Soil & Tillage Research 145 (2015) 55–61

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Wettability and biogeochemical properties of the drilosphere and casts of endogeic earthworms in pear orchard

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ARTICLE INFO

Article history:
Received 30 May 2014
Received in revised form 4 August 2014
Accepted 16 August 2014

Keywords:
Pear orchard
Endogeic earthworms
Earthworm system
Water movement
Organic carbon
Microbial activity

ABSTRACT

The aim of this work was to evaluate the effect of endogeic earthworms on the burrow system (burrow wall 0–3 mm, transitional zone 3–7 mm, bulk soil ≥ 20 mm from the burrow wall) and cast aggregates of a loess soil under pear orchard. This effect was tested by determining wettability and selected biogeochemical properties (organic carbon, potential redox, respiration, denitrification and methanogenic potentials, and ammonium and nitrate N) using soil from each compartment immediately after sampling. Wetting was measured with an apparatus consisting of a sponge connected with a graduated capillary tube and biogeochemical soil properties using standard methods. The mean wetting rate was the lowest in the cast aggregates and burrow walls (0.154 and 0.542 $mm^3 s^{-1}$) and the highest in bulk soil (1.016 $mm^3 s^{-1}$). Total organic carbon, C_{org} (range 1.59–2.40%), microbial carbon, C_{mic} (range 0.567–1.85 $mg\,g^{-1}$) and C_{mic}:C_{org} ratio (range 3.57–7.69%) followed the ranking series: cast aggregates > burrow walls > transition zone > bulk soil with the lowest relative differences between the cast aggregates and burrow walls. The same compartment arrangement was observed for denitrification potential (range 34.7–98.0 mg N_2O-N kg^{-1} day^{-1}), respiration rate (range 11.3–56.0 mg CO_2-C kg^{-1} day^{-1}), metabolic quotient qCO_2 (respiration to microbial biomass ratio) (range 0.83–1.56 μg CO_2-C mg^{-1} C_{mic} h^{-1}), and methane production (range 4.00–429.9 mg CH_4-C kg^{-1}). Foregoing indicates that C-enriched burrows and cast aggregates are the least wettable and encouraging habitats for the growth and activity of microorganisms. Ammonium N concentrations were not influenced by earthworms, but concentrations of nitrate N and N_{tot} were significantly greater in the earthworm affected compartments than in the bulk soil. Principal component analysis (PCA) showed high sensitivity of wettability to concentrations of C_{org} and C_{mic} and C_{mic}:C_{org} ratio. The quantitative description of the spatial distribution of the wettability and the biogeochemical properties in the earthworm system may have implications to the understanding of lateral movement of water in the earthworm inhabited soils.

1. Introduction

In terms of biomass earthworms are considered as the most important soil invertebrates in the temperate soil ecosystem (Römbke et al., 2005). With respect to soil structure earthworms are the most important ecosystem engineers (Lavelle et al., 1997; Jégou et al., 2001). They burrow through the soil by pushing soil aside and by ingesting and egesting soil and at the same time displace the soil radially and axially (Barnett et al., 2009) forming burrows as macropores. As they feed, earthworms participate in plant residue decomposition, nutrient cycling, and redistribution of organic carbon and nutrients in the soil profile (Don et al., 2008; Teng et al., 2012) and removal of organic contaminants from soil (Rodriguez-Campos et al., 2014). The translocation of C from surface layer to the subsoil decreases the C vulnerability to mineralization (Don et al., 2008; Lal, 2009). Comparative study of a 35 year-old apple orchard soil and conventionally tilled field showed that herbicide leaching was lower from orchard due to the greater organic matter content and the presence of earthworm burrows with burrow linings that adsorb herbicide, and thus prevent ground water pollution (Siczek et al., 2008). The presence of earthworms is considered as a sign of "healthy" soil (Boivin and Kohler-Milleret, 2011) and the associated burrows as an effective measure of soil 'physical quality' (Birkás et al., 2004; McKenzie

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http://dx.doi.org/10.1016/j.still.2014.08.010
0167-1987/© 2014 Published by Elsevier B.V.

et al., 2011). Therefore many orchard ground cover and weed management practices aim to enhance soil biological diversity including earthworms (e.g., Andersen et al., 2013).

There have been numerous studies examining the morphology and geometry of deep (up to 3 m) and permanent burrows made by anecic *Lumbricus terrestris* (Jégou et al., 2002; Capowiez et al., 2009) with respect to their role in preferential saturated water flow in soil profile (Alaoui et al., 2011), solute transport and pesticide concentrations (Capowiez et al., 2006), surface runoff (Guebert and Gardner, 2001) and root growth and distribution (Lipiec and Hatano, 2003; Głąb, 2013).

Much less studies were performed on soil physical properties at the interface between burrow void and surrounding soil. Of particular importance is the region influenced directly by earthworms (within several millimeter), which is called drilosphere (Schrader et al., 2007), analogically to the rhizosphere of plant roots. Using X-ray computed tomography Rogasik et al. (2014) revealed that the bulk density decreased from the inner to outer boundary of anecic *L. terrestris* drilosphere that can be due to radial and axial pressure and soil displacement during burrowing (Barnett et al., 2009). Besides physical modifications, regular mucous secretions into the soil earthworm burrows result in elevated concentrations of soluble organic C and organic N that may serve as a substrate for microorganisms (Jégou et al., 2001).

Interactions between earthworms and microorganisms are also observed in earthworm casts as newly formed aggregates. They start already in the earthworm gut as a result of initial mixing of C and mineral particles (Bossuyt et al., 2005; Mummey et al., 2006). Adsorption of the occluded C on mineral surfaces and formation of the organo-mineral complexes contribute to the improved stability of the cast aggregates. Stable casts enhance organic carbon sequestration (Görres et al., 2001) and increase the overall structural stability of a soil and thereby resistance to soil physical degradation (Blanchart et al., 1999; Zhang and Horn, 2001; Ogunwole et al., 2014). The role of earthworms in the formation of organic-rich aggregates is of importance in orchards with little or no cultivation (Jongmans et al., 2003).

Recent results suggest that the heterogeneity of bulk density and carbon concentrations at structural surfaces in the drilosphere may largely affect lateral transfer of water and solutes from burrow wall to bulk soil during preferential flow (Leue et al., 2013; Rogasik et al., 2014). However, a thorough understanding of physical and biological properties of lateral water flow from burrow wall to matrix soil is missing even though it is recognized as a functional domain of the soil (Marhan and Scheu, 2006; Rogasik et al., 2014). This gap refers particularly to endogeic earthworms that live in a wide range habitat including tropical humid soils in Asia (Bottinelli et al., 2010) and temperate and continental climates in Europe (Pitkänen and Nuutinen, 1997). Living in the upper mineral soil and consuming large amounts of soil endogeic earthworms are able to detect and ingest nutrient hot spots (Marhan and Scheu, 2006).

In this study, we tested the hypothesis that alterations in soil structure and organic carbon concentrations made by endogeic earthworms decline the wettability of burrow wall and cast aggregates. We also determined selected biogeochemical characteristics to better understanding relation of conductive and biological functions of the earthworm affected compartments. To our knowledge this has not been investigated before.

2. Materials and methods

2.1. Site and soil sampling

The study site is situated at the experimental farm of the Lublin University of Life Sciences in Felin (51°15′N, 22° 35′E), in the south-eastern part of Poland. The climate is moderately warm continental. Long-term annual mean temperature and precipitation at the experimental site are 7.4 °C and 572 mm, respectively. The soil is an Orthic Luvisol developed from loess, over limestone with silt loam texture containing (in g kg^{-1}) 660 sand (2–0.02 mm), 280 silt (0.02–0.002 mm) and 60 clay (<0.002 mm), pH (H_2O) 5.85, bulk density 1.33 Mg m^{-3} and particle density 2.61 Mg m^{-3} (Lipiec et al., 2012). The research area with respect to genesis and textural composition of soils is rather uniform (Dobrzański and Zawadzki, 1951). The study was conducted in a 50 year-old pear orchard with a permanent sward consisted of various grasses and legumes that was mown in the inter-rows during growing season. It is inhabited mostly by endogeic and anecic earthworms. The endogeic *Aporrectodea caliginosa* and *Allolobophora chlorotica* and the anecic *L. terrestris* are common earthworm species in Poland and Central Europe. The presence of the endogeic *A. caliginosa* in the study orchard was identified using the key of Sims and Gerard (1985). The earthworms were unpigmented and had the length approximately 60–80 mm. We observed that they dig burrows of 4–5 mm in diameter, and therefore such burrows were selected for further studying.

We defined the following compartments (i) the burrow wall (BW) up to 3 mm from the lumen of the burrow wall (ii) the transition zone (TZ) of 3–7 mm from the lumen of the burrow wall, (iii) the bulk soil (BS), situated at least 20 mm from the BW and (iv) the earthworm cast aggregates (CA). We used similar compartments to those in Jégou et al. (2001). The in situ samples for direct measurements of biogeochemical characteristics were collected by scraping the burrow walls and earthworm cast aggregates manually from the soil next to the burrow entrance at the upper 10 cm (on May 2011). Soil water content at sampling was 16.1% w/w (soil water potential − 48 kPa) that does not limit the performance of earthworms (Holmstrup, 2001).

2.2. Wettability

To determine the wettability in the drillosphere undisturbed soil with visible earthworm burrows were taken in situ into containers (10 cm× 10 cm× 10 cm) at the same time as soil samples for analysis of the concentrations of organic C, N and microbial characteristics (Section 2.1). Then after careful bisecting the burrows along the length using a scalpel blade intact soil samples were taken from the BW (with surrounding soil behind), TZ (3 mm behind the BW after removing the most inner part of the wall) and BS. Separate measurements were done for the cast aggregates. Wetting was measured with an apparatus consisting of a sponge connected with a graduated capillary tube (1.5 mm diameter) filled with 500 mm^3 of water (Leeds-Harrison et al., 1994). When connection between the aggregate and the sponge appeared, the flow rate of water from the horizontal capillary tube as a function of time was taken as a measure of wettability (wetting rate). Measurements were performed in five replicates. Wettability rates ($mm^3\,s^{-1}$) were calculated from the slope of the relationship between cumulative wetting (mm^3) and time (s).

2.3. Biogeochemical characteristics

Soil organic carbon (C_{org}) and inorganic carbon (C_{inorg}) were determined in three replicates by means of TOC-VCPH analyzer (Shimadzu, Japan). Soil N concentration was measured by modified Kjeldahl method using Behr S4-1225P apparatus (Labor Technik, Germany). Nitrate (NO_3^-) and ammonium (NH_4^+) concentration in the soil were determined in extracts (0.01 M $CaCl_2$) using flow-type spectrophotometric analyzer, FIA-Star 5010 (Foss Tecator).

Soil microbial biomass (C_{mic}) was determined using the substrate induced respiration (SIR) method based on the initial respiratory response of the microbial population to amendment with an excess