



PAÚL ANDRÉS JIMÉNEZ JIMÉNEZ

**FACTORS CONTRIBUTING TO SOIL CRUSTING AND ITS
RELATIONSHIP WITH SOIL AGGREGATE STABILITY IN
AGRICULTURAL LANDS IN SOUTHERN MALI, WEST
AFRICAN REGION**

**LAVRAS – MG
2024**

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Dissertação apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Ciência do Solo, área de concentração em Recursos Ambientais e Uso da Terra, para a obtenção do título de Mestre.

Prof. Dr. Marx Leandro Naves Silva
Orientador

Prof. Dr. Nilton Curi
Coorientador

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**FATORES QUE CONTRIBUEM PARA O ENCROSTAMENTO DO SOLO E SUA
RELAÇÃO COM A ESTABILIDADE DE AGREGADOS DO SOLO EM TERRAS
AGRÍCOLAS NO SUL DO MALI, REGIÃO OCIDENTAL DA ÁFRICA**

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Dr. Marx Leandro Naves Silva
Dr. Diego Tassinari
Dr. Edicarlos Damacena de Souza

UFLA
UFLA
UFR

Prof. Dr. Marx Leandro Naves Silva
Orientador

Prof. Dr. Nilton Curi
Coorientador

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ABSTRACT

This dissertation focused on studying soil crusting in agricultural soils in Southern Mali, as part of an international cooperation project titled "Preservation of Productive Potential in Cotton-Producing Areas in Mali - Cotton Soils", involving the Federal University of Lavras (UFLA). Soil crusting and sealing pose significant challenges in agricultural regions, especially in Sub-Saharan Africa where small-scale farming is prevalent. Soil crusting entails the development of thin, rigid, impermeable layers on the soil surface, leading to reduced water infiltration, increased runoff and erosion, and decreased germination, seedling emergence, and productivity. Various factors such as rainfall intensity, topography, soil attributes, and inadequate soil management influence this process. To understand the factors affecting soil crusting and aggregate stability in Southern Mali, this study aimed to (1) investigate the impact of specific soil attributes (physical, chemical, mineralogical) on soil crust formation, and (2) evaluate soil aggregate stability under agricultural and native vegetation, and assess the relationships between different structural stability indices, soil attributes, and soil crusting susceptibility. Soils from agricultural and native areas in the Sikasso district of Southern Mali were sampled from the top 10 cm and analyzed for various physical, chemical, mineralogical, and micromorphological attributes. Soil aggregate stability was assessed using three methodologies: wet sieving, the High Energy Moisture Characteristic (HEMC) method, and Clay Dispersion. The studied soils exhibited high silt and fine sand contents, and low organic matter leading to significant crusting formation. They displayed a high risk of aggregate disruption and moderate susceptibility to soil crusting. Native vegetation areas showed higher structural stability indices and lower crusting susceptibility compared to agricultural sites. Additionally, a significant negative linear relationship was found between crusting susceptibility and aggregate structural stability indices. To enhance soil aggregate stability, implementing effective management practices is crucial, particularly focusing on cover crops for soil protection and increasing organic matter content.

Keywords: Mali-Africa soil crusting; soil aggregate stability; agriculture;

RESUMO

Esta dissertação teve como foco o estudo do encrostamento em solos agrícolas no Sul do Mali, como parte de um projeto de cooperação internacional intitulado "Preservação do Potencial Produtivo nas Áreas Produtoras de Algodão no Mali - Solos de Algodão", envolvendo a Universidade Federal de Lavras (UFLA). A formação de crostas e o selamento do solo representam desafios significativos em regiões agrícolas, especialmente na África Subsaariana, onde a agricultura em pequena escala é predominante. A formação de crostas do solo envolve o desenvolvimento de camadas finas, rígidas, e impermeáveis na superfície do solo, resultando na redução da infiltração de água, aumento do escoamento superficial e erosão, e diminuição da germinação, emergência de plântulas e produtividade. Vários fatores como intensidade da precipitação, topografia, atributos do solo, e manejo inadequado influenciam esse processo. Para compreender os fatores que afetam a formação de crostas e a estabilidade dos agregados do solo no Sul do Mali, este estudo teve como objetivo (1) investigar o impacto de atributos específicos do solo (físicos, químicos, mineralógicos) na formação de crostas do solo, e (2) avaliar a estabilidade dos agregados do solo sob vegetação agrícola e nativa, e avaliar as relações entre diferentes índices de estabilidade estrutural, atributos do solo, e susceptibilidade à formação de crostas do solo. Solos de áreas agrícolas e nativas no distrito de Sikasso, no Sul do Mali, foram amostrados nos primeiros 10 cm e analisados quanto a diversos atributos físicos, químicos, mineralógicos e micromorfológicos. A estabilidade dos agregados do solo foi avaliada usando três metodologias: peneiramento úmido, o método da Curva Característica de Umidade de Alta Energia (HEMC), e Dispersão de Argila. Os solos estudados apresentaram altos teores de silte e areia fina, e baixo teor de matéria orgânica, levando à formação significativa de crostas. Eles mostraram um alto risco de desprendimento de partículas e uma susceptibilidade moderada à formação de crostas do solo. As áreas de vegetação nativa apresentaram índices de estabilidade estrutural mais altos e menor susceptibilidade à formação de crostas em comparação com os locais agrícolas. Além disso, foi encontrada uma relação linear negativa significativa entre a susceptibilidade à formação de crostas e os índices de estabilidade estrutural de agregados. Para melhorar a estabilidade dos agregados do solo, a implementação de práticas de manejo eficazes é crucial, com foco especial no uso de culturas de cobertura para proteção do solo e aumento do teor de matéria orgânica.

Palavras-chave: Encrostamento do solo; Estabilidade de agregados do solo; Agricultura; Mali-África

INDICADORES DE IMPACTO

O estudo sobre a formação de crostas do solo em terras agrícolas no Sul do Mali revela impactos significativos tanto sociais quanto econômicos. O encrostamento do solo representa um desafio crítico para regiões agrícolas, especialmente na África Subsaariana, onde a agricultura de pequena escala predomina. Este fenômeno reduz a infiltração de água, aumenta o escoamento superficial e a erosão, além de prejudicar a germinação, emergência de plântulas e produtividade das culturas. Os resultados indicam que áreas com vegetação nativa apresentam índices mais elevados de estabilidade estrutural do solo e menor suscetibilidade à crostificação, em comparação com áreas agrícolas. Do ponto de vista social, os impactos se concentram na melhoria da segurança alimentar e na sustentabilidade das práticas agrícolas locais. A implementação de práticas de manejo eficazes, como o uso de culturas de cobertura para proteção do solo e aumento do teor de matéria orgânica, pode mitigar os efeitos adversos do encrostamento do solo, beneficiando diretamente os agricultores locais e suas comunidades. Economicamente, a adoção dessas práticas pode levar a um aumento na produtividade agrícola, redução dos custos associados à erosão e maior eficiência no uso da água. Além disso, a pesquisa fornece uma base científica para desenvolver políticas de manejo sustentável do solo, alinhadas aos Objetivos de Desenvolvimento Sustentável da ONU, particularmente os relacionados à agricultura sustentável e à vida terrestre. Além disso, a pesquisa fornece uma base científica para desenvolver políticas de manejo sustentável do solo, alinhadas aos Objetivos de Desenvolvimento Sustentável da ONU, particularmente os relacionados à Fome Zero e Agricultura Sustentável (ODS 2), Ação Contra a Mudança Global do Clima (ODS 13), Vida Terrestre (ODS 15) e Parcerias e Meios de Implementação (ODS 17). A integração dessas práticas com os ODS promove um desenvolvimento agrícola mais equilibrado e sustentável, abordando as necessidades das gerações presentes e futuras.

IMPACT INDICATORS

The study on soil crust formation in agricultural lands in Southern Mali reveals significant social and economic impacts. Soil crusting poses a critical challenge to agricultural regions, especially in Sub-Saharan Africa, where small-scale agriculture predominates. This phenomenon reduces water infiltration, increases surface runoff and erosion, and hinders seed germination, seedling emergence, and crop productivity. Results indicate that areas with native vegetation exhibit higher levels of soil structural stability and lower susceptibility to crusting compared to agricultural areas. Socially, the impacts focus on improving food security and sustainability of local agricultural practices. Implementing effective management practices, such as using cover crops to protect soil and increasing organic matter content, can mitigate the adverse effects of soil crusting, directly benefiting local farmers and their communities. Economically, adopting these practices can lead to increased agricultural productivity, reduced erosion-related costs, and greater water use efficiency. Furthermore, the research provides a scientific basis for developing sustainable soil management policies aligned with the UN Sustainable Development Goals (SDGs), particularly those related to sustainable agriculture and terrestrial life. This integration supports goals such as Zero Hunger and Sustainable Agriculture (SDG 2), Climate Action (SDG 13), Life on Land (SDG 15), and Partnerships for the Goals (SDG 17), promoting a more balanced and sustainable agricultural development that addresses the needs of present and future generations.

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FIRST SECTION

1 INTRODUCTION

Soil, a thin layer of material that covers the Earth's surface, is critical to human survival since it serves as a medium for agricultural production, which accounts for 95% of global food supply (Borrelli *et al.*, 2020). Soil degradation is a major issue in agriculture, with severe consequences for soil health, crop yield, and food security. Soil deterioration, which includes erosion, nutrients depletion, compaction, and crusting, has resulted in a considerable decrease in soil quality and production. As a result, crop yields have decreased in many parts of the world (Lal, 2015).

Soil crusting is progressively gaining recognition as a primary form of soil degradation; the process of crust or seal formation on the soil surface is a prevalent occurrence in numerous cultivated soils globally, especially in arid and semiarid regions. Soil crusts are identified by the development of a thin and compact layer on the soil surface that has lower porosity and higher penetration resistance compared to the underlying soil. This layer is formed due to the disintegration of soil structural units resulting from the impact of raindrops and subsequent drying (Pagliai, 2008). Soil crusts can give rise to a multitude of agronomic and environmental problems. These issues include decreased water infiltration, reduced rainfall effectiveness and irrigation efficiency, poor seedling emergence and inhibited germination, inhibited aeration, surface ponding, increased runoff, and erosion (Laker e Nortjé, 2019).

The susceptibility of soils to crust formation is influenced not only by external factors, like raindrop impact, but also by several intrinsic soil properties such as soil texture, mineralogical composition, organic matter content, cation exchange capacity, and aggregate stability (Laker e Nortjé, 2019; Pagliai, 2008). The risk or probability of soil crusting and sealing formation can be inferred by measuring aggregate stability (Bissonnais, Le, 1996).

The soils in the study area, Siani and Bandiagara II Villages in the Sikasso district in southern Mali, were classified as Plinthosols (Santos *et al.*, 2023), characterized by a subsurface layer of hard and brittle material known as plinthite. Plinthic soils are known for their low fertility and poor water-holding capacity, which makes them challenging for agriculture (Gehring, Keller e Heller, 1992).

The objective of this study was (i) to analyze soil attributes impacting the formation of soil crusts and evaluate some of these factors using indicators such as the structural stability index (StI), particle separability index (PSI), and crust susceptibility index (CSI); and (2) to measure and evaluate the aggregate stability of soils under agricultural use and native

vegetation, and assess the relationships between various indices of soil aggregate stability—such as Geometric Mean Diameter (GMD), Weighted Mean Diameter (WMD), and Wet Aggregate Stability (WAS) derived by the wet sieving method employing two types of sample pre-treatments: without pre-wetting and with slow pre-wetting; Stability Ratio (SR) derived by the High Energy Moisture Characteristic (HEMC) method; and Clay Dispersion Index (CDI)—with soil attributes and the Crusting Susceptibility Index (CSI).

2 LITERATURE REVIEW

2.1 Soil degradation

The term "soil" has numerous meanings, just like many other everyday words. Soil is the natural environment in which plants grow, according to its conventional definition. Another definition of soil is a natural body made up of layers (soil horizons) composed of organic material, air, water, and weathered mineral components. Soil supports 95% of the world's food production and provides ecosystem services like biomass generation, pollutant filtration, and mass and energy transfer between spheres (Borrelli *et al.*, 2017).

Thus, the term "soil degradation" refers to a broad range of changes in soil qualities caused by natural or anthropic factors that alter their structure and quality, such as deforestation and the removal of native vegetation, agricultural practices, overgrazing, overexploitation of vegetation for domestic use, and industrial activities (Gomiero, 2016).

Soil degradation can occur through the following processes: physical (soil sealing, compaction, soil crusting and erosion), chemical (soil organic matter, acidification, and salinization), biological (loss of soil organic matter, loss of biodiversity), and ecological (Ferreira *et al.*, 2022; Lal, 2015). The following elements affect the type of degradation: soil intrinsic features (physical, chemical), climate (precipitation, temperature, evaporation), characteristics of the topography (slope, drainage), and vegetation (Lal, 2015).

Soil physical degradation influences soil porosity, water infiltration and retention, surface runoff, soil compaction, variations in land surface temperature, soil organic matter content, and other changes in soil structure (Rabot *et al.*, 2018). Chemical degradation of the soil is characterized by a decrease in soil fertility, a decrease in cation exchange capacity (CEC) due to an increase in aluminum content, soil salinization, acidification, alkalinization, and lack of plant nutrients (Richmond, 2015).

Soil biodegradation is assessed through soil organic carbon (SOC) content. In fact, the loss of native vegetation reduces SOC because intensive cultivation degrades its quality.

Ecological degradation is the fourth type of soil degradation that results from the combination of physical, chemical, and biological degradation. The disruption of the ecosystem carried on by alterations to the soil's organic matter, and elemental cycling can be used to identify ecological deterioration (Lal, 2015; Nascimento *et al.*, 2022).

The factors that contribute to soil degradation are varied and complicated, including biophysical factors like land use, cropping systems, farming practices, deforestation; socioeconomic factors like poverty; and political factors like government policies, political instability, and conflicts (Barrett e Bevis, 2015).

2.1.1 Soil physical degradation

The destruction of the quantity and structure of soil pores and peds is referred to as soil physical degradation. It is a lengthy process that involves several steps, starting with structural degradation and concluding with the differential loss of smaller particles through erosion (Omuto, 2008).

Physical degradation gradually degrades the soil pores, which transports nutrients, air, and moisture to support plant biomass production. Also, it influences soil surface features, which have an adverse effect on water infiltration, the ability of the land to absorb heat from the atmosphere, and the overall aesthetic appeal of the landscape (Feddema, 1998).

2.2 Soil crusting

Soil crusting is a globally recognized phenomenon that occurs in a wide range of soils and environmental conditions and is increasingly recognized as one of the most important forms of soil degradation. Crust formation at the soil surface is a common occurrence in several cultivated soils around the world, especially in arid and semiarid regions (Valentin, 1991).

Soil crusts are recognized by the formation of a thin and dense layer at the soil surface that is less porous and more resistant to penetration than the underlying soil layers. Their thickness typically ranges from 1 mm to 5 cm. (Valentin e Bresson, 1997).

Soil crusts are changes in the soil surface caused by natural events such as raindrop impacts and subsequent drying (Pagliai, 2008). Soil crust formation begins when rainfall seals the soil surface by breaking down soil aggregates into fine particles, leading to the filling of pores. When these features dry, they become more compact, rigid, and brittle than the underlying soil materials. They also change the size, number, and arrangement of the pores. Frequently, a wet crust is referred to as a seal, formed by the same process as soil crusts. Thus,

crust formation is the result of the consolidation, drying, and hardening of the seal (Bissonnais, Le, 1996). As a result, crusting leads to a variety of agronomic and environmental problems, such as: decreased effectiveness of rainfall and irrigation, poor seedling emergence, enhanced runoff, restricted infiltration, surface ponding, and erosion (Almajmaie *et al.*, 2017).

There are three main categories of crust: chemical crust, biological crust, and physical crust. Chemical crusts are formed due to salt incrustations on the soil surface in arid and semi-arid regions. Biological soil crusts are complex aggregations of soil particles and organisms, including cyanobacteria, algae, lichen, and moss. They serve as an organizing factor in drylands and are a critical component of desert ecosystems (Reeve *et al.*, 2023).

Physical soil crusts are created when water and, to a lesser extent, wind interact with soil particles on bare soil, and may be structural or depositional. Therefore, there are two types of physical soil crusts: (i) structural crusts, which are created by the slumping and slaking caused by the impact of raindrops, and (ii) erosion and depositional crusts, which are formed by the laterally transported and deposited finer soil particles (Badorreck, Gerke e Hüttl, 2013).

Structural crusts: The formation of structural crusts occurs in-situ and results from the action of rainfall, which causes physiochemical aggregate dispersion and fine particle obstruction of soil pores. Three steps are involved in the creation of soil structural crusts. First, as a result of the impact of the raindrops, fine and coarse soil particles begin to segregate when exposed to rainfall. Following the infiltration of rainwater into the soil, the small particles cause pore spaces to become clogged, resulting in the formation of a thin and dense layer on the soil surface (Chen *et al.*, 1980). Based on morphological and physical characteristics, structural crusts were described and categorized into the following sub-groups: slaking crusts, sieving crusts, infilling crusts, and coalescing crusts (Valentin e Bresson, 1992).

Slaking crusts are composed of a fine-particle layer and rougher sections of partially broken-down clods. They consist of a thin (1 mm to 5 mm thick) dense layer with a distinct border from the layer underneath it. Slaking crusts develop when soils have a high enough percentage of clay (15-20%) to retain and compress air during wetting, causing aggregates to breakdown. Moreover, the procedure may entail swelling and infilling. Slaking crusts can form even when the soil is shielded from the impact of rainfall because they are primarily created by wetness (Valentin e Ruiz Figueroa, 1987).

Sieving crusts: The formation of sieving crusts is caused by the impact of raindrops on sand and sandy-loam soils, where the aggregates are very fragile. This sorting of the soil particles concentrates the coarser particles at the top and the finer particles in the deeper

positions. The textural differentiation results from a sieving process. Sand and sandy-loam soils are most commonly affected by this kind of crusting (Valentin e Bresson, 1997).

Infiltrating crusts typically occur on medium-textured (loam) soils as a result of the impact of raindrops that erode the top of surface layer aggregates, causing silt particles to separate and void space to be sealed to a depth of a few millimeters below the surface. A distinct textural composition is what better defines these crusts (Valentin e Bresson, 1997).

Coalescing crusts are created in wet soils by the drop energy driving force when the soil material is in a viscous state. They frequently have a thickness of up to 20 mm, are packed more densely than the underlying horizon, and exhibit a gradual transition with the underlying layer, for which they are sometimes referred to as transitional microhorizons. Porosity is low in the upper few millimeters of the crust and gradually rises with depth (Valentin e Bresson, 1997).

Erosion crusts are distinguished by their smooth surfaces. They are the result of structural crusts being eroded by water. Erosional crusts form as a result of the erosion of sieving crusts, which occurs when the loose coarse textured upper layer is stripped away by overland flow, leaving the underlying layer of fine particles at the surface. They are plasmic layers that are 100 μm to 1 mm thick, dense, and coherent (Valentin e Bresson, 1997).

Depositional crusts are formed by a sedimentary layer that lies on top of a previously formed structural crust. The sedimentary layer can be very thick, 5 to 10 mm or more. Depositional crusts form after a structural crust seals the surface and concentrates detached particles from eroded clods or ridges in inter clods micro deposition or furrows via micro-scale run-off (Valentin e Bresson, 1997).

The depositional crusts were divided into runoff and still depositional crusts. Runoff depositional crusts are distinguished by alternating very thin layers with contrasting textures. These crusts can develop to be several centimeters thick, especially if they form between two ridges or under furrow irrigation. They almost always overlie structural crusts, with which they have sharp boundaries.

Still depositional crusts are composed of densely packed and well-sorted particles, the size of which increases with depth. The vertical particle size distribution, with coarser particles at the bottom and finer particles at the top, the result is a grain size distribution opposite to that observed in sieving structural crusts.

2.3 Soil crust formation processes

Several processes, which occur simultaneously or in succession, may be involved in crust formation. Crust formation occurs as a result of two mechanisms: (i) physical

disintegration of soil aggregates surface caused by wetting of the dry aggregates and/or the impact energy of the raindrops, followed by compaction of the disintegrated aggregates; and (ii) physicochemical dispersion of soil clays, which then migrate into the soil with the infiltrating water, clogging pores instantly beneath the surface and forming a low permeability layer (Laker e Nortjé, 2019). The following mechanisms are presumed to play an important role in the formation of soil crusts:

Wetting is important in loamy and clayey soils. When dry soil is quickly moistened, air is trapped, and pressure differences disturb soil aggregates. Simultaneous swelling (depending on clay mineralogical composition) aids the disruption process even more. Oversaturation of the top few millimeters of soil causes suspended, dispersed clay to fill the particle interstices, forming a structural type surface crust. Slaking of dry aggregates can occur independently of impact forces due to rapid wetting (Bullard *et al.*, 2018).

Raindrop impact is the major cause of crusting on sandy soils. Sandy aggregates are quite fragile and thus easily break down when impacted by raindrops. In a series of steps or processes, the physical impact of raindrops, soil particle detachment, displacement, clogging of soil pores, reduction in infiltration, increased runoff, and erosion are some of the ways that raindrops break down soils. Rainfall characteristics like amount and intensity of rainfall, along with raindrop size and velocity at impact, determine how much raindrop impact affects crust formation (Bullard *et al.*, 2018; Fan *et al.*, 2008).

Runoff: One of the main factors causing soil movement, transporting sediments, and accounting for the redistribution of rainfall water is runoff. Runoff causes particle lateral movement as well as sorting. It promotes the development of a dense, laminated crust known as a "runoff depositional" crust. It can have a significant impact on water regimes and vegetation patterns, especially in arid and semi-arid environments where incoming rainfall is unsatisfactory to maintain an ongoing plant cover (Bissonnais, Le, Bruand e Jamagne, 1989).

Slaking has been identified as the primary mechanism responsible for aggregate breakdown in clayey soils. When large, dry soil aggregates are abruptly submerged in water, they disintegrate into smaller microaggregates, a process known as slaking (Emerson, 1964).

Slaking happens when aggregates are not strong enough to withstand the internal stresses brought on by rapid water absorption. Internal stresses are caused by the different ways that clay particles swell, by air that is trapped in soil pores and that escapes, by the quick release of heat during wetting, and by the mechanical action of water movement (Emerson, 1964). Disaggregation by raindrop impact or slaking may also be followed by clay dispersion (Almajmaie *et al.*, 2017).

Clay dispersion is frequently linked to soil crusting and the obstruction of conducting pores in both surface- and subsurface-level soils (Almajmaie, Abbas, Hardie, Doyle, *et al.*, 2017). The amount of clay dispersion is determined by the following factors: (i) clay charge characteristics; (ii) cation ratios, particularly the exchangeable sodium percentage (ESP); (iii) the electrolyte concentration of infiltration water; and (iv) attractive forces between colloidal particles. Elevated concentrations of exchangeable potassium may also cause soil dispersion, high exchangeable potassium percentage (EPP) soils are more likely to experience soil disaggregation than low EPP soils (Agassi, Morin e Shainberg, 1985).

Drying: As the water content is reduced during drying, the surface crust's strength increases exponentially. Due to variations in compression forces between the microlayers, platy structures may crack or curl. This phenomenon is pronounced in the case of sedimentary crust.

2.4 Soil properties related to crust formation

There are some soils that have a greater tendency to develop crusts than others. Soil crusting susceptibility is influenced not only by external factors, such as raindrop impact through the mechanisms described above, but also by intrinsic soil factors.

Soil texture is a key factor affecting soil crusting, which refers to the relative proportions of different soil particle sizes (e.g., sand, silt, clay, gravel, and cobble), playing a crucial role in determining the likelihood of soil crusting. The size, shape, and surface area of soil particles are important factors that can affect the hydraulic properties of the soil, which in turn can affect the formation of soil crusts. (Bullard *et al.*, 2018).

Several studies have shown that soil texture influences crust formation. Soil with a high clay content tends to form more stable aggregates, which can result in a lower rate of crust formation (Pagliai, 2008). However, the effect of clay mineralogy on crust formation is complex and can vary depending on the type of clay minerals present, which modify this generalization (Valentin e Bresson, 1997).

Soils with a medium texture, characterized by a clay content of less than 20%, are highly prone to the formation of crusts. In the case of soils with an extremely high sand content, it is likely that the quantity of clay, upon dispersion, is inadequate to block the conducting pores situated at the surface of the soil (Al-Naser, 2018).

The tendency of a soil to form a crust depends on aggregate stability (Bissonnais, Le, 1996). There is a positive correlation between aggregate stability and clay content, clay fraction in soils with >20% clay content acts as a binding agent, increasing soil aggregate stability and preventing crust formation caused by raindrop impact. However, in soils with <20% clay

content, the clay acts as a substrate for crust formation, reducing the hydraulic conductivity of the crust. Several research works have indicated that the soil texture with higher susceptibility to surface crust formation comprises roughly 90% sand and 10% silt or clay content (Wakindiki e Ben-Hur, 2002).

Clay minerals, in particular, play an important role in soil crust formation as they influence soil structure, soil water retention, and nutrient availability. The likelihood of soil crusting is linked to the stability of its structure, which tends to increase with a rise in the amount of clay present in the soil. The clay particles act as a binding agent, serving as cement that binds soil particles together into aggregates. Hence, the stability of these aggregates against the erosive impact of rainfall should also amplify as the clay content of the soil rises. The most common clay minerals found in soil crusts are smectites, micas, illites, chlorites, and kaolinites (Wilson, 1999).

Soils that contain smectite, illite, and micaceous minerals have higher tendency to develop crusts, while soils with kaolinite minerals are less susceptible to crusting (Alnaser e Alkhafagi, 2020).

The dispersal capacity of soils with illite minerals is moderate and can occasionally surpass that of soils with smectite minerals. In soils where 2:1 clay is prevalent; the stability of aggregates is primarily influenced by polyvalent metal-organic matter complexes that act as bridges connecting the negatively charged clay platelets. On the other hand, the stability of soils dominated by 1:1 clay is primarily linked to the inherent binding capacity of the minerals themselves. The potential for aggregate slaking and crust formation in soils can be ranked in descending order based on their clay mineralogy as follows: smectitic > illitic > kaolinitic (Oades e Waters, 1991).

Organic matter (OM) plays a vital role as a binding agent in soil, thereby promoting the stabilization of soil aggregates. As a result, it is expected that OM will increase the soil's resistance to crust formation. (Bissonnais, Le, 1996). It is known that the effect of organic matter on soil aggregation is contingent on its size. Specifically, micro-aggregates consisting of primary mineral particles are connected via bacterial, fungal, and plant residues, while macro-aggregates are formed by the linking of micro-aggregates through temporary binding agents such as polysaccharides derived from plants (Six, Elliott e Paustian, 2000). The stability of sandy loam soil aggregates and the likelihood of crust formation were found to increase as the organic matter (OM) content fell below the critical threshold value of 3% (Guerra, 1994).

Clay dispersion is considered one of the factors that contribute to the formation of soil crusts and the reduction of soil infiltration rates. The ability of saturating cations to disperse

and flocculate colloidal materials makes them a crucial factor in the formation of soil crusts (Pagliai, 2008). Monovalent cations such as Na^+ and K^+ are considered dispersing agents, while bivalent cations such as Ca^{2+} and Mg^{2+} are considered non-dispersive cations. Soils that contain a significant amount of polyvalent cations, such as Fe^{3+} , Al^{3+} , and Ca^{2+} , have been shown to enhance soil aggregation (Wakindiki e Ben-Hur, 2002).

A widely recognized fact is that a significant proportion of exchangeable sodium (high ESP), and sometimes exchangeable magnesium, promotes the dispersion of clay, leading to increased crusting. Historically, there has been a simplistic perspective that significant adverse impacts of sodium (Na) on soil physical properties, such as crusting and reduced infiltration caused by clay dispersion, only occur when the Exchangeable Sodium Percentage (ESP) surpasses 15% (Pagliai, 2008).

2.5 Effects of agricultural practices on soil crusting formation

Soil agricultural practices, including tillage operations, crop selection, the application of fertilizers, and pre-emergent herbicides, are expected to exert notable direct and indirect impacts on soil crust properties and formation (Bajracharya e Lal, 1998).

Soil quality is intricately linked to soil structure, and a significant portion of the environmental harm observed in intensive arable lands, including erosion, desertification, and vulnerability to compaction, can be attributed to the deterioration of soil structure. Soil structure is a crucial soil property with significant implications for crop productivity. It directly influences root penetration depth, soil water storage capacity, as well as the movement of air, water, and soil biota (Pagliai, Vignozzi e Pellegrini, 2004).

Soil tillage is considered one of the most significant soil management practices that affect soil crusting. The primary objectives of soil tillage are to prepare a suitable seedbed for planting and to manage weeds effectively. Tillage exerts dual effects on crusting. On the one hand, it disrupts the formation of crusts, which is often necessary in semi-arid regions where these crusts impede the emergence of seedlings. Conversely, tillage can contribute to the development of crusts by generating small aggregates that are more susceptible to rapid breakdown compared to larger clods (Pagliai, Vignozzi e Pellegrini, 2004).

The process of tillage erosion is directly affected by the compaction resulting from machinery traffic. Soil compaction has been identified as one of the main processes leading to the degradation of soil structure, resulting in a reduction of soil porosity and compromising the physical quality of agricultural lands. This type of degradation occurs as a result of increased traffic intensity and applied load (Dias Junior *et al.*, 2005).

The impact of fertilizers and herbicides for weed control on the surface structure of agricultural soils can yield contradictory results. The various weed management systems employed in crop cultivation, including pre- and post-emergence herbicide applications, have the potential to modify the soil's chemical, physical-hydraulic, and biological characteristics. These alterations subsequently impact the compressive behavior of the soil and, consequently, its load-bearing capacity (Araujo-Junior *et al.*, 2008).

Constant use of the weed management system with pre-emergence herbicide exposes the soil to raindrop impact, which enhances the soil surface sealing, making it more susceptible to erosive agents. Consequently, the disintegration and loss of water absorption capacity due to pore clogging cause greater surface runoff, which intensifies erosion (Faria *et al.*, 1998). The direct impact of raindrops and the wetting and drying cycles, as well as the herbicide's action as a structure-disrupting agent, cause particle rearrangement, resulting in the formation of water-impermeable layers due to clay particle migration that obstructs the pores (Araujo-Junior *et al.*, 2008).

2.6 Soil structure

The environment and edaphic conditions are significantly influenced by soil structure, which also plays a critical role in controlling soil function. Therefore, soil structure exerts a profound influence on the physical, chemical, and biological processes that underpin the life-sustaining functions of soils. Soil structure can be broadly divided into two categories: those that focus on the size, shape, and arrangement of solid soil particles and those that also consider the size, shape, and arrangement of both solid particles and pores within the soil (Six *et al.*, 2000).

Soil structure is defined as "the size, shape, and arrangement of solids and voids, continuity of pores and voids, their capacity to retain and transmit fluids and organic and inorganic substances; and their ability to support vigorous root growth and development". It can also be defined as the arrangement of individual soil particles into secondary particles or aggregates and the porous space associated with them (Lal, 1991).

Aggregates are secondary particles that originate from the binding of primary mineral particles with various organic and inorganic substances. Aggregation occurs as a consequence of particle rearrangement, flocculation, and cementation (Duiker *et al.*, 2003).

The formation of soil structure is influenced by several factors, including the presence of cations (which can form ionic bonds), interactions between clay particles (such as adhesion between clay and water particles and electrostatic attraction between positively charged edges

and negatively charged faces of clay lattices), the impact of soil organic matter (which can form organic bonds), and the activity of biological components like roots, soil fauna, and microorganisms. Furthermore, environmental conditions, soil management practices, plant-mediated processes, and fluctuations in moisture content due to drying and wetting cycles also contribute significantly to the development and maintenance of soil structure, especially in agricultural soils (Six *et al.*, 2004).

In agriculture, a well-structured soil is extremely important because it promotes maximum plant growth by offering good aeration, effective water movement and storage, optimal biological activity, stability, and decreases susceptibility to erosion and surface crusting (Papadopoulos, 2011). Having a favorable soil structure with high aggregate stability is crucial for improving soil fertility, increasing agronomic productivity, enhancing porosity, and decreasing erodibility and surface crusting (Bronick e Lal, 2005).

2.6.1 Evaluation of soil structure

The soil structure can be qualitatively evaluated by studying morphological aspects that allow for distinguishing different types of structures. These aspects include shape (single-grained, granular, platy, angular, subangular, prismatic, columnar, and massive), size (very fine, fine, medium, coarse, and very coarse), and degree of development of the structure (structureless, weak, medium, and strong) based on the force required to break it (Bronick e Lal, 2005; Rabot *et al.*, 2018). From a quantitative point of view, soil structure can also be assessed using structural indices such as bulk density, total porosity, pore size distribution, consistency, and aggregate stability (Papadopoulos, 2011).

An effective method for evaluating the soil structure in agricultural soils involves characterizing it based on three key aspects: structural form, which refers to the geometric shape of the soil particles and aggregates; structural stability, which refers to the ability of the soil to resist external forces that may cause breakdown or deformation of soil structure; and structural resilience, which refers to the capacity of the soil to recover its original structure after disturbance (Rabot *et al.*, 2018).

Direct methods for assessing soil structure involve various techniques such as measuring aggregate size and stability, visually examining the structural form, and observing morphological structural features through microscopy or image analysis using tools like CT scans, electrical resistivity tomography, and thin sections (Pagliai, Vignozzi e Pellegrini, 2004; Young, Crawford e Rappoldt, 2001).

Measuring and evaluating changes in soil structure, both qualitatively and quantitatively, serves as a fundamental basis for studying physical soil degradation processes and devising effective soil management strategies (Pagliai, Vignozzi e Pellegrini, 2004).

2.6.2 Soil aggregate stability

Aggregate stability refers to the ability of soil aggregates to resist external stresses, including tillage, swelling and shrinking processes, and rapid wetting from raindrops that can lead to aggregate disintegration. Assessing soil aggregate stability is an effective approach to evaluating its structural condition. It is a parameter that evaluates the ability of soil aggregates to withstand disintegration or fragmentation into smaller particles, which can lead to the development of soil crusts. Measuring aggregate stability can also provide valuable insights into the probability or risk of a soil forming surface crusts (Amezketta *et al.*, 2003; Bissonnais, Le, 1996).

There are several techniques available to measure soil aggregate stability, and each of these methods replicates a particular mechanism of aggregate disintegration (Papadopoulos, 2011). Various methods have been used to determine aggregate stability, including wet sieving, simulating raindrop energy impact, ultrasonic dispersion, or the breakdown of aggregates after sudden immersion in water and clay dispersion (Bissonnais, Le, 1996) .

The most commonly used technique for measuring aggregate stability is wet sieving. Nevertheless, this particular method has faced criticism for not considering all potential mechanisms contributing to aggregate breakdown, particularly the impact of raindrops. Additionally, it has been observed that this method tends to place excessive emphasis on breakdown through slaking, while not allowing enough time for dispersion and flocculation to occur (Almajmaie *et al.*, 2017).

Le Bissonnais (1996) introduced the wet sieving procedure known as the "unified framework," which incorporates the utilization of water and ethanol as wetting agents, as well as varying rates of wetting (both slow and fast), and the application of mechanical energy through shaking following pre-wetting.

Another technique for measuring aggregate stability is called High Energy Moisture Characteristic (HEMC), which involves the analysis of the moisture release curve at extremely low suctions. This method assesses the water retention capacity of soil aggregates under high-energy conditions, providing valuable information about their stability and resistance to disaggregation (Pierson e Mulla, 1989). This technique's primary advantage over conventional methods lies in the implementation of a controlled wetting process, where only hydration

energy and trapped air are responsible for the breakdown of aggregates. The methodology involves calculating an index of aggregate stability by measuring changes in the distribution of pore sizes resulting from rapid and slow wetting of the aggregates (Levy e Mamedov, 2002; Silva *et al.*, 2014).

Field aggregates can undergo disintegration due to dispersion processes. The dispersion of clay can be evaluated through qualitative and quantitative assessments, wherein the turbidity or concentration of suspended clay is compared under varying conditions of fluid composition or agitation intensity. These tests provide valuable insights into the extent of clay dispersion within soil aggregates (Almajmaie *et al.*, 2017).

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SECOND SECTION – ARTICLES

ARTICLE 1 - FACTORS GOVERNING CRUSTING FORMATION IN SOILS IN SOUTHERN MALI, WEST AFRICA: EVALUATION OF SUSCEPTIBILITY INDICES

*Article prepared in accordance with the guidelines of Catena Journal

Abstract

In Southern Mali and neighboring semi-arid regions of the Sahel, soil crusting and sealing are common and significant phenomena for people who depend on agriculture for their livelihoods. Soil crusting and sealing involve the formation of thin, hard, impermeable layers on the soil surface, leading to reduced water infiltration, increased runoff and erosion, as well as decreased germination, seedling emergence, and productivity. This process depends on factors such as rainfall intensity, topography, soil attributes, and inadequate soil management. Here, we aimed to analyze soil attributes that impact the formation of soil crusts and evaluate some of these factors using the following indicators: structural stability index (StI), particle separability index (PSI), and crust susceptibility index (CSI). Soils from agricultural and native areas in Southern Mali were sampled and examined for various physical, chemical, mineralogical, and micromorphological attributes. The studied soils were marked by high silt and fine sand contents, low organic matter and vegetation cover, and inadequate soil management practices leading to prolonged periods of bare soil, contributing significantly to crusting formation. Kaolinitic clays and low Ca^{2+} and Mg^{2+} contents apparently did not affect crusting formation. The PSI revealed a high risk of aggregate disruption in both agricultural and native lands. Conversely, the StI demonstrated that native lands sustained a limited risk of structural degradation, while agricultural soils exhibited a higher risk to soil crusting. Finally, the CSI indicated moderate levels of susceptibility to soil crusting. The conspicuous presence of Fe nodules may increase soil susceptibility to degradation. The adoption of sound management practices with a primary focus on using cover crops for soil protection and increased organic matter is essential.

Keywords: Soil sealing, soil mineralogy, soil degradation, indicators, soil micromorphology.

1. Introduction

Soil surface sealing and crusting is a globally relevant phenomenon that occurs in a wide range of soils and environmental conditions, particularly in regions with arid and semi-arid climates. It is one of the most important forms of soil physical degradation (Levy, 2011; Sumner and Miller, 1992; Valentin, 2005). Soil surface sealing and crusting formation in agricultural lands poses a significant challenge for farmers in Southern Mali, West Africa, decreasing soil quality and crop yields, with substantial economic losses (Picard et al., 2005; Santos et al., 2023).

Soil crusts are thin, compact mineral layers formed on the soil surface, ranging in thickness from 1 mm to 50 mm (Evans and Buol, 1968), and are less permeable and less prone to root penetration than underlying soil layers (Valentin and Bresson, 1997). They typically form after aggregate disruption and dispersion under direct rainfall impact or excessive irrigation with large water drops, followed by the subsequent deposition processes and drying (Pagliai, 2008). Soil sealing and crusting present both agronomic and environmental challenges. Soil sealing leads to a decreased infiltration rate and moisture in subsoils, reduced groundwater recharge, increased runoff, and favors rill and gully erosion (Almajmaie et al., 2017; Tarchitzky et al., 1984; Wang et al., 2023). When the crust is formed, seed germination and root penetration are restricted, ultimately leading to reduced crop productivity (Manyevere et al., 2015; Pagliai, 2008; Valentin, 1995).

The susceptibility of soils to crusting and sealing is influenced by various interconnected factors. External factors include environmental variables like climate conditions, rainfall characteristics, and topographical features (Laker and Nortjé, 2019; Valentin, 2018). Additionally, susceptibility to sealing and crusting is higher on bare soil or low vegetation cover, and under intense land management practices, such as conventional tillage (Graef and Stahr, 2000; Sanogo et al., 2022; Valentin, 1995). Soil crusting is also influenced by intrinsic soil factors such as soil type, texture and clay mineralogy, closely linked to soil parent material, as well as contents of soil organic matter and exchangeable cations. These internal factors play a significant role in determining soil susceptibility to physicochemical changes in surface aggregation (Lado and Ben-Hur, 2004; Manyevere et al., 2015). Soil crusting can occur on soils of various textures, but is particularly common on those rich in silt and fine sand. However, it is not always straightforward to pinpoint a specific texture most prone to crusting, because detailed particle-size distribution of sandy soils is seldom assessed (Alnaser and Alkhafagi,

2020; Badorreck et al., 2013). Conversely, soils with high clay contents tend to form more stable aggregates, not favoring crust formation (Pagliai, 2010).

Clay mineralogy also plays a role, since soils containing smectite and micaceous minerals are more prone to crust formation, while those rich in kaolinite are less susceptible (Nciizah and Wakindiki, 2014; Wilson, 1999). Soil parent material significantly influences soil crusting susceptibility by determining clay mineralogy and texture (Laker and Nortjé, 2019). Exchangeable cations are crucial for soil crusting development due to their ability to disperse or flocculate colloidal materials (Alnaser and Alkhafagi, 2020). Monovalent cations like Na^+ and K^+ act as dispersing agents, ultimately increasing soil crusting while cations such as Ca^{2+} , Mg^{2+} , and Al^{3+} are considered non-dispersive (Levy, 2011). Finally soil organic matter is widely recognized for its role in stabilizing aggregates, preventing dispersion induced by the raindrop impact (Le Bissonnais and Arrouays, 1997; Pagliai, 2010; Sela et al., 2012).

In Southern Mali, soil sealing and crusting is a widespread issue on agricultural lands and is recognized as a major challenge affecting agricultural productivity (Drissa, 2014; Ickowicz et al., 2012). In the region, soil crusting typically occurs during periods of intense rainfall (Graef and Stahr, 2000; Valentin, 2005). However, specific soil attributes that increase vulnerability to crusting remain unknown in the studied areas. This study addresses this knowledge gap by evaluating various susceptibility indices and soil characterization to enhance understanding of crusting formation in this region. Thus, we aimed to: (i) identify the key factors influencing soil crusting formation in Southern Mali; and (ii) evaluate susceptibility indices to quantify the vulnerability of such soils to crusting.

2. Material and methods

2.1 Study area environmental settings

The study area, including the villages of Siani ($5^{\circ}34.8' \text{ W}$, $12^{\circ}10.8' \text{ N}$) and Bandiagara II ($5^{\circ}45.6' \text{ W}$, $11^{\circ}40.2' \text{ N}$), is located in southern Mali (Figure 1), specifically in the Sikasso Administrative Region. The climate can be categorized as Aw in the Köppen/Geiger classification, marked by distinct dry and rainy seasons, typical of a tropical savanna. The rainy season extends from June to October, accounting for the majority of the annual precipitation, with an annual rainfall of $1073 \pm 187 \text{ mm}$ (Coulibaly et al., 2023; Toure et al., 2016). The average temperature in the region is around 27°C , with April the warmest month, with an

average temperature of 35°C and January the coldest, with an average temperature of 25°C (Time and Data, 2023; Toure et al., 2016).

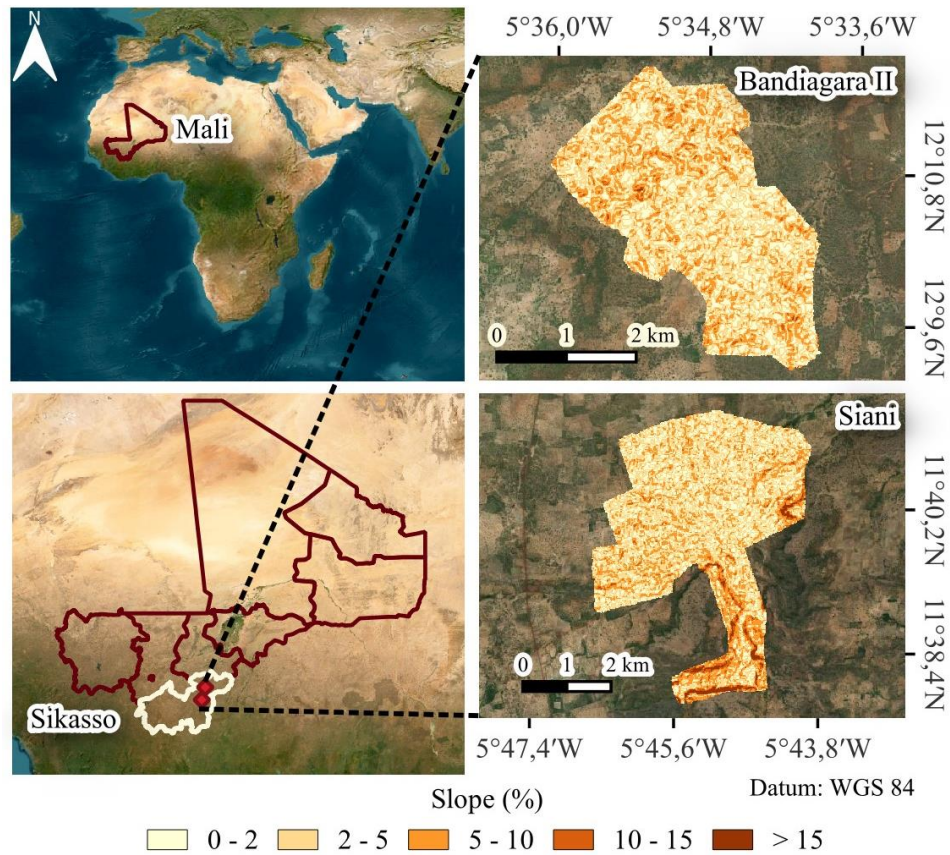


Fig. 1. Location and slope map of the villages of Siani and Bandiagara II villages in the Sikasso Region, Southern Mali, Africa.

Mali is part of the West African Craton, primarily of Archean and Paleoproterozoic ages exceeding 2,000 million years. These ancient formations unconformably underlie Neoproterozoic sediments and the Paleozoic Taoudeni Basin (Toukara et al., 2017). The study area encompasses diverse geological formations, including Precambrian materials such as sandstones, a volcano-sedimentary sequence, intrusive igneous rocks, and thick weathering mantles. Lithostratigraphic units consist of meta-greywackes, metasiltsstones, meta-argillites, slates, and schists. Additionally, Tertiary sedimentary deposits feature a significant lateritic layer, alongside mud, chalk, sandstone, and ferruginous beds (Doumbia et al., 1998; Gómez-Escalonilla et al., 2022; Wane et al., 2021; Wilde et al., 2021). Local soils are widely variable in texture although generally present yellowish colors. Iron-rich Plinthosols (WRB; IUSS Working Group WRB, 2015) stretch from the southern regions into the Sahelian belt (Kidron et al., 2010; Valentin, 1995). Several soil physical limitations occur, including inadequate water infiltration, erosion susceptibility, stoniness, and inherently low fertility (Santos et al., 2023).

The southern part of Mali is its main agricultural area, with cereals as the primary food staples. Rice, maize, sorghum, millet, and peanuts are the main crops for human consumption, while cotton is the prevailing cash crop (Beaman et al., 2023; Sanogo et al., 2022). Two villages in Southern Mali with similar land use and management were selected, Siani and Bandiagara II. In each village, two sites were selected, one under agriculture and another under native vegetation, which were savannas characterized by a mixture of woody (Kalinganire et al., 2007; Sanogo et al., 2022), shrubby (Sotelo Montes et al., 2014), and grassy (Ibrahim et al., 2018; Picard et al., 2005) components. The main woody species are Karité (*Vitellaria paradoxa*), Néré (*Parkia biglobosa*), Baobab (*Adansonia digitata*), and Acacia (*Acacia macrostachya*). The agricultural plots range in size from 5 to 35 ha, where maize, sorghum, millet and peanut crops have been cultivated in annual succession with cotton. Soil preparation, planting, fertilization, crop management, and harvesting operations are carried out manually or with the help of animal traction. The fertilization is made with a NPK formulated (10-10-10), in the amount of 150 kg ha⁻¹ at the time of planting.

2.1. Soil sampling and characterization analyses

A total of 24 composite soil samples from a depth of 0–10 cm were taken, being 17 samples from Siani and seven from Bandiagara II. Soil samples were air-dried and sieved through a 2-mm mesh to obtain the fine earth fraction, used to determine particle size distribution and soil chemical properties. Briefly, the contents of total sand, fine and coarse silt, and clay were determined using the pipette method (Gee and Bauder, 1986). The very coarse, coarse, medium, fine, and very fine sand fractions were further quantified using dry sieving with specific mesh openings (Donagemma et al., 2017). Additionally, four undisturbed soil samples were collected in both regions for micromorphological analysis.

Soil pH was determined in a soil: solution ratio of 1:2.5 in both water and in a 1 mol L⁻¹ KCl solution. Soil organic carbon content was determined using 0.0667 mol L⁻¹ K-dichromate solution and concentrated sulfuric acid (Fontana and Campos, 2017). Exchangeable Ca²⁺, Mg²⁺, and Al³⁺ were extracted using a 1 mol L⁻¹ KCl solution and quantified through inductively coupled plasma atomic emission spectrometry (ICP-OES). Exchangeable Na⁺ and K⁺ were extracted using Mehlich-1 solution and quantified using ICP-OES. The potential acidity (H + Al) was assessed via a volumetric approach involving extraction with a 0.5 mol L⁻¹ Ca-acetate solution at pH 7.0 (Campos et al., 2017).

2.2. Mineralogical and Micromorphological analysis

The mineralogical characterization of soils was determined by X-ray diffraction. It was carried out on 10 samples, five from Siani and five from Banadiagara II. Samples ($\varnothing < 2$ mm) were gently macerated in an agate mortar to obtain homogeneous non-oriented powder, passed through a 0.25 mm sieve. After that, they were analyzed with a Bruker D2 PHASER diffractometer, with $\text{CuK}\alpha$ ($\lambda = 1.54 \text{ \AA}$) radiation, equipped with a Ni filter, using a voltage of 30 kVA and current intensity of 10 mA. The irradiation ranged from 4 to $50^\circ 2\theta$ at $0.02^\circ 2\theta \text{ s}^{-1}$. We obtained the XRD patterns with the Diffract Suite Eva software, and the interpretation of the diffractograms was made with the support of the tables elaborated by Brindley and Brown (1984).

Undisturbed soil samples were collected at the 0–10 cm depth using Kubiena boxes and sealed with PVC film for transport, then air-dried for two months, oven-dried at 40°C for seven days, followed by 60°C for three days, and finally 100°C for 24 hours. This multi-step drying regime aimed to minimize the development of cracks associated with rapid desiccation. Samples were then impregnated with epoxy resin and de-aerated under vacuum to minimize air for three days. The samples were then hardened at 100°C for 4 hours and subsequently cured at 140°C for 4 hours. The resin blocks were cut and mounted onto glass slides to show a vertical soil surface, then cut, lapped and polished again to a $30 \mu\text{m}$ thickness with a diamond saw and lapping wheel (Zinn et al., 2020). Thin section description and interpretation followed Stoops (2003).

2.3. Assessment of soil crusting susceptibility

The soil susceptibility to soil surface crusting focuses on understanding soil crusting as a dynamic process regulated by the soil intrinsic attributes. The *Structural stability index* (StI) indicates the potential for soil structural degradation associated with SOC depletion. It was determined using Equation (1) proposed by Pieri (1992) that quantifies soil aggregate stability based on soil organic carbon, silt, and clay contents:

$$\text{StI} = \frac{1.72 \times \text{SOC}}{\text{Clay} + \text{Silt}} \times 100 \quad \text{Eq. (1)}$$

where SOC is the soil organic carbon content (%) and Clay + Silt is the combined clay and silt content of the soil (%). A $\text{StI} < 5\%$ suggests structural degradation, while a StI between 5 and 7 % indicates a high risk of structural degradation. A StI between 7 and 9 % suggests a low risk

of structural degradation, and a StI > 9 % suggests a sufficient SOC to maintain structural stability (Pulido Moncada et al., 2014).

The *Particle separability index* (PSI) denotes the likelihood of predominantly mineral soils with low organic matter content to undergo particle separation, leading to the formation of a surface sealing when the soil becomes moistened or experiences heavy rainfall. It is calculated as suggested by Florentino (1998) as Equation (2).

$$PSI = \frac{\text{Clay}}{\text{Silt} + \text{Sf} + \text{Svf}} \quad \text{Eq. (2)}$$

where: clay and silt represent the percentage of the respective particle sizes; Sf is the percentage of fine sand particles (100-250 μm); and Svf is the percentage of very fine sand (50-100 μm). PSI values above 2 indicate very low susceptibility; 1 to 2 indicate low susceptibility; 0.5 to 1 moderate susceptibility; 0.2 to 0.5 high susceptibility; and below 0.2 to very high susceptibility.

The *Crusting susceptibility index* (CSI) is applied to evaluate the susceptibility of soils to surface crusting (FAO, 1980), and is determined by the relation between soil organic matter and the fine texture fractions (fine silt, coarse silt, and clay) using Equation (3).

$$CSI = \frac{1.5 \text{Sif} + 0.75 \text{Sc}}{\text{Clay} + (10 \times \text{SOM})} \quad \text{Eq. (3)}$$

where Sif is the percentage of fine silt (2-20 μm), Sc is the percentage of coarse silt (20-50 μm), clay is the percentage of clay, and SOM is the percentage of soil organic matter content. A CSI value ≤ 0.2 indicates no risk of crust formation; values between 0.2 and 2 indicate moderate risk; and values ≥ 2 high risk of crust formation.

2.4. Statistical analyses

Principal Component Analysis (PCA) was used to identify and validate correlations among the studied variables. Pearson correlation ($p \leq 0.05$) was employed to analyze the correlations among groups of variables, including texture, chemical attributes, and susceptibility indices. Fisher's discriminant analysis was used as an inferential tool, based on the discriminations revealed by PCA. Prior probabilities of classification were specified based on sample size for each group (Reg = 0 and Reg = 1), corresponding to the Siani and Bandiagara II regions, respectively. Hit rates of texture, chemistry attributes, and susceptibility indices for samples under agricultural use were computed by generating the confusion matrix. Native vegetation

samples were excluded from discriminant analysis due to their limited number of observations. All analyses were conducted using the software R v.4.3.3 (R Core Team, 2024).

3. Results

3.1. Soil physical and chemical attributes

In the Siani village, the 0-10 cm soil layer of agricultural and native vegetation soils had a sandy loam texture (Table 1). In Bandiagara II, the agricultural soils were loams, whereas native vegetation soils consist of clay loams. More specifically, soils in Bandiagara II presented higher clay and total silt contents, and lower fine sand, than those in Siani.

Table 1

Particle size distribution of surface horizon soils from Siani and Bandiagara II villages, Southern Mali.

Soil Samples	Particle size distribution ¹										Textural class ²
	VCS	CS	MS	FS	VFS	Total Sand	SiC	SiF	Total silt	C	
	g kg ⁻¹										
Siani											
Agricultural	25±13	18±7	79±42	342±10	158±41	622±116	182±83	113±31	294±10	83±39	SL
Native (Savanna)	30±7	42±7	147±1	293±19	99±25	610±99	165±21	90±42	255±21	135±78	SL
Bandiagara II											
Agricultural	16±13	17±7	84±25	277±49	91±23	436±94	286±31	118±50	404±67	160±53	L
Native (Savanna)	26±0.0	19±0.0	75±0.0	225±0.0	74±0.0	419±0.0	173±0.0	130±0.0	303±0.0	279±0.0	CL

Values are mean ± standard deviation. (1) VCS: very coarse sand (2 – 1 mm); CS: coarse sand (1 – 0.5 mm); MS: medium sand (0.5 – 0.25 mm); FS: fine sand (0.25 – 0.10 mm); VFS: very fine sand (0.10 – 0.05 mm); Total sand: (2 – 0.05 mm); SiC: coarse silt (0.05 – 0.02 mm); SiF: fine silt (0.02 – 0.002 mm); Total silt (0.05 – 0.002 mm): silt; C: clay (<0.002 mm). (2) SL: sandy loam; L: loam; CL: clay loam.

In the Siani sites, the average pH for agricultural soils was 5.9, while native vegetation soils had an average pH of 6.05 (Table 2), both framed as slightly acidic. Conversely, in Bandiagara II region, the average pH in agricultural soils was 5.4, lower than the corresponding agricultural soils in Siani. However, the native vegetation soils in Bandiagara II exhibit a significantly higher pH (6.9), framing it as almost neutral.

Among the exchangeable cations, Ca²⁺ and Mg²⁺ were predominant both in Siani and Bandiagara II regions, with higher concentrations under native vegetation areas, which also occurred for K⁺. The soils in both regions, regardless of land use, had a low cation exchange capacity (CEC), with values ranging from 6.3 to 13.7 cmol_c kg⁻¹. However, when comparing

native vegetation areas to cultivated ones, native vegetation areas in both regions have higher CEC values, due to higher organic matter contents. In general, soils exhibited low organic carbon (TOC) contents. In Siani, the average TOC in cultivated soils was 9.2 g kg⁻¹, whereas in native vegetation areas, it was substantially higher (21.9 g kg⁻¹). Similarly, in Bandiagara II, the average organic carbon (TOC) content in cultivated soils was 8.8 g kg⁻¹, while in native vegetation soils, it was notably higher (32.5 g kg⁻¹).

Table 2

Chemical attributes of surface soils from Siani and Bandiagara II villages, Southern Mali, in the Sudano-Sahelian region, West Africa.

Soil Samples	pH	K ⁺	Na ⁺	Ca ²⁺	Mg ²⁺	Al ³⁺	H ⁺ +Al ³⁺	Sum of bases	CEC	Base saturation	Al saturation	TOC
		cmol _c dm ⁻³									%	
Siani												
Agricultural	5.9±0.6	0.3±0.1	0.01±0.003	2.9±1.9	1.2±1.0	0.1±0.001	1.9±0.6	4.4±2.9	6.3±3.1	67.2±11.8	2.8±1.1	9.2±5.7
Native (Savanna)	6.05±0.07	0.7±0.1	0.01±0.003	4.9±1.8	3.0±1.2	0.2±0.1	2.2±0.2	8.6±2.9	10.8±3.1	79.4±4.0	1.7±0.2	21.9±9.0
Bandiagara II												
Agricultural	5.4±0.5	0.2±0.04	0.002±0.002	2.7±1.1	1.3±0.4	0.3±0.003	2.9±0.9	4.2±1.5	7.1±1.2	58.2±12.3	7.7.3±1.3	8.8±2.7
Native (Savanna)	6.9±0.0	0.4±0.0	0.004±0.0	4.8±0.0	3.5±0.0	0.2±0.0	4.9±0.0	8.80±0.0	13.7±0.0	64.2±0.0	2.2±0.0	32.5±0.0

Values are the mean of treatments ± standard deviation. CEC: cation exchange capacity (CEC = Na⁺ + K⁺ + Ca²⁺ + Mg²⁺ + Al³⁺ + H⁺); TOC: total organic carbon.

3.2. Soil mineralogy and micromorphology

X-ray diffraction (XRD) analysis and the diffractograms are presented in Figure 2. The dominant minerals were kaolinite and quartz, although smaller peaks of micas, feldspars, and titanium oxides (anatase and rutile) were also identified. In general, there were stronger peaks of kaolinite in the soil samples from the native vegetation soils, consistent with higher mean clay contents (Table 1). A small peak of gibbsite was noticed in one soil in each village.

Seen in prepared thin sections, soil microstructure in the Siani village consisted of moderately separated and moderately developed subangular blocks featuring planar voids (Figures 3c, 3d). The coarse material is predominantly subrounded and moderately sorted quartz grains as well as opaque ferruginous nodules with sharp boundaries, probably inherited (Figures 3c, 3d). The fine material (micromass) has a clear to nebulous brown-reddish coloration, and exhibits birrefringent fabrics varying from undifferentiated to speckled, (Figures 3a, 3b). The distribution pattern of coarse-to-fine (c:f) components is characterized by an open-spaced to close porphyric type. Pedofeatures included dendritic and typical ferruginous nodules with sizes ranging from millimeters to centimeters.

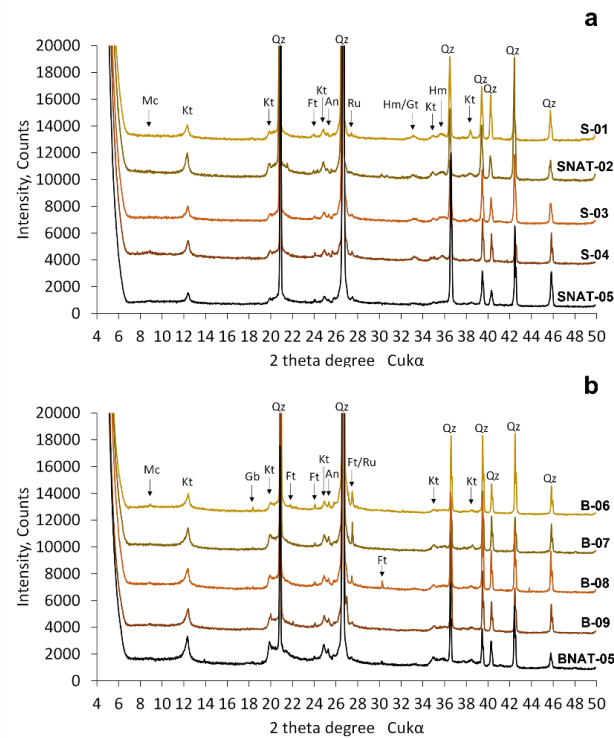


Fig. 2. X-ray diffraction patterns of surface soil horizons from Siani (a) and Bandiagara II (b), Mali, West Africa. Mc: mica; Kt: kaolinite; Gb: gibbsite; Qz: quartz; Ft: feldspar; An: anatase; Ru: rutile; Hm: hematite; and Gt: goethite.

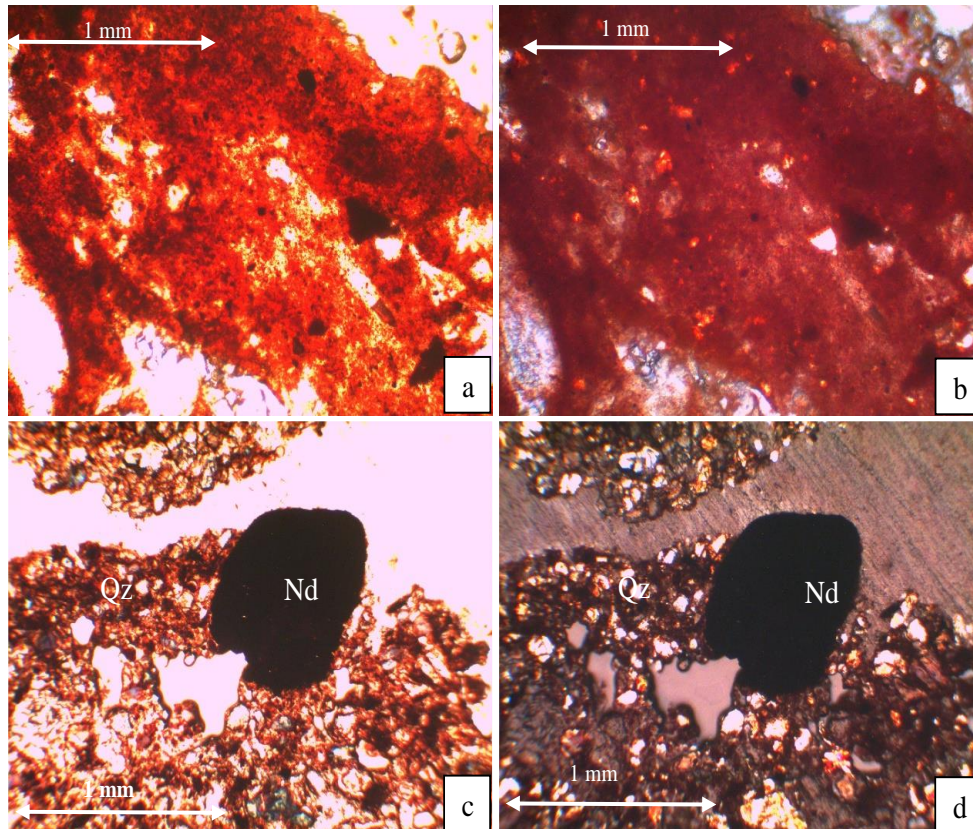


Fig. 3. Soil thin sections from Siani, Mali, West Africa: images (4a: 100x and 4c: 40x) under plain polarized light – PPL and (4b: 100x and 4d: 40x) under cross-polarized light - XPL. Presence of a reddish micromass, coarse quartz material (Qz), and iron nodule (Nd).

3.3. Indices of soil crusting susceptibility and correlation with soil attributes

In the cultivated areas of Siani Village, soil samples showed a PSI <0.2 (Table 3), suggesting a very high risk to particle separability. In contrast, in the native vegetation areas, soil samples showed high susceptibility. In Bandiagara II, agricultural soils had a PSI <0.2, indicating a high risk to particle separability. Conversely, the native vegetation soils had a moderate risk. The StI results in the two villages showed a significant contrast between agricultural and native vegetation soils (Table 3). In agricultural areas, StI values were below 5, indicating structural degradation. Conversely, in native vegetation areas, StI values ranged between 5 and > 9, suggesting a lower risk to no risk of structural degradation.

The CSI, used to assess soil susceptibility to surface crusting, indicated an invariable moderate risk of soil crusting formation based on the average results for both villages and land uses (Table 3). Most (87 %) of the CSI results for agricultural soils of Siani (< 0.2 CSI < 2) indicated a moderate risk of soil crusting formation and 13 % surpassed the CSI threshold of > 2, indicating a high risk of crust formation. In contrast all native vegetation soils displayed a moderate risk to crusting formation. In agricultural soils of Bandiagara II, the SCI results indicated that 83% of the samples have a moderate risk to crusting, while 17% have a high risk. In the native vegetation area, all soils exhibited a moderate risk.

Table 3

Soil crusting susceptibility index mean values in the Siani and Bandiagara II Villages, Southern Mali.

Soil Samples	Particle separability index (PSI)		Structural stability index (StI)		Crusting susceptibility index (CSI)	
	Value	Risk	Value	Degradation risk	Value	Risk
Siani						
Agricultural	0.1±0.1	Very high	4.3±2.2	Very high	1.4±0.6	Moderate
Native (Savanna)	0.2±0.1	High	9.5±1.6	No risk	0.5±0.1	Moderate
Bandiagara II						
Agricultural	0.2±0.1	High	2.8±1.0	Very high	1.3±0.5	Moderate
Native (Savanna)	0.5±0.0	Moderate	9.6±0.0	No risk	0.4±0.0	Moderate

Values are the mean of indices± standard deviation.

The results from the principal component analysis (Figure 4), examining the correlation between soil physicochemical attributes, land use types, and soil crusting assessment indices (PSI, StI and CSI), accounted for 63.3 % of the total variance (PC1: 35.6 % and PC2: 28.0 %). The first principal component (PC1), more strongly related to soil organic carbon and sorptive complex (CEC, available nutrients), was positively related to StI and negatively related to CSI,

both indices that consider organic carbon content, whereas PSI was also influenced by the second principal component (PC2), which was mainly defined by sand and silt contents. In addition, the Pearson correlation matrix between soil physicochemical attributes and the indices used to assess soil crusting are shown in Figure 5.

The PSI results showed a negative correlation with the total sand content (Figure 5a) and a positive correlation with exchangeable cations Al^{3+} , Mg^{2+} , and CEC as well as with TOC (Figure 5b). The StI results indicated a positive correlation with coarse sand content (Figure 5a) as well as with exchangeable Ca^{2+} and Mg^{2+} , CEC and the sum of bases (Figure 5b), and a negative correlation with coarse silt. The CSI index exhibited a negative correlation with coarse sand (Figure 5a), as well as with exchangeable Ca^{2+} and Mg^{2+} , CEC and the sum of bases (Figure 5b).

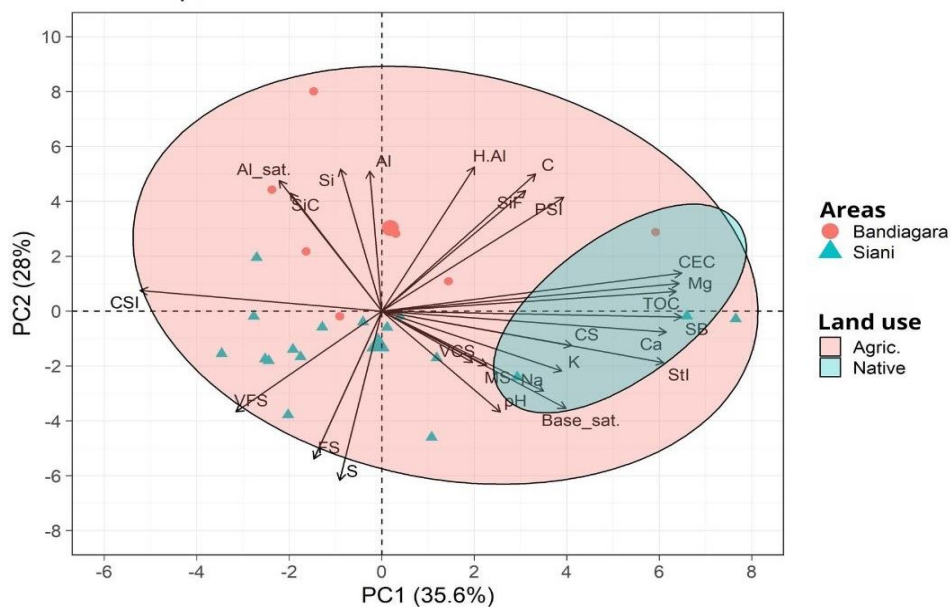


Fig.4. Principal component analysis of soil physical and chemical attributes and indices for assessing soil crusting susceptibility (PSI, StI, and CSI) of the different land uses in Southern Mali, West Africa.

The results in Table 4 were obtained from Fisher's discriminant analysis. The classifier exhibited estimated sensitivity rates of approximately 100% (precision and accuracy) for texture variables, 88 and 100% (precision) and 90% (accuracy) for chemical variables, and 88 and 80% (precision) and 87% (accuracy) for index variables. The similarity among these rates provides statistical evidence supporting the classifier generated by Fisher's discriminant analysis as possessing reasonable discrimination.

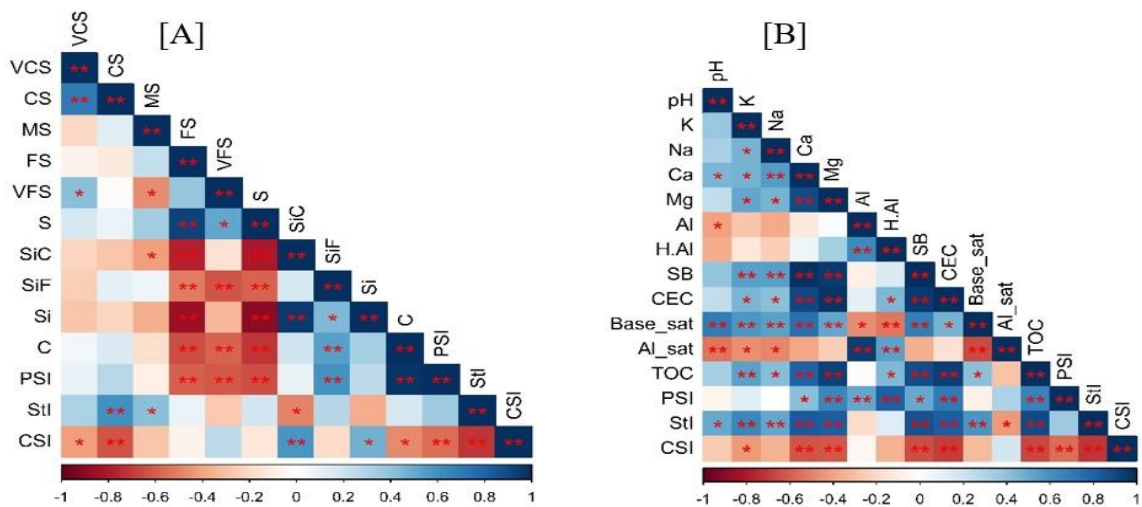


Fig.5. Pearson correlation analysis of soil physical (a) and chemical (b) attributes with indices for assessing soil crusting susceptibility (PSI, StI, and CSI) in Southern Mali, West Africa. Significance levels: ** ($p \leq 0.01$) and * ($p \leq 0.05$).

Table 4

Classification of the regions obtained by Fisher's discriminant analysis, considering the a priori classification probabilities defined by Reg 0 ($p = 0.73$) – Siani – and Reg 1 ($p = 0.27$) – Bandiagara II, Mali, West Africa.

Texture variables				
Classification	Region	Predicted		Producers precision
		Reg 0	Reg 1	
Observed	Reg 0	15	0	100%
	Reg 1	0	6	100%
Total	N=21	15	6	
Global hit (accuracy)	100%			
Chemical variables				
Classification	Region	Predicted		Producers precision
		Reg 0	Reg 1	
Observed	Reg 0	15	0	88%
	Reg 1	2	4	100%
Total	N=21	17	4	
Global hit (accuracy)	90%			
Index susceptibilities variables				
Classification	Region	Predicted		Producers precision
		Reg 0	Reg 1	
Observed	Reg 0	16	1	88%
	Reg 1	2	4	80%
Total	N=23	18	5	
Global hit (accuracy)	87%			

4. Discussion

4.1. The influence of soil attributes on soil crusting formation

The vulnerability of soils in the southern region of Mali to crust formation is influenced by various soil attributes such as texture, mineralogy, organic matter, and exchangeable cations, along with environmental conditions. Surface soils in Siani and Bandiagara II were identified as sandy loam and loam, respectively, with a clay content of less than 135 and 270 g kg⁻¹. According to Watt and Valentin (1991), soils with < 200 g kg⁻¹ clay content exhibit a high susceptibility to crusting. In recent studies that assessed crusting susceptibility for the semi-arid Mediterranean region, sandy loam and loam were framed as textures with moderate and high-risk levels, respectively (Karamesouti et al., 2023).

The texture of Malian soils is predominantly represented by silt and sand (particularly fine sand), their sum averaging around 91% in Siani and 83% in Bandiagara II. Various research studies conducted across multiple African regions, including Côte d'Ivoire (Lafforgue and Naah, 1976), Mali, and Niger (Valentin, 1991), have consistently shown that soil textures highly prone to surface crust formation generally consist of approximately 90% sand and 10% silt or clay content. This textural composition is reflected in a high risk of particle separability (PSI), making soils in this region more vulnerable to disaggregation into individual particles and promoting dispersion during rainfall and runoff, thus increasing susceptibility to crust formation.

The total organic carbon content varied across land uses within the studied areas, agricultural sites showed an average content of less than 1 % while native vegetation soils below 3 %. Fullen (1991) observed that loamy sand soils with TOC content below 1 % are susceptible to both crusting and erosion, findings consistent with those in the studied agricultural soils. In contrast, Guerra (1994) identified 2 % TOC as a critical threshold for sandy loam soils, a level comparable to that observed in the soils of the studied areas. The difference in TOC content between agricultural and native land uses in the studied area was approximately 1.5%. This is clearly reflected in the structural stability index, indicating that the organic matter content in agricultural soils is insufficient to maintain good structural stability. As a result, they are susceptible to crust formation.

In the soils of Siani and Bandiagara II villages, Ca²⁺ was the predominant cation in the exchange complex, with a lesser amount of Mg²⁺ (Table 2), particularly higher in soils under native vegetation; and both are considered flocculating ions. Conversely, cations considered dispersive of clays, such as Na⁺ (Levy, 2011; Valentin, 1995) are very low to nil. In some cases,

the presence of exchangeable Mg can lead to clay dispersion, increasing the likelihood of soil crusting. Studies in South Africa have identified a critical Mg:Ca ratio threshold, indicating significant clay dispersion when the ratio ranges between 1.5:1 and 3:1, or even when it exceeds 1:1 (Laker and Nortjé, 2019). However, in the soils of Siani and Bandiagara, the Mg:Ca ratio was less than 1, suggesting that Mg is not contributing to increased susceptibility to soil crusting.

The studied soils predominantly consist of primary minerals like quartz but also secondary Fe oxide nodules in the coarse fraction (Fig. 3), and kaolinite, goethite and hematite in the clay fraction (Fig. 2). This composition is about the same as reported by Santos et al. (2023) in the same region. It is recognized that smectites, compared to illite (clay micas) and kaolinite, are more prone to dispersion and crusting (Alnaser and Alkhafagi, 2020; Frenkel et al., 1978; Levy and Van der Watt, 1988). However, in the studied soils 2:1 minerals are likely much less abundant than kaolinite and Fe oxides (Fig. 2), so it can be safely concluded that clay mineralogy is not a significant factor promoting crusting.

The micromorphological evidence of ferruginous nodules, ranging from millimeters to centimeters (Fig. 3), indicates the considerable influence of plinthite or laterite as part of the soil parent material, since nodule features such as smooth outlines and abrupt borders suggest an inherited character rather than current formation in situ. In fact, plinthites and Fe concretions are prominent features in many southern Mali soils (Santos et al., 2023). The abundance and large size of the nodules suggest prolonged, extensive weathering and leaching processes (Butt and Bristow, 2013; Ye et al., 2017) under a warm, moist climate, resulting in accumulation of Fe nodules. The vulnerability of soils to crusting in the studied region is perhaps aggravated by the prevalent low-gradient terrain and the likely presence of subsurface impermeable layers of plinthic soils. In the Sahel, Valentin (1995) indicated that soils derived from schists, which are common in the studied region, tend to be richer in silt, generally revealing severe crusting problems.

4.2. Indices for assessing susceptibility to soil crusting based on soil attributes

The PSI results for Siani and Bandiagara II indicated a moderate to very high risk of particle separation, attributed to the high fine sand and silt contents. However, in the native vegetation soils of Bandiagara II, where the clay content was higher, the risk of particle separability decreased to moderate. The PSI confirms that crust formation is influenced by the stability of its structure, which typically improves with higher clay content.

The StI results showed a clear difference in structural degradation risk between agricultural and native vegetation soils in both areas. Agricultural soils exhibited a substantial structural degradation index, while native areas maintained sufficient soil structure due to their organic matter content. Although the StI index does not consider the interaction between factors such as soil organic matter and clay mineralogy (Pulido Moncada et al., 2014), it is consistent with the crucial role of low organic matter contents in crust formation risks at the cultivated sites.

The results obtained from the CSI analysis reveal a consistent moderate risk of crusting in all soils, both agricultural and native. A portion of the agricultural soils in both Siani and Bandiagara II exceeded critical levels, indicating an increased probability of crust formation. The susceptibility of Southern Mali's soils to crusting is mainly attributed to their high proportions of silt, fine and very fine sand contents, along with the limited presence of organic matter, especially in agricultural soils

Conclusions

The susceptibility of soils to crusting in the Villages of Siani and Bandiagara II is influenced by various soil attributes such as high contents of fine sand, very fine sand, silt, and low clay contents, and low organic matter content.

The low carbon organic content in the cultivated soils can be most attributed to: 1) naturally limited organic matter stabilization due to low clay contents in soils 2) inadequate soil management practices and nutrient depletion, resulting in low plant cover and low organic inputs to soils, which ultimately has a deleterious effect in soil structure and thus in aggregate disruption and crusting. StI results indicated that native vegetation soils had a low risk of structural degradation, while agricultural soils exhibited a high risk, implying increased susceptibility to soil crusting.

The local environmental settings, coupled with inadequate soil management practices adopted, such as prolonged bare soil exposure during the dry season and limited coverage under crops such as cotton, and excess animal grazing during the wet season, significantly contribute to the development of soil crusting. These findings indicate that improvements are possible if management changes towards increased plant cover and organic matter inputs, reachable by liming and better fertilization practices and cultivation, can enhance the structural stability. The increments in vegetation cover must also protect the soil surface from heavy rain impacts and thus mitigate crusting risks.

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ARTICLE 2 - ASSESSING SOIL AGGREGATE STABILITY IN SOUTHERN MALI: A KEY INDICATOR OF SOIL CRUSTING SUSCEPTIBILITY

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Abstract

Soil crusting poses a pervasive challenge to agriculture and environmental functions, manifesting across diverse soil and climatic contexts. Notably, cultivated soils in the southern region of Mali, situated within the Sahel area of West Africa, exhibit heightened sensitivity to crusting formation. The genesis of soil crusting primarily stems from the disintegration of soil aggregates and detachment of soil fragments induced by rainfall; hence, susceptibility to crusting formation can be inferred from aggregate stability measurements. This study aimed to measure and evaluate the aggregate stability of soils under agricultural use and native vegetation and to assess the relationships between various indices of soil aggregate stability—such as Geometric Mean Diameter (GMD), Weighted Mean Diameter (WMD), and Wet Aggregate Stability (WAS) derived by the wet sieving method employing two types of sample pre-treatments: without pre-wetting and with slow pre-wetting; Stability Ratio (SR) derived by the High Energy Moisture Characteristic (HEMC) method; and Clay Dispersion Index (CDI)—with soil attributes and the Crusting Susceptibility Index (CSI). Soil aggregates were collected from a depth of 0 to 10 cm at 24 sites in the Sikasso district of Southern Mali. These samples were analyzed for particle size and chemical attributes, including exchangeable cations and soil organic carbon (TOC). The relationships between aggregate stability and soil properties were examined using Spearman correlation and principal component analysis (PCA). Additionally, the link between aggregate stability and crusting susceptibility was evaluated using linear regression analysis. The texture of the majority of soils in the study area was sandy loam. The results indicated the following: (1) Sites with native vegetation exhibited higher values in structural stability indices and lower crusting susceptibility compared to agricultural sites. (2) Soil aggregate stability indices such as GMD, WMD, WAS, and SR showed a positive correlation with soil properties that enhance aggregation, including TOC, Ca^{2+} , Mg^{2+} , Al^{3+} and CEC. Conversely, CDI was negatively associated with these properties. The CSI showed a positive correlation with coarse silt and very fine sand and a negative correlation with clay, TOC, Ca^{2+} , Mg^{2+} , and Al^{3+} . (3) A negative and significant linear relationship was observed between crusting susceptibility and aggregate stability indices WAS, GMD, MWD, and SR. Conversely, a positive and significant correlation was identified between CSI and CDI. The results demonstrate that SR derived from the HEMC method and CDI are effective indicators for estimating soil crusting in sandy loam soils of Southern Mali, compared to indices derived from the wet sieving method. The agricultural practices utilized in the region have caused physical and chemical degradation of the soils, thereby reducing the structural stability of soil aggregates. Therefore, it is imperative to improve aggregate stability through conservation practices that promote vegetation cover and increase organic matter content.

Keywords: Sealing, Structural stability ratio, Wet sieving, Clay dispersion, HEMC.

1. Introduction

Soil degradation presents a critical challenge in hydrology, environmental management, and agriculture, exerting adverse effects on soil health, crop yield, and food security (Assouline, 2004; Mrubata et al., 2024). Soil crusting contributes to a decrease in soil infiltration rate, an increase in surface runoff, diminished groundwater recharge, and facilitates the occurrence of erosion (Wang et al., 2023). Furthermore, soil crusting inhibits seed germination and restricts root penetration, leading to a reduction in crop productivity (Pagliai, 2008; Valentin, 1995). Soil crusting and sealing are emerging as prominent manifestations of soil degradation, characterized by the formation of dense and thin surface layers. The development of surface crusts or seals primarily occurs in bare soils, especially in extensive semi-arid regions characterized by low soil organic matter content and poor structural stability (Levy, 2011; Valentin, 2005).

Soil crust formation involves several processes that can happen simultaneously or sequentially. It occurs through two main mechanisms: (i) the physical breakdown of soil aggregates' surfaces due to the wetting of dry aggregates or the impact of raindrops, followed by compaction upon drying; and (ii) the physicochemical dispersion of soil clays, which migrate into the soil with infiltrating water, leading to pore clogging beneath the surface and the formation of a low permeability layer (Levy, 2011). The onset and development of this process are impacted by soil organic matter, texture, mineralogy, exchangeable cations, soil cover, and previous moisture conditions (Carmi and Berliner, 2008; Lado and Ben-Hur, 2004; Neave and Rayburg, 2007).

The risk or probability of soil crusting and sealing formation can be inferred by measuring aggregate stability. Aggregate stability refers to the ability of soil aggregates to resist external stresses, including tillage, swelling and shrinking processes, and rapid wetting from raindrops that can lead to aggregate disintegration (Le Bissonnais, 1996).

Assessing soil aggregate stability involves evaluating the ability of soil aggregates to resist disaggregation or fragmentation into smaller particles and microaggregates. These smaller particles can be easily transported by runoff and splash, contributing to the formation of soil crusting and sealing (Amezketta et al., 2003; Le Bissonnais, 1996). The primary mechanisms of aggregate breakdown comprise: (i) breakdown from raindrop impact (Nearing and Bradford, 1985); (ii) slaking by air compression, which is caused by the compression of entrapped air during wetting (Le Bissonnais and Arrouays, 1997); (iii) slaking by differential clay swelling; and (iv) physico-chemical dispersion due to osmotic stress (Shainberg, 1992).

Several methods are available for determining soil aggregate stability. Commonly employed techniques include wet and dry sieving (Kemper and Rosenau, 1986; Le Bissonnais, 1996), the drop test technique (Farres, 1980), the application of ultrasonic energy (North, 1976), and various measures of dispersion. The variety of methods used to measure aggregate stability can be attributed to the presence of multiple breakdown mechanisms and methodological considerations. Among the methodologies available for assessing aggregate stability based on mechanisms of aggregate breakdown associated with surface crusting are aggregate stability in water, clay dispersion and high energy moisture characteristic.

Aggregate stability in water, widely used across various soil types, involves aggregate size classes via wet sieving after subjecting samples to water flow using a mechanical oscillatory shaker. During wet sieving, aggregate breakdown is primarily caused by slaking, with additional effects from water movement during sieve lifting and abrasion on the sieve surface (Almajmaie et al., 2017a). Incorporating slow pre-wetting by capillarity is a common practice to reduce aggregate breakdown caused by air compression within aggregates (Silva et al., 2020).

The formation of crusting and sealing is influenced by clay dispersion because soil aggregates in the field can break down due to dispersion processes. Since clay dispersion can be easily measured in laboratory conditions, it can be used to predict soil susceptibility to crust and seal formation (Levy et al., 1993).

Additionally, one less common method utilized for assessing soil aggregate stability is the High Energy Moisture Characteristic (HEMC) method (Pierson and Mulla, 1989). In this method, the wetting process is accurately controlled, and the energy of hydration and entrapped air are the only forces responsible for the breakdown of aggregates (Levy and Mamedov, 2002). The HEMC method is highly sensitive and efficient at detecting even small differences in aggregate stability (Avanzi et al., 2011).

Most studies conducted in both arid and tropical soil regions have shown that aggregate stability is a widely used physical indicator of soil susceptibility to erosion (Nciizah and Wakindiki, 2015). However, there are few studies directly linking it to crust formation susceptibility (Almajmaie et al., 2017b; Levy and Mamedov, 2002), particularly in West African regions. Nevertheless, there is a lack of consensus regarding the most appropriate aggregate stability indices to employ, and the assessment of soil erodibility and crustability in the field is a laborious, time-consuming, and expensive process (Amézketa, 1999).

The objective of this study was (i) to measure and evaluate the aggregate stability of soils under agricultural use and native vegetation and (ii) to assess the relationships between various indices of soil aggregate stability, such as Geometric Mean Diameter (GMD), Weighted Mean Diameter (WMD), Wet Aggregate Stability (WAS), Clay Dispersion Index (CDI) and Stability Ratio (SR), with soil properties and Crusting Susceptibility Index (CSI), in land from Southern Mali.

2. Material and methods

2.1. Study area

The study area, including the villages of Siani and Bandiagara II (Figure 1), is located in the southern region of Mali, specifically in the Sikasso district. This area is situated approximately 350 kilometers from the country's capital, Bamako.

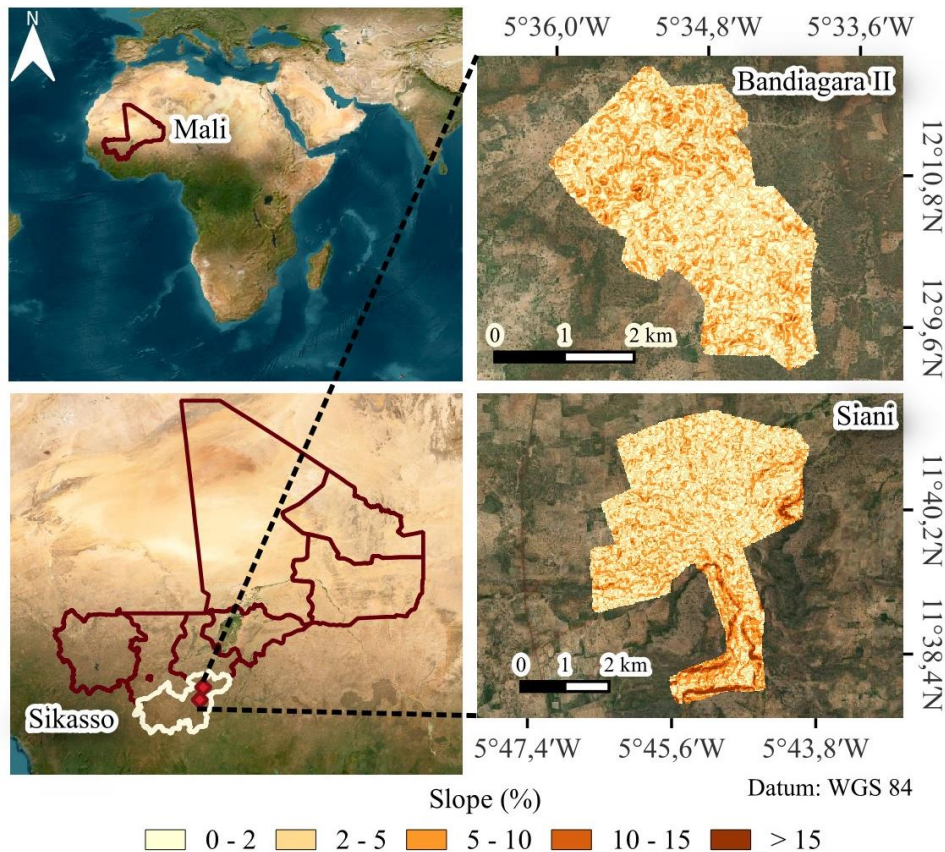


Fig. 1. Location and slope map of Siani and Bandiagara II villages in the Sikasso Province, Southern region of Mali, Africa.

The climate in the southern region of Mali is characterized by distinct dry and rainy seasons, typical of a tropical savanna climate (classified as "Aw" according to the Köppen and Geiger classification system). The average temperature in this region is around 27°C, with April being the hottest month of the year with an average temperature of 35°C and January being the coldest

month with an average temperature of 25°C. The rainy season extends from June to October, accounting for the majority of the annual precipitation, with an annual rainfall of 1073 ± 187 mm (Coulibaly et al., 2023).

Soil samples were collected under two different land uses, with one obtained from agricultural areas and another from areas with native savanna vegetation. The southern Mali region is largely agricultural, focusing on crop production such as maize, sorghum, millet, and peanuts, with cotton as the primary cash crop. Agricultural plots range from 5 to 35 hectares, with manual or animal-driven methods used for soil preparation, planting, fertilization, and harvesting. Basic NPK fertilization is commonly applied.

The vegetation cover in the savanna areas from which soil samples were collected exhibits a diverse array of woody and shrubby species, including Karité (*Vitellaria paradoxa*), Néré (*Parkia biglobosa*), Baobab (*Adansonia digitata*), and Acacia (*Acacia macrostachya*) (Sanogo et al., 2022).

Plinthites highly influence the soils of southern Mali, where massive ferricretes, a general term for ferruginous crusts cemented by iron oxide minerals, are found closer to the soil surface (Gehring et al., 1992). According to Santos et al. (2023), the soils in the study area were primarily classified as Plinthosols with physical limitations such as poor drainage and low inherent soil fertility.

2.2. Soil sampling and analyses

Twenty-four disturbed soil samples were collected at a depth of 0–10 cm from the Sikasso region, specifically from the villages of Siani and Bandiagara II. These samples were then air-dried and sieved for analysis according to each methodology applied. Soil samples were sieved through a 2-mm diameter to obtain the air-dried fine earth fraction (ADFE), which was then used to determine mineral particle size distribution and soil chemical parameters.

Soil texture was determined using the pipette method (Gee and Bauder, 1986) and fine and coarse silt and sand fractions were also analyzed using sieving with specific mesh openings.

Soil pH was assessed using calibrated glass electrodes in a 1:2.5 soil-to-solution ratio with both water and 1 mol L⁻¹ KCl solution. Soil organic carbon content was determined via the wet oxidation method, utilizing a 0.0667 mol L⁻¹ potassium dichromate solution and concentrated sulfuric acid (Fontana and Campos, 2017). Exchangeable cations Ca²⁺ and Mg²⁺, along with exchangeable acidity (Al³⁺), were extracted using a 1 mol L⁻¹ KCl solution, while Na⁺ and K⁺

were extracted with a Mehlich-1 solution, then analyzed via inductively coupled plasma atomic emission spectrometry (ICP-OES) (Campos et al., 2017).

2.3. Crusting susceptibility index (CSI)

The CSI is utilized to assess the susceptibility of soils to surface crusting, as outlined by F.A.O. (1980). It is determined based on the relationship between soil organic matter and the fine texture fractions (fine silt, coarse silt, and clay), as described in Equation 1.

$$CSI = \frac{1.5 Sif + 0.75 Sc}{Clay + (10 \times SOM)} \quad \text{Eq. (1)}$$

where Sif is % fine silt (2-20 μ m), Sc is % coarse silt (20-50 μ m), clay (%) (<2 μ m), and SOM is % soil organic matter content.

A CSI value ≤ 0.2 indicates no risk of crust formation; values between 0.2 and 2 indicate a moderate risk; and a value ≥ 2 indicates a high risk of crust formation.

2.4. Assessment of soil aggregate stability

2.4.1. Wet sieving method

Soil aggregate stability in water was assessed following the methodology adapted by Tisdall and Oades (1979), employing a vertical oscillation apparatus akin to that of Yoder (1936). Soil aggregates ranging from 2 to 8 mm in diameter were utilized, employing two types of sample pre-treatments: (1) without pre-wetting, and (2) with slow pre-wetting achieved through capillary action on moist filter paper. Following pre-treatment, 25 g of soil aggregates per treatment underwent wet sieving for 15 minutes using a mechanical apparatus featuring vertical oscillation within a water-filled container, outfitted with two sets of sieves with mesh sizes of 2.00, 1.00, 0.50, 0.25, and 0.105 mm.

Aggregate size distribution was assessed by calculating the Geometric Mean Diameter “GMD” (Equation 2) and the Weighted Mean Diameter “WMD” (Equation 3) (Kemper and Rosenau, 1986), which were determined based on the percentages of aggregates retained in each size class according to the following equations:

$$WMD = \sum_{i=1}^n (X_i w_i) \quad \text{Eq. (2)}$$

$$GMD = \exp \left[\frac{\sum_{i=1}^n w_p \log(X_i)}{\sum_{i=1}^n w_i} \right] \quad \text{Eq. (3)}$$

where: X_i = average diameter of classes (mm); and w_i = proportion of each class in relation to total weight (%).

Wet aggregate stability (WAS) was measured using the single sieve method (Kemper and Rosenau, 1986). Subsequently, the soil material retained on the sieves of size classes (<2, 2-1, 1-0.50, 0.50-0.25, and <0.25 mm) was collected, oven-dried, and weighed. Sand content was determined using NaOH 1M as dispersing agent. The wet aggregate stability (WAS; %) was then calculated as follows:

$$WAS = \left(\frac{\text{Retained soil material} - \text{Sand}}{\text{Soil sample} - \text{Sand}} \right) 100 \quad \text{Eq. (4)}$$

2.4.2. High Energy Moisture Characteristic “HEMC” Method

To assess soil aggregate stability using the high-energy moisture characteristic (HEMC) technique, detailed instructions are provided by Levy and Mamedov (2002) and Silva et al. (2014). The equipment utilized for this method was developed by Avanzi et al. (2011).

For the experiment, 15 grams of dry aggregates (0.5 –1.0 mm in diameter) were placed in pre-saturated funnels. Thin layers of aggregates were spread on porous material in the funnels (Levy and Mamedov, 2002). The funnel bottom was connected to a peristaltic pump via tubing for rapid (100 mm h⁻¹) and slow (2 mm h⁻¹) wetting. Soil aggregates were thoroughly saturated with standing water. A tension of 0.1 kPa was applied, and moisture values were used to generate soil moisture curves for each wetting rate. Drainage volume and water content were recorded after a 2-minute equilibrium period.

The soil aggregate stability index was determined by comparing the differences in soil water retention curves under fast and slow wetting conditions (Fig. 2a). Key parameters, including Volume of Drainable Pores (VDP), Modal Suction (MS), Structure Index (SI), and Stability Ratio (SR), were evaluated for both native and agricultural land use samples.

A moisture characteristic curve (MC = f (ψ)) was constructed covering a matric potential (ψ) range from 0 to -6 kPa, achieved through the displacement of a water column within the 0.0-0.60 m interval (Fig. 2b) To accurately assess the volume of drainable pores (VDP) and modal suction (MS), the moisture characteristic curves were fitted using a modified van Genuchten model, as proposed by Pierson and Mulla (1989).

The VDP corresponds to the area under the moisture characteristic curve and above the dotted baseline. The MS represents the matric potential (ψ , J kg^{-1}) at the peak of the moisture characteristic curve ($d\theta/d\psi$), where θ denotes the water content (kg kg^{-1}) (Fig. 2a).

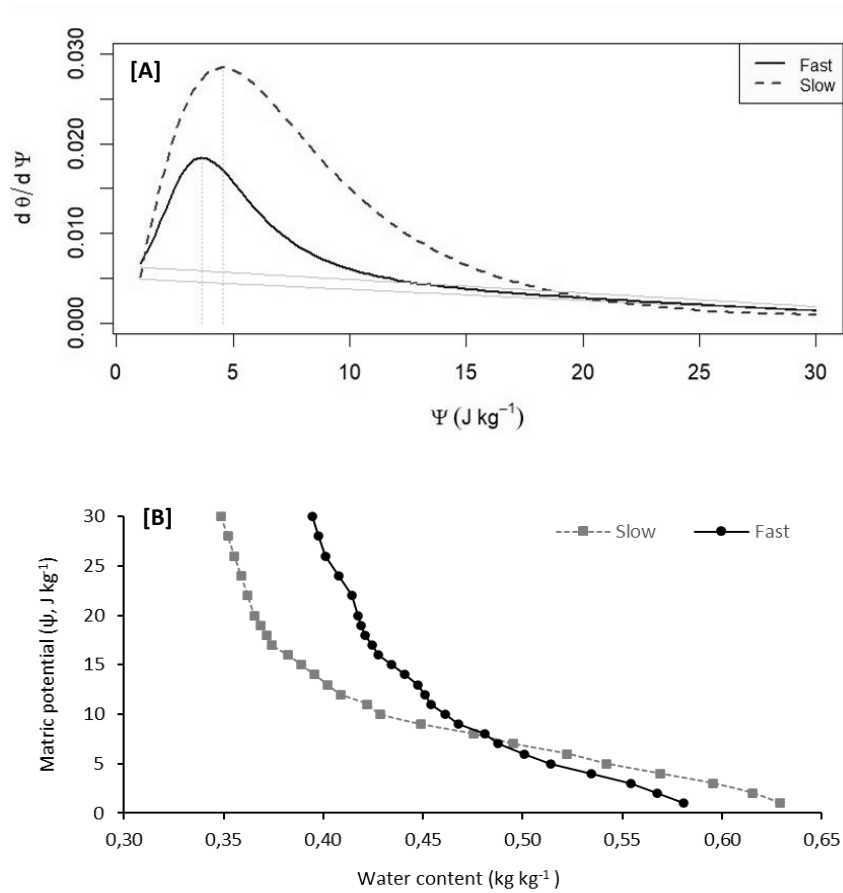


Fig. 2. Schematic representation of (A) specific water capacity curves for fast and slow wetting and (B) the water drainage curve or moisture release.

The SI for each wetting rate was computed using Equation 5 (Collis-George and Figueroa, 1984; Pierson and Mulla, 1989).

$$SI = VDP/MS \quad \text{Eq. (5)}$$

The SR calculated according to Equation 6 proposed by Pierson and Mulla (1989) serves to evaluate soil aggregate stability on a relative scale from zero to one, providing a measure of aggregate resistance to slaking.

$$SR = SI_{fast} / SI_{slow} \quad \text{Eq. (6)}$$

The parameters MS, VDP, and SR for both fast and slow wetting were computed using the HEMC application from the soilphysics v 5.0 package in RStudio (Silva and Lima, 2022).

2.4.3. Clay dispersion

Clay dispersion was measured using the spontaneous dispersion method in water. In this method, 10 g of air-dried fine earth fraction (ADFE) was placed in a 500 mL jar, maintaining a soil-to-solution ratio of 1:50. Then, 300 mL of distilled water was added along the sides of the jar. The solution was agitated for 16 hours at 50 rpm using a Wagner shaker (Teixeira et al., 2017). Clay dispersion was assessed using the pipette method (Gee and Bauder, 1986). The amount of suspended clay was determined gravimetrically by extracting a 10 mL aliquot from a depth of 5 cm and drying it at 105°C. The clay flocculation index “CFI” being an index of clay aggregation, was determined by comparing the total clay and clay dispersed in water without the chemical dispersant. Conversely, the clay dispersion index “CDI” reflects the natural degree of soil dispersion. These indices were calculated according to Equations 7 and 8, respectively.

$$CFI = \left(\frac{TC - WDC}{TC} \right) \times 100 \quad \text{Eq. (7)}$$

$$CDI = 100 - CFI \quad \text{Eq. (8)}$$

where TC is total clay or clay from chemically dispersed soil, and WDC is water-dispersible clay.

A higher CFI indicates that the soil has a greater ability to form stable aggregates, while higher values of the CDI indicate a greater capacity of the soil to disperse. (Basga et al., 2018; Igwe et al., 2009).

2.5. Statical analysis

Principal Component Analysis (PCA) was used to identify correlations among the studied variables. Pearson correlation ($p \leq 0.05$) was employed to analyze the correlations between variables, including texture, chemical attributes, and aggregate stability indices. Linear regression and correlation analyses between aggregation indices (MWD, GMD, WAS, CDI, and SR) and CSI were conducted. To proceed with the analyses, after verifying the premises through linear models, which were subjected to normality, heteroscedasticity and variance test through graphical visualization (Kozak and Piepho, 2018) using the gvlma v1.0 package (Peña and Slate, 2006), the qqPlot function from the car v3.1-2 package (Fox and Weisberg, 2019), and the Shapiro-Wilk test. When necessary, some observations were considered to be outliers, as they were detrimental to the modeling, and square root were applied. It was necessary to employ the square root method for MWDpm and WAS data. Subsequently, an F-test analysis

($P < 0.05$) was conducted comparing aggregate indices (MWD, GMD, WAS, CDI, and SR) with CSI. All analyses were performed using the software R v.4.3.3 (R Core Team, 2024).

3. Results

3.1. Physical and chemical attributes

The predominant texture in both agricultural and native vegetation soils was sand, constituting 57% and 55% of the total composition, respectively, with greater amounts of fine and very fine sand (Table 1). The clay content was higher in native vegetation soils (18%) compared to agricultural soils (10%), while the silt content was slightly higher in agricultural soils (32%) compared to native vegetation soils (27%). In both agricultural and native vegetation soils, a predominant presence of the coarse silt fraction (21% and 17%, respectively) was observed, surpassing the fine silt fraction (11% and 10%, respectively). The agricultural and native vegetation soils were classified as sandy loam. The WDC content was quite similar in both agricultural and native vegetation soils, with values of 55 and 58 g kg^{-1} , respectively.

Table 1

Particle size distribution of surface horizon soils (0-10 cm) from Sikasso district, Southern Mali

Land use	Particle size distribution ¹										Textural class ²
	VCCS	MS	FS	VFS	S	SiC	SiF	Si	C	WDC	
	g kg^{-1}										
Agricultural	40±20	81±38	309±103	139±47	569±138	212±86	114±36	326±105	105±55	55±25	SL
Native (Savanna)	63±19	125±95	270±41	91±23	549±133	168±16	103±38	271±31	183±100	58±41	SL

Values are the mean of treatments \pm standard deviation (1) VCCS: very coarse sand plus coarse sand (2 – 0,5 mm); MS: medium sand (0,5 – 0,25 mm); FS: fine sand (0,25 – 0,10 mm); VFS: very fine sand (0,10 – 0,05 mm); S: sand (2 – 0,05 mm); SiC: coarse silt (0,05 – 0,02 mm); SiF: fine silt (0,02 – 0,002 mm); Si (0,05 – 0,002 mm): silt; C: clay (<0.002 mm); WDC: water- dispersible clay (2) SL: sandy loam.

The soil chemical attributes exhibited significant variation among land uses (Table 2), particularly in the exchangeable cations Ca^{2+} , Mg^{2+} and total organic carbon. The agricultural soils were moderately acidic, with a mean $\text{pH}_{\text{H}_2\text{O}}$ value of 5.8, while the native vegetation soils were slightly acidic, with a mean $\text{pH}_{\text{H}_2\text{O}}$ value of 6.3. Overall, the soils exhibited a low organic C content, agricultural soils presenting an average value of $9.1 \pm 5.0 \text{ g kg}^{-1}$, whereas native soils displayed slightly more than double that amount, with an average value of $25.4 \pm 8.9 \text{ g kg}^{-1}$.

Table 2

Chemical attributes of surface soils (0-10 cm) from Sikasso district, Southern Mali, in the Sudano-Sahelian region, West Africa

Land use	pH	K ⁺	Na ⁺	Ca ²⁺	Mg ²⁺	Al ³⁺	H ⁺ +Al ³⁺	CEC	Base saturation	TOC
		cmol _c dm ⁻³							%	g kg ⁻¹
Agricultural	5.8±0.6	0.3±0.1	0.005±0.003	2.9±1.7	1.2±0.9	0.2±0.02	2.2±0.8	6.5±2.7	65±12	9.1±5.0
Native (Savanna)	6.3±0.5	0.6±0.2	0.01±0.003	4.9±1.3	3.2±0.9	0.2±0.01	3.1±1.5	11.7±2.8	74.3±9.2	25.4±8.9

Values are the mean of treatments ± standard deviation. CEC: cation exchange capacity (CEC = Na⁺ + K⁺ + Ca²⁺ + Mg²⁺ + Al³⁺ + H⁺); TOC: total organic carbon

The soils exhibited low cation exchange capacity (CEC), with mean values of 6.5±2.7 cmol_c kg⁻¹ in agricultural soils and 11.7±2.8 cmol_c kg⁻¹ in native vegetation soils. The average content of cations in the sorptive complex was higher in native vegetation soils compared to agricultural soils. In both agricultural and native vegetation soils, Ca²⁺ was the dominant cation in the sorptive complex, with values of 2.9±1.7 cmol_c kg⁻¹ and 4.9±1.3 cmol_c kg⁻¹, respectively.

3.2. Parameters of soil aggregate stability and correlation with crusting index

The native vegetation soils demonstrated higher values of soil aggregate stability parameters, including CFI, GMW, MWD, WAS, and SR, in comparison to agricultural soils. The average CDI values revealed higher clay dispersion in agricultural soils, with 55% clay dispersing in water on average, compared to 35% in native vegetation soils (Table 3).

The mean values of GMD in native vegetation soils, whether with pre-wetting (4.3±0.7 mm) or without pre-wetting (3.7±1.7 mm), exceeded those found in agricultural soils (2.9±1.2 mm) and (1.8±1.2 mm), respectively (Table 3). These values indicated a 50% and 100% increase in GMD in native vegetation soils. The mean values of MWD were higher than the values of GMD. The MWD pre-wetting value in native vegetation soils (4.5±0.7 mm) was 13% higher than the mean value (4.0±0.9 mm) of agricultural soils, while in without-wetting, it was 38% higher, with values of 4.4±0.9 mm and 3.2±1.1 mm (Table 3), respectively. Pre-wetting increased the values of the aggregation indices GMD and MWD in both land use types. However, it had a greater influence on agricultural soils, where GMD increased by 60% and MWD by 20%.

The mean values of WAS indicated a high percentage of stable aggregates in both land use types. In native vegetation soils (92±5%), the percentage was higher, while in agricultural soils, it was 62±23%.

The Stability Ratio (SR) is evaluated on a scale from 0 to 1, where higher values signify greater stability. Both land use types displayed mean SR values below the 0.5 threshold. Specifically,

in native vegetation soils, the SR value (0.43 ± 0.3) was 80% higher than that in agricultural soils (0.24 ± 0.07).

The mean CSI values for agricultural and native vegetation soils were within the range of 0.2 to 2, indicating a moderate risk of crust formation. However, native vegetation soils exhibited a higher mean value (1.4 ± 0.6) compared to agricultural soils (0.5 ± 0.1).

Table 3

Parameters of soil aggregate stability and crust formation index in agricultural and native vegetation soils of southern Mali

Land Use	CFI %	CDI	GMD		MWD		WAS %	SR	CSI
			Pre-wet. mm	Without-wet	Pre-wet.	Without-wett.			
Agricultural	45±12	55±12	2.9±1.2	1.8±1.2	4.0±0.9	3.2±1.1	62±23	0.24±0.07	1.4±0.6
Native (Savanna)	65±9	35±9	4.3±0.7	3.7±1.7	4.5±0.7	4.4±0.9	92±5	0.43±0.3	0.5±0.1

Values are the mean of treatments \pm standard deviation. CFI: clay flocculation index; CDI: clay dispersion index; GMD: geometric mean diameter; MWD: mean weight diameter; WAS: wet aggregate stability; SR: stability ratio; CSI: crusting susceptibility index.

The Pearson correlation analysis revealed significant correlations (Fig. 3). CDI showed a positive correlation with fine and very fine sand, as well as with the total sand content, and a negative correlation with fine silt, total silt, TOC, and cations (K^+ , Ca^{2+} , Mg^{2+} , Al^{+3}), as well as CEC. The indices GMD and MWD, both with and without pre-wetting, exhibited a significant positive correlation with the coarse and very coarse sand fractions, as well as with clay and with TOC, Ca^{2+} , Mg^{2+} , Al^{+3} , and CEC, while exhibiting a negative correlation with the coarse silt fraction. The SR and WAS demonstrated a positive correlation with the coarse and very coarse sand fractions, fine silt, clay, TOC, Ca^{2+} , Mg^{2+} , Al^{+3} , and CEC, and a negative correlation with very fine sand and the clay dispersion index. The CSI showed a high significant negative correlation ($p \leq 0.05$) with the indices GMD_pm, GMD_wm, MWD_pm, MWD_wm, WAS, and positive correlation with CDI. This indicates that lower indices of soil aggregate structural stability are associated with a higher susceptibility to crust formation.

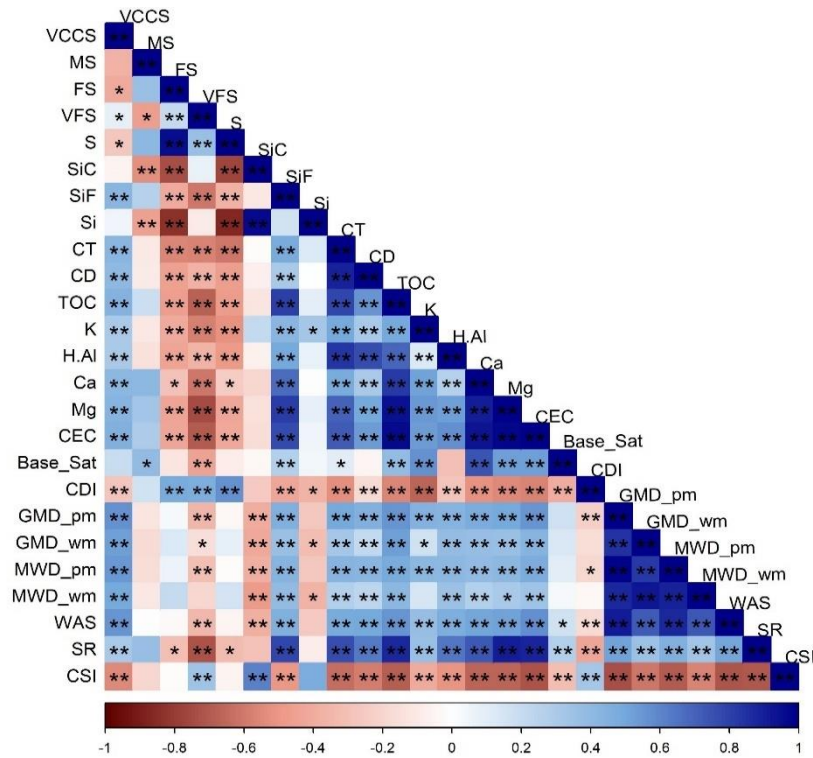


Fig. 3. Pearson correlation analysis of soil physical and chemical attributes, crusting susceptibility index, and soil aggregate stability indices in southern Mali, West Africa. VCCS: very coarse sand plus coarse sand; MS: medium sand; FS: fine sand; VFS: very fine sand; S: sand; SiC: coarse silt; SiF: fine silt; Si: silt; CT: total clay; CD: water- dispersible clay; TOC: total organic carbon; CEC: cation exchange capacity; CDI: clay dispersion index; GMD: geometric mean diameter; MWD: mean weight diameter; WAS: wet aggregate stability; SR: stability ratio; CSI: crusting susceptibility index. Significance levels: ** ($p \leq 0.01$) and * ($p \leq 0.05$).

The findings from the principal component analysis, as illustrated in Figure 4, explore the relationship between soil physicochemical attributes, soil crusting index, and aggregate stability indices. In PC1, the eigenvectors revealed that MWD, GWD, WAS, SR, TOC, and CEC exhibited positive loadings, showing a positive contribution to PC1. Conversely, CDI and CSI demonstrated negative loadings, indicating an inverse relationship with PC1. The results of the PCA indicated that PC1 was the most critical component, explaining a substantial proportion of the variability in the soil aggregate indices influenced by land use. These results encompassed a substantial portion, amounting to 64.8% of the total variance, with PC1 contributing 44.5% and PC2 contributing 20.3%. While SR, from the HEMC method, was closely related to PC1, strongly related to clay, organic carbon and sorptive complex (CEC, nutrient content); the remaining aggregation indices (GMD, MWD and CDI), as well as CSI, were somewhat related to PC2, defined mainly by sand and silt contents, highlighting the influence of different soil factors depending on the method for assessing aggregate stability

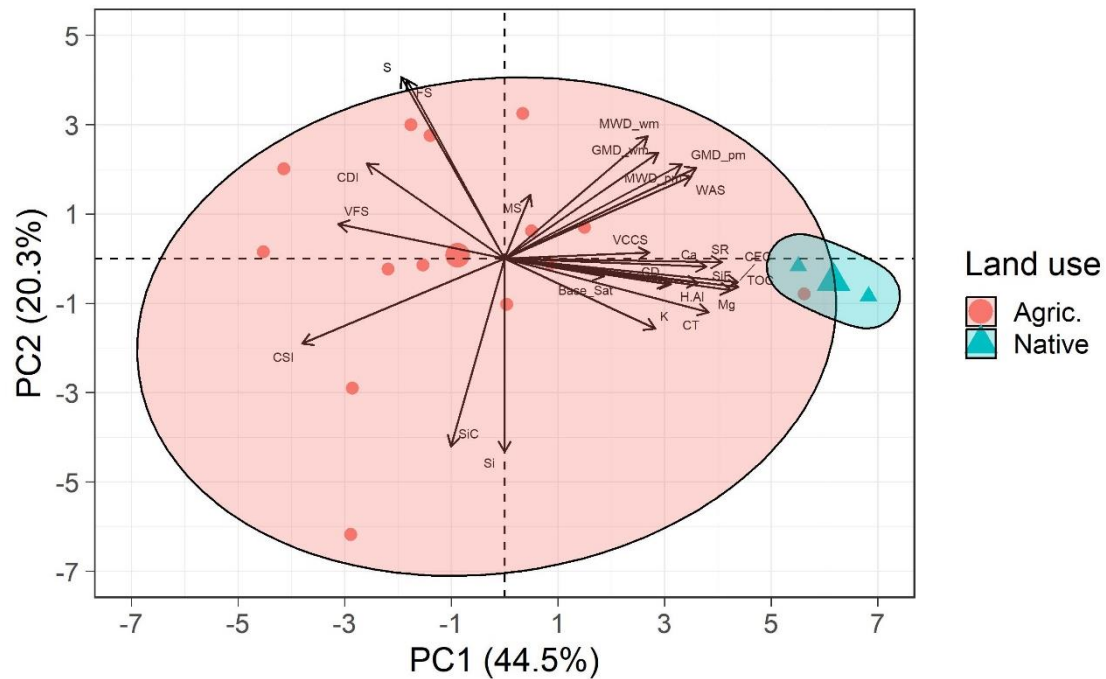


Fig. 4. Principal component analysis of soil physical and chemical attributes, crusting susceptibility, and aggregate stability indices in different land use in Southern Mali. VCCS: very coarse sand plus coarse sand; MS: medium sand; FS: fine sand; VFS: very fine sand; S: sand; SiC: coarse silt; SiF: fine silt; Si: silt; CT: total clay; CD: water-dispersible clay; TOC: total organic carbon; CEC: cation exchange capacity; CDI: clay dispersion index; GMD: geometric mean diameter; MWD: mean weight diameter; WAS: wet aggregate stability; SR: stability ratio; CSI: crusting susceptibility index

As observed in the clustering depicted in Fig. 4, soils under native vegetation showed strong correlations with TOC, CEC, and SR, exhibiting positive values of PC1. In both agricultural and native vegetation soils, the PCA indicated that as MWD, GMD, WAS, and SR increased, the CDI and CSI decreased, as also evidenced in Figure 3.

4. Discussion

4.1. Aggregate stability indices and soil properties

The agricultural and native vegetation soils in southern Mali were identified as sandy loam, characterized by elevated levels of fine and very fine sand, alongside silt, and low clay and organic carbon content, indicating a moderate susceptibility to soil crusting, as evidenced by the crusting susceptibility index (CSI) (Table 3). These soils share a similar sensitivity to crust formation with sandy and stony soils found in the Sahel area of West Africa (Valentin, 1995; Watt and Valentin, 1991).

Soil aggregate stability is widely recognized as an indicator of soil resistance to erosion and the quality of tillage (Barthès and Roose, 2002; Xia et al., 2022). Moreover, it can also serve as an

indicator of soil susceptibility to crust formation. The indices derived from various methodologies for assessing structural stability can be correlated with the mechanisms involved in soil crust formation. For instance, aggregate breakdown correlates with MWD, GMD, and WAS, slaking with SR, and particle dispersion with CDI.

The mean values of GMD (1.8 to 4.3 mm) and MWD (3.2 to 4.5 mm) observed in the soils of the region (Table 3) generally indicate a significant percentage of macroaggregates (>2mm). However, native vegetation soils exhibit even higher values, indicating greater structural stability. Similar GMD values ranging from 4.2 to 3.6 mm were observed in bare Cambisol in Brazil, aligning with those observed in native vegetation soil (Oliveira et al., 2024). The lowest values of GMD and MWD obtained in the analyses conducted without pre-wetting highlight the significance of pre-wetting in assessing the structural stability of soil aggregates and its impact on the susceptibility of soils to erosive processes, particularly in agricultural regions (Duval et al., 2016; Silva et al., 2020). This suggests that soils with low moisture content exposed to disintegrating forces, such as heavy rainfall, are more prone to particle disintegration and consequently the development of surface crusting.

Stable soils are defined by a greater prevalence of macroaggregates, while soils prone to erosion are characterized by a higher prevalence of microaggregates (Xia et al., 2022). In the studied region of Southern Mali, the soils were classified as plinthic soils, characterized by the significant influence of Plinthites, which result in the presence of friable nodules, continuous indurated crusts, and ironstones composed primarily of iron oxide-rich clay mineralogy and quartz. (Roquin et al., 1990; Santos et al., 2023). In oxide-rich soils, oxides act as the primary binding agents between soil particles (Lima et al., 2022), facilitating the formation of aggregates ranging from millimeters to centimeters in size, as observed in high percentages of stable aggregates (WAS), particularly noticeable in native vegetation soils, ultimately leading to increased GMD and MWD values. However, despite this aggregation, susceptibility to crust formation remained significant, as indicated by CSI values.

In Southern Mali, Plinthosols exhibit susceptibility to the formation of both coarse pavement crusts, a type of soil crust found in arid sandy soils, characterized by embedded pebbles and a pronounced vesicular structure, especially beneath coarse fragments (Bresson and Valentin, 1994), as well as gravel crusts, where coarse fragments are firmly embedded within a structural crust, making them resistant to removal from the soil surface (Valentin and Casenave, 1992).

The CDI values (35 to 55%) calculated in Southern Mali resembled those reported by Igwe (2005) for sandy loam Inceptisols and Alfisols abundant in kaolinite in Nigeria. The susceptibility of the clay fraction to disperse in water influences soil erodibility, aggregate stability, and soil crusting (Igwe, 2005). Agricultural soils in Southern Mali displayed higher CDI values compared to native vegetation soils, indicating a greater susceptibility to soil crusting. In agricultural soils with elevated levels of WDC, common in Southern Mali, challenges arise during tillage and heavy rainfall events, where soil dispersion occurs upon saturation with water, leading to the breakdown of soil aggregates and the formation of seals and crusts. Previous studies suggested that soil dispersion is influenced by factors such as the chemical composition of exchangeable cations, the presence of iron and aluminum oxides, and organic carbon content (Oster et al., 1980). Soils with low organic carbon content tend to experience more severe clay dispersion in water, contributing to increased soil crusting (Igwe, 2005).

The disparity in SR index values from HEMC between native vegetation and agricultural soils signifies a variation in structural stability attributed to differing land uses. The notably higher mean SR index value recorded in native vegetation soils (0.43) compared to agricultural soils (0.24) suggests superior soil structure resilience in natural ecosystems. The findings from this study are consistent with previous research conducted in diverse geographical regions, revealing variability in stability ratio (SR) values across different land uses and soil types. Levy and Mamedov (2002) reported SR values ranging from 0.28 to 0.39 in soils with similar clay content in Israel, indicating comparable levels of soil structural stability. In contrast, Sharifi et al. (2021) observed higher SR values (0.6–0.7) in undisturbed rangeland and protected forest areas with sandy and sandy loam soils in Iran. Furthermore, Avanzi et al. (2011) documented higher SR values between 0.59 and 0.7 in a Plintossolo under eucalypt plantations and native forest in Brazil. Similarly, Silva et al. (2014) reported SR values ranging from 0.33 to 0.58 in conventional and differentiated systems in clayey Oxisols in Brazil.

Previous research has indicated that the process of soil aggregate formation and stabilization is affected by both inherent soil characteristics and land management practices, with soil organic matter playing a critical role in improving the cohesion and hydrophobicity of soil aggregates (Erktan et al., 2015; Six et al., 2000). Overall, a positive correlation was observed between soil aggregate stability and cations such as Ca^{2+} and Mg^{2+} , as well as parameters like CEC, clay content, and organic carbon content. Conversely, the crusting susceptibility index exhibited a negative correlation with the indices of structural stability and a positive correlation with the

clay dispersion index (Fig. 3). The significant relationships between aggregate stability and clay content, as well as organic matter, are well-established and widely acknowledged (Amézqueta, 1999).

The organic carbon content in the soils of Southern Mali was notably poor, measuring below 25 g kg⁻¹ in native vegetation soils and substantially lower, measuring less than 9 g kg⁻¹ in agricultural soils. The observed decrease in TOC and exchangeable cations in agricultural soils, leading to structural degradation, can be primarily attributed to prevalent management practices in the study region, where farmers frequently collect crop residues to feed their livestock and burn those unsuitable for animal consumption, such as cotton stalks, thereby significantly diminishing the soil's organic matter content and essential nutrient cations. Moreover, this degradation is further intensified by the soil remaining exposed to solar radiation for most of the year. The exposure subjects soil aggregates to repeated wet-dry cycles, accelerating the decomposition of organic matter and weakening soil aggregate stability (Igwe and Nwokocha, 2006). Consequently, these conditions lead to a rapid decline in soil structure, increasing susceptibility to crust formation.

4.2. Soil crusting susceptibility and aggregate stability indices

A negative and significant relationship was observed between the crusting susceptibility index (CSI) and aggregate stability indices (WAS, GMD_pm, GMD_wm, MWD_pm, MWD_wm, and SR), indicating a decrease in CSI as WAS, GMD, MWD, and SR increased (Fig 5). Conversely, a positive and significant correlation was identified between the CSI and CDI, indicating an increase in CSI associated with increasing CDI (Fig. 5a). The coefficients of determination (R^2) for the indices (MWD_pm, GMD_pm, MWD_wm, GMD_wm, WAS, SR, and CDI) ranged from 0.22 to 0.49, with MWD_pm showing the lowest R^2 value and CDI the highest (Fig. 5).

The commonly used aggregate stability indices to predict soil erodibility, such as MWD, GMD, and WAS, exhibited weak correlations with the crusting susceptibility (Fig. 5) in the Plinthosols studied in southern Mali. Despite being the most common method for assessing aggregate stability, the indices derived from the wet sieving method have been criticized for not considering all potential mechanisms responsible for aggregate breakdown, particularly the impact of raindrops. Additionally, this method tends to give excessive importance to breakdown by slaking while not providing enough time for dispersion and flocculation (Kemper and Rosenau, 1986). Various studies have demonstrated that erodibility is strongly negatively

correlated with indices such as GMD, MWD, and WAS obtained from wet-sieving (Ahmadi et al., 2011; Nciizah and Wakindiki, 2015). However, soil crusting and the disaggregation of field soils are largely caused by the impact of raindrops, a factor that is not simulated in wet-sieving tests (Almajmaie et al., 2017b). The difference in correlation between the pre-wetting and without pre-wetting treatments of aggregates reflects that when a soil has adequate moisture, slaking and dispersion are reduced, and consequently, crusting is minimized (Silva et al., 2020).

In the sandy loam soils of Southern Mali, the CDI demonstrated the highest correlation coefficient with crusting susceptibility when compared to other aggregate stability indices (Fig. 5a). Various studies have remarked that the clay dispersion ratio and dispersion ratio are good indices for predicting erodibility and the risk of surface sealing and crusting (Igwe et al., 2009; Nciizah and Wakindiki, 2015). Lado et al. (2004) demonstrated that the initial stage in the formation of surface sealing begins with the disintegration and subsequent dispersion of microaggregates.

Correlation analyses revealed that the SR derived by HEMC had a greater and significant efficacy in predicting soil susceptibility to crusting formation in sandy loam phinthic soils (Fig. 5g). This finding aligns with results reported by Levy and Miller (1997), who found strong correlations between aggregate stability indices obtained with the HEMC method and seal formation indices in southeastern U.S. soils. Consequently, SR emerges as a valuable indicator of susceptibility to crust formation. The HEMC method has recently emerged as a highly practical and suitable approach for assessing soil structural stability in arid and semi-arid regions, encompassing a broad spectrum of stability levels. Its applicability is particularly notable in soils with inherently weak structural stability, such as sandy soils, where conventional methods often struggle to accurately characterize structural integrity (Baiamonte et al., 2019; Sharifi et al., 2021).

The significant negative correlation observed between CSI and TOC (Fig. 5h) underscores the influential role of organic carbon in shaping soil structure. Organic matter contributes to decreasing dispersivity, resulting in enhanced aggregate stability (Lado and Ben-Hur, 2004).

For a comprehensive understanding of soil structural stability and the prediction of soil crusting formation, it is essential to evaluate both macro- and microaggregate stability (Amezketta et al., 2003). Igwe et al. (1995) found that CDI was a more effective predictor of potential soil loss than GMD and MWD in southeastern Nigeria. These findings align with those observed in the evaluation of indices used to assess soil crusting susceptibility in Mali, where the stability ratio

(SR) derived from the HEMC method and CDI were identified as superior predictors of potential soil crusting compared to GMD, MWD, and WAS indices.

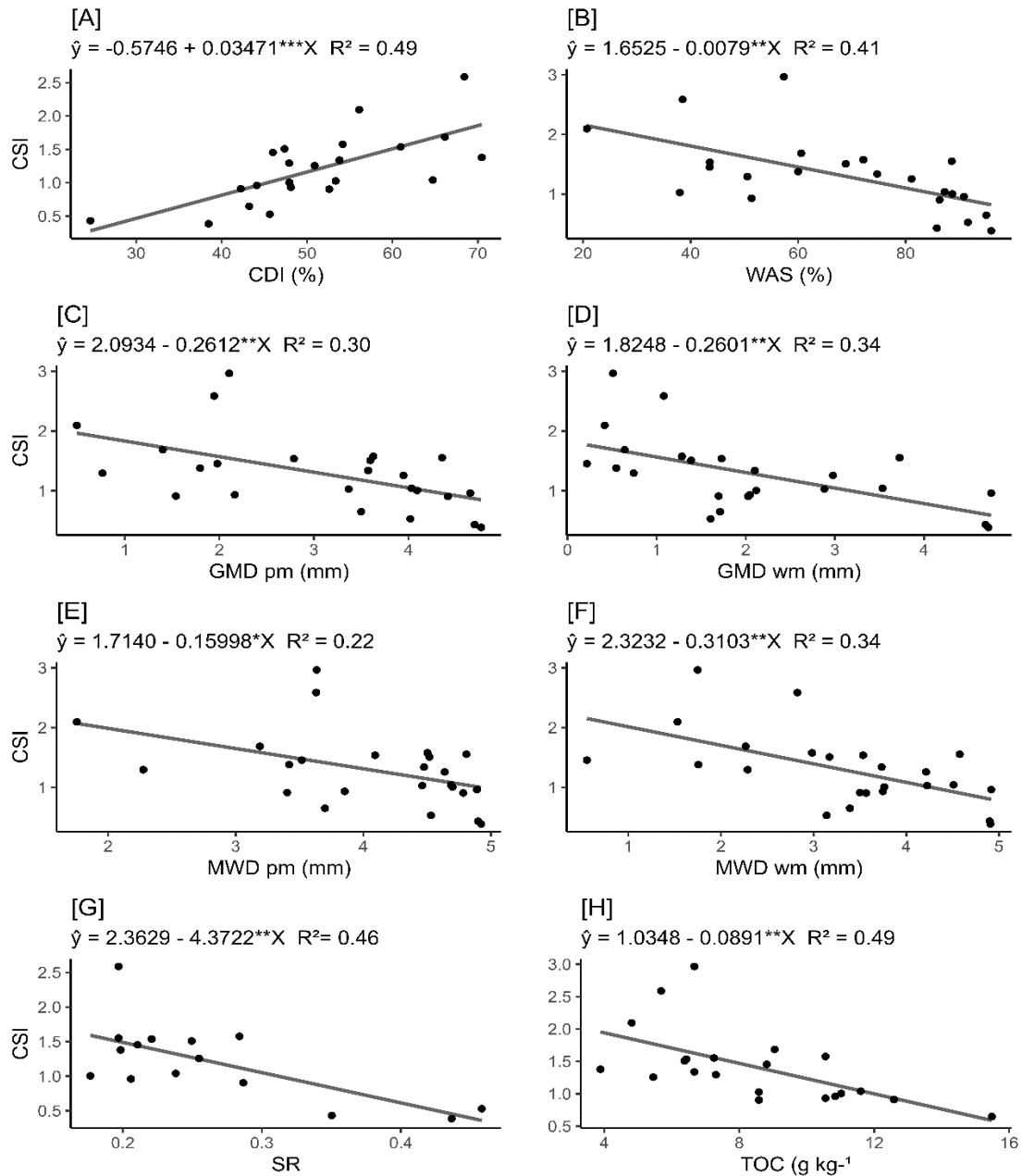


Fig. 5. Relationship between the Crusting Susceptibility Index (CSI) and soil aggregate stability indices. Figures (A-G) depict the correlations with CDI, WAS, GMD_pm, GMD_wm, MWD_pm, MWD_wm, and SR, while Figure (H) represents the correlations between CSI and TOC. Significance levels: ***($p \leq 0.001$), ** ($p \leq 0.01$) and * ($p \leq 0.05$).

In semiarid areas, the presence of soil crusts can worsen desertification by reducing plant cover, leading to overgrazing, leaving the soil exposed, and ultimately causing soil aggregates to break down and crusting formation (Assouline, 2004). Therefore, strategies must be implemented in

the studied region to maintain aggregate structure and stability, focusing on preserving vegetation cover and increasing organic matter.

Conclusions

Land use in southern Mali has a significant impact on soil aggregate stability, as evidenced by higher values of structural stability indices (CFI, GMD, MWD, WAS, and SR) in areas covered by native vegetation compared to agricultural areas. Soils under agricultural use also exhibited higher values of crusting susceptibility; however, both agricultural and native vegetation soils were characterized as moderate risk based on the CSI. This highlights that the agricultural practices utilized in the region have caused both physical and chemical degradation of the soils, thereby reducing the structural stability of soil aggregates and increasing the risk of soil crust formation.

In general, wet sieving indices like GMD, MWD, WAS, and SR indicate a positive relationship between aggregate stability and factors promoting aggregation (e.g., Ca^{2+} , Mg^{2+} and Al^{+3}) and TOC. The high content of very fine sand and coarse silt, along with low clay and TOC contents, are soil factors that contribute to soil crusting formation. The positive correlation observed between aggregate stability and polyvalent cations indicates an opportunity to improve aggregate stability by increasing organic matter content and through conservation practices, such as promoting vegetation cover.

In the studied area of southern Mali, crusting susceptibility tends to be negatively correlated with GMD, WAS, SR, and TOC and positively correlated with CDI. The stability ratio (SR) derived from the HEMC method and CDI emerge as superior predictors of soil susceptibility to crusting formation compared to GMD, MWD, and WAS.

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FINAL CONSIDERATIONS

This study provided a comprehensive examination of the physical, chemical, mineralogical, and micromorphological soil attributes that influence soil crusting in two rural villages, Siani and Bandiagara II, in Southern Mali, West Africa, where soil crusting poses significant challenges to agriculture. By evaluating various susceptibility indices, including the Particle Separability Index, Structural Stability Index, and Crusting Susceptibility Index, this study has facilitated a deeper understanding of the factors behind crusting formation and quantified the risk of crusting. The main results revealed that both physical attributes, such as high silt and fine sand content, and the lack of organic carbon, particularly in agricultural areas, contribute significantly to crusting formation. The crusting index indicated a moderate risk of crusting in these soils. These findings underscore the importance of combining detailed analysis of soil attributes with susceptibility indices to effectively evaluate the risk of crusting formation.

This study assessed the relationships between various indices of soil aggregate stability and crusting susceptibility in the study area. The main findings revealed that sites with soil native vegetation exhibited higher values of structural stability indices and lower crusting susceptibility compared to agricultural sites. Additionally, a significant negative linear relationship was observed between crusting susceptibility and aggregate stability indices. These results highlight the importance of using a range of aggregate stability indices that are closely related to the processes of crust formation. The strong correlations between aggregate stability and crusting susceptibility underscore the critical role of soil structure in determining the propensity for crust development.

These findings have important implications for soil management practices, suggesting that maintaining and enhancing soil aggregate stability could be an effective strategy for mitigating the negative impacts of soil crusting on agricultural productivity in the study region. The promotion of practices that increase organic matter content and improve aggregate stability is essential for maintaining agricultural productivity and preventing crust formation, which can exacerbate desertification in semi-arid regions. Future research should focus on specific soil management strategies that can be implemented on a large scale to improve aggregate stability and soil resilience in the face of climate change and agricultural intensification.