Effect of mesofaunal activity on the rehabilitation of sealed soil surfaces

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Abstract

The impact of soil mesofauna on the rehabilitation of soil surfaces sealed by rainfall was investigated in a long-term laboratory experiment. Fifteen undisturbed soil monoliths from the Ap horizon of a Gleyic Podzoluvisol/Haplic Luvisol derived from loess were obtained after conventional tillage and seedbed preparation. The soil of this site is known to be susceptible to surface sealing as a result of rainfall activity. All monoliths were defaunated in a microwave oven and then inoculated with mesofauna, some with 300 individuals of Collembola and others with 200 individuals of Enchytraeidae. Additional monoliths were left uninoculated for comparison. Ten monoliths were then treated with simulated rainfall (intensity: 29 mm h⁻¹; time: 60 min) to form a surface seal. The roughness of all 15 monoliths was measured using a non-contact laser scanner immediately and after 6 and 18 months. Differences in the soil surface roughness were assumed to indicate mesofaunal activities and intrinsic soil processes. Soil surface roughness was significantly different between monoliths with and without rainfall impact. Monoliths subjected to rainfall showed significant differences in soil surface roughness between those with and without mesofauna as well as between monoliths inoculated with Collembola and Enchytraeidae. The roughness differences detected between unsealed monoliths were not significant. Over the entire experimental time of 18 months the relative changes in sealed uninoculated monoliths were much lower than the alterations as a result of mesofaunal activities. The results show that within a few months the activities of Collembola and Enchytraeidae distinctly contribute to the rehabilitation of sealed soil surfaces and the development of a finely structured soil surface microrelief. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Enchytraeidae; Collembola; Soil surface crusts; Soil surface roughness; Soil rehabilitation

1. Introduction

Soil surface sealing is of paramount importance in surface runoff and soil erosion processes. In the temperate climate of Central Europe, runoff and soil erosion predominantly occur on cultivated land with non-permanent vegetation cover (Kwaad, 1991). Freshly-tilled unvegetated soils typically have a high water infiltration capacity such that runoff occurs infrequently with intensive rainfall events. However, with exposure to rainfall over time a soil crust develops on exposed soil surfaces which prevents infiltration. During rain events soil aggregates break apart when the kinetic energy of raindrops impacting soil surfaces is converted into radial forces that result in a splash off of soil particles (Al-Durrah and Bradford, 1991).
The detached soil particles form a smooth dense seal a few mm thick on the soil surface (Roth and Helming, 1992; Fohrer et al., 1999). Despite the thinness of the layer, the hydraulic conductivity of such a seal is usually more than one order of magnitude lower than the unsealed soil surface (McIntyre, 1958; Ela et al., 1992; Roth et al., 1995). The result of the sealing process is an exponential decrease in the infiltration rate and a subsequent increase in soil erosion and runoff. After the soil seal dries, a surface crust forms which restricts infiltration as well as water, heat and air exchange between soil and atmosphere until the crust is broken (Valentin and Bresson, 1992; Cresswell et al., 1993). The latter process may be initiated physically through swelling and/or shrinking, biologically through root growth and/or soil faunal activity or mechanically through tillage and traffic operations. This paper focuses on the effect of soil faunal activity on structural changes in sealed soil surfaces.

The effects of soil macrofauna on soil structure, infiltration and water fluxes have been extensively investigated especially for earthworms (see reviews by, e.g. Lee and Foster, 1991; Makeschin, 1997), termites (Lobry de Bruyn and Conacher, 1990) and ants (Lal, 1988; Lobry de Bruyn and Conacher, 1994). Particularly in arable soils the burrowing activity of earthworms significantly impacts soil structure and properties. Lavelle (1994) applied the concept of ‘ecosystem-engineers’ to describe the bioturbative activities of earthworms and termites. Lavelle (1994) and Lavelle et al. (1997) applied the Jones et al. (1994) idea of ‘physical ecosystem engineering by organisms’ in detailing the direct and indirect effects of burrowing and cast production on soil physical and chemical processes. The available access to biotic and abiotic habitat resources by other soil organisms is also a result of these macrofaunal activities.

In addition to these smaller macrofauna, other studies on bioturbation focussed on the impact of larger macrofauna, e.g. mammals such as ground squirrels (Citellus spec.), moles (Talpa europaea) (review: Graff and Makeschin, 1979) and badgers (Meles meles) (Neal and Roper, 1991). While capable of moving soil volumes as great as 120t ha\(^{-1}\) a\(^{-1}\), the single permanent burrow system, limited population densities and frequencies of these larger species in mid-European arable land suggest that the more prevalent, smaller macrofauna may more significantly impact soil structural and physical properties (Graff and Makeschin, 1979; Neal and Roper, 1991).

Although less intensively researched than macrofauna, the impact of mesofauna on soil fertility through consumption of soil organic matter and casts of larger animals is well-accepted (e.g. Dawod and FitzPatrick, 1993). The effects of their burrowing activities in compacted soils have also been observed (Schrader et al., 1997). Enchytraeidae, in particular, have been found to be important bioindicators for abiotic characteristics in the soil environment (Röhrig et al., 1998; Graefe and Schmelz, 1999). Moreover, air permeability and hydraulic conductivity were shown to increase as a result of enchytraeid activities (Didden, 1990; van Vliet et al., 1998). In the case of Collembola, Heisler et al. (1996) measured a significant increase in aggregate stability of their casts in comparison to soil aggregates of the same size. However, the description or quantification of these effects creates methodological problems as great as these animals are small. Until now few studies have considered mesofauna to be ‘ecosystem engineers’ as described by Schrader (1999) for Collembola and Enchytraeidae.

The analysis of mesofaunal activities requires methods that allow a non-destructive characterisation of mesofauna-related soil structural changes. Babel and Vogel (1989) and Rusek (1986) used micromorphological methods to investigate the effects of Collembola and Enchytraeidae on soil microstructure. Micromorphological methods are very effective in the visualisation of soil structural properties at a high resolution (Bresson and Boiffin, 1990). However, this method is destructive to soil structure and precludes long-term, repeated analyses of soil structural changes. X-rays at a resolution of about 1 mm are non-destructive and highly effective in studying soil structure and hence, a well-established analytical tool in soil science research (Heijs et al., 1995; Langmaack et al., 1999). However, for purposes of characterising mesofaunal activity, a resolution much higher than 1 mm is required. Although, the technology for computed tomography for analysis of soil pores to 10–50 \(\mu\)m has already been developed (Reinken et al., 1995), the appropriate equipment is difficult to locate. Schrader et al. (1997) used a laser microrelief meter to analyse the burrowing activities of Enchytraeidae and Collembola in compacted soils. This non-contact
and non-destructive equipment scans the morphology of the soil surface at a resolution of 0.3 mm (Helming, 1992). Without any intervening extraneous influences morphological changes observed on the soil surface are indicative of sub-surface soil structural changes as a result of faunal activities. The effects of collembolan and enchytraeid activities on the topography of previously sealed soil surfaces were investigated through the use of a laser microrelief meter in the present study.

This research was inspired by the results of Kladivko et al. (1986), Roth and Joschko (1991) and Mando and Miedema (1997) which demonstrated the structural changes of crusted soils and the reduction of surface runoff due to earthworm burrowing and termite activities. The purpose was to investigate whether soil mesofauna contribute to, or even accelerate the rehabilitation of sealed soil surfaces through their burrowing activities. Soil core samples were inoculated with Collembola and Enchytraeidae in defined numbers and subjected to a simulated rainstorm. The soil type chosen is highly susceptible to surface sealing processes. Alterations in the artificially created seal were detected by measuring the topography of the soil surface immediately after the rainstorm application and at 6 and 18 month intervals.

2. Material and methods

2.1. Experimental design

In autumn 1996, 15 undisturbed soil monoliths (h:5 cm, Ø: 11 cm, A: 95 cm²) were obtained from the Ap-horizon of a Gleyic Podzoluvisol/Haplic Luvisol derived from loess (FitzPatrick, 1986; FAO, 1988) (approximate German equivalent: Pseudogley-Parabraunerde aus Loess) after basic tillage and seedbed preparation practices were performed. According to AG Boden (1994) the soil is classified as a sandy loamy silt (Uls) with 26.2% sand, 60.9% silt and 12.9% clay. The arable land site is located in the sloping Solling area (Lower-Saxony, Germany) and very susceptible to surface sealing and soil erosion. The annual mean precipitation is 810 mm.

As described by Schrader et al. (1997) the monoliths were defaunated in a microwave oven for 6 min at 750 W. Comparing the convenient defaunation techniques microwaving, deep freezing and biocide application, Huhta et al. (1989) recommended microwaving as most effective. Only nematodes occasionally recovered from microwaved treatments.

Six of the 15 monoliths were inoculated with Collembola (300 individuals of Folsonia candida ≡ 30 000 m⁻²), six with Enchytraeidae (200 individuals of Enchytraeus minutus and E. lacteus ≡ 20 000 m⁻²) and the remaining three were not inoculated. These densities are within the upper range for typical mesofaunal populations in arable land (Tischler, 1965; Didden, 1993).

At the end of the experiment all monoliths were checked for the presence of mesofauna. Control, i.e. uninoculated monoliths were still without Enchytraeidae and Collembola, while both taxa were reduced in abundance in inoculated monoliths.

2.2. Rainfall simulation

To create a surface seal, soil monoliths were subjected to a simulated rainstorm generated with a rainfall simulator as described by Roth and Helming (1992). In brief, the rainfall simulator consists of a 1 m² drop-producing unit with 2500 capillaries mounted 7 m above the box containing the soil monoliths. The drop size distribution was randomised around a median drop size of 2.89 mm. The rainfall kinetic energy produced was 25.80 J m⁻² mm⁻¹, which corresponds to about 99.5% of natural rainfall kinetic energy at 30 mm h⁻¹ rainfall intensity (Laws and Parsons, 1943).

Rainfall was applied to 10 of the 15 monoliths (4 with Collembola, 4 with Enchytraeidae, 2 uninoculated) for 60 min to instigate the formation of a sealed surface. The actual rainfall intensity was 29 mm h⁻¹. The soil monoliths were placed under the rainfall device at a 5% slope to prevent the soil surfaces from ponding and to allow for sampling of the generated surface water runoff. The arrangement of the soil monoliths under the rainfall simulator with hoses for runoff collection is shown in Fig. 1.

Thus, the experiment comprised the following treatments: four sealed and two unsealed monoliths inoculated with Collembola, the same number of monoliths inoculated with Enchytraeidae, and two sealed and one unsealed uninoculated (no fauna) monoliths.
2.3. Soil surface scanning

Immediately after rainfall application the surface topography of all monoliths was measured with a non-contact laser microrelief meter, as described by Helming (1992). In brief, the laser microrelief meter consists of an aluminium frame supporting a sledge with a mounted laser probe, consisting of a laser source and an optical sensor. The $x$- and $y$-direction movement of the laser probe is software-controlled and driven by two stepping motors. As the laser probe moves, height values are collected and stored in a computer. This scanning movement allows the topography of areas from a few cm$^2$ to a maximum of 1 m$^2$ to be digitised with 0.3 mm horizontal and 0.2 mm vertical resolutions, respectively. The result is a surface digital elevation model (DEM) with regular grid spacing.

A 7 cm $\times$ 7 cm area at the centre of each monolith surface was digitised to measure the surface topography. A grid spacing of 0.3 mm resulted in a DEM of 52,900 height values per area. For analysis purposes the dimensionless roughness index ‘specific surface area’ (SSA), representing the ratio of the surface area measured to the projected surface on a plane perpendicular to the laser beam, was calculated based on the procedures of Helming et al. (1993). Briefly, the method consists of summing up the surface area of each 3 mm $\times$ 3 mm grid square. The surface area of each grid square was determined by calculating the area of the four triangles derived from the four elevation points of the grid plus a linearly interpolated midpoint. In previous studies the SSA index was determined to be a suitable parameter for the characterisation of soil surface topographies (Helming et al., 1993; Schrader et al., 1997).

The alterations of the created seal were monitored by measuring the topography of the soil surface with the non-contact laser microrelief meter immediately after the rainstorm application (time $t_0$) as well as 6 (time $t_6$) and 18 months (time $t_{18}$) later. Between the measurements, the soil monoliths were stored at 20°C in dark and humid conditions (Schrader et al., 1997). For comparison of the different treatments...
and measurement dates the relative differences of the SSA values were calculated. By definition the lowest possible value of SSA is 1.0 (totally plane surface): we therefore subtracted 1.0 from all SSA values before determining the percentage differences between treatments. The Mann–Whitney-U-test was used for statistical analysis.

3. Results

Water saturation of the soil occurred 11 min and surface runoff 16 min after rainstorm simulation began. After 16 min the infiltration rate decreased rapidly and the runoff rate increased. At the end of the experiments soil loss as a result of surface runoff averaged 92.28 g m\(^{-2}\). After the rainfall simulation a seal had developed on the soil surfaces of the monoliths.

The differences in the mean specific surface area (SSA) values between unsealed (1.45) and sealed (1.31) soil surfaces immediately after the rainstorm impact (time \(t_0\)) were statistically significant (Fig. 2). The smoothening of the soil surface after the rainstorm is reflected in the mean SSA of sealed monoliths, which is 31.1% lower than for unsealed monoliths.

Macroscopically no noticeable soil surface differences between Enchytraeidae and Collembola were visible at either \(t_6\) or \(t_{18}\). Effects of 6 months of enchytraeid activity on the previously sealed and unsealed surfaces are shown as an example in Fig. 3. In both these cases, the burrowing activity of Enchytraeidae resulted in a rougher surface with a higher SSA. In particular, the initially sealed surface appears to be more finely structured, i.e. rougher after 6 months of enchytraeid activity (Fig. 3). In this case, SSA increased by 17.2% during the first 6 months of the experiment. After the same time period, the unsealed surface showed an increase in SSA of 24.1% at \(t_6\).

When the SSA data for sealed and unsealed treatments over the entire period of the experiment (\(t_0–t_{18}\)) are pooled, the influence of the inoculated mesofauna on the sealed surfaces in comparison with uninoculated treatments becomes more apparent. In the sealed treatments, the mean SSA was significantly higher for Enchytraeidae and Collembola inoculated monoliths compared to monoliths without inoculated fauna (Fig. 4). Furthermore, the higher mean SSA for Collembola compared to Enchytraeidae was also statistically significant. The mean SSA of uninoculated monoliths was 34.3% lower than for monoliths with Collembola and 25.8% lower than for monoliths with Enchytraeidae. Mesofaunal activity had no effect in the case of unsealed monoliths (Fig. 5).

Differences in the mean SSA-values of the sealed monoliths (\(\equiv \Delta SSA\)) can be due to the surfaces becoming rougher (positive \(\Delta SSA\)) or smoother (negative \(\Delta SSA\)) in all cases from date to date measurement (Table 1). No clear direction in roughness development was determined either for uninoculated or inoculated sealed monoliths. Nevertheless, \(\Delta SSA\) showed lower differences for uninoculated monoliths compared to those with collembolan and enchytraeid activity over the entire experimental period (\((t_{18}–t_0)\) in

![Fig. 2. Box-plot of the specific surface area (SSA) of sealed and unsealed monoliths at the start of the experiment (\(t_0\)). Each box represents half of the values and the bars represent ranges recorded, the solid line marks the median inside each box. The different letters indicate that the treatments are significantly different based on the Mann–Whitney-U-test, \(p \leq 0.05\).](image)

<table>
<thead>
<tr>
<th>Time Period</th>
<th>No fauna</th>
<th>Collembola</th>
<th>Enchytraeidae</th>
</tr>
</thead>
<tbody>
<tr>
<td>(t_0–t_6)</td>
<td>+0.025</td>
<td>+0.013</td>
<td>-0.008</td>
</tr>
<tr>
<td>(t_6–t_{18})</td>
<td>-0.020</td>
<td>-0.053</td>
<td>+0.048</td>
</tr>
<tr>
<td>(t_{18}–t_0)</td>
<td>+0.005</td>
<td>-0.040</td>
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Fig. 3. Examples of surface characteristics of two soil monoliths inoculated with Enchytraeidae. Top: sealed surfaces. Bottom: unsealed surfaces. $t_0 =$ start of the experiment, $t_6 =$ 6 months later. Visualisation based on digital elevation models with 0.3 mm grid spacing obtained with a non-contact laser scanner. Specific surface area (SSA) is an index of roughness. The grey levels indicate elevation levels from 1 (light = low) to 21 mm (dark = high).

Table 1). Neglecting the sign (+/−) of the ΔSSA data and calculating the relative differences between the measurements (ΔSSA (%)) provides the most striking indication of the changes in the surface roughness for the sealed monoliths (Fig. 6). Except for Collembola at $t_0–t_6$, ΔSSA (%) was always higher for mesofaunal inoculated monoliths. The greatest changes in the soil surface due to enchytraeid activity appear to have occurred within the first period. Nearly the same degree of relative change was measured in the collembolan and enchytraeid treatments during the second period ($t_6–t_{18}$). The uninoculated monoliths also experienced nearly the same degree of relative change in period one ($t_0–t_6$) as in period two ($t_6–t_{18}$). Over the total experimental period ($t_0–t_{18}$) the relative changes in uninoculated monoliths were much lower ($\approx 0.4\%$) than the alterations as a result of mesofaunal activities ($\approx 3\%$).
Fig. 4. Box-plot of the specific surface area (SSA) of sealed monoliths inoculated with Collembola and Enchytraeidae and with no inoculated fauna for the entire 18 months experimental period ($t_0 - t_{18}$) based on three dates of measurement. Each box represents half of the values and the bars represent ranges recorded, the solid line marks the median inside each box. Treatments indicated by different letters are significantly different based on the Mann–Whitney-U-test, $p < 0.05$.

Fig. 5. Box-plot of the specific surface area (SSA) of unsealed monoliths inoculated with Collembola and Enchytraeidae and with no inoculated fauna for the entire 18 months experimental period ($t_0 - t_{18}$) based on three dates of measurement. Each box represents half of the values recorded, the bars represent ranges and the solid line marks the median inside each box. Treatments are not significantly different based on the Mann–Whitney-U-test, $p < 0.05$.

4. Discussion

The smoothening of the surface, as reflected by the decreasing SSA values is a precondition for the sealing process which occurs after a rainstorm event (Zobeck and Onstad, 1987; Rudolph et al., 1997). The topography of the soil surface is therefore a good indicator for the existence of a surface seal.

Collembola and Enchytraeidae are clearly able to affect the morphology of soil surfaces through their burrowing activities leading to superficially deposited casts. Generally, this cast deposition results in a decrease or increase in the SSA, indicating a smoother or rougher surface, respectively. A higher SSA in inoculated monoliths has also been demonstrated in previous experiments conducted with compacted soil monoliths (Schrader et al., 1997). In the case of unsealed surfaces in the present study no significant difference in SSA between inoculated and uninoculated monoliths was visible (Fig. 5). On the other hand, it can be concluded for sealed soil surfaces that mesofauna are able to penetrate the seal (Fig. 4). The minero-organic casts of Collembola and Enchytraeidae create a finely structured topography, i.e. a rougher surface which results in an increased SSA. Moreover, irrespective of the surface roughness these fine cast aggregates of both mesofaunal groups enhance the stability of the soil structure at the microscale (Trappmann, 1953; Heisler et al., 1996).

The relative changes in SSA from Collembola and Enchytraeidae burrowing activities in sealed monoliths were distinctly higher than in uninoculated monoliths. The change in the surface seal is the most significant development, regardless of the direction of change. Usually, one would expect a rougher surface as a consequence of mesofaunal activity and seal disruption. However, a change towards a smoother surface is also possible when mesofaunal activity...
leads to a reorganisation of surface inhomogeneities into smaller scale inhomogeneities which are below the measurement scale of resolution (Schrader et al., 1997). The change itself demonstrates that mesofauna are able to alter the otherwise static sealed surface and thereby initiate and enhance the rehabilitation of sealed soil surfaces. An increase in the infiltration capacity of the soil will be the consequence of the surface changes. On a larger scale, similar rehabilitation processes were investigated for earthworms (Kladi-vko et al., 1986) and termites (Mando and Miedema, 1997). The activities of both macrofaunal groups led to improved infiltration rates (Mando et al., 1996).

Positive $\Delta$SSA values (Table 1) indicate an increase in surface roughness by cast deposition, whereas negative values occur if for example small cracks are filled with fine mesofaunal casts resulting in a decreasing surface roughness. Despite the fact that $\Delta$SSA was negative for Collembola and positive for Enchytraeidae for the entire experimental period (Table 1), their activity may be regarded as similar in terms of the alteration of the surface ignoring the direction of this alteration. This becomes more clear after calculating $\Delta$SSA in (%) terms (Fig. 6). Thus, for sealed surfaces the $\Delta$SSA (%) for the total experimental period ($t_0-t_{18}$) is nearly the same for Enchytraeidae and Collembola in the present experiment. The results of this research suggest that the contribution of mesofauna to soil structure is only apparent in cases in which the soil is exposed to exogenous physical and/or mechanical impacts and corresponding changes in soil properties and structure occur. When surface sealing (this study) or soil compaction (Schrader et al., 1997) take place, mesofaunal activities may counteract such changes in the soil structure and accelerate the rehabilitation processes of the soil surface.

Changes in sealed soil surfaces as a result of intrinsic soil processes are reflected in the $\Delta$SSA (%) of uninoculated monoliths (0.4%). Like macrofaunal activities these processes also contribute to a rehabilitation of sealed soil surfaces. In general, swelling and shrinking are two main intrinsic soil processes depending on the water balance and clay content of the soil (Dexter, 1988). However, such processes appeared to be of little significance over the 18 months experimental period in the present case where conditions were kept constant. Consequently, the contribution of mesofaunal activity to the rehabilitation of soil surface seals should not be underestimated. The impacts of mesofauna activity on soil structure should be considered in addition to those of macrofauna when physical processes, such as flux processes are evaluated. The experiments of Didden (1990) and van Vliet et al. (1998) reveal a general increase in air permeability and saturated hydraulic conductivity as a result of enchytraeid burrowing activity.

The burrowing activities of Collembola and Enchytraeidae both directly and indirectly affect soil physical and chemical processes (e.g. Trappmann, 1953; Didden, 1990; Heisler et al., 1996; Schrader et al., 1997; van Vliet et al., 1998). As a result the access to biotic and abiotic habitat resources for other soil organisms is controlled, or at least strongly influenced by these prominent members of the mesofaunal community. Accordingly, the burrowing activities of Collembola and Enchytraeidae in general, which can for example lead to the rehabilitation of sealed soil surfaces are consistent with the concept of ‘physical ecosystem engineering by organisms’ (Jones et al., 1994) and should be included in the category of Lavelle’s (1994) ‘ecosystem engineers’.

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