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Temporal dynamics of earthworm-related macroporosity in tilled and non-tilled cropping systems

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A B S T R A C T

Tillage influences first soil structure and then soil organisms such as earthworms, which are highly involved in the creation of soil macroporosity. This study assessed the temporal dynamics of earthworm-related macroporosity in two ploughed and one unploughed cropping systems. Three sampling dates were chosen: one month before ploughing, and one and five months after the event. Earthworm communities, able to rebuild the macroporosity, were sampled one and five months after ploughing. Before ploughing, the burrow continuity, i.e., the number of burrows with a vertical length greater than 5 cm, was not significantly different in the three systems. It was stable between the three sampling dates in the unploughed system but it decreased by 65% and 46% after ploughing (i.e., in two months) in the organic and the conventional systems, respectively. Five months after ploughing, the burrow continuity remained between two and four times lower than in the unploughed living mulch cropping system. Earthworm biomass was higher and burrow system characteristics (i.e. burrow volume and continuity) were more stable over time in the non-tilled with a living mulch cropping system than in the tilled systems. Earthworm-produced macroporosity was thus substantially decreased after ploughing in conventional and organic systems and had still not totally recovered 5 months later. This can lead to large functional consequences on soil structure and thus on air and water fluxes in the soil.

1. Introduction

Due to their digging activity, earthworms are highly involved in the creation of soil macroporosity (Bottinelli et al., 2010; Ehlers, 1975). According to Darwin (1881), “the plough is one of the most ancient and most valuable of man's inventions; but long before he existed the land was regularly ploughed and still continues to be thus ploughed by earthworms”. Earthworm burrows affect soil porosity and aggregation and thus modify the transfer of water, air and nutrients through the soil (Ehlers, 1975; Fischer et al., 2014; Shipitalo and Le Bayon, 2004). These modifications depend on the three dimensional architecture of the burrow systems (McCoy et al., 1994; Munyankusi et al., 1994) and especially continuity and inter-connectivity between burrows (Capowiez et al., 2014; Monestiez and Kretzschmar, 1992).

Agricultural practices in arable land, including tillage and pesticide use, can have an impact on earthworm communities. Tillage significantly modifies both the soil structure and earthworm communities (Chan, 2001; Crittenden et al., 2014; Ernst and Emmerling, 2009). Ploughing destroys most of the burrows and specifically decreases their continuity (Langmaack et al., 2002). It also harms and exposes to predation larger earthworms (i.e., anecic) (Chan, 2001) which are responsible for the creation of large-sized macropores (Capowiez et al., 2015). That said, ploughing mainly affect earthworm communities when it is newly implemented or stopped (Ernst and Emmerling, 2009) but once a tillage routine becomes established for several years it no longer appears to disturb them. In other words, in the long-term, earthworm communities might have been selected by tillage in regularly ploughed systems. A new ploughing event could have no strong effect because earthworm communities would be accustomed to this physical disturbance (De Oliveira et al., 2012). Some earthworms, such as endogeic species, may even be favored by ploughing. It may expose them to bird predation but at the same time assist population growth by burying soil organic matter that was previously at the soil surface and thus not readily available. Reproduction and recruitment may thus be enhanced just after tillage due to the increase in nutritional resources (Chan, 2001).

Alternative cropping systems are being proposed as a way of limiting environmental damage and moving towards more sustainable agricultural practices. Conservation systems, involving no-ploughing or reduced tillage and a permanent plant cover, have been implemented mainly to avoid soil erosion. In these systems, earthworms are thought

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Table 1
Wheat crop management in the three cropping systems. “Living mulch” refers to the “direct seeding living mulch-based cropping system”.

Cropping system	Conventional	Organic	Living mulch
Crop rotation between 2010 and 2013	Pea, wheat, oilseed rape, wheat	Wheat, barley/pea, alfalfa, wheat	Wheat/alfalfa, alfalfa, alfalfa, wheat/alfalfa
Permanent plant cover	No	No	Alfalfa
Ploughing (in autumn)	Each year, except after pea	Each year	–
Date of the last ploughing	October 2012	October 2012	–
Fertilizers	N, P, K, S	No	N, P, K, S
Pesticide use (March 2012–March 2013)	Herbicides, growth regulator, fungicides	No	Herbicides, molluscicides
Wheat yield (t ha^{-1}) (on average over the last five years)	9.9	7.2	6.1

to somehow “replace” the tillage effect (sensus Darwin). Soil is aerated through the creation of macroporosity by endogeic and anecic species and the behavior of anecic earthworms leads to organic matter being buried (Chan, 2001, 2004). However, it remains unclear whether these earthworm effects are of sufficient impact to replace the benefits of tillage. Other alternative cropping systems using less chemical inputs, such as integrated and organic systems, have been proposed to reduce non-intentional impacts of chemical inputs on the environment and human health. All these alternative cropping systems are likely to influence the abundance and activity of earthworm communities (De Oliveira et al., 2012; Pelosi et al., 2015). For instance, under field conditions, Pelosi et al. (2013) highlighted a negative influence of pesticides on three earthworm species depending on their propensity to forage and live at the soil surface.

Considering the variations in earthworm population size and the mechanical damages following a tillage event (Chan, 2001; De Oliveira et al., 2012), earthworm-related macroporosity will probably vary greatly. We suggest that the anecic earthworms increase their activity to rebuild their burrows (i.e., their habitat) whereas endogeic earthworms tend to reduce their burrowing activities since organic matter is now available in great quantities within the soil. Indeed, Hughes et al. (1996) had shown a negative relationship between burrow length and availability in organic matter for endogeic earthworms. Furthermore, for these earthworms, burrowing will become far easier and less costly in energy due to the loose structure of the soil. Overall, earthworm burrow systems are dynamic systems resulting from the balance between burrow creation and burrow destruction under the influence of climate, biotic interactions and soil management (Capowiez et al., 2001; Ligthart, 1997).

Here we aimed to assess, under field conditions, the temporal dynamics of earthworm-related macroporosity in relation with a tillage event as well as the earthworm communities. For this, we selected two ploughed systems (one organic and one conventional cropping system) and one unploughed cropping system (living mulch) considered here as the system without ploughing. To assess the temporal dynamics of soil macroporosity, three sampling periods were chosen: one month before the ploughing event, then one and five months after it. Earthworm communities were sampled one and five months after the ploughing to explain the dynamics of earthworm-related macroporosity in the different cropping systems. In the unploughed system, we expected soil macroporosity to be higher and more constant over time than in the ploughed fields.

2. Material and methods

2.1. Site, soils and cropping systems

Our experimental site was located in Versailles, 15 km South-West of Paris (48°48′N, 2°08′E). The experimental site was established in 1997 and was under conventional agriculture before this date. The soil is a deep luvisol (FAO classification), with a neutral pH and on average 58% silt, 25% sand and 17% clay. The climate is temperate, with a mean annual rainfall of 640 mm and a mean annual temperature of 10.4 °C.

The three experimental cropping systems (Table 1) were a conventional system, an organic system (both tilled) and a living mulch cropping system (non-tilled). In the organic cropping system, no manure or other external organic amendments were added. The organic system was managed following the rules of the AB France label, without synthetic pesticides or mineral fertilizers. Weeds were limited by soil tillage, crop succession, weed smothering by crop density, and changes in crop sowing date. Nutrient export was limited by straw return. In the living mulch cropping system, the permanent plant cover (Table 1) was killed with herbicides in order to plant the main crop. The conventional system was managed with pesticides and tillage. Ploughing (moldboard ploughing, in October 2012) involved soil inversion to 25–30 cm depth and use of a combined drill. In the living mulch cropping system, no-till involved mechanical disturbance in the top 3 cm, without soil inversion (Semeato machinery). Harrowing was not used in the latter system but it was done twice a year, in autumn, in the ploughed systems.

pt?>The trial was divided into two replicates (i.e. two blocks). In each replicate, a 1 ha randomized plot of each system was divided into two subplots in which a rotation was established so that there was a winter wheat crop in one of the two subplots every year. Soil cores and earthworms were studied in the six plots under winter wheat, i.e., the same sampling areas for the two (for earthworms) or three (for soil cores) sampling periods. At the first sampling period for soil cores (i.e., one month before ploughing), the soil was bare, except in the living mulch cropping system.

In 2011, in the conventional system, the organic system and the living mulch cropping system, the C/N ratio in the top 20 cm of soil was respectively 10.5, 10.1, and 10.8 and the organic matter content was 17.8, 17.1, and 21.5 g kg^{-1} respectively. The calcium carbonate ($CaCO_3$) content was 0.9 g kg^{-1} and the pH was between 7.2 and 7.4 in the three cropping systems. Soil bulk density (20 cm depth) in the three cropping systems was 1.49, 1.18, and 1.51 respectively in spring 2011.

Table 2
Total precipitation (mm) and mean soil temperatures (°C) at 10 cm depth, in Versailles the two months preceding sampling. “Before ploughing” means in September 2012, “one month after ploughing” means in November 2012, and “five months after ploughing” means in March 2013.

Sampling date	Before ploughing	One month after ploughing	Five months after ploughing
Mean of minimal soil temperature (°C)	18.4	12.3	4.5
Mean of maximal soil temperature (°C)	22.0	13.6	5.2
Total of precipitation (mm)	33.5	180.0	79.5