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Original article

Morphological description of soil structure patterns produced by earthworm bioturbation at the profile scale

D. Piron [a,b,*], G. Pérès [a], V. Hallaire [c,d], D. Cluzeau [a]

[a] UMR 6553 EcoBio, Univ-Rennes 1, CNRS, Station Biologique, F-35380 Paimpont, France
[b] UMR 5245 EcoLab, (CNRS-INPT-ENSAT-UPS), F-31326 Castanet-Tolosan, France
[c] INRA, UMR 1069 Sol Agro et hydrosystème Spatialisation, F-35000 Rennes, France
[d] Agrocampus Ouest, UMR 1069 Sol Agro et hydrosystème Spatialisation, F-35000 Rennes, France

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ABSTRACT

In cultivated soils, Soil structure mainly results from climatic, anthropogenic and biological processes. Nevertheless, few field methods evaluating the quality of soil structure consider the contribution of biological processes. In order to include earthworm biostructures in the field description of soil-structure, an original method is proposed in this paper. Soil profiles under different agricultural practices were examined to distinguish soil-structure patterns, notably those resulting from earthworm bioturbation. The relevance of naked eye observation was tested by a micromorphological approach, using image analysis on thin sections. Then, the application of this method was illustrated by mapping soil profiles.

Our study led to the creation of a typology (i.e. classification system) of eleven soil-structure patterns, taking into account anthropogenic processes (e.g. compaction, soil tillage), root activity and earthworm activity. Seven patterns were attributed to earthworm activity in the form of burrows or casts. Three burrow features were distinguished, differentiating between filled burrows, or empty burrows with a brown cutan or without visible cutan. Four patterns of cast packing were distinguished, differentiating between cast aggregates that were fresh, welded, compacted, or combined with burrow features. This typology appears relevant for developing a field tool to describe and spatially quantify soil structure.

1. Introduction

The physical structure of soils provides essential ecosystem services such as plant growth, water, gas fluxes and biological activities. Thus, agricultural soil management should preserve the physical structure of soils, as underlined in the European Union's Common Agricultural Policy. Soil-structure is defined as the arrangement of particles and associated pores in soil on scales ranging from nanometres to decimetres [45]. Most of these structural features are the results of pedoclimatic, anthropogenic or biological processes which contribute to soil quality in different ways. To evaluate soil structure, field methods have been developed to take into account the impact of agricultural practices. These methods, based on field observations by the naked eye, focus on structures resulting from physical and anthropogenic processes [3,40,44] but rarely consider structures resulting from biological processes [36]. Biological processes, however, are widely known to influence soil quality via their strong impact on soil structures. For example, roots act upon soil structure via numerous mechanisms of aggregation (e.g. tensile strength during root growth, drying of soil and root exudates) [42]. The impact of earthworms was underlined in the past by Darwin [17], and these organisms are widely recognised as major biological agents in temperate soil agro-systems. Earthworm bioturbation produces two kinds of soil-structures: burrows and casts. Burrows are produced by excavation (i.e. ingestion and casting of soil material) or by pushing the soil aside [30]. Casts are ingested soil materials excreted on the surface and belowground in ovoid or spherical pellets, 2–5 mm in diameter [19]. Earthworm casts constitute a significant part of soil aggregates [38]; however, it is difficult to estimate cast deposition in the soil matrix [39]. The impact of an earthworm on soil structure is strongly related to which of the three main ecological groups it belongs [37,38]: (i) epigeic species live on the soil surface, rarely dig burrow and deposit small casts on the surface; (ii) anecic species live in permanent burrows and deposit casts mostly on the surface but also on burrow walls; (iii) endogeic species make extensive, temporary burrows and frequently fill burrow sections with casts.

* Corresponding author. UMR 6553 EcoBio, Univ-Rennes 1, CNRS, Station Biologique, F-35380 Paimpont, France.
E-mail address: pirondenis@orange.fr (D. Piron).

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Earthworm biostructures influence soil functions such as water infiltration and retention [20,24,33], and thus control other biological activities; therefore, earthworms are considered engineers of the soil ecosystem [32]. In the agricultural context, earthworm activities (e.g. foraging and casting) are strongly impacted by agricultural practices such as organic matter inputs [29,41,47,48], soil tillage [46], pesticide applications [52], and soil compaction [34]. In this way, agricultural practices act upon biological soil functioning.

Different methods have been developed to describe features of earthworm activity in the field. Some methods focus on tubular macroporosity related to earthworm burrowing activities [47,53]. Others characterise casting activities, but are limited to aboveground earthworm casts [4,51], even though most casts are excreted belowground [1,5,15]. Studies of belowground casts are usually limited to micromorphological approaches using microscopes [18,49,54]. No field method has been performed considering casts as soil structures, although Bouché [7] and Boyle et al. [9] noted that casts could be described with the naked eye using morphological and colour criteria. Therefore, it appears feasible to complement normal diagnostic methods with the identification of soil structures resulting from biological activity.

This paper proposes a novel method that includes earthworm biostructures (i.e. burrows and belowground casts) in a field description of soil structure. A typology (i.e. classification system) of soil-structure patterns was created from observations of differing soil profiles. A micromorphological approach was developed to test the objectivity of field observations and to validate the typology. Then, the application of this method was illustrated by mapping soil profiles.

2. Materials and methods

2.1. Study site

Soil profile descriptions were performed at the Kerguéhennec research site (managed by the Brittany Chamber of Agriculture), France (47°52′48"N, 02°46′23"W). The climate is temperate oceanic, with a mean annual precipitation of 890 mm. The soil has a loamy, sandy clay texture (at 0–45 cm) which is derived from the weathering of schist and classified as a Dystric Cambisol [21]. At 0–25 cm and 25–45 cm, the mean OM contents are 4.3% and 2.5%, respectively.

Experimental plots allowed us to compare six agricultural–management scenarios (each 6 years old) reflecting a wide range of anthropogenic and biological impacts. Three tillage practices were performed: conventional tillage (ploughing to 20–25 cm), reduced tillage (harrowing to 5–10 cm), and no tillage (seeds planted with disks). Tillage practices were nested with mineral (120 kg N ha^{-1} yr^{-1}) and organic fertilisation (40 t poultry manure ha^{-1} yr^{-1}, corresponding to 2.2 t C ha^{-1} yr^{-1}). To obtain a similar N input, mineral fertiliser was added to correct the N deficiency of poultry manure. During the experiment, the field was planted with wheat in a crop–fallow sequence (wheat–maize–wheat–rape). The last tillage activities were performed in November before sowing and fertiliser application in March.

2.2. Field identification of soil-structure patterns

Six pits were dug, and soil profiles (100 cm wide and 60 cm deep) were sampled during the spring. The soil profiles were carefully prepared with a knife to preserve the roughness and original aspect of the bare soil aggregates, as recommended by Brewer [10]. Next, soil structure was described with the naked eye alone to avoid disrupting the soil profile with a tactile assessment. Using references which define characteristics of earthworm biostructures [10,14,23], a set of morphological and colourimetric criteria was used to locate features of earthworm bioturbation. Soil-structure patterns were identified in the field and classified according to their presumed origins. A grid frame (5 × 5 cm) was placed vertically against the surface of the soil profile to facilitate the delineation and free-hand mapping of soil-structure patterns.

2.3. Micromorphological analysis

To validate the pertinence of visual soil structure assessment, Brewer [10] and Vogel and Babel [55] advised using an instrument which provides quantitative information. Thus, 2D-image analysis was used to investigate fine scale morphological criteria and describe the macroporosity quantitatively.

Twenty-one undisturbed soil blocks (16 cm × 9 cm × 5 cm) were collected from each soil profile between 5 and 30 cm in depth to obtain samples of each soil-structure pattern. Following the procedure of Ringrose-Voase [50], blocks were dried using water-acetone exchange and were impregnated with a polyester resin containing a fluorescent dye. Then, blocks were cut vertically into thin sections and polished. Soil-structure patterns were visually delineated on thin sections, and certain patterns were selected for further examination. For each selected soil-structure pattern, three images were captured using optical microscopy (15×) with a digital camera under reflected UV light, which rendered the solid phase dark and the pores bright. Images were digitised at 1200 × 1100 pixels with a spatial resolution of 5.88 μm $pixel^{-1}$, which corresponded to an area of 7 × 6.5 mm. Using OPTIMAS software (Meyer Instruments, Inc., Houston, Texas, USA), images were segmented into binary images of the pore space.

Porosity was quantified on binary images using: (i) total macroporosity, expressing the proportion of pixels belonging to the pore space and (ii) pore classification, after being grouped into "poroids" [43]. Pore classification was determined according to pore size and shape. Pore size was measured by its area on the binary image and categorised into four size classes: class 1 for small pore [0.017–0.04 mm^2 class 2 for medium pore, 0.04–0.16 mm^2 class 3 for large pore, 0.16–2.56 mm^2 and class 4 for very large pore > 2.56 mm^2. Pore shape was measured using the elongation index e with $e = (\text{perimeter})^2/(4 \times \pi \times \text{area})$ [16]. Three shape classes were defined to distinguish between tubular voids (T), cracks (C) and packing voids (P) [25]. Pores were then characterised by the combination of their size and shape (e.g. P1 for small packing void). Soil macroporosity data were compared using the non-parametric Mann–Whitney U test, at $p < 0.05$.

3. Results

3.1. Field description of soil-structure patterns

Initial examination of the soil profile revealed surfaces of differing roughness and composed of soil-structure patterns resulting from a variety of processes; some earthworm biostructures required more detailed examination. We distinguished eleven soil-structure patterns by their main origin (anthropogenic, biogenic and indefinite) (Table 1).

Processes were considered to be **a**nthropogenic (**A**) when soil-structure patterns resulted from agricultural machinery traffic or soil tillage. Two anthropogenic patterns were distinguished:

- **Ac**: exhibits a **c**ompacted structure with little roughness in which no aggregates and few pores were observed (Fig. 1a). This pattern was observed in small patches in the soil profile.