SOIL SEALING AND CRUSTING EFFECTS ON INFILTRATION, EROSION AND MICROBIAL COMPOSITION UNDER DIFFERENT RAINFALL INTENSITIES AND SLOPE CONDITIONS.

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DEDICATION.

This dissertation is dedicated to my family to whom I am grateful for the support.
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DECLARATION

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I declare that the above dissertation/thesis is my own work and that all the sources that I have used or quoted have been indicated and acknowledged by means of complete references.

27 MAY 2019

SIGNATURE DATE
ABSTRACT

Soil crusting is a major land degradation driver in arid regions because of variations in rainfall characteristics and inherently poor soils. This study aimed to determine the effects of rainfall intensity and slope steepness on soil sealing and crusting and the effects on infiltration rate, runoff, erosion and microbial composition in selected soils of different texture and mineralogy. A rotating disc rainfall simulator was used to apply rainfall varying in intensity (RI) (45 mm/h, 70 mm/h and 100 mm/h) to six soils (K1, K2, K3, S1, S2 & S3) at two slopes (5° and 8°). The effects of these two factors on crusting (strength (CS) & thickness (CT)) and subsequent effects on infiltration (IR), runoff (RO) and erosion (SL) were determined. The number of bacterial communities was also measured before and after each subsequent treatment. The potential of these microbes to solubilize phosphorus, fix nitrogen and produce indole acetic acid was measured. The high clay smectitic soils (S1, S2 & S3) developed the strongest crusts with S2 showing significantly (p <0.05) highest CS of 18.54 Kpa at 45 mm/h intensity and 8° slope. Soil K3 had the lowest CS (5.4 Kpa) at 100mm/h and 8°. Soils K1, K2 and K3 are non-swelling sandy loams, with good drainage, hence low crustability. Infiltration rate generally decreased between 45 mm/h and 70 mm/h and increased again going to 100 mm/h and the effect of slope was soil dependent. However, the highest IR values, 33.32 mm/h and lowest 7.97 mm/h, were obtained at 70 mm/h and 5° for soils K3 and S3, respectively. The higher infiltration rate at the highest intensity compared to the medium one can be attributed to reduced sealing due to lower slaking forces at high energy rainfall. Runoff expectedly showed an opposite trend to that of IR, being highest at 70 mm/h and 5°. Soil loss increased with increasing intensity and slope for the low-medium clay kaolinitic soils with K1 being most erodible (468.2 kg/ha) at 100 mm/h and 8°. Soils S3 (1248.13 kg/ha) and S2 (1145.55 kg/ha) were statistically (p <0.05) similar and the most erodible at 100 mm/h and 70 mm/h, respectively. Nitrogen fixing bacteria were affected by slope gradient whilst indole acetic acid responded to rainfall intensity.
Edaphic factors proved more influential when it came to phosphorus solubilization. The study showed that high clay smectitic soils are vulnerable to crusting and that the type of clay can be more influential than the amount. The study also found that soil conditions were the most influential factor when it came to total number of bacteria and the numbers of phosphate solubilizing bacteria. On the other hand, no statistically significant changes were observed for nitrogen fixation and indole acetic acid production. The interactive nature of the factors involved in crusting suggests that a study of other parameters could provide further illumination.

**Keywords**

Bacteria, clay mineralogy, climate change, crust strength, erosion, infiltration rate, rainfall simulation, runoff, soil crusting, soil organisms
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CHAPTER ONE

1. INTRODUCTION

1.1 Background of the study

Soil compaction has severe agricultural and environmental implications worldwide, including South Africa (Mitchell & Berry, 2001; Lipiec & Hatano, 2003). Soil compaction is whereby soil particles are pressed closely together resulting in high bulk density and low pore space (SSSA, 2008). The resultant increase in bulk density and corresponding decrease in porosity negatively affects physical, chemical and biological soil properties and hence low soil productivity (Assouline, 2004). The ensuing high bulk density restricts root growth, impedes gaseous exchange and reduces water infiltration among other effects, which all lead to poor crop yield (Lipiec and Hatano, 2003; McKenzie, 2010).

Soils can be compacted artificially or naturally. On one hand, tillage and traffic represent the most prominent agents of artificial soil compaction. For instance, heavy farm equipment can exert 82.7 KPa of force onto the soil surface reaching down to a depth of 60 cm into the subsoil (McKenzie, 2010). On the other hand, natural soil compaction is caused by raindrop impact and may occur on the soil surface and manifest as seals (wet) or crusts (dry) (Assouline, 2004). Soil seals and crusts are denser and have lower porosity than the material directly below them (Neave & Rayburg, 2007). Surface sealing has severe agricultural, hydrological, and environmental effects (Assouline, 2004) such as reduced water infiltration, increased runoff and soil erosion (Tang et al. 2002; Augeard et al. 2007). Consequently, soil sealing and crustng cause loss of plant nutrients especially nitrogen and phosphorus (Liu R et al. 2014) and beneficial microorganisms (Castro et al. 2010).
Research has shown that global warming will bring changes in rainfall characteristics (Nciizah & Wakindiki, 2014a). The frequency of extreme rainfall and drought events is projected to increase in South Africa up to the year 2050 relative to the period between 1961-2000 (LTAS Phase 1 technical report (no 1 0f 6), 2013). Rainfall induced surface sealing will thus be a common feature as a result of higher intensity rainfall events, which is the norm in semi-arid areas (Mills & Fey, 2004). Soils in these areas are characterized by poor development and thus reduced stability. The degree of seal formation is dependent on a soil’s erodibility and rainfall erosivity (Wakindiki & Ben-Hur, 2002), and land use management (Lipiec & Hatano, 2003). Many experiments have confirmed that soil texture and mineralogy are key soil properties that determine erodibility (Le Bissonnais & Arrouays, 1997; Lado & Ben-Hur, 2004; Ben-Hur & Wakindiki, 2004) while rainfall intensity and duration control erosivity (Moussouni et al 2014; Liu et al. 2011).

There is considerable evidence that surface crusting is on the rise in both humid and dry climates such as in South Africa (Mzezewa & van Rensburg, 2011). Surface seals and crusts frequently form on bare soil in the arid and semi-arid regions (Tang et al. 2002; Hussein et al. 2010) because of the high intensity rainfall events (Mills & Fey, 2004). Nciizah and Wakindiki (2014a) noted that in South Africa a limited amount of work has been done on the effects of changing rainfall intensity on soil structural attributes. The present study will investigate the phenomenon of soil sealing and crusting because of raindrop impact and its effects on the infiltration rate, erosion and microbial composition of soils of different texture and mineralogy using a rainfall simulator.
1.2 Problem Statement

The threat of climate change on agriculture is now a reality. Global initiatives such as the Global Soil Partnership and the National policies on Climate Smart Agriculture (Tang et al. 2002; Hussein et al. 2010 and Mnkeni & Mutengwa, 2014) call for urgent measures to reverse the adverse effects of climate change. Knowledge on how the soil hydraulic properties and degradation will respond to a changing climate in South African is scarce (Mills & Fey, 2004; Nciizah & Wakindiki, 2014a). Moreover, the response of beneficial microorganism populations is largely unknown. Optimization of soil management practices requires an understanding of soil physical, chemical and biological properties (Delgado & Gomez, 2016). Soil microbes are very sensitive to changes in moisture, aeration and nutrient availability, which are affected by changes in the physical condition of the soil such as porosity and bulk density (Pereira et al. 2013). It is therefore important that studies be conducted to accumulate practical knowledge on the possible effects of climate change on the soil environment and subsequently human livelihoods. For example, South Africa is estimated to lose about 12.6 tons/ha/year of soil to erosion (Le Roux, 2014). Moreover, none of the previous studies have accounted for microbes lost with the eroded soil.

Climate change is predicted to alter the existing rainfall characteristics (Nciizah & Wakindiki, 2014a), with significant changes in rainfall variability and intensity projected throughout South Africa (UNICEF, 2011). Therefore, soil sealing and crusting is expected to increase and attract sustained interest from researchers. Nevertheless, little research linking changing climate scenarios with natural surface soil compaction under various land use and management is available in South Africa (Nciizah and Wakindiki 2014a). Other researchers, for instance, Mills and Fey (2004) studied the effects of land use on organic matter and surface crusting while
Blignaut et al. (2009) looked at the sensitivity of agricultural production to climate change. Other researchers mostly focused on impact and adaptation (Pandey et al. 2009; WIREs Clim change, 2014)

1.3 Aims and objectives of the study

The aim of the study was to determine the effects of climate change induced soil sealing and crusting on infiltration rate, soil loss and microbial composition in soils of different texture and mineralogy using a rainfall simulator.

The specific objectives of the study are to determine:

1. The effect of rainfall intensity and slope gradient on crust strength and thickness in soils of different texture and mineralogy:
2. The effect of rainfall intensity and slope gradient on infiltration rate, runoff and erosion.
3. The effect of soil crusting and erosion on soil microbial composition in soils of different texture and mineralogy.

1.4 Hypotheses

a) $H_0$: The crust strength and thickness of the study soils is not affected by simulated rainfall intensity and slope gradient.

b) $H_0$: The infiltration rate of the study soils is not affected by simulated rainfall intensity and slope steepness.

c) $H_0$: The amount of soil loss due to runoff is not affected by simulated rainfall intensity and slope steepness.

d) $H_0$: Erosion and runoff have no effect on soil microbial communities
2.1 Overview

The advent of climate change and the possible impact it will have on soil resources has led to increased interest in studies aimed at finding ways to predict, assess and mitigate its effects (Tang et al. 2002; Hussein et al. 2010 & Mnkeni & Mutengwa, 2014). This chapter presents a review of literature on soil surface sealing and crusting and the related effects on soil properties. The influence of climatic factors, particularly rainfall characteristics, is the primary driver of soil surface sealing and crusting. The last section of this chapter will discuss the influence of climate on soil properties.

2.2 Soil surface sealing and crusting

A soil is compacted when the particles are compressed into a smaller volume resulting in reduced porosity and increased bulk density (McKenzie, 2010). The energy transferred on to soil by falling raindrops represents the most prominent agent of natural soil compaction. When soil compaction occurs at the soil surface it is known as soil crusting (McKenzie, 2010). Lado et al (2004) stated that a soil seal has a skin seal layer resulting from raindrop impact overlying a washed-in layer of low porosity that is caused by accumulation of small particles. Falling raindrops induce crusting through aggregate breakdown, particle dispersion and micro-sedimentation in the larger pores during the wetting phase (Mills and Fey, 2004; Cavazza et al. 2008; Wuddivira et al. 2009). The consensus is that seal formation is a two-step dynamic process of aggregate breakdown by raindrop impact and slaking. The next step is the deposition of particles in the larger pores in the soil surface resulting in a thin dense layer that hardens to
form a crust upon drying (Le Bissonnais & Arrouays, 1997; Ben-Hur & Agassi, 1997; Assouline, 2004; Badoreck et al. 2012 and Sajjadi & Mahmoodabadi, 2015). Raindrop impact is more prominent when soil aggregates are wet (Wuddivira et al. 2008).

According to Moussouni et al. (2013), when raindrops hit the soil, they transfer their energy on to the soil body, which subsequently increases soil erodibility. This is because the impact of raindrops results in slaking and aggregate breakdown, which leads to seal formation (Lajos, 2008; Sajjadi & Mahmoodabadi, 2015) (Fig 1). To this effect, Slattery and Brian (1994) found that seals of 0.3 to 0.8 mm thickness formed on a crust prone soil under simulated rainfall of 32 mm/h intensity and 1 hour duration at a slope gradient of 5°. Lajos (2008) asserts that with subsequent rainstorms the thickness of a crust can increase when a cover crust develops on top of the depositional crust (Fig 2.1). On the other hand, Romkens et al. (2001) found that in an increasing intensity sequence, sediment concentration increased gradually for the 3rd storm but increased sharply for the 4th storm as a result of development of incisions as the raindrops broke down the surface seal. This implies that the effects of soil sealing on soil loss tend to increase with rainfall duration.
In their study, Neave and Rayburg (2007) highlighted that the strength of a crust formed on a soil in a semi-arid region increased by up to three times compared to the original value after a single simulated rainstorm. According to Jakab et al. (2013), occasional heavy rainfall events are among the factors that influence topsoil properties particularly from the perspective of run-
off, infiltration and erosion processes. The soil system can change as a result of its interaction with rainfall and most often the consequences of this interaction are soil surface sealing and crusting and selective erosion (Jakab et al. 2013). Soil sealing is also known to affect soil porosity because of the increased bulk density (Nhantumbo & Cambule, 2006), which eventually affects infiltration and soil microbes.

2.3 Factors affecting soil surface sealing and crusting

Organic matter content, particle size distribution, mineralogy, electrolyte concentration and surface cover are among the soil factors that affect crust formation (Agassi et al. 1981; Wakindiki & Ben-Hur, 2002; Lado et al. 2004; Neave and Rayburg, 2007; Carmi & Berliner, 2008; Nciizah & Wakindiki, 2014a). The influence of texture, clay mineralogy and organic matter on soil crusting is reviewed in this section.

2.3.1 Texture

The influence of particle size distribution on crusting is mostly related to the clay fraction. High clay content normally translates to strong aggregates because clay is a binding agent. According to Bois-Fayos et al. (2001), crust formation has been shown to be low in soils with high clay content because clay particles act as cementing agents. Keller and Hakansson (2010) added that lower compaction in soils of higher clay content can be attributed to the positive correlation between organic matter and clay content above 30%. According to Pagliai (2010), soils with clay content below 21% tend to be prone to crusting. On the other hand, Ben-Hur and Lado (2008) stated that when clay content exceeds 41% slaking forces are enhanced resulting in more clay particles being available for the development of a surface seal. The
influence of clay content is also modified by the mineralogy and cation exchange capacity (Pagliai, 2007).

2.3.2 Clay mineralogy

Morin (1993) stated that the type of clay mineral and its electro-chemical properties determine the arrangements of soil particles on which the stability of aggregates depend. Wakindiki and Ben-Hur (2002) found that soils dominated by kaolinite were more stable than montmorillonites due to lower dispersivity. This is because kaolinite particles are arranged as 1:1 sheets held together by van der Waal’s forces and hydrogen bonds, which do not allow water and electrolytes to penetrate (Morin, 1993). The difference in layer structure of the clay minerals (Fig 2.3) results in differences in swelling potential when exposed to moisture, hence the difference in stability (Chen & Peng, 2018).

![Diagram of clay mineral structures](image)

Figure 2.3 Schematic representation of the structures of kaolinite, montmorillonite and illite

Source: Chen and Peng (2018)

2.3.3 Soil organic matter.

Soil organic matter represents one of the binding agents in soil aggregation. Zhao et al. (2017) stated that soil organic matter is involved in different aggregate formation and stabilization
processes, which include forming complexes with sesquioxides to enhance the tensile strength of aggregates. Lado et al (2004) found that low organic matter soils developed a denser and thicker seal as result of low aggregate stability and high dispersivity relative to their high organic matter counterparts. In their study, they found that an increase in organic matter from 2.3% to 3.5% reduced clay dispersion at the surface and therefore seal formation. This indicates that an increase of just 1 percentage point in organic matter alleviates seal formation.

2.4 Effects of soil surface sealing and crusting on soil hydraulic properties and soil erosion

Soil surface crusting tends to affect those soil properties that relate to the movement of air and water known as hydraulic properties (Allen et al, 2011). Hussein et al. (2010) agree that crusting is the single most significant factor that affects infiltration processes. Dexter (2004) stated that the signs of poor soil physical quality are related through their link to poor soil structure. The phenomenon affects soil hydraulic properties because of its influence on soil properties connected to permeability such as porosity and bulk density. The amount of runoff generated by a rainfall or irrigation event is primarily governed by infiltrability and hydraulic conductivity (Roberts and Clanton, 2000).

Under sealing conditions, the infiltration rate is also affected by the rearrangement of the particles in the crust and its thickness (Wakindiki & Ben-Hur, 2002). For example, a kaolinitic soil with a thin crust and no washed-in zone showed a gradual reduction in infiltration rate compared to one with a washed-in layer in a montmorillonite. Jakab et al (2013) also found lower infiltration rate and higher runoff in one soil that was exposed to the same rainfall of 60 mm/h before and after a crust had formed.
The effects of soil sealing on soil hydraulic properties can be of a positive nature in certain conditions, such as during the dynamic phase of the phenomenon. The decrease in ponding time accompanied by increasing rainfall intensity results in high infiltration rate after extended exposure to rainfall because the infiltration curve decreases more rapidly (Assouline, 2004). Mualem et al (1993) also showed that the saturated zone within the seal layer becomes shallow with increasing intensity even if the cumulative rainfall is the same and this induces higher infiltration rate. The increased infiltration rate can be accredited to such processes as i) seal destruction by raindrop impact ii) reduction of seal thickness by erosion and iii) protection offered by accumulated water to the seal layer (Assouline, 2004). Assouline and Ben-Hur (2006) and Sajjadi and Mahmoodabadi (2015) also found similar results which they credited to a thinner layer and poorly established seal layer due to higher erosion and lower component of raindrop impact.

Soil erosion entails the detachment, transportation and deposition of soil material by erosive agents such as water, wind and gravity amongst others (Brady & Weil, 2008). Soil erodibility is the intrinsic susceptibility of soil to erosion and is affected by soil properties such as texture, clay mineralogy and soil organic matter (Descroix et al. 2001). The type of clay mineral and its electro-chemical properties determine the arrangements of soil particles on which the stability of aggregates depend (Morin 1993) and as such clay mineralogy has been found to affect the tendency of soils to crust (Mills & Fey, 2004). Soil loss as a result of runoff during soil erosion by water is known to be affected by slope steepness (Descroix et al. 2001) and crust formation (Le Bissonnais and Arrouays, 1997). South Africa, with its erosion prone soils
(Le Roux et al. 2008), is vulnerable to the effects of water erosion in the changing climate regime.

2.5 Response of soil microorganisms to soil surface sealing and crusting

Soil microorganisms are some of the most significant factors that influence soil quality and plant productivity (Hill et al. 2000). It is thus important that the composition and diversity of soil microbes be monitored to attain an understanding of the influence of selected factors and land use management strategies. These organisms play a vital role in the sustainable functioning of ecosystems through their work in nutrient cycling (Hill et al. 2000), organic matter regulation and modification of soil physical properties and water regimes amongst other things (Pimentel, 2006; Mandal and Neenu, 2012).

Soil compaction can affect microbial activity, organic matter and nutrient cycling processes (Silva et al. 2011). Semi-arid regions are susceptible to drying and wetting stresses due to the unreliability of rainfall events (Fierer et al. 2003). According to Castro et al (2010), changes in soil moisture conditions can have direct and indirect impacts on soil microbes. Rapid changes in water potential favour gram-positive bacteria and fungi that have thicker cell walls and solutes compatible for osmoregulation (Fierer et al. 2003).

Although agronomic production is influenced by biotic soil characteristics (Duponnois et al. (2006), there is a deficiency of information regarding micro-flora transported by runoff. Variation in soil microbial diversity with soil depth and soil health is mostly influenced by the physical properties and soil organic matter content (Bhatia, 2008). Soil redistribution in water eroded landscapes is significantly correlated to microbial biomass carbon content. (Xiao Jun et
Therefore, soil erosion is likely to reduce the overall biomass, productivity and biodiversity of microbes (Pimentel, 2006). Moreover, erosion rates above 10-20 times soil formation rates decrease the abundance and diversity of soil organisms. Furthermore, erosion processes create depositional environments, which have indirect consequences like reduced microbial habitat availability (Baxter et al. 2013).

The influence of erosion on the soil resource is governed by the variations in the types and therefore mechanisms involved. Three main types of soil erosion are recognized:

- **Sheet erosion**

  This form of erosion generally occurs when water moves uniformly downslope and the effects are normally not discernible until after it has progressed for extended periods of time (SSSA, 2008). The most prominent of these effects is the removal of the organic matter from the soil surface which renders the soil vulnerable to soil crusting and deprives soil life of food.

- **Rill and inter-rill erosion**

  The progression of sheet erosion leads to rill and inter-rill erosion. As the water continues to flow over the landscape rills are formed as a result of water concentration in the depressions that form (Brady & Weil, 2008). The water that continues to flow over the areas between these rills constitutes inter-rill erosion.

- **Gully erosion**

  The most server of all the forms of water erosion is gully erosion. This is common in steep slopes and is caused by the removal of soil from the lower regions and progressively upslope, resulting in the formation of deep channels called gullies. These gullies can affect agricultural traffic and also reduce the moisture levels of surrounding areas by inducing excessive drainage.
2.6 Effects of climate change on soil physical, chemical and biological properties

Global warming is due to changes in the gas composition of the atmosphere (Varallyay, 2010). Changes in temperature, rainfall patterns and other aspects of climate have been observed from the 20th century and are expected to occur even beyond the 21st (IPCC, 2001). The WMO (2001) stated that the nine warmest years since 1860 have occurred after 1990. In South Africa, average yearly temperatures have risen by one and a half times the global average of 0.65°C over the last half century and extreme rainfall events are more frequent (WIREs Clim. Change, 2014). Mason et al (1999) found that 70% of South Africa has experienced an increase in the occurrence of extreme rainfall events between the periods of 1931-1960 and 1961-1990. Blignaut et al (2009) state that South Africa has been approximately 2% hotter and at least 6% drier over the decade between 1997-2006. These changes will only result in the deterioration of soil productivity because these parameters are integral to soil physical, chemical and biological properties.

Soil physical properties affect water and air movement as well as conditions affecting plant growth and soil erosion processes (Allen et al, 2011). According to Varallyay (2010), climate change and its hydrological concerns may result in changes in soil conditions. Allen et al (2011) state that the key soil physical properties relevant to climate change include soil structure, bulk density, soil surface cover and infiltration. Lal & Kimble, (2001) state that bulk density has biomass productivity and environmental effects. They proceed to assert that the biomass productivity effects involve influence on root growth and proliferation and eventually nutrient and water uptake while the environmental effects include aeration, soil moisture regime, runoff and erosion. Climate change may increase soil bulk density as a result of organic carbon losses caused by increased decomposition due to higher temperatures, which ultimately results in soils
prone to compaction by climate change stresses such increase variability and intensity of rainfall and drought events (Allen, 2011). Due to the fact that soil properties are interactive in nature, the increased bulk density will result in lower porosity then reduced infiltration. The most common direct impact of climate change on soil structure is the aggregate destructing role of raindrops and subsequent runoff (Varallyay, 2010).

Climate change will also affect the biological aspects of soils, which are regulated by soil microorganisms. For example, changes in precipitation regimes may have direct and indirect impacts on soil microbial communities (Castro et al. 2010). Indirectly, the impacts would include reduced habitat availability as a result of erosion processes (Baxter et al. 2013) According to Fierer et al. (2003) changes in water potential would result in conditions where gram positive bacteria and fungi that have thicker cell walls and osmoregulation compatible solutes would be favoured.

Temperature and moisture are the two parameters regulated by climate change that have the most influence on the growth, composition and activity of soil microorganisms (Mandal & Neenu, 2012). Bhatia (2008) stated that variations in microbial populations and activities occur prior to those changes that can indicate soil degradation and/or amelioration. According to Nannipieri et al (2003) microbial and biochemical characteristics are used as soil quality indicators because they are sensitive to change and are central to the cycling of nutrients such as C & N. This section of the paper contains a review of literature on the impact of climate change, with emphasis on rainfall characteristics, on soil surface compaction (crusting) and the subsequent effects on soil infiltration, erosion and soil microbial diversity.
3. MATERIALS AND METHODS

3.1 Sampling sites

Soil samples were collected from six sites shown on the map below (Fig 3.1). The soils were grouped according to their texture and mineralogy. Three kaolinitic with low to medium clay content (K1, K2 and K3) and three smectitic soils with high clay content (S1, S2 and S3) were selected. Land type data maps were used to identify sites where the different types of soils occur in and around the Gauteng province.

Figure 3.1 Map showing the points where the samples were taken
3.2 Soil sampling and Preparation

The samples were taken from the top layer (0-20 cm) of the soil, air dried and then sieved to pass through a 2 mm sieve. Soil pH was determined in a 1:1.25 soil: water suspension using a laboratory pH meter and particle size distribution by the hydrometer method (Beretta et al. 2014). In essence, the procedure entails the sieving and sedimentation of a soil/water/calgon suspension to separate particles of different sizes based on their settling velocity as determined by Stoke’s law. The fast wetting treatment (Le Bissonais, 2016) was used to determine aggregate stability. Five grams of homogenized (sieved to a range of 3-5 mm) soils were immersed in deionized water for 10 minutes and then transferred to a 50 µm (in this study the 53 µm was used due to the 50 µm being unavailable) previously immersed in ethanol to determine fraction size distribution. The size distribution was determined by dry sieving through a set of six sieves (2000, 1000, 500, 200, 100 & 50 µm) and the last step was the calculation of the mean weight diameter by multiplying the sum of mass fraction remaining on each sieve by the mean diameter of the adjacent sieve.

The 1M neutral ammonium acetate method (van Rreeuwilk, 2002) was used to determine CEC. The cations were extracted from the soil sample by a 1 molar ammonium acetate solution at pH 7. The soil solution was shaken for two hours, centrifugation was used to separate the liquid and solid phases, and determination of the concentration of the cations was done using an ICP-OES. The principle is that the excess ammonium displaces the cations from the exchange sites to the solution.

Organic carbon was determined using the Walkley-Black method (Wang et al. 2012). Soil organic matter was oxidized with 1 normal potassium dichromate in the presence of sulphuric
acid and the percentage amount of organic carbon was calculated from the amount of dichromate remaining after titration with ferrous sulphate. Mineralogical composition of the soil samples was determined by X-ray diffraction (XRD) (Shrivastava, 2009). The procedure entails the separation of the clay fraction from the soil material and exposure to x-rays. The peaks of the diffractogram obtained correspond to the type and relative amount of mineral present. The methods selected for these analyses are not the only methods available. They were selected due to cost effectiveness, efficiency, labour intensity and suitability to intended applications.

3.3 Rainfall simulation experiment

A rotating disc rainfall simulator was used to apply storms varying in intensity to the six soils at varying slope gradients. The simulator holds four rainulator trays (60 cm×30 cm × 5cm) each with a capacity of 5 kg of soil and the highest intensity that can be applied is 150 mm/h. The trays are perforated to allow collection of the water that percolates. To ensure that no soil passes through the trays, they were lined with a selectively permeable cloth. After processing, the soils were placed in the trays ensuring that they reach up to the brim so that runoff was not blocked by the brim of the tray. The soils were then pre-wetted by capillary with tap water at 0.7 dS/m to achieve saturation before being exposed to the rainfall.

The rainfall simulator was used to apply rainfall at three different intensities (45, 70 and 100 mm/h) at two different slope gradients (5° and 8°) to the soils in triplicate. The rainfall duration was kept at 20 mins as this coincided with the final infiltration rate. A number of researchers have studied rainfall intensities ranging from 10 to 60 mm/h (Romkens et al. 2001; Ben-Hur & Wakindiki, 2004 Liu et al. 2011; Jakab et al. 2013; Nciizah & Wakindiki, 2014). In this study,
slightly higher intensities were selected according to reported estimations of climate change (Mason et al. 1999; Fauchereau et al. 2003). The measurement of parameters for each experiment is given below.

3.4 Measurements

The section below describes the procedures for making the required measurements for each of the four objectives. Two experiments were conducted, one to achieve the first two objectives and another one to achieve the third objective.

3.4.1 Rainfall simulation experiment

3.4.1.1 Infiltration rate

The amount of water percolating through the soil was collected in a graduated cylinder and recorded at each complete rotation of the rainfall simulator.

3.4.1.2 Runoff and erosion

A beaker was used to collect the runoff. The liquid phase of the runoff was then decanted and measured. Soil loss was determined as the mass of the sediment collected from each plot during the simulation after drying at 105 °C for 24 h (Nciizah & Wakindiki, 2014; Cao et al. 2015).
3.4.1.3 Crust parameters

a) Penetration Resistance (PR)

Penetration resistance was used as an index to estimate crust strength. After exposure to the rainstorms, the samples were allowed to air dry for a week (7 days) (Wakindiki & Ben-Hur, 2002; Ncizah & Wakindiki, 2014a) and a hand held cone penetrometer was used to measure PR. The penetration resistance measurements were taken from nine positions in each tray.

b) Crust thickness

A Vernier caliper was used to measure crust thickness. A piece of the crust was broken off and used for measurement with the Vernier caliper. This measurement represents another indicator of crust strength because thicker crusts offer greater resistance.

3.4.2 Microbial community analysis experiment

Culturing techniques have traditionally been used to analyze soil microbial communities (Hill et al. 2000). The technique was used to study microbial communities in the soils before and after exposure to simulated rainfall. The analysis of the communities was focused on the difference in the total numbers of microbes found in the soil and the difference in some beneficial bacteria numbers. Beneficial bacteria, for the purpose of this study, are those that are able to solubilize phosphorus, fix nitrogen and produce indole acetic acid.

3.4.2.1 Microbial isolation
Microbial isolates from each of the soils were obtained by plating serial dilutions \((10^6-10^{12})\) in nutrient agar followed by incubation at 25°C for 24-48 hours. The dilution with the most visible and countable colonies was selected for the computation of colony forming units (CFUs) according to equation 1:

\[
\frac{CFU}{ml} = \frac{\text{number of colonies}}{\text{dilution factor}} \quad [1]
\]

Colonies were then picked from these plates, purified by streaking (SGM, 2006), and kept for use in subsequent analyses.

### 3.4.2.2 Nitrogen fixation

The isolated bacteria were inoculated on Burks’s N-free medium and incubated for 7 days at 30°C (Stella & Suhaimi 2010). The number of colonies formed was then computed.

### 3.4.2.3 Phosphorus solubilization

Bacterial strains were cultivated in NBRIP broth for 48 hours and inoculated on NBRIP agar plates and incubated at 30°C for 7 days. The method was adapted from the works of Nautiyal (1999) and Baig et al. (2010). A halo zone around the colonies indicated phosphate solubilization potential. The diameter of the halo zone was used to classify the strains as either low (<1cm), medium (1-2cm) and high (>2cm) phosphate solubilizers (Baig et al. 2010).
3.4.2.4 Indole acetic acid production

The selected strains were cultured in 5 ml of nutrient broth for 24 hours and then centrifuged for 15 minutes at 100000xg at 4°C (Reetha et al. 2014). 2 ml of the supernatant was then mixed with two drops of orthophosphoric acid. The development of a pink colour indicated a positive result while yellow indicated a negative.

3.5 Experimental design and data Analysis

The study was laid out in a complete randomized design with a 2×2×3 factorial to assess the effects of two different slopes (5° and 8°) and three different intensities (45, 70 and 100 mm/h) on two soil groups (high and low activity clays). The data was subjected to ANOVA using the JMP version 14 statistics software (SAS institute, 2015). The means were separated by Fischer’s protected least square differences at a confidence interval of 95. Regression analysis between the crust parameters and selected soil properties was also performed.
CHAPTER FOUR

4. RESULTS

4.1 Initial soil characterization

The smectitic soils (S1, S2 and S3) were characterized as neutral to alkaline with pH values above seven and relatively higher levels of bases. The highly weathered kaolinitic soils (K1, K2 and K3) on the other hand had pH values below seven with K2 highest at 6.2 and K1 more acidic at 4.21 (Table 4.1). The kaolinitic soils were sandy while the smectitic soils contained high clay content of 50% and above (Table 4.2).

Table 4. 1 Selected chemical properties of the study soils

<table>
<thead>
<tr>
<th>Sample</th>
<th>pH</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
<th>Na</th>
<th>CEC</th>
<th>SAR</th>
<th>ESP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Meq/100g</td>
<td></td>
<td></td>
<td>Meq/100g</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K1</td>
<td>4.2</td>
<td>0.1</td>
<td>1.9</td>
<td>0.4</td>
<td>0.014</td>
<td>2.5</td>
<td>0.01</td>
<td>0.6</td>
</tr>
<tr>
<td>K2</td>
<td>6.3</td>
<td>0.9</td>
<td>2.7</td>
<td>1</td>
<td>0.014</td>
<td>11.1</td>
<td>0.01</td>
<td>0.31</td>
</tr>
<tr>
<td>K3</td>
<td>5.3</td>
<td>0.3</td>
<td>3.5</td>
<td>1</td>
<td>0.008</td>
<td>20.7</td>
<td>0.005</td>
<td>0.17</td>
</tr>
<tr>
<td>S1</td>
<td>7.6</td>
<td>0.5</td>
<td>36</td>
<td>13.7</td>
<td>0.07</td>
<td>43.4</td>
<td>0.01</td>
<td>0.14</td>
</tr>
<tr>
<td>S2</td>
<td>7</td>
<td>2.1</td>
<td>37.7</td>
<td>10.8</td>
<td>0.06</td>
<td>49.6</td>
<td>0.01</td>
<td>0.13</td>
</tr>
<tr>
<td>S3</td>
<td>8.2</td>
<td>0.7</td>
<td>32.7</td>
<td>21.7</td>
<td>0.1</td>
<td>42.6</td>
<td>0.02</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Table 4. 2 OC, texture, aggregate stability and mineralogy of study soils

<table>
<thead>
<tr>
<th>Soil</th>
<th>OC (%)</th>
<th>PSD (%)</th>
<th>MWD (mm)</th>
<th>Mineralogy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sand</td>
<td>Silt</td>
<td>Clay</td>
<td>Kaolinite</td>
</tr>
<tr>
<td>K1</td>
<td>2.29</td>
<td>66</td>
<td>8</td>
<td>26</td>
</tr>
<tr>
<td>K2</td>
<td>1.34</td>
<td>76</td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td>K3</td>
<td>1.01</td>
<td>52</td>
<td>8</td>
<td>40</td>
</tr>
<tr>
<td>S1</td>
<td>1.39</td>
<td>36</td>
<td>14</td>
<td>50</td>
</tr>
<tr>
<td>S2</td>
<td>1.51</td>
<td>34</td>
<td>14</td>
<td>52</td>
</tr>
<tr>
<td>S3</td>
<td>1.21</td>
<td>34</td>
<td>12</td>
<td>54</td>
</tr>
</tbody>
</table>
4.2 Effect of soil type, rainfall intensity and slope gradient on crust strength

The interaction among the three factors significantly \( p < 0.001 \) affected crust strength (Table 4.3).

Table 4. 3 ANOVA table for the effects of soil type, rainfall intensity and slope gradient on crust strength

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>F Ratio</th>
<th>Prob &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil type</td>
<td>5</td>
<td>290.53361</td>
<td>67.</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>RI (mm/h)</td>
<td>2</td>
<td>176.52292</td>
<td>103.17</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>Soil type*RI (mm/h)</td>
<td>10</td>
<td>97.8904</td>
<td>11.44</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>Slope(degrees)</td>
<td>1</td>
<td>3.36724</td>
<td>3.94</td>
<td>0.0511</td>
</tr>
<tr>
<td>Soil type*Slope(degrees)</td>
<td>5</td>
<td>76.46953</td>
<td>17.88</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>RI (mm/h)*Slope(degrees)</td>
<td>2</td>
<td>7.49679</td>
<td>4.38</td>
<td>0.0160*</td>
</tr>
<tr>
<td>Soil type*RI (mm/h)*Slope(degrees)</td>
<td>10</td>
<td>87.26476</td>
<td>10.20</td>
<td>&lt;.0001*</td>
</tr>
</tbody>
</table>

*significant difference at \( p < 0.05 \)

On one hand, the highest crust strength (18.54 Kpa) was observed on soil S2 at 45 mm/h intensity and 8° slope, (Figure 4.1). This soil had the highest organic carbon and the mineralogy was dominated by smectite and quartz with kaolinite accounting for less than 1% by weight.

On the other hand, soil K3, which had the lowest amount of sodium and highest amount of iron oxides, developed crusts with the lowest strength (5.4 Kpa) when exposed to the highest RI and slope i.e. 100 mm/h rainfall and 8° slope respectively. This was however not significantly different from the crust strength of the other kaolinitic soils K1 and K2. Generally, crust strength decreased as slope and rainfall intensity increased regardless of soil type. There were no statistically significant differences in crust strength among the six soils when exposed to 70 mm/h rainfall at 5° slope.
4.3 Effect of soil type, rainfall intensity and slope gradient on crust thickness

All three factors exerted a significant ($p < 0.05$) influence on crust thickness except for the interaction between soil type and slope gradient (Table 4.4). Moreover, there was significant ($p < 0.05$) interaction among soil type, rainfall intensity and slope gradient on crust thickness.
Table 4. 4 ANOVA table for the effects of soil type, rainfall intensity and slope gradient on crust thickness.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>F Ratio</th>
<th>Prob &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil type</td>
<td>5</td>
<td>708.17105</td>
<td>60.85</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>RI (mm/h)</td>
<td>2</td>
<td>190.94524</td>
<td>41.02</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>Soil type*RI (mm/h)</td>
<td>10</td>
<td>167.50088</td>
<td>7.20</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>Slope(degrees)</td>
<td>1</td>
<td>22.00521</td>
<td>9.45</td>
<td>0.0030*</td>
</tr>
<tr>
<td>Soil type*Slope(degrees)</td>
<td>5</td>
<td>22.20816</td>
<td>1.91</td>
<td>0.1035</td>
</tr>
<tr>
<td>RI (mm/h)*Slope(degrees)</td>
<td>2</td>
<td>19.13585</td>
<td>4.11</td>
<td>0.0204*</td>
</tr>
<tr>
<td>Soil type*RI (mm/h)*Slope(degrees)</td>
<td>10</td>
<td>67.86849</td>
<td>2.92</td>
<td>0.0040*</td>
</tr>
</tbody>
</table>

*significant difference at p <0.05

The interactive effects of the three main factors on crust thickness (Figure 4.2) were relatively similar to those on crust strength. The thickest crust (17.77 mm) occurred under the influence of 45 mm/h intensity at 8° slope on S3, which had the highest amount of clay and the only soil that contained illite among the smectitic soils. For the high clay smectite dominated soils (S1, S2 and S3), the crust thickness evened out from 70/5 (RI/Slope) through 100/8. The kaolinitic, low to medium clay soils started with thin crusts at 45/5 with a sharp increase going to 45/8 and then falling even lower at 70/5 and 70/8 before rising again at 100/5 and 100/8. K2, with the lowest clay content and iron oxides formed the thickest crust among the kaolinitic soils at 45/8.
Figure 4.2 Effects of rainfall intensity (RI) slope gradient and soil properties on crust thickness (CT). Error bars indicate standard error.

4.4 Effect of soil type, rainfall intensity and slope gradient on infiltration rate.

The interactive effects of the three factors significantly (p<0.05) affected infiltration rate (Table 4.5).

Table 4.5 ANOVA table for the effects of soil type, rainfall intensity and slope gradient on infiltration rate

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>F Ratio</th>
<th>Prob &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil type</td>
<td>5</td>
<td>3746.1129</td>
<td>199.40</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>RI (mm/h)</td>
<td>2</td>
<td>380.3234</td>
<td>50.61</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>Soil type*RI (mm/h)</td>
<td>10</td>
<td>180</td>
<td>4.79</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>Slope(degrees)</td>
<td>1</td>
<td>144.2491</td>
<td>38.39</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>Soil type*Slope(degrees)</td>
<td>5</td>
<td>319.8988</td>
<td>17.03</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>RI (mm/h)*Slope(degrees)</td>
<td>2</td>
<td>90.7389</td>
<td>12.07</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>Soil type*RI (mm/h)*Slope(degrees)</td>
<td>10</td>
<td>456.0143</td>
<td>12.14</td>
<td>&lt;.0001*</td>
</tr>
</tbody>
</table>

*significant difference at p<0.05
The infiltration rate was consistently higher for soils K1 and K2 across all treatments, but decreased significantly at higher intensities (Fig 4.3). Soil K2 had significantly higher (p<0.05) infiltration rates (33.32 and 27.89 mm/h) than K1 and K3 at 70/5 and 100/5, respectively. Under these conditions, K2 also developed the thinnest crusts among the three. Soil S3 had significantly lower infiltration rate compared to S1 and S2 across all treatments except for 45/8 where S1 was lowest. Soil S3 at 70/5 had the lowest infiltration rate. The crust strength and thickness of S3 was also significantly higher under the same conditions when compared to S1 and S2. Soils K3 and S2 had statistically similar infiltration rates at 45/8 while a significant difference was observed at 70/8.
Figure 4.3 Effects of rainfall intensity (RI) slope gradient and soil properties on infiltration rate (IR). Error bars indicate standard error

4.5 Effect of soil type, rainfall intensity and slope gradient on runoff

Runoff was significantly affected by rainfall intensity, slope and soil properties albeit to varying degrees (Table 4.6). For all soils, the lowest runoff was observed at the lowest intensity of 45 mm/h (Figure 4.4.). All the soils obtained their peak runoff amounts at 70/5 with soils S1 and S3 being significantly higher than the rest with their values of 1800 ml and 1674.07 ml, respectively. The influence of slope was again not apparent at the highest intensity of 100 mm/h for all the soils except for K1 and K2. At this intensity soils K1 and K2 showed significant decreases of 21 % and 18 %, respectively with an increase in slope.
Table 4. 6 ANOVA table for the effects of soil type, rainfall intensity and slope gradient on runoff

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>F Ratio</th>
<th>Prob &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil type</td>
<td>5</td>
<td>13527029</td>
<td>94.52</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>RI (mm/h)</td>
<td>2</td>
<td>41661494</td>
<td>727.80</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>Soil type*RI (mm/h)</td>
<td>10</td>
<td>6416659</td>
<td>22.42</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>Slope(degrees)</td>
<td>1</td>
<td>212091</td>
<td>7.41</td>
<td>0.0081*</td>
</tr>
<tr>
<td>Soil type*Slope(degrees)</td>
<td>5</td>
<td>388032</td>
<td>2.71</td>
<td>0.0266*</td>
</tr>
<tr>
<td>RI (mm/h)*Slope(degrees)</td>
<td>2</td>
<td>2901338</td>
<td>50.68</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>Soil type*RI (mm/h)*Slope(degrees)</td>
<td>10</td>
<td>2058579</td>
<td>7.19</td>
<td>&lt;.0001*</td>
</tr>
</tbody>
</table>

*significant difference at p<0.05

Figure 4.4 Effects of rainfall intensity (RI) slope gradient and slope properties on runoff (RO).

Error bars indicate standard error

4.6 Effect of soil type, rainfall intensity and slope gradient on soil loss

Similar to the other soil parameters soil loss was significantly affected by all the three main factors (Table 4.7). The interaction between the three main effects was also statistically significant (P < 0.001).
Table 4. ANOVA table for the effects of soil type, rainfall intensity and slope gradient on soil loss

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>F Ratio</th>
<th>Prob &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil type</td>
<td>5</td>
<td>3662742.6</td>
<td>144.45</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>RI (mm/h)</td>
<td>2</td>
<td>2987908.9</td>
<td>294.59</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>Soil type*RI (mm/h)</td>
<td>10</td>
<td>3507595.2</td>
<td>69.17</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>Slope(degrees)</td>
<td>1</td>
<td>817602.8</td>
<td>161.22</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>Soil type*Slope(degrees)</td>
<td>5</td>
<td>96982</td>
<td>3.82</td>
<td>0.0040*</td>
</tr>
<tr>
<td>RI (mm/h)*Slope(degrees)</td>
<td>2</td>
<td>294623.8</td>
<td>29.05</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>Soil type #*RI(mm/h)*Slope(degrees)</td>
<td>10</td>
<td>359368.7</td>
<td>7.09</td>
<td>&lt;.0001*</td>
</tr>
</tbody>
</table>

*significant difference at p<0.05

Soil loss gradually increased with an increase in rainfall intensity and slope steepness for kaolinitic soils (Figure 4.5). Moreover, for smectitic soils, soil loss increased with increasing intensity and slope especially for S3. Soils S1 and S2, which contained less kaolinite and more smectite than S3, lost more soil when exposed to the medium intensity of 70 mm/h. However, soils S3 at 100/8 (1248.13 kg/ha) and S2 at 70/8 (1145.55 kg/ha) were statically similar and the most erodible. The erodibility of the kaolinitic soils was highest at the highest intensity and slope steepness. Soil K3 at 100/8 (369.67 kg/ha) was statically similar to S3 at 70/5 (338.15 kg/ha).
4.7 Effect of soil type, rainfall intensity and slope gradient on number of bacteria

The number of bacterial colonies was significantly affected by all the treatment factors (Table 4.8). Moreover, the interactive effects among the three factors significantly (p<0.001) affected the number of bacterial colonies.
Table 4. 8 ANOVA table for the effects of soil type, rainfall intensity and slope gradient number of bacteria

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>F Ratio</th>
<th>Prob &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil type</td>
<td>5</td>
<td>1.74E+30</td>
<td>143.36</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>RI (mm/h)</td>
<td>2</td>
<td>1.61E+30</td>
<td>330.53</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>Soil type*RI (mm/h)</td>
<td>10</td>
<td>4.40E+30</td>
<td>181.12</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>Slope(degrees)</td>
<td>1</td>
<td>1.95E+30</td>
<td>801.73</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>Soil type*Slope(degrees)</td>
<td>5</td>
<td>1.68E+30</td>
<td>138.40</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>RI (mm/h)*Slope(degrees)</td>
<td>2</td>
<td>1.68E+30</td>
<td>344.81</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>Soil type*RI (mm/h)*Slope(degrees)</td>
<td>10</td>
<td>4.35E+30</td>
<td>178.94</td>
<td>&lt;.0001*</td>
</tr>
</tbody>
</table>

*significant difference at p<0.05

After exposure to the first treatment combination (45/5) all the soils had higher numbers of bacteria except for soils K2 and S1, which showed a decrease and were statistically the same (Table 4.9). Moving from treatment 45/8 to 100/5 there were no significant changes and the trend showed a gradual decrease and then an increase again at 100/5 for all the soils except for soils K1 and S1 which decreased at 70/5 and rose at 70/8 and 100/5. The numbers again dropped after the last treatment and the statistics indicate that the soils were grouped according to the pairs K1 and K3; K2 and S1 and S2 and S3.

Table 4. 9 Mean separation of the treatment effects on soil bacterial counts

<table>
<thead>
<tr>
<th>Soil</th>
<th>Initial condition</th>
<th>45/5</th>
<th>45/8</th>
<th>70/5</th>
<th>70/8</th>
<th>100/5</th>
<th>100/8</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>8.05E+13</td>
<td>2.05E+14&lt;sup&gt;d&lt;/sup&gt;</td>
<td>5.20E+12&lt;sup&gt;e&lt;/sup&gt;</td>
<td>2.02E+11&lt;sup&gt;c&lt;/sup&gt;</td>
<td>6.00E+13&lt;sup&gt;e&lt;/sup&gt;</td>
<td>2.10E+14&lt;sup&gt;c&lt;/sup&gt;</td>
<td>2.30E+12&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>K2</td>
<td>9.78E+13&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1.90E+13&lt;sup&gt;c&lt;/sup&gt;</td>
<td>6.20E+12&lt;sup&gt;e&lt;/sup&gt;</td>
<td>1.60E+10&lt;sup&gt;e&lt;/sup&gt;</td>
<td>8.00E+09&lt;sup&gt;e&lt;/sup&gt;</td>
<td>5.60E+14&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1.85E+12&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>K3</td>
<td>4.61E+14&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.42E+15&lt;sup&gt;a&lt;/sup&gt;</td>
<td>4.60E+12&lt;sup&gt;e&lt;/sup&gt;</td>
<td>3.10E+12&lt;sup&gt;e&lt;/sup&gt;</td>
<td>3.50E+11&lt;sup&gt;c&lt;/sup&gt;</td>
<td>2.95E+14&lt;sup&gt;c&lt;/sup&gt;</td>
<td>4.50E+13&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>S1</td>
<td>1.12E+14&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1.32E+11&lt;sup&gt;c&lt;/sup&gt;</td>
<td>2.20E+11&lt;sup&gt;e&lt;/sup&gt;</td>
<td>6.60E+10&lt;sup&gt;e&lt;/sup&gt;</td>
<td>3.00E+13&lt;sup&gt;e&lt;/sup&gt;</td>
<td>6.35E+14&lt;sup&gt;c&lt;/sup&gt;</td>
<td>5.35E+12&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>S2</td>
<td>2.97E+14&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.76E+15&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2.54E+13&lt;sup&gt;e&lt;/sup&gt;</td>
<td>5.30E+10&lt;sup&gt;e&lt;/sup&gt;</td>
<td>1.30E+10&lt;sup&gt;e&lt;/sup&gt;</td>
<td>2.80E+12&lt;sup&gt;e&lt;/sup&gt;</td>
<td>1.20E+12&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>S3</td>
<td>2.21E+12&lt;sup&gt;d&lt;/sup&gt;</td>
<td>1.05E+13&lt;sup&gt;e&lt;/sup&gt;</td>
<td>2.02E+10&lt;sup&gt;e&lt;/sup&gt;</td>
<td>1.14E+11&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1.50E+10&lt;sup&gt;e&lt;/sup&gt;</td>
<td>1.50E+12&lt;sup&gt;e&lt;/sup&gt;</td>
<td>1.10E+12&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

33
4.8 Effect of soil type, rainfall intensity and slope gradient phosphate solubilization

The soils contained predominately low and medium potential Phosphate solubilizing bacteria (PSB) as evidenced by the values below 1 and 2 cm, respectively (Fig 6). The only exception is K3, which shows the occurrence of high potential PSB with a 2.5 cm halo zone diameter. The application of the treatments however dropped the value. No PSB were found on soils K2 and S1 after exposure to treatment 70/8 and likewise for S1 and S2 after treatment 100/5. Another notable observation is that the high clay smectitic soils generally had statistically more phosphate solubilizing potential.

![Graph showing treatment effects on phosphate solubilizing bacteria](image)

Figure 4.6 Treatment effects on phosphate solubilizing bacteria, error bars indicate standard error
4.9 Effect of soil type, rainfall intensity and slope gradient on nitrogen fixation

The number of nitrogen fixing bacteria were highest at slope 5° (1.68E+12) but this was still statistically similar to values before exposure to simulated rainfall (1.47E+12) (Table 4.12).

The number of nitrogen fixing bacteria dropped when the slope was raised to 8°.

Table 4. 10 ANOVA table for the effects of soil type, rainfall intensity and slope gradient on nitrogen fixing bacteria

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F ratio</th>
<th>Prob &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td>Levels</td>
<td>5</td>
<td>5.23E+23</td>
<td>1.05E+23</td>
<td>0.0919</td>
<td>0.9930</td>
</tr>
<tr>
<td></td>
<td>Error</td>
<td>36</td>
<td>4.10E+25</td>
<td>1.14E+24</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>41</td>
<td>4.15E+25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RI</td>
<td>Levels</td>
<td>3</td>
<td>2.75E+24</td>
<td>9.16E+23</td>
<td>0.8986</td>
<td>0.4509</td>
</tr>
<tr>
<td></td>
<td>Error</td>
<td>38</td>
<td>3.87E+25</td>
<td>1.02E+24</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>41</td>
<td>4.15E+25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slope</td>
<td>Levels</td>
<td>2</td>
<td>4.66E+24</td>
<td>2.33E+24</td>
<td>2.4668</td>
<td>0.0980</td>
</tr>
<tr>
<td></td>
<td>Error</td>
<td>39</td>
<td>3.68E+25</td>
<td>9.44E+23</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>41</td>
<td>4.15E+25</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.10 Effect of soil type, rainfall intensity and slope gradient on indole acetic acid producing bacteria

The potential of bacteria to produce Indole acetic acid was not affected by any of the three factors (Table 4.12).

Table 4. 11 ANOVA table of treatment effects on indole acetic acid producing bacteria

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F ratio</th>
<th>Prob &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td>Levels</td>
<td>5</td>
<td>2.6589</td>
<td>0.53</td>
<td>1.1616</td>
<td>0.3468</td>
</tr>
<tr>
<td></td>
<td>Error</td>
<td>36</td>
<td>16.4810</td>
<td>0.46</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>41</td>
<td>19.1399</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RI</td>
<td>Levels</td>
<td>3</td>
<td>2.6822</td>
<td>0.89</td>
<td>2.0644</td>
<td>0.1212</td>
</tr>
<tr>
<td></td>
<td>Error</td>
<td>38</td>
<td>16.4576</td>
<td>0.43</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>41</td>
<td>19.1399</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slope</td>
<td>Levels</td>
<td>2</td>
<td>0.9537</td>
<td>0.48</td>
<td>1.0227</td>
<td>0.3691</td>
</tr>
<tr>
<td></td>
<td>Error</td>
<td>39</td>
<td>18.1861</td>
<td>0.47</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>41</td>
<td>19.1399</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.11 Relationship between soil crusting and selected soil properties.

The relationships between the crust parameters strength and thickness and selected soil properties are shown on figs 4.7 and 4.8, respectively. IR was the only parameter to have a significant (p < 0.05) inverse relationship with crust strength ($R^2 = 0.84$) and thickness ($R^2 = 0.85$). OM on the other had virtually no relationship with both CS and CT with the $R^2$ values very close to Zero (Fig 4.7b and 4.8b). An increase in crusting is again shown to increase soil loss with both parameters having a significant positive relationship with CS ($R^2 = 0.98$) and CT ($R^2 = 0.96$). The remaining parameters (clay, CEC, SAR and RO) also showed positive linear relationships with the crust parameters having an $R^2$ above 0.6.
Figure 4.7 Regression analysis of CS vs a) Clay, b) OC, c) CEC, d) SAR, e) IR, f) RO and g) SL.
Figure 4.8 Regression analysis of CT vs a) Clay, b) OC, c) CEC, d) SAR, e) IR, f) RO and g) SL.
CHAPTER FIVE

5. DISCUSSION

5.1 Soil sealing and crusting

Soil surface crusting is affected by soil physical, chemical and biological properties, external factors such as rainfall characteristics, slope, and management practices. In the current study, the kaolinitic soils showed significantly lower crustability compared to the smectitic soils. The kaolinitic soils contained iron oxides hematite and goethite, which are known cementing agents unlike the smectitic soils (Table 4.2) (Nciizah and Wakindiki, 2014b). The aggregate stability influence was evident in that the only soil classified as unstable (S2) show the highest crustability at even the lowest rainfall intensity. It should however be noted that the aggregate stability of the soils differs markedly. This observation further suggests the interactive nature of the factors that influence soil sealing and crusting.

The sandy loam texture of the kaolinitic soils also suggests improved drainage and the low activity of the clays mean porosity reduction through swelling is negligible (Medinski et al. 2009 & Habel, 2013). The crustability of the soils also decreased with increasing rainfall intensity and slope gradient across the different mineralogies. Other researchers (Zejun et al 2002; Ribolzi et al. 2011; Nciizah and Wakindiki, 2014a) also observed this. This is explicable by the observation that an increase in raindrop kinetic energy reduces the slaking forces and thus seal development (Ben-Hur and Lado, 2008 & Assouline and Ben-Hur, 2006). This is because higher energy raindrops encourage mechanical breakdown rather than slaking (Darboux et al. 2016), which results in increased soil loss (Ben-Hur & Lado, 2008). Han et al. (2016), assert that the slaking effect of raindrops on soil aggregates becomes more significant with increasing wetting rate. It is however important to note the influence of such properties as clay content, mineralogy and exchangeable sodium percentage on aggregate stability.

In this study, the kaolinites (K1, 2 & 3) showed low crustability even at high rainfall intensity compared to the smectites (S1, 2 & 3). The smectites had the highest clay content, which would translate to greater stability due to the cementing ability of clay, but the relatively low ESP rendered them prone to slaking forces and therefore seal formation. According to Ben-Hur and Lado (2008), an increase in ESP results in lower slaking forces due to increased dispersivity.
The stability of the kaolinites on the other hand, is due mostly to the type of clay and the presence of iron minerals of goethite and hematite (sesquioxides), which also act as aggregate binding agents.

The crustability of the fine textured smectite dominated soils was significantly higher. The regression analysis shows a strong positive relationship between crust strength and both clay content and cation exchange capacity. According to Joshi (2017), the greater cohesive forces in fine textured soils increase the sealing efficiency of soil crusts because clay particles can clog the bigger pores and lower the hydraulic conductivity. On the other hand, Ben-Hur and Wakindiki (2004) stated that soils with smectite are more dispersive than kaolinitic soils due to their swelling characteristics. It has been established that clay dispersion is one of the processes involved in crust formation (Mill & Fey, 2004; Medinski et al. 2009; Jakab et al. 2013). Yilmaz et al. (2005) also stated that the stability of soils decreases with increasing smectite to kaolinite ratio and decrease in Ca/Mg ratio. The results of the study also showed that the crust strength and thickness of the study soils generally increased when the slope increased from 5° to 8°. The findings of Ben-Hur and Wakindiki (2004) suggest that an increase in slope steepness should have a slight effect on aggregate breakdown because the reduction in the vertical component raindrop impact is small. It follows then that the change in crustability would not be significant. In the same study Ben-Hur and Wakindiki (2004), found that the effect of slope increased with increasing dispersivity. This explains the observation that in the current study the soil (S3) with least amount of smectite was least affected by slope gradient.

5.2 Infiltration rate

The phenomenon of soil crusting affects a number of soil properties. The movement of water into the soil is one such property and the ripple effects extend to runoff and soil loss. In the study, the infiltration rate decreased with increasing rainfall intensity and slope steepness, albeit with noticeable fluctuations between treatments. Decreasing infiltration rate as rainfall intensity increased can be attributed to the sealing effect as the moisture content increases and the formation of a surface seal as a result of slaking (Hamza & Anderson, 2005 and Jakab et al, 2013). The sandy loam kaolinitic soils consistently showed higher infiltration rate compared to the heavy textured smectitic soils with lower pore size distribution. Han et al (2016) found that the infiltration rate of red loam soil exhibited three phases: gradual change in infiltration
coupled with increasing cumulative infiltration followed by a rapid drop as the pores are blocked and lastly an increase as a result of removal of obstructing factors as the rain continued.

Another observation in this study was that infiltration increased at 100 mm/h at 5° and 8° compared to 70 mm/h at 8° slope. This could be due to the unsteady conditions caused by the continuous formation-destruction processes during seal development (Han et al 2016). Under unsteady conditions, infiltration rate increases with increasing slope steepness and rainfall intensity (Sajjadi and Mahmoodabadi, 2015). According to Assouline and Ben-Hur (2006) high intensity rainfall and steep slope reduce the perpendicular component of raindrop impact and thus seal development. The infiltration of water into the soil is increased at steep slopes due to faster depletion of pre-detached soil resulting in poor seal development (Sajjadi and Mahmoodabadi, 2015). Furthermore, higher rainfall intensity results in increased stream power, which enhances removal of fine particles during seal development (Sajjadi and Mahmoodabadi, 2015). Ribolzi et al. (2011) assert that high intensity rainfall results in increased crusting at flat slopes compared to steep slopes.

5.3 Runoff and soil loss

Generally, the studied soils showed an increase in runoff and subsequently soil loss as the rainfall intensity and slope increased albeit with fluctuations as a result interaction with other parameters. This is consistent with findings of other investigators (Wakindiki & Ben-Hur, 2004; Mohamadi & Kavian, 2015; Nciizah & Wakindiki, 2015). The observed differences in the response of the different soils indicates the influence of soil properties. For example, the kaolinitic soils showed lower soil loss values compared to the smectitic soils. Wakindiki and Ben-Hur (2004), concur that kaolinitic soils are less erodible than smectitic soils, which are more dispersive. They found that soil loss was more pronounced in a soil dominated by smectite than one dominated by kaolinite even though the texture and organic matter were similar. The 2:1 structure of the smectitic clays makes them swell when wetted resulting in porosity reduction and faster runoff initiation. In this study, this is indicated by the difference in soil loss between soil S1 and K3, which both had high clay (50 and 40 %, respectively). This indicates that the type of clay is more influential than the amount when the clay content is high, which is in agreement with the findings of Assouline (2004).
Another interesting observation in the current study is that crusting and soil loss were highest in the high clay soils. Clay content is known to be a cementing agent and thus soils high in clay content are generally stable. However, Bu et al. (2014) reported similar results in that soil loss was higher in high clay soils compared to low clay soils. According to Yılmaz et al. (2005) high clay does not always translate to improved stability because the properties of the particular clay are important. These soils had the highest clay, but the type of clay played a more significant role. Soils with a mineralogy dominated by smectite are known to swell when wetted and shrink when dried out (Brady & Weil, 2008). Wakindiki and Ben (2002) also found inverse soil loss values for soil of similar clay content but different mineralogy. The higher clay content also means lower hydraulic conductivity and therefore runoff is initiated earlier compared to low and moderate clay content soils.

The influence of slope gradient is another factor that determines infiltration rate, runoff and subsequently erosion (Sajjadi & Mahmoodabadi, 2015). In this study, the values of runoff and soil loss increased with increasing slope gradient except at the medium (70 mm/h) intensity and 8° slope where there was a decrease. According to Ribolzi et al. (2011), surface seals developed on steep slopes can be more permeable than those formed on flatter slopes. This can be attributed to the negligible decrease in the perpendicular component of raindrop impact as slope steepness increases. This explains the observation that the same soil can produce greater runoff and lower soil loss under the same conditions (Assouline & Ben-Hur, 2006). Sajjadi and Mahmoodabadi (2015) also stated that an increase in infiltration at steep slopes is caused by reduced seal development as detached material is depleted.

**5.4 Soil bacterial counts**

According to Martinez-Mera and Torregroza (2017) and Reese et al. (2017), microbial communities are affected by such properties as pH, organic matter and soil moisture. Other authors add that major nutrients, soil texture, root exudates and climate also exert an influence (Stutter & Richards, 2012; van Horn et al. 2013; Cao et al. 2016; Nkuekam et al. 2018). Soil bacteria prefer slightly neutral to alkaline pH and appreciable amounts of soil organic matter (Martinez-Mera & Torregroza, 2017). In the current study, initial bacterial counts showed that soil K3 had the highest number of bacteria than all the other soils. An apparent difference with soil K3 is that the texture allows for a balance between drainage and water holding capacity with the clay content at 40% and sand at 52%. The neutral to alkaline pH of the smectitic soils
and their relatively higher organic carbon and exchangeable bases explain their high numbers. The bacterial counts also showed a trend that corresponds to the changes in soil conditions due to the treatments. The numbers started high and gradually decreased as the treatments progressed. Infiltration rate started high, dropped and increased again at the 100mm/h treatment at both slopes. The most important factor affecting the microbial counts was soil type compared to rainfall intensity and slope. The influence of rainfall intensity and slope was mainly as a result of their influence on soil loss, with the microbial counts being lower for the soils that experienced greater soil loss.

5.5 Phosphate solubilizing potential

The initial conditions of phosphate solubilizing potential correspond to the initial conditions of bacterial numbers with soil type being the dominant factor. The loss of microbes due to runoff and soil loss was again the indirect effect of rainfall intensity and slope. K3 had the highest phosphate solubilizing potential followed by the smectitic soils with K1 and K2 bringing up lowest. This observation corresponds well with literature in that K3 is acidic and S3 is alkaline. In acidic soils, the P that is bound to Fe and Al compounds is solubilized through the release of protons by phosphate solubilizing bacteria resulting in the lowering of negative charge of adsorption surfaces thereby encouraging the sorption of phosphate anions (Jusop et al. 2013). In the case of alkaline soils, P is usually bound to calcium ions and is solubilized through the production of organic acids (Khan et al. 2014). Under conditions of low Fe, the microbes produce complexing agents known as siderophores that can solubilize the Fe in both organic and inorganic compounds thereby releasing the phosphate (Jones & Oburger, 2011). In microbes, siderophores are responsible for the transportation of iron (Jones & Oburger, 2011). Organic P is also mineralized by PSB through the secretion of enzymes that utilize the P as a substrate and in turn convert it to inorganic forms (Khan et al. 2014).

5.6 Nitrogen fixing bacteria

In the case of nitrogen fixation, the results showed that the steep slope of 8° had lowest number of nitrogen fixing bacteria. This could be explained by the fact that steep slopes favour runoff and reduced infiltration and therefore reduced soil moisture. Coskan et al. (2013) state that nitrogen fixing bacteria tend to thrive in soil with high water holding capacity. The reduction of infiltration and poor aeration associated with crusted soils is responsible for the reduction in
nitrogen fixation because nitrogen fixing bacteria require moisture and oxygen for optimum function.

5.7 Indole acetic acid production

Indole acetic acid on the other hand was highest under high rainfall intensity. pH, carbon and nitrogen levels and temperature (Scarcella et al. 2017) mostly affect indole acetic acid production. It is therefore reasonable to assume that factors that influence these three factors would subsequently affect indole acetic acid production. At high rainfall intensity, the crusting of the study soils was low and therefore the effects were not pronounced. This is in agreement with the findings of Mohite (2013), that indole acetic production is improved under conditions of low oxygen, such as when a soil is compacted and porosity is reduced.
6.1 Conclusions

The aim of the study was to determine the crustability of soils with different texture and mineralogy as affected by rainfall intensity and slope gradient and the subsequent effects on soil infiltration rate, runoff and soil loss and soil microbial composition. The findings suggest that:

I. Increasing rainfall intensity increases crustability but only up to a certain threshold depending on other parameters. This was evident in the study in that the medium intensity had a more pronounced influence on crust strength than the highest intensity.

II. Soil texture and mineralogy play an important role in crust formation processes. Heavy textured (high clay) soils with swelling and shrinking properties are prone to crusting. This highlighted the interactive nature between amount and type of clay because high clay soils would have been expected to be more stable.

III. The study also found that sealing and crusting has negative effects on infiltration rate, runoff and soil loss. An increase in crustability favoured reduced infiltration and increased runoff and soil loss.

IV. Bacterial composition and phosphate solubilization were influenced by soil properties more than rainfall intensity and slope while no significant influence was observed for nitrogen fixation and indole acetic acid production.

6.2 Recommendations

It is recommended that further research be conducted to improve the understanding of the intrinsic processes that determine the effects of the factors. This is particularly important because the interaction of two or more factors tends to result in an almost knew effect that is
not yet understood. Acquisition of a comprehensive understanding of the properties and processes involved in how the soil resource responds to stresses is vital for its sustainable use to benefit all who depend on it. The soil resource is integral to all aspects of life and therefore requires careful handling which can only be achieved with complete understanding. Sustainable management of crust prone soils mandates practices that will integrate irrigation scheduling, organic matter incorporation and maintenance of ground cover. Cultivation procedures should also consider changes in rainfall variability and landscape topography.

The current study could be improved by paying attention to other relevant properties and indices to further elucidate the complexities of the interactive effects. There are properties that can explain the behavior of swelling clays further like the atterberg limits. A study of the pressure changes associated with wetting and drying could explain the dynamics of crust formation even better. The response of the soil microbes can be explained better by assessing more than just changes in their populations but also their activity and functionality. Land use management also plays a role in the modification of soil properties and improved understanding will afford land users the opportunity to devise more efficient and sustainable practices.
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