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Location-dependency of earthworm response to reduced tillage on sandy soil

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ABSTRACT

Since earthworms are of functional importance in soils, understanding their sensitivity to tillage is of importance for the design of sustainable management systems. The effect of reduced, ploughless tillage on earthworm abundance was explored during a 10-year observational study on a producer's field on sandy soil. The analysis of tillage effects is complicated by the fact that earthworms are not only affected by tillage but also by soil properties.

We analyzed the spatial distribution pattern of earthworms (*Lumbricidae*) in a heterogeneous 74 ha field in Northeast Brandenburg, Germany. Earthworm populations were assessed by means of handsorting along 4 transects on 42 permanent plots which were partly under conventional, partly under reduced tillage. Different earthworm activity parameters were calculated for each plot and related to soil properties such as soil texture and organic carbon in 0 to 15 cm. In addition, paired plots were analyzed at both sides of the dividing line between the tillage systems.

The analysis of paired plots indicated that finer textured soils react more positively to tillage reduction than sandy soils. State-space analysis confirmed that soil texture was important in all cases for estimating earthworm parameters along the transects. Organic carbon in 0 to 15 cm, indicative of the tillage system, was an especially important predictor for maximal abundances of earthworms in the year 2000. Our observations also suggest higher spatial variability of earthworm abundances and closer relationships between earthworms and soil texture under reduced tillage. For separating soil from management effects in landscape scale studies, approaches are promising which take into account the spatial variability of soil properties and soil biota.

1. Introduction

Earthworms belong to the most important biota in agricultural soils: they generate soil structure, promote plant growth and affect carbon and nitrogen cycling (Lee, 1985; Edwards and Bohlen, 1996; Lavelle et al., 2006; Don et al., 2008). In these soils earthworms should therefore be impaired as little as possible by management operations and tillage practices.

Tillage, especially mouldboard ploughing, is detrimental to earthworms because it destroys their habitat and buries the plant remains which serve as food for the animals. The reduction of tillage is known to increase earthworm populations on a variety of soils (Wyss and Glasstetter, 1992; Wardle, 1995; Hubbard et al., 1999; Kladivko, 2001; Chan, 2001; Brown et al., 2003; Johnson-Maynard et al., 2007). There are however exceptions from this general pattern. Kladivko et al. (1997) reported that on some of their study sites no-tillage effects were minor; they attributed these findings to site characteristics such as low clay content. The modification of tillage effects on earthworms by soil texture is highly probable, given the dependence of earthworms on soil moisture.

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Soil-specific reactions of earthworms to tillage operations may have consequences for the earthworm–soil relationship. In their seminal paper, Kladivko et al. (1997) reported, that earthworm abundances in no-till fields were positively correlated with clay content whereas earthworm numbers under conventional tillage were not correlated with soil properties. If soil properties determine the response of earthworms to tillage reduction in the sense, that with increased clay content effects are increased, then close relationships between earthworm numbers and soil properties are to be expected in no-till fields. The need for analyzing site-specific, location-dependent reactions of earthworms to tillage reduction has been expressed (Nuutinen et al., 1998); a thorough analysis however has not been done yet.

For analyzing the location-dependency of tillage effects on earthworms, it is necessary to separate soil from tillage effects. In their farm scale study, Kladivko et al. (1997) analyzed pairs of fields on the same soil type under conventional and under no-tillage. However, the differences between the study sites in their responding to tillage reduction could not be fully ascribed to soil texture differences since other factors varied as well such as crop history and weather. Therefore, as a first step to analysis, approaches may be helpful which focus on examining the locations with different soil texture within one field site. Subsequently, earthworm abundances at these locations may be analyzed spatially.

Soil spatial analyses have gained increased recognition during recent years (Nielsen et al., 1983, 1994; Nielsen and Alemi, 1989; Wendroth et al., 1992, 2001; Van Kessel and Wendroth, 2001; Ettema and Wardle, 2002; Nielsen and Wendroth, 2003). Spatial analyses focus on the change of soil variables across the landscape (Nielsen and Wendroth, 2003); they help to exploit the information contained in the spatial pattern of soil chemical, physical or biological properties. In the past, spatial analyses were used to characterize earthworm distributions, which have long been known to be highly variable, and to relate them to soil properties (Guild, 1952; Poier and Richter, 1992; Rossi et al., 1997; Cannavacciuolo et al., 1998; Nuutinen et al., 1998; Decaens and Rossi, 2001; Jiménez et al., 2006; Joschko et al., 2006). Tillage related spatial studies on earthworms are scarce (Blackshaw et al., 2007).

Spatial analyses offer a great potential for analyzing soil-specific management effects since they may help to distinguish between management effect and natural variability (Nielsen and Wendroth, 2003, p. 360). The authors suggested to superimpose different management systems on local gradients of soil properties and to analyze spatially the variable of interest crossing the landscape. We followed this suggestion and carried out an on-farm observational field study on a 74 ha agricultural site on dry sandy soil in Northeast Germany.

It was the objective of our study to analyze the effect of reduced tillage compared to conventional tillage on earthworm populations on different locations within the field site. Reduced tillage belongs to the intermediate tillage systems along the continuum between ploughing and direct drilling. It is a common tillage type which deserves special research interest regarding its soil ecological effects (Kladivko, 2001).

We hypothesized that on the heterogeneous soil studied, no uniform response of earthworms to tillage reduction existed but rather location-dependent responses across the landscape. Response patterns should be related to soil attributes such as soil texture and organic carbon content. The effect of tillage reduction should be more pronounced on finer textured soils, and the relationship between earthworm abundances and soil properties should be closer under reduced tillage as suggested by Kladivko et al. (1997).

2. Methods

2.1. Study site, experimental design

The study was carried out at a 74 ha heterogenous field belonging to the Komturei Lietzen in the state of Brandenburg, Germany (Fig. 1). The field is situated within a smoothly rolling groundmoraine landscape, with sandy layers over loam. Within this highly variable landscape, Luvisols (Fig. 1) are the dominating soil type (WRB-FAO; Seyfarth et al., 1999). The site is characterized by 9.6 °C mean annual temperature and 472 mm mean annual precipitation (1992–2004).

The field had been under conventional tillage until 1996. Following harvest in September 1996, non-inverting, ploughless tillage was established in one-half of the field. The other half continued to be conventionally tilled (Table 1). Residue cover at the time of planting was <15% in both systems. The ploughless system is called "reduced tillage" throughout this article, since energy input and depth of soil disturbance is reduced (Cannell, 1985). This definition, however, deviates from the definition of the Conservation Tillage Information Centre (West Lafayette, IN, USA) (www.ctic.purdue.edu) according to which reduced tillage systems are characterized by a residue cover of 15–30%. Amounts of fertilizer and pesticides were the same in both tillage systems except in 1997 and 1998, when additional herbicides were applied in the reduced tillage system.

Within the field, 42 monitoring plots ($2\ \mathrm{m} \times 15\ \mathrm{m}$) were permanently installed in 4 transects following the main slope and tillage direction, with 21 plots for each tillage system (Fig. 1). The distances between the 42 plots were irregular: the plot locations were selected according to yield performance during harvest 1996 to obtain the following: (1) a wide variety of soils distributed over the whole field; (2) 10 matching pairs of similar soils, according to visual yield assessment, in the two middle transects at both sides of the dividing line (Cochran, 1983). As consequence of this selection procedure, the distances between neighbouring plots varied between 24 and 262 m with a mean distance of approximately $70\ \mathrm{m} \pm 33\%$ (Fig. 1a and b).

The crop rotation was as follows: winter wheat (1996), winter rye (1997, 1998), oilseed rape (1999), winter rye (2000, 2001, 2002), oilseed rape (2003), winter wheat (2004), grain maize (2005) and peas (2006).

Soil properties, such as soil texture and organic carbon content, differed slightly between the two sides of the field carrying the two different tillage regimes. The range of values for the fine particles content (particles $< 6.3\ \mu\mathrm{m}$) was higher under reduced tillage (9.5%) compared to conventional tillage (6.3%) (see Section 2.3). In respect to organic carbon, similarly, the range of values was slightly higher under reduced tillage (0.51%) compared to conventional tillage (0.45%) (Table 2).

Table 1
Tillage operations at Lietzen: tools and working depths.

Operation	Conventional	Reduced
Secondary tillage	Rotary harrow, 3–8 cm	Rotary harrow, 3–8 cm
Primary tillage	Plough, 25 cm (and in 4 of the 10 years precision cultivator, 15–18 cm)	Precision cultivator, 15–18 cm

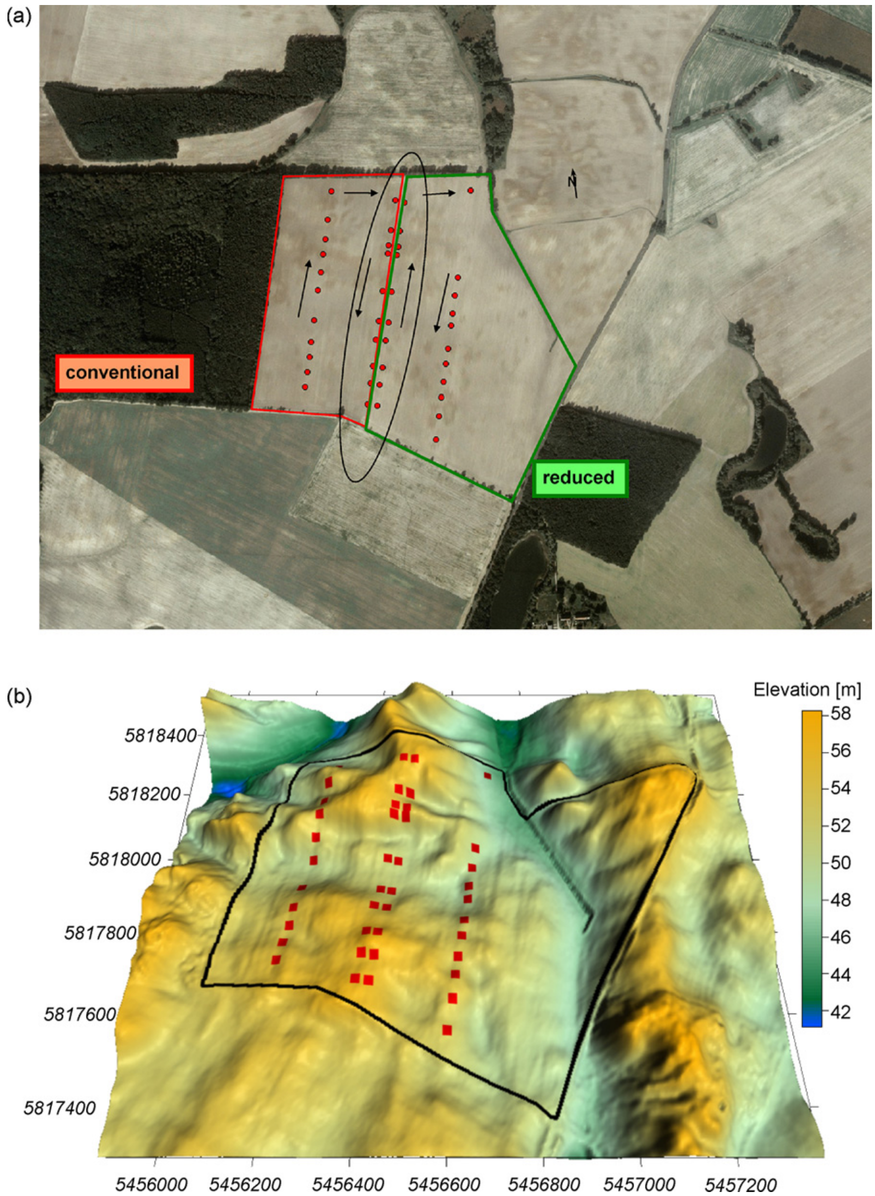

Fig. 1. (a) Lietzen experimental design: 42 plots arranged along 4 transects in tillage direction. Ellipse marks position of 10 pairs of similar plots at both sides of the dividing line. Spatial analysis (state-space analysis) was performed with all 42 plots in direction of the arrows (photo: Landesvermessung and Geodatenbasisinformation Brandenburg). (b) Digital elevation model from the Lietzen site, with 42 plots; ATKIS-DGM5 (Landesvermessung and Geodatenbasisinformation Brandenburg).

2.2. Earthworm sampling

At each of the 42 plots, earthworms were assessed in September 1996 prior to the installation of the two tillage variants and subsequently in spring (April/May) of the following years up to 2006. In 2000, 2003, 2005 and 2006, additional samplings were carried out in autumn (September, October, November). Earthworms were collected at each of the 42 plots by handsorting one 50 cm × 50 cm × 20 cm (w, l, depth) soil block immediately after sampling. In the dry soils sampled here, handsorting has proved to be the optimal sampling method not only for shallow burrowing endogeic earthworms but also for juvenile *Lumbricus terrestris*;

Table 2
Selected soil properties at the Lietzen site.

	All plots				Reduced Tillage				Conventional Tillage			
	Mean	Min	Max	S.D.	Mean	Min	Max	S.D.	Mean	Min	Max	S.D.
% Clay	6.0	3.2	10.5	1.8	6.0	3.2	10.5	1.8	6.0	3.6	9.6	1.7
% FP	8.1	3.9	13.4	2.2	8.0	3.9	13.4	2.5	8.1	5.3	11.6	1.8
% OC	0.8	0.5	1.1	0.1	0.8	0.6	1.1	0.2	0.7	0.5	1.0	0.1
% N_t	0.07	0.05	0.1	0.01	0.08	0.05	0.1	0.02	0.06	0.05	0.09	0.01
pH	6.6	5.0	7.6	0.55	6.5	5.0	7.4	0.89	6.7	6.1	7.6	0.54

FP = fine particles < 6.3 μm, OC = organic carbon, N_t = total nitrogen; results from 2004; samples from 0 to 15 cm, soil texture 0 to 30 cm soil depth.

adult *Lumbricus terrestris* may however be underestimated by this sampling method (Kladivko et al., 1997), since they may escape into deeper soil depths when the digging is started.

The worms were counted and identified to species level according to Sims and Gerard (1985) and Graff (1953). In most cases, juveniles were also identified to species level; all individuals were considered in the abundance calculations. Since earthworm abundances were closely related to biomass, only abundances were considered in this paper.

For characterizing earthworm populations during the observation period, different parameters were chosen. First, average earthworm abundance for each plot was calculated based on spring and autumn samples between May 1997 and September 2006.

Second, the average rate of change of abundance was calculated for each plot according to the formula

$$\delta A_j = \frac{1}{n}\sum_{j=1}^{n}|A_{i,j} - A_{i,j-1}| \quad (1)$$

with abundance A at location i and index of temporal observation j from spring samples during the observation period from 1997 to 2006. The unit of this parameter is number of earthworms $m^{-2}\ a^{-1}$.

Both parameters were calculated for the whole earthworm community.

Third, the total number of earthworms was analyzed for each plot from spring 2000, 3.5 years after introduction of reduced tillage at the site. The year 2000 had the maximum earthworm abundance of the entire study and was chosen since this year was likely to show the maximum differences possible between the tillage system and between the sampling locations.

In order to identify soil-specific, location-dependent responses of earthworm activity to tillage, 10 pairs of plots in the two middle transects at both sides of the dividing line (Fig. 1a and b) with fine particle contents below and above 7.1% were analyzed for relationships between soil texture and tillage effects (see Sections 2.3 and 2.4).

2.3. Soil sampling and analysis

For additional soil physical and chemical parameters, standard analyses were carried out on soil samples taken in August/September 1996 and 2004 from 0 to 15 cm and 15 to 30 cm soil depth. For that purpose 6–10 soil samples were taken with an auger with a self-driving soil sampling device and pooled. The samples were located more or less on a straight line in an area of c. 2 m × 2 m at the southern end of each of the 42 plots (Fig. 1a and b). Samples for soil texture analysis were pooled from 0 to 15 cm and 15 to 30 cm; all other samples were analyzed separately.

Soil pH was measured potentiometrically in 0.1 M KCL suspension. Total soil carbon and total nitrogen content was analyzed after dry combustion at 1250 °C using a CNS-2000 analyzer (LECO, Ltd., Mönchengladbach, Germany) (DIN ISO 10694, 1996; DIN ISO 13878, 1998). Prior to C and N analysis plant remains were manually selected and discarded from the analysis. Carbonate carbon was determined after application of phosphoric acid by electric conductivity measurement of carbon dioxide evolution (Schlichting et al., 1995). Organic C content was calculated as the difference of total C and carbonate carbon. Cation exchange capacity was determined with $BaCl_2$ solution according to DIN ISO 11260 (1997). Soil texture was determined by wet-sieving and sedimentation with Köhn-Pipette method after organic C destruction with H_2O_2 and chemical dispersion using $Na_4P_2O_7$ (Hartge and Horn, 1992). The content of fine particles (FP) was calculated from total clay content plus content of fine silt (<6.3 μm).

Samples for the assessment of earthworm populations and evaluating soil attributes were taken in maximally 2–3 m distance from each other.

2.4. Statistical analysis

Since earthworm abundances and soil properties were spatially structured, the possibility for the application of classical statistics was limited. In addition, the paired samples along the dividing line (Fig. 1) constituted pseudoreplicates (Hurlbert, 1984), and simple inferential statistics was not appropriate. Therefore, only medians were compared calculated from 5, 10 or 21 plots under each tillage system.

The distribution of variables was analyzed with Q–Q plots (Timmer, 1998). Earthworm abundance parameters were log-normally distributed; therefore a log-transformation (log $(x + 1)$) was carried out before further analysis. For analysis of the relationship between earthworm parameters (average abundance, rate of annual change of abundance, maximum abundance) and soil properties (% fine particles, organic carbon 0 to 15 cm) under each tillage system, the rank correlation coefficient r_s was determined (STATISTICA 7.0).

For spatial analysis, values for each earthworm parameter and soil properties along the four transects were combined to one single data row and plotted as a continuous sequence beginning with the first plot of the left transect and ending with the first plot of the right transect (see Fig. 1 a and b; Stevenson et al., 2001). The sequence of plots at the endpoints of the transects was chosen so that distances between plots were minimized.

2.4.1. State-space analysis: theory

With state-space analysis, the system's state, characterized by a state variable or a set of variables, is analyzed on its way through space or time (Nielsen and Wendroth, 2003). The state Z_i at a given location i is related to the state at the previous location $i - 1$ described by the state equation $Z_i = \Phi Z_{i-1} + \omega_i$, where Φ is a matrix of transition coefficients and ω_i is an error term (Nielsen and Alemi, 1989; Wendroth et al., 1992, 1997; Nielsen and Wendroth, 2003). The state variables are related to observed variables Y_i through $Y_i = M_i Z_i + \upsilon_I$, where M_i is a matrix of observation coefficients characterizing the relationship between underlying state and observation, and υ_i is an error term quantifying the measurement uncertainty or noise (Nielsen and Alemi, 1989; Wendroth et al., 1992, 1997; Nielsen and Wendroth, 2003; Timm et al., 2003). A Kalman filter with an EM (Expectation-Maximization) algorithm helps to separate between noise and "reliable" data (Nielsen and Alemi, 1989; Nielsen and Wendroth, 2003). The challenge is, to select appropriate variables which characterize the system's state under consideration.

2.4.2. State-space analysis: application

For state-space modelling, variables showing autocorrelation and cross-correlations were selected for the state vector (Nielsen and Wendroth, 2003). Autocorrelations were calculated in order to characterize spatial dependencies between adjacent plots. In addition, semivariogram analysis was carried out (Isaaks and Srivastava, 1989; Nielsen and Wendroth, 2003). Variogram modeling was done with SURFER (Golden Software) using automatet least squares procedure with manual adjustment. Cross-correlations were calculated to identify potential spatial relations between earthworm abundances and soil properties.

Subsequently, state-space analysis was carried out according to Nielsen and Wendroth (2003). First, the data were normalized (Nielsen and Wendroth, 2003). For analysis the program STATE (R.

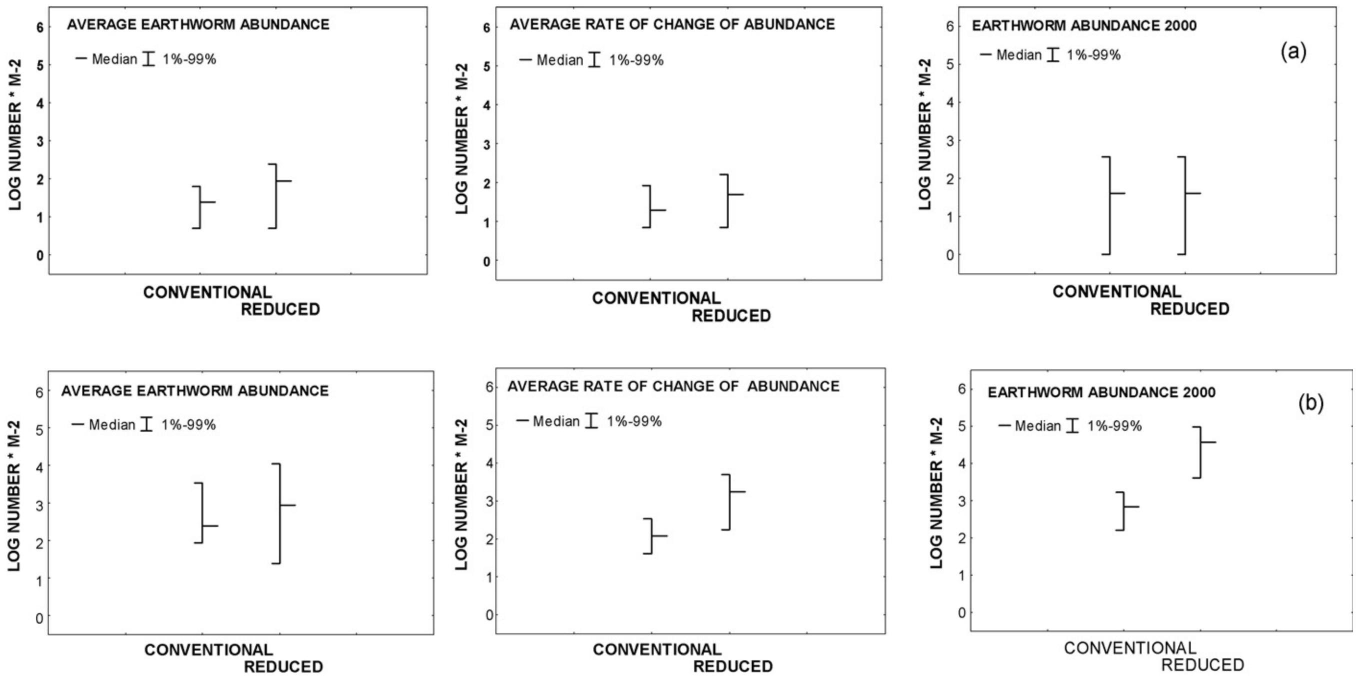

Fig. 2. Location-specific effect of tillage: (a) Average earthworm abundance, rate of change of abundance and maximal abundance in 2000 in 10 paired plots with fine particles content ≤7.1% at both sides of the dividing line between the two tillage systems. (b) Average earthworm abundance, rate of change of abundance and maximal abundance in 2000 in 10 paired plots with fine particles content >7.1% at both sides of the dividing line between the two tillage systems.

Shumway, provided by courtesy of Ole Wendroth) was used. The data were analyzed as if the plots were equally spaced.

To evaluate model quality, a cross-validation was carried out. Data values for the dependent variable (earthworm abundance parameters) were omitted according to procedures suggested by Nielsen and Wendroth (2003) as follows: the first value of each series was always considered in the analysis, and subsequent to this assessment, every other data value, or two out of three successive data values were omitted. Values for the omitted earthworm numbers were estimated from spatial dependencies of this parameter to the independent variables.

3. Results

Earthworm activity at Lietzen was characterized by a mean abundance of 12 individuals per m^2, with a maximal abundance of 152 individuals per m^2 at one plot (Table 3). Main earthworm species was the shallow-working *Aporrectodea caliginosa* (Savigny), besides *A. rosea* (Savigny) and the deep-burrowing *Lumbricus terrestris* L. The proportion of *L. terrestris*, which may however be underestimated by the sampling method, varied between 2 and 55% of all individuals in different sampling campaigns. The proportion of *L. terrestris* was increased under reduced tillage.

3.1. Effect of tillage on earthworm activity

When medians of the average earthworm activity for all 21 plots under conventional and 21 plots under reduced tillage were compared, the effect of tillage appeared to be minor. Average earthworm abundance and the average rate of change of abundance during the 10-year observation period were almost identical in both sides of the field. Only the spring 2000 maximal earthworm abundance showed a moderate difference between the tillage systems, with increased values under reduced tillage. Similarly, when medians of 10 matching pairs of plots along the two middle transects (Fig. 1 a and b) were compared, almost no difference could be detected in the three earthworm abundance parameters studied (data not presented).

Subsequently, a classification of the 20 paired plots based on soil texture was carried out. Whereas in five pairs of sandy plots (fine particle content ≤7.1%) differences between the tillage system were negligible (Fig. 2a), differences were found in plots with finer textured soils: earthworm activity was increased in two parameters under reduced tillage (Fig. 2b). In the parameter rate of change of abundance differences were smaller than in the spring 2000 abundance.

3.2. Relationship between earthworm activity and soil properties

Rank correlation analysis of earthworm activity and soil properties indicated that, in addition to soil texture, earthworm activity was closely related to the organic matter content in the upper 0 to 15 cm soil depth, indicated by organic carbon content (Table 4). Total N was considered redundant because of C and N coupling in soils.

The relationship between earthworm activity and soil texture appeared to be affected by the tillage system (Table 5). Average abundance and the rate of abundance change were slightly closer

Table 3
Summary statistics of earthworm parameters.

	Mean	Min	Max	S.D.
Average earthworm abundance 1997–2006 (number m^{-2})	11.9	0	56.0	12.75
Rate of abundance change from year to year (number m^{-2} a^{-1})	10.0	0	44.0	10.31
Abundance 2000 (number m^{-2})	27.0	0	152.0	39.80

Table 4
Relationship between earthworm activity and soil properties (0 to 15 cm, soil texture 0 to 30 cm; Spearman rank correlation coefficient r_s, only significant relations stated, $p < 0.05$).

	OC	N_t	pH	FP	CEC	P	K	Mg
Average earthworm abundance	0.67	0.73	0.43	0.73	0.55	ns	0.53	0.47
Average rate of change of abundance	0.63	0.72	0.48	0.76	0.58	ns	0.65	0.46
Earthworm abundance 2000	0.81	0.86	0.43	0.71	0.70	ns	0.72	0.41

Soil analyses from autumn 2004.
OC = organic carbon, N_t = total nitrogen, FP = fine particles content (particles < 6.3 μm), CEC = cation exchange capacity, P = plant available phosphate, K = plant available potassium, Mg = plant available magnesium.

Table 5
Relationship between earthworm activity and soil texture (fine particles content, 0 to 30 cm) and organic carbon (0 to 15 cm) under reduced and conventional tillage (Spearman rank correlation coefficient, only significant relations stated; in 1996 there were no tillage variants installed yet).

Parameters	Fine particles content			Organic carbon content		
	All plots	Reduced	Conv.	All plots	Reduced	Conv.
Earthworm abundance 1996 (initial situation)	0.63	(0.66)	(0.57)	0.57	(0.75)	(ns)
Average earthworm abundance	0.73	0.83	0.73	0.67	0.82	0.48
Average rate of change of abundance	0.76	0.87	0.71	0.63	0.78	ns
Earthworm abundance 2000	0.71	0.91	0.59	0.81	0.88	0.64

Earthworm abundance 1996 correlated with soil properties 1996, all other data correlated with soil properties 2004.

related to soil texture under reduced compared to conventional tillage. In the maximal year 2000, however, the relationship between earthworm abundance and soil texture was distinctly closer in plots under reduced tillage; this result was in contrast to the initial situation in autumn 1996, where both sides of the field exhibited similar patterns (Table 5). After the introduction of reduced tillage, the earthworm–soil texture relationship seemed to be strengthened under reduced tillage. The relationship between earthworm abundance and organic carbon seemed to be more complicated, but there was also a tendency towards strengthening the relationship under reduced tillage.

3.3. Spatial analyses of earthworm activity and soil properties

All earthworm abundance parameters along the four transects showed considerable spatial variability; the fluctuations in space were however not random but followed a certain pattern (Fig. 3).

The spatial pattern of earthworm activity was similar in all earthworm parameters studied; characteristic features were lower values under conventional tillage and increased values under reduced tillage at certain plots (Fig. 3). Spatial variability was more pronounced under reduced tillage compared to conventional tillage, indicated by the higher amplitude at the right side of the graphs. The degree of variability however depended on the parameter under consideration. While the average abundance fluctuated only slightly, maximal variations were found in earthworm abundances 2000 (Fig. 3). In that year, abundances ranged from approximately 150 to 0 worms m^{-2} under reduced tillage compared to a more consistent distribution under conventional tillage ranging from approximately 30 worms m^{-2} to nil observations. Zero values under reduced tillage were also found in parameters "average rate of change" and "average earthworm abundance" at certain locations (Fig. 3).

Organic carbon content (0 to 15 cm) and soil texture (fine particles content, 0 to 30 cm) were spatially closely related to earthworm activity. Minima and maxima often coincided (Fig. 3), i.e. at location 10 (minimum for organic carbon and average earthworm activity), at location 29 (maximum for fine particles content and earthworm activity) and at locations 32–33 (minima for organic carbon, fine particles content and earthworm activity.

Semivariogram analysis revealed spatial structures in earthworm parameters and soil properties fine particles content and organic carbon (Fig. 4). Small-scale variability was not captured well which is indicated by the large nugget variance. However, all variograms consistently indicate large-scale processes of earthworm activity and soil properties along the transects with ranges around 300 m.

Autoregressive state-space analysis was carried out to estimate earthworm activity at each location with soil texture and organic carbon content (0 to 15 cm) considering the information from neighboring locations. With state-space analysis, *average earthworm abundances* along the transects were estimated with soil texture (fine particles content, FP) and organic carbon (Fig. 5). About 70% of variability of earthworm abundances could be explained with these parameters even when every other value of earthworm abundance was omitted in the analysis. The parameter fine particles content was slightly more important for predicting earthworm abundance than organic carbon indicated by the larger transition coefficient for this state variable (Fig. 5).

With state-space analysis, the *average rates of change* could also be estimated along the transects with fine particles content and organic carbon, even when every other value was omitted in the analysis (Fig. 6). 80% of variability could be explained with these soil properties. In this case, the relative contribution of organic carbon exceeded the contribution of soil texture to the estimation. Whereas soil texture contributed with about 17% to the estimation, the relative contribution of organic carbon amounted to 32%. Neighboring values for the rate of change however contributed with almost 50% to the estimation.

Similarly, *earthworm abundances in 2000* could be estimated with state-space analysis based on organic carbon and fine particles (FP) even when only every third (Fig. 7) or every fourth value (data not shown) was considered. The relative importance of organic carbon as predictor was considerably higher than that of soil texture (Fig. 7): organic carbon contributed with 98% to the estimation whereas soil texture contributed only with about 6%.

4. Discussion

In a long-term study, earthworm abundances from an "on-farm" tillage experiment were analyzed for the influence of

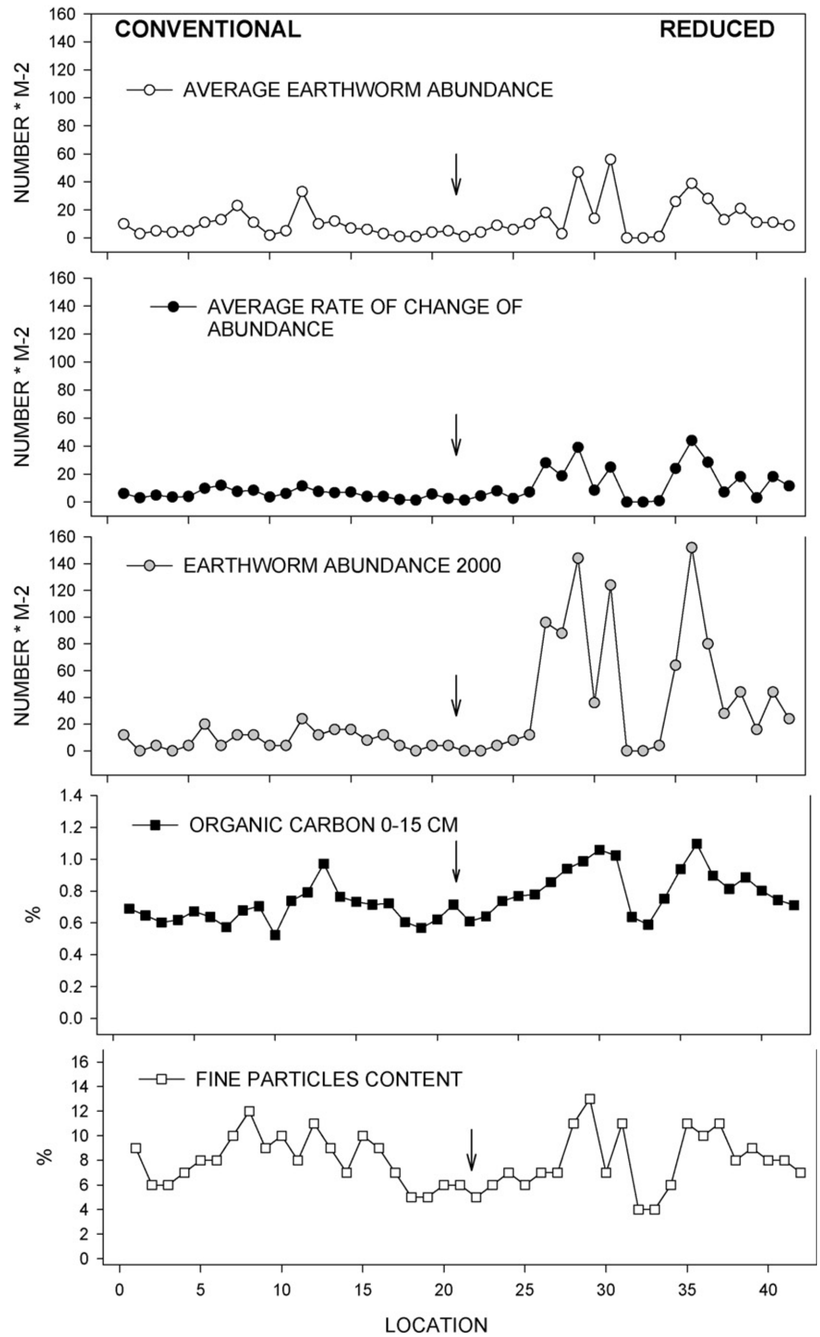

Fig. 3. Spatial pattern of earthworm activity (average earthworm abundance, rate of change of earthworm abundances, earthworm abundance in 2000) and organic carbon (OC) and fine particles content (FP) under conventional (plot 1–21) and reduced tillage (plot 22–42) along four transects which were stretched into one transect. Arrow indicates change of tillage system in the "virtual" transect.

reduced tillage on earthworm populations in sandy soil. When the effect of tillage on soil biota is studied, usually means or medians from differently tilled plots are compared (Kladivko et al., 1997; Johnson-Maynard et al., 2007; Rahman et al., 2007; Pfiffner and Luka, 2007; Metzke et al., 2007). When we proceeded accordingly, we found that median earthworm abundance and the rate of change of abundances in 21 plots each did not differ between conventional and reduced tillage. Only in 2000, a year with maximum earthworm activity and presumably optimal environmental conditions, earthworm abundance was higher under reduced compared to conventional tillage.

However, the information contained in spatial averages is limited (Nielsen and Wendroth, 2003). This is especially true for heterogeneous soils like our field site where soil texture and related soil properties vary considerably over short distances. Soil texture differences between sampling locations may mask tillage effects (Strudley et al., 2008). Under these circumstances, a substantial information gain is achieved when the location of observations are considered (Nielsen and Wendroth, 2003).

In our analysis, the first step towards local differentiation of observations was the separation of differently textured plots by classifying them into two texture classes. Since finer textured soils reacted more positively to tillage reduction than coarse-grained soils, our observations suggest a location-dependent effect of reduced tillage on two earthworm abundance parameters, the rate of abundance change and maximal abundance (Fig. 2 a and b);

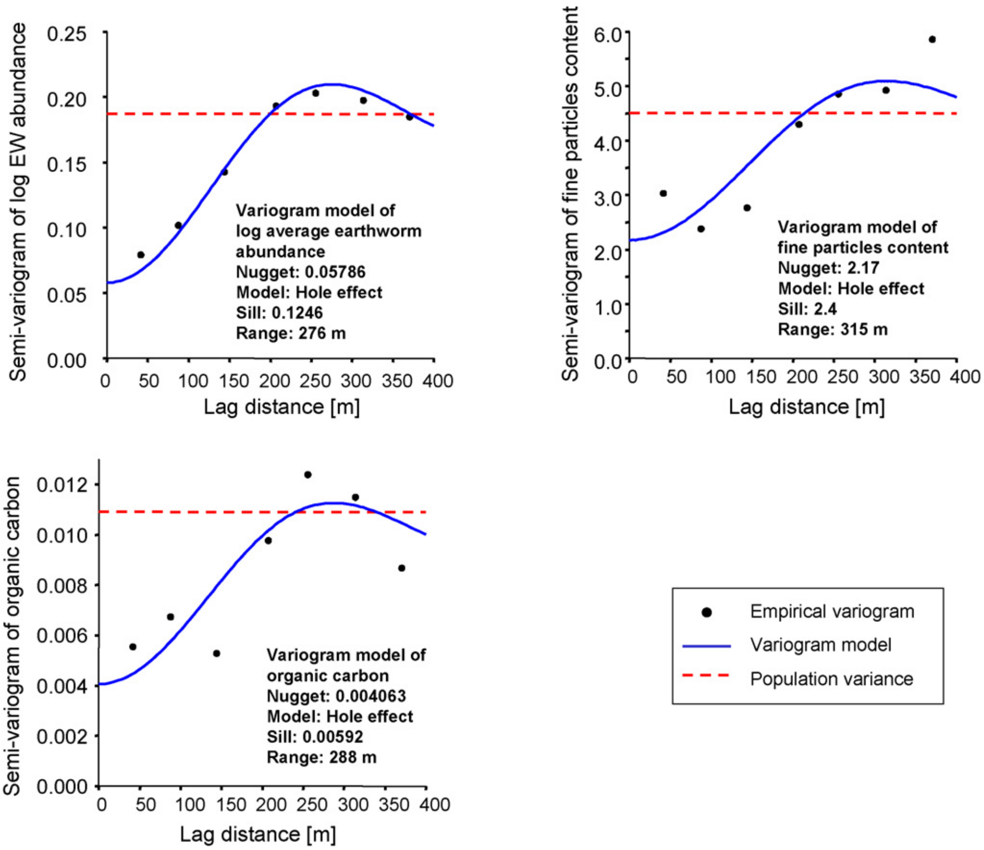

Fig. 4. Semivariograms for average earthworm abundances and selected soil properties (organic carbon, fine particles content); omni directional variograms: empirical variogram (black dots), variogram model (line), population variance (dashed line).

average earthworm abundance however seemed to be unaffected by tillage (see below). A higher fine particles content increases the water holding capacity of the soil and may thus positively affect the reproduction rate of the earthworm population. Our observations thus support the hypothesis of the location-dependency of tillage effects (Kladivko et al., 1997); it was the first hypothesis of our study.

The next step towards considering the location of observations was the analysis of the complete spatial series of earthworms and soils, derived from 4 transects under two tillage regimes (Fig. 3).

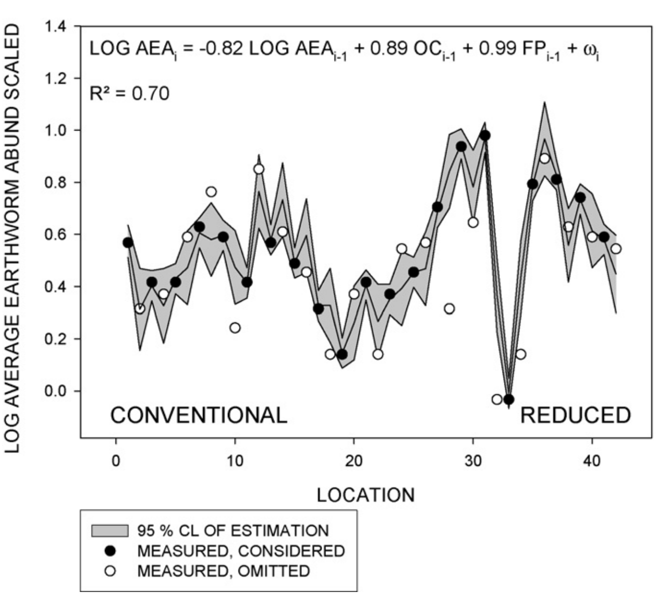

Fig. 5. Estimation of average earthworm abundance with organic carbon content (0 to 15 cm) and fine particles content, when every other value of earthworm abundance is omitted (state-space analysis, after Nielsen and Wendroth, 2003); CL = confidence limits.

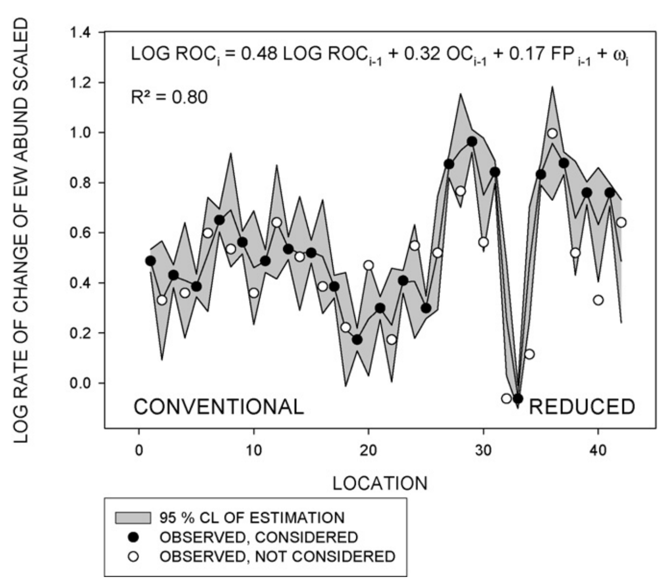

Fig. 6. Estimation of the rate of change of earthworm abundances with organic carbon content (0 to 15 cm) and fine particles content, when every other value of earthworm abundance is omitted (state-space analysis, after Nielsen and Wendroth, 2003); CL = confidence limits.

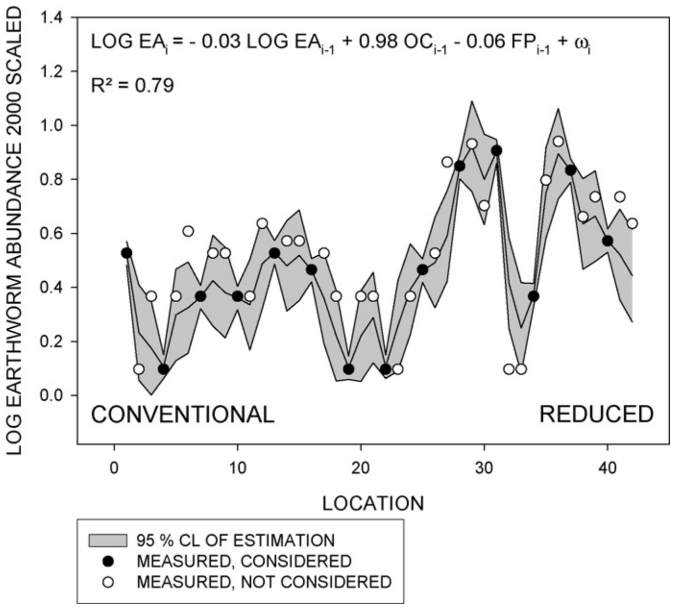

Fig. 7. Estimation of earthworm abundances in 2000 with organic carbon content (0 to 15 cm) and fine particle content, when two out of three values are omitted (state-space analysis, after Nielsen and Wendroth, 2003); CL = confidence limits.

This closer look on locations was necessary since neither the two halves of the field nor the pairs of plots were completely identical—a problem which is often encountered in field situations (Hurlbert, 1984). Rank correlation analyses helped to select the most important soil properties being related to earthworm activity: the content of fine particles (<6.3 μm) and the organic carbon content in 0 to 15 cm soil depth. While soil texture characterizes the physical environment for earthworms, the organic carbon content informs about the food availability in soil. Soil texture and organic carbon content are known to be main factors determining earthworm abundances in different soils (Hendrix et al., 1992; Edwards and Bohlen, 1996; Baker et al., 1998). Recently, soil texture and soil organic carbon has been used for classifying earthworm populations in agricultural soils in Brandenburg (Krück et al., 2006).

In a rolling landscape, soil texture depends on soil type and slope position. Tillage influences soil texture only to a negligible extent. The organic carbon content near the soil surface, however, is not only influenced by soil texture but also depends strongly on the tillage regime. Under reduced tillage, the organic carbon content in the upper cm of soil is known to increase as a consequence of plant residue placement near the soil surface (Lal et al., 1998; Tebrügge and Düring, 1999; Conant et al., 2007). At the Lietzen site, in both tillage systems, organic carbon content in 0 to 15 cm soil depth increased during the observation period; under reduced tillage however, increments were far more pronounced (Joschko et al., 2007).

Earthworms may influence carbon distribution and carbon stocks in soils (Shuster et al., 2001; Don et al., 2008); at our field site however tillage can be considered as the main agent for organic matter stratification in the topsoil because of generally low earthworm abundances. An increase of organic carbon in 0 to 15 cm soil depth after tillage alteration has been observed at all plots; earthworm activity, however, was confined to certain plots (Fig. 3).

For characterizing the earthworm populations during the 10-year observation period, different earthworm abundance parameters were used. The long-term average of earthworm abundances characterizes the general spatial pattern of earthworm activity between 1997 and 2006. The rate of change of earthworm abundances contains important information about the inherent potential of the earthworm population to recover after disturbances or severe environmental conditions. In the current study, the year 2003 was a drought year in whole Europe (Ciais et al., 2005) and had severe impact on the earthworm population in Lietzen (Joschko et al., in preparation). The rate of recovery of a biological response function following a perturbation or stress is called resilience (Griffiths et al., 2001; Ritz et al., 2004); thus, the average rate of change of earthworm abundances may serve as indicator of resilience of the earthworm population. With the earthworm abundances from the year 2000, a snap shot from the earthworm population under presumably optimal environmental conditions could be characterized, when differences between the tillage systems and between locations were highest.

Because sampling positions were located along 4 transects which followed the working direction and the relief of the site (Fig. 2), soil properties as well as earthworm activity parameters exhibited autocorrelations which had to be considered in the statistical analysis. Classical, ordinary least squares linear regression analysis was unsuited because observations were not independent from each other. Therefore, quantification of the earthworm–soil relationships across the transects was carried out by autoregressive state-space analysis (Nielsen and Wendroth, 2003). This technique, derived from time series analysis, enables one to model the variation of the dependent variables, i.e. the earthworm abundance parameters along the transects, as a function of earthworm abundance, organic carbon and soil texture at neighbouring sample locations. In this approach, the dependent variable may be perceived as moving in state-space along the two axes soil texture and organic carbon along the transects, crossing the two tillage systems. Since one state variable, the organic carbon content near the soil surface, was dependent on the tillage system, one model was sufficient for the whole data set.

With multivariate state-space analysis, we analyzed the relative importance of soil texture versus organic carbon in 0 to 15 cm soil depth for predicting earthworm activity along the transects. The relative importance of the two predictors varied between the earthworm abundance parameters, as the transition coefficients reveal: for estimating the average earthworm abundance during the observation period soil texture was slightly more important than organic carbon (Fig. 5). For estimating the rate of change and maximal abundance in 2000 however, the parameter organic carbon was more important, indicated by the larger transition coefficients (Figs. 6 and 7). Organic carbon was especially important as predictor in case of maximal abundances in 2000: this parameter contributed with 92% to the estimation.

On the assumption that organic carbon distribution in 0 to 15 cm was mainly the result of management operations, these results may be interpreted as follows. Under optimal environmental conditions, as in spring 2000, earthworms react disproportionately positively in fine-particle rich locations where organic carbon near the soil surface is increased, i.e. when tillage is reduced. This reaction is quite in contrast to the average earthworm abundance; in this case the amount of organic carbon near the soil surface, i.e. the tillage system, is of lesser importance and earthworm activity is mainly determined by soil texture. We may conclude from these findings that for the resilience potential and the optimal performance of the earthworm population as in 2000 the reduction of tillage is of special importance whereas the average earthworm abundance depends mainly on soil texture.

Our analysis shows that the influence of soil texture, and thus the location-dependency (Pringle and Lark, 2007), is present in all earthworm abundance parameters studied; the relative importance of soil texture to the estimation however varies according to the parameter under consideration. The results of the state-space analysis, i.e. the quantitative relationships between earthworm activity and soil properties under different tillage regimes, may now be tested as new hypotheses on other fields and soils; the transferability of results achieved by means of spatial statistical tools has been stressed by Nielsen and Wendroth (2003).

Another advantage of state-space analysis is that this analysis accounts for local disparities between variables across the spatial series. As can be seen in Fig. 3 and Table 5, the relationship between earthworm abundance parameters and soil texture is different under conventional and reduced tillage, though the relationship itself exists throughout the series (see below). State-space analysis considers local response functions between the variables of interest (Nielsen and Wendroth, 2003).

The location-dependency of earthworm responses to tillage reduction may lead to increased spatial variability of earthworm abundances under reduced tillage: if earthworms react disproportionally positively on locations with increased fine particle and organic carbon content, then variations become larger. Indeed, spatial variability of the tillage sensitive parameters rate of abundance change and maximum abundance 2000 were considerably increased under reduced tillage—to a larger extent as the average earthworm abundance which is thought to be mainly determined by soil texture (Fig. 3). Our results suggest that, in case of reduced tillage, the basic soil-induced pattern is exaggerated whereas in case of conventional tillage the pattern is flattened, at least in the management-influenced parameters rate of abundance change and maximal earthworm abundance (Fig. 3). Increased variability of soil properties, such as bulk density or total carbon, under no-tillage compared to conventional tillage has been reported by Perfect and Caron (2002), and has been attributed to the homogenizing effect of conventional tillage operations.

Another possible consequence of the location-dependency of the earthworm reaction to tillage reduction are closer relationships to soil properties under reduced compared to conventional tillage (Kladivko et al., 1997), as formulated as hypothesis in our study. Indeed, the relationship between the maximal earthworm abundance and soil texture was considerably closer under reduced compared to conventional tillage in contrast to the initial situation (Fig. 3, Table 5). However, no such clear-cut effect of tillage reduction was observed with respect to organic carbon. There may be interaction influences between soil texture and organic carbon that are contributing to these observations.

Despite the caveats, our observations partly support the findings of Kladivko et al. (1997), but further studies are warranted to verify these observations. If closer relationships, induced by tillage reduction, are substantiated on other soils, the existence of a general mechanism might be considered. It might be speculated that under reduced tillage favourable conditions enable the potential earthworm community to be manifested, which is determined by soil properties such as soil texture and organic carbon. The lower perturbation rate under reduced tillage may also enhance the self-organization of the soil community (Lavelle et al., 2006). In contrast, earthworms under conventional tillage apparently cannot fully exploit the potential inherent in the soil, and the relations between earthworm populations and soil properties are consequently less close. Closer relations between earthworm populations and soil properties under reduced tillage may be interpreted as indicator of a sustainable management system acting on soil biota in tilled soils. The degree of the relationship between biodiversity characteristics and environmental variables was recently discussed as indicator of sustainability (Vellend et al., 2007). This concept might also be applicable to soil ecological parameters in agricultural soils and should be studied more closely.

Our study comprises a first step towards spatial analyses of tillage effects on earthworms at the field scale. Several aspects of the experimental design could be optimized in future studies. Equidistant and more numerous sample locations should lead to closer spatial relationships between earthworm activity and soil properties and yield more robust state-space models.

5. Summary and conclusion

Despite homogeneous management, no uniform response of earthworms to tillage reduction was found during 10 years observation of earthworm populations in a large field on sandy soils which was partly under reduced and partly under conventional tillage. Instead, local responses of earthworm activity to tillage reduction were observed, with apparently increased tillage effects on the finer textured of these sandy soils. Our results are compatible with the concept that soil differences such as soil texture induce the basic abundance pattern of earthworms in agricultural soils which is modulated by management practices such as tillage (Fox et al., 2004).

State-space analyses enabled to describe earthworm activity along transects as function of soil texture and organic carbon near the soil surface, the latter of which is influenced by the tillage system. Thus, relationships between earthworm abundances and soil properties under different tillage regimes could be identified which are obscured when only means are compared. The quantitative results derived from this analysis may serve as hypotheses which subsequently can be tested on other fields and soils.

In our study, the omission of ploughing and the reduction of working depth from 25 to 18 cm obviously evoked considerable ecological changes in the soil, even though the spatial extent of tillage was the same in both tillage variants. The potentially large ecological effect of small differences in soil management should be studied more closely.

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