Effects of soil characteristics and farm types on earthworm populations in Hungarian organic, permaculture and conventional farms

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Abstract

Farming systems with differing intensities have various impacts on soil biota. The objective of our study was to assess the effects of different farm types (conventional, organic and permaculture) and soil characteristics on earthworm populations. The main consideration was that scientific knowledge on permaculture farms in regards to soil fauna is missing. According to our hypothesis permaculture farms provide the most ideal conditions for earthworms. Fifteen micro-farms (0.3–2 ha) with similar agro-ecological features were selected for comparison in the North-Central part of Hungary. These were all horticultural farms with diverse crop rotations. The basic difference was the intensity of the farming activities. Earthworms were sampled in May and September (2020) with six replicates on each farm (90 samples in total). Earthworms found in the 25×25×25 cm soil blocks were hand-sorted. Five soil samples from each site were analysed for texture, pH, soil organic matter, macro- and micronutrient content in September (2020). Seven endogeic and three epigeic earthworm species were detected. In September species numbers were higher, in the average of the earthworm species number and Shannon diversity there were lower differences, a stronger positive relationship was found between CaCO 3 content and earthworm abundance, adult earthworm average was strongly and positively affected by magnesium content. Earthworm species number was significantly higher in permaculture farms while earthworm abundance was also significantly higher but only in May. This partly validates our zero hypotheses that permaculture farms have the best performance in providing good conditions for earthworm populations.

1. Introduction

The natural values of the various ecosystems provide valuable assets for humans and these assets are evaluated by the ecosystem service concept (MEA 2005). The evaluation of ecosystem services of the natural environment is used in many international studies, e.g. evaluating biodiversity (Garbach et al. 2014) and soil (Dominati et al. 2010, Dominati et al. 2014) in agroecosystems, land cover data on farm-scale (Burke et al. 2020), cover crops on temperate soils (Blanco-Canqui et al. 2015) and valuing earthworms (Blouin et al. 2013, Schon and Dominati 2020). Hungarian studies were concentrating on village level (Prohászka et al. 2020), nature conservation areas (Ábrám et al. 2019) and soils (Nel and Szilágyi 2018). Soils provide ecosystem services of high importance for our survival, e.g. climate regulation (Malatinszky 2016), carbon storage (Nel and Szilágyi 2018), nutrient and water cycling (Dominati et al. 2014). Modification of potential production capabilities of soils has always been an important topic (Slámová et al. 2015, Frantál et al. 2015). Despite its crucial role, the soil is still less appreciated and is not managed responsibly (Adhikari and Hartemink 2016, Lüscher et al. 2016), even though there has been research and monitoring dealing with the evaluation of systems and possible positive soil quality change, e.g. after the abandonment of arable fields (Botos et al. 2019).

Soils have many contributions to ecosystem services delivery and their assessment has been investigated by various authors (Knops et al. 2001, Crossman et al. 2013, Calzolari et al. 2016, Jónsson and Davíðsdóttir 2016, Baveye 2017, Chalhoub et al. 2020).

Earthworms play a vital role in soil biology (Blouin et al. 2013, Spurgeon et al. 2013, Drobnik et al. 2018, Schon and Dominati 2020), they are also referred to as ecosystem engineers as they make burrows by moving in the soil, mixing and aerating soil layers and modifying soil structure, thus contributing to soil formation (Lavelle et al. 1997, Lavelle 2012, Bartlett 2010). In a more general sense, earthworms can be considered key players in the soil food web, not to mention nutrient cycling, furthermore, decomposing of organic materials and combining the organic and mineral parts of the soil (Lavelle et al. 1997). This way earthworms are good indicators of soil health and are part of the supporting processes of soil as being part of the soil biota (Dominati et al. 2014).

There are various ways of managing production at the farm level, the most significant factor affecting soil biological activity is soil cultivation (Dale and Polasky 2007, Barrios 2007, Birkás 2008, Bommarco et al. 2013, Dekemati et al. 2019, Vršič et al. 2021). Furthermore, soil cover (e.g. mulching) can tremendously increase the amount of soil moisture and this moisture helps to maintain soil life (Birkás et al. 2010). Inadequate soil management can cause compaction (Dekemati et al. 2019) and reduced water holding capacity (Shestak and Busse 2005). We can conclude that maintaining good soil quality depends greatly on the farmers and land managers in all agro-ecosystems.

Previous studies in Hungary investigated the effect of different soil cultivation systems on soil characteristics and earthworm abundance and found that no-tillage parcels had the highest abundance (Dekemati et al. 2019), however, others found that soil and land-use type, available Ca^{2+}, Mg^{2+} and soil moisture content has no explicit correlation with earthworm biomass and abundance, although species richness and abundance are mostly greatest in grasslands and lowest in arable lands, probably due to soil tillage (Weldmichel et al. 2020).

We have made a preliminary study in 2019 on earthworm abundance on only three farms (one per each category) in Szentendre Island, Hungary and found the highest average abundance in the permaculture farm followed by organic and then the conventional site. We did not determine the earthworm species, only assessed their abundance (Szilágyi et al. 2019).

Permaculture farming is a complex design system that goes beyond the principles of organic farming and creates a sustainable human environment (Mollison 1988). Permaculture is not only a set of practices or a cropping technique, it is a holistic approach how practitioners look at farming and its role in the ecosystem (Holmgren 2002, Hathaway 2015). By organic – also known as biological or ecological – farming we mean a complex farming alternative, which enables the production of healthy food under environmentally friendly and controlled conditions with special restrictions on soil nutrient supply and plant protection methods. Organic farming also builds on using natural processes, instead of substituting them with external inputs while – by definition – conventional farming tries to exclude or minimise the natural factors which affect their farming conditions and prefers using external inputs, infrastructures, etc. (Sandhu et al. 2008, Kremen and Miles 2012) to maximise yields. Conventional farming is a yield-driven, intensive form of agriculture, which relies primarily on the use of synthetic pesticides and fertilisers and often uses monoculture on large fields. Soil quality is an important focus of both extensive farming systems. In organic farming they try to improve and sustain soil quality by crop rotation, adding organic manure instead of chemical fertilisers (Gomiero et al. 2011), while in permaculture, farmers try to minimise soil disturbance, cover the surface with mulch, use complex polycultures and companion planting (Tombeur et al. 2018). No-tillage is getting more acknowledged generally but there is a special focus on it in permaculture although it is still not a prevalent technique (Ujj 2006). It must be emphasised that the chosen farms are not extreme examples of their types: permaculture and organic farms have not only ecological considerations on the farms and they need to make compromises between ecological and economic performance in general, and neither are the conventional farms extremely intensive. All farms are producing vegetables for the market, so nutrient management is of high importance. However, most of the examined conventional farms are trying to reduce the use of an extreme portion of chemicals (pesticides and fertilisers) whenever it is possible.

The objective of our study was to assess the effects of different farm types (conventional, organic and permaculture) and soil characteristics on the earthworm populations and to evaluate which farm type can be considered a more ideal earthworm habitat. The main consideration was that scientific knowledge on permaculture systems in regards to soil fauna indicators is missing. Assessment of effects of soil characteristics has not been discussed encompassing such a wide array of different variables. Our preliminary hypothesis was that permaculture farms provide the most ideal conditions for earthworms, while conventional farms do the least. This assumption also means better ecosystem services provided by this type of farm. We also presumed that some soil characteristics have significant effects on earthworm population composition.

2. Materials And Methods

2.1. Description of the study sites

Fifteen sites, 5 permaculture (P), 5 organic (O) and 5 conventional (C) farms (N = 15) were selected with similar size (0.3-2 hectares) and agro-ecological features in North-Central Hungary, horticultural production with diverse crop rotation (Fig. 1.) based on data provided by farmers (Csorba et al. 2018).

Permaculture farms were selected from the database of the Hungarian Permaculture Association (Http1). There were 15 farms in the proximity of Budapest; from those, we selected five which produce vegetables for the market, as horticulture is the main type in profitable permaculture farms. The other farms have either other types of production (animal husbandry, fruit production) or have a focus on self-sufficiency rather than growing for selling. As for organic farms, the main selection criteria above the production type (horticulture having open fields, not only greenhouses), were the scale (small scale, less than 3 hectares), the location (preferably close to the conventional and permaculture farms) and organic certification officially by one of the certification bodies. In case of conventional farms, artificial fertilizers and synthetic plant protection products were applied. We tried to select farms in pairs having similar agro-ecological conditions (soil type and climate).

Photo documentary on the research sites is published on Zenodo (together with photos of soil profiles (Szilágyi and Centeri 2022). Some basic parameters on the sites are in Table 1. On most farms, intensive irrigation is applied (except for P1, P4, P5 and C2). The age of the farms also matters when comparisons are made. Both permaculture and organic farms are relatively young, 5–10 years on average while the conventional farms had the longest history of cultivation (30–40 years on average). Soil cultivation is more intensive in conventional farms (except for C3) while minimal tillage and different soil covering techniques are applied on organic and permaculture farms.

Table 1
Some basic parameters of the studied permaculture, organic and conventional farms

Farms	Coor-dinates	Altitude (m, a.s.l.)	Size (ha)	Starting year	Irrigation	Management
P1	47.661693, 19.234455	189	0.55	2012	only manual	very extensive, lot of weeds
P2	47.946250, 19.442365	205	0.24	2014	MSI[1]	minimal soil disturbance, shallow cultivation, permanent beds, compost cover, clayey, extensive composting
P3	47.753374, 19.099580	102	0.8	2007	MSDI[2]	normal soil cultivation, compost covering
P4	47.779768, 19.025435	208	0.26	2010	some irrigation	some soil tillage
P5	47.812954, 18.978751	102	0.19	2011	very minimal irrigation	forest garden, thick mulch, polyculture beds
O1	47.542750, 19.614077	124	0.4	2010	permanent professional irrigation with MS[3]	minimal soil disturbance, shallow cultivation, permanent beds, compost covering,
O2	47.615303, 19.568106	135	0.13	1997	MSDI	conventional tillage, ploughing, no mulch
O3	47.862032, 19.504153	174	0.23	2019	MSDI	permanent beds, shallow soil cultivation
O4	47.931193, 19.441476	224	0.42	2020	MSI	permanent beds, shallow soil cultivation
O5	47.694567, 19.098417	103	1.3	2005	MSI	very weedy, no mulch, conventional tillage/ploughing
C1	47.542750, 19.614077	124	0.4	< 1990	MSI	conventional tillage, ploughing, no mulch
C2	47.933814, 19.283107	165	0.46	< 1990	minimum irrigation by watering pipe	conventional tillage, rotation hoe, no mulch
C3	47.910747, 19.373940	235	0.1	2013	MSDI	no/minimum tillage or shallow cultivation
C4	48.040578, 19.163024	165	0.22	< 1990	intensive irrigation (flooding and dripping)	frequent use of rotation hoe (soil cultivation + weed killing), no mulch
C5	47.726901, 19.099894	104	1.21	< 1990	intensive irrigation (flooding and dripping)	intensive soil cultivation (tillage, ridge cultivation, cultivator), no mulch

[1]MSI=Micro Sprinkler Irrigation, [2]MSDI=Micro Sprinker/Drip Irrigation, [3]MS=Micro Sprinkler

2.2. Used methods and other factors during sampling

Earthworm populations were sampled on the 21–23rd of May and the 11–13th of September 2020. In Hungary in most studies, the earthworms are sampled in spring or autumn, as earthworms are most active in these periods (Dekemati et al. 2019). May was considered relatively dry compared to the average rainfall data from previous years. The average monthly precipitation of 1981–2010 was ~ 63 mm/month while in 2020 it was ~ 35 mm/month and the previous month was even drier (~ 43 versus ~ 10 mm/month, same years as for May). September was also drier than the average, ~ 55 mm/month of 1981–2010 versus ~ 38 mm/month in 2020, however, the August of 2020 had more precipitation, ~ 82 mm/h than the average ~ 63 mm/h of 1981–2010 (Http 2). Soil blocks (25×25×25 cm) were excavated *in situ* in six replicates at each site, placed on a plastic sheet and were thoroughly hand-sorted for earthworms (ISO 2006). The numbers were recorded on-site, the biomass was measured and the earthworms were preserved in 70% ethanol later in the laboratory, placed in 4% formaldehyde solution for fixation, then stored in 70% ethanol for species identification. The adult earthworm specimen were determined to species level by the external and internal characteristics of earthworms, based on Csuzdi and Zicsi (2003) and Csuzdi (2007), species were allocated to earthworm functional groups as defined by previous authors (Bottinelli et al. 2020). Soil horizons and types were assessed by a Pürckhauer type soil core sampler (1 m depth) between 11–13th of September, 2020. Five soil samples from each site were analyzed in an accredited soil laboratory: one physical (Arany-type soil texture coefficient (MSZ-08-0205-2:1978) and 13 chemical (SOM (%, (MSZ 08-0210:1977, MSZ-08-0452: 1980), pH (KCl), total salt (%), $CaCO_3$ (%) (MSZ-08-0452: 1980), N-NO_2-NO_3, Mg, S, K_2O, P_2O_5, Na, Cu, Mn, Zn (the latter all in ppm, all according to (MSZ 20135:1999) parameters. Data from soil laboratory analysis are published on zenodo (Szilágyi and Centeri 2021). Soil type, the total thickness of all humus layers and soil organic matter data have been published in previous papers (Szilágyi et al. 2021, Centeri et al. 2021).

2.3. Data analysis

We calculated juvenile, adult and all earthworm average for every site as species number and Shannon diversity index (Oksanen 2020) based on all collected presence-absence and abundance data of earthworms. During analyses, GLM models were performed to test relationships between different explanatory variables like farm types and different soil characteristics. The type of farms was categorical and all others (soil characteristics, abundance and diversity estimators) were numerical variables. All numerical variables were checked for normality and other distribution families gamma and inverse gaussian F with Shapiro-Wilk normality test, gamma_test, and ig_test. In some cases, link ‘log’ was applied in models to explain variability more appropriately. Different GLM post hoc tests and Tukey HSD tests were applied to determine significant differences ($p < 0.05$) between numerical variables in relation to different types of farms. Every calculation was made in R 3.5.1. programming environment (R Core team 2018) by the ‘multcomp’, ‘rsq’, ‘goft’ and the ‘vegan’ packages.

3. Results

3.1. Earthworm composition in May and September 2020

Ten earthworm species were identified from the samples during the survey. Table 3. shows the proportion of the different species by farm types.

Table 3
Species composition of earthworm samples from the different types of farms in May and September 2020

Farm type	Species	Proportion (%)	Species	Proportion (%)
Permaculture	**May 2020**	45.7	**September 2020**	40.6
	Allolobophora chlorotica	31.4	*Dendrobaena veneta*	21.9
	Aporrectodea rosea	11.4	*Allolobophora chlorotica*	20.3
	Aporrectodea caliginosa	5.7	*Aporrectodea rosea*	7.8
	Octolasion lacteum	2.9	*Octolasion lacteum*	4.7
	Dendrobaena veneta	2.9	*Aporrectodea caliginosa*	3.1
	Bimastos rubidus		*Eisenia fetida*	1.6
			Aporrectodea georgii	
Organic	**May 2020**	62.5	**September 2020**	50.0
	Aporrectodea rosea	25.0	*Allolobophora chlorotica*	20.0
	Allolobophora chlorotica	12.5	*Proctodrilus opisthoductus*	18.0
	Aporrectodea georgii		*Aporrectodea rosea*	6.0
			Aporrectodea georgii	2.0
			Octolasion lacteum	2.0
			Bimastos rubidus	2.0
			Proctodrilus tuberculatus	
Conventional	**May 2020**	35.3	**September 2020**	42.3
	Allolobophora chlorotica	29.4	*Allolobophora chlorotica*	30.8
	Aporrectodea rosea	29.4	*Eisenia fetida*	7.7
	Aporrectodea caliginosa	5.9	*Aporrectodea rosea*	7.7
	Octolasion lacteum		*Aporrectodea georgii*	7.7
			Octolasion lacteum	3.8
			Aporrectodea caliginosa	

Considering the number of earthworm species between May and September 2020, we can state that more species were detected in September on all farm systems. *A. chlorotica* and *A. rosea*, were found on all farms in both seasons in different proportions. These are very common endogeic earthworm species. *A. caliginosa* is also quite common species in the region in arable land and under grassy vegetation as well (Csuzdi et al. 2003), however, it was not found in the sampling sites of the organic farms in either of the sampling times. As for permaculture, *D. veneta* was only 2.9% in the samples in May, however, by September, this proportion increased vastly (40.6%).

Overall, *A. rosea* had the highest proportion (62.5%) in the organic farming system in May 2020 while the lowest proportion of presence (1.6%) belongs to the *A. georgii* in the permaculture farming systems in September 2020.

3.2. Relationships between farm types, different soil characteristics and earthworm abundances and diversity in May and September

In May, management type affected all earthworm abundance and diversity strongly, but in September, much less explanatory power was experienced. Arany-type soil texture and proportion of soil organic matter strongly and positively affected the abundance and also species number in May and had a strong relationship on the abundance in September. Strong, positive relationships were experienced between $CaCO_3$ concentration and earthworm abundance values in September, but not in May (Table 4–5.). The concentration of nitrogen strongly and positively affected earthworm abundances in May and September. Potassium concentration strongly positively affected all earthworm abundances and species numbers either in May or in September and had a strong, positive effect on Shannon diversity in May. Adult earthworm average was strongly and positively affected by magnesium in September. The concentration of sulfur had strong, positive effects on earthworm abundances and species number in May and September and had a strong, positive effect on Shannon diversity in May. All earthworm and adult earthworm values were strongly affected by Na-concentration in September, but not in May. Soil salt concentration showed a strong and positive relationship with earthworm abundances and species number in May and September and showed a positive relationship with Shannon diversity in May. Total thickness of all humus layers, pH, P, Cu, Mn and Zn concentrations neither strongly affected earthworm abundance and diversity in May nor in September.

Table 4

Effects of farm type and soil explanatory variables on dependent variables in May 2020 on juvenile earthworm average, adult earthworm average, all earthworm average per site, Shannon diversity and species number. Relationships are expressed by unadjusted R-squared values. The strongest relationships ($R^2 \geq 0.200$) are written in bold. Negative relationships are signed by the (-) symbol after R^2 values. Every other relationship, where (-) signs are absent is positive.

Explanatory variables	*Juvenile earthworm average*	*Adult earthworm average*	*All earthworms average per site*	*Shannon diversity*	*Species number per site*
Farm type	**0.381**	**0.268**	**0.417**	**0.405**	**0.419**
Arany-type soil texture coefficient	**0.216**	0.124	**0.253**	0.183	**0.255**
Total thickness of all humus layers	0.159	0.025	0.149	0.074	0.042
SOM%	**0.423**	**0.353**	**0.566**	0.121	**0.249**
$CaCO_3$	0.008	0.164	0.009	0.180	0.146
pH	0.004	0.034	0.003	0.077	0.030
$N\text{-}NO_2\text{-}NO_3$	0.098	**0.360**	**0.208**	0.153	0.184
P_2O_5	0.056	0.130	0.099	0.026	0.053
K_2O	**0.467**	**0.376**	**0.609**	**0.239**	**0.357**
Mg	0.013	0.022	0.026	0.003	0.014
S	0.022	**0.755**	**0.026**	**0.201**	**0.308**
Na	0.002	0.021	0.005	0.014	0.007
Cu	0.011(-)	0.044(-)	0.025(-)	0.043(-)	0.056(-)
Mn	0.044	0.046(-)	0.017	0.034(-)	0.014(-)
Zn	0.002(-)	0.007	0.002	0.016(-)	0.001(-)
total salt	0.071	**0.323**	**0.175**	**0.245**	**0.323**

Table 5
Effects of farm type and soil explanatory variables on dependent variables in September 2020 on juvenile earthworm average, adult earthworm average, all earthworm average per site, Shannon diversity and species number. Relationships are expressed by unadjusted R-squared values. The strongest relationships ($R^2 \geq 0.200$) are written in bold. Negative relationships are signed by the (-) symbol after R^2 values. Every other relationship, where (-) signs are absent is positive.

Explanatory variables	***Juvenile earthworm average***	***Adult earthworm average***	***All earthworms average per site***	***Shannon diversity***	***Species number per site***
Farm type	0.019	0.147	0.019	0.120	0.119
Arany-type soil texture coefficient	**0.208**	**0.320**	**0.300**	0.053	0.109
Total thickness of all humus layers	0.168	0.023	0.149	0.115	0.059
SOM%	**0.205**	**0.278**	**0.285**	0.061	0.174
$CaCO_3$	0.188	**0.277**	**0.268**	0.105	0.153
pH	0.056	0.148	0.097	0.087(-)	0.002(-)
$N\text{-}NO_2\text{-}NO_3$	**0.228**	**0.443**	**0.355**	0.009	0.147
P_2O_5	0.181	0.025	0.161	0.001	0.016
K_2O	**0.347**	**0.338**	**0.440**	0.121	**0.221**
Mg	0.104	**0.318**	0.191	0.000(-)	0.067
S	0.135	**0.291**	**0.218**	0.185	**0.352**
Na	0.096	**0.572**	**0.234**	0.004	0.121
Cu	0.031(-)	0.106(-)	0.059(-)	0.161(-)	0.098(-)
Mn	0.026(-)	0.100(-)	0.052(-)	0.013(-)	0.039(-)
Zn	0.046	0.001(-)	0.029	0.020	0.026
Total salt	**0.272**	**0.567**	**0.433**	0.034	**0.205**

Based on the effects of farm types, best-fitted models were chosen for analyses. Only data of May 2020 showed relatively stronger relationships ($R^2 \geq 0.200$) between farm types and earthworm abundances and diversity (see Table 4–5). Earthworm species number was significantly higher in permaculture farms in May compared to organic farms (Fig. 2, e.), but not differed from conventional farms. No other significant differences were experienced.

4. Discussion

4.1. Earthworm species composition

Altogether, seven endogeic and three epigeic earthworm species were detected out of the three functional groups (Csuzdi 2003), no anecic species were found. *Allolobophora chlorotica, Aporrectodea caliginosa* and *Aporrectodea rosea* are typical synanthropic species. They can be observed in several land uses, e.g. grassy areas, lawns, gardens and wooded sites (Csuzdi and Zicsi 2003; Csuzdi 2007). *A. chlorotica* and *A. rosea* are common almost in any soil type, but they prefer and can be found in greater abundances in soils with higher moisture and organic matter content. *A. caliginosa* can survive even in sandy and highly disturbed soils. These species belong to the endogeic group, i. e. they live, burrow and feed in the mineral soil layer, usually in the top horizons. *Aporrectodea georgii* is also an endogeic earthworm, but it has a greater abundance in clayey soils with greater soil moisture content. *P. opisthoductus, P. tuberculatus* and *O. lacteum* species also belong to the endogeic group, thus they mostly live, burrow and feed in the topsoil layers (Csuzdi 2007).

In our research, two endogeic earthworm species (*A. chlorotica* and *A. rosea*) were found in all the examined farms, in both examined seasons mostly with the greatest proportion. There was only one exception, permaculture (September 2020) where *D. veneta* had the highest proportion (40.6%). *A. caliginosa* and *O. lacteum* were also very common on the examined farms.

Three epigeic species were also found on the farms. *Eisenia fetida* is the so-called manure worm, it is the most suitable for vermicomposting due to its high proliferation rate. It has been introduced worldwide and, thus, has high variations in its morphological characteristics (Csuzdi 2007). In our study, *E. fetida* was only found in permaculture and conventional farms, only in autumn.

Dendrobaena veneta is a widely distributed peregrine species with high variations in morphological characteristics. It can be mostly found in manure and compost, and it is suitable for vermicomposting. It has been spread all over Europe mainly due to vermicomposting activities (Csuzdi 2007). This species was only found in permaculture farms, probably distributed by the animal manure or compost additions to these farms.

Bimastos rubidus, an epigeic earthworm species (earlier called *Dendrodrilus rubidus*) can be found under logs or stones and also in manure. They have widely spread peregrine earthworms (Csuzdi 2007). They were found only on permaculture and organic farms, but not in conventional ones since they need a lot of organic debris or manure on the field to survive.

4.2. Possible effects of soil characteristics on earthworm performance

The pH of the soil samples was quite homogeneous, 6.2 was the lowest and 7.7 was the highest value, so the pH range was between the mid-range of the slightly acid to the mid-range of the slightly alkalic category. We can consider these soils as good horticultural soils for the majority of the plants produced.

The pH was most likely not an influencing factor of earthworm numbers, abundance and diversity in the investigated farms in our analyses. Our results are similar to those of Lofs-Holmin (1986) who found that pH values between 4.5 and 7.0 did not have a great effect on the presence of earthworms in permanent pastures, based on which Boag et al. (1997) also concluded that the detected soil pH range was between 4.5-7.0 on 68 of the arable fields they examined, thus, they assumed that pH had little effect on earthworm communities. However, Johnson (2009) found that high soil moisture content and close-to-neutral pH have a strong connection with earthworm populations. Prastowo et al. (2020) found that higher soil organic matter with lower pH in the topsoil might explain the higher number of earthworms, to some extent. The relation between earthworms-acidity-soil organic matter is reasonable as soil organic matter is mostly acidic, but the connection is not necessarily strict.

The $CaCO_3$ content of the soils was in the very low (0.1–0.5%) and low (1.1–4.5) range, and some of them were in the medium range (8.7–13.3%). Bernard et al. (2009) found that adding crushed lime to the soil may increase the earthworm population. Holland et al. (2018) describe in their review that positive impacts of liming on biodiversity have been observed in many ecological studies, especially increased earthworm abundance that serves as prey for grassland birds.

According to various authors (Pfiffner and Mäder 1998, Scullion et al. 2002, Bernard et al. 2009), soil organic matter (SOM) has a great influence on earthworms and *vice versa*, however, there was not a great variation in SOM in the investigated areas, the lowest value was in the case of a sandy soil type (Arenosol) but even in these cases the amount of SOM reached 1.6% that is considered as a good amount for sandy soil. The highest value was 5.3% which is a normal maximum value under continental climate. The relation between the soil organic matter content and the juvenile/adult/all earthworm averages were strong in the examined soils, however, this strong relation was not found between soil organic matter vs. Shannon diversity, nor species number per site. Furthermore, interestingly, the total thickness of all humus layers (Szilágyi et al. 2021) did not have a strong correlation with any examined earthworm data.

Soil texture is also an influencing factor (Pfiffner and Mäder 1998, Scullion et al. 2002, Bernard et al. 2009). Sandy soils are known to have smaller numbers of earthworms as they tend to get dry very quickly and do not have the necessary volume of fallen litter, so do not favour earthworms. However, according to the Arany texture index, there was one farm in each farming system where texture reached the limit of coarse sand (Arany texture index below 25 is considered as coarse sand, between 25 and 30 it is sand), so we cannot consider sand content as an influencing factor when comparing farming systems. The reason for this in these horticulture farms, on one hand, that irrigation is almost always applied due to the production type, and on the other hand, there is enough organic matter as horticulture farms are normally either use organic fertilizers, or mulch, or both. Furthermore, organic and permaculture farms are often taking great care of having plant cover for a long period during the vegetation season and beyond, as long as possible. Moreover, the permaculture farms are often having other, positively influencing factors, such as bushes and trees that both help providing an extra amount of shade (helping the longer moist state of the soil that favour earthworms) and fallen leaves and branches and sometimes fruits.

There are also interesting findings that the Na-content and the total salt content had the highest correlation with the average number of adult earthworms. Furthermore, the juvenile earthworm average number was not strongly correlated with the Na-content ($R^2 < 0.1$).

There was a negative correlation in all earthworm characteristics versus Cu- and Mn-content. Similar correlations were found by Paoletti et al. (1999) between copper and several species (including *Aporrectodea caliginosa*), total earthworm abundance and biomass were found severely reduced by copper input in orchards and vineyards. Eijsackers et al. (2005) also found a negative correlation between copper-containing fungicides and earthworms. Copper in soil resulted in decreased burrowing rate and avoidance of these copper-containing soils.

There were no articles found on Google Scholar, nor google.com related to the relation between Na, Cu or Mn content and earthworms on horticulture farms. The majority of the articles are in relation to soil contamination or vermicompost, simple analysis of farms is very rare if non-existent.

Permaculture farms had the highest abundance of earthworms, which was significant in May (Szilágyi et al 2021). Previous studies found higher earthworm abundance in no-tillage compared to other tillage types (Boag et al. 1997, House and Parmelee 1985, Van Capelle et al. 2012, Deekemati et al. 2019). Based on the field soil examination it is of great importance to know as much soil information as possible (i.e. soil thickness, soil organic matter content, texture, soil management, fertilisers used, soil moisture content at the time of the counting, soil cover, etc.) for considering earthworms data as a good indicator for soil quality assessment. The importance of considering multiple soil factors is also emphasised in the literature (Lofs-Holmin 1986, Nadolny et al. 2020). In our pilot study, we have found similar patterns in 2019, based on three farms (Szilágyi et al. 2019) which are in line with what we explored in soil quality during sustainability assessment of permaculture farms compared to organic and conventional farms (Szilágyi et al. 2018). The relatively low sample size (15 farms, 5–5 farms from each farm type) is an issue for the statistical analysis and our analyses showed that with a greater sample size and a more robust database we could have probably found more significant statistical results. Finally, it is worth mentioning that the suitability of earthworms as indicators changes rapidly with soil moisture content. Our future goal is to further explore connections of soil biota characteristics to ecosystem service delivery and also assess the attitude, motivation and management decisions of the farmers as their perception of biodiversity (Kelemen et al. 2013) and ecosystem services determine of what will happen on the farm management level.

5. Conclusions

The pH did not influence earthworm numbers, abundance and diversity. Conclusion cannot be made between examined earthworm parameters and extreme (too low or too high) pH values.

The well-known fact that earthworms avoid sandy soils does not apply to irrigated farms because the soil moisture content is regulated, not to mention the food supply of roots and plant debris that is normally much lower in sandy soils under natural conditions.

An important conclusion is that the Na- and the total salt content has the highest correlation with the average number of adult earthworms in the examined Hungarian horticultural farms. Furthermore, the juvenile earthworm average number shows an opposite relation: was not strongly correlated with the Na-content (R2 < 0.1).

Based on our results and the literature review, we can conclude that the negative correlation between Cu and Mn content is not known in horticultural farms and it provides a way forward for research to find the reason for these negative correlations.

We can conclude that there are differences between May and September. In September species numbers were higher, in the average of the earthworm species number and Shannon diversity there were lower differences between farms, a stronger positive relationship was found between $CaCO_3$ concentration and earthworm abundance, adult earthworm average was strongly and positively affected by magnesium content.

We can conclude that earthworm species number was significantly higher in permaculture farms but only in May and only compared to organic farms since no difference was found between permaculture and conventional farms while earthworm abundance was significantly higher in permaculture farms but only in May compared to both organic and conventional farms. These results partly validates our zero hypotheses that permaculture farms have the best performance in providing good conditions for earthworm poulations.

Declarations

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Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

Alfréd Szilágyi, Barbara Simon, Csaba Centeri and Péter Nagy conceived and designed the experiments; Alfréd Szilágyi, Evelin Plachi, Csaba Centeri performed the experiments; Barbara Simon identified the species, Róbert Kun performed the statistical analysis, Alfréd Szilágyi, Barbara Simon, Csaba Centeri analysed the data; Alfréd Szilágyi, Barbara Simon, Csaba Centeri and Kun Róbert wrote the paper. All authors read and approved the final manuscript.

Data Availability

Authors made soil laboratory and photo documentary on the sites and their soils available in Zenodo database (Szilágyi et al. 2021, Centeri et al. 2021).

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Figures

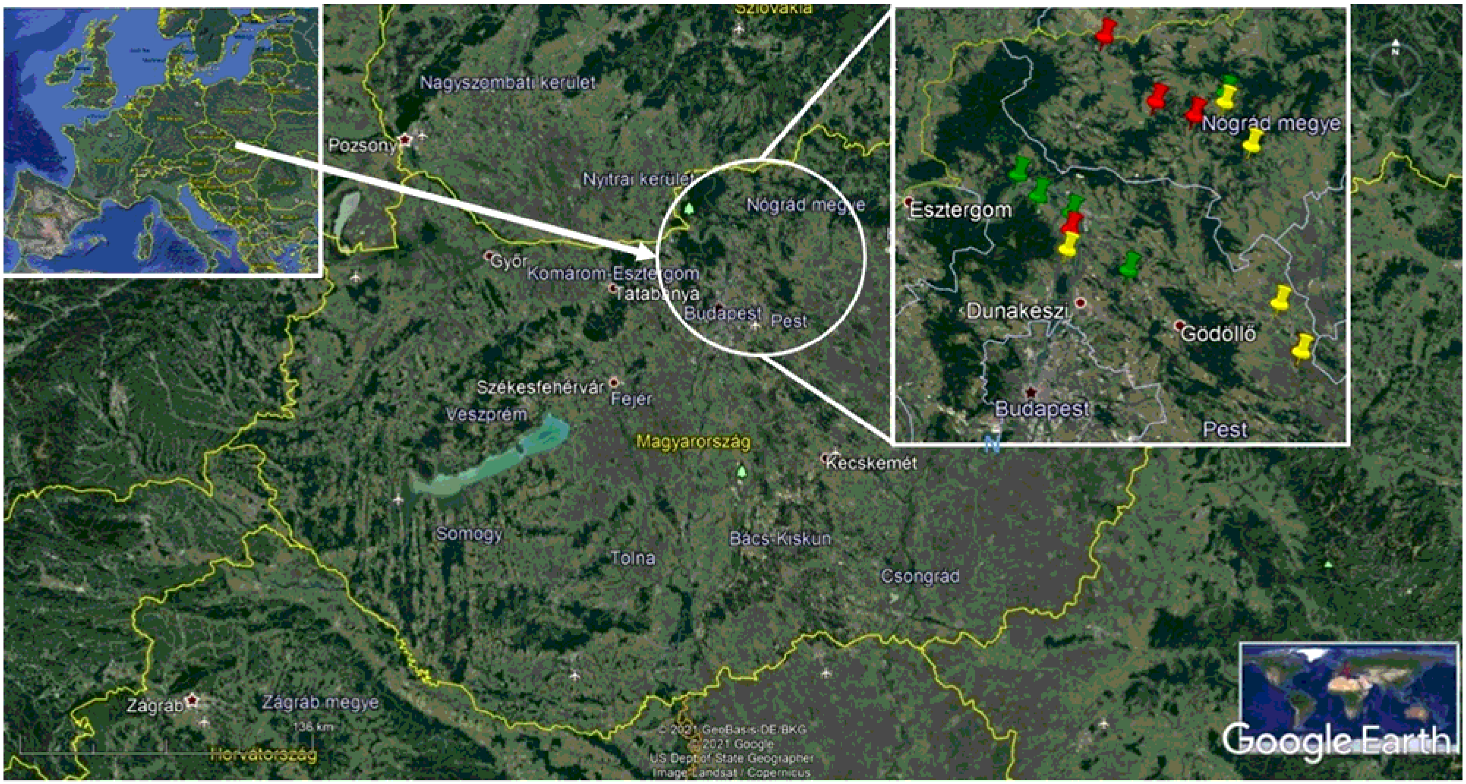

Figure 1

Location of the studied sites (green points: permaculture farms, yellow points: organic farms, red points: conventional farms) (Source: Google Earth Pro 2020)