987) promoted no-till farming in West Africa but suggested deep plowing every two years to break up crusts and mix the soil. Hoogmoed and Stroosnijder (1984b) found that, in sandy Mali Alfisols, mixing the surface increased infiltration for several rain events before the seal reformed. Drying time and temperature can also affect the strength of the dry crust (Rose, 1962).

Intrinsic variables in seal formation are the soil properties which influence sealing. The major soil characteristic which prevents the development of a surface seal is the resistance of aggregates to destruction. In single grained soils, or soils with little or no aggregation, the texture of the soils is the dominant factor affecting

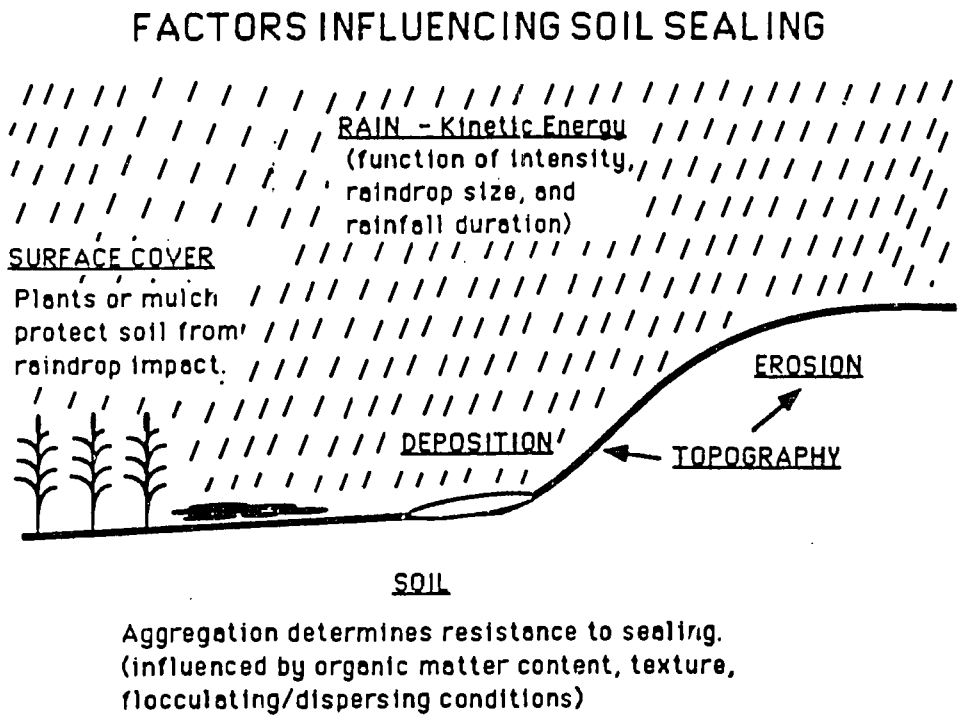

Figure 4. Extrinsic and intrinsic factors involved in soil sealing.

crusting. Monnier and Stengel (1982) have constructed a textural triangle showing the structural stability of soils in France according to their texture. They found that crusting risks are highest for medium textured soils with high silt contents and also in soils with high sand and low silt contents. Other soil properties which affect aggregation are organic matter content, mineralogy, type of ions saturating clays, salt content, and the presence of amorphous cements. Bonding can occur directly between clay particles, or with cation or polymer bridges. Inter-particle clay bonding in West African soils is low because of the low surface charge of the clays.

The organic matter content of soils is directly related to the stability of soil aggregates (Ferry and Olsen, 1975). In soils with significant amounts of organic matter, macro-aggregation can be controlled by management, while micro-aggregation is a characteristic of the soil independent of management (Tisdall and Oades, 1982). Since the formation and stability of aggregates are the key factors in determining whether a soil will form a seal, organic matter management, along with plant or mulch cover for protection, seem to be the best options for controlling sealing in most soils.

Type of clay minerals also influences seal formation. Van der Watt and Valentin (1992) have observed that the more stable soils in West Africa contain kaolinite, while those containing smectite and illite are more prone to sealing. This is likely due to differences in dispersion/flocculation conditions or differences in cementing agent contents in soils with different clay types. Iron oxides can

contribute to soil strength, therefore affecting the hardness of the dry crust. Shadfan, Dixon, and Calhoun (1985) found a positive correlation between dithionite-extractable iron and soil strength, and a negative correlation between the ratio of oxalate to dithionite extractable iron and soil strength. Ferrihydrite or iron polycations have a strong soil aggregating ability when added to soils, especially in the presence of organic matter (Bartoli et al., 1988a, b). Van der Watt and Valentin (1992) suggest that sesquioxides only contribute to soil strength in humid areas. In arid areas, iron oxides exist as discrete particles and not as coatings of clay surfaces (Uehara and Jones, 1974). Iron oxides probably do not act as cements until they form a continuous matrix (Uehara and Jones, 1974). Associations between kaolinite and iron oxides may contribute to aggregation, but this can be disrupted by specific adsorption of silicate ions (Golden and Dixon, 1985).

Uehara and Jones (1974) suggest that in hard crusting soils of the arid and semi-arid regions, amorphous silica is most likely the cementing agent. Factors influencing silica gel formation and dynamics are pH, temperature, and wetting and drying cycles. (Brown and Mahler, 1988). These factors affect the degree of polymerization and sorption characteristics of silica.

Perrier (1986) proposed that the rapid pH changes accompanying wetting and the high surface temperature along with the additional heat of wetting alter the adsorption characteristics of clays and iron hydroxides and accelerate chemical reactions involved in the hardening of the crusts.

Physico-chemical dispersion of clays is often cited as the process causing soil sealing (Agassi et al., 1981; Gal et al., 1984; Sumner, 1992; van der Watt and Valentin, 1992; West, et al., 1992). Soils which are chemically dispersed seal more easily, due to slaking and suspension of clays. Typically, increasing dispersion of clays by Na saturation of the clay lowers infiltration rates (Greene et al., 1988).

A common feature of soils with surface seals is a vesicular structure in microlayers just below the surface. These usually develop after several wetting and drying cycles in tilled soil (Figueira and Stoops, 1983; Miller, 1971). Spherical pores develop through air entrapment in successive wetting and drying cycles by differential wetting.

Some research has been done on the processes of seal formation in West African soils. Erosion and crusting has been reported in West Africa since 1910 (Dregne, 1990). Boiffin (1984) showed that the thickness of the affected layer is directly related to the kinetic energy of the rain. Hoogmoed and Stroosnijder (1984) described a depositional type of crust in Mali, showing the effects of tillage on seal reformation. Casenave and Valentin (1988) identified six different types of surface crusts: drying, layered structural, erosion (later stage of structural), runoff depositional, standing water depositional, and desert pavement. But, despite this wealth of published results on processes of seal formation, there is very little information on the influence of soil properties on seal formation.

CHAPTER IV

MATERIALS AND METHODS

SITE SELECTION AND SAMPLING

The purpose of the field studies was to characterize the occurrence of surface seals at locations in Niger and Mali and to obtain a measure of the strength and permeability of the seals. Since preliminary results were used to select sites, some results are presented in this chapter and not repeated in later chapters.

Two locations were selected for study. The first location was near the village of Hamdallaye, about 35 km northeast of Niamey, Niger, on the research site of the Integrated Management of Agricultural Watersheds project (Figure 5). This site is being studied by the Texas A&M University Soil Management Collaborative Research Program (TropSoils) in collaboration with the Niger National Institute for Agronomic Research (INRAN). The second location was the Cinzana Research Station of the Institute for Rural Economic Research (IER) in Mali. These locations were chosen because of availability of detailed soil maps, collaboration with TropSoils personnel working there, and for relating information gained from this study to current research being conducted. For reasons to be explained later, most of

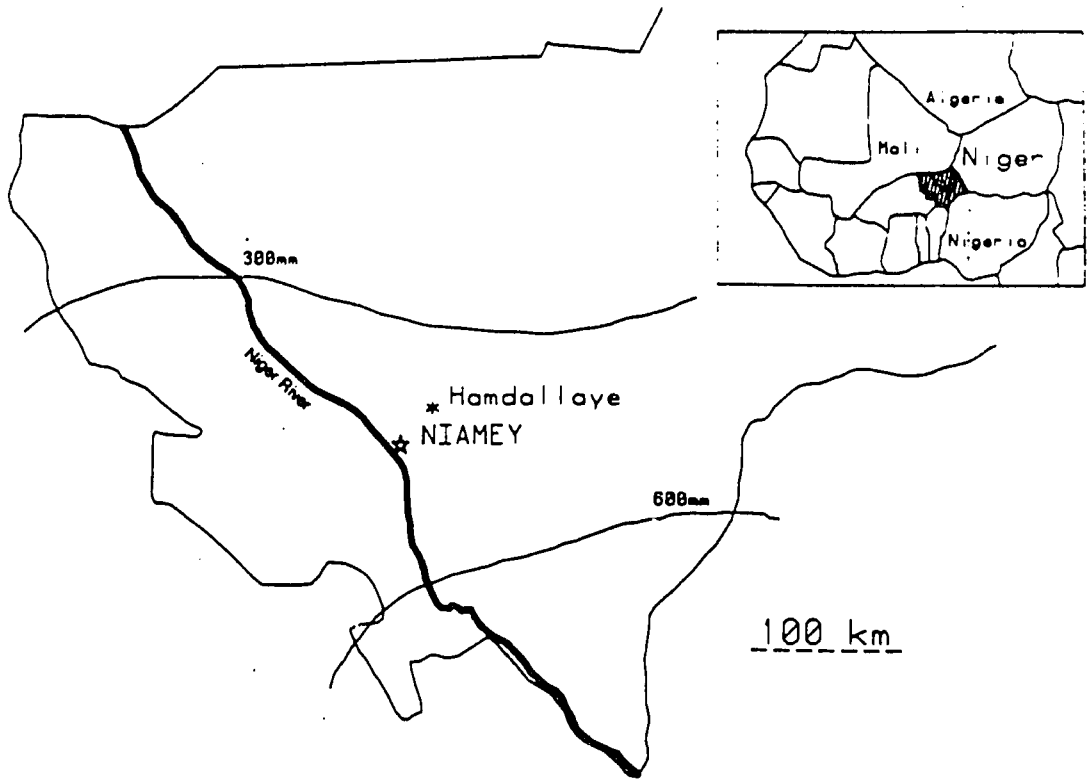

Figure 5. Map of western Niger showing location of Hamdallaye. From Manu et al. (1991).

the work for this study was done on the Niger soils, and the soils from Mali are only dealt with briefly.

At the Hamdallaye location, five sites were chosen for this study. The sites were located on the five main soil series on a 500 ha watershed, representing a variety of slope positions and soil textures, from sandy loam to sand (Figures 6a and 6b). These soils are classified as Typic Kandiustalfs and one Typic Haplustult (from soil descriptions from Manu et al., 1991). The watershed is bounded by a laterite plateau at the top, and the valley floor at the bottom. The Tondo Kakasia series is weathered from Continental Terminal parent materials forming the plateau. It is deep red, and about fifty percent of the soil in the area is sealed. This area has a meso-scale relief of 20 to 40 cm with vegetated woody and brushy areas occupying the higher elevations (Figure 7). Lower elevations are typically bare, and exposed roots of brush growing in the lower elevations gave evidence of recent erosion. In the rest of the watershed, it was evident that soil sealing took place in areas which had been eroded by wind or water, exposing the finer-textured subsoil (Figure 8). Land was used in this area for growing millet with some shrub and grass fallowed areas. In general, sealing was most severe immediately below the plateau and near gullies. Infiltration and penetrometer measurements in Niger were done in June and August 1991, after several rainfall events but before crop emergence.

At Cinzana, the study sites were more difficult to choose. Many of the sites which were initially considered to be crusted were actually found to be compacted by

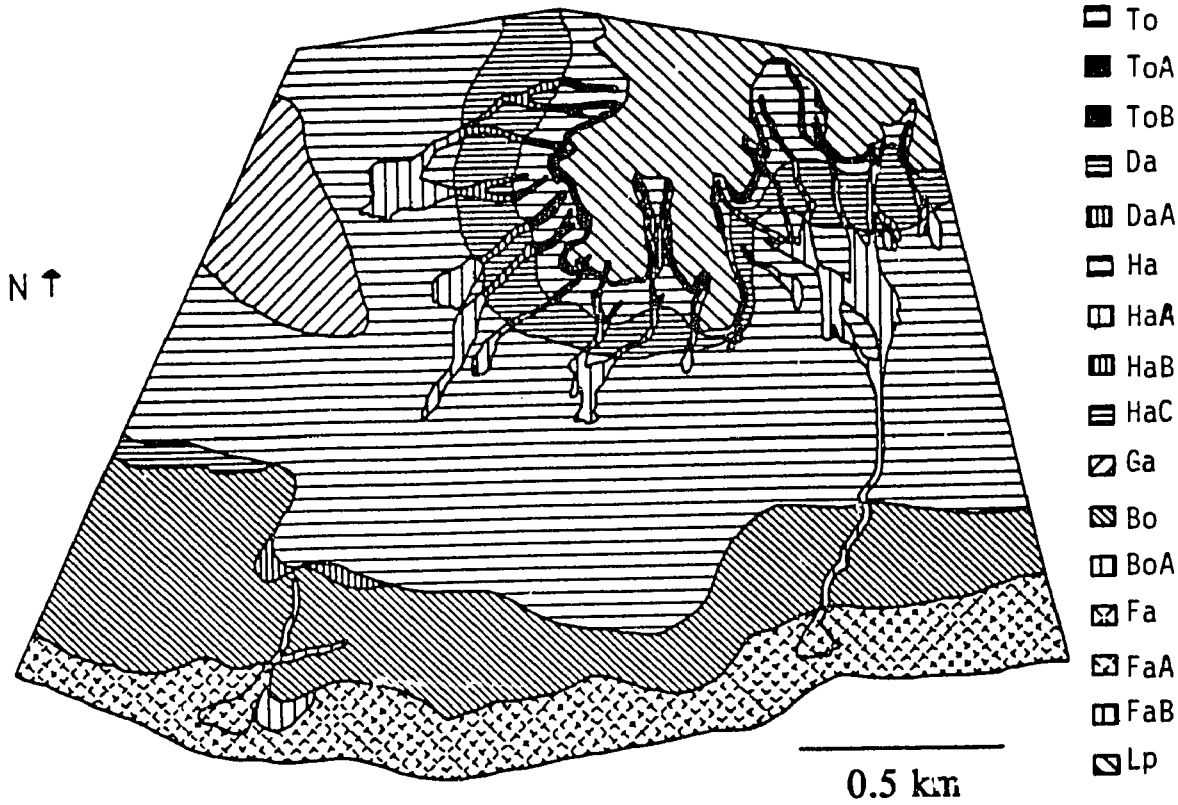

Figure 6a. Soil map of the Integrated Management of Agricultural Watersheds (IMAW) research site at Hamdallaye, Niger. From Manu et al. (1991).

SYMBOL	MAP UNIT
To	Tondo Kakasia sandy loam, 3-8% slope
ToA	Tondo Kakasia sandy loam, stony phase, 3-8% slope
ToB	Tondo Kakasia sandy loam, gullied phase, 3-8% slope
Da	Dantiandou sand, 2-3% slope
DaA	Dantiandou sand, gullied phase, 2-3% slope
Ha	Hamdallaye sand, 1/2-2% slope
HaA	Hamdallaye sand, overwash phase, 1/2-2% slope
HaB	Hamdallaye sand, lithic phase, 2-3% slope
HaC	Hamdallaye sand, lithic phase, 5-7% slope
Ga	Gangani Kirey loam sand, 0-1/2% slope
Bo	Bokotchili sand, 1/2-2% slope
BoA	Bokotchili sand, gullied phase, 1/2-2% slope
Fa	Falanke loamy sand, 5-7% slope
FaA	Falanke loamy sand, overwash phase, 5-7% slope
FaB	Falanke loamy sand, lithic phase, 5-7% slope
Lat	Plateau sandy loam, 0-1% slope

Figure 6b. Soil map legend.

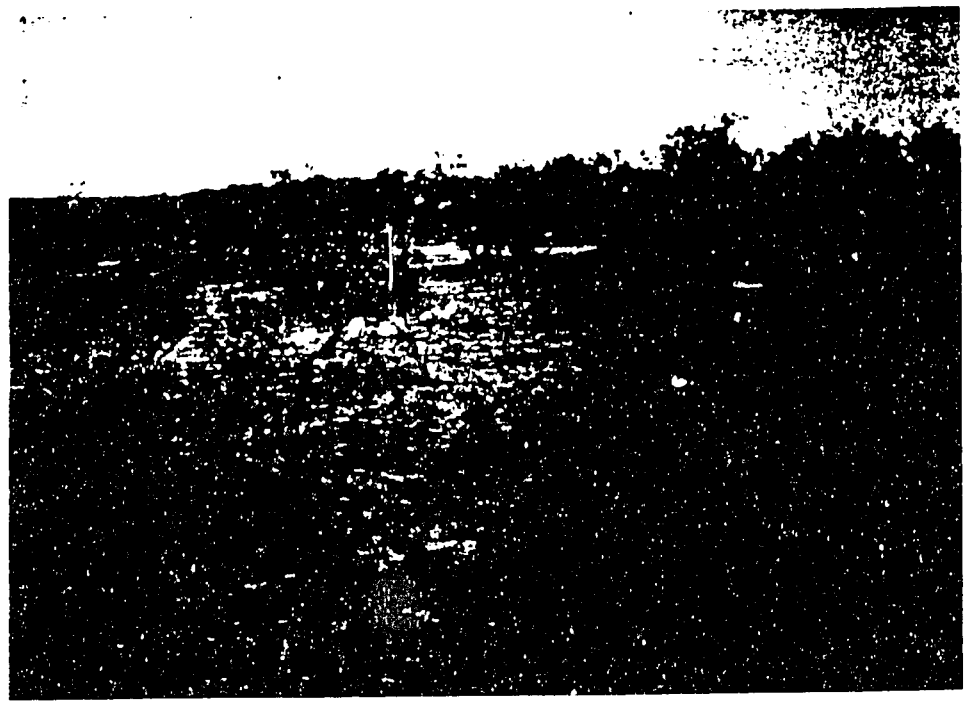

Figure 7. High meso-scale relief in the Tondo Kakasia soil at Hamdallaye.

Figure 8. Typical mid-slope sealed area in the Dantiandou soil at Hamdallaye.

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heavy animal traffic (Figure 9). Also, many sealed sites were the result of mound-building termites which brought fine material to the surface (Figure 10). Many clay rich sites observed were possibly sites of previous termite mounds. Cultivated fields showed sealing between ridges from deposition of clay (Figure 11), and fallow fields had diverse histories which made it difficult to select a site which would be characteristic of soils of the surrounding region. Two long-term fallow fields on the station were chosen (Figures 12 and 13). The soils were a sandy loam (map designation site M2) and a loamy sand (site B12). Site M2 was classified as an Oxic Haplustalf and site B12 as a Plinthic Haplustalf. Both showed some evidence of animal traffic. In the finer-textured soils than these, there was so much evidence of animal traffic and termite activity, and the depth of massive and impermeable soil was so great, that although the soils gave an appearance of being crusted, the immediate surface had the same hardness and permeability as the underlying soil.

For paired sealed and unsealed sites of each soil series, the following field work was done. Sealed sites and unsealed sites within 30 meters of each other which appeared to be representative of soil surfaces within the soil series were chosen. The landscape position, vegetation, and land use were recorded (Table 1). Three repeated measurements of infiltration using a disk infiltrometer (Perroux and White, 1988) were made on: a) sealed site, b) unsealed site, and c) sealed site where the surface was disturbed to 1 cm depth. The disk infiltrometer was used because of it's easy portability, low water consumption, and accuracy of measurement compared

Figure 9. Site of heavy animal traffic at the Cinzana Experiment Station in Mali.

Figure 10. Previous termite mound at the Cinzana Experiment Station.

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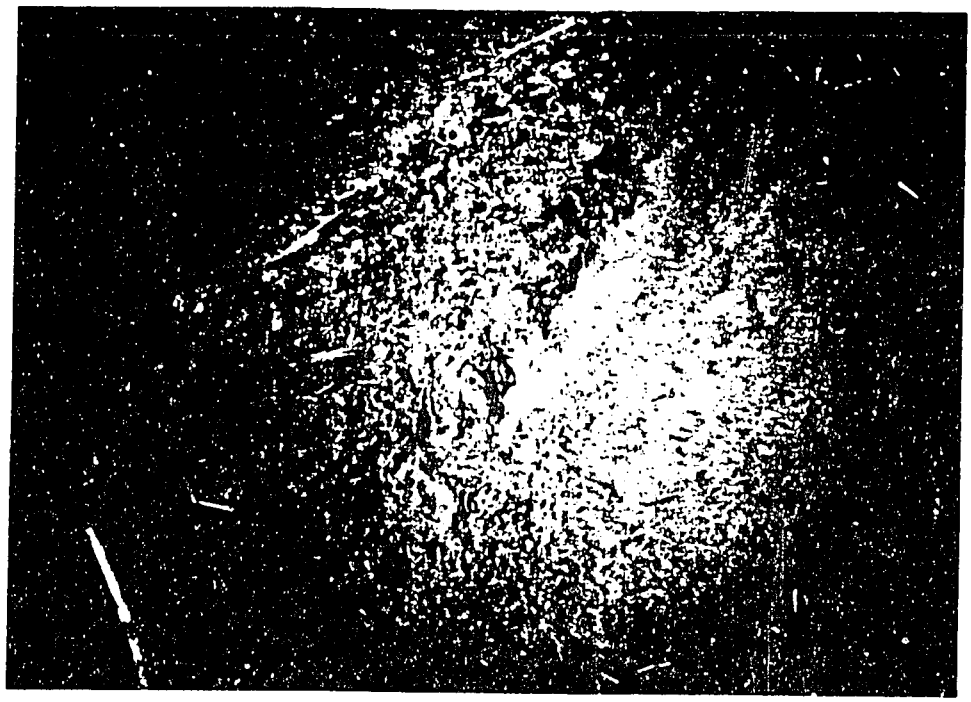

Figure 11. Sealing between ridges in a cultivated field at the Cinzana Experiment Station.

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Figure 12. Sample site M2 at the Cinzana Experiment Station, also showing disk infiltrometer.

Figure 13. Sample site B12 at the Cinzana Experiment Station with sealed area in the foreground.

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to rainfall simulators. Although infiltration was not measured under rainfall, the disk infiltrometer measurements give an indication of the presence of a surface seal and it's effect on hydraulic conductivity.

Table 1. Landscape position, vegetation, and land use of the six Hamdallaye soils.

Soil	Landscape Position (slope)	Vegetation	Land Use	Area Sealed
Tondo Kakasia*	shoulder (3-8%)	natural shrub	never cultivated	50 %
Dantiandou*	upper backslope (2-3%)	cultivated crops, natural shrub	50% cropped 50% fallow	< 5 %
Hamdallaye*	middle backslope (1/2-2%)	cultivated crops, natural shrub	50% cropped 50% fallow	< 5 %
Bokotchili*	lower backslope (1/2-2%)	cultivated crops, natural shrub	50% cropped 50% fallow	< 5 %
Falanke*	footslope (5-7%)	cultivated crops, natural shrub	50% cropped 50% fallow	< 5 %
Gangani**	middle backslope (0-1/2%)	cultivated crops, natural shrub	20% cropped 80% fallow	80 %

* Classified as Typic (Psammentic) Kandiustalf.
** Classified as Typic (Petroferric) Kanhaplustult.

Twelve penetrometer measurements were taken at each site, under both dry and saturated conditions, using a pocket penetrometer (Bradford, 1986). The pocket penetrometer was chosen because of it's small size and weight, and because it is a good measure of unconfined strength at the surface of the soil compared to cone

penetrometers. Cone penetrometers usually show extremely low resistance at the surface because the soil is easily pierced by the point of the cone.

Both sealed and unsealed soils were sampled for laboratory analysis. Samples included intact blocks for thin sectioning and bulk samples for chemical and physical analysis. Duplicate intact blocks of the surface 3.5 cm were taken by excavating around a 5-cm by 10-cm column and placing a Kubiena tin around the column. A space of 0.5 cm was left at the top of the Kubiena tin. Cheesecloth was placed in the tin, on the surface of the soil, and the rest of the tin was filled with loose sand. Cellulose acetate was sprayed on the loose sand to stabilize it. The blocks were then transported to Texas A&M University, College Station, Texas, without evidence of disturbance in most cases. Bulk samples were sampled at the following depths for the sealed sites at Hamdallaye: 0 to 0.5 cm, 0.5 to 2.5 cm, and 2.5 to 5 cm. A crust sample was collected by lightly scraping the crust with a knife after brushing off any loose sand, and collecting the dislodged material. This sample was normally 1 to 3 mm deep and is identified as 0-C; the C standing for crust. The unsealed sites were only sampled from 0 to 5 cm. At Cinzana, both sealed and unsealed sites were sampled from 0 to 5 cm.

LABORATORY ANALYSIS

The intact blocks and bulk samples were brought to Texas A&M University, College Station, and the following analyses were performed.

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Thin sections were prepared from the intact blocks and described with a petrographic microscope. A fluorescent dye was added to the polyester resin used to impregnate the blocks in order to photograph the blocks under ultraviolet light and analyze pore space using image analysis. Initial pore space analysis revealed that other than vesicular pores, pores in the samples were simple packing voids with no preferred orientation.

The thin sections were also observed under a scanning electron microscope using backscattered imaging and energy dispersive X-ray spectroscopy. The thin sections were polished with successively finer aluminum oxide powders (25, 17.5, 9.5, 3, and 1 μm) to eliminate any topography effect, and then sputter coated with gold.

Bulk samples were dried and sieved through a 2 mm sieve. Particle size analysis was done by sedimentation in a sodium hexametaphosphate solution using a hydrometer (Gee and Bauder, 1986). In addition to this standard treatment, particle size was measured in distilled water to determine percent water dispersable clay, and also in sodium hexametaphosphate after removal of free iron by citrate-dithionite treatment. The extraction of free iron was done to provide information on the role of iron oxides in permanent cementing of particles.

West et al. (1987) measured ZPC of 2.8 to 3.2 in similar soils. Since dispersion and flocculation of variable charge clays is related to pH and ZPC, soil pH was measured in 1:1 distilled water and 1 M KCl. Aggregation may be

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influenced by cements such as oxides or silica. Free iron and aluminum oxides were extracted with sodium citrate-dithionite and ammonium oxalate and then iron and aluminum were measured using atomic absorption spectroscopy (Jackson et al., 1986). Soluble silica was extracted in 0.05 M NaCl by the method of Herbillon et al. (1977) and silica was measured using atomic absorption. Exchangeable cations were extracted with ammonium acetate and calcium, magnesium, potassium, and sodium were measured by atomic absorption (Thomas, 1982). Exchangeable acidity was measured by titrating a 1 M KCl extract (10 grams soil/150 mL 1 M KCl) with NaOH. Organic carbon was determined using the Walkley-Black method (Nelson and Sommers, 1982).

Mineralogy was determined on sand, silt, and clay by X-ray diffraction. Total iron was measured in sand, silt, and whole soil using X-ray spectroscopy. Mineralogy determinations were supplemented by transmission electron microscope observations of clay fractions.

Modulus of rupture was measured by the method of Richards (1953). The following treatments were used: (A) an untreated sample; (B) a sample saturated with $CaCl_2$ as explained later; (C) a sample treated with hydrogen peroxide to remove organic matter and then Ca saturated; (D) a sample treated with hydrogen peroxide and sodium citrate-dithionite (DCB) to remove organic matter and free iron oxides and then Ca saturated; (E) a control sample treated like D, but without sodium dithionite. The soil was Ca satured as follows. Forty grams of soil was shaken in

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100 mL of 1 M $CaCl_2$, then centrifuged, and the supernatant was decanted. This procedure was repeated again with 1 M $CaCl_2$, and then with distilled water until the soil dispersed. A few drops of 1 M $CaCl_2$ were added to reflocculate the clays, and the solution was centrifuged and decanted. All samples were dried, passed through a 2-mm sieve, placed in 39 by 52 by 10-mm brass molds, and settled to a bulk density of 1.46 Mg/m^3. This bulk density is the average density that dried, sieved samples reached when tapped for several minutes in a graduated cylinder. The soils were wetted to saturation, and then dried in the molds at 60° C for two days.

Water-stable aggregates were measured by wet sieving 10 g of 2- to 4-mm aggregates in 0.5-mm sieves for three minutes at 35 cycles per second (Kemper and Rosenau, 1986). The 2- to 4-mm aggregates were obtained by dry sieving a combined 0-5 cm bulk soil sample through a 4-mm and then a 2-mm sieve. The aggregates were pre-wetted with an aerosol spray.

A rotating disk rainfall simulator similar to that described by Morin et al. (1967) was used to create seals under controlled conditions. This rainfall simulator has kinetic energy, drop size, and terminal velocity values very close to natural rain. A rotating platform was placed under the simulator to reduce rainfall variability. Rainwater was collected and used for the simulations. The rainwater had an electrical conductivity of 0.020 dS/m. The bulk Hamdallaye soil was used for this experiment. To procure enough soil for the experiment, the bulk soil from all depths of the sealed sites were proportionally mixed by depth for a composite sample of

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each soil series. Five cm deep, eight cm diameter tin cans were used as soil containers. A hole was cut in the bottom of the cans, and a 1.3-cm diameter, 40-cm long fiberglass rope was hung from the bottom of the can. The top of the rope was spread out in the can to insure good contact with the soil. The rope was placed inside polypropylene tubing, so that it formed a 40-cm hanging water column. A slit was cut down the side of the can to allow water to flow off the surface of the soil. The slit was covered by a screen to minimize soil loss. Soil was placed in the cans to a depth of 3 cm. The cans were set on the rotating platform with a 7% slope towards the slit in the side of the can.

The intensity of the artificial rain was chosen from data compiled by Sivakumar (1987). He reported peak rainfall intensities near Niamey, Niger at 386 mm/h. In a 4-year period, 36% of the rains fell with average intensities of >50 mm/h, and 13% with intensities of >100 mm/h. A value close to 100 mm/h was chosen for this experiment to compromise between peak intensities and average intensities of natural rainfall. The soils were subjected to rain at an intensity of 90 mm per hour for the following treatments: (A) control with untreated bulk soil; (B) soils saturated with sodium, and then rinsed by addition of distilled water, centrifugation, and decanting, until they dispersed; (C) soils saturated with calcium; (D) untreated soils with a drying cycle between rainfall events of 60° C during the day and 25° C at night; (E) a treatment which received 120 min of continuous rain. Treatments A, B, C, and D received thirty minute rains with one week natural drying

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period between the rains. Drying temperatures for treatments A, B, and C ranged from 30 to 40° C. Three repeated measures of each soil were done on each treatment for the 120 min. total rain treatments to estimate variability. Cans were also removed in each treatment for impregnation after only one 30 min rainfall, and cans were removed for impregnation in treatments A and D after 60 and 90 min total rainfalls. Table 2 shows the experimental design. The 120 min total rainfall treatments were replicated three times, and the others only once. After the soils were dried, they were impregnated with polyester resin and thin sections were prepared and analyzed as described above for the field samples.

Table 2. Summary of rainfall simulator experiment.

	Total Rainfall Received (min)			
Soil Treatments	30	60	90	120
(A) Control	+	+	+	+
(B) Na-Saturated	+			+
(C) Ca-Saturated	+			+
(D) Dried at 60°C	+	+	+	+
(E) Continuous Rain				+

note: + designates all six Hamdallaye soil series used in this treatment.

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CHAPTER V

RESULTS AND DISCUSSION

FIELD STUDIES

The first objective of these studies was to identify sealing and crusting soils in West African Alfisols and to define the processes and degree of sealing or crusting. Surface seals were identified visually first, and then the degree of sealing or crusting was measured by the effect of the seal on infiltration and penetrometer resistance. The processes of sealing can be deduced from field observations and micromorphological observations of thin sections. Field observations and infiltration and penetrometer measurements will be discussed in this section.

An extensive gully system, numerous outwash fans and many areas of exposed subsoil are evidence of erosion at the IMAW watershed at Hamdallaye, Niger. Soil sealing on the watershed is related to erosion. The soils have thick argillic horizons which are often exposed by wind and water erosion. It is these exposed subsoils that are most prone to sealing. Most of the sealed soils on the watershed occur in the Tondo Kakasia (Figure 14) and the Gangani Kirey (Figure 15) soils, which are not used for millet production. Millet is grown in sandy patches within the Gangani Kirey, but nothing grows on the sealed surfaces. The Tondo Kakasia is on a steep (8%) slope just below the laterite plateau. The Gangani

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Figure 14. Laterite plateau above the Tondo Kakasia soil at Hamdallaye.

Figure 15. Severe sealing on the Gangani soil at Hamdallaye.

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Kirey (0-.5% slope) is on a laterite outcrop midway down the watershed. This indicated that sealing is often related to recently weathered laterite. Sealing also occurred in the agricultural soils, and usually occurred near gulleys or on steeper slopes which were eroded (Figure 16). Occasionally seals occurred in deflationary depressions caused by wind erosion, especially in the Hamdallaye soil series (Figure 17). A thorough description of the soils, vegetation, land use, and extent of erosion in this area is contained in TropSoils Bulletin No. 91-03 (Manu et. al., 1991).

Many of the soils at the Cinzana research station in Mali have dense, hard surfaces which appear to be crusted. The broad use of the term crusting makes it difficult to say that these soils are not crusted, but as explained in chapter 4, the dense, hard surfaces are often due to compaction by animal traffic and are at least 10 cm deep. At the M2 site, the infiltration under a disk infiltrometer did not increase when the surface was disturbed, as in many other sites which appeared crusted (Table 3). At the B12 site, the infiltration rate increased when the surface was disturbed, which indicates a dense surface feature rather than deep compaction. Most of these soils are much finer textured than the soils at Hamdallaye, and very susceptible to compaction. The amount of animal traffic on fallow fields is high enough that many of the crusted sites would be better akin to a road or cattle trail than an agricultural field. Deterioration of soil structure by cultivation, loss of organic matter and dispersive conditions cause other agricultural fields which did not receive heavy animal traffic to still form hard, dense surfaces. Extensive areas were

Figure 16. Gulley erosion in the Bokotchili soil at Hamdallaye.

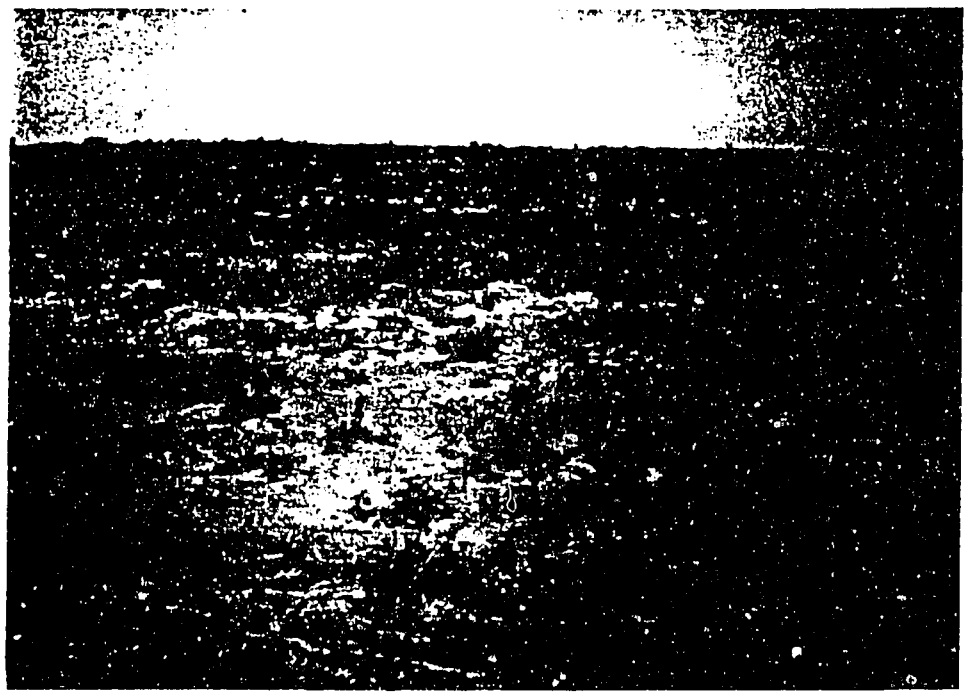

Figure 17. Deflationary wind erosion on the Hamdallaye soil at Hamdallaye.

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effected by sites of active or previous termite mounds which were also very hard and dense. Regardless of the process, though, all of the soils studied except those with depositional seals were affected throughout the upper soil horizons, rather than just at the surface. For this reason, the use of the terms crust or seal is probably not appropriate.

Table 3. Infiltration rates in μm/sec for two soils at the Cinzana Experiment Station. Each number is an average of three replicates.

Plot	Sealed Site	Unsealed Site	Disturbed Site
	----------	μm/s	----------
M2	52	> 130	52
B12	33	> 130	80

Surface seals also occurred on a micro-scale between ridges in cultivated fields. These appeared to be a combination of structural and depositional crusts. These fields were not studied because there was no way of measuring infiltration on them due to the surface roughness. Although the time spent in Mali was only two weeks, one could conclude that the soils in the cultivated fields have lost their structure due to oxidation of organic matter from tillage and residue removal, and in some cases through dispersion from build-up of salts from irrigation. Along with

heavy animal traffic and intense rainfall, these factors have led to a compacted surface horizon in many of the soils.

In order to characterize the degree of seal formation, steady state infiltration measurements using a disk infiltrometer were conducted on each of the Hamdallaye soils, on undisturbed sealed sites, disturbed sealed sites, and unsealed sites. Infiltration was measured for 15 to 60 min, depending on the time it took for the rate of infiltration to become fairly constant. The maximum delivery rate of the infiltrometer was 130 μm/s. In most of the unsealed sites, the initial infiltration rate was greater than 130 μm/s, and usually the delivery rate of the infiltrometer was also exceeded when sealed sites were disturbed (Table 4). Steady state infiltration rates were much lower than the potential delivery rate of the infiltrometer for sealed sites, showing that surface layers restrict infiltration. Measurements made on disturbed sites before and after brief rainfall events revealed that before the rain the infiltration rate was high, but immediately after the rain the infiltration rate decreased to the same value as before disturbance. This suggests that these surfaces seal quickly, and after only one rainfall event. In addition to infiltration measurements, observations of the sites during rainfall events showed that all of the sealed sites caused runoff or ponding, and all of the unsealed sites did not.

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Table 4. Final infiltration rates in μm/s for five soils at Hamdallaye. Each number is an average of three replicates.

Soil Series	Sealed Site	Unsealed Site	Disturbed Site
	----------	μm/s	----------
Tondo Kakasia (To)	2.8	62	> 130
Dantiandou (Da)	103	> 130	> 130
Hamdallaye (Ha)	56	> 130	> 130
Bokotchili (Bo)	9	> 130	110
Falanke (Fa)	73	> 130	> 130

Although the disk infiltrometer measurements do not accurately represent infiltration under rainfall, they are useful in identifying surface layers that limit infiltration. This was especially true in the Mali soils, where many measurements on supposedly crusted sites showed that the subsoil infiltration rate was the same as the surface, indicating that the surface was not a limiting factor in infiltration. During the selection of study sites at the Cinzana station, only the sealed soil on the B12 mapping unit was found to have an infiltration rate higher when the surface was disturbed compared to undisturbed (Table 3).

The penetrometer measurements also show a large difference between penetration resistance of surface seals and paired unsealed sites in the Hamdallaye soils, especially when the soil was dry (Table 5). Wet penetrometer measurements were taken immediately after infiltration measurements, so that the soil was saturated. The dry penetrometer measurements were taken from two to five days

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after rains. Although the soils all appeared very dry when these measurements were made, the hardness of the dry crusted sites might not be comparable, since penetration resistance is heavily dependent on moisture content, and the crusted sites had enough clay that hardening may have continued under the heat of the sun for several days after initial drying. Penetrometer readings are generally higher for the finer-textured soils than the coarse-textured soils, for both wet and dry conditions, indicating the role of clay content in hardness of the crust.

Goyal (1980) summarized seedling emergence forces reported in the literature for various crops, ranging from 0.5 Mg/m^2 in alfalfa to 10 Mg/m^2 in cotton. This shows a large difference in seedling emergence strength between crops. The penetrometer measurements may not directly relate to seedling emergence forces, especially since seedlings exert a force over a long period of time. But, the values of unconfined strength in the dry sealed sites averaged 36 Mg/m^2, which is much higher than the seedling emergence forces of any of the crops listed by Goyal. Therefore, the seals probably would inhibit seedling emergence.

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Table 5. Penetrometer measurements under wet and dry conditions for five soils at Hamdallaye in Mg/m^2 unconfined strength. Each number is an average of 12 replicates.

	Sealed Site		Unsealed Site	
Soil Series	Dry	Wet	Dry	Wet
	---------- Mg/m^2 ----------			
Tondo Kakasia	> 45	13.3	4.7	3.3
Dantiandou	18.4	8.4	5.6	2.7
Hamdallaye	28.2	1.3	3.7	1.7
Bokotchili	> 45	5.5	4.2	1.1
Falanke	> 45	6.8	3.9	< 0.1
All Soils (average)	36.3	7.1	4.4	1.8

THIN SECTION ANALYSIS

In order to further characterize the seals and to determine the processes of seal formation, thin sections of intact surface samples were analyzed. Thin sections were cut vertically through the impregnated blocks. All of the Hamdallaye crusted sites are similar morphologically. All have a 0.1- to 1-mm thick continuous plasmic layer either on the surface or within 4 mm of the surface (Figure 18). Some still had a thin layer of clean sand overlying the clay layer (Figure 19), but frequently this sand layer was lost during sample preparation. The presence of these two layers is diagnostic of structural seals. The major difference in the soil one to three cm below the surface between sealed and unsealed soils was the higher clay content of the

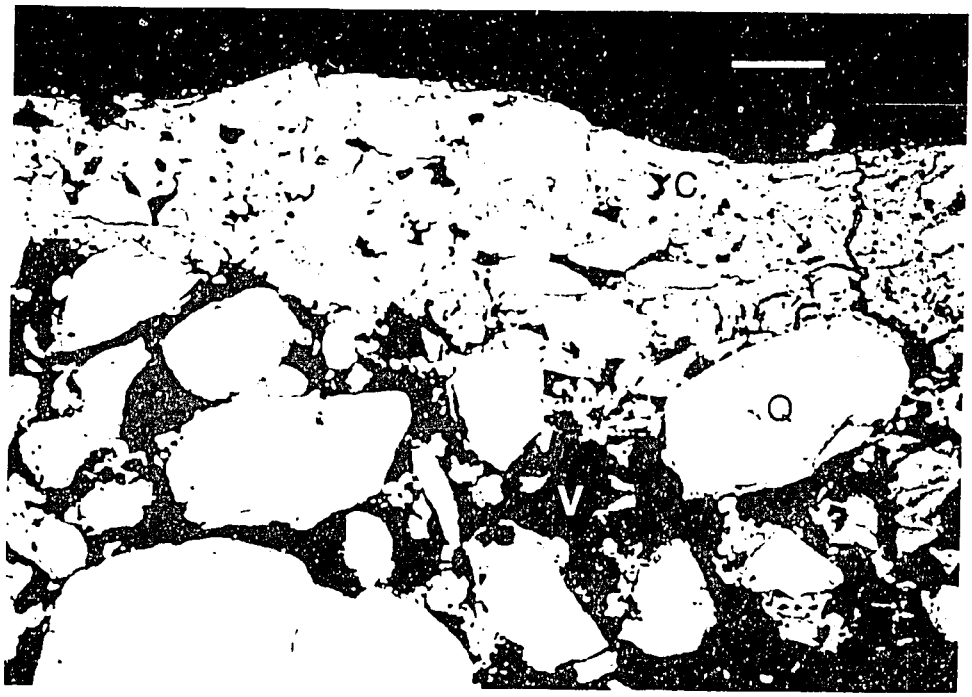

Figure 18. SEM backscattered micrograph of surface of Tondo Kakasia series showing clay seal. Q = quartz grain. C = clay. V = void. Bar is 100 μm.

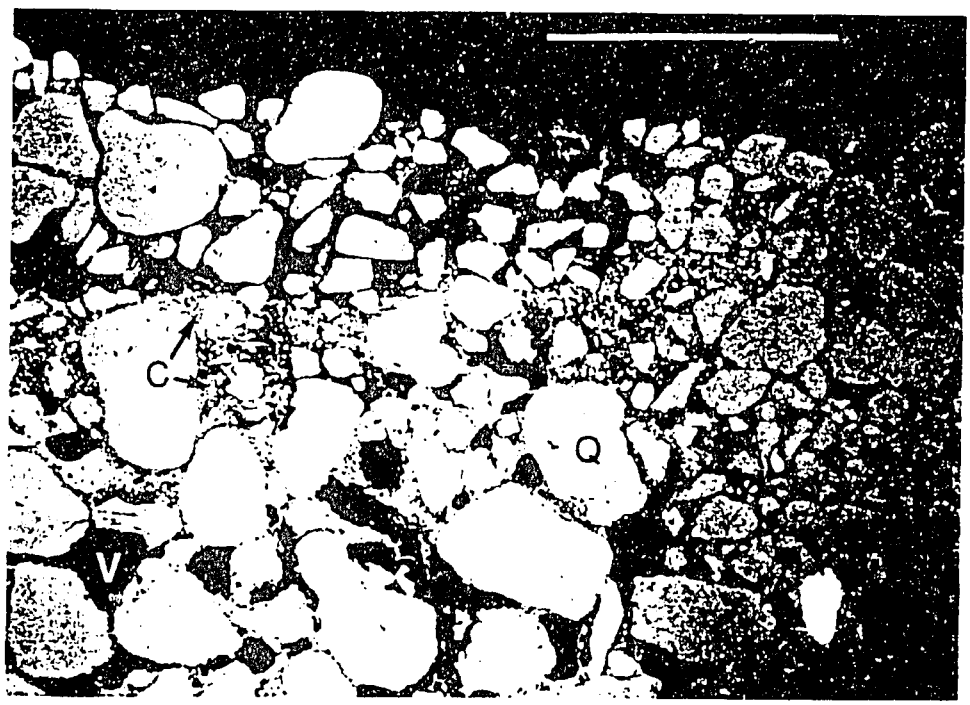

Figure 19. SEM backscattered micrograph of surface of Dantiandou series, showing clay infilling and sand layer above. Q=quartz grain. C=clay. V=void. Bar is 1 mm.

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sealed soils. The unsealed soils have a granular s-matrix particle distribution, with clay being present almost exclusively as coatings on sand and silt grains. The sealed soils have a granular to intertextic s-matrix particle distribution depending on clay content, with clay existing mostly as coatings on sand and silt grains and as bridges between grains. Voids in the samples were mostly simple packing voids, with some vesicular pores and very few continuous large pores.

Thin section analysis of the intact blocks from Mali revealed that the B12 sealed soil had a depositional crust, and the M2 sealed soil did not have any differentiated layers. The infiltration measurements showed that the M2 soil had a lower infiltration rate than the paired unsealed soil, but infiltration was no higher when the surface was disturbed. Along with the thin section analysis, infiltration rates on undisturbed and disturbed areas shows that no surface seal or crust was present on the M2 soil. Since the seal on the B12 soil was due to deposition of material on the surface, and not influenced by the soil properties, measurements of soil properties on the Mali soils were not conducted. Nevertheless, an important result of the Mali field studies and thin section analysis was that soils which often appeared crusted on the Cinzana Research Station may be sites of heavy animal traffic or soil degradation that leads to deep compaction, rather than a surface seal.

Since the ultimate soil properties which affect sealing are the pore size distribution and pore continuity, pore size analysis was attempted by photographing the polished impregnated blocks under ultraviolet light. No useful information was

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gained by this method because of the lack of continuous macropores and the lack of resolution of the prints at small pore sizes, so pore size analysis was done on SEM micrographs.

Image analysis of negatives taken from thin sections allowed measurement of pores down to 2 μm diameter. The diameter reported herein is the effective diameter that a given pore would have, considering it's area, if it were perfectly round. Measurements of pore-size distributions were taken on the Tondo Kakasia and the Falanke thin sections. Three measurements within the sealed layer (0 to 0.4 mm depth) and three below the sealed layer (0.5 to 1.5 mm depth) were taken. No pores larger than 1000 μm were found. The pores were divided into four different size classes, according to Brewer (1976): (1) macrovoids, > 75 μm; (2) mesovoids, 30-75 μm; (3) microvoids, 5-30 μm; (4) ultramicrovoids, < 0.1 μm. In the Tondo Kakasia soil, total amount of porosity in the seal was only 10.5%, compared to 36% in the soil below the seal. Most of the porosity in the seal is from pores with diameters between 5 and 30 μm, while most of the porosity in the soil below the seal is due to pores larger than 75 μm (Figure 20). Similarly, the total porosity in the Falanke soil is much lower in the seal (16%) than the soil below it (31%). The porosity in the Falanke soil is due largely to 30 to 75 μm diameter pores in the seal and > 75 μm pores in the soil below the seal (Figure 21). The seals in all of the thin sections were unbroken by large pores horizontally. Therefore, the pore size

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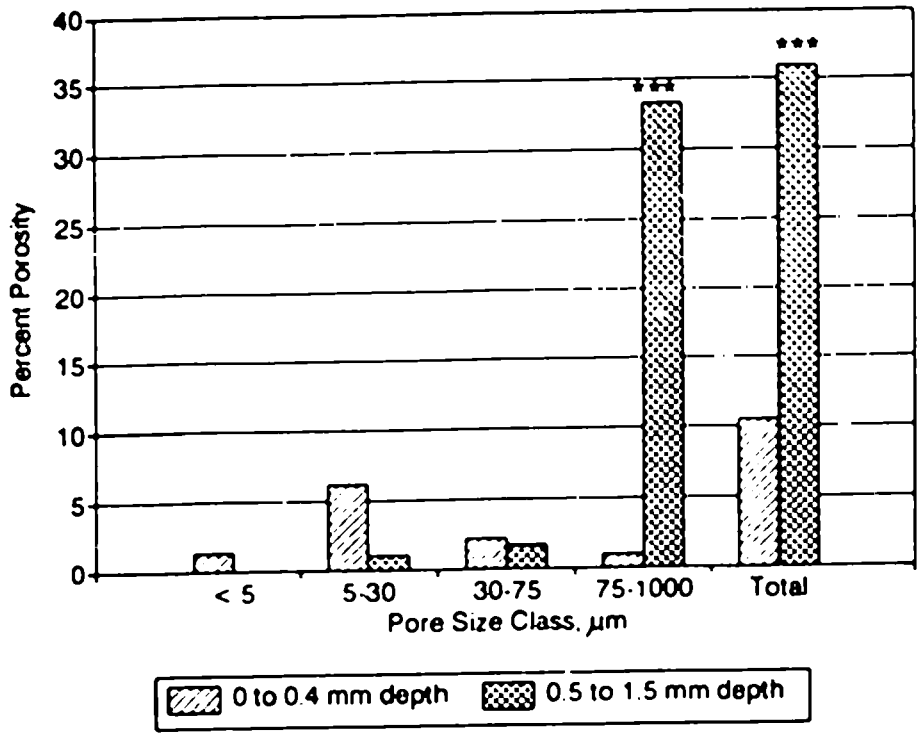

Figure 20. Pore-size distribution in the Tondo Kakasia soil. *, **, and *** denote significant differences between depths for each pore size class at P= 0.05, 0.01, and 0.001, respectively.

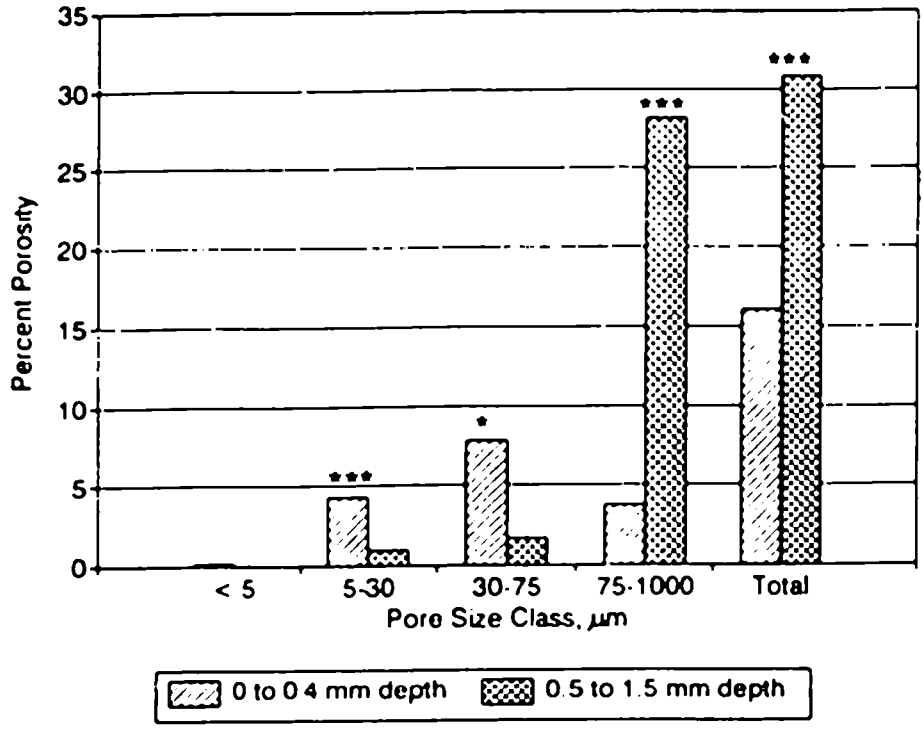

Figure 21. Pore-size distribution in the Falanke soil. *, **, and *** denote significant differences between depths for each pore size class at P= 0.05, 0.01, and 0.001, respectively.

analysis supports the conclusion that, due to the absence of large pores in the seals, the seals form a restrictive layer that limits water infiltration.

PHYSICAL AND CHEMICAL PROPERTIES

The second objective of this study was to determine the soil properties which affect sealing in the selected soils. The properties which influence soil structure are particle-size distribution, aggregating agents, and dispersion/flocculation properties of the clays. The following analyses were done on the six Hamdallaye soils on both sealed and unsealed samples. The sealed samples were analyzed at four depths: 0 to 0.5 cm, 0.5 to 2.5 cm, 2.5 to 5 cm, and 0-C (crust sample). The unsealed samples were analyzed at one depth of 0 to 5 cm. For those data for which only summaries are given, complete data is contained in the appendix.

Mineralogy

Mineralogical determinations by X-ray diffraction showed that all of the sand fractions of all soils was mostly quartz, with some feldspars and iron and titanium oxides. The silts consisted of mostly quartz, feldspars, and kaolinite, with trace amounts of hematite. The clays consisted of mostly kaolinite with some illite. Small peaks of goethite were detected occasionally in all size fractions. The presence of illite indicates that there are some permanent charged surfaces, but the dominance of kaolinite indicates a low charged, highly weathered, relatively inert system.

Information on the distribution of elements within a sample can be gained by element mapping with an energy dispersive X-ray spectrometer and SEM. This was used to identify the distribution of iron in the thin sections. Much of the iron is present as discrete sand particles, but all of the clay size materials contain a significant amount of iron, showing the presence of short-range ordered iron mixed with the clay. This analysis showed that much more iron oxide is present in the sand and silt fractions than shows up by X-ray diffraction, and that short-range ordered iron oxides could be closely associated with the clays, although the resolution of SEM is not fine enough to determine the form of iron oxides or their association with clays. The presence of short-range ordered iron oxides closely associated with clays suggests that iron oxides may contribute to cementing.

Particle-Size Distributions

Clay contents for all soils and depths ranged from 0.01 to 0.22 kg/kg (Figure 22). Silt contents ranged from 2 to 50 g/kg. Clay and silt contents were slightly higher in the 0-C sample than the lower depth samples in most soils. Clay and silt contents were much higher in the 0-C sample than lower depths in the Hamdallaye and Gangani soils. The Hamdallaye and Gangani soils have the lowest slopes of the sites studied (0 to 2%). This indicates that the sealed sites in these soils could be receiving deposition of fine materials. Particle-size distributions were unchanged by extraction with sodium citrate-dithionite, indicating that iron is not playing a major

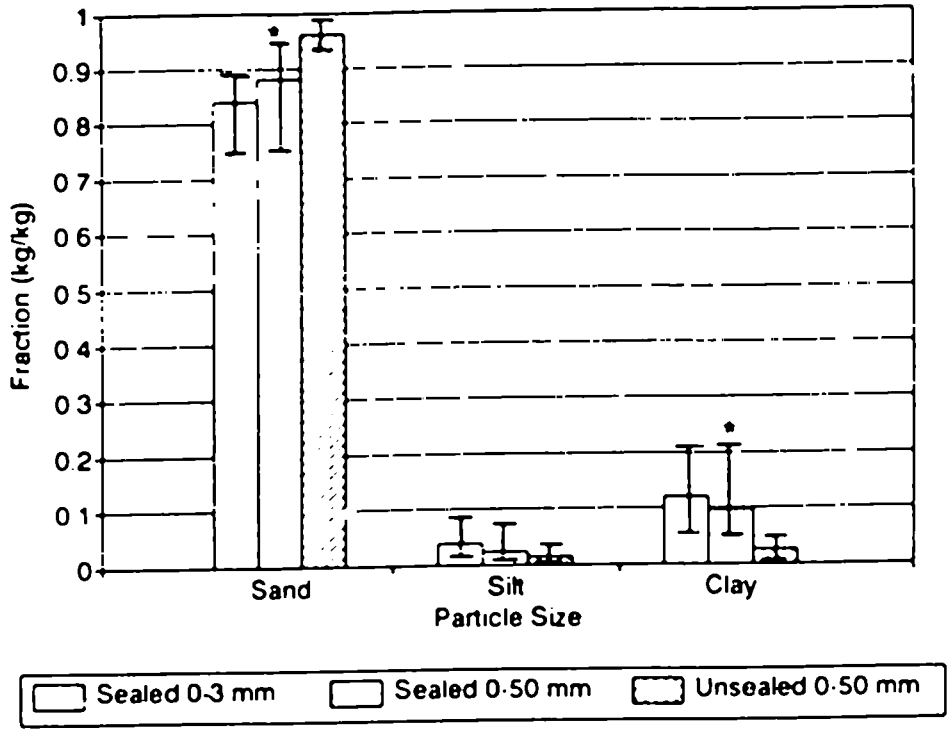

Figure 22. Range and means of percent sand, silt, and clay for the Hamdallaye soils. n=6. *, **, and *** indicate significant differences between sealed and unsealed sites at 0-50 mm depths at probability levels of 0.05, 0.01, and 0.001, respectively.

role in cementing (Figure 23). Water-dispersable clay averaged about one fourth of the total amount of clay. This is in contrast to higher water-dispersable clay (80 to 100%) in similar soils reported by West, et al. (1987). The difference between the results probably lies in the higher pH of the soils studied by them, and therefore greater dispersibility of clays because of greater distance from the ZPC. Although water-dispersable clay is low, the presence of argillic horizons shows downward movement of clays in these soils. Silt content is often a good indicator of sealing behavior (Monnier and Stengel, 1982), but silt contents are generally low in these soils. Of the 12 Hamdallaye sites sampled, all those with less than 5% clay were sealed while all soils with more than 5% were not (Figure 22). This suggests that clay content is an important factor determining seal formation in these soils.

Chemical Properties

Soil chemical properties influence sealing by affecting aggregation and dispersion/flocculation. Extractable iron and aluminum correlate with clay content between soil series (Table 6). No depth effects other than those attributable to clay content were found. An example is the close correlation of citrate-dithionite extractable aluminum with clay content at all depths and sample sites (Figure 24). This correlation suggests that differences in these properties between the different soil series and depths are due mostly to differences in clay content. Therefore, in

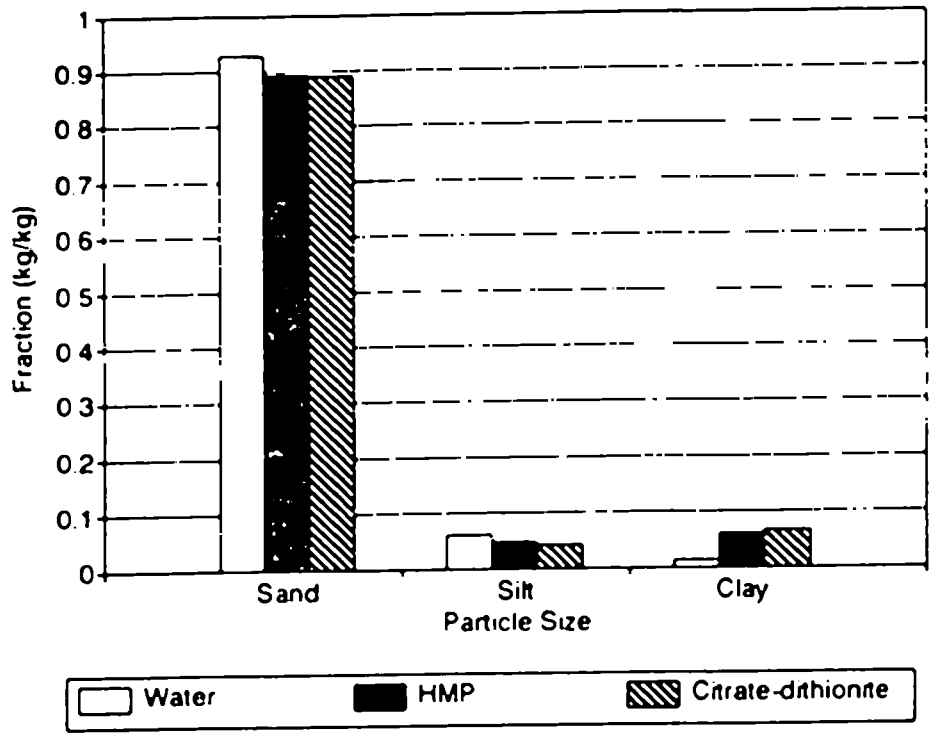

Figure 23. A typical particle size distribution with three dispersing treatments. Dantiandou sealed soil, 0-50 mm depth.

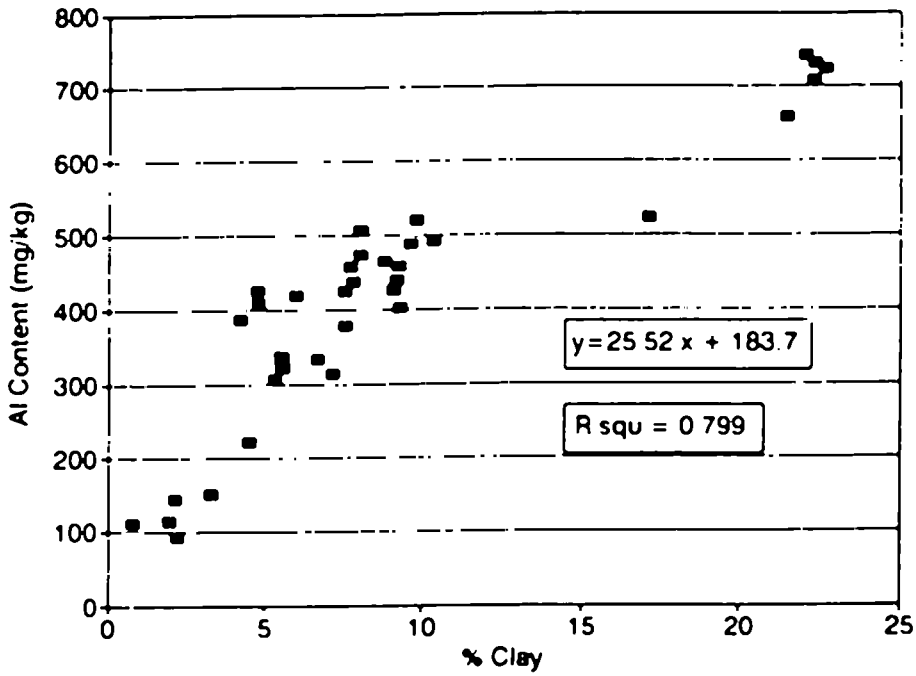

Figure 24. Correlation of clay with citrate-dithionite extractable Al for the Hamdallaye soils, including all depths, and both sealed and unsealed sites.

order to simplify the presentation of data, all depths are included in a weighted average for the following properties. Comparison of means between sealed and unsealed sites was done using Student's *t*. Either equal or unequal sample variance models were used depending on the results of an F test for homogeneity of variance.

Table 6. Linear correlation of Fe and Al with clay content for all Hamdallaye soils, all sample depths, and sealed and unsealed sites combined. n=30.

Soil Property	R^2	Constant	X coefficient
DCB Fe	.804***	1161	312.9
Amm. Ox. Fe	.252**	167.6	4.46
DCB Al	.799**	183.7	25.52
Am. Ox. Al	.516***	158.5	11.25

, * denote significant correlations at P= .01 and .001, respectively.

Total iron ranged from 0.5 to 2 percent (Figure 25). Citrate-dithionite (DCB) extractable iron ranged from 0.7 to 8.8 g/kg, and oxalate extractable (AO) iron ranged from 90 to 300 mg/kg (Figure 26). DCB iron was 15 to 50 percent of total iron, and AO iron was 2 to 12 percent of the amount of DCB iron. Most of the total iron is present in the clay fractions (Figure 27).

Citrate-dithionite extractable aluminum ranged from 90 to 740 mg/kg, and oxalate extractable aluminum ranged from 50 to 390 mg/kg (Figure 28). The ratio of oxalate to DCB aluminum is high, showing that although the amount of free aluminum oxides is low, most of it was in an active form. The low total amounts of

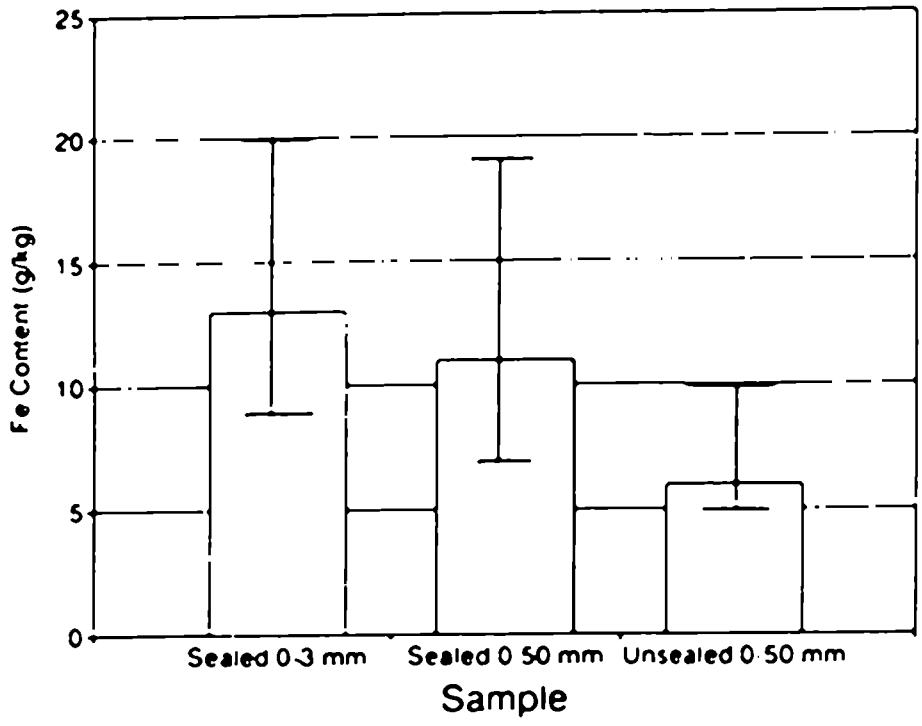

Figure 25 Total iron in the Hamdallaye soils Range and means for n = 6. Sealed and unsealed 0-50 mm samples are significantly different at the 0.05 probability level.

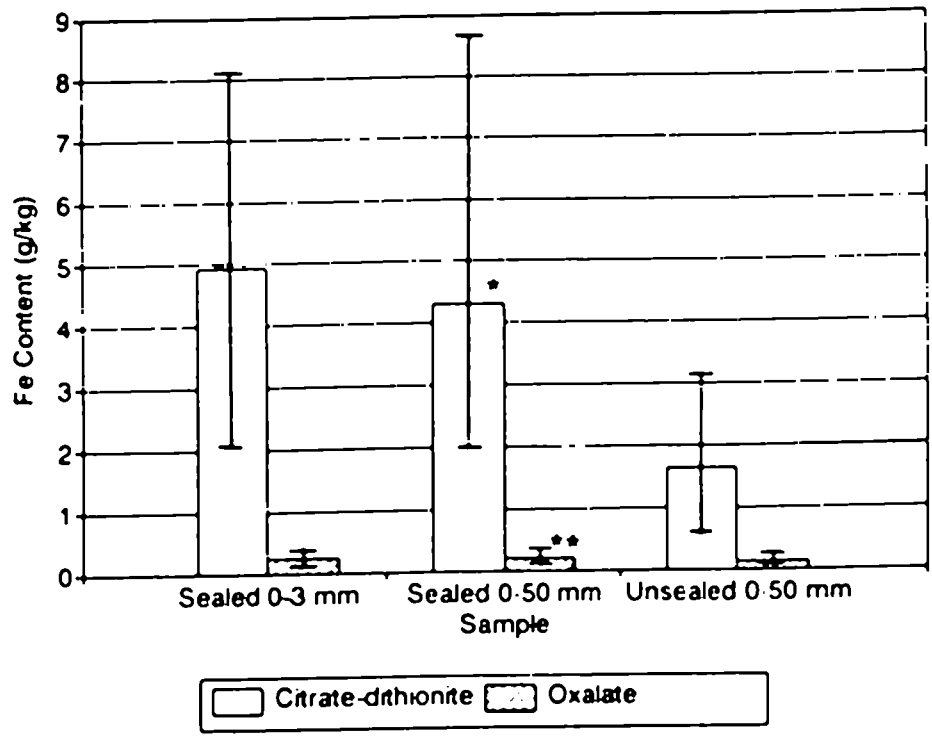

Figure 26. Range and means of oxalate extractable and citrate-dithionite extractable iron. Hamdallaye soils. n=6. * and ** denote significant differences between 0-50 mm depth samples of sealed and unsealed sites at probability levels of 0.05 and 0.01, respectively.

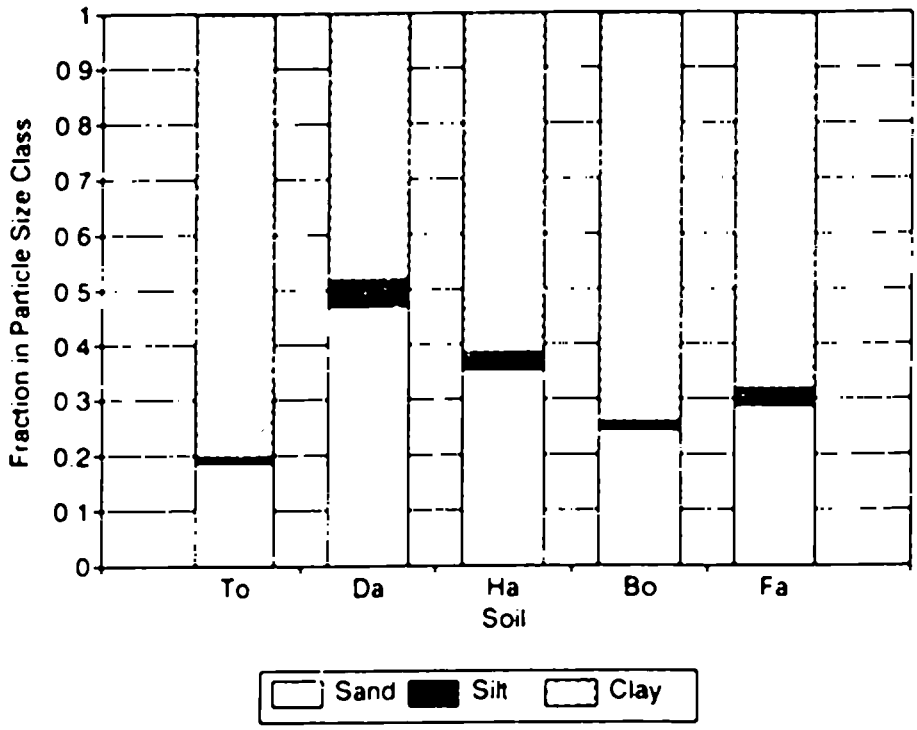

Figure 27. Total iron in different particle sizes in the 0 - 50 mm samples for the Hamdallaye soils.

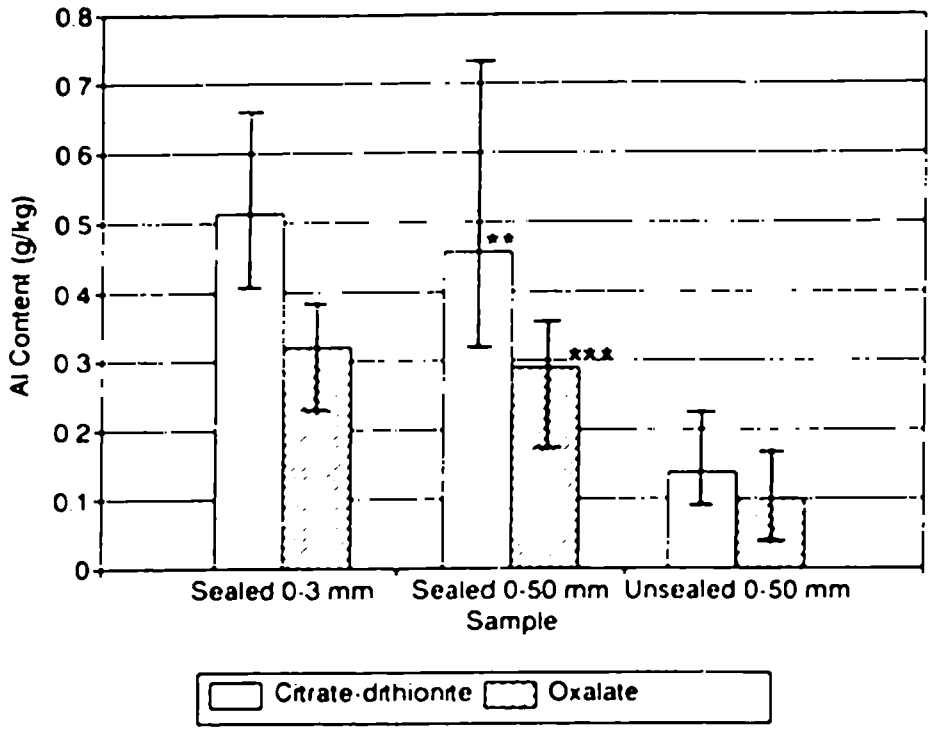

Figure 28. Range and means of oxalate extractable and citrate-dithionite extractable aluminum in the Hamdallaye soils. n=6. ** and *** denote significant differences between sealed and unsealed 0-50 mm samples at probability levels of 0.01 and 0.001, respectively.

active Fe and Al oxides supports the conclusion from the texture experiments that oxides do not contribute strongly to particle cementing. Also, the highest degree of sealing is in the soils with higher amounts of clays, which also have higher amounts of oxides, indicating that oxides may contribute to cohesive strength of the seals during drying, but do not inhibit disaggregation by rainfall and therefore do not inhibit sealing.

Differences between pH in water and pH in KCl were about -1 (Table 7), indicating moderately negatively charged clays (Parfitt, 1980). The low pH of the sealed sites is close to that of the subsoil of the unsealed sites. Since the seals are created when the topsoil is removed and the more susceptible subsoil is exposed, the sealed sites have soil properties similar to the subsoils of the unsealed sites. Cation exchange capacities ranged from 0.6 to 1.2 (cmol +)/kg, and were not correlated with percent clay. This suggests that much of the cation exchange sites were due to organic matter. Organic carbon contents ranged from .09 to .2 %, and were slightly higher in the uncrusted sites. High calcium saturation and low pH caused the sealed soils to be chemically flocculated, but lack of organic matter or other bonding agents favored clay suspension by rainfall. Although clays were easily suspended mechanically, they settled quickly in distilled water. Chemically conditions that favor flocculation of clays may have encouraged seal formation because clays that remained dispersed could have moved through the soil more easily, would not clog pores, and therefore would slow sealing.

Table 7. Summary of soil properties. Average of 0 to 5 cm depths and the six Hamdallaye soils.

Soil Property	Sealed Site	Unsealed Site
pH in water	4.9***	6.2
pH in KCl	3.1***	5.1
CEC (cmol +/kg)	1.1***	0.7
Base Saturation (%)	63.0**	88.0
ESP (%)	0.5**	0.1
Organic Carbon (%)	0.13	0.16

, * denote significant differences between sealed and unsealed sites at 0.01 and 0.001 probability levels, respectively.

Water-Stable Aggregation

Water-stable aggregates were 79 to 88 g/kg in the sealed soils and 41 to 64 g/kg in the unsealed soils, calculated as the amount of > 4-mm aggregates which survived wet sieving through a 2-mm sieve (Figure 29). This seemed to indicate high aggregation in the sealed soils, but only 0.25 to 12 percent of the whole soil remained on the 2-mm sieve during the collection of aggregates for wet sieving. Values for water-stable aggregates are much lower when expressed on a whole soil basis (Figure 30). Water-stable aggregation is higher in the sealed soils because of higher clay contents, and therefore more opportunity for inter-particle bonding.

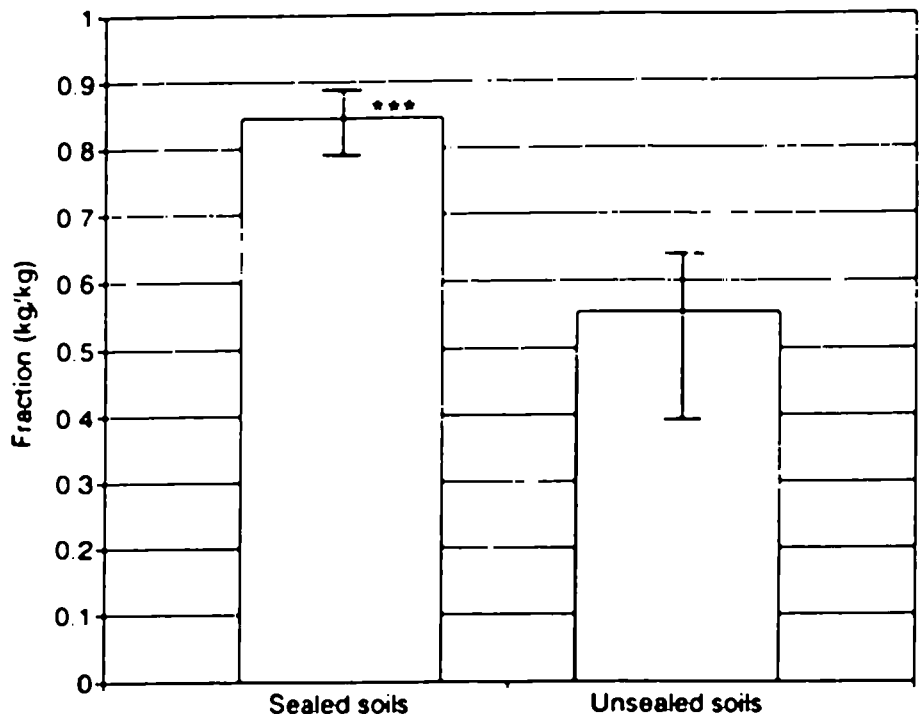

Figure 29. Range and means of percent water stable aggregates for Hamdallaye soils. n=6. *** Sealed and unsealed soils are significantly different at 0.001 probability level.

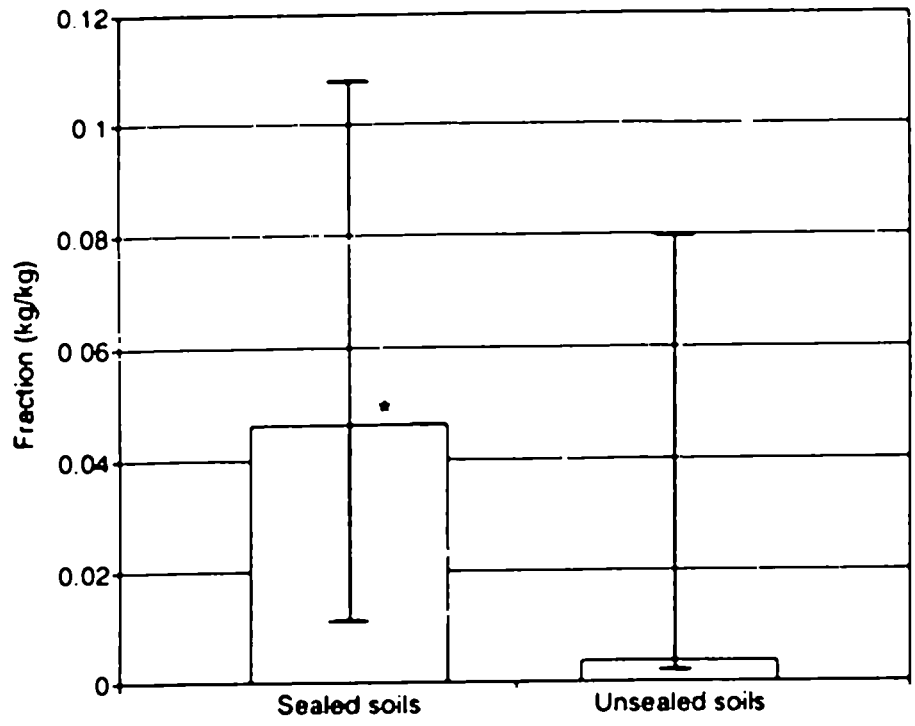

Figure 30. Range and means of percent water stable aggregates expressed on a whole soil basis. n=6. * Sealed and unsealed soils are significantly different at 0.05 probability level.

Soil Strength

A common measure of soil cohesive strength is the modulus of rupture, which is related to the strength of aggregation. Although iron oxides may not contribute to the strength of wet aggregates, they may affect the dry cohesive strength of the soil. In addition to standard measurements, several chemical treatments were done in order to look at the effect of removal of organic matter and iron oxides on soil strength. These treatments were: (A) an untreated sample (standard method); (B) a sample saturated with Ca; (C) a sample treated with hydrogen peroxide and then saturated with Ca; (D) a sample treated with hydrogen peroxide and sodium citrate-dithionite and then saturated with Ca; (E) a control sample treated like D, but without the sodium dithionite. Modulus of rupture increased significantly over treatment A with any of the chemical treatments. The statistical test is very conservative due to some missing data (Table 8). The hypothesis for this experiment was that if there were any contribution of iron oxides or organic matter to soil strength, then hydrogen peroxide or citrate-dithionite treatments should decrease the modulus of rupture. But, instead of decreasing the modulus of rupture, all of the chemical treatments, including just Ca saturation, increased the modulus of rupture. This may be explained by the breakdown of aggregates into primary particles, giving a higher effective surface area, and therefore more opportunity for surface to surface bonding, and increased soil strength. The breakdown of aggregates was accomplished in the chemical treatments by repeated mixing, dissolution of iron and

organic matter, dispersing, and centrifuging. The result is that not removing iron and organic matter contributed to the integrity of microaggregates in treatments A and B, preventing the formation of a more massive structure, and decreasing the modulus of rupture.

Table 8. Comparison of means of modulus of rupture experiment by least significant difference within soils. Values are in kPa. n=1 to 3. Treatment (A) control; (B) Ca saturated; (C) peroxide, then Ca saturated; (D) peroxide, DCB, Ca saturated; (E) control similar to D without dithionite.

	Treatment				
Soil	A	B	C	D	E
	kPa				
To	23.6[a*]	100.3[ab]	155.0[bc]	333.8[d]	222.9[cd]
Da	52.1[a]	99.5[a]	220.2[b]	484.4[b]	281.9[b]
Ha	35.5[a]	131.0[a]	173.4[a]	196.4[a]	235.1[a]
Bo	24.7[a]	138.2[ab]	145.0[ab]	192.5[abc]	226.7[bc]
Fa	34.3[a]	129.2[b]	210.0[bc]	176.9[bc]	259.5[c]
Ga	31.9[a]	90.7[ab]	252.1[cd]	187.0[bc]	331.4[d]

* Treatment means with the same letter are not significantly different at $\alpha = 0.05$.
Comparisons are only made within soils, i.e. across rows in the table.

RAINFALL SIMULATION

Measurements of soil chemical and physical properties on the Hamdallaye soils suggests that the main soil properties controlling soil sealing are the texture and dispersion/flocullation conditions of the soils. There were several reasons for

conducting the following experiment. The first was to observe the formation of surface seals in all six of the Hamdallaye sealed soil samples under controlled conditions, with time and drying cycles as variables. The second was to observe seal formation while varying the dispersing/flocculating conditions of the soils. The different textures of the Hamdallaye soils gives an indication of the influence of texture on sealing, and the sodium and calcium saturation gives an indication of the influence of chemical dispersion or flocculation on sealing.

The surface seals generated with the rainfall simulator had up to four distinguishable surface layers, labeled S1 through S4. A typical seal is shown in Figure 31. The top layer consisted of a 0.4- to 1.5-mm thick layer of coarse sand, without clay coatings (S1) Below this was a 0.2- to 0.8-mm thick very fine sand and silt layer (S2). This layer was often made up of clay floccules. Below these layers there was a 1- to 8-mm thick layer of clay-depleted material (S3). Often this layer was barely distinguishable from the unaltered soil. The deepest altered layer was a 0.3- to 1.2-mm thick washed-in clay layer (S4).

Replication of the 120 minute rainfall treatments gave an estimate of variability for the thickness of each of the surface layers. The coefficients of variability ranged from 0 to 1.75, averaging about 0.50. Since the entire experiment was not replicated, it was not possible to do a statistical comparison of means, but the high amount of variability in the replicated treatments indicated that large differences in layer thickness must be present to distinguish significant differences

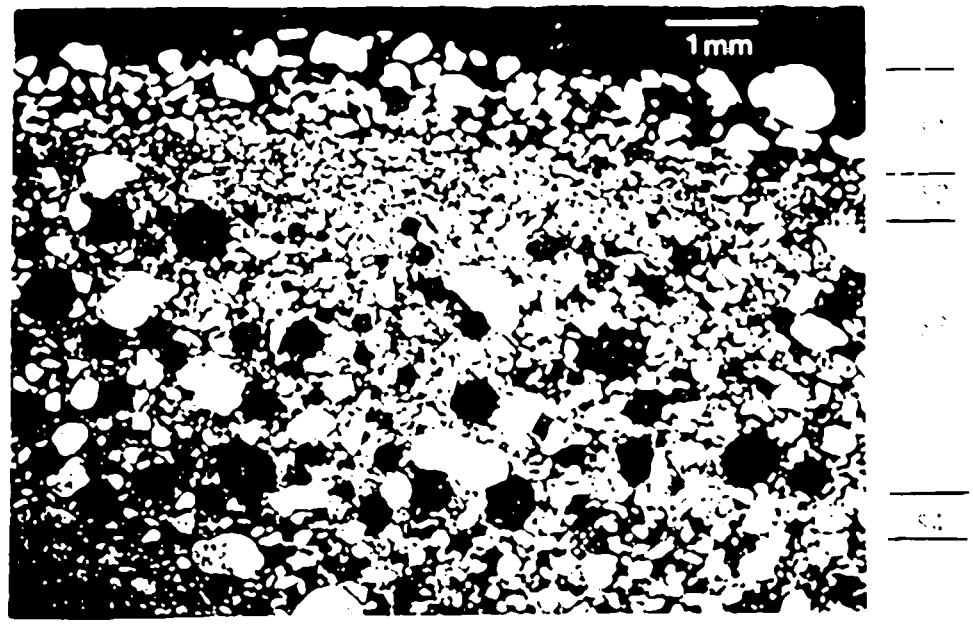

Figure 31. SEM backscattered micrograph of the surface of the Dantiandou soil after 120 minutes of rainfall, showing four-layer seal. (S1) Bare sand layer; (S2) fine sand and silt layer; (S3) clay-depleted layer; (S4) clay accumulation layer.

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among treatment effects. In addition to measurements of thicknesses of these layers, observations about the continuity and density of the layers were also made. These factors will be considered in the following discussion.

There was no broad trend of seal formation over time that applies to all of the soils. There was no distinguishable difference in treatments A (Control), C (Ca-saturated), D (high temperature drying), or E (continuous rainfall). The only treatment effect that was significant was the Na-saturated treatment. In the Na-saturated soils, most of the clay eluviated out of the whole soil by the end of the second 30-min rain (Figure 32) except in the Tondo Kakasia and Gangani soils. The Na-saturated Falanke and Hamdallaye soils developed a washed in (S4) layer at 30 min, but this disappeared after additional rainfall. The S1 layer was present in almost all of the samples, but sometimes was washed away and was usually discontinuous. The S2 layer was present in 40% of the samples, and occurred randomly in all soils and in all treatments and rainfall times.

The Tondo Kakasia and Gangani soils developed much differently than the rest of the soils (Figure 33). These soils had much higher clay contents, and did not form the same type of washed-in layers. They only had a clean sand layer (S1), and immediately below this, a zone of clay concentration that appeared similar to the S4 layers in the other soils, but without an overlying S3 layer.

In most cases, the depth of the surface layers did not change with number of rainfall events. In the Dantiandou and Hamdallaye soil samples, which were the

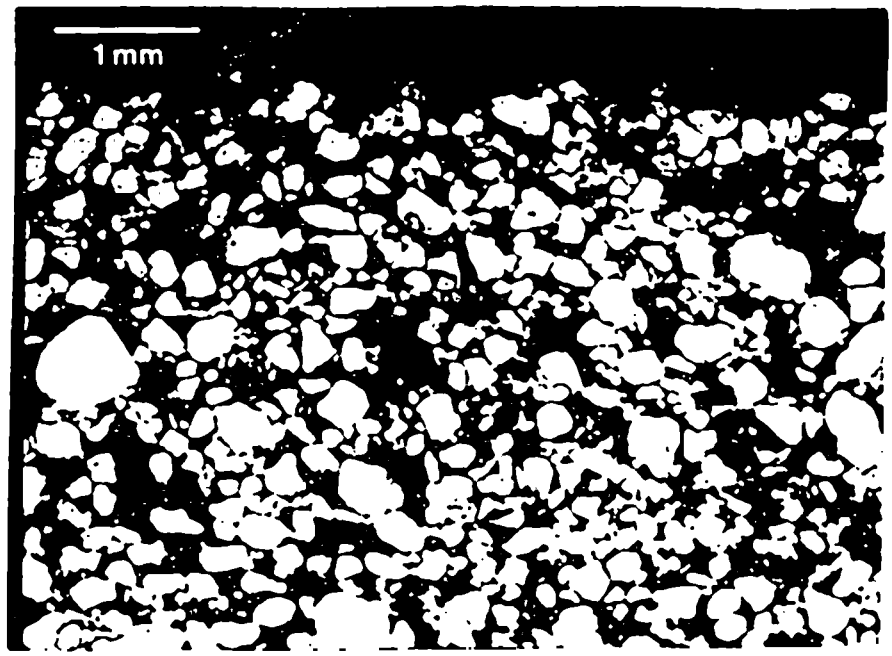

Figure 32 SEM backscattered micrograph of the surface of the Na-saturated Bokotchi soil after 30 minutes of rainfall, showing elaviated soil

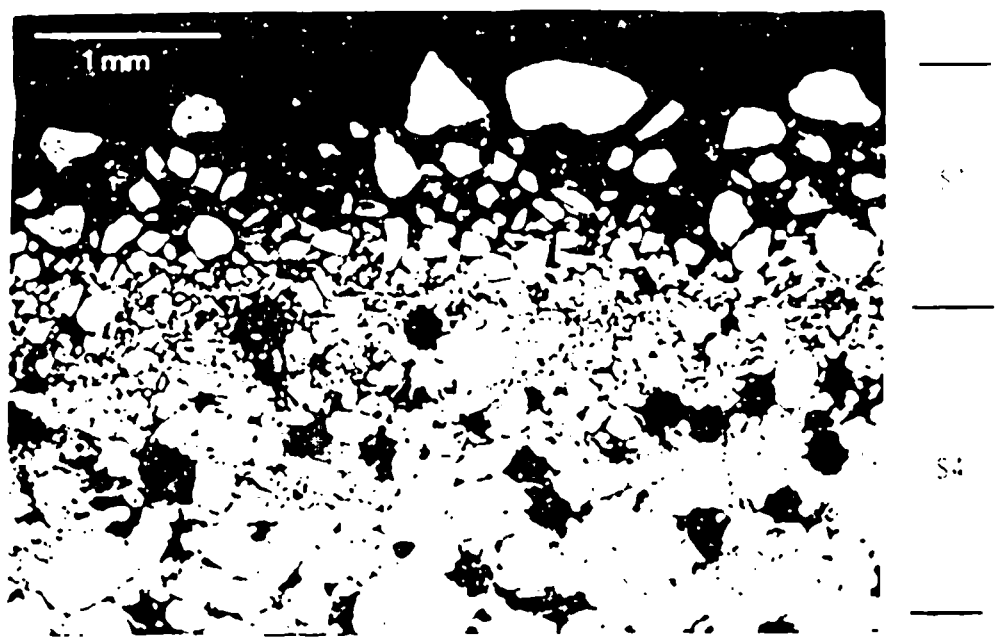

Figure 33 SEM backscattered micrograph of the surface of the Gangani soil after 120 minutes of rainfall, showing a two layer seal (S1) Sand, (S4) clay accumulation

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samples with the least amount of clay, the S4 layer did not develop until after the first 30 min rainfall. These two soils also had less dense and less continuous washed-in layers (S4) than the Bokotchili and Falanke soils. This indicates that seals develop faster, and to a higher degree in the finer-textured soils. Tarchitzky et al. (1984) suggest that this washed-in clay layer is not stable, but that as it breaks, the suction forces below the seal create rapid water flow at the break that draws clays into open pores, causing a continuous repair of the seal.

The number of vesicular pores increased with each rainfall event. There were only a few vesicular pores in the 30 minute rainfall treatments and in the 120 min continuous rainfall treatment, indicating the need for successive wetting and drying for vesicular pore formation. This is in concordance with the findings of Figueira and Stoops (1983) on the formation of vesicular pores in a sandy clay loam. Vesicular pores appeared in soils with all textures and chemical treatments. They were usually at a depth of one to three mm, and were sometimes adjacent to the surface. They always occurred above the washed-in (S4) layer if it was present, but also appeared in the Na-saturated samples. Since the Na-saturated samples had vesicular pores and were not sealed and had high infiltration rates, vesicular pores are not diagnostic of seals. The process of air entrapment is probably by differential wetting at the beginning of the rain, and possibly by air driven into the soil during the rain. The presence of vesicular pores very close to the surface with no dense layer above them was curious. The soil above the washed-in layer must have acted

as a viscous fluid in order for the low pressure entrapped air to form near-perfect spheres. As a raindrop hits the surface and deforms the soil, the entrapped air would be compressed, and should break through the surface. Perhaps the air bubbles close to the surface are not stable and would soon be expelled.

The lack of morphological differences between the samples dried in naturally and those dried in the oven does not mean that drying temperature has no effect on seal formation. Rose (1962) showed that infiltration rates were reduced by half in crusted samples which were dried at high temperatures. Perhaps if infiltration measurements had been made, some effect would have been found. But, modulus of rupture measurements did not show any influence of drying temperature on soil strength, which may support the conclusion that low drying temperature does not effect seal strength, and therefore seal development in successive rains.

Drying between rains did not effect seal formation except for the presence of more vesicular pores after later rainfalls. Ben-Hur et al. (1985) showed that drying between rains increased infiltration because of formation of cracks and alteration of structure. This would not occur to the same extent on the Hamdallaye soils because of the low clay content and the absence of shrinking/swelling clays.

The soils in which the clays eluviated out of the samples when they were dispersed had clay contents of 6 to 10.4% (Table 9). The soils which still formed seals when dispersed had 21.1% clay (Tondo Kakasia) and 9% clay (Gangani). The Gangani has an 8.3% silt content, which is much higher than any of the other soils.

Ben-Hur and Shainberg (1989) found that seal formation increased with increased dispersion of clays when the clay content was greater than 7%, and seal formation decreased with increased dispersion of clays when clay content was less than 7% in soils with low silt to clay ratios. In order to better explain the effects of dispersion on sealing, studying soils with a wider variety of clay and silt contents with varying silt to clay ratios would be necessary.

Table 9. Particle-size distributions of the six soils used in the rainfall simulator experiment.

Soil	Sand	Silt	Clay
	----------	%	----------
Tondo Kakasia	77.0	1.9	21.1
Dantiandou	90.9	3.1	6.0
Hamdallaye	92.2	0.3	7.5
Bokotchili	87.8	1.8	10.4
Falanke	88.1	2.7	9.2
Gangani	82.7	8.3	9.0

There are differences in the way the surface seals appear in the intact field samples and the rainfall-simulator-prepared samples. Although all of the field samples had washed in layers, many did not have other characteristic layers above the washed in layer. Although the loss of these layers was partly due to sample transport and preparation, another factor was topography. The rainfall simulator

prepared samples were initially placed at a slope of 7%, but quickly became level under the influence of the rainfall due to the small sample area. Therefore, there was very little runoff, and no deposition. Under field conditions, the Hamdallaye soils were on slopes from 0.5 to 8%. The presence of surface layers above a washed-in layer was more common on the soils with lower slopes, showing that the coarse material left on top was easily eroded. The process of seal formation is similar between the field samples and the rainfall simulator prepared samples, with the difference being that the field samples also experience erosion of the top layers at higher slopes and deposition of runon material at lower slopes.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Surface seals occur in the Hamdallaye watershed in areas where the clay content is greater than five percent. These are usually areas where the topsoil has been eroded and truncated to expose finer-textured subsoils, or in recently weathered laterite. Seals are often associated with gullies or deflationary depressions. They form quickly after rainfall and reduce infiltration significantly.

Infiltration measurements and thin section analysis of the Mali soils shows that structural seals do not exist in these samples. Infiltration measurements across the Cinzana Research Station show that many of the places that were considered to be crusted are actually deeply compacted soils, often due to animal traffic, and often as a consequence of soil degradation through intense cultivation. Management of these soils for reduced sealing must include reducing animal traffic, along with cultivation practices which enhance aggregation.

Most of the soil chemical and physical properties correlate well with clay contents. Because of this, it is not possible to separate the effects of possible cements (iron and aluminum oxides and silica) from texture effects on infiltration.

Nevertheless, several conclusions can be made about the influence of the other soil properties. Some aggregation was evident. Aggregates that survived dry sieving were water stable. Only about 25% of the clay fraction was water dispersable, which is probably due to low pH and low ESP. But, the strength of aggregates is not enough to withstand raindrop impact because of the absence of any strong aggregating agents. This was shown by the low amount of active iron oxides and silica, the low amount of organic carbon, and the low charge characteristics of the clays. When dry, the seals in the field became hard. The modulus of rupture experiment showed that removing iron oxides and organic matter increased dry soil strength. This was probably due to destruction of aggregates causing increased bulk density and increased particle contact.

Rainfall simulator studies showed that the dispersion of the clays eliminated sealing in the treatments with less than 10% clay. Dispersability of clays is too often given as a general reason for surface sealing without considering texture as a factor (Gal et al., 1984, Bresson and Valentin, 1992, Agassi et al., 1981., Helalia et al., 1988). In finer-textured soils clay dispersion enhances seal formation, but these data suggest that in coarser textured soils, clay dispersion can actually deter sealing. In many soils, silt content is diagnostic of sealing. The cause of sealing is close packing of particles due to clogging of pores by silt sized particles. In the Hamdallaye soils, silt-sized clay aggregates behave as silt particles in the process of clogging pores. Perhaps a good indicator of sealing behavior in sandy soils with

more silt than the Hamdallaye soils would be the sum of silt and non-dispersable silt-sized clay floccules.

The seals in the rainfall simulator experiment formed after the first 30 minute rainfall event, and were not significantly altered after this, except for the increase in vesicular pores. Various wetting/drying cycles did not effect the development of the seals. Four distinct surface layers occurred in most of the seals: (S1) a 0.4- to 1.5-mm thick layer of coarse sand, free of clay coatings; (S2) a 0.2- to 0.8-mm thick very fine sand and silt layer; (S3) a 1- to 8-mm thick layer of clay-depleted material; (S4) a 0.3- to 1.2-mm thick washed-in clay layer. The soils with clay contents between 5 and 10 percent formed four-layered structural seals, while those with higher clay contents formed two-layered structural seals.

The two-layered seal, which consists of a washed-out (may be similar to S1, S2, or S3) and a washed-in (S4) layer, is the most commonly reported type of structural seal in the literature, and is most common in finer-textured soils. Valentin (1991) has described three-layer seals which consist of layers which herein have been designated S1, S2, and S4. The absence of the S3 layer (1- to 8-mm thick layer of clay-depleted material) in the literature is probably due to the fact that in most soils in the field, soil is being removed by erosion, so that the amount of total material above the clay layer is reduced.

Although there are many factors which influence soil sealing, a general hierarchical model of soil sealing including the influence of soil properties could be

proposed. External factors such as plant or mulch cover, rainfall intensity and duration, landscape position, and initial water content are all very important in determining the occurrence and rate of seal formation. But, in most conditions and given enough time, most non-swelling bare soils will become impermeable to water because of clogging of surface pores by silt-sized particles after disaggregation by rainfall. Soil sealing occurs because of close packing of particles. The principle soil properties influencing particle packing are particle-size distribution and aggregation, which are also co-related. Soils with higher levels and higher strengths of aggregation will resist sealing longer than those with weak aggregation. When aggregates are destroyed and clays are suspended, the remaining factor is soil texture. Soils with silt contents or silt-sized clay aggregate contents higher than 5% will seal, while those with less will not. All of the other soil properties which affect soil sealing such as organic matter type and content, inorganic cements, and flocullation/dispersion conditions are important only as they aggregate stability. The role of all of these factors, both intrinsic and extrinsic, is to prevent disaggregation and particle redistribution.

The proposed hierarchical model for soil structural sealing therefore is as follows (Figure 34). The soil texture appears in different ways at different levels. (1) The primary level is the chemical dispersivity of the clays. If the chemical conditions in the soil favor dispersion and the silt-sized particles are greater than 5%, it will seal. (2) The secondary level is the plant, mulch, or rock cover. If cover is

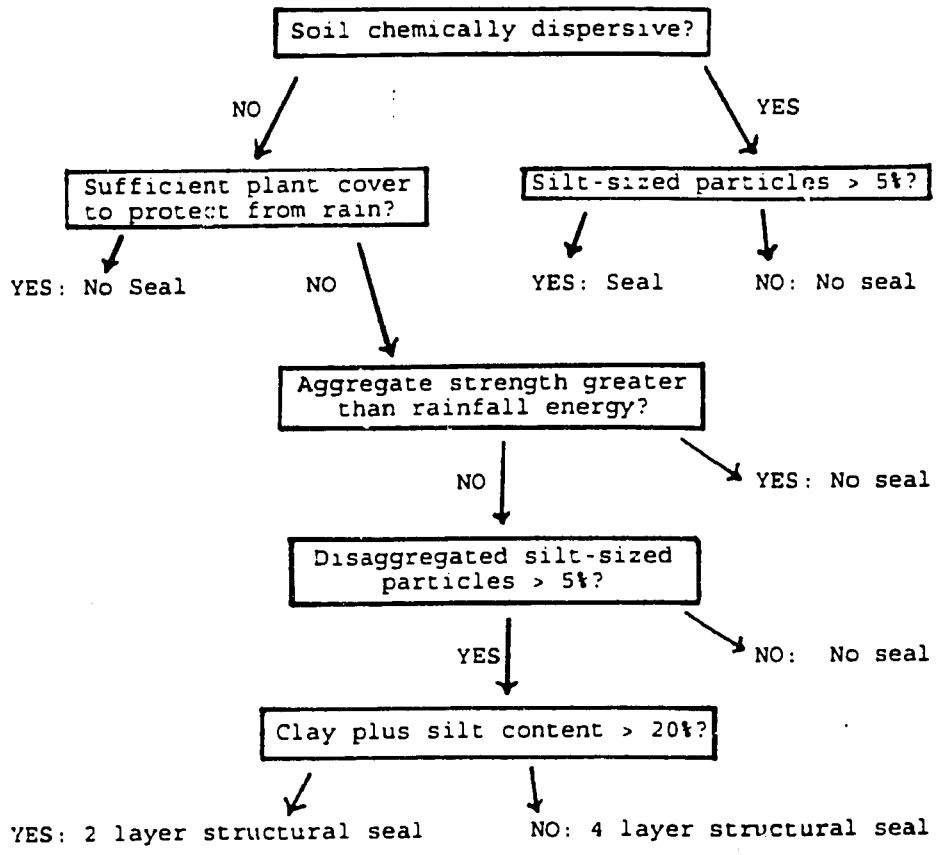

Figure 34. Proposed model of soil sealing.

sufficient to protect the soil from disaggregation by raindrops, the soil will not seal. (3) The tertiary level is the aggregate strength. If the aggregate strength is high enough to withstand the destructive energy of the rainfall, the soil will not seal. Given enough time, rainfall energy will always exceed aggregate strength. (4) The quaternary level is the soil texture. Although the exact limits have not been worked out, the determinant appears to be the amount of silt-sized particles, including silt and silt-sized clay floccules. If the amount of silt-sized particles is less than 5%, and the clay content is low, the soil will not seal. If silt-sized particle content is greater than 5%, then the soils will seal. Then, the amount of silt and clay, perhaps at a limit of about 20% based on the rainfall simulator experiment, determines the type of structural crust. A soil with greater than 20% silt plus clay will develop a two layer structural seal, and a soil with less than 20% silt plus clay will form a four layer seal.

The best management for soils in the Sahel is to prevent further degradation of soils. It has been shown that seals most often occur in this area by exposure of finer-textured subsoils by erosion, so erosion control would reduce soil sealing. Methods of reducing erosion such as building micro-catchments on highly susceptible areas to encourage plant growth are being used at Hamdallaye, and seem to show promise. Another major management consideration is providing plant or mulch cover to reduce the disaggregation by rainfall. This is difficult to do in the Sahel, where plant matter is scarce and valuable at the end of the dry season, which is the

same time when it is most necessary for soil cover. Providing plant cover would also reduce erosion, which would be an added benefit for controling sealing. By leaving plant material on these soils to protect the soil from raindrop impact, more plant material would also be eventually incorporated into the soil. This would cause a build up of organic matter contents and strengthen aggregation, thereby decreasing the risk of sealing.

Management options are few because of low-input subsistence farming on these soils. In the case of the Hamdallaye soils, runoff from sealed areas may even be a benefit by harvesting water for lower slope positions, especially since the most heavily sealed areas are towards the top of the plateau. Whether or not increased erosion will result in increased areas of sealing soils is not known, especially since the sandy topsoil is constantly being moved by wind, and can be replaced. The destabilization of these surfaces, though, could conceivably result in the concentration of sands in some areas (i.e. dunes), exposure of more of the finer-textured subsoil, and increased sealing. This would result in less land area for cultivation. Because of this risk, efforts should be made to stabilize and protect soils that are susceptible to sealing by maintaining plant cover, particularly by afforestation of the plateau and the higher slopes.

Because of the limited amount of data on the influence of soil properties on surface sealing in Alfisols, there are still many opportunities for research. The amounts of active oxides and silica is low in these soils, and therefore inorganic

cements may not be a controlling factor in seal formation. Other soils with higher amounts of inorganic cements might be found to resist sealing because of stronger aggregation. Soils with higher amounts of silts would be expected to behave differently, and it would be interesting to test the hypothesis that the diagnostic limit of particle size for sealing in these soils is about 20% silt + stable silt-sized particles. Further study is needed to test the effects of pH and clay contents and the degree of flocculation on sealed and unsealed kaolinitic soils in order to test the hypothesis that low pH and therefore flocculated clays (increasing the number of silt-sized particles) enhances seal formation in sandy soils. Finally, in terms of management, it is questionable whether organic matter contents could be maintained at high enough levels to build aggregates which would resist destruction by rainfall on bare soils in the Sahel. Because crop residues are valuable as fodder and for other household purposes, very few management options are available for improving organic matter status in the region.

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Soil Descriptions

From Manu, et al., (1991).

L **Plateau soil series (Lp)**

WITHIN vegetated area

Location: IMAW watershed. This pedon is located in the middle of the laterite plateau within a vegetated area.

Landform:	laterite plateau	Slope:	0-1%
Topography:	level	Drainage:	poorly drained
Parent Material:	laterite		

Horizon	Depth (cm)	Soil description (colors are for moist soil)
A1	0-8	Dark brown (7.5YR 4/4) fine sandy loam; brown (7.5YR 5/4) dry; thin platy; hard; friable; many fine, few medium roots; intense biologic activity on the surface (termites); common biocasts, biochambers, biotubules, and biochannels; clear smooth boundary.
A2	8-16	Strong brown (7.5YR 4/6) gravelly sandy clay loam; brown (7.5YR 5/4) dry; weak coarse subangular blocky (between gravels); hard; friable; many fine and medium roots; many biopores; many biochannels; many biocasts with infilling of dark grayish brown (10YR 4/2) sand; gradual smooth boundary.
Bt1	16-34	Yellowish red (5YR 5/6) gravelly sandy clay loam; reddish yellow (5YR 6/6) dry; granular (between gravels); hard; firm; many fine and medium and few large roots; many biopores; gradual smooth boundary.
Bt2	34-60	Yellowish red (5YR 5/8) gravelly clay; reddish yellow (5YR 6/6) dry; granular (between gravels); no consistence; many medium and fine roots; abrupt wavy boundary.
	>60	Laterite

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L **Plateau soil series (continued)**

OUTSIDE vegetated area

Location: IMAW watershed. This pedon is located in the middle of the laterite plateau outside of a vegetated area.

Landform:	Laterite plateau	Slope:	0-1%
Topography:	level	Drainage:	poorly drained
Parent Material:	laterite		

Horizon	Depth (cm)	Soil description (colors are for moist soil)
A1	0-4	Reddish brown (5YR 4/4) fine sandy loam; light brown (7.5YR 6/4) dry; strong coarse subangular blocky parting to thin platy; extremely hard; friable; hard surface crust (1 mm thick); some vesicular pores; few fine roots; few biochannels; few ironstone gravels; abrupt wavy boundary.
A2	4-18	Strong brown (7.5YR 5/6) gravelly fine sandy loam; light brown (7.5YR 6/4) dry; granular (between gravels); no consistence; few fine (dead) roots; very few biochannels; ironstone concretions up to 15 cm dia.; clear smooth boundary.
B	18-35	Strong brown (7.5YR 5/6) gravelly sandy clay loam; reddish yellow (7.5YR 6/6) dry; weakly developed subangular blocky; few fine (dead) roots; few biochannels; gradual smooth boundary.
BC	35-54	Strong brown (7.5YR 5/6) gravelly sandy clay; reddish yellow (7.5YR 7/6) dry; weakly developed subangular blocky (between gravels); very few fine (dead) roots; no biochannels; few laterite cobbles; abrupt wavy boundary.
	> 54	Laterite

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II. Tondo Kakasia soil series (To)

Location: IMAW watershed. This pedon is located 390 meters NW of permanent marker Archie.

Landform:	upper backslope	Slope:	3-8%
Topography:	undulating	Drainage:	well drained
Parent Material:	Continental Terminal	Pedon #:	5-B
Pedon Location:	fallow area		

Horizon	Depth (cm)	Soil description (colors are for moist soil)
A	0-4	Strong brown (7.5YR 4/6) fine sand, reddish yellow (7.5YR 6/6) dry; thin platy; hard; firm; few fine roots associated with biopores; common biochannels (2-3 mm); common biochambers (5 mm); many biopores; large rounded quartz grains; horizon is layered with lamellae 2-3 mm thick; pH 5.9; abrupt wavy boundary.
A2	4-19	Yellowish red (5YR 5/6) loamy fine sand; strong coarse subangular blocky; slightly hard; very firm; common fine roots; few medium roots; many biochannels (1-5 mm); few biopores; common biochambers; laterite gravels up to 1 cm dia.; few charcoal fragments; pH 5.3; clear smooth boundary.
AB	19-35	Red (2.5YR 4/8) loamy fine sand; strong coarse subangular blocky; hard; firm; common fine roots associated with biopores; common biochannels; few biochambers (2 cm dia.); root channels (2 cm); consistence is variable throughout the horizon; pH 5.2; gradual smooth boundary.
Bt1	35-47	Red (2.5YR 4/8) loamy fine sand; weak coarse subangular blocky; slightly hard; firm; common fine roots; few medium roots; common biochannels; small charcoal fragments; clear smooth boundary.
Bt2	47-64	Red (2.5YR 4/8) loamy coarse sand; weak coarse subangular blocky; hard; friable; common fine roots; few medium roots; common biochannels; very few laterite gravels; pH 5.5; gradual smooth boundary.

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II. Tondo Kakasia soil series (continued)

Bt3 64-87 Red (2.5YR 4/8) loamy fine sand; weak coarse subangular blocky; slightly hard; friable; few fine and medium roots; few large roots; common biochannels; pH 5.4; gradual smooth boundary.

BC 87-119 Red (2.4YR 4/8) loamy fine sand; coarse subangular blocky; slightly hard; friable; few large biochannels; few laterite gravels (to 1 cm dia.); pH 5.2; gradual smooth boundary.

C1 119-145 Red (2.5YR 4/8) loamy fine sand; coarse subang· iar blocky; slightly hard; friable; very few fine roots; few small (<1 cm) and few large (4 cm) laterite gravles; pH 5.2; consistence is variable throughout the horizon.

C2 145-200 Red (2.5YR 4/8) loamy fine sand; strong coarse subangular blocky; very hard; friable; very few fine roots; very few medium roots; pH 5.3; dry in the upper 20 cm of the horizon and moist below.

** Laterite was found in hand auger samples taken from a depth of 310 cm below the soil surface.

III. Dantiandou soil series (Da)

Location: IMAW watershed. This pedon is located 250 m west of the permanent rain gauge on the plateau.

Landform:	upper backslope	Slope:	2-3%
Topography:	gently sloping	Pedon #:	1-A
Parent Material:	eolian sand	Drainage:	well drained
Pedon Location:	millet field		

Horizon Depth (cm) Soil description (colors are for moist soil)

Ap1 0-3 Yellowish red (5YR 4/6) sand; yellowish red (5YR 5/6) dry; loose grains; extremely weak; pH 6.3; abrupt smooth boundary.

Ap2 3-7 Yellowish red (5YR 4/6) sand; yellowish red (5YR 5/6) dry; thin platy with bands of dark reddish brown (5YR 3/4) sand; slightly hard; friable; few fine roots; common vesicular pores; few biopores (1-3 mm dia.); pH 6.0; abrupt smooth boundary.

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III. Dantiandou soil series (continued)

A 7-20 Strong brown (7.5YR 4/6) fine sand; strong brown (7.5YR 5/6) dry; weak coarse subangular blocky structure; slightly hard, friable; few fine roots; common biochannels, biocasts, biotubules (1-3 mm dia.); few charcoal fragments (1-2 mm); pH 5.3; gradual smooth boundary.

B/A 20-36 Strong brown (7.5YR 4/6) sand; strong brown (7.5YR 5/6) dry; weak coarse subangular blocky structure; slightly hard; friable; few fine roots; common biopores; few biochannels (up to 1 cm); few crotovinas (3-4 mm); pH 5.2; gradual smooth boundary.

Bt1 36-52 Yellowish red (5YR 5/8) fine sand; reddish yellow (5YR 6/8) dry; weak coarse subangular blocky structure; slightly hard, friable; few fine roots; common biopores, biochambers (1-2 mm); pH 5.0; gradual smooth boundary.

Bt2 52-73 Yellowish red (5YR 5/8) sand; reddish yellow (5YR 6/8) dry; weak coarse subangular blocky structure; slightly hard; friable; few fine roots; few biochambers (1-2 cm); few root channels (to 4 cm); few crotovinas (to 9cm), charcoal fragments (1-3 mm); pH 5.1; gradual smooth boundary.

Bt3 73-93 Red (2.5YR 4/8) sand, reddish yellow (5YR 6/8) dry; weak coarse subangular blocky structure; slightly hard; friable, few fine roots; few biocasts; few biochannels (2mm); few biopores (4 mm); few crotovinas; few root channels (up to 1.5 cm); charcoal fragments (1-3 mm); few laterite gravels (to 3 cm); pH 5.1; gradual smooth boundary.

Bt4 93-130 Red (2.5YR 4/8) loamy fine sand; reddish yellow (5YR 6/8) dry; weak coarse subangular blocky structure; slightly hard; friable; few fine roots; very few biopores; few charcoal fragments; pH 5.0; gradual smooth boundary.

* Samples below 130 cm were taken with a hand auger.

Bt5 130-170 Red (2.5YR 4/8) sand; reddish yellow (5YR 6/8) dry; weak coarse subangular blocky structure; slightly hard; friable; pH 5.2.

Bt6 170-200 Red (2.5YR 4/8) sand; red (2.5YR 5/8) dry; pH 5.2.

** Auger samples taken to 300 cm below the soil surface contained no laterite gravels.

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IV. Hamdallaye soil series (Ha)

Location: IMAW watershed. This pedon is located 470 m SE of permanent marker I-F.

Landform:	middle backslope	Slope:	1/2-2%
Topography:	gently undulating	Pedon#:	3-A
Parent Material:	eolian sand	Drainage:	well drained
Pedon Location:	millet field		

Horizon	Depth (cm)	Soil description (colors are for moist soil)
A1	0-7	Yellowish red (5YR 4/6) sand; strong brown (7.5YR 5/6) dry; weak coarse subangular blocky structure; hard; friable; common fine roots; few biochambers (2.5 mm); few biochannels (2.3 mm); thin vesicular crust (1 mm thick) at upper boundary; subtle reddish brown (5YR 5/4) banding of sand throughout horizon; pH 5.2;clear wavy boundary.
A2	7-24	Yellowish red (5YR 4/6) sand; yellowish red (5YR 5/6) dry; weak coarse subangular blocky structure; hard; friable; common fine roots; common biopores; many fine biochannels; few crotovinas (up to 3 cm); few pottery shards; charcoal fragments; pH 5.1;gradual smooth boundary.
A/B	24-50	Red (2.5YR 4/8) sand; yellowish red (5YR 5/8) dry; weak coarse subangular blocky structure; slightly hard; friable; common fine roots; few medium roots; few biochannels (1-3cm); very large crotovina (15 cm); few laterite gravels (1-2 mm); pH 5.0; gradual smooth boundary.
Bt1	50-102	Red (2.5YR 4/8) sand; red (2.5YR 5/8) dry; weak coarse subangular blocky structure; slightly hard; friable; common fine roots; few medium roots; few large roots; few small biochambers; few large crotovinas (up to 2 cm dia.); charcoal fragments; pH 5.1; gradual smooth boundary.
Bt2	102-148	Red (2.5YR 4/8) sand; weak coarse subangular blocky structure; slighty hard; friable; few fine roots; few medium roots; few biochannels (2-3 mm); few ironstone concretions (2-5 mm); termite activity indicated in presence of very hard nodules formed of biochannels; pH 4.9; gradual smooth boundary.
Bt3	148-179	Red (2.5YR 4/8) sand; pH 5.2.
Bt4	179-200	Red (2.5YR 4/8) sand; pH 5.3.

*Samples below 150 cm were taken with a hand auger.
**Laterite gravels were found 300 cm below the soil surface.

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V. Gangani Kirey soil series (GaK)

Location: IMAW watershed. This pedon is located 360m SW of permanent marker I-C.

Landform:	footslope	Slope:	0-1/2%
Topography:	planar	Drainage:	mod. well drained
Parent Material:	Continental Terminal	Pedon#:	2-A
Pedon Location:	fallow area		

Horizon	Depth (cm)	Soil Description (colors are for moist soil)
Ap	0-8	Yellowish red (5YR 4/6) sand; strong brown (7.5YR 5/6) dry; thin platy structure with bands of reddish brown (5YR 4/4) sand; slightly hard; friable, many fine roots; many vesicular pores; many biopores; few biochambers (to 1 cm); few biochannels (1-4 mm); pH 5.6; abrupt smooth boundary.
2A	8-17	Dark brown (7.5YR 3/4) loamy sand; dark brown (7.5YR 4/4) dry; strong coarse subangular blocky structure; hard; firm; many fine roots; common biochannels (1-3 mm); common biopores (1-4 mm); few biochambers (to 5mm); pH 5.1; clear smooth boundary.
2A/B	17-27	Yellowish red (5YR 4/6) loamy sand; strong brown (7.5YR 5/6) dry; moderately weak coarse subangular blocky structure; hard; friable; few fine roots, few biopores (to 3 cm); ironstone concretions comprise 5% of soil material; pH 5.1; gradual smooth boundary.
2Bt1	27-35	Red (2.5YR 4/6) sandy loam; yellowish red (5YR 5/8) dry; weak coarse subangular blocky structure; hard; friable; many fine roots; few medium roots; many biopores (1-3 mm); few charcoal fragments; ironstone concretions comprise 2-5% of soil; pH 5.0; abrupt wavy boundary.
2Bt2	35-53	Red (2.5YR 4/6) sandy loam; reddish yellow (5YR 6/8) dry; moderately weak coarse subangular blocky structure; slightly hard; friable; many fine roots; few medium roots; few large roots; many biopores; many biotubules; subrounded ironstone concretions comprise 10-20% of soil; pH 5.1; abrupt wavy boundary.
2C	>53	Indurated laterite.

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VI. Bokotchili soil series (Bo)

Location: IMAW watershed. This pedon is located 450 meters NE of the village of Falanke Kaina.

Landform:	lower backslope	Slope:	1/2-2%
Topography:	gently undulating	Pedon#:	3-B
Parent Material:	eolian sand	Drainage:	well drained
Pedon Location:	fallow area		

Horizon	Depth (cm)	Soil description (colors are for moist soil)
A1	0-13	Dark brown (7.5YR 4/4) sand; brown (7.5YR 5/4) dry; thin platy; weak; friable; banded sand grains; many fine and common medium roots; common biopores and biochambers (up to 1 cm); pH 6.0; many laterite gravels (2-3 mm); clear smooth boundary.
A2	13-30	Dark brown (7.5YR 4/4) sand; strong brown (7.5YR 5/6) dry; weak coarse subangular blocky; slightly hard; friable; common fine roots; few medium roots; few biochambers (2-4 mm); few crotovinas (to 4 cm); pH 5.6; clear smooth boundary.
A/B	13-49	Strong brown (5YR 4/6) sand; yellowish red (5YR 4.6) dry; weak coarse subangular blocky; weak; friable; common fine roots; few medium roots; many biochannels (2-3 mm); few crotovinas with infilling of very pale brown (10YR 7/3) sand; pH 5.3; few laterite gravels (2-3 cm); few charcoal fragments (up to 5mm); clear smooth boundary.
Bt1	49-74	Yellowish red (5YR 5/8) sand; red (2.5YR 4/8) dry; weak coarse subangular blocky; slightly hard; friable; common fine and few medium roots; few biochannels; few biochambers; few crotovinas (to 3 cm); few charcoal fragments (5 mm); few laterite gravels (2-3 cm); pH 5.0; gradual smooth boundary.
Bt2	74-95	Yellowish red (5YR 5/8) sand (both humid and dry); weak coarse subangular blocky; weak; friable; common fine roots; few medium roots; few biochambers (5 mm); few laterite gravels (2-3 cm); pH 5.1; gradual smooth boundary.
Bt3	95-144	Red (2.5YR 5/8) sand; reddish yellow (5YR 5/8) dry; weak coarse subangular blocky; slightly hard; friable; few fine and medium roots; few biochambers; few biochannels; pH 5.4; gradual smooth boundary.

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VI. Bokotchili soil series (continued)

B/C 144-182 Red (2.5YR 4/8) sand; yellowish red (5YR 5/8) dry; weak, coarse subangular blocky; slightly hard; friable; few medium roots; few fine roots; few biochambers; few biochannels; few crotovinas (2-4 cm dia.); few laterite gravels (2-3 mm); pH 5.4; gradual smooth boundary.

C1 182-200 Red (2.5YR 4/8) sand; yellowish red (5YR 5/8) dry; coarse subangular blocky; slightly hard; friable; few fine roots; few laterite gravels (1-2 mm); pH 5.7; gradual smooth boundary.

* Auger samples taken to 350 cm below the soil surface contained no laterite.

VII. Falanke soil series (Fa)

Location: IMAW watershed. This pedon is located 470m east of Falanke Kaina, 25m upslope of the valley floor.

Landform:	toeslope	Slope:	5-7%
Topography:	undulating	Pedon#:	4-B
Parent Material:	eolian sand	Drainage:	well drained
Pedon Location:	millet field		

Horizon Depth (cm) Soil description (colors are for moist soil)

A1 0-4 Strong brown (7.5YR 4/6) sand; thin platy structure; hard; friable; vesicular pores; common fine roots; common medium roots; common biochannels (2-3 mm); inclusions of reddish yellow (7.5YR 7/6) sand; abrupt wavy boundary.

A2 4-15 Strong brown (7.5YR 6/4) loamy sand; weak coarse subangular blocky; very hard; friable; common fine roots; few biochambers (to 1cm); common biopores; few charcoal fragments; inclusions of dark brown (10YR 4/3) sand; pH 5.3; abrupt wavy boundary.

A/B 15-31 Yellowish red (5YR 5/8) loamy sand; reddish yellow (5YR 6/8) dry; weak coarse subangular blocky; extremely hard; friable; common fine roots; few medium roots; common biopores; common biochannels (1-3 mm); common biochambers (to 1 cm); many biocasts with dark brown (7.5YR 3/4) infilling; few charcoal fragments; pH 5.1; abrupt smooth boundary.

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VII. Falanke soil series (continued)

Bt1 31-51 Yellowish red (5YR 5/8) loamy sand; reddish yellow (5YR 6/8) dry; weak coarse subangular blocky; weak; friable; common fine roots; common biochambers (to 1 cm); common biopores; few biochannels; few charcoal fragments; pH 5.3; gradual smooth boundary.

Bt2 51-79 Yellowish red (5YR 5/8) loamy sand; reddish yellow (7.5YR 6/8) dry; nearly massive parting to weak coarse subangular blocky; weak; friable; common fine roots; few medium roots; common biochannels (1-3 mm); common biochambers (4-7 mm); common biopores (1-2 mm); few charcoal fragments; pH 5.4;gradual smooth boundary.

Bt3 79-105 Yellowish red (5YR 5/8) loamy sand; reddish yellow (7.5YR 6/8) dry; nearly massive; weak; friable; few fine roots; few large roots; common root channels (5 mm dia.); common biocasts with yellowish brown (10YR 5/4) sand infilling; pH 5.2; gradual smooth boundary.

B/C 105-126 Yellowish red (5YR 5/8) loamy sand; reddish yellow (7.5YR 6/8) dry; nearly massive; weak; friable; common biochambers (to 3 cm); very hard biocasts related to termite activity; pH 5.6; gradual smooth boundary.

C1 126-164 Yellowish red (5YR 5/8) loamy sand; reddish yellow (7.5YR 6/8) dry; nearly massive; slightly hard; friable; few fine roots; few biochambers; few biochannels; common biopores; pH 5.8; gradual smooth boundary.

C2 164-200 Yellowish red (5YR 5/8) sand; reddish yellow (7.5YR 6/8) dry; massive; slightly hard; friable; few fine roots; few biopores; few biocasts with reddish yellow (7.5YR 6/6) sand infilling; pH 5.8.

** No laterite gravels were found in samples taken to 325 cm below the soil surface with a hand auger.

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Thin Section Descriptions

Hamdallaye Intact Field Samples

1. Tondo Kakasia sealed.
   Granular; weakly intertextic to agglomeroplasmic; many simple packing voids; few to many 0.2 to 0.5 mm nodules; many 5-30 μm grain cutans; 0.5-2.5 mm surface crust; 10 μm strongly oriented layer above crust.

2. Tondo Kakasia unsealed.
   Granular; many simple packing voids many 0.1 to 0.7 mm nodules; few 5-20 μm grain cutans; no crust.

3. Bokotchili sealed.
   Granular; many simple packing voids; very few 0.1 to 1 mm nodules; many 5-15 μm grain cutans; 0.1 to 0.7 mm surface crust.

4. Bokotchili unsealed.
   Granular; many simple packing voids; very few 0.1-0.5 mm nodules; very few 3-5 μm grain cutans; no crust.

5. Dantiandou sealed.
   Granular; many simple packing voids; many 0.1 to 1 mm nodules; many 5-15 μm grain cutans; 0.1 to 0.2 mm surface clay crust with 1.5 mm layer of bare sand grains above this.

6. Dantiandou unsealed.
   Granular; many simple packing voids; many 0.2 to 2 mm nodules; very few 5 μm grain cutans; no crust but some sorting of surface with fine sand and silt at surface.

7. Hamdallaye sealed.
   Granular; many simple packing voids; few 0.1-0.3 mm nodules; some 5-20 μm grain cutans; 0.1 to 0.4 continuous clay layer at surface; 0-1 mm layer of bare sand above clay layer.

8. Hamdallaye unsealed.
   Granular; many simple packing voids few 0.1-0.3 nodules; some 1.5 mm nodules; few 5-20 μm grain cutans; no crust.

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9. Falanke sealed.
   Granular; zones of intertextic; many simple packing voids; few 0.1-0.6 mm nodules; 0.1-0.8 mm mostly continuous clay and fine silt layer at surface.

10. Falanke unsealed.
    Granular; many simple packing voids; very few 0.2-0.4 mm nodules; some 5 μm grain cutans; weak non-continuous clay accumulation laer 0.8 to 1.6 mm below surface.

11. Gangani sealed.
    Granular to intertextic; many simple packing voids; some metavughs; many 0.1-1 mm nodules; many 5-15 μm grain cutans; 0.1 to 2 mm zone dense clay layer at surface.

12. Gangani unsealed.
    Granular; many simple packing voids; some 0.5-2 mm vesicular pores; few 3-10 μm grain cutans; two layers of clay and silt accumulation at 5 and 12 mm depths, appear to be old depositional surfaces.

Cinzana Intact Field Samples

1. M2 sealed.
   Granular; many simple packing voids; many 0.1-1 mm nodules; some 5-10μm grain cutans; no differentiation of structure at surface.

2. M2 unsealed.
   Granular; simple packing voids; many meta and orthovughs and metachannels; some 0.1-0.5 mm nodules; very few 5-15 μm grain cutans; no crust.

3. B12 sealed.
   Granular; simple packing voids; one metachannel; 1 metavugh; few .1-.8 mm nodules; few 5-15 μm grain cutans; 0.1 to 1 mm depositional crust with strongly oriented clay layer at surface.

4. B12 unsealed.
   Granular; simple packing voids; some metavughs; few 0.1-0.6 mm nodules; few 5 μm grain cutans; many fecal pellets; buried depositional crust at 1 cm depth.

APPENDIX B

SOIL CHEMICAL AND PHYSICAL DATA

Table A1. Summary of selected chemical properties. Hamdallaye soils.

Soil Series	Paired Samples	pH Water	pH KCl	Fe - DCB (ppm)	Al - DCB (ppm)	Fe - OX (ppm)	Al - OX (ppm)	Soluble Si (ppm)	Total Fe (%)
To	Sealed (0-3 mm)	4.9	4.2	8160	659	268	333	9.0	2.0
To	Sealed (0-5 cm)	4.6	3.7	8733	731	218	392	6.1	1.9
To	Unsealed (0-5 cm)	6.3	5.0	3130	222	154	102		1.0
Da	Sealed (0-3 mm)	5.7	4.4	4985	419	271	267	6.7	1.3
Da	Sealed (0-5 cm)	5.0	3.9	3614	322	194	176	3.9	0.9
Da	Unsealed (0-5 cm)	6.6	5.4	1530	114	98	51		0.6
Ha	Sealed (0-3 mm)	4.6	4.0	4900	507	222	321	6.0	1.1
Ha	Sealed (0-5 cm)	4.7	3.9	3685	410	199	268	4.5	0.9
Ha	Unsealed (0-5 cm)	6.3	5.1	1380	112	127	111		0.5
Bo	Sealed (0-3 mm)	4.8	3.9	2870	489	247	375	6.9	0.9
Bo	Sealed (0-5 cm)	4.6	3.8	2093	378	198	307	4.1	0.7
Bo	Unsealed (0-5 cm)	6.1	5.1	784	94	93	80		0.5
Fa	Sealed (0-3 mm)	5.0	4.0	3735	492	213	304	6.7	1.1
Fa	Sealed (0-5 cm)	4.7	3.9	3402	440	178	309	5.7	0.9
Fa	Unsealed (0-5 cm)	5.9	4.7	1430	151	124	157		0.6
All Soils	Sealed (0-3 mm)	5.0	4.1	4930	513	244	320	7.1	1.3
(average)	Sealed (0-5 cm)	4.7	3.8	4305	456	197	290	4.9	1.1
	Unsealed (0-5 cm)	6.2	5.1	1651	139	119	100		0.6

DCB = citrate-dithionite
OX = oxalate

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Table A2. Soil chemical and physical properties. Hamdallaye soils.

SAMPLE ID cm depth	Water pH	KCl pH	d pH	HMP SAND	HMP SILT	HMP CLAY	Organic C
				%			%
ToC 0-C	4.90	4.24	-0.66	75.23	3.31	21.46	0.10
ToC 0-.5	4.86	3.90	-0.96	75.56	2.10	22.34	0.09
ToC .5-2.5	4.54	3.68	-0.86	76.61	0.69	22.70	0.12
ToC 2.5-5	4.55	3.72	-0.83	76.62	1.30	22.08	0.11
ToC 0-5	4.58	3.72	-0.85	76.51	1.14	22.35	0.11
ToUC	6.25	5.02	-1.23	92.63	2.87	4.50	0.20
DaC 0-C	5.70	4.36	-1.34	89.23	4.77	6.00	0.17
DaC 0-.5	5.38	4.11	-1.27	90.92	2.40	6.68	0.14
DaC .5-2.5	5.09	3.95	-1.14	92.99	1.49	5.52	0.13
DaC 2.5-5	4.82	3.90	-0.92	93.17	1.40	5.34	0.10
DaC 0-5	4.98	3.94	-1.04	92.87	1.58	5.55	0.12
DaUC	6.55	5.44	-1.11	96.71	1.29	2.00	0.14
HaC 0-C	4.59	3.99	-0.60	90.25	1.71	8.04	0.16
HaC 0-.5	4.93	3.98	-0.95	90.95	1.29	7.76	0.13
HaC .5-2.5	4.53	3.90	-0.63	94.44	0.77	4.79	0.10
HaC 2.5-5	4.79	3.90	-0.89	94.45	1.35	4.20	0.09
HaC 0-5	4.70	3.91	-0.79	94.10	1.11	4.79	0.10
HaUC	6.28	5.11	-1.17	98.68	0.52	0.80	0.12
BoC 0-C	4.80	3.93	-0.87	88.15	2.21	9.64	0.17
BoC 0-.5	5.00	3.81	-1.19	88.51	1.66	9.83	0.13
BoC .5-2.5	4.82	3.81	-1.01	91.79	0.66	7.55	0.11
BoC 2.5-5	4.44	3.73	-0.71	92.18	0.64	7.18	0.10
BoC 0-5	4.65	3.77	-0.88	91.66	0.75	7.59	0.11
BoUC	6.08	5.05	-1.03	96.18	1.58	2.24	0.15
FaC 0-C	4.96	3.99	-0.97	86.52	3.12	10.36	0.17
FaC 0-.5	4.99	3.87	-1.12	88.65	2.04	9.31	0.15
FaC .5-2.5	4.80	3.87	-0.93	89.20	1.68	9.12	0.14
FaC 2.5-5	4.65	3.85	-0.80	88.54	2.20	9.26	0.15
FaC 0-5	4.74	3.86	-0.88	88.82	1.98	9.21	0.15
FaUC	5.86	4.71	-1.15	96.49	0.17	3.34	0.17
GaC 0-C	5.48	3.93	-1.55	74.82	8.04	17.14	
GaC 0-.5	5.38	3.73	-1.65	81.62	9.56	8.82	0.22
GaC .5-2.5	4.91	3.57	-1.34	83.69	8.47	7.84	0.21
GaC 2.5-5	4.57	3.55	-1.02	84.90	7.00	8.10	0.20
GaC 0-5	4.79	3.58	-1.21	84.09	7.84	8.07	0.21
GaUC	5.92	4.92	-1.00	96.26	1.56	2.18	0.20

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Table A2. (cont'd.)

SAMPLE ID cm depth	DCB FE	DCB AL	AO FE	AO AL	AO/DCB FE	AO/DCB AL
	mg/kg				%	%
ToC 0-C	8160	658.5	268	333	3.28	50.57
ToC 0-.5	8410	708	220	350	2.62	49.44
ToC .5-2.5	9030	724	220	404	2.44	55.80
ToC 2.5-5	8560	742	216	390	2.52	52.56
ToC 0-5	8733	731.4	218	391.6	2.50	53.54
ToUC	3130	222	154	102	4.92	45.95
DaC 0-C	4985	419	271	267	5.44	63.72
DaC 0-.5	4070	334	205	193	5.04	57.78
DaC .5-2.5	3930	337	210	184	5.34	54.60
DaC 2.5-5	3270	307	178	166	5.44	54.07
DaC 0-5	3614	321.7	193.5	175.9	5.35	54.68
DaUC	1530	114	98	51	6.41	44.74
HaC 0-C	4900	507	221.5	321	4.52	63.31
HaC 0-.5	4500	458	252	333	5.60	72.71
HaC .5-2.5	3450	426	205	266	5.94	62.44
HaC 2.5-5	3710	387	184	257	4.96	66.41
HaC 0-5	3685	409.7	199.2	268.2	5.41	65.46
HaUC	1380	112	127	111	9.20	99.11
BoC 0-C	2870	489	247	375	8.61	76.69
BoC 0-.5	2810	520	247	363	8.79	69.81
BoC .5-2.5	2280	424	186	311	8.16	73.35
BoC 2.5-5	1800	313	197	292	10.94	93.29
BoC 0-5	2093	378.1	197.6	306.7	9.44	81.12
BoUC	784	94	93	80	11.86	85.11
FaC 0-C	3735	492	212.5	304	5.69	61.79
FaC 0-.5	3070	402	191	309	6.22	76.87
FaC .5-2.5	3400	426	176	297	5.18	69.72
FaC 2.5-5	3470	458	177	318	5.10	69.43
FaC 0-5	3402	439.6	178	308.7	5.23	70.22
FaUC	1430	151	124	157	8.67	103.97
GaC 0-C	5125	523.5	298.5	249	5.82	47.56
GaC 0-.5	4080	465	290	271	7.11	58.28
GaC .5-2.5	3800	437	302	279	7.95	63.84
GaC 2.5-5	4690	506	268	300	5.71	59.29
GaC 0-5	4273	474.3	283.8	288.7	6.64	60.87
GaUC	1740	144	176	115	10.11	79.86

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Table A2. (cont'd.)

SAMPLE ID cm depth	S: mg/kg	Total Fe Sand %	Total Fe Silt %	Total Fe Clay %	Total Fe Whole %	DCB:Total Fe fraction
ToC 0-C	8 98	0 77	2 78	6 28	2 02	40 40
ToC 0- 5	8 02	0 62	2 40	6 22	1 91	44 03
ToC 5-2 5	6 33	0 53	2.27	6 81	1 97	45 84
ToC 2 5-5	5 52	0 39	2 22	7 21	1 92	44 58
ToC 0-5	6 09	0 47	2 26	6 95	1 94	45 04
ToUC		0 68	2 44	6 89	1 01	30 99
DaC 0-C	6 68	0 67	3 18	9 05	1 29	38 64
DaC 0- 5	3 58	0 53	3 11	7 90	1 08	37 69
DaC 5-2 5	4 03	0 50	2 95	7 71	0 93	42 26
DaC 2 5-5	3 95	0 45	2.86	8 58	0 92	35 54
DaC 0-5	3 95	0 48	2.92	8 17	0 94	38 45
DaUC		0 42	2.61	6 96	0 58	26 38
HaC 0-C	5 96	0 32	2 92	8 93	1 06	46 23
HaC 0- 5	5 20	0 34	2 79	8 85	1 03	43 69
HaC 5-2 5	4 45	0 36	2 63	10 81	0 88	39 20
HaC 2 5-5	4 43	0 31	2 51	13 08	0 88	42 16
HaC 0-5	4 52	0 34	2 59	11 75	0 90	41 17
HaUC		0 33	2 40	24 11	0 53	26 04
BoC 0-C	6 92	0 17	1 95	7 51	0 92	31 20
BoC 0- 5	6 28	0 19	1 75	6 53	0 84	33 45
BoC 5-2 5	4 43	0 19	1 50	6 83	0 70	32 57
BoC 2 5-5	3 45	0 18	1 39	6 64	0 65	27 69
BoC 0-5	4 13	0 18	1 47	6 71	0 69	30 38
BoUC		0 30	1 96	7 04	0 48	16 33
FaC 0-C	6 72	0 22	1 82	7 72	1 05	35 57
FaC 0- 5	5 90	0 21	1 66	7 39	0 91	33 74
FaC 5-2 5	5 70	0 24	1 52	6 73	0 85	40 00
FaC 2 5-5	5 65	0 36	1 52	6 56	0 96	36 15
FaC 0-5	5 70	0 30	1 53	6 71	0 91	37 34
FaUC		0 41	2 09	4 66	0 55	26 00
GaC 0-C	8 37		2 84	9 93	1 93	26 55
GaC 0- 5	6 28		2 74	16 19	1 69	24 14
GaC 5-2 5	7 90		2 81	21 45	1 92	19 79
GaC 2 5-5	7 08		2 70	20 63	1 86	25 22
GaC 0-5	7 33	0 00	2 75	20 52	1 87	22 89
GaUC			2 68	38 91	0 89	19 55

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Table A2. (cont'd.)

SAMPLE ID	Fraction of Total Fe		
	Sand	Silt	Clay
cm depth	%		
ToC 0-C	28.71	4.56	66.73
ToC 0-.5	24.61	2.64	72.75
ToC .5-2.5	20.77	0.80	78.44
ToC 2.5-5	15.56	1.50	82.93
ToC 0-5	18.58	1.32	80.13
ToUC	62.36	6.93	30.70
DaC 0-C	46.14	11.76	42.10
DaC 0-.5	44.20	6.91	48.89
DaC .5-2.5	49.49	4.73	45.78
DaC 2.5-5	45.57	4.63	49.80
DaC 0-5	46.98	4.91	48.17
DaUC	70.20	5.81	24.00
HaC 0-C	27.59	4.71	67.70
HaC 0-.5	29.85	3.49	66.66
HaC .5-2.5	38.85	2.30	58.85
HaC 2.5-5	33.70	3.85	62.45
HaC 0-5	35.28	3.21	62.92
HaUC	61.26	2.35	36.39
BoC 0-C	16.67	4.68	78.64
BoC 0-.5	20.13	3.46	76.42
BoC .5-2.5	24.91	1.41	73.67
BoC 2.5-5	25.24	1.37	73.39
BoC 0-5	24.49	1.60	73.91
BoUC	60.71	6.45	32.83
FaC 0-C	18.46	5.41	76.13
FaC 0-.5	20.65	3.72	75.63
FaC .5-2.5	24.77	3.00	72.23
FaC 2.5-5	33.20	3.48	63.31
FaC 0-5	28.82	3.33	67.87
FaUC	71.05	0.65	28.30
GaC 0-C		11.83	88.17
GaC 0-.5		15.50	84.50
GaC .5-2.5		12.40	87.60
GaC 2.5-5		10.16	89.84
GaC 0-5		11.55	88.66
GaUC		4.70	95.30

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Table A3. Ammonium acetate extract data. Hamdallaye soils.

Sample	ppm Ca	ppm Mg	ppm K	ppm Na	meq/100 g Ca	Mg	K	Na	Sum	meq/100g Clay	Exch. Bases meq/100g	KCl Exch. Acidity meq/100g	CEC	% B.S.	ESP
ToC 0-C A	22.18	5.01	6.13	0.25	0.55	0.21	0.08	0.01	0.84	3.93	0.84	0.29	1.13	74.60	0.48
ToC 0-C B	22.46	5.10	6.21	0.33	0.56	0.21	0.08	0.01	0.86	3.99	0.86	0.27	1.13	75.77	0.63
ToUC	16.15	5.59	8.34	0.05	0.40	0.23	0.11	0.00	0.74	16.46	0.74	0.07	0.82	90.83	0.13
DaC 0-C	18.95	4.48	6.33	0.28	0.47	0.18	0.08	0.01	0.74	12.40	0.74	0.19	0.94	79.57	0.65
DaUC	14.34	3.86	3.22	0.05	0.36	0.16	0.04	0.00	0.56	27.94	0.56	0.06	0.62	90.57	0.18
HaC 0-C	10.55	2.38	5.35	0.19	0.26	0.10	0.07	0.00	0.43	5.39	0.43	0.51	0.94	45.98	0.44
HaUC	14.50	3.77	5.71	0.08	0.36	0.16	0.07	0.00	0.59	73.96	0.59	0.08	0.67	88.47	0.26
BoC 0-C	17.37	4.04	6.99	0.14	0.43	0.17	0.09	0.00	0.69	7.18	0.69	0.50	1.19	58.05	0.26
BoUC	14.88	4.20	5.13	0.01	0.37	0.17	0.07	0.00	0.61	27.23	0.61	0.07	0.68	89.23	0.03
FaC 0-C	15.64	4.58	7.10	0.15	0.39	0.19	0.09	0.00	0.67	6.49	0.87	0.46	1.13	59.42	0.29
FaUC	11.47	3.59	4.41	0.00	0.29	0.15	0.06	0.00	0.49	14.68	0.49	0.11	0.60	82.13	0.00
GaC 0-C	18.91	4.78	7.26	0.07	0.47	0.20	0.09	0.00	0.76	4.46	0.76	0.36	1.12	67.96	0.14
GaC 0-C	19.14	4.69	7.33	0.10	0.48	0.19	0.09	0.00	0.77	4.48	0.77	0.35	1.11	68.88	0.20
GaUC	17.52	4.86	6.57	0.00	0.44	0.20	0.08	0.00	0.72	32.78	0.72	0.08	0.81	89.52	0.00
Plateau	125.40	26.30	16.61	2.70	3.13	1.08	0.21	0.06	4.48	21.24	4.48	0.07	4.56	98.36	1.29

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Table A4. Water stable 2- to 4- mm aggregates. Hamdallaye Soils.

		> 2 mm agg. in whole soil	water stable aggregates	water stable aggregates in whole soil
		%		
To	Sealed	11.97	87.80	10.51
	Unsealed	1.31	63.50	0.83
Da	Sealed	4.26	84.20	3.59
	Unsealed	0.25	57.10	0.14
Ha	Sealed	1.60	84.50	1.35
	Unsealed	0.33	40.60	0.13
Bo	Sealed	4.59	79.00	3.63
	Unsealed	0.50	64.20	0.32
Fa	Sealed	4.66	87.20	4.06
	Unsealed	0.74	51.20	0.38
Average of all soils	Sealed	5.42	84.50	4.63
	Unsealed	0.63	55.30	0.36

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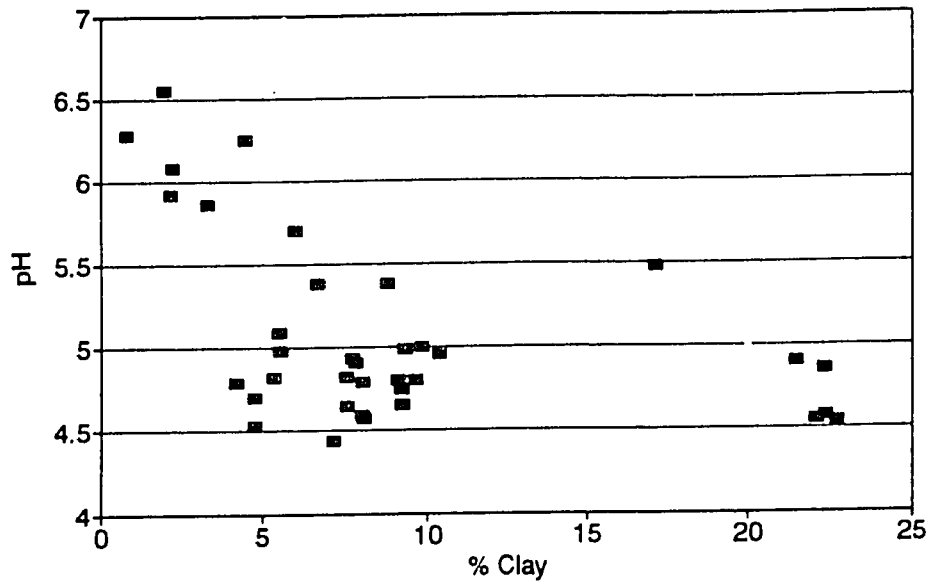

Figure A1. Water pH vs clay content. All Hamdallaye soils at all depths. n=30.

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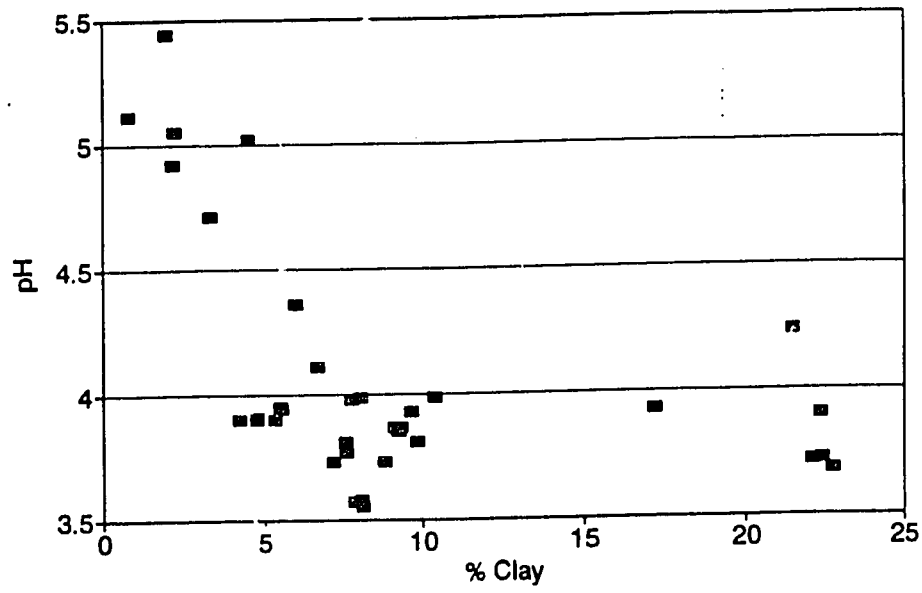

Figure A2. KCl pH vs clay content. All Hamdallaye soils at all depths. n=30.

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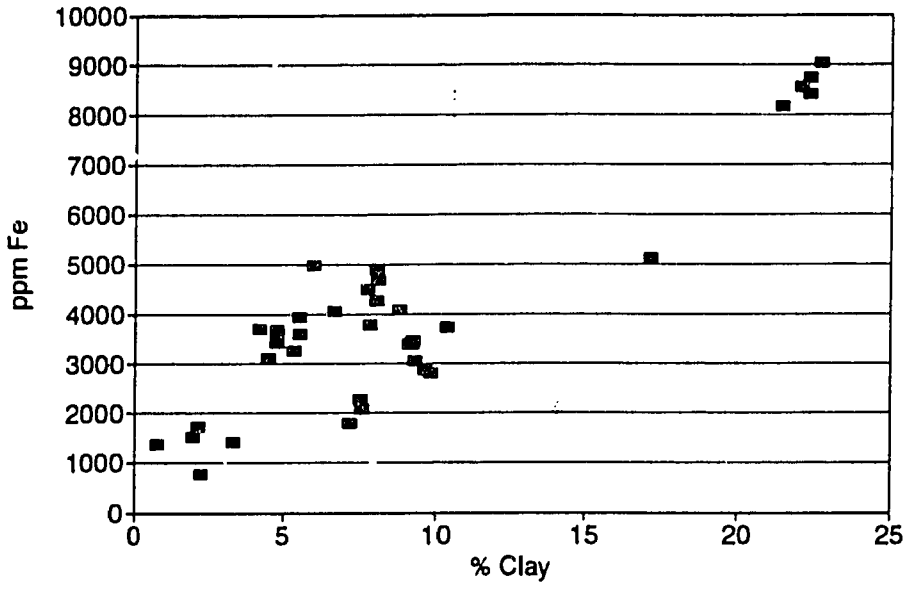

Figure A3. DCB Fe vs clay content. All Hamdallaye soils at all depths. n=30.

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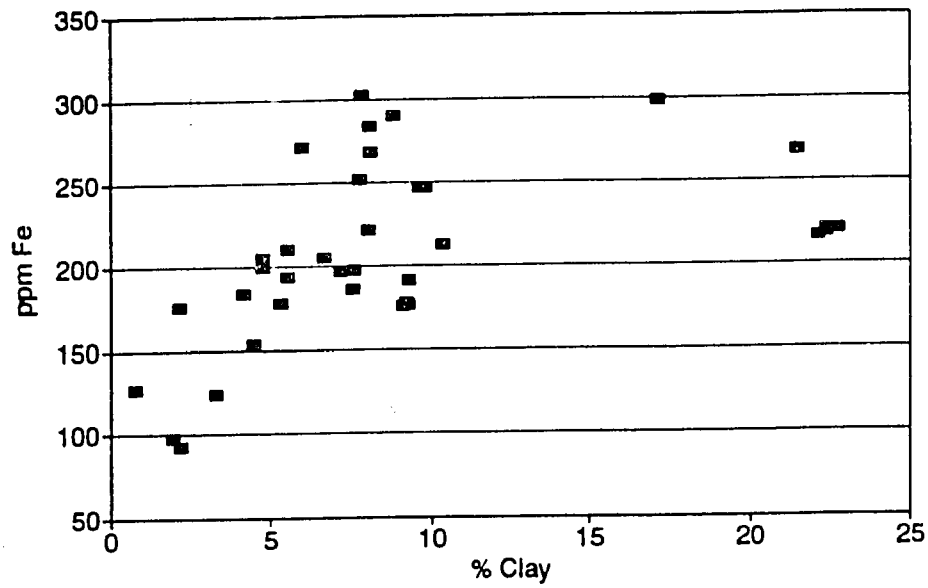

Figure A4. Amm. Ox. Fe vs clay content. All Hamdallaye soils at all depths. n=30.

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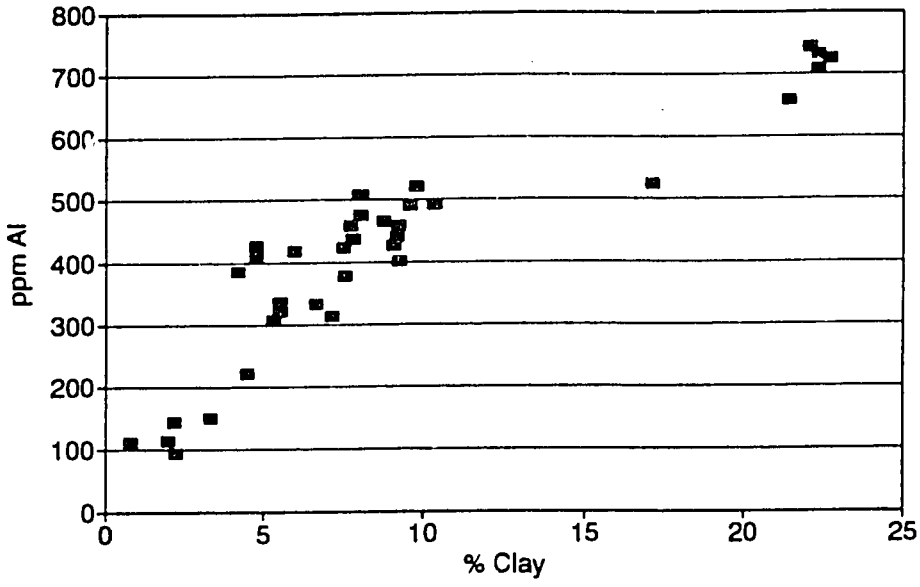

Figure A5. DCB Al vs clay content. All Hamdallaye soils at all depths. n=30.

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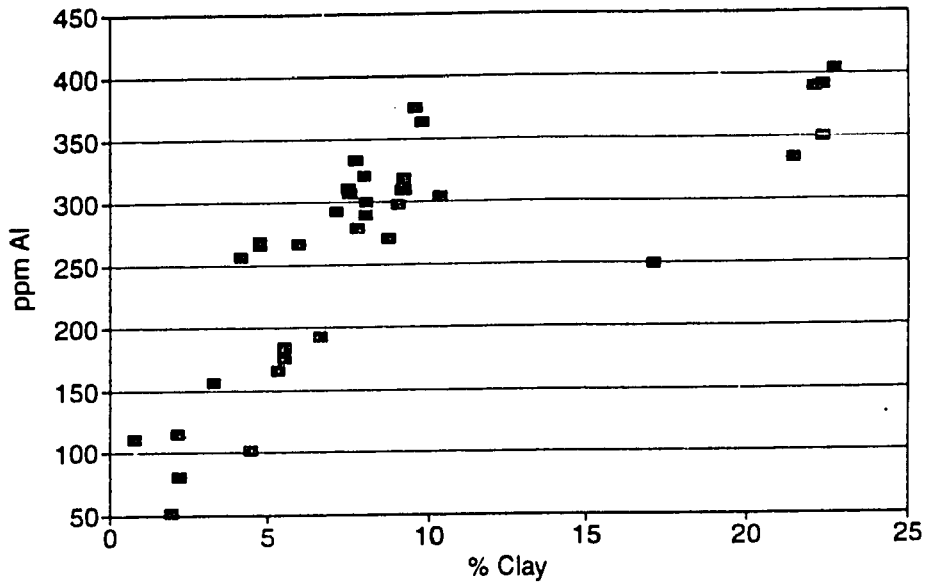

Figure A6. Amm. Ox. Al vs clay content. All Hamdallaye soils at all depths. n=30.

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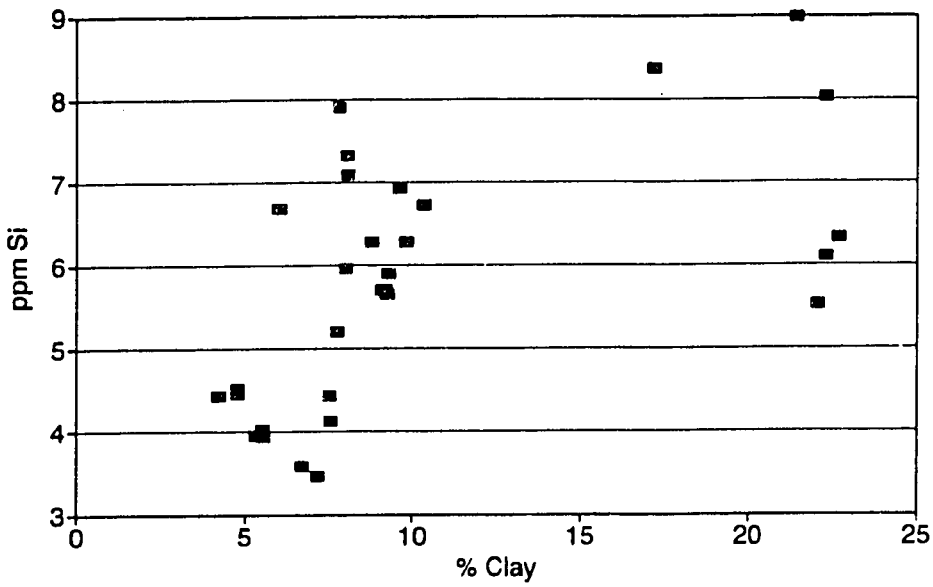

Figure A7. Soluble Si vs clay content. All Hamdallaye soils at all depths. n=30.

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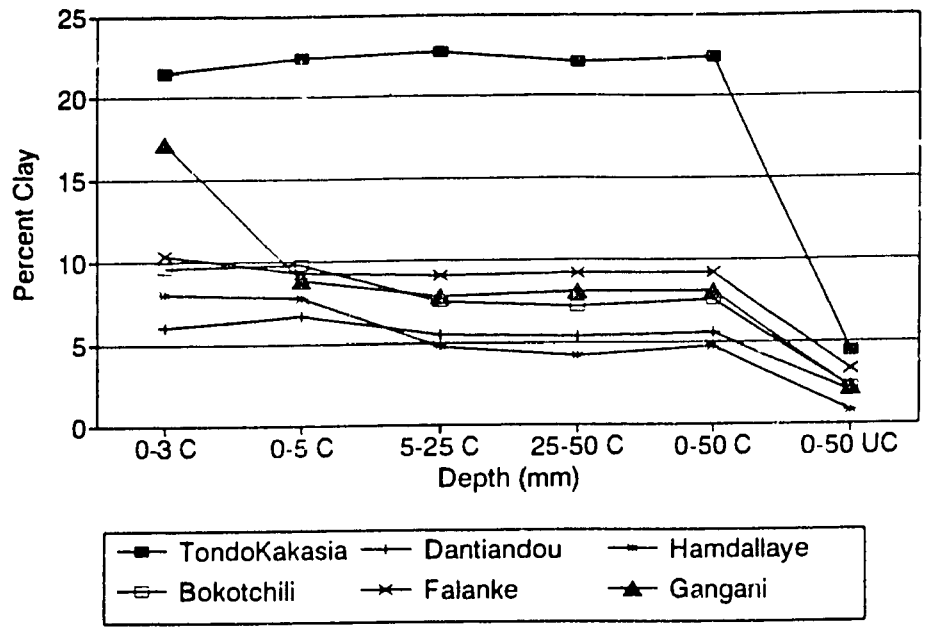

Figure A8. Clay content vs depth. C = seal, UC = unsealed.

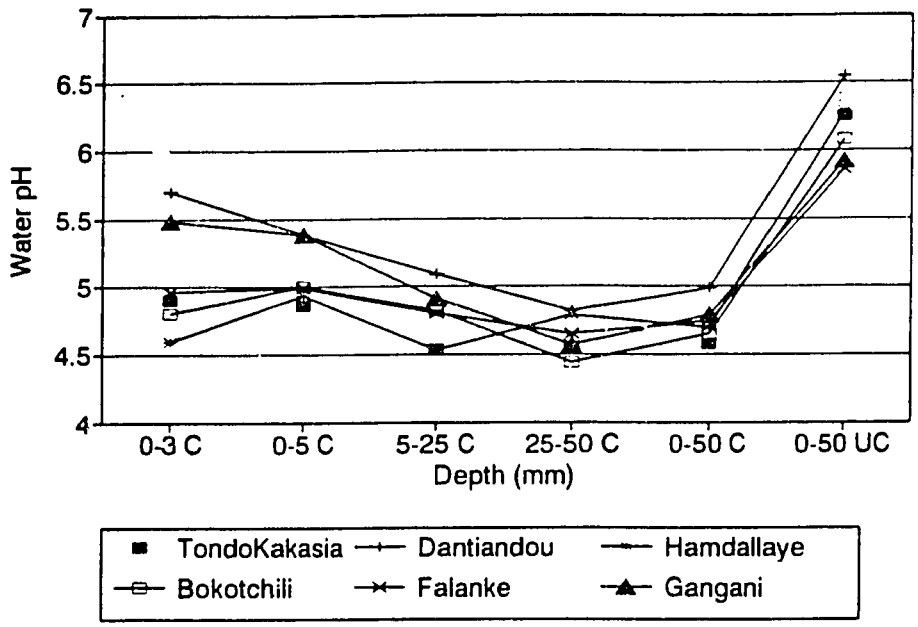

Figure A9. Water pH vs depth. C = seal, UC = unsealed.

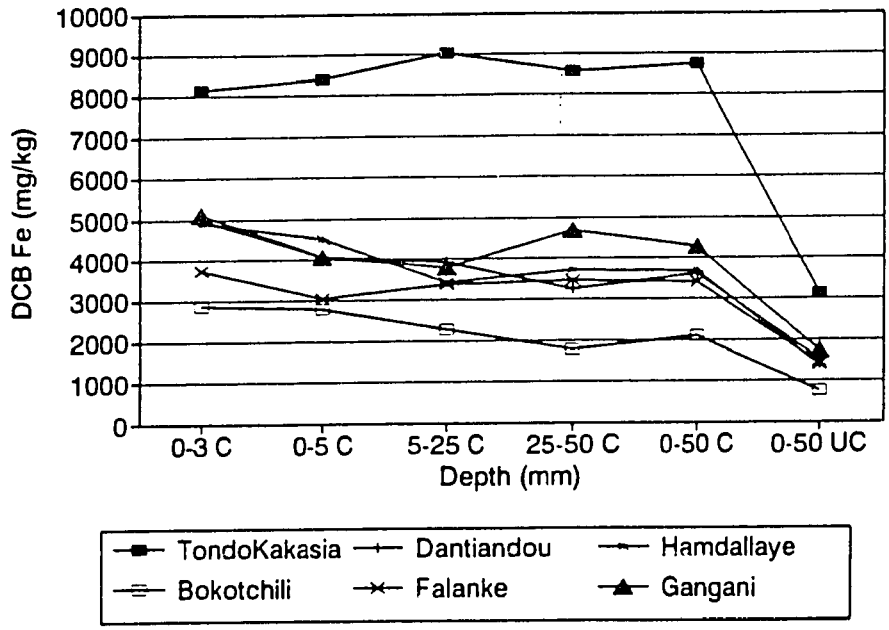

Figure A10. DCB Fe vs depth. C = seal, UC = unsealed.

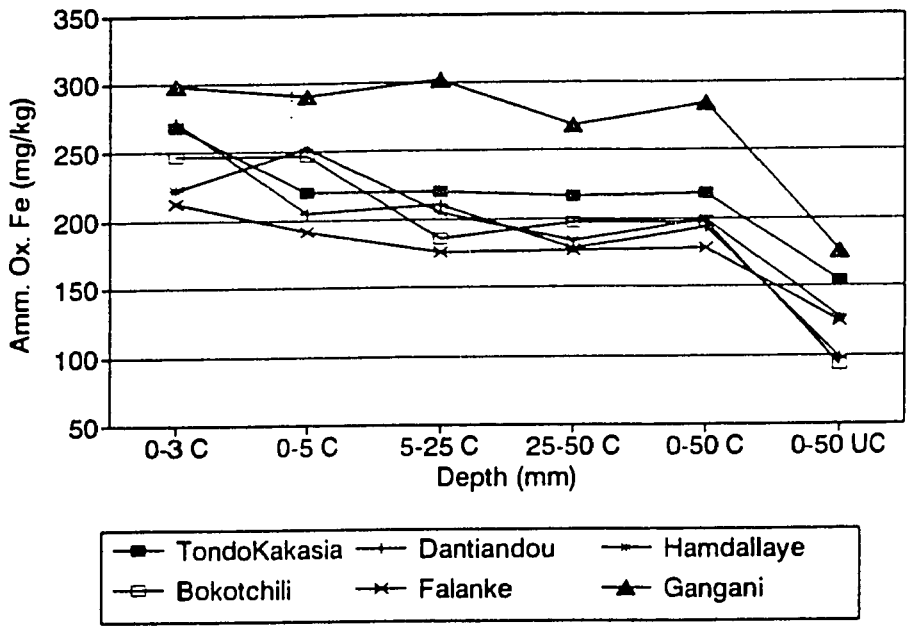

Figure A11. Amm. Ox. Fe vs depth. C = seal, UC = unsealed.

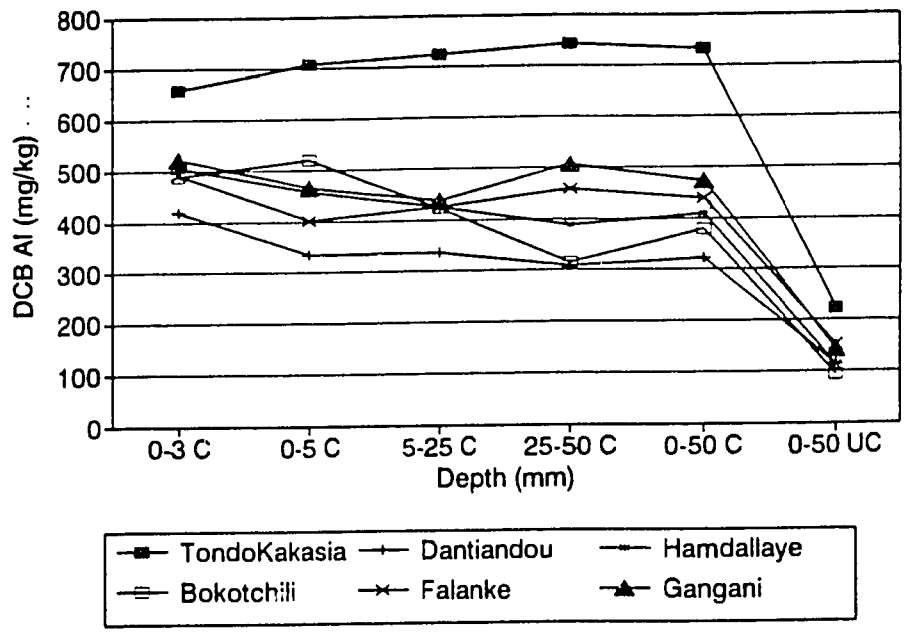

Figure A12. DCB Al vs depth. C = seal, UC = unsealed.

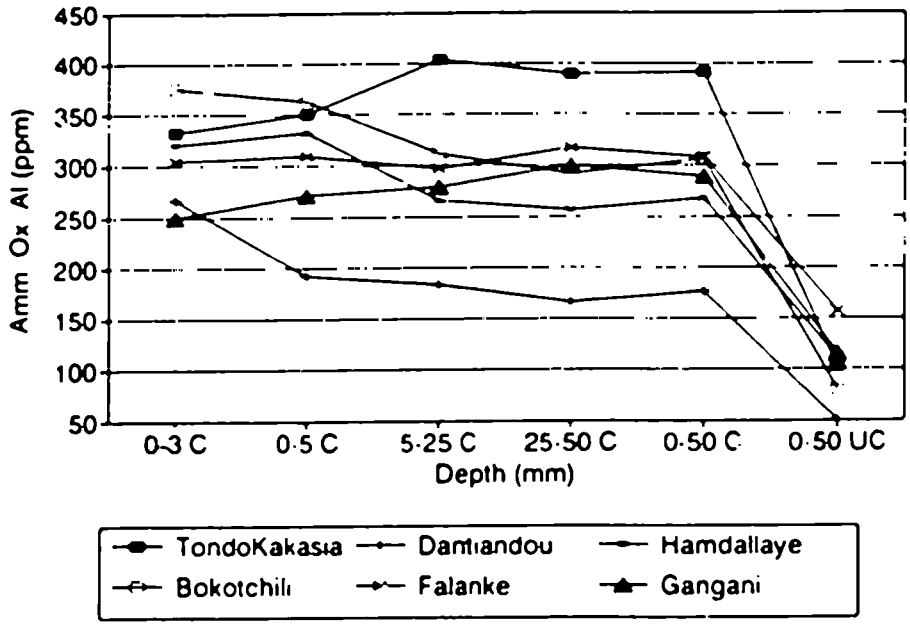

Figure A13. Am. Ox. Al vs depth. C = seal, UC = unsealed.

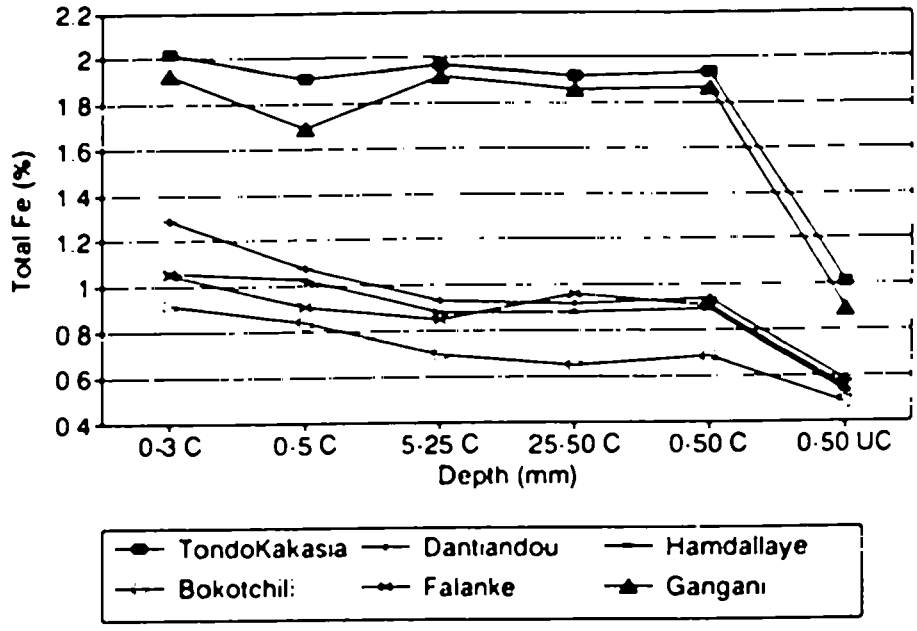

Figure A14. Total Fe vs depth. C = seal, UC = unsealed.

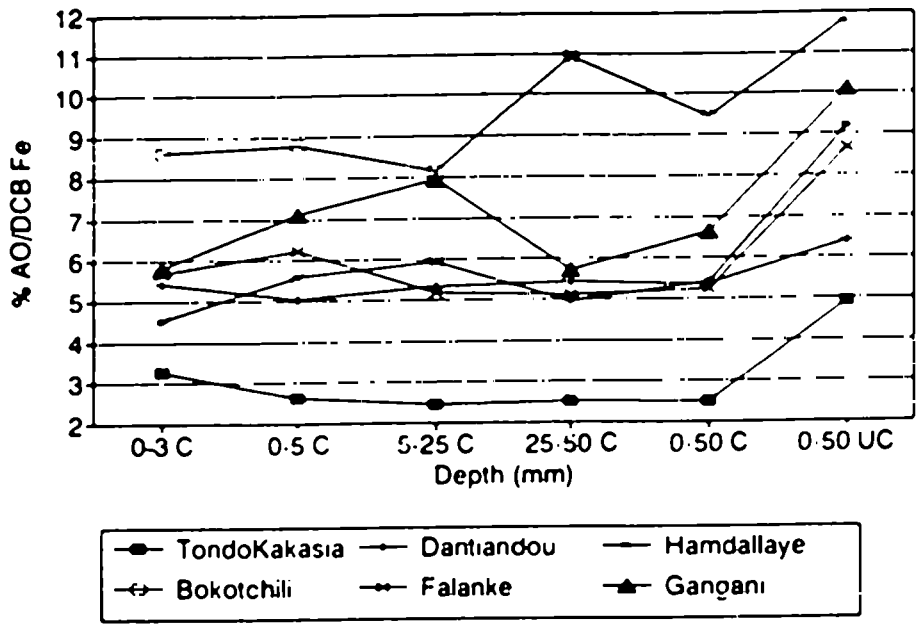

Figure A15. Am. Ox./ DCB Fe vs depth. C = seal, UC = unsealed.

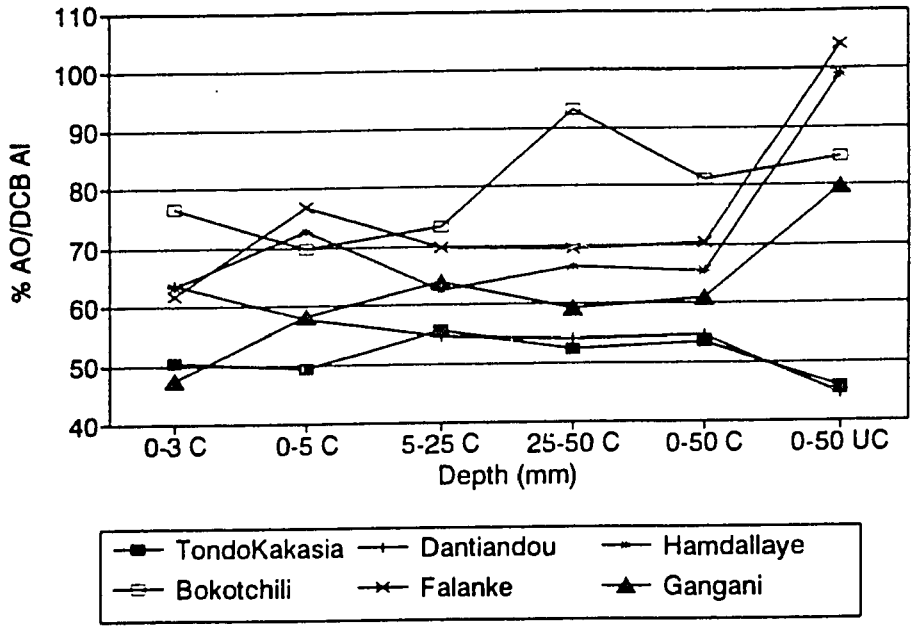

Figure A16. Am. Ox./ DCB Al vs depth. C = seal, UC = unsealed.

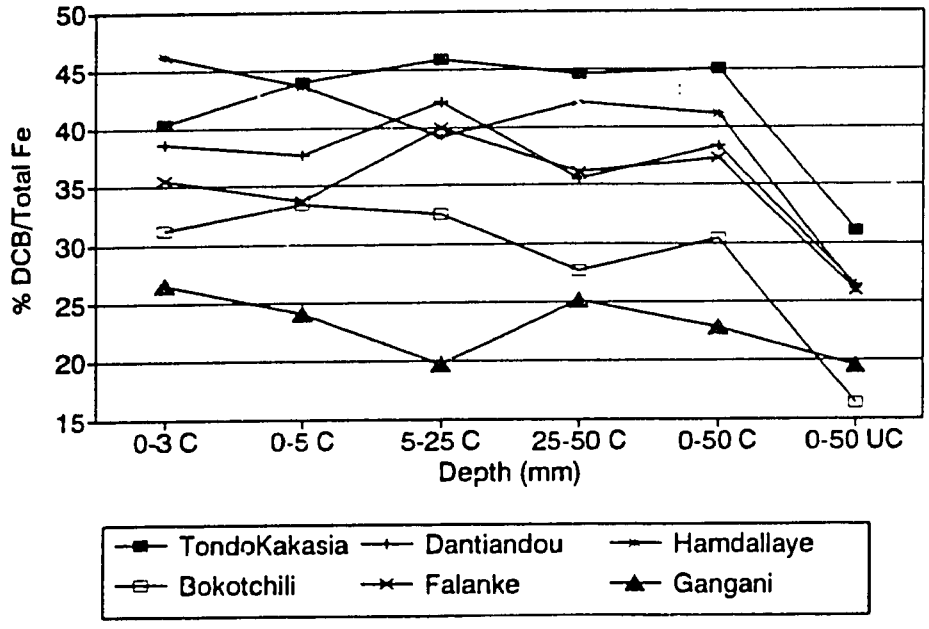

Figure A17. DCB/ Total Fe vs depth. C = seal, UC = unsealed.

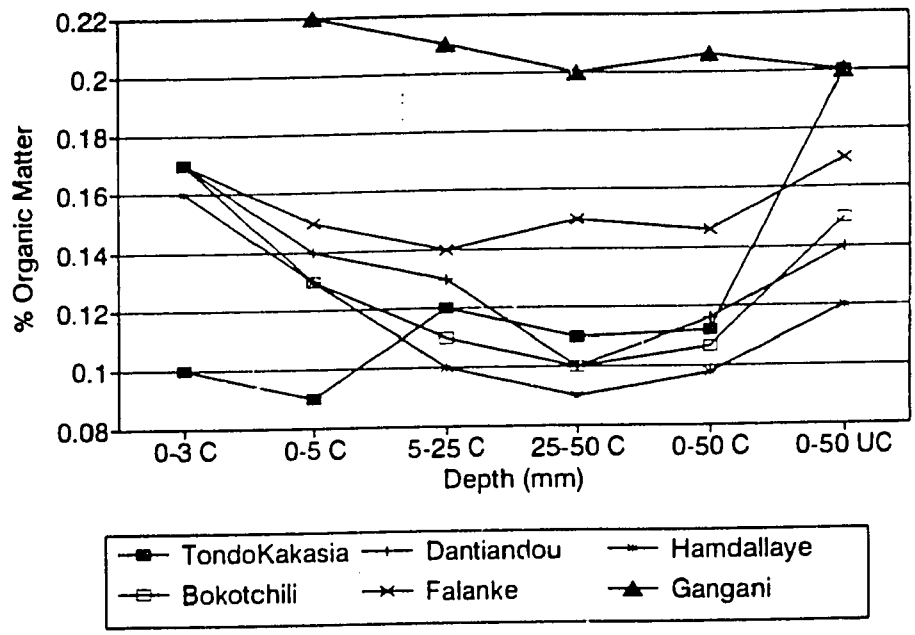

Figure A18. Organic matter content vs depth. C = seal, UC = unsealed.

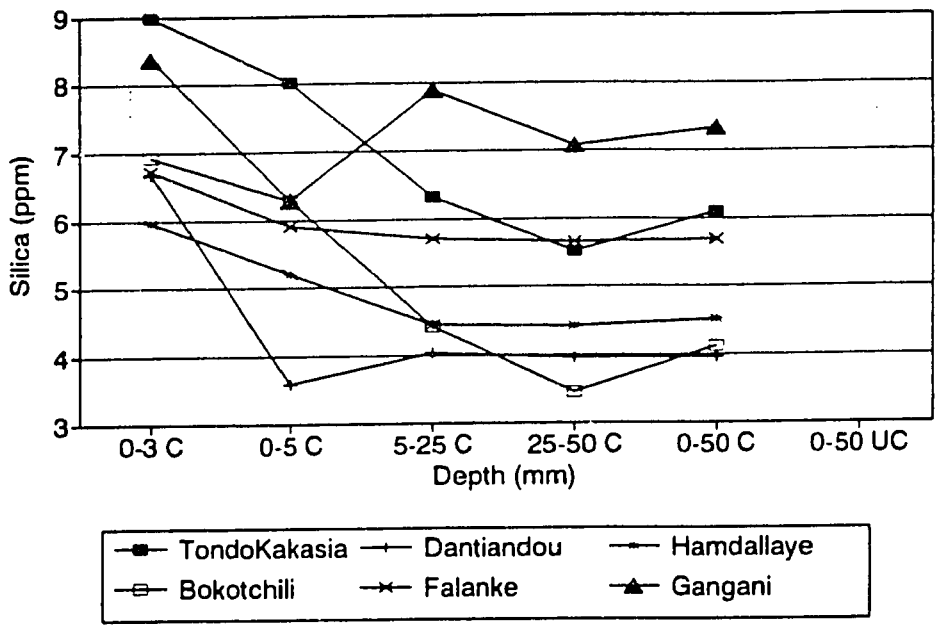

Figure A19. Soluble Si vs depth. C = seal, UC = unsealed.

APPENDIX C

RAINFALL SIMULATOR CHEMICAL AND PHYSICAL DATA

Table A5. Rainfall simulator thin section data. dtb = depth to bottom of layer.

Soil	Rainfall (min)	Treatment	Seal Layer dtb S1	Thickness S2	dtb S3	Thickness S4	Vesicular Pores
			mm				
To	30	A	1.0	0.0	0.0	0.6	none
Da	30	A	1.0	0.0	0.0	0.0	none
Ha	30	A	1.0	0.0	0.0	0.0	none
Bo	30	A	1.0	0.0	4.2	0.3	none
Fa	30	A	2.0	0.8	6.0	0.3	none
Ga	30	A	0.6	0.3	2.0	0.4	none
To	30	B	0.4	0.0	0.0	0.2	none
Da	30	B	1.0	0.0	0.0	0.0	few
Ha	30	B	0.4	0.0	3.5	0.2	none
Bo	30	B	0.6	0.0	0.0	0.0	none
Fa	30	B	2.5	0.0	4.0	0.5	few
Ga	30	B	0.0	0.0	0.0	0.0	none
To	30	C	0.0	0.0	0.0	0.2	none
Da	30	C	0.8	0.2	0.0	0.0	none
Ha	30	C	0.5	0.0	1.5	1.0	none
Bo	30	C	0.8	0.2	1.6	0.2	none
Fa	30	C	0.8	0.4	2.2	0.3	none
Ga	30	C	0.0	0.0	0.0	0.0	none
To	30	D	0.8	0.0	0.0	0.4	none
Da	30	D	0.5	0.0	0.0	0.0	few
Ha	30	D	1.0	0.0	0.0	0.0	none
Bo	30	D	1.5	0.0	3.0	0.3	none
Fa	30	D	1.2	0.3	4.0	0.4	none
Ga	30	D	0.8	0.3	2.0	0.4	none

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Table A5. (cont'd.)

Soil	Rainfall (min)	Treatment	Seal Layer dtb S1	Thickness S2	dtb S3	Thickness S4	Vesicular Pores
			---mm---				
To	60	A	1.0	0.0	0.0	1.0	none
Da	60	A	1.0	0.4	6.5	0.4	few
Ha	60	A	1.2	0.4	3.5	0.4	some
Bo	60	A	0.6	0.0	2.5	0.8	none
Fa	60	A	1.0	0.4	5.0	0.4	few
Ga	60	A	0.8	0.0	1.8	0.6	few
To	60	D	0.7	0.5	1.5	0.4	none
Da	60	D	1.0	0.0	3.0	0.4	few
Ha	60	D	0.8	0.0	3.5	0.4	some
Bo	60	D	0.8	0.0	3.0	0.6	many
Fa	60	D	1.8	0.4	3.5	0.5	some
Ga	60	D	0.3	0.2	2.5	0.4	some
To	60	A	0.5	0.0	1.0	0.6	some
Da	90	A	1.0	0.4	7.5	0.4	many
Ha	90	A	0.5	0.0	0.0	0.0	some
Bo	90	A	1.2	0.0	2.5	0.6	some
Fa	90	A	0.0	0.4	2.0	1.2	many
Ga	90	A	0.4	0.2	1.0	0.5	few
To	90	D	0.8	0.0	1.2	1.0	few
Da	90	D	1.0	0.3	5.5	0.2	many
Ha	90	D	0.5	0.0	4.0	1.0	few
Bo	90	D	1.5	0.4	5.0	0.4	some
Fa	90	D	0.4	0.4	2.5	0.8	many
Ga	90	D	0.4	0.2	2.0	0.6	many

Table A5. (cont'd)

Soil	Rainfall (min)	Treatment	Seal Layer dtb S1	Thickness S2	dtb S3	Thickness S4	Vesicular Pores
			----------mm----------				
To	120	A	0.8	0.0	1.2	1.3	none
Da	120	A	1.0	0.2	5.0	0.7	many
Ha	120	A	1.2	0.3	7.7	0.3	many
Bo	120	A	1.2	1.0	3.0	0.4	many
Fa	120	A	0.7	0.2	1.3	0.7	few
Ga	120	A	0.4	0.0	3.0	0.8	many
To	120	B	0.5	0.0	0.5	0.4	few
Da	120	B	0.0	0.6	0.0	0.0	many
Ha	120	B	0.0	0.0	0.0	0.0	some
Bo	120	B	0.0	0.0	0.0	0.0	many
Fa	120	B	0.9	0.1	0.0	0.0	some
Ga	120	B	0.0	0.6	0.6	0.4	none
To	120	C	0.8	0.0	0.8	1.0	few
Da	120	C	1.0	0.8	4.5	0.4	many
Ha	120	C	1.2	0.0	2.9	0.3	some
Bo	120	C	0.0	0.0	1.8	0.9	many
Fa	120	C	0.3	0.0	1.3	0.4	some
Ga	120	C	0.4	0.6	2.2	0.4	many
To	120	D	0.6	0.0	0.0	0.9	few
Da	120	D	1.0	0.0	7.5	0.3	many
Ha	120	D	1.7	0.0	5.0	0.1	some
Bo	120	D	0.8	0.0	1.5	0.5	few
Fa	120	D	1.3	0.3	5.0	0.5	some
Ga	120	D	0.0	0.0	1.2	1.0	many
To	120	E	0.8	0.0	0.0	0.4	none
Da	120	E	0.4	0.6	5.0	0.6	few
Ha	120	E	1.6	0.3	7.5	0.4	none
Bo	120	E	0.8	0.3	2.0	0.6	few
Fa	120	E	1.0	0.0	5.0	0.8	none
Ga	120	E	0.2	0.0	0.0	0.6	none

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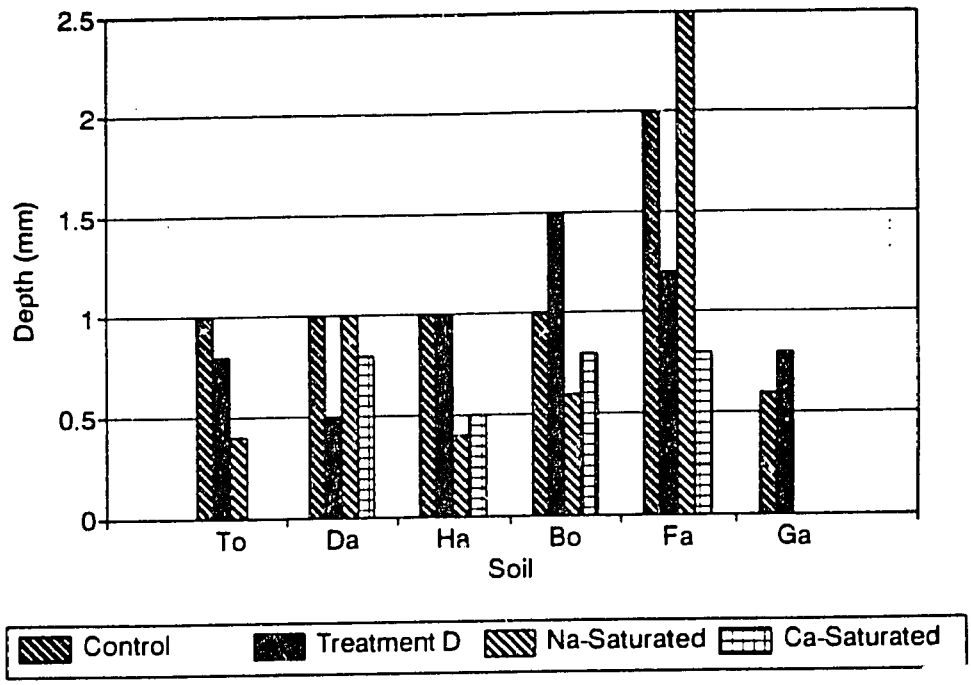

Figure A20. Thickness of S1 layer, 30 minutes of rainfall.

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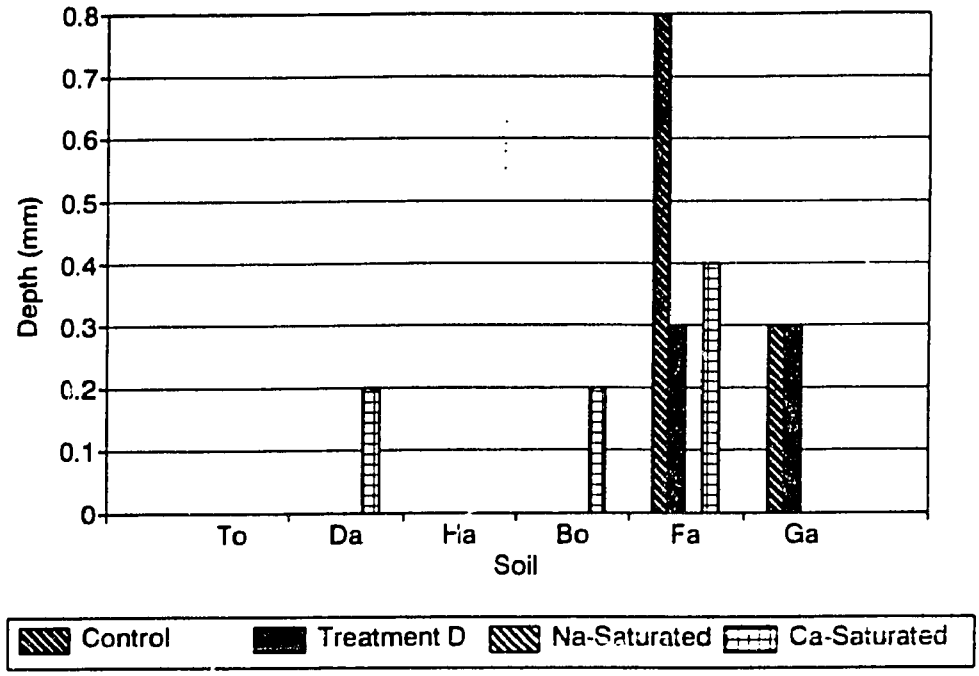

Figure A21. Thickness of S2 layer, 30 minutes of rainfall.

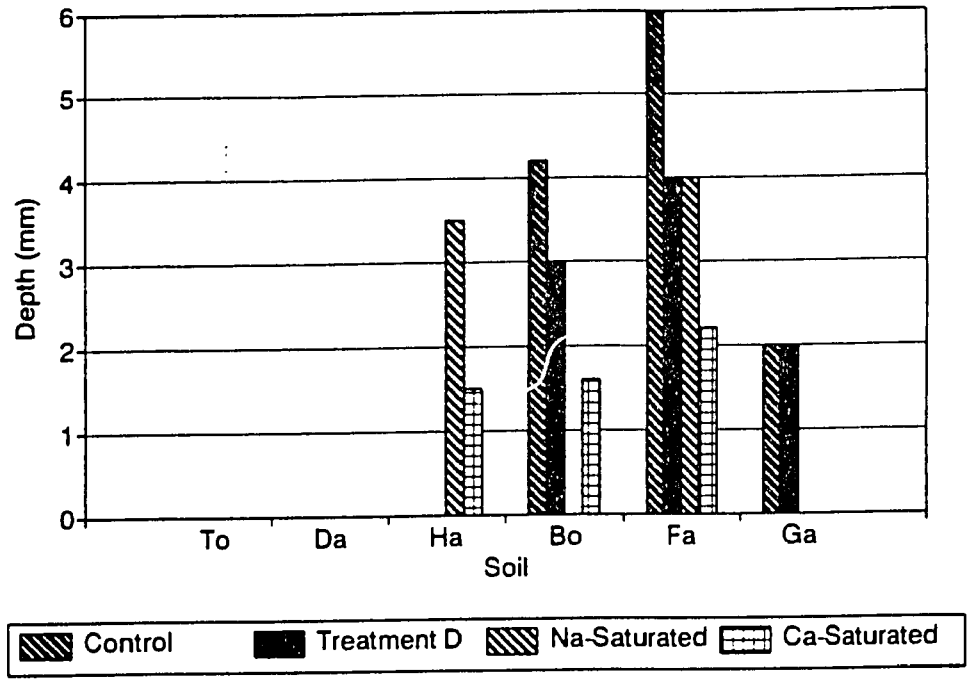

Figure A22. Thickness of S3 layer, 30 minutes of rainfall.

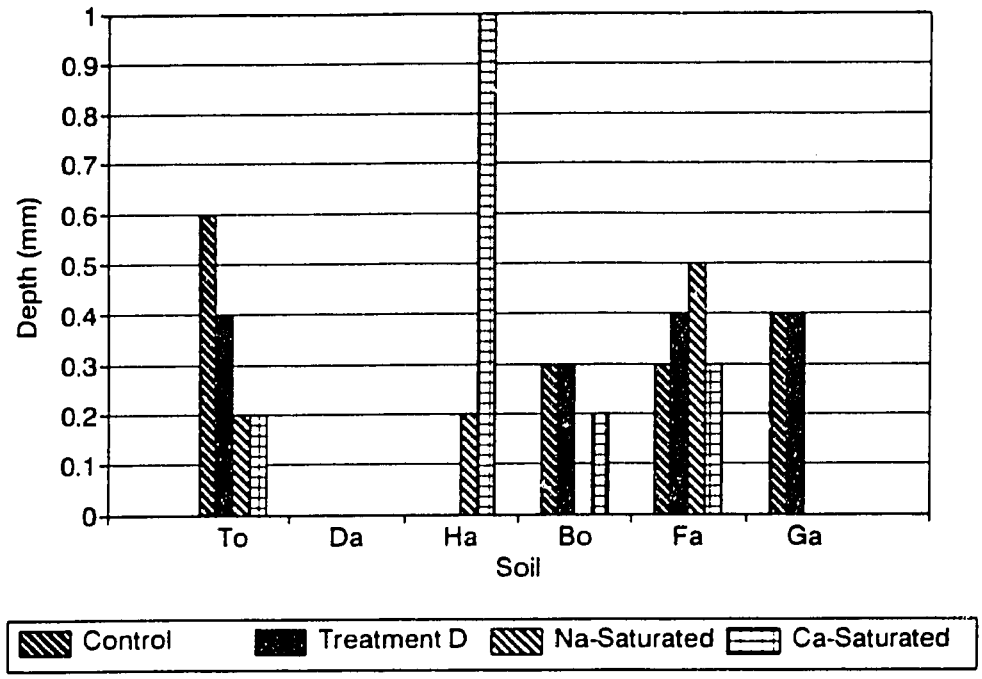

Figure A23. Thickness of S4 layer, 30 minutes of rainfall.

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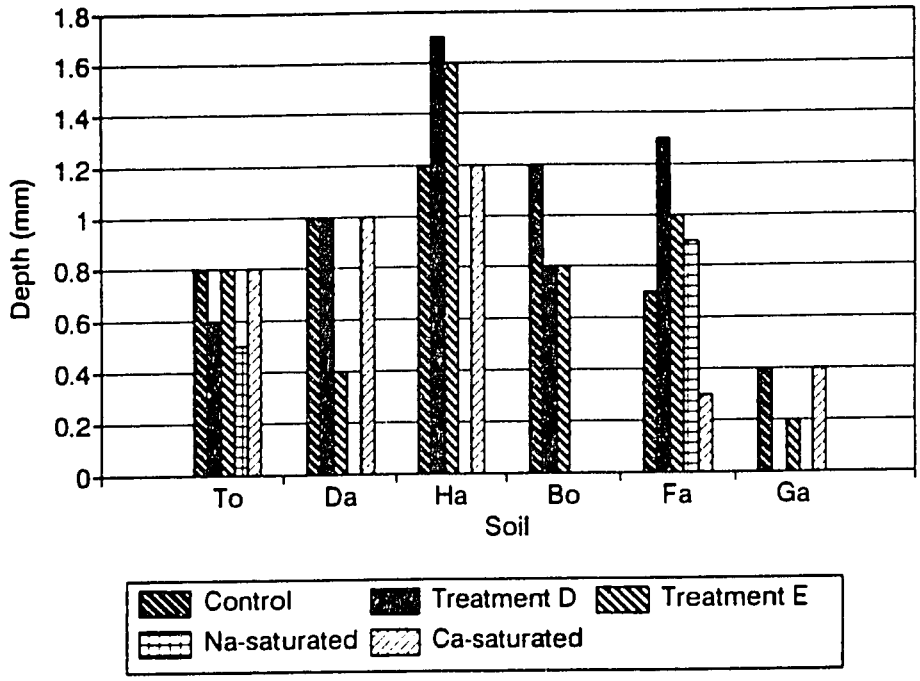

Figure A24. Thickness of S1 layer, 120 minutes of rainfall.

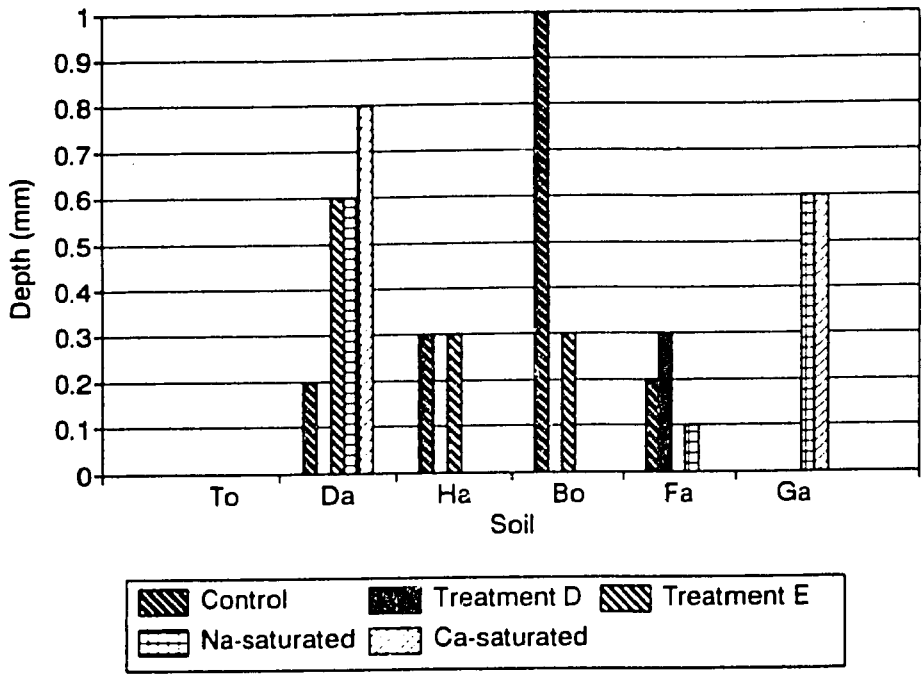

Figure A25. Thickness of S2 layer, 120 minutes of rainfall.

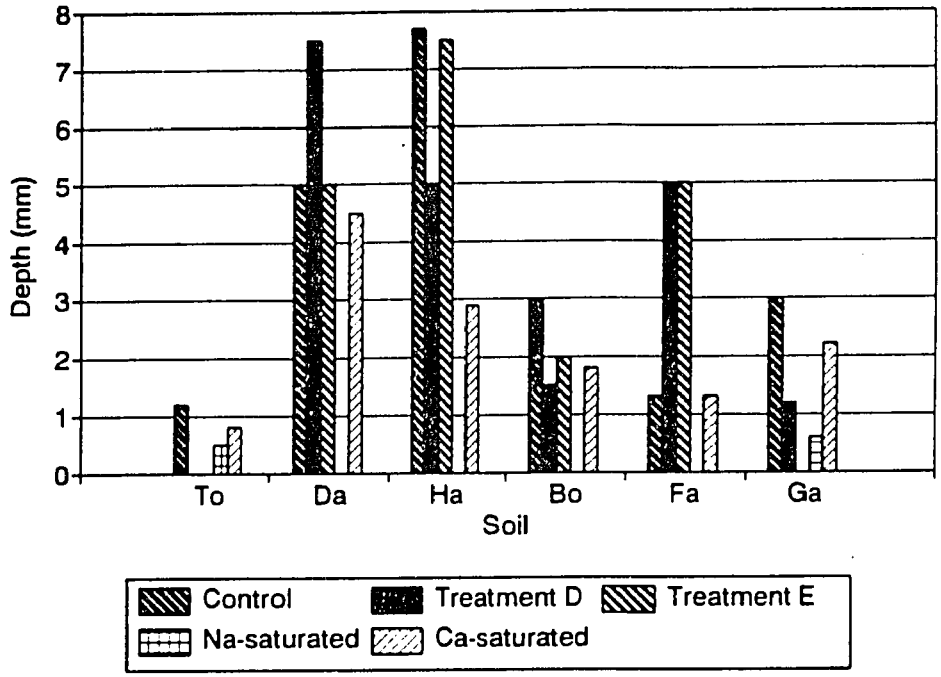

Figure A26. Thickness of S3 layer, 120 minutes of rainfall.

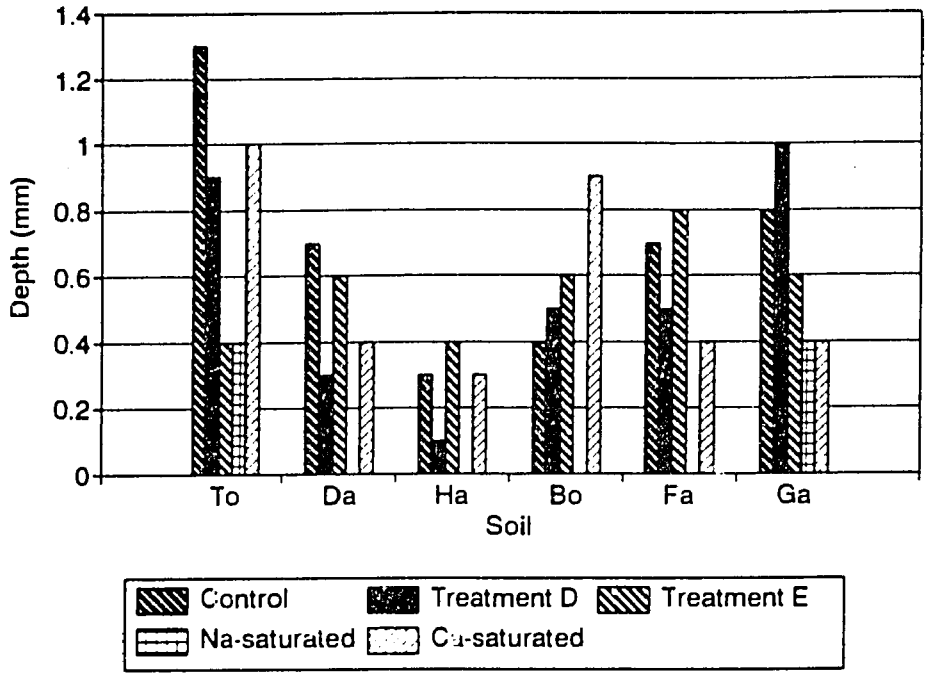

Figure A27. Thickness of S4 layer, 120 minutes of rainfall.

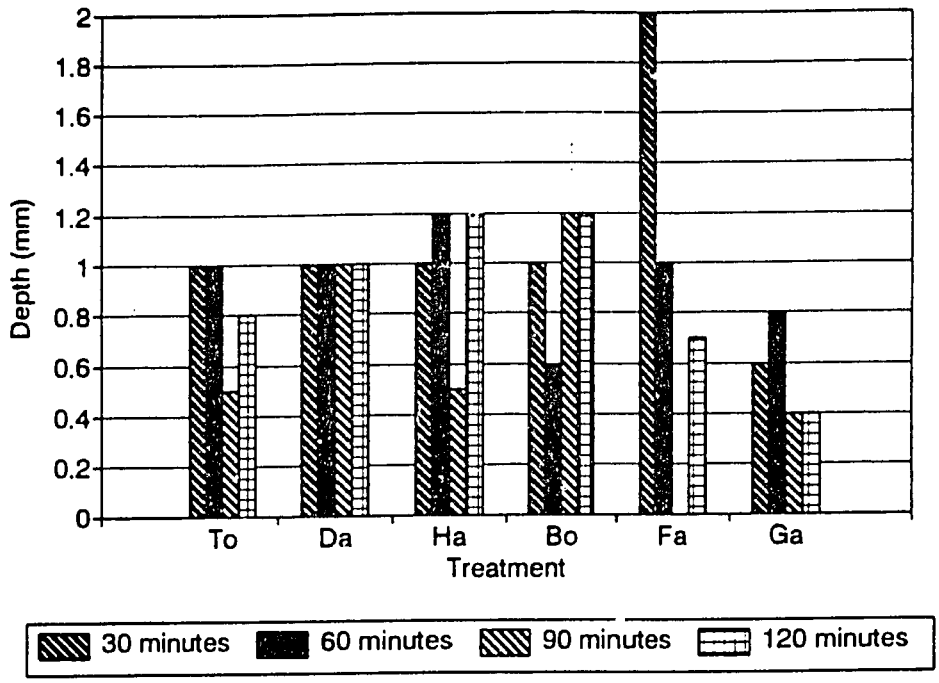

Figure A28. Thickness of S1 layer, control treatment.

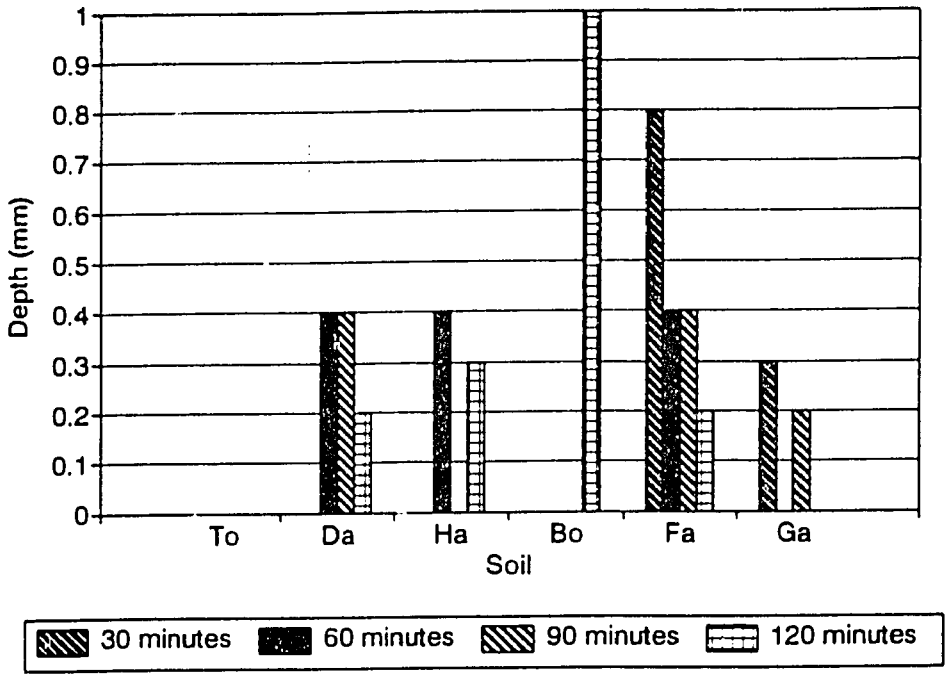

Figure A29. Thickness of S2 layer, control treatment.

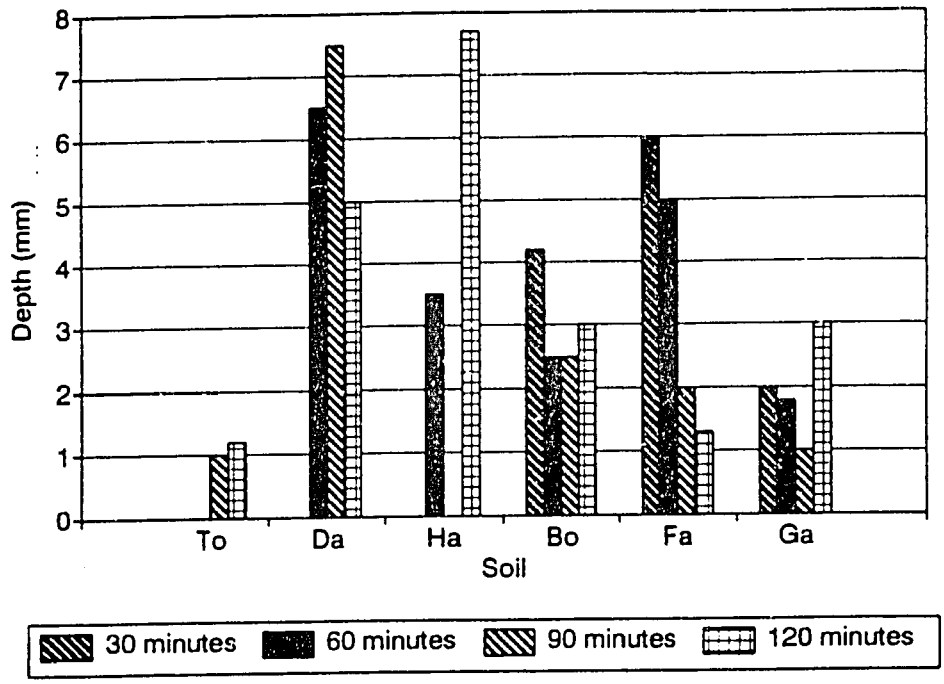

Figure A30. Thickness of S3 layer, control treatment.

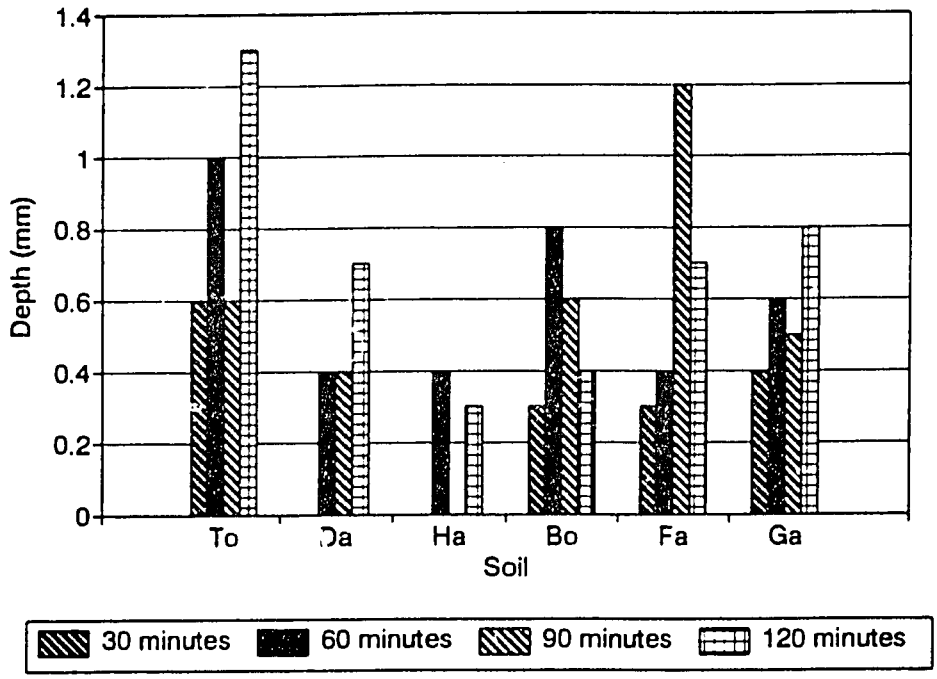

Figure A31. Thickness of S4 layer, control treatment.

VITA

Justin Wayne Heil was born in Elgin, North Dakota on July 23, 1962. He was raised in a large, loving family in Ft. Collins, CO. He first became interested in agriculture by working on his grandfather's farm in North Dakota. He received a B.S. degree from Colorado State University in Agronomy in 1986 and an M.S. from Colorado State University in Soil Science in 1988.

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