Biologia **64**/3: 470—473, 2009
Section Botany
DOI: 10.2478/s11756-009-0107-6

The relation between runoff generation and temporal stability of soil macropores in a fine sandy loam

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Abstract: During rainfall events, macropores are generally considered to play a dominant role in infiltration after matrix ponding has occurred. Once ponding has been initiated on the soil matrix, surface runoff may be generated at rainfall intensities less than the saturated hydraulic conductivity of the soil. The amount of runoff will depend on detention storage and how efficiently the surface flow is captured by soil macropores. The efficiency of surface water removal by macropores is diminished if surface vents become clogged sealed by washed-in sediment during the runoff event.

Post-event opening of surface vents by the animals that created them can remove evidence of the sealing process and so it is particularly important to examine the temporal stability of the soil surface during rainfall events.

In this paper evidence of macropore clogging and post-event clearing of the surface vents is presented. A fine sandy loam passed through a 2 mm diameter sieve was packed into two boxes, each with a surface area of 0.5 m^2. The boxes were irrigated at 28 mm h^{-1} using a low energy rainfall sprinkler. This application rate exceeded the saturated hydraulic conductivity of the soil matrix. After measuring runoff and infiltration from the boxes, one box was held as a control and the second was inoculated with earthworms. After four weeks the inoculated box had a burrow density at the soil surface of 380 m^{-2}, with an average diameter of 5 mm.

Macropore sealing occurred immediately after ponding and runoff from the macroporous soil was only 10.7% less than a control with no macropores. Within 24 h after cessation of simulated rainfall the earthworms had cleared washed in material from over 95% of burrow vents. Time to matrix ponding was well predicted using hydraulic parameters characteristic of the soil matrix, indicating that matrix sealing was not significant under the experimental conditions.

Key words: earthworms; macropores; surface sealing; runoff

Introduction

During rainfall events, macropores play a dominant role in infiltration after matrix ponding has occurred (Clothier & Smettem 1990; Jarvis 2007). The time to matrix ponding for a given rainfall event can be predicted if the unsaturated soil hydraulic properties are known (White & Broadbridge 1988).

Simple analytical estimation of the time-to-incipient ponding of the soil matrix requires information on the saturated hydraulic conductivity of the soil 'matrix', K_m (mm h^{-1}) and sorptivity, S_m(mm $\mathrm{h}^{-1/2}$). The sorptivity also depends on the soil texture and the initial, or antecedent water content (Parlange & Smith 1976). For rainfall into an isothermal, rigid, homogenous soil with a uniform initial water content, the time-to-incipient ponding (h) is given by Broadbridge & White (1987):

$$t_\mathrm{p} = M(S_\mathrm{m}^2/K_\mathrm{m}\overline{R}_\mathrm{p}) \ln\{R(t_\mathrm{p})/[R(t_\mathrm{p}) - K_\mathrm{m}]\} \qquad (1)$$

where $\underline{R(t_\mathrm{p})}$ is the rainfall rate at incipient ponding (mm h^{-1}), $\overline{R}(t_\mathrm{p})$ is the mean rainfall rate up to ponding and M is a parameter that ranges from 0.5 to 0.66 depending on the strength of the θ dependence of the soil hydraulic properties. If $M = 0.5$ then we have the approximate model of Parlange & Smith (1976). A value of 0.55 can be conveniently applied to most field soils (White et al. 1989)

To adjust S_m for different initial moisture contents Braud et al. (2005) derived the expression:

$$S_\mathrm{m}(\theta_0, \theta_\mathrm{m}) = S_\mathrm{m}(\mathrm{airdry}, \theta_\mathrm{m})\frac{\theta_\mathrm{m} - \theta_0}{\theta_\mathrm{m}}\frac{K_\mathrm{m} - K_0}{K_\mathrm{m}} \qquad (2)$$

where θ_m is the matrix saturated volumetric water content, θ_0 is the initial volumetric water content and K_o is the initial hydraulic conductivity. Under field conditions it is assumed that S_m at an air dry initial condition is the maximum S_m

In the case of a soil initially drier than field capacity the initial hydraulic conductivity, K_o, is usually in orders of magnitude less than the matrix saturated hydraulic conductivity and Eq. 2 can be simplified to:

$$S_\mathrm{m}(\theta_0, \theta_\mathrm{m}) = S_\mathrm{m}(\mathrm{airdry}, \theta_\mathrm{m})\frac{\theta_\mathrm{m} - \theta_0}{\theta_\mathrm{m}} \qquad (3)$$

After matrix ponding has occurred, surface runoff may be generated over the soil matrix between macropores for rainfall intensities less than the saturated hydraulic conductivity (K_{sat}) of the soil (matrix plus macropore domains). In the post-ponding period, flow into soil macropores can occur when the water entry-pressure of the macropores is exceeded at some point on the interface with the surrounding matrix (Jarvis 2007). Runoff generation then depends on how efficiently the macropore system removes ponded water, rather than K_{sat} of the macropore-matrix system.

In the Mediterranean climatic region of southern Australia many soils classified as xeralfs (Soil Survey Staff 1988) have a weakly structured, coarse textured surface horizon that are depleted of clay and prone to deterioration with frequent cropping and cultivation (Hamblin 1984). To improve soil macroporosity and infiltration, adoption of conservation tillage and practices that increase earthworm numbers have been recommended for over 20 years (Rovira et al. 1987). However, the common earthworm species (by numbers per hectare) across this agricultural region are introduced exotic Lumbricidae that have been shown to burrow extensively within the topsoil, rather than creating deep permanent burrows (Capowiez et al. 2001).

Under both natural rainfall and high energy sprinkler infiltration the consolidation of tilled soil and sealing of macropore openings in tilled and untilled soil have been observed in xeralfs (Somaratne & Smettem 1993). The question as to whether earthworm burrows can actually reduce surface runoff from xeralfs is therefore important for soil conservation and management strategies. In this study the objective is to determine the influence of surface vented earthworm burrows on runoff from a fine sandy loam (xeralf) under controlled low energy rainfall conditions.

Material and methods

A calcareous sandy loam topsoil (Calcic Rhodoxeralf; Soil Survey Staff 1988) from a site described by Smettem et al. (1992) was used in this study. Soil collected from the surface 0.1 m had an organic carbon content of 1.4% and a texture of 11% clay, 19% silt (2–20 µm) and 69% sand.

Air-dried soil was passed through a 2 mm sieve and then packed to a bulk density of 1.35 Mg m^{-3} into 0.5 m wide × 1.0 m long × 0.12 m deep clear plastic boxes to a depth of 90 mm over a 30 mm thick layer of coarse sand. The boxes were set at a slope of 5° and placed under a low energy rainfall sprinkler (Ross & Bridge 1985). The sprinkler head comprised 1000 hollow polythene needles arranged with a spacing of 10 mm between needles in rows 100 mm apart. The entire unit was moved with a stepper motor at a rate of 20 mm s^{-1} to produce a drop spacing of 5 mm to 10 mm between the rows and to ensure that drops did not continuously fall on the same spot. Rain intensity was maintained at 28 mm h^{-1} using a peristaltic pump. Drop diameter was 2.6 mm, average falling height was 0.25 m, and drop kinetic energy was only 2 J mm^{-1} m^{-2}.

Initially, two boxes of repacked air-dry soil were irrigated. The time to ponding was noted as the time required for a continuous free water film to appear on the soil surface. The time to runoff was recorded and the volume of runoff was measured continuously during and immediately after irrigation. Infiltration was calculated as the difference between rainfall and runoff. The depth of the wetting front was also recorded by visual observation through the sides of the boxes. Initial and final soil moisture contents were measured by TDR using dual 20 cm rods inserted horizontally at 2 cm depth through a slots cut in the sides of the boxes. This experimental procedure was followed for all subsequent experiments.

After performing these initial experiments, earthworms were introduced to one of the trays. A total of 200 adult earthworms were introduced, comprising equal numbers of species *Aporrectodea trapezoides* and *Aporrectodea rosea* (Lumbricidae). The surface of this tray was mulched with moistened, partially decomposed plant residue.

After four weeks the mulch was removed by hand and loosened surface casts were carefully removed using a small portable vacuum cleaner. The size and location of all surface vented burrows were recorded onto plastic sheets (Chadoeuf et al. 1994). The trays with and without macropores were then re-irrigated at 28 mm h^{-1} and runoff was recorded.

Prediction of time to matrix ponding using Eq. 1 required measurement of S_{m} and K_{m}. This was done using triplicate cores of 10 cm length and 78.5 cm^2 area repacked to the same bulk density as the boxes. Infiltration was measured using a tension infiltrometer at a slight negative supply potential, h_{o}, of –20 mm. S_{m} was obtained from the early square root of time behavior at an air dry antecedent moisture content of 0.04 m^3 m^{-3} and K_{m} was obtained using the permeameter method of Clothier & White (1981).

Results

Measured runoff and infiltration rates calculated from rainfall minus runoff over 0.083 h time increments from the two boxes prior to earthworm introduction are shown in Fig. 1. Initial water content was 0.04 m^3 m^{-3} and runoff commenced at 0.183 h for both boxes. Results show that runoff from the boxes was practically identical, so that one box could be held as a control for comparison to the box with introduced earthworms. Using a measured S_{m} of 16 mm $h^{-1/2}$ and K_{m} of 5 mm h^{-1} the estimated time to matrix ponding (Eq. 1) was 0.198 h, which is only slightly longer than observed.

The distribution of earthworm burrow diameters at the soil surface after four weeks burrowing activity is shown in Fig. 2. Over 60% of the burrows had diameters between 4 and 6 mm and the sum of the burrow diameters is 1003 mm, which is twice the cross-section of the box. The pre-rainfall event burrow surface opening density was 380 m^{-2} which is similar to the density of introduced earthworms (400 m^{-2}).

Assuming flowlines are parallel and a burrow opening captures flow from upslope, the potential efficiency of the burrows in removing surface runoff can be estimated using the map of burrow openings at the soil surface. For example, a 5 mm diameter burrow 200 mm upslope from the discharge collection end of the box captures runoff from a length of 800 × 5 mm width but does not prevent runoff generation from a downslope area of 10 cm^2. The sum for all burrow openings with uninterrupted flowlines (not recaptured by another burrow) to the discharge collection face gives the area of matrix ponding not captured by burrow openings. For the

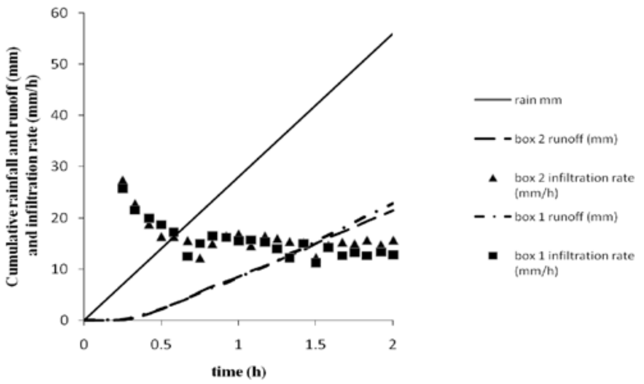

Fig. 1. Comparison of cumulative runoff (mm) and infiltration rate (mm h^{-1}) for the two repacked boxes.

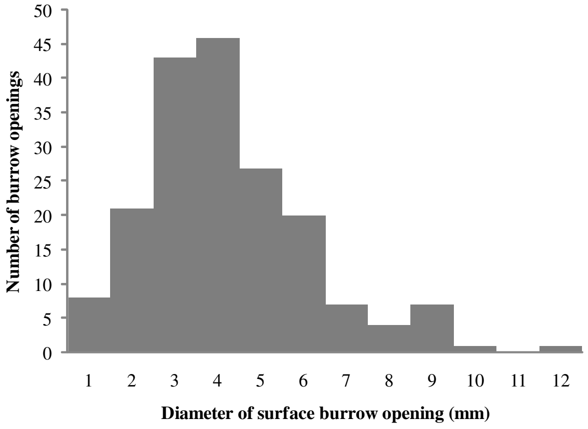

Fig. 2. Frequency distribution of burrow diameters venting at the soil surface.

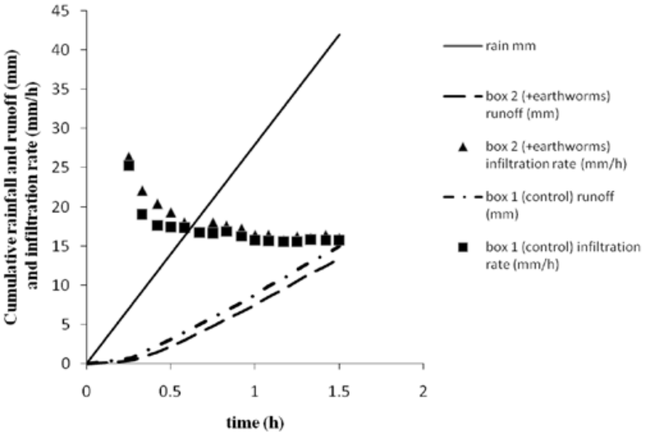

Fig. 3. Comparison of cumulative runoff (mm) and infiltration rate (mm h^{-1}) for the box with earthworms and the control (no earthworms).

mapped burrow distribution runoff could be reduced by 60% under this flow capture scenario.

A comparison of runoff and infiltration from the boxes with and without earthworms is shown in Fig. 3. Due to the effect of the mulch cover the antecedent moisture content was slightly greater in the box with earthworms (0.24 m^3 m^{-3}) than in the control box (0.17 m^3 m^{-3}). This resulted in a slightly earlier time to matrix ponding (0.042 h compared to 0.067 h). Adjusting S_m for the effect of initial moisture content using Eq. 3 (with $\theta_m = 0.43$) gave matrix ponding times (Eq. 1) of 0.031 h for the box with earthworms and 0.063 h for the control.

After 1.5 h sprinkler supply the cumulative runoff from the earthworm box was 13.4 mm compared to 15.0 mm for the control. This 10.7% reduction is considerably less than estimated for the runoff capture scenario and occurred in the first 0.5 h. By this time it was observed that all the burrow openings had become clogged with transported material.

Discussion

The process of macropore sealing by washed in fine material, primarily arising from collapse of the burrow walls has been shown to substantially reduce the efficiency of earthworm burrows to capture and remove surface runoff. Because this process is dynamic and 95% of the burrow openings were re-established within 24 h after cessation of rainfall it is important that observations of the surface condition are made during the rainfall event. In such soils, the estimation of K_{sat} and other macropore-related hydraulic properties from morphological schemes (McKenzie et al. 1991) should be avoided.

Up to the time of matrix ponding there appears to be little or no disturbance of the soil surface and the use of time to ponding estimations for rigid soils (Eq. 1), allowing for different initial moisture contents (Eq. 3) appear to be remarkably accurate.

In this particular soil, the earthworms have not stabilized the surface burrow openings sufficiently to withstand low energy rainfall and the walls appear to collapse with the onset of surface runoff. The role of plant roots and soil conditioners in stabilizing burrow openings is the focus of ongoing research.

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Received November 4, 2008
Accepted January 22, 2009