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Occasional reduced tillage in organic farming can promote earthworm performance and resource efficiency

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ABSTRACT

Reduced tillage has several advantages over conventional tillage (CT), including the promotion of earthworm communities and the reduction of input of energy and labour. However, its application in organic farming is mainly hindered through increasing weed pressure. One way to counteract this drawback might be to introduce occasional reduced tillage (ORT), which means applying methods of reduced tillage only in combination with selected crops. Against this background we hypothesized that (i) ORT rapidly promotes biomass, abundance and species richness of earthworm communities and that (ii) ORT generates a financial surplus for farmers. Therefore, a field experiment was established for triticale (*x Triticosecale*) cultivation on loamy soils in Northern Germany. The influence of tillage regimes on earthworms was investigated in a non-randomized design with $n = 3$ fields for the ORT and CT treatment. Earthworm biomass, abundance and species richness were investigated in October 2012 and in April and October 2013. Yields were determined for the three fields under each tillage system, each field with four non-randomized replicates, before harvest in 2013. The ORT treatment consisted of two to three tillage operations prior to seeding with a maximal cultivation depth of 15 cm and without ploughing, whereas the CT treatment consisted of a ploughing depth of 25–30 cm and one to four other steps for seedbed preparation prior to seeding. In total, seven earthworm species were identified. Our data revealed that earthworm biomass was significantly reduced under CT, both four weeks and about seven months after tillage. This effect holds true for the number of earthworm individuals in autumn (four weeks after ploughing), but not for the number of earthworm individuals in spring (seven months after ploughing). Results of contribution margin analysis showed no consistent trend referring to tillage measures. Two fields, which performed well under CT, showed a financial surplus (+24% and +13%) when managed with ORT. At the same time one field, performing poorly under CT, generated financial deficits (-10%) under ORT. Overall ORT had immediate positive effects on earthworm populations. Furthermore, this management scheme might have positive effects on the economic outcomes of organic crop rotations if overall growing conditions are sufficient. Along with methods usually applied to investigate earthworm performance, we checked whether the number of surface casts could help estimate earthworm performance. It became apparent that the number of surface casts cannot be used as a general predictor of earthworm performance. The number of individuals of *Lumbricus terrestris*, the number of anecic individuals and the total earthworm biomass can be estimated the most reliable by counting surface casts.

1. Introduction

The reduction of tillage intensity, including methods for reducing tillage depth to no-till systems, has been a topic in conventional farming research for many years now and some researchers postulate reduced tillage to be the next agricultural revolution (Krauss et al., 2010). In recent decades it also became a topic in European organic farming research (Mäder and Berner, 2012).

In organic farming, reduced tillage without ploughing can reduce erosion, enhance macroporosity, and promote microbial activity and carbon storage (Peigné et al., 2007). It is also associated with less run-off and leaching of nutrients, reduced fuel use, and faster tillage (Peigné et al., 2007). However, Peigné et al. (2007)

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emphasize possible disadvantages, including greater pressure from grass weeds; less suitability than ploughing for poorly drained, unstable soils or high rainfall areas; restricted N availability and restricted choice of crops. Of the expected drawbacks listed, increasing weed pressure under reduced tillage measures is the most discussed (Krauss et al., 2010; Mäder and Berner, 2012; Metzke et al., 2007). Additionally, in long-term experiments, a change of weed community structure to the dominance of perennial species including competitive grasses has been determined (Peigné et al., 2007). Therefore Metzke et al. (2007) see a conflict of interest between setting aside the plough to promote, e.g., habitat conditions for soil biota (Pfiffner and Mäder, 1997) and intensive ploughing for weed control.

This is where the main line of conflict is drawn when dealing with reduced tillage or no-till systems in organic farming: the promotion of desirable ecosystem services on the one hand versus the risk of increased weed pressure which may consequently cause losses in yields, on the other hand. However, there is an ongoing debate concerning potential drawbacks of reduced tillage and consequent possible reduction of yields. In light of this discussion some attention has been paid to strategies of occasional reduced tillage (ORT) and occasional direct seeding, which means applying methods of reduced tillage/direct seeding only in combination with selected crops (Massucati, 2013). According to Carter (1994) this management scheme, which he calls rotational tillage, can maintain an adequate weed-control and can also have positive influence on sustainable soil management (e.g., prevention of soil compaction, plant disease control) in humid regions when compared to permanent reduced tillage.

In agricultural cropping systems reduced tillage without ploughing (i.e., non-turning soil management) generally favours soil biodiversity and especially earthworms (Carr et al., 2013; van Capelle et al., 2012). At the same time it needs to be kept in mind that species may react differently to the same management measures. In some studies for example the abundance of *Aporrectodea caliginosa* increased when a plough was used for soil cultivation (Peigné et al., 2009; Pelosi et al., 2014). However, according to van Capelle et al. (2012) the overall positive effect of reduced tillage on earthworms is due to interacting effects of reduced injuries, decreased exposure to predators at the soil surface, microclimate changes and an increased availability of organic matter providing a convenient food source in the upper soil layers. Especially for anecic species the reduced destruction of their vertical burrows is supposed to be important. Earthworms function as ecosystem engineers positively changing soil chemical, physical, and biological properties. The positive effects of earthworms on nutrient turn-over and transfer, for bio-aggregation of soil particles and on a porous soil structure that positively influences root growth and water infiltration (Kautz et al., 2013) are beneficial in all farming systems. But these ecosystem services are important in sustaining soil fertility and stabilizing crop rotation yields especially in low input farming. Farmers try to benefit from these services by applying reduced tillage in organic farming (Metzke et al., 2007). This targeted support of ecosystem services to improve cultivation conditions is what Kuntz et al. (2013) call eco-intensification.

Like in our study earthworms are regularly used as bioindicators, e.g. for management changes or soil contamination (Fründ et al., 2011). This is because today much is already known about earthworm behaviour and ecology, and because earthworms can be detected in the field by the naked eye. Nevertheless, there are also some reasons against using earthworms as bioindicators. Generally, methods combining application of specific expellants with hand-sorting of soil are used to study the performance of earthworm communities (Čoja et al., 2008). These methods are time consuming, labour-intensive and require expert knowledge. Alternatively, the activity of earthworm communities can be estimated by counting and mapping soil surface markings of earthworms, like casts and burrow openings (Ehrmann, 2003). Fründ (2010) proposed the use of surface markings of earthworms as a first step when evaluating soil conditions.

In the present case study under on-farm conditions we tested the following hypotheses: In organic crop rotations occasional reduced tillage (ORT) (i) rapidly promotes biomass, abundance and species richness (referred to as performance in the following) of earthworm communities and (ii) generates a financial surplus for farmers. Additionally we checked whether the counting of surface casts is a reliable method to predict the performance of earthworm communities.

2. Material and methods

2.1. Study site

The experimental farm in Trenthorst has been managed under the EU Organic Standards 2092/91 and 834/2007 since 2001 and is

Table 1
Crop rotations, amount of chargeable N-application and soil conditions at the three experimental fields. Each field belonging to one farming system serving the needs of one group of farming animals (dairy, ruminant II, pig).

Farming system	Dairy	Ruminant II	Pig
Crop rotation	clover-grass clover-grass maize winter wheat field bean/oat triticale	clover-grass maize winter wheat field pea/spring barley triticale	clover-grass clover-grass spring barley field pea/false flax winter barley field bean triticale
Chargeable amount of N (kg ha^{-1})			
2012	72	53	105
2013	22	27	25
pH	6.8	6.5	6.5
Nutrient content (mg 100 g^{-1})			
P	5.7	7.4	6.0
K	9.5	17.5	13.4
Mg	9.3	12.5	12.8
Texture (%)			
Clay (< 2 μm)	17	20	21
Silt (2–50 μm)	35	38	38
Sand (50–2000 μm)	46	40	40

situated in Schleswig Holstein, Germany near Luebeck (53°46′N, 10°31′E). Soil types on the site are Stagnic Luvisols from boulder clay with silty-loamy texture. Bulk densities of the topsoil are between 1.3–1.5 g cm^{-3} and the C-N-ratio of about 10 lies in a range which is known to be typical for high yielding agricultural land (Blume et al., 2010). In 2012 and 2013, the pH of the soils of the three fields under study was in the optimal range between 6.4 and 6.9. The marine climate, with a mean annual rainfall of 700 mm, well distributed throughout the year, and a mean annual temperature of 8.8 °C, offers favourable cropping conditions. In the experimental farm a long-term monitoring scheme has been established for 12 years in three farming systems: dairy, ruminant II, pig. Each system consists of fixed fields and a fixed crop rotation. As the crop rotations have been designed to serve the needs of particular farm animals, the respective farming systems and the crop rotations are named according to these animals. The farming systems differ mainly in the input of livestock manure, forage cultivation, and percentage of clover-grass in the crop rotation scheme. The soil textures are rather similar and according to German fertilization recommendations soils are sufficiently supplied with P, K, and Mg and pH of soils are adequate for arable land (Table 1). All rotations start with clover-grass in year one and end with triticale. Each field of the three rotations includes two long term monitoring plots of one hectare. Therein four geo-referenced permanent sampling points are located. Within the fields studied here these permanent sampling points are located on a square at distances of 60 m. Soil sampling distances larger than 20–50 m assure the inclusion of spatial variability of chemical and physical soil parameters in this landscape (Haneklaus et al., 1998).

2.2. Soil management and experimental design

In summer 2012 three fields were halved (Fig. S1), each belonging to one of the three crop rotations. At this time all rotations were in the second cycle since conversion to organic farming. One half-field was managed with ploughing (CT: conventional tillage) and the other half without ploughing (ORT: occasional reduced tillage). Within our study conventional and reduced tillage are defined according to ASAE (2005). For the study presented here, CT includes the use of a two-sided mouldboard plough, with a working depth of 25–30 cm, whereas on the half-fields managed with measures of reduced tillage no mouldboard plough was used and tillage depth was a maximum of 15 cm. Reduced tillage was conducted for two years; in 2012 before growing triticale and in 2013 before clover-grass. Table 2 summarizes the agricultural management measures in summer/autumn 2012 and summer 2013. Implements used were a chisel plough, a spring tooth harrow, and a rotary or a disc harrow in changing combinations, according to site conditions. To minimise probable management problems with increased weed pressure due to reduced tillage in the crop rotation, we decided to establish our experiment on reduced tillage before drilling the last crop of the crop rotations. On the one hand this is triticale in all rotations, which is known to regularly achieve good yields, while weed pressure is known to be moderate. On the other hand, in each rotation the crop following triticale is clover-grass (Table 1). This part of the rotation is suitable to use ORT, because green forage crops have high competitive power and intensive weed control is possible in mowing regimes. Due to inappropriate weather conditions in spring 2013 (heavy rainfalls), no mechanical weed control was conducted in triticale in that year on any of the three fields under study. During our study no survey of weed densities was conducted.

2.3. Earthworm sampling

Earthworm sampling took place in October 2012 and in April and October 2013; which was one month (October) and seven months (April) after ploughing. Earthworms were sampled using Allyl isothiocyanate (Zaborski, 2003) coupled with hand-sorting at three locations per 10 m transects (at 1–1.5 m, 4.75–5.25 m and 8.5–9 m) (Fig. S2). Here, pits of 0.5 × 0.5 × 0.1 m were excavated and the soil screened for earthworms. The Allyl isothiocyanate solution (0.8 ml of 95%—Allyl isothiocyanate, 16 ml methanol, 10 l H_2O) was poured into these pits in two portions of 5 l to expel earthworms from deeper soil layers. Earthworm biomass and density per square meter was measured in the laboratory, and adult and sub-adult individuals were identified to species level. Two transects were sampled on each half-field. These transects had a distance well above 50 m to avoid autocorrelation between the samples (Haneklaus et al., 1998; Valckx et al., 2011). This is only a precautionary measure, as the statistical methods used do not rely on independent (i.e., not auto-correlated) samples (c.f. Section 2.6). New transects were selected for the samplings in October 2012, April 2013, and October 2013.

We had to cope with some technical problems while sampling earthworms with the combined method of hand-sorting and application of Allyl isothiocyanate. The silty-loamy soils tend to build aggregates which are difficult to split when searching for earthworms. Furthermore, these soils, also called minute soils, are often too dry or too moist to absorb larger quantities of water. Therefore, we only used ten litres of Allyl isothiocyanate solution instead of the twenty litres mentioned in the appropriate standard for the hand-sorting and extraction of earthworms (ISO, 2006).

Casts were counted on the soil surface along the same transects (10 m long; 0.4 m wide) before earthworm sampling (Fig. S2). Each earthworm cast discretely visible on the soil surface was counted, no matter how closely casts were spaced, although they might have been produced by the same earthworm individual. If necessary, plants were bent over by hand to ensure a good view of the soil surface. This was easily possible, because plants were a maximum

Table 2
Agricultural measures applied for soil management on the three experimental fields, each belonging to one out of three farming systems (dairy, ruminant II, pig), from August to October 2012 and in August 2013. CT: conventional tillage; ORT: occasional reduced tillage.

Agricultural machinery used (ASABE, 2009)		2012						2013					
	Working depth (cm)	Dairy		Ruminant II		Pig		Dairy		Ruminant II		Pig	
		CT	ORT	CT	ORT	CT	ORT	CT	ORT	CT	ORT	CT	ORT
Chisel plow for stubble cultivation	10–15	x	x	x	x	x	x	x	x	2x	2x	x	x
Two way moldboard plow (5-furrow) with packer	25–30	x		x		x				x		x	
Two way moldboard plow (4-furrow)	25–30							x					
Chisel plow	10–15				2x		2x	x	x	x	x	x	x
Spring teeth harrow	10–15			x		2x							
Rotary harrow	10		x	x		x						x	x
Seed drill + front-mounted disc harrow	5–10	x	x	x	x	x	x	x	x	x	x	x	x

20 cm in height. Following pre-tests in September 2012, and in contradiction to Ehrmann (2003), for practical reasons burrow openings were not considered because they could not be distinguished from other biopores at the soil surface. As there was no mulch layer on the soil surface, middens were only very few in number and were therefore not considered in this study. Actually only earthworm casts were counted. To avoid uncontrolled bias in cast counting this was always done by the same person.

All working steps were finished for one transect within a single day, so that there was no rainfall event between cast counting and earthworm extraction. Furthermore, no heavy rainfall event occurred during the three observation periods, so that results within the three periods are comparable.

Earthworm sampling could not be conducted on the field belonging to the dairy rotation in October 2012 because of delayed seeding. Furthermore, data for earthworm biomass is missing for one transect from the ORT treatment on the dairy field in October 2013 due to handling errors in the laboratory (Table S1).

2.4. Crop yields

Yields of triticale were determined by harvesting 2 m^2 by hand at each of the four permanent sampling points per half-field (cf. Section 2.1, Fig. S1). After the sheaves had been dried at 30 °C for 60 h, they were threshed by a universal threshing machine to calculate yields of grain and straw.

2.5. Economic evaluation

We conducted a contribution analysis to estimate the economic outcomes of the tillage regimes. Fuel consumption of the different agricultural operations was calculated using the appropriate tool provided by KTBL (2014a). According to KTBL (2014b) costs were assumed as follows: triticale seed 0.74 € kg^{-1}; diesel 1 € l^{-1}; cost of labour 15 € h^{-1}; loss of interest 3% per annum; sales profit of triticale 313 € t^{-1}.

2.6. Statistics

All statistical analyses were conducted using R 3.1.2 (R Development Core Team, 2014). As we had to cope with spatial and temporal hierarchical data we used mixed effects models. According to the distribution of dependent variables we used R package lme4 (Bates et al., 2014) for linear mixed effects models (LMMs) and R package glmmADMB (Fournier et al., 2012; Skaug et al., 2015) for generalised linear mixed effects models (GLMMs). All GLMMs were calculated for negative-binomial distributed count data. The default link-function for negative-binomial data in glmmADMB is the log. We used BIC for model selection, as this information criterion is more suitable for small datasets and prefers simpler models (Dormann, 2013). For some analyses (cf. Table 3) after modelling we conducted multiple group comparisons using R package multcomp with single-step method for p-adjustment (Hothorn et al., 2008). The statistical influence of fixed effects was tested using the likelihood-ratio-test (LR-test) (Dormann, 2013).

Table 3 summarizes the results of modelling the influence of tillage regimes (CT vs. ORT) on different aspects of the earthworm communities and on yields of triticale. All models in this table, except that for yields, use management type (CT vs. ORT) and date (October 2012, April 2013, October 2013) and the interaction of these two as fixed effects. Additionally the factor field (dairy, ruminant II, pig) is used as random intercept effect. The model for yields uses management type as fixed effect and field as random intercept effect.

3. Results

3.1. Earthworm performance

During the entire study including all plots 7887 earthworm individuals were collected out of which 35% were adult or subadult, so that they could be determined to species level. Out of these, 80% were endogeic, 18% anecic, and 2% epigeic individuals.

Table 3
Results of statistical modelling to reveal the influence of management (CT vs. ORT) on different aspects of earthworm performance (biomass, species number, number of individuals) and crop yields. Variable Type with the factors CT (conventional tillage) and ORT (occasional reduced tillage). Variable Date with the factors October 2012, April 2013 and October 2013.

Dependend variable	Results LR-Test			Results of pairwise comparisons of treatments				
	Effect	p			Mean ± SE		p	
					CT	ORT		
Earthorm biomass per m^2	Type	4.19×10^{-7}	***	Oct.12	26.1 ± 1.0	76.1 ± 1.0	0.012	*
	Date	0.0026	**	Apr.13	40.0 ± 7.8	84.4 ± 7.8	0.0051	**
	Type × Date	0.017	*	Oct.13	35.9 ± 7.8	144.1 ± 9.1	8.73×10^{-11}	***
Number of earthworm species per m^2	Type	3.41×10^{-7}	***	Oct.12	2.5 ± 0.1	5.5 ± 0.1	5.49×10^{-10}	***
	Date	0.0037	**	Apr.13	4.2 ± 0.1	4.7 ± 0.1	0.48	
	Type × Date	0.0012	**	Oct.13	3.7 ± 0.1	5.3 ± 0.1	4.32×10^{-5}	***
Number of earthworm individuals per m^2	Type	1.22×10^{-7}	***	Oct.12	62.5 ± 3.8	202.0 ± 12.2	0.0012	**
	Date	5.73×10^{-7}	***	Apr.13	77.4 ± 14.2	121.5 ± 22.3	0.1	
	Type × Date	0.0093	*	Oct.13	97.1 ± 17.8	406.2 ± 74.6	5.42×10^{-6}	***
Number of surface casts per transect	Type	0.024	*	Oct.12	11.8 ± 0.9	18.9 ± 1.4	0.74	
	Date	0.012	*	Apr.13	9.6 ± 1.0	22.1 ± 2.2	0.034	*
	Type × Date	0.77		Oct.13	23.3 ± 2.4	42.7 ± 4.3	0.45	
Number of endogeic Individuals per m^2	Type	3.10×10^{-7}	***	Oct.12	48.7 ± 5.1	164.9 ± 17.2	0.0017	**
	Date	0.00018	***	Apr.13	64.8 ± 13.2	98.2 ± 19.9	0.19	
	Type × Date	0.0093	**	Oct.13	74.8 ± 15.2	318.5 ± 64.6	1.66×10^{-5}	***
Number of anecic Individuals per m^2	Type	7.98×10^{-6}	***	Oct.12	11.0 ± 2.0	26.0 ± 4.7	0.12	
	Date	1.95×10^{-5}	***	Apr.13	9.5 ± 1.7	17.0 ± 3.1	0.098	
	Type × Date	0.071		Oct.13	18.1 ± 3.3	77.9 ± 14.0	0.0002	***
Kernel yield DM [t ha^{-1}]	Type	0.68			4.0 ± 0.2	3.9 ± 0.2		

*,**,***: Significant at *P*.

Seven species were identified within the sub-adult and adult earthworm individuals (Table S1). *A. caliginosa*, accounting for 45%, was the most abundant species. *Allolobophora chlorotica* accounted for 29% of the (sub)-adult individuals, while the remaining five species were below 10% (*Aporrectodea rosea* 6%, *Aporrectodea longa* subadult 6%, *Lumbricus terrestris* subadult 5%, *A. longa* 4%, *L. terrestris* 3%, *Lumbricus rubellus* 1%, *Lumbricus castaneus* <1%). As juvenile individuals (62% of all individuals collected) were only separated according to the shape of their prostomium, they were divided into epilob and tanylob individuals. Epilob juveniles, which can be fully assigned to endogeic species in this study, dominated with 86% of all juvenile individuals found. Altogether 3% of individuals could not be identified.

Statistical modelling revealed significant differences for earthworm biomass between the two treatments at all three dates studied (Table 3; Fig. 1), with higher values realised under ORT. Differences in the number of all earthworm individuals between management types were only significant in October 2012 (CT: 62.5 ± 3.7 Ind. m^{-2}; ORT: 202.0 ± 12.2 Ind. m^{-2}) and October 2013 (CT: 97.1 ± 17.8 Ind. m^{-2}; ORT: 406.2 ± 74.6 Ind. m^{-2}), which coincides with results for the number of endogeic individuals (Table 3; Fig. 2; Fig. 3). Here again higher values could be measured under ORT. The number of anecic individuals was significantly different between the two management treatments in October 2013 (CT: 18.1 ± 3.3 Ind. m^{-2}; ORT: 77.9 ± 14.0 Ind. m^{-2}) (Table 3), again with higher values under ORT.

The number of species was significantly different between the two tillage treatments in October 2012 (CT: 2.5 ± 0.1 Sp. m^{-2}; ORT: 5.5 ± 0.1 Sp. m^{-2}) and October 2013 (CT: 3.7 ± 0.1 Sp. m^{-2}; ORT: 5.3 ± 0.1 Sp. m^{-2}) (Table 3), with higher values under ORT.

In October 2012 *L. rubellus* and *L. castaneus* were rare (1x and 3x, respectively) under ORT but did not occur under CT. While *A. chlorotica* was present in all plots under ORT, it did not occur in any plot under CT. With three occurrences under ORT *L. terrestris* was more frequent under this management type than under CT with two occurrences (Table S1).

In October 2013 species composition under ORT and CT again mainly differed in the occurrence of *Lumbricus*-species. While *L. terrestis* was present in all transects under ORT (6x) it occurred in only two CT-transects. *L. rubellus* and *L. castaneus* were found each with one occurrence under ORT and none under CT (Table S1).

3.2. Earthworm cast production

The number of earthworm casts only differed significantly between tillage treatments in April 2013 (Table 3). Table 4 summarizes the influence of different variables on the number of earthworm casts. Highest coefficients of determination were obtained for the number of individuals of *L. terrestris* ($r^2 = 0.61$), for the number of anecic individuals ($r^2 = 0.44$) and earthworm biomass ($r^2 = 0.39$).

3.3. Yield and economic assessment

Statistical modelling showed no significant influence of management type on kernel yields of triticale (Table 3). Table 5 sums up the results of a contribution margin analysis of the tillage systems under study. While two fields gained a financial surplus under ORT (+24% and +10%), the third field generated losses (-10%). As soon as reduced tillage caused decreasing yields (Fig. 4), the positive financial effects of ORT-treatment were offset, because the selling price of triticale was the most important factor in the calculation.

4. Discussion

In general, the high variability of earthworm abundance and biomass, heterogeneous soil conditions, and differing definitions of management schemes in other studies (Chan, 2001; Kladivko, 2001) complicate the derivation of universally valid statements on interactions between soil management and earthworm performance.

However, in accordance with Peigné et al. (2009), we found that earthworms react immediately to different management measures. After both tillage events there was a significant decline in the number of individuals under CT and therefore a positive effect of ORT. The number of individuals aligned till spring in the different treatments, what is in accordance with Crittenden et al. (2014). In contrast, the biomass under CT did not reach comparable levels to ORT in spring after it declined due to tillage measures under CT in autumn. These different developments of biomass and number of individuals are because biomass mainly depends on the number of sub-adult and adult, slowly reproducing, anecic species (*L. terrestris*,*A. longa*), whereas the number of individuals is mainly

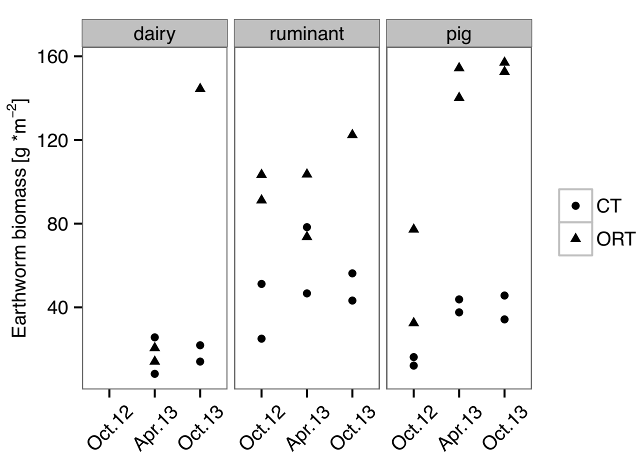

Fig. 1. Earthworm biomass separated per field, month and management type. Each field belonging to one farming system serving the needs of one group of farming animals (dairy, ruminant II, pig). Samplings were carried out in October 2012, April 2013 and October 2013. ORT = occasional reduced tillage, CT = conventional tillage. Trenthorst, Germany 2012/2013.

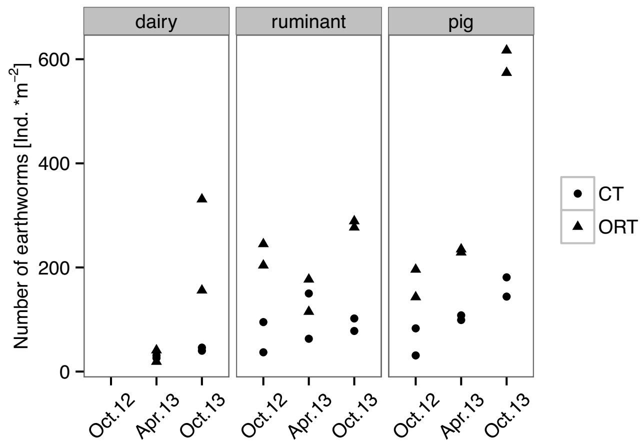

Fig. 2. Number of earthworm individuals separated per field, month and management type. Each field belonging to one farming system serving the needs of one group of farming animals (dairy, ruminant II, pig). Examinations were carried out in October 2012, April 2013 and October 2013. ORT = occasional reduced tillage, CT = conventional tillage. Trenthorst, Germany 2012/2013.

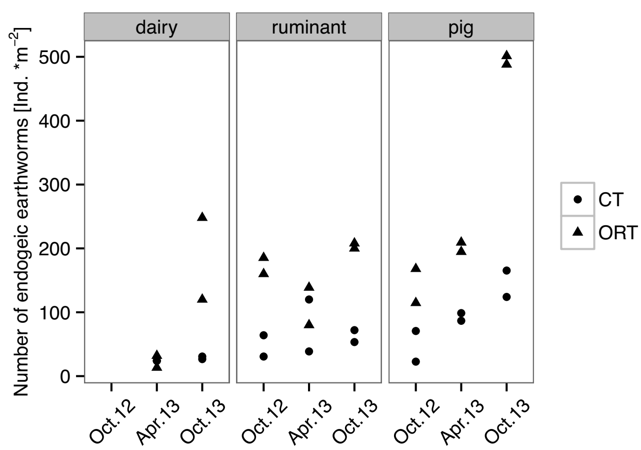

Fig. 3. Number of endogeic earthworm individuals separated per field, month and management type. Each field belonging to one farming system serving the needs of one group of farming animals (dairy, ruminant II, pig). Examinations were carried out in October 2012, April 2013 and October 2013. ORT = occasional reduced tillage, CT = conventional tillage. Trenthorst, Germany 2012/2013.

Table 4

Results of statistical modelling to reveal variables influencing the number of earthworm casts. Variable Type with the factors CT (conventional tillage) and ORT (occasional reduced tillage). Variable Date with the factors October 2012, April 2013 and October 2013. Variable Field with the factors dairy, ruminant II, and pig. Varaiable Transect with four transects within each field. Notation of model components is as follows: 1|Var2 –> random intercept; 1 + Var1|Var2 –> random intercept and random slope; Var2/Var3 –> Var3 nested in Var2.

Dependend variable	Model		Results LR-Test			Coefficients of determination R^2
	Fixed effects	Random effects	Effect	p		
Number of casts	Biomass	1|Field	Biomass	0.00026	***	0.39
Number of casts	Number of earthworm individuals	1|Field	Number of earthworm individuals	0.002	**	0.29
Number of casts	Number of endogeic individuals	1|Field	Number of endogeic individuals	0.0037	**	0.26
Number of casts	Number of individuals: *Aporrectodea caliginosa*	1|Field	Number of individuals: *Aporrectodea caliginosa*	0.00071	***	0.36
Number of casts	Number of amecic individuals	1|Field	Number of amecic individuals	0.00027	**	0.44
Number of casts	Number of individuals: *Lumbricus terrestris*	1|Field 1|Date	Number of individuals: *Lumbricus terrestris*	0.0018	**	0.61

,*: Significant at *P*.

the number of endogeic individuals, with a higher reproductive rate and shorter generation time (Jeffery et al., 2010).

In accordance with our results adult individuals of the endogeic *A. caliginosa* were found to dominate in cultivated (De Oliveira et al., 2012; Riley et al., 2008), particularly in organic (Peigné et al., 2009), fields and endogeic juveniles were found to be most abundant in intensively tilled soils (De Oliveira et al., 2012; Smith et al., 2008).

Results of studies concerning endogeic species under measures of reduced tillage are inconsistent (Chan, 2001). Nevertheless,

Table 5
Contribution margin of triticale production in the two tillage systems (CT vs ORT) in three different organic farming systems (dairy, ruminant II, pig).

	Yield (kernels) DM [t ha^{-1}]		Benefit [€ ha^{-1}]		Variable costs [€ ha^{-1}]		Marginal return [€ ha^{-1}]	
	CT	ORT	CT	ORT	CT	ORT	CT	ORT
Dairy	3.08	3.50	965	1096	308	282	657	814
Ruminant II	4.28	3.59	1338	1122	380	261	959	861
Pig	4.67	4.72	1462	1479	416	300	1046	1178

DM = dry matter; ORT = occasional reduced tillage; CT = conventional tillage. Grey panels indicate management with the highest surplus in each farming system.

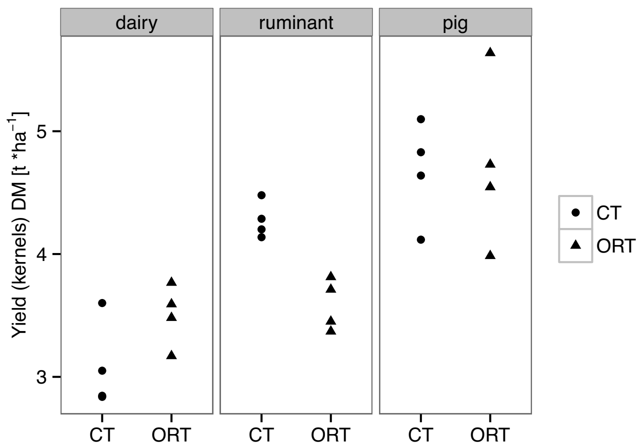

Fig. 4. Kernel yield of triticale separated per field and management type. Each field belonging to one farming system serving the needs of one group of farming animals (dairy, ruminant II, pigs). Examinations were carried out in October 2012, April 2013 and October 2013. ORT = occasional reduced tillage, CT = conventional tillage. Trenthorst, Germany 2012/2013.

increasing performance is regularly linked to increased availability of organic material, e.g. as a result of ploughing of ley (Boström, 1995). In our study we could not find positive effects of CT on the number of endogeic individuals, as we did not have a positive effect of increased availability of organic material.

It is generally assumed that there is a negative effect of ploughing on anecic species, as these worms are at higher risk of being mechanically injured because of their larger bodies, and because their permanent burrows are destroyed by the plough (Chan, 2001). We only found a significant difference for the number of anecic individuals between tillage treatments in October 2013 when the ORT half-fields had not been ploughed for nearly two years (last ploughing in summer/autumn 2011). Therefore, although our study was rather short-termed, we assume that anecic species benefit more slowly from reduced tillage, when compared to endogeic species, due to their longer generation time.

Higher species richness occurred under reduced tillage in October 2012 and 2013, which is in accordance with other case studies (Emmerling, 2001; Ernst and Emmerling, 2009) and a review on this topic by van Capelle et al. (2012). This differences in species number seem to be due to the different sensitivity of earthworm species in response to intensive tillage. Ivask et al. (2007) could show, that species rare under CT, like *L. terrestris, A. chlorotica* and *L. castaneus*, react more sensitive to intensive tillage measures.

Like results from other studies on earthworm biomass, density, and species richness and diversity the results of our study have first of all to be considered as bound to the soil and climatic conditions of our study area. For future studies the use of measures of functional diversity could be helpful to compare earthworm communities within different study areas, as Pelosi et al. (2014) found that earthworm functional diversity increases with decreasing tillage intensity irrespective of the soil type and climatic conditions.

Until now studies have focussed on the importance of earthworm casts for formation of soil structure (Bronick and Lal, 2005; Larink et al., 2001), or nutrient availability (Asawalam, 2006; Kuczak et al., 2006; Le Bayon and Binet, 2006; Whalen et al., 2004). To our knowledge there are no studies establishing correlations between surface castings and earthworm performance. We found the highest coefficients of determination between number of *L. terrestris* individuals and the number of casts, between the number of anecic individuals and the number of casts and between overall earthworm biomass and the number of casts. This, in our view, seems to be logical as the large anecic worms strongly influence the biomass of earthworm communities. Scullion and Ramshaw (1988) found that adult individuals of many species produce surface casts, with quantities decreasing in the order *A. longa*/*L. terrestris*, *A. caliginosa*, *L. rubellus*, *A. chlorotica* and that when these species are part of one population, larger species tend to dominate the production of surface casts. We found that counting surface casts provides an opportunity to deduce the effects of different tillage intensities on the population of *L. terrestris*, a species of great ecological importance. Additionally counting surface casts can direct attention to the important ecosystem under our feet and raise awareness for possibilities for its further improvement.

All of our results on earthworm communities and performance and the usability of earthworm casts for prediction of earthworm performance are based on results from a rather short sampling period when dealing with topics related to soil biology. Nevertheless positive effects of ORT on earthworm performance and positive correlations between the number of surface casts and the number of individuals of *L. terrestris* could be revealed. A replicated experiment could be useful to assure results. Additionally a study on earthworm communities when reusing the plough, after setting it aside for one year, could reveal if there are any long-term effects in cropping systems with ORT. Furthermore it would be interesting to investigate if there are any measurable effects of enhanced earthworm biomass and abundance on ecosystem services like water balance, development of soil structure or decomposition of crop residuals (Bertrand et al., 2015).

In organic farming, yields from fields under reduced tillage might be comparable to those from ploughed fields (Berner et al., 2008), especially when manure or compost were amended (Berner et al., 2008; Mäder and Berner, 2012). We found that under adequate conditions (intensive organic management with 20–30% clover-grass in the crop rotation and application of livestock manure) occasional reduced tillage does not cause severe losses in yield of triticale at the end of a crop rotation. Crowley and Döring (2012) got similar results in England, with yields of spring oat and spring barley slightly, but not significantly, enhanced under a two-year reduced tillage treatment in an organic farming system. Due to this, Crowley and Döring (2012) also revealed improved resource efficiency in terms of fuel consumption and time needed to conduct tillage operations. This can also be confirmed for ORT by our study, where yields do not decrease and contribution analysis of triticale production revealed financial benefits of the ORT-treatment.

We are well aware that the contribution analysis presented in this study is very simplistic and is only based on one-year results. Nevertheless, we wanted to point out that reduced tillage can, besides promoting earthworms, also generate a financial surplus. Therefore, we recommend integrating economic analysis into more studies on management measures potentially beneficial for environment, as it is more likely that those measures will be broadly integrated into farming practices, if at least no financial losses are to be expected.

5. Conclusions

In organic farming, occasional reduced tillage (ORT) immediately promotes earthworm performance (abundance, biomass, species richness). Based on our on-farm results, ORT is suitable to promote earthworm performance in organic farming systems at least for the time ORT is applied. It turned out that counting surface casts of earthworms is an appropriate way of estimating the performance of *L. terrestris*, an ecologically important earthworm species.

In future studies it would be interesting to investigate (i) if enhanced abundance and biomass of earthworms has positive effects on ecosystem services and (ii) how resilient earthworm communities in systems using ORT are after subsequent ploughing.

Furthermore, in organic fields belonging to crop rotations generating high yields under conventional tillage (CT), yields under ORT were found to be at the same level. Here also positive economic effects were determined with ORT. While yields were steady, costs for fuel and labour could be reduced.

In contrast to either tillage or no-tillage approaches, ORT aims to adapt the tillage regime specifically to crops, soil conditions and weed pressure. Therefore, good knowledge of the current soil conditions and the performance of single crops are needed. However, financial surplus seems possible when considering the entire crop rotation, with a simultaneous promotion of earthworms.

So from our data we could show that reducing tillage intensity is positively influencing earthworm communities already in the short term, which can have positive ecological and economic outcomes.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apsoil.2016.01.017.

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