Rainfall intensity effects on crusting and mode of seedling emergence in some quartz-dominated South African soils

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ABSTRACT

Predicted changes in rainfall intensity due to climate change are likely to influence key soil health parameters, especially structural attributes and crop growth. Variations in rainfall intensity will impact crop production negatively. It is therefore imperative to investigate the interaction between predicted increases in rainfall intensity and key soil health parameters, particularly in relation to soil structural attributes and plant growth. The objectives of this study were to determine the effects of rainfall intensity on soil crust formation and mode of seedling emergence in soils dominated by primary minerals. Soil samples were collected from the top 200 mm, air dried and then packed uniformly into plastic pots, which were perforated at the bottom. Three maize seeds of equal size were planted in a triangular pattern in each pot at a depth of 30 mm, after which the pots were pre-wetted by capillary. The samples were then subjected to simulated rainfall at 3 intensities, i.e., 30, 45 and 60 mm/h, for 5 min. Rainfall intensity significantly ($P < 0.05$) affected crust strength and mean emergence day (MED), but not emergence percentage (EMP) and shoot length ($P > 0.05$). The 60 mm/h rainfall intensity resulted in the highest crust strength and MED. The strength of crust for all three rainfall intensities was influenced by quartz content, soil organic matter, clay and hematite. Most seedlings emerged through cracks, which resulted in rainfall intensity having no significant effects on seedling EMP and shoot length. We concluded that any increase in rainfall intensity is likely to increase the severity of crusting in these soils. However, soils with extensive cracking are likely to have higher EMP and lower MED and more vigorous seedlings despite the strength of the crust. As a result, post-planting tillage methods that enhance crust cracking may be employed to enhance seedling emergence and growth in these soils.

Keywords: climate change, crusting, mineralogy, penetration resistance, soil organic matter

INTRODUCTION

Changes in climate are projected to cause variations in rainfall characteristics (IPCC, 2007; Davis, 2010; Allen et al., 2011). Global climate models have shown that global warming will increase the intensity of extreme precipitation events, even in areas where mean rainfall decreases with longer periods between rainfall events (IPCC, 2007). Moreover, similar regional models have indicated significant changes in rainfall intensity in South Africa (UNICEF, 2011). An up to 50% increase in the intensity of 10-year high-rainfall events along the east coast of South Africa was predicted by Mason et al. (1999) and Shongwe et al. (2009). In general, such variations in rainfall patterns and intensity, coupled with rising temperature, affect crop yield directly and indirectly through changes in irrigation water availability (Soriano-Soto et al., 1995; Nelson et al., 2009). Whilst it is generally agreed that changes in climate will have dire effects on agriculture, the exact nature of these biophysical effects and the human responses to them are complex and uncertain, thus adding considerable uncertainty to assessment efforts (Adams et al, 1998; Walthall et al., 2012). For instance, crop simulation models usually used to determine the effects of climate change on crop productivity have limitations, which include isolation from the variety and variability of factors and conditions that affect production in the field (Adams et al., 1998; Nelson et al., 2013). In a USDA report (Walthall et al., 2012), it was noted that a healthy soil should have appropriate levels of nutrients necessary for the production of healthy plants, moderately high levels of organic matter, a soil structure with good aggregation of the primary soil particles and macro-porosity, moderate pH levels, thickness sufficient to store adequate water for plants, a healthy microbial community, and absence of elements or compounds in concentrations toxic for plant, animal, and microbial life. However, changes in climate, particularly rainfall intensity, will result in sealing, crusting, erosion and loss of organic matter, which influences soil health although the effects are complex. Therefore, it is imperative to investigate the interaction between the predicted increases in rainfall intensity, key soil health parameters, especially structural attributes, and plant growth. Such an understanding will assist in adapting to change and hence reduce vulnerability to climate change.

Soil structure determines aggregate stability and organic matter turnover, which, in turn, affect crust formation (Wakindiki and Ben-Hur, 2002; Augeard et al., 2008; Fan et al., 2008; Allen et al., 2011). Apart from the soil properties, rainfall characteristics, especially intensity, affect crust formation (Assouline, 2004; Liu et al., 2011). Accordingly, at high intensity, rainfall exceeds the infiltration capacity of the soil more quickly, leading to ponding (Hillel, 1998). In that saturated condition, the soil structure is less stable and the soil aggregates break down faster under raindrop impact and rapid wetting (Liu et al., 2011). Moreover, higher rainfall intensity produces larger size raindrops with higher impact energy that enhances crust formation (Moussouni et al., 2013). However, in South Africa, work simulating the effects of changing rainfall intensity due to climate change on soil structure attributes such as crust formation is scant.

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Furthermore, many soils in the Eastern Cape Province are dominated by unstable quartz minerals and are prone to crusting (Nciizah and Wakindiki, 2012).

Optimum crop establishment depends on the physical condition of the seedbed. A proper seedbed should provide good seed–soil contact, nutrition, water-holding capacity and aeration. Extreme rainfall events affect soil infiltration, crusting, runoff generation and erosion (Auzet et al., 2004). The formation of crusts at the soil–atmosphere interface adversely affects crop establishment because seedling emergence and early root growth are impaired (Rapp et al., 2000; Braumhardt et al., 2004).

Nonetheless, the ability of seedlings to penetrate soil crusts depends on seedling properties, e.g., species (Rapp et al., 2000), type of seedling emergence, i.e., whether it is epigeal or hypogeal (Hyatt et al., 2007), and crust properties such as strength and thickness, which are likely to be influenced by changes in rainfall intensity (Hillel, 2003). Crust properties are mostly related to soil water content, texture and mineralogy (Wakindiki and Ben Hur, 2002). Equally, the same soil properties affect crust crack properties (Aubertot et al., 2002). Cracks in crusts facilitate seedling emergence (Aubertot et al., 2002). In the absence of cracking in the crusts, seedlings emerge by (i) exerting sufficient pressure to displace soil material, (ii) a group of seedlings exerting sufficient total force to rupture and lift a portion of the crust and (iii) transferring water from roots to the shoot tip to soften the crust (Aubertot et al., 2002). In order to improve crop establishment, it is particularly important to study how maize seedlings emerge through the crust. Therefore, the objectives of this study were to determine (i) the effect of rainfall intensity on soil crust formation and (ii) the mode and mechanism of seedling emergence in some crusted South African soils with varying texture and mineralogy.

MATERIALS AND METHODS

Soil sampling and characterisation

Soils from the following ecotopes; Alice Jozini, Mbems Koedosvlei, Lujiko Leeufontein, Phandulwazi Jozini and Amatola Jozini were selected for this study based on findings from earlier studies by Nciizah and Wakindiki (2014). These soils had the least kaolinite and smectite and highest quartz content. Soil samples were collected from the top 200 mm, air dried for a week and passed through a 2 mm sieve and characterised for relevant soil properties (Table 1). The following soil parameters were measured: pH and EC, following methods described by Okalebo et al. (2000); particle size distribution, according to Gee and Or (2002); SOM content following Cambardella et al. (2001); and soil mineralogy according to the Rietveld method as described by Zabala et al. (2007).

Experimental design and procedure

Soil collected from the five ecotopes was packed uniformly into plastic pots which were perforated at the bottom. The pots were arranged in a completely randomised design (CRD) with 3 treatments and 5 replicates were used for this study. The treatments were the different rainfall intensities, and the replicates were the five ecotopes. The pots had a diameter of 125 mm and a depth of 100 mm. These pots were similar to those used by Rapp et al. (2000). To prevent soil loss from the pots and allow drainage, filter paper was placed at the bottom of each pot before packing the soil. The 2-mm aggregate size, which was shown to be highly susceptible to crusting in earlier studies (Nciizah and Wakindiki, 2012), was used in this experiment. A medium season-length maize cultivar, PAN 6479, was used in this study. Three maize seeds of equal size were planted in a triangular pattern in each pot to minimise interaction among the seedlings. A planting depth of 30 mm was used for all of the pots. After planting, the pots were pre-wetted by capillary action.

Rainfall simulation

A rainfall simulator (LUW, Eijkelkamp Equipment, 6987 ZG Giesbeck, Netherlands) was used. The simulator had 49 capillary tubes and raindrops of 5.9 mm in diameter. The soil samples were then subjected to simulated rainfall at 3 intensities, namely, 30, 45 and 60 mm/h, for 5 min. These intensities were selected based on Stocking and Elwel's (1976) definition of erosive rainfall, which is a storm with a 5-min intensity exceeding 25 mm/h. Since rainfall intensity has been projected to increase by up to 50% (Mason et al., 1999) a maximum intensity of 60 mm/h was selected. Moreover, similar rainfall intensities were used by Liu et al. (2011) and Romnkens et al. (2001). After the simulation, the pots were placed in the glasshouse.

Measurements

The number of emerging seedlings was recorded daily for 10 days. From the daily counts, emergence percentage (EMP) and mean emergence time (EMT) were calculated using the formulae of Ellis and Roberts (1980) as follows:

$$EMP = \left(\frac{Number\ of\ emerged\ seedlings}{Number\ of\ seeds\ planted} \right) \times 100 \qquad (1)$$

$$EMT = \frac{\sum (nd)}{\sum n} \qquad (2)$$

where:

n = number of seedlings emerged on day d

d = day number

$\sum n$ = total number of emerged seedlings

At the end of the emergence period, shoot length was measured with a ruler. Mode of seedling emergence was observed and recorded and assigned to one of the following categories: penetration (P), breaking with creation of one or more fragments (B), breaking and lifting of a fragment (BL), lifting of an existing fragment (L), and emergence through a crack (C) (Aubertot et al., 2002). The mass of crust fragments moved by emerged seedlings was recorded at the end of the emergence period (Aubertot et al., 2002). Non-emerged seeds were removed to determine the reason for non-emergence and classified into 3 classes: non-germinated seeds (NG), abnormal seedlings (AB), and seedlings blocked by crust (SB).

Crust strength was measured in each treatment from 3 positions, by steadily pushing a flat point hand-held penetrometer (Geotest Instrument Corp) into the top 5 mm of the soil.

Statistical analysis

Analysis of variance (ANOVA) was performed using JMP 10 (SAS Institute, 2012). Mean separations were done using Fisher's protected least significant differences (LSD) at $P < 0.05$.

TABLE 1
Selected physical, chemical and mineralogical properties for the 5 ecotopes

Ecotope	Management	*PSD (%)			EC ($\mu S \cdot m^{-1}$)	Textural class	Climate	pH	SOM (%)	Soil mineralogy (%)		
		Sand	Clay	Silt						H$^{\#}$	Q	S
Alice Jozini	Cultivation	60	12	28	47.9	SL	SA	5.7	35.7	0.29	77.01	-
Amatola Jozini	Cultivation	47	37	16	28.47	SCL	SH	5.80	66.1	1.91	28.88	14.7
Mbems Koedosvlei	Pasture	56	21	23	55.17	SCL	SA	5.65	34.3	1.1	77.35	-
Lujiko Leeufontein	Cultivation	68	19	11	52.23	SL	SA	5.45	38.2	0.63	75.14	-
Phandulwazi Jozini	Pasture	58	21	21	37.80	SCL	SA	5.49	24.7	0.58	86.85	-

**PSD = particle size distribution*
H$^{\#}$ = hematite, Q = quartz, S = smectite
SL = sandy loam, SCL = sandy clay loam, L = loam
SA = semi-arid, SH = sub-humid (Nciizah and Wakindiki, 2012)*

TABLE 2
Exchangeable bases, sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP) for the five soils

	Exchangeable bases cmol(+)/kg				
Ecotope	Na	Mg	Ca	SAR	ESP
Alice Jozini	1.12	2.07	77.31	0.12	2.08
Amatola Jozini	0.16	2.80	87.65	0.01	1.96
Lujiko Leeufontein	0.31	1.54	32.15	0.06	2.00
Mbems Koedosvlei	0.30	1.48	31.41	0.06	2.00
Phandulwazi Jozini	0.45	1.11	26.17	0.09	2.04

(From: Nciizah and Wakindiki, 2014)

RESULTS

Chemical, physical and mineralogical properties of study soils

Some chemical, physical and mineralogical properties of the soils used in this study are shown in Table 1. The most dominant textural classes were sandy clay loam and sandy loam (Table 1) whilst the soil mineralogy was dominated by primary minerals, mainly quartz. Climatic conditions were mostly semi-arid. Exchangeable bases, exchangeable sodium percentage (ESP) and sodium absorption ratio (SAR) of the soils are shown in Table 2. The SAR for all the soils was below 15 cmol(+)/kg whilst the ESP was below 6% for all the soils.

Effect of rainfall intensity on crust strength

Crust strength, which was measured as penetration resistance (PR), was significantly affected by rainfall intensity ($P < 0.05$). Penetration resistance values of 1.97, 2.24 and 2.42 kg/m^2 were obtained for the 30, 45 and 60 mm/h rainfall intensities, respectively (Fig. 1).

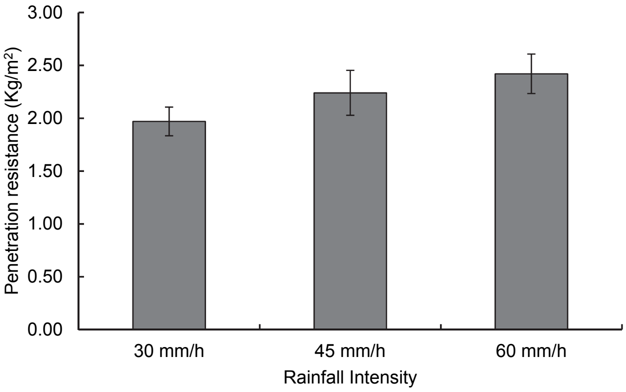

Figure 1
Crust strength as affected by rainfall intensity. Error bars represent standard error.

Relationship between soil mineralogy (hematite and quartz), clay content, soil organic matter and penetration resistance

The relationship between crust strength, SOM and mineralogy was analysed because crusting is influenced by these parameters. Crust strength significantly ($P < 0.05$) increased with an increase in quartz content for all three rainfall intensities (Fig. 2). The coefficient of determination was 0.67 for the 60 mm/h intensity, 0.81 for 30 mm/h and 0.83 for the 45 mm/h intensity. Contrary to this, penetration resistance decreased significantly ($P < 0.05$) with an increase in hematite ($R^2 = -0.73$, -0.76 and -0.55), clay ($R^2 = 0.86$, 0.66 and 0.70) and SOM ($R^2 = 0.64$, 0.87 and 0.80), respectively, for the 30, 45 and 60 mm/h rainfall intensities (Fig. 2).

Effect of rainfall intensity on mean emergence day

Rainfall intensity had significant effects ($P < 0.05$) on mean emergence day (MED) of maize. The highest MED, 9.04, was observed after exposing the seedlings to 60 mm/h whilst the 45 mm/h rainfall intensity resulted in the earliest emergence. However, there were no significant differences in MED between the 30 and 45 mm/h rainfall intensities (Fig. 3).

Effect of rainfall intensity on maize seedling emergence percentage

Although rainfall intensity did not significantly affect seedling

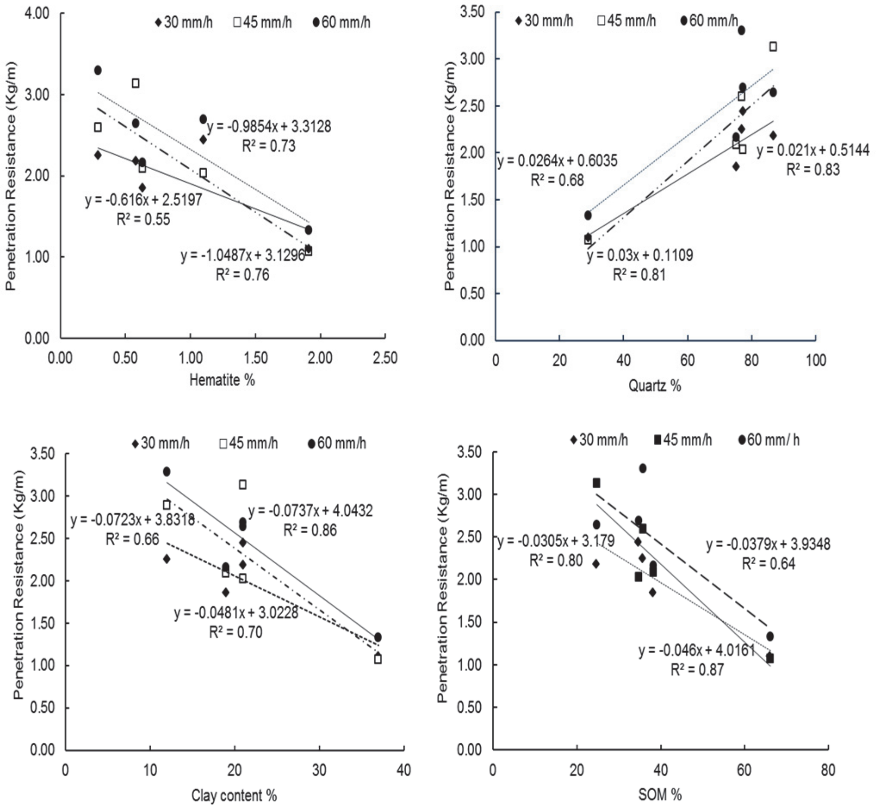

Figure 2
Relationship between hematite, quartz, clay and SOM content and penetration resistance for the three rainfall intensities

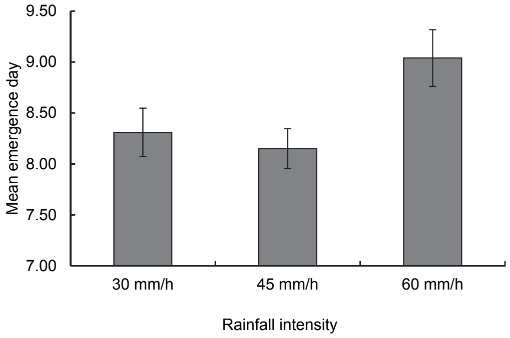

Figure 3
Effect of rainfall intensity on mean emergence day. Error bars represent standard error.

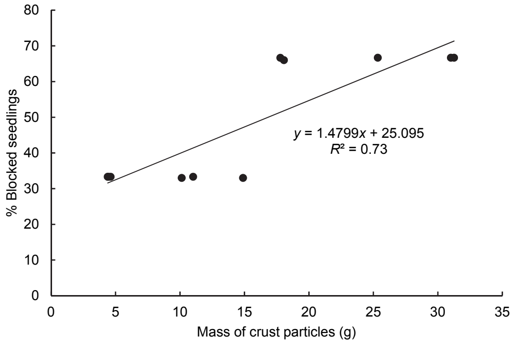

Figure 5
Relationship between mass of un-lifted crust fragments and percentage of blocked seedlings

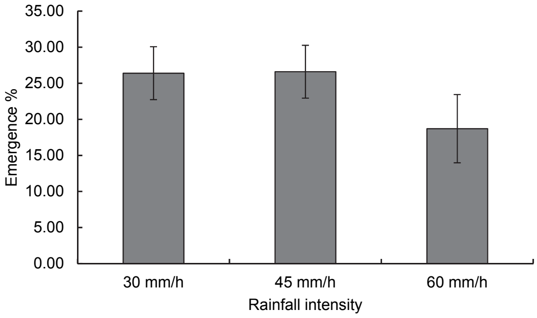

Figure 4
Effect of rainfall intensity on EMP. Error bars represent standard error.

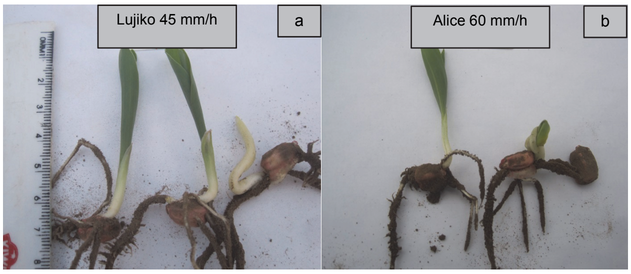

Figure 6
Deformed coleoptile (a) and leafing out (b) due to high crust strength compared to normal seedlings.

EMP ($P > 0.05$), emergence decreased in the following order: 30 mm/h > 45 mm/h > 60 mm/h (Fig. 4). However, most seedlings did not emerge fully because of the weight of broken crust fragments (Figs 5–8).

The mass of crust fragments that were broken but not lifted by the seedlings was plotted against the percentage of germinated but blocked seedlings (Fig. 5). The percentage of blocked seedlings significantly increased with an increase in

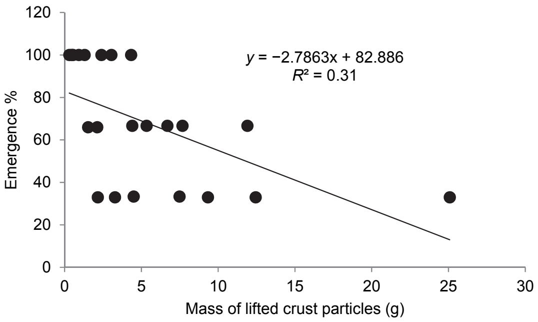

Figure 7
Relationship between mass of lifted crust fragments and emergence percentage

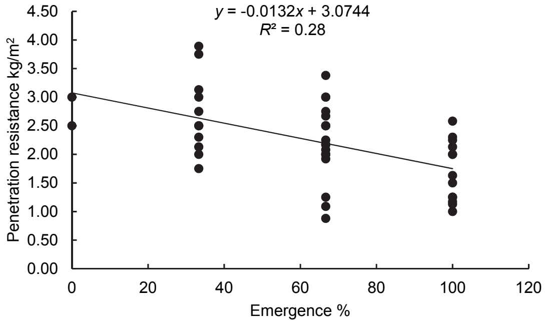

Figure 8
Relationship between penetration resistance and emergence

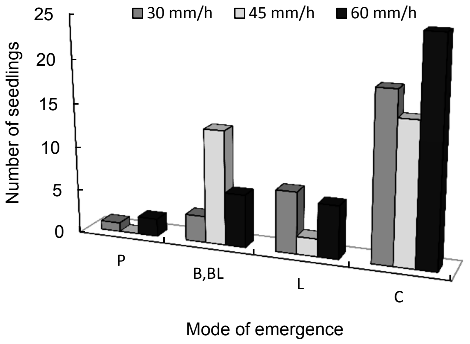

Figure 9
Effect of rainfall intensity on shoot length. Error bars represent standard error.

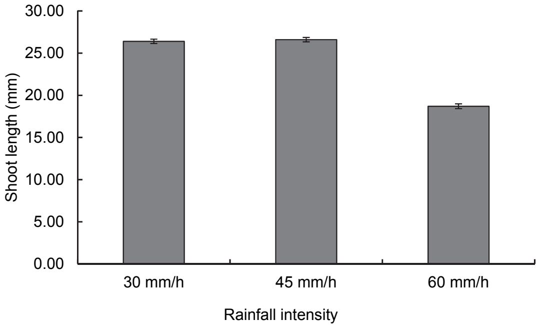

Figure 10
Distribution of mode of seedling emergence for each rainfall intensity: P = penetration, B = breaking, BL = breaking and lifting, L = lifting, C = cracks.

the mass of crust fragments ($R^2 = 0.73$). Figure 6a shows two seedlings that managed to emerge and one coleoptile that failed to overcome the strength of the crust, whilst Fig. 6b shows two seedlings that emerged and one blocked seedling that leafed out in the soil. Crust fragments with a mass as low as 4.5 g were strong enough to prevent seedling emergence. On the contrary, seedling emergence increased as the mass of crust fragments decreased (Fig. 7). Seedling emergence significantly ($P < 0.05$) decreased as mass of crust fragments increased ($R^2 = -0.33$). Moreover, EMP significantly ($P < 0.05$) decreased with an increase in crust strength ($R^2 = 0.28$) (Fig. 8).

Effect of soil type and rainfall intensity on shoot length

Rainfall intensity did not significantly affect ($P > 0.05$) shoot length. However, the 60 mm/h rainfall intensity had the shortest plants with a length of 18.7 mm (Table 2) (Fig. 9).

Effect of rainfall intensity on mode of seedling emergence

The seedlings that emerged were grouped by mode of emergence for each rainfall intensity level. Emergence through cracks was the most common mode of seedling emergence for all three rainfall intensities. A few seedlings emerged through crust penetration (Fig. 10).

DISCUSSION

Effect of soil type and rainfall intensity on crust strength

Crust strength increased as rainfall intensity increased from 30 mm/h to 60 mm/h (Figs 1, 2) because the increase in rainfall intensity increased susceptibility to soil crusting. Assouline (2004) suggested that rainfall intensity and the concomitant kinetic energy are significant in defining the seal properties, rate of sealing and ultimately crusting. Higher intensities induce ponding, saturating the surface, which decreases aggregate stability leading to slaking and extreme crusting on drying (Liu et al., 2011). Therefore, the higher crust strength after 60 mm/h than both 30 and 45 mm/h significantly increased crust formation. Moreover, the high-impact energy and flow velocity from high-intensity rainfall increases the tearing of soil particles, which increases crusting tendencies (Moussouni et al., 2013). However, crust strength increased significantly with an increase in quartz for all three rainfall intensities (Fig. 2). Quartz increases crusting tendencies due to its inertness, which renders the soil highly dispersive (Buhman et al., 1996; Nciizah and Wakindiki, 2014). The significant negative relationships between crust strength and SOM at all rainfall intensities could be due to reduction of clay wettability of aggregates, which reduces wetting rate and degree of slaking and subsequently crusting (Chenu et al., 2000). Crust strength was also regressed with clay content and significant negative relationships were observed for all three rainfall intensities (Fig. 2). This result indicates that high clay content reduces susceptibility to crusting despite the intensity of the rainfall. Similarly, in a study to determine the carbon (C) protective capacity of silt and clay particles, Six et al. (2002) observed a positive influence of clay and silt particles on C stabilisation. High C stabilisation improves aggregate stability which in turn reduces soil slaking and crusting.

Effect of rainfall intensity on mean emergence day

It is possible that the differences in MED due to rainfall intensity were a consequence of increased crust strength that increased with increase in rainfall intensity. In other studies, rainfall intensity was observed to promote seal formation and subsequently crusting (Assouline, 2004). This study showed that seedlings emerged significantly earlier at 30 and 45 mm/h than at 60 mm/h. This result could be attributed to the strength of the crust that delayed seedling emergence, as shown by the positive relationship between crust strength and MED (0.10). Other authors have noted that soil crusting delays seedling emergence with the extent of the delay depending on the strength of crust and ability of the seedling to overcome the impedance (Borselli et al., 1996; Aubertot et al., 2002; Braumhardt et al., 2004).

Effect of rainfall intensity on emergence percentage

Although, rainfall intensity did not significantly affect EMP, the general trend in EMP observed was 30 mm/h > 45 mm/h > 60 mm/h. However, the effects of rainfall intensity on EMP could be indirect through effects of crust strength. To this effect, a significant negative relationship ($R^2 = -0.30$) was observed between crust strength and EMP (Fig. 8). Moreover, the percentage of blocked seedlings increased with an increase in the mass of crust fragments (Fig. 6). The non-significance of the effects of rainfall intensity on EMP could be ascribed to seedling emergence through cracks. Incidentally, emergence through cracks was the dominant seedling emergence mode within each rainfall intensity treatment. Similar observations were made by Borselli et al. (1996), who observed a strong relationship between crust cracking and seedling emergence due to provision of easy pathways for seedlings. Additionally, as the seedlings emerge they further enhance crust cracking (Borselli et al., 1996), which could explain the high percentage of seedlings that emerged through cracks (60%) in the present study.

After the experiment, all non-emerged seedlings were removed and we observed that all the seeds had germinated. Consequently, the non-emerged seedlings failed to break, lift or penetrate the crust. Since most of the seedlings partially broke the crust but failed to lift it, the mass of the broken crust fragments was weighed and regressed with the percentage of blocked seedlings (Fig. 5). The mass of the crust had significant positive effects on the percentage of blocked seedlings. Similarly, Dürr and Aubertot (2000) observed an increase in the percentage of seedlings blocked under aggregates laid on the soil surface or buried in the soil layer. They concluded that emergence was decreased because of the increasing number of seedlings trapped with increasing size of the aggregates, both for aggregates left at the soil surface and those buried in the soil. The same reasoning applies to this study. After failure to lift the crust fragments, the blocked seedlings tried to navigate around the fragments, which often resulted in deformed coleoptiles (Fig. 6a). Similar observations were reported by Hyatt et al. (2007) who noted that when seedlings encounter a crust they attempt to deviate from vertical growth to circumvent it; however, failure to overcome the barrier buries the seedlings under the crust resulting in low EMP. However, in this study, in some cases, the mesocotyl was unable to elongate long enough to enable the coleoptile to completely go round the fragments resulting in the first leaf prematurely splitting through the coleoptiles and subsequently leafing out underground (Fig. 6b). Leafing out underground has been reported to be one of the most common effects of soil crusting.

Effect of rainfall intensity on shoot length

Similar to the effects on EMP, rainfall intensity did not have significant effects on shoot length, although the 60 mm/h rainfall intensity resulted in the shortest plants. This non-significance in length differences could once more be attributed to the emergence of seedlings through cracked surfaces (Fig. 10). Seedlings that emerged through cracks took longer to emerge compared to those that emerged through crust penetration. It is however possible that after emerging through the cracks the seedlings were able to recover and hence no significant differences in shoot length were observed. Averaged across all treatments, shoot length significantly decreased with an increase in MED ($R^2 = -0.58$). This decrease was probably due to the fact that some seedlings emerged earlier than others. Nonetheless, a negative but statistically insignificant relationship was observed between shoot length and crust strength ($R^2 = 0.12$). This indicated that the shoot length for seedlings encountering high soil strength may be reduced. Young et al. (1997) reported the existence of shoot-inhibiting signals generated by seedling roots growing in conditions high in mechanical impedance, such as those found in crusted soils.

Effect of rainfall intensity on mode of seedling emergence

Most seedlings emerged through crust cracks, especially for the 60 mm/h rainfall intensity. This cracking improved seedling emergence as is shown by the lack of significant differences in EMP (Fig. 4) among the rainfall intensity treatments. Borselli et al. (1996) found significant relationships between seedling emergence and crust cracking, although some of the cracking was caused by the emerging seedling. Crust penetration was the least common emergence mode. Emergence through crust penetration is easier when the crust is wet enough for the seedling to deform it (Aubertot et al., 2002).

CONCLUSIONS

The aim of this study was to determine the effects of rainfall intensity on crusting and mode of seedling emergence. The strength of the crust increased as rainfall intensity increased from 30 to 60 mm/h. Therefore any increase in rainfall intensity is likely to increase the severity of crusting in these soils. However, the effect of rainfall intensity on crust strength depended on SOM, clay content and mineralogy of the soils, as indicated by the significance of the relationships. Soils with high quartz, low clay and low SOM contents are likely to experience severe crusting as rainfall intensity increases due to climate change. Increasing rainfall intensity from 30 mm/h to 60 mm/h delayed seedling emergence; the final MED was influenced by crust strength and cracking, which was the main seedling emergence mode. Consequently soils with extensive cracking are likely to have higher EMP and lower MED and more vigorous seedlings despite the strength of the crust. Moreover, post-planting tillage methods that enhance crust cracking may be employed to enhance seedling emergence and growth in these soils.

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