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The effect of soil crust on the generation of runoff on small plots in an arid environment

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ABSTRACT

In arid zones, runoff is frequently generated as a result of the crust development on the soil surface. This crust is a thin layer of greater density, high shear strength, finer pores and has a lower saturated hydraulic conductivity than the underlying soil. The objective of the research reported herein was to study the factors that influence the generation of runoff in small plots under natural rainfall conditions. Factors studied were crust permeability, roughness, soil salt content and time gaps between the rain showers.

The field trial was carried out in the Mashash experimental runoff farm in Israel's Negev desert. Runoff was measured on eight plots using a tipping-bucket system (resolution 0.01 mm s^{-1}). Rainfall intensity was recorded on-site with a rainfall gauge (resolution 0.25 mm s^{-1}). Two treatments were studied: long-term rainfall-induced crusts (LTC) that had developed over a period of years (three plots), and complete destruction of the crust (ICU) by cultivation to a depth of 0.2 m with a rotary tiller before the beginning of the trial (five plots).

Surface roughness was characterized by the surface RMS height obtained from laser micro-relief measurements before and during the season. Prior to the onset of rain, roughness was similar for all the ICU plots. One month thereafter, roughness had decreased sharply, but exhibited no further change until the end of the season. Roughness of LTC plots did not change during the season and was lower than that of the ICU plots.

After ~21 mm of cumulative rain, the average runoff yield was similar for both ICU and LTC plots, even though roughness in the former did not reach the low values of the LTC plots.

Although the variability in roughness among individual LTC plots was very small, large differences were observed in the collected runoff. The same phenomenon was observed for the ICU plots. Moreover, the runoff yields in two ICU plots were consistently higher than those in two LTC plots while three other ICU plots produced much less runoff.

Apparent saturated hydraulic conductivity (AHC) was measured on mounds and depressions. In the ICU plots the average AHC of the mounds was markedly higher than that of the depressions while the AHC values of mounds were very similar.

No mounds or depressions were observed in the LTC plots, and their AHC was similar to that of depressions in ICU plots. The results indicate that the apparent saturated hydraulic conductivity of the upper soil layer was not directly linked to the runoff generation.

Treatment effect was significant only for the first two rainfall events, but the presence of salts in the upper soil layer significantly affected runoff generation during the last four rain events of the season.

Analysis of runoff and time gaps between the runoff-producing rain showers showed a clear relationship between runoff yields and average rainfall intensity, the degree of correlation between them improving with a decrease in the length of the gap.

1. Introduction

The infiltration of water into bare soil can be markedly reduced by the formation of a crust on the soil surface (Morin et al., 1989). The extent of the reduction depends upon soil type, surface conditions, and rainfall characteristics. Thus it is important to understand the effects of crusting on runoff generation.

Crust formation in the unstable soils of arid regions usually results from the combined effect of raindrop impact energy and the dispersion of clay particles. These factors reduce the hydraulic conductivity of the soil surface and hence infiltration rate into the soil (Morin and Benjamini, 1977; Agassi et al., 1985; Ben-Hur et al., 1987). It is also responsible for the modification of mechanical properties which can initiate seedling emergence problems (Cousin et al., 2005).

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Valentin and Bresson (1992) categorized surface crusts, according to their formation, into three major classes: structural crusts, erosion crusts and depositional crusts. Whereas structural crusts are formed by the impact of water droplets, depositional crusts are formed by the translocation of fine particles and their deposition at a certain distance from their original location (Valentin and Bresson, 1992). Fox et al. (1998) studied the spatial variability of crust characteristics in the field. They concluded that structural crusts have lower hydraulic resistance than depositional crusts generated by the deposition of detached particles in microdepressions.

The crust's hydraulic properties are a result of its structure. A number of authors have characterized fully formed crusts at the end of a rainfall event as consisting of a compact, approx. 0.1-mm thick skin covering a 1.5- to 3.0-mm thick washed-in or broken-aggregate region of decreased porosity (McIntyre, 1958a,b; Tackett and Pearson, 1965; Chen et al., 1980). Levy et al. (1988a) noted the presence of small mounds protruding from relatively smooth plains in structural crusts. Mounds and plains exhibited different permeabilities, with higher values in the former.

The generation of runoff has also been linked to soil-surface roughness, which was considered a factor delaying the reduction in infiltration due to crusting (Burwell and Larson, 1969; Falayi and Bouma, 1975).

The surface roughness and soil clods cause spatial variation in crusting (Falayi and Bouma, 1975; Levy et al., 1988a). Contradictory evidence has been presented for the effect of roughness on the generation of runoff. Helming et al. (1998a) showed that the effect of surface roughness on runoff generation is relatively small when the slope length is close to 4 m. These findings are in sharp contrast to other field and laboratory experiments carried out on small plots and involving slope lengths of less than 1 m, in which it was found that roughness substantially affects runoff (Cogo et al., 1983; Zobeck and Onstad, 1987; Renard et al., 1997). However, real catchments have slopes which are usually over 10 m in length, and there is no information on the effect of micro-relief on plots of this size. The recent development of laser roughness scanners for measurements of soil micro-relief provides an efficient tool for roughness studies. These instruments are usually used to study changes in soil-surface roughness after simulated rainfalls (Huang and Bradford, 1990; Helming et al.,1998b).

Neave and Rayburg (2006) studied soil crust and seal development in response to structural (or raindrop-impact-induced) and depositional (or runoff-induced) processes on a semiarid area and found that seal development does not directly mirror crust formation.

Bedaiwy (2007) compared the mechanical and hydraulic resistances of crusted soils and found that for any given kinetic energy the mechanical resistance was greater in the silt-loam soil and attributed this fact to the intrinsic resistance and crust thickness. The hydraulic resistance measured by steady-state infiltration rate was much lower in crusted clay than crusted silt-loam soil.

The objective of the research was to study the factors that influence the generation of runoff in small plots under natural rainfall conditions.

2. Materials and methods

The field trial was carried out at the Mashash experimental runoff farm (Ben-Gurion University of the Negev, Israel). Runoff intensities were measured on eight plots during the winter of 2000–2001. Each plot had a runoff production area of ~250 m^2 (16 m × 16 m) at the lowest end of which a tipping bucket (resolution 0.01 mm s^{-1}) was installed. A magnetic pick-up system was connected to a one-channel event data-logger. Rainfall intensity was recorded on-site with a rainfall gauge (resolution 0.25 mm s^{-1}). Three of the eight plots had rainfall-induced crusts that had developed over a period of years, and in the five remaining plots, the crust was completely destroyed by cultivation with a rotary tiller to a depth of 0.2 m before the beginning of the trial. The soil was sandy loess composed of 55% sand, 21% silt and 24% clay particles. The average slope of the plots was 2%.

Surface roughness was characterized by the surface RMS height obtained from laser micro-relief measurements before and during the season. Automated laser surface scanner BGU GSS 1800 developed at the remote sensing laboratory of Geographical Faculty of the Ben-Gurion University of the Negev (Blumberg et al., 2002) was used. The laser meter was mounted on a special tripod, and an area of 1 m^2 was scanned on each plot. Approximately 80,000 points were recorded and stored and a 3D model of the surface was generated for each plot, using each measurement, with a vertical resolution of 1 mm and a horizontal resolution of 5 mm. The degree of roughness was quantified by the RMS values of surface height. Roughness measurements were carried out immediately after cultivation, midway through and after the rainy season for the same area within each plot.

A total of 77 mm of rain were registered during the measurement period (Dec 2000–Apr 2001). The maximum intensity of the rains that produced runoff varied from 2 mm h^{-1} to 41 mm h^{-1} and all storms were characterized by high temporal variability. Runoff coefficients (RC), computed as the ratio between runoff and rainfall amounts, were obtained for each runoff event during the season.

The falling head micropermeameter (Levy et al., 1988a) was adapted for field use to measure the apparent hydraulic conductivity (AHC) of the upper layer of the soil.

3. Results and analyses

3.1. Roughness

Results of the measurements carried out in the plots throughout the season are presented in Fig. 1.

Large differences between plots with long-term crusts (LTC) and those that were initially cultivated (ICU), are evident prior to the onset of the rains. After a number of rainfall events totalling 28 mm, the RMS values of ICU-plots decreased sharply (from 18.7 mm to 7.82 mm) and significantly (t-test, unequal variances; $p<0.05$). During the same period, the changes in the roughness of the LTC plots were of the same order of magnitude as the expected measurement errors. Additional rainfall events did not further affect the measured roughness of either plot type, and at the end of the season the RMS differences between treatments were significant (t-test, unequal variances; $p<0.05$). The average RMS of the ICU plots was 7.38 mm, and. 2.57 mm for the LTC plots.

The differences between the first and second roughness measurements were significant for the ICU plots, whereas those between the second and third measurements were not. No significant

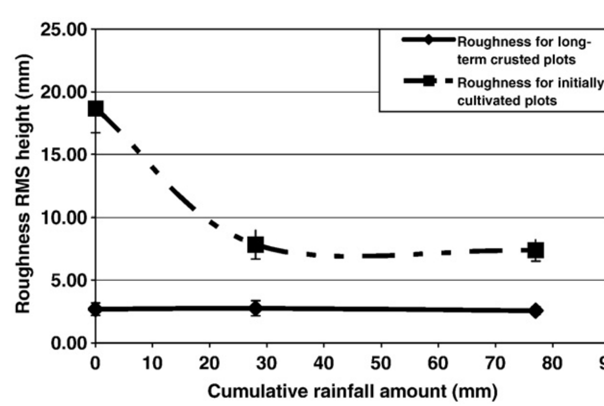

Fig. 1. Roughness change in ICU and LTC plots over one rain season. Bars denote one standard deviation.