Further development of indicators for the assessment of soil biodiversity using the example of earthworms and springtails (Collembola) with particular reference to organic farming

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"Effective ecological functioning, and hence the future of our civilisation, crucially depends upon the soil biota. Life in earth drives life on Earth, and soil biodiversity represents a vast biological engine, driving processes upon which our very survival depends". (Jeffery et al., 2010)

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II.2.2 Short-term effects of reduced tillage on soil collembolan communities; page 58.
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Part I General introduction

I.1 Introduction: The importance of a diverse soil fauna

Healthy soils constantly provide ecosystem services crucial for human existence (Pérès et al., 2011). It has been hypothesized that soil degradation could cause the collapse of entire human societies (Montgomery, 2007). Soils play an important role in the Earth' system by ensuring processes such as primary production. Soils provide plants with water, nutrients and the substrate for taking root. A vast number of interconnected processes that maintain the provisioning of ecosystem services take place in the soil (Pulleman et al., 2012; Wall et al., 2012). Besides physico-chemical processes, biologically mediated processes are of utmost importance for soil-based ecosystem services. These processes range from biological weathering via biological nitrogen fixation to pest and disease control (Jeffery et al., 2010). The estimated global biological nitrogen fixation in agroecosystems is about 40-48 million tonnes per year with symbiotic microorganisms capable of fixing up to 300 kg N $ha^{-1}a^{-1}$ (Jeffery et al., 2010). Furthermore, soil biota play a major role in the recycling of nutrients from organic residues and thus in the nutrient provision for plants (Pulleman et al., 2012).

Diverse communities of soil fauna play a crucial role in ensuring a sufficient and permanent provision of ecosystem functions. According to the Convention on Biological Diversity (CBD) biodiversity (including soil biodiversity) comprises the inter- and intraspecific diversity as well as the diversity of ecosystems (UNCED, 1992). Greater biodiversity in soils has three main advantages in terms of soil functioning (Jeffery et al., 2010):

- Repertoire: Biologically mediated ecosystem functions can only be carried out when organisms capable of delivering them are present. More diverse systems will consequently carry the ability to perform more functions.
- Interactions: Most ecosystem functions are the result of complex interactions between different soil organisms. In a more diverse system, more interactions are potentially possible and the loss of some interactions can be offset.
- Redundancy: From an ecological perspective redundancy is not a negative term. In a system with a high level of redundancy, different organisms are able to carry out the same function, which makes the entire system more resilient.

Different farming approaches use soils in different ways. On the one hand, conventional farming relies heavily on external inputs of fertilisers and agrochemicals, which leads to a replacement of ecosystem services (Giller et al., 1997). On the other hand, organic farming tries to use natural resources sustainably and foster ecological processes in the soil (Stockdale and Watson, 2009). One of the main features of organic farming is the consideration of the closed substance cycle principle, which is formulated most prominently in the IFOAM principles of organic agriculture (Luttikholt, 2007). The main component of closed cycles in organic agricultural systems is the soil. Eve Balfour and Albert Howard claimed healthy soils to be the foundation of agriculture already in the 1940s (Balfour, 1943; Howard, 1943). To make the best use of ecosystem services provided by the soil, organic farms aim to enhance and maintain diverse and stable soil organism communities. However, while an overall positive effect of organic farming on biodiversity can be shown, it is less clear in the context of soil biodiversity (Rahmann, 2011; Tuck et al., 2014).

I.2 The current state of knowledge

I.2.1 The functional role of earthworms

Earthworms are the most important representatives of soil macrofauna in temperate regions (Wurst et al., 2012). They are abundant (Pérès et al., 2011) and reach an average biomass between 30 and 100 g m^{-2} with the maximum values ranging from 200 to 400 g m^{-2} (Orgiazzi et al., 2016a). Earthworms incorporate organic matter into the mineral soil matrix and support the activity of other soil organisms by ingesting, mixing, egesting, and loosening different soil components. Through their burrowing activity, earthworms create stable aggregates and contribute to the maintenance of a stable soil structure (Bertrand et al., 2015). Furthermore, earthworm burrows and casts are considered to be hot-spots of microbial activity (Athmann et al., 2017). It is estimated that 10-74 kg N $ha^{-1}a^{-1}$ can be relocated in agroecosystems by earthworm communities (Jeffery et al., 2010), which may be the reason for the positive effect of earthworms on above-ground primary production (Blouin et al., 2013). The importance of earthworms, which are considered to be keystone species (Blouin et al., 2013; Pulleman et al., 2012), is nowadays widely recognized. Therefore, in some parts of the US Midwest, a reintroduction of *Lumbricus terrestris* (Linnaeus, 1758), which has been strongly reduced by intensive tillage, is currently being discussed (Cavigelli et al., 2012).

I.2.2 The functional role of collembolans

Like earthworms, the soil mesofauna (mainly acari and collembolans) is feeding on organic matter and, therefore, directly enhances decomposition. However, its indirect influence on decomposition and nutrient cycles is of much higher importance. Collembolans and acari feed on different components of the soil microfauna and microflora and thus stimulate the growth and activity of these groups, which are highly important for organic matter degradation and nutrient release (Gange, 2000; Jeffery et al., 2010). Depending on their abundance, which varies widely between 500 and 250,000 individuals m^{-2} in croplands across Europe (Cluzeau et al., 2012), collembolans can thus considerably influence nutrient cycling and release. Chahartaghi et al. (2005) showed that collembolans can be assigned to three different feeding guilds ranging from phycophages/herbivores to primary and secondary decomposers.

I.2.3 Indicators for soil biodiversity

In order to foster soil organism communities, one needs to establish ways of describing their status and development. The assessment of these communities is not simple as they show complex spatial and temporal patterns depending on land use, cultivated crop type, or annualized effects (Bardgett and van der Putten, 2014). Indicators are used to describe the status of abiotic and biotic systems. As the technical term “indicator” is not universally defined, a definition has to be established before developing and applying indicator systems (Heink and Kowarik, 2010).

According to Heink and Kowarik (2010) indictors derived from soil biodiversity can be defined and used in different ways. On the one hand, the number of species or the abundance of a certain species can be used as an indicator to describe the status of an organism group or a single species, respectively (*indicators as measures*). On the other hand, the occurrence of a species can be used as an indicator for the contamination of soil, for instance (*indicators as sensors*). Overall, Heink and Kowarik (2010) give the following broad definition of indicators: “*An indicator in ecology and environmental planning is a component or a measure of environmentally relevant phenomena used to depict or evaluate environmental conditions or changes or to set environmental goals. Environmentally relevant phenomena are pressures, states, and responses as defined by the OECD (2003).*” Pulleman et al. (2012) specify that they “*define biological indicators as (characteristics of) organisms whose response, in terms of presence/absence, abundance, activity, morphology, physiology or behaviour, gives information on the conditions of a habitat or ecosystem.*”

Invertebrates are potentially valuable bioindicators as (i) they are sensitive to local conditions because of their small size, (ii) mobile species may move in response to changing conditions, (iii) their short generation time results in numerical response, (iv) they are altogether variable in terms of ecological characteristics, (v) they account for a substantial amount of species diversity, and (vi) they are a functionally important component of the overall biodiversity (Gerlach et al., 2013).

Bispo et al. (2009) aimed to identify indicators suitable for soil biodiversity monitoring all over Europe and developed a tiered system of indicators with three priority levels. Priority Level I comprised (i) abundance, biomass, and species richness of earthworms, (ii) abundance and species richness of collembolans, and (iii) microbial respiration (ENVASSO-Project: Bispo et al., 2009; Pulleman et al., 2012). Earthworms were chosen as Level I indicators due to their great importance as ecosystem engineers, collembolans due to the facilitation of microbial succession, and microbial respiration as an expression of the decomposition processes in soil, which mainly depend on soil microorganisms (Bispo et al., 2009).

Using the logical sieve approach according to Ritz et al. (2009), a list of indicators first published by Faber et al. (2013) were evaluated. This process revealed the composition of bacteria, archaea, and fungi, determined by molecular methods, as top indicators for soil quality on the European scale

(EcoFINDERS-Project: Stone et al., 2016). When evaluating the indicators, ranked by Stone et al. (2016) according to cost efficiency and policy relevance, Griffiths et al. (2016) ended up with a minimum set of indicators, comprising earthworms, functional genes, and bait lamina, to monitor water regulation, carbon sequestration, and nutrient provision.

Due to their ecological importance and because they are visually easily detectable, earthworms are frequently used as indicators to describe the soil fauna (Turbé et al., 2010). Furthermore, it is relatively easy to determine earthworm species, at least in temperate regions (Paoletti, 1999). In Germany, for instance, only approximately 40 species are present (Lehmitz et al., 2014), and the number of local species is often as low as ten or fewer (Orgiazzi et al., 2016a). Data on the entire earthworm community as well as the presence or biomass of sensitive species can both be used as indicators for environmental conditions (Heink and Kowarik, 2010). Sensitive species in terms of soil tillage are anecic species like *L. terrestris* and *Aporrectodea longa* (Ude, 1885).

Collembolans, one of the most abundant groups of the soil mesofauna, are influenced by various biotic and abiotic soil conditions. Since they are linked to their ecological niche in the soil in multiple ways, are rather sedentary, and their community compositions at given sites are rather stable, collembolans have a high aptitude as bioindicators (van Straalen, 1998). Nevertheless, describing collembolan communities is more complex than describing earthworm communities. Collembolans have to be extracted from soil samples in the laboratory by using technical facilities like the MacFadyen extractor (MacFadyen, 1961). Prior to identification, individuals have to be mounted on microscope slides. An identification is only possible by using a microscope, requires expert knowledge, and is time-consuming.

Depending on the level of knowledge on their characteristics different indicators seem to be appropriate to describe earthworms and collembolan communities. When investigating earthworms, a high overall abundance and biomass is a reliable indicator for intensive burrowing and incorporation of organic matter into the soil. High biomass seems to be the best indicator as it is mainly caused by a high abundance of large anecic individuals (*L. terrestris*, *A. longa*) that establish permanent vertical burrows and incorporate residues from the soil surface into the soil matrix.

In the case of collembolans in particular the presence or abundance of specialised species as well as the overall species composition are potential indicators for environmental conditions.

I.2.4 Organic farming methods with a potential impact on soil fauna

To evaluate the applicability of bio-indicators, they have to be applied when comparing different farming treatments (Griffiths et al., 2016). As the amount and quality of organic matter (which depend on the applied crop rotation) and the tillage intensity mainly have an impact on soil organisms (Stockdale and Watson, 2009), the differences in these two factors were used as examples for different farming treatments in the identification of indicators for soil biodiversity in this thesis.

I.2.4.1 Crop rotations

Cropping systems as components of mixed farms and stockless arable systems are typical for organic farming. These systems differ in terms of the share of forage legumes in the crop rotation, and in the missing availability and use of farmyard manure in stockless arable farming.

The two crop rotations that were compared in this thesis to investigate indicators for soil fauna mainly differed in the amount and quality of organic matter used and thus in their fertilisation regime. In the stockless system, plant residues remaining on the field after the harvest and forage legume cultivation in one out of six years had to maintain soil fertility. In the mixed system, farmyard manure (slurry and solid manure) was applied, and forage legumes were cultivated in two out of six years. The addition of organic matter and the integration of perennial forage legumes into crop rotations are known to overall positively influence soil fauna (Cavigelli et al., 2012). However, different groups of soil animals react differently. The overall positive effect of organic matter addition on earthworms is well known. However, different earthworm species and earthworm ecological groups react in specific ways to differences in the amount and quality of organic matter added (Bertrand et al., 2015).

The influence of organic fertilisers on collembolans is still under debate. Platen and Glemnitz (2016) found in a two-year-long field experiment that the application of digestate from biogas production has a positive effect on collembolan abundance. On the contrary, Pommeresche et al. (2017) described negative short-term effects of slurry application on collembolan abundance, with more negative effects on epigeic than endogeic species. Furthermore, Jagers op Akkerhuis et al. (2008) showed that the method of slurry application can influence the effect the fertiliser has on collembolan communities.

I.2.4.2 Reduced tillage

To overcome problems of soil erosion and to reduce production costs, conservation tillage has been applied in conventional farming since the 1950s (van Capelle et al., 2012). Conservation tillage comprises all tillage systems which leave at least 30 % of the soil surface covered by residues after seeding (Peigné et al., 2007). Tillage intensity can be reduced to different intensities. While in the United States mainly no-till systems are discussed and developed, European organic farming research focusses on reduced tillage (Mäder and Berner, 2012). In European reduced tillage systems, either the depth of mouldboard ploughing is reduced or methods that avoid soil inversion are applied. Organic farming could benefit from the possible positive effects of conservation tillage, such as reduced erosion, greater macroporosity, increased microbial activity, enhanced carbon storage, less run-off and leaching, reduced fuel use, and faster tillage (Peigné et al., 2007). The positive effects of conservation tillage on aggregate stability are potentially increased in organic farming compared to conventional farming because of improved starting conditions in terms of biological activity, fostered by the constant application of organic matter (Peigné et al., 2007).

However, there are special obstacles in organic farming that still hinder a wider application of conservation/reduced tillage methods. The most prominent problems in organic farming with reduced tillage intensity are decreased nitrogen availability and increased weed pressure (Peigné et al., 2007). It is not obvious which of these two factors causes the yield decrease frequently found under reduced tillage on organic farms (Mäder and Berner, 2012). As organic farming still largely relies on ploughing, e.g. for weed management, Stockdale and Watson (2009) hypothesise that integrating methods of reduced tillage might be one of the last remaining key questions for organic arable farming systems.

Cooper et al. (2016) showed in a meta-analysis that shallow inversion tillage in organic arable systems only causes slight yield reductions (- 5.5 %) while maintaining adequate weed control and causing significantly increasing soil carbon stocks in comparison to deep inversion tillage. Although a reduced tillage intensity leads to an average yield reduction of about 7-8 % (Cooper et al., 2016), fuel and labour costs can be reduced at the same time (Soane et al., 2012), resulting in an approach that could be of economic interest. Due to the explicit aim of making optimal use of natural resources, a high standard of management is always required in organic farming. This is even more relevant when combining organic farming and reduced tillage (Peigné et al., 2007).

Massucati (2013) and Dang et al. (2015) have discussed ways of using systems of occasional reduced tillage to overcome the known obstacles and at the same time make use of the advantages of reduced tillage.

The potential beneficial effect of occasional (reduced) tillage for soil health has been discussed by Athmann et al. (2017), who showed that *L. terrestris* can positively alter soil nutrient availability and microbial activity within six months.

I.3 Aims of the thesis

In this thesis, the characteristics of earthworm and collembolan communities are evaluated with regards to their usability as indicators for soil biodiversity. Indicators that can be easily applied also by non-experts are identified.

Fründ (2010) suggested using surface markings of earthworms – burrow openings, middens, and surface casts – as simple indicators for a first assessment of the status of earthworm communities. This thesis investigates the assessment of earthworm abundance and biomass by using earthworm surface markings. If this method can be applied successfully, the assessment of earthworm communities will become more efficient in terms of time consumption and technical resources.

Since the biomass of collembolans is hard to determine and their abundance is highly variable in time and space, most of the information about this group can presumably be derived from their species composition, which is determined by species richness and the abundance of single species. Research on the diversity-function relationship in soil biota communities has revealed that the community composition is of greater value than species diversity *per se* because of functional redundancy among soil organisms (Bardgett and van der Putten, 2014). Besides using species richness as an indicator to describe collembolan communities, this thesis (I) further investigates methods to make optimal use of the collected information and (ii) tries to find methods to describe collembolan communities based on species traits.

According to Turnhout et al. (2007) descriptive ecological indicators are used in this thesis in a nested structure. In the first step abundance biomass, species richness, and surface markings are used to describe the state of earthworm communities. The state of collembolan communities is described in terms of abundance, species richness, and community structure. Subsequently, the state of earthworm and collembolan communities are used to evaluate the influence of different soil management measures on soil biodiversity and soil health. This approach follows the procedure proposed by Doran and Zeiss (2000) in order to describe soil health by assessing soil biota and then using soil health as a measure of the sustainability of agricultural systems. Finally, general conclusions regarding the usability of parameters describing earthworm and collembolan communities as indicators for soil biodiversity are derived.

Furthermore, this thesis aims to contribute to the ongoing discussion on reduced tillage in organic farming. Therefore, a system in which the plough is only set aside occasionally when cultivating suitable crops in adequate position within the crop rotation is proposed. In this context, crops that are known to perform well under the given site conditions in terms of yield stability and weed suppression are described as suitable. We chose the year before growing clover-grass leys as an adequate position in the crop rotation, as the cultivation of this forage legume provides good opportunities for weed control. This approach is henceforth called occasional reduced tillage (ORT, cf. II.1.1). Thus, the second important aspect of this thesis, besides further development of indicators, is to describe short-term effects of reduced tillage on soil macro- and mesofauna under conditions of organic farming and to study the applicability of indicators for soil biodiversity under different tillage procedures in organic arable systems.

To sum up, the overall aim of this thesis is to promote the development of “easy-to-use” biological indicators and make optimal use of information gathered on soil fauna communities to assess soil biodiversity. To reach this aim, the influence of different crop rotations and reduced tillage intensity on soil meso- and macrofauna in organic farming was studied as an example. For this purpose, the following sub goals were defined:

- SG I: Quantification of the influence of occasional reduced tillage (ORT) on earthworm and collembolan communities. (II.1.1 / II.2.1 / II.2.2)
- SG II: Assessment of the impact of reduced tillage on earthworms in organic farming. (II.1.2)
- SG III: Quantification of the influence of ten years of different organic arable cropping systems on collembolan communities. (II.2.1)
- SG IV: Assessment of the suitability of earthworm casts on the soil surface as an indicator for the state of earthworm communities. (II.1.1)
- SG V: Assessment of the suitability of the composition of collembolan life-forms as indicator for differences in collembolan communities caused by different management systems. (II.2.1 / II.2.2)

I.4 Study site

The field studies presented in this thesis were conducted at the experimental station of the Thuenen-Institute of Organic Farming in Trenthorst/Wulmenau, Schleswig Holstein, northern Germany (53°46’N, 10°31’E). The station has been managed under the EU Organic Standards 2092/91 and 834/2007 since its conversion from conventional farming in 2001. The field studies (Sections II.1.1, II.2.1, II.2.2) were undertaken between 2012 and 2014. Soil types on the site are Stagnic Luvisols from boulder clay with silty-loamy texture and bulk densities of the topsoil between 1.3-1.5 Mg m^{-3}. The C:N-ratio of about 10 lies in a range known to be typical for high-yielding agricultural land (Blume et al., 2010). The Atlantic 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 station, four farming systems have been established: dairy cow, ruminant II, pig, and stockless (Figure 1). Each system consists of fixed fields and one fixed crop rotation. As the first three of the crop rotations are part of mixed farming systems and have been designed to serve the needs of particular farm animals, the respective farming systems and the crop rotations are named according to those animals. The fourth crop rotation/farming system is a cash crop system without animal husbandry and is therefore called stockless. The farming area is nearly flat, and soil conditions are rather similar among the systems. Crop rotations comprise similar elements (Table 1, Table 8). Therefore, fields from the three rotations with the input of farmyard manure can be seen as replicates when cultivated with identical crops. According to German fertilisation recommendations, soils have been sufficiently supplied with P, K, and Mg. The soil pH of 6.3-6.5 is typical for arable land in temperate regions.

I.5 Structure of the thesis

Following the introduction, Part II of the thesis presents three journal articles (Sections II.1.1, II.1.2, II.2.1) and one conference paper (Section II.2.2), which investigate the different topics of the thesis outlined in Section I.3. The first paper focusses on the short- to medium-term influences of occasional reduced tillage on earthworm communities. Furthermore, the usability of earthworm surface casts as an indicator for earthworm abundance and biomass is studied and a rough evaluation of the economic impact of occasional reduced tillage is presented.

The second paper consists of a meta-analysis which examines the impact of tillage intensity reduction in organic farming on earthworms.

Following these two papers focussing on earthworms, the third journal paper and the conference paper assess the influence of different crop rotations and tillage systems on collembolan communities and try to identify indicators to describe management differences.

Part III of the thesis summarises the results of the papers presented in Part II. Afterwards, these results are combined and discussed together. Finally, overall conclusions are drawn and a brief outlook on indicators for soil biodiversity and soil health is presented.

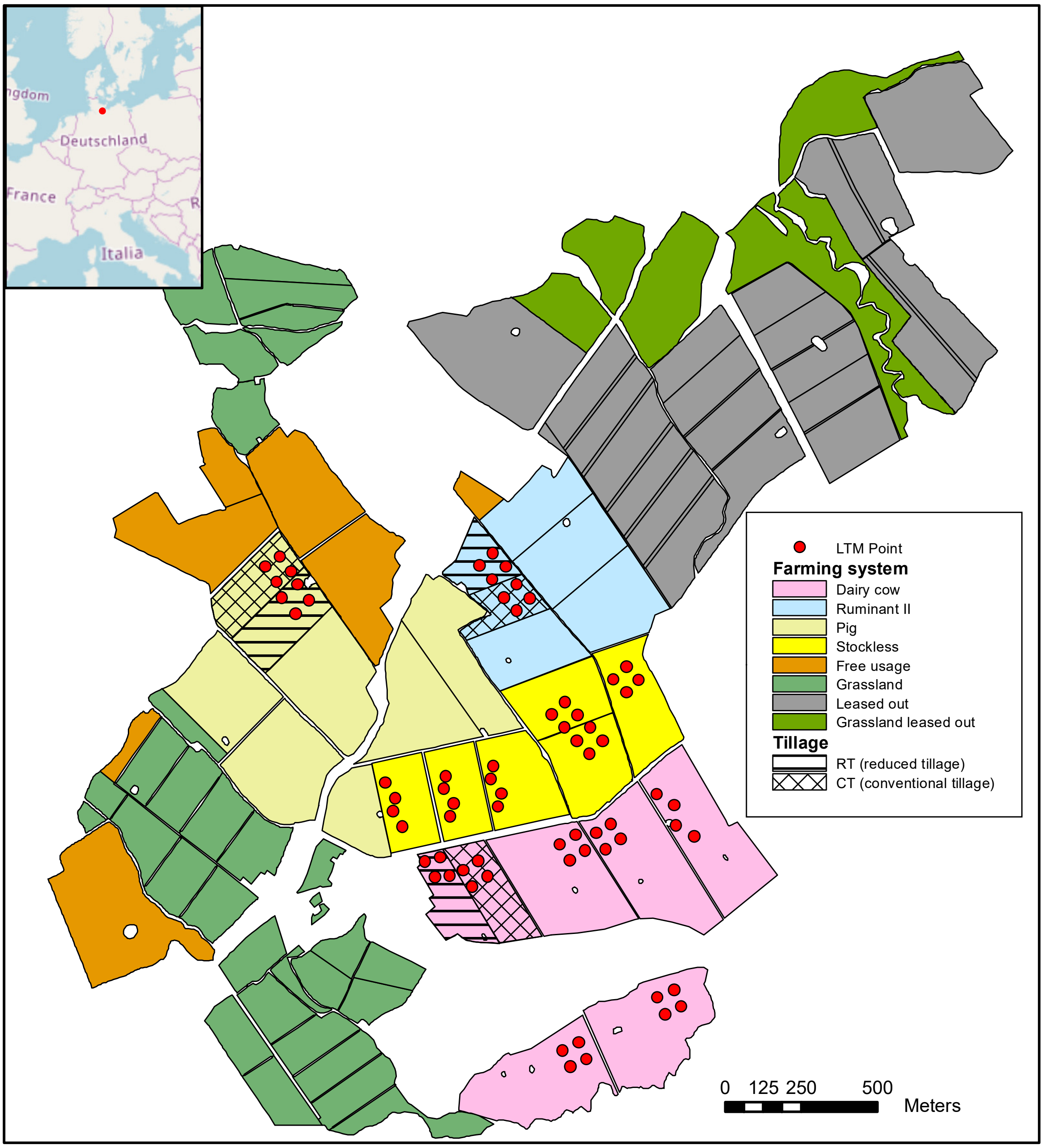

Figure 1: Map showing the experimental station in Trenthorst/Wulmenau and the different farming systems realised. Red circles indicate the location of the LTM-points used in this thesis.
Top left: Location of Trenthorst/Wulmenau. Basemap © OpenStreetMap (and) contributors, CC-BY-SA.

Part II **Paper**

II.1 Earthworms

II.1.1 Occasional reduced tillage in organic farming can promote earthworm performance and resource efficiency

Moos et al. (2016), Applied Soil Ecology 103, 22-30. DOI: 10.1016/j.apsoil.2016.01.017.

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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.

Keywords: tillage, soil biodiversity, agro economics, biodiversity indicators, earthworm casts.

II.1.1.1 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) 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.

II.1.1.2 Material & Methods

II.1.1.2.1 Study site

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

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 100g^{-1})			
P	5.7	7.4	6.0
K	9.5	17.5	13.4
Mg	9.3	12.5	12.8
Texture (%)			
Clay (< 2µm)	17	20	21
Silt (2-50 µm)	35	38	38
Sand (50-2000 µm)	46	40	40

P and K: CAL extract (Schüller, 1969), Mg: $CaCl_2$ extract (Schachtschabel, 1954). Mean ± standard deviation.

II.1.1.2.2 Soil management and experimental design

In summer 2012 three fields were halved (Figure 1), 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 disk 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 grass-clover 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.

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.

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

II.1.1.2.3 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) (Figure A 1). Here, pits of 0.5x0.5x0.1 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 (II.1.1.2.6). 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 (Figure A 1). 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 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 A 1).

II.1.1.2.4 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 (Figure 1). After the sheaves had been dried at 30 °C for 60 hours, they were threshed by a universal threshing machine to calculate yields of grain and straw.

II.1.1.2.5 Economical 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}.

II.1.1.2.6 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., 2015b) 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 slope effect. The model for yields uses management type as fixed effect and field as random slope effect.

II.1.1.3 Results

II.1.1.3.1 Earthworm performance

During the entire study including all plots 7887 earthworm individuals were collected out of which 35 % were adult or sub-adult, so that they could be determined to species level. Out of these, 80 % were endogeic, 18 % anecic, and 2 % epigeic individuals. Seven species were identified within the sub-adult and adult earthworm individuals (Table A 1). *Aporrectodea 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; Figure 2), 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; Figure 3; Figure 4). 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.

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.

	Results LR-Test			Results of pairwise comparisons of treatments				
Dependent variable	Effect	p			Mean ± SE		p	
					CT	ORT		
	Type	$4.19*10^{-7}$	***	Oct.12	26.1 ± 1.0	76.1 ± 1.0	0.012	*
Earthworm biomass per m^2	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	$8.73*10^{-11}$	***
	Type	$3.41*10^{-7}$	***	Oct.12	2.5 ± 0.1	5.5 ± 0.1	$5.49*10^{-10}$	***
Number of earthworm species per m^2	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	$4.32*10^{-5}$	***
	Type	$1.22*10^{-7}$	***	Oct.12	62.5 ± 3.8	202.0 ± 12.2	0.0012	**
Number of earthworm individuals per m^2	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	$5.42*10^{-6}$	***
	Type	0.024	*	Oct.12	11.8 ± 0.9	18.9 ± 1.4	0.74	
Number of surface casts per transect	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	
	Type	$3.10*10^{-7}$	***	Oct.12	48.7 ± 5.1	164.9 ± 17.2	0.0017	**
Number of endogeic Individuals per m^2	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	$1.66*10^{-5}$	***
	Type	$7.98*10^{-6}$	***	Oct.12	11.0 ± 2.0	26.0 ± 4.7	0.12	
Number of anecic Individuals per m^2	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		

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

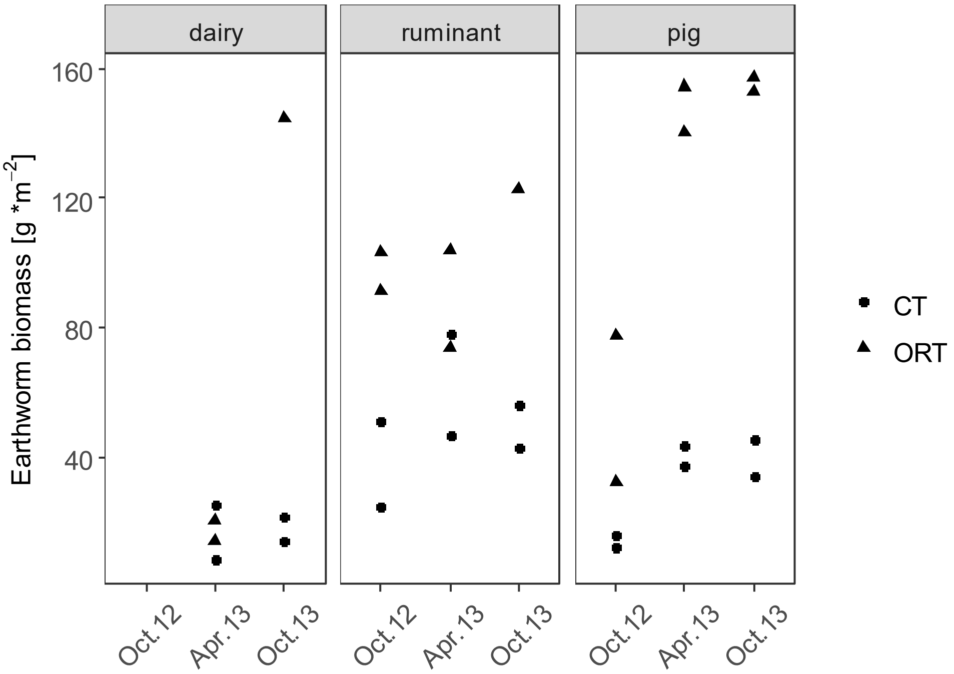

Figure 2: Earthworm biomass separated per field, month and management type. Each field belonging to one farming system serving the needs of one group of farming animals (dairy, ruminant II, pig). Samplings were carried out in October 2012, April 2013 and October 2013. ORT= occasional reduced tillage,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

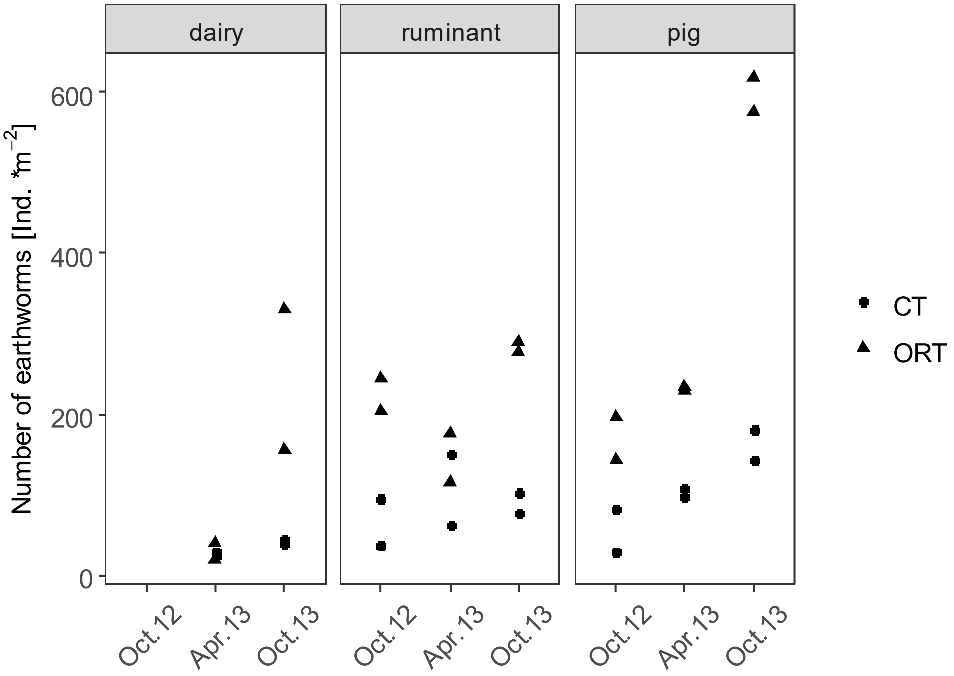

Figure 3: Number of earthworm individuals separated per field, month and management type. Each field belonging to one farming system serving the needs of one group of farming animals (dairy, ruminant II, pigs). Examinations were carried out in October 2012, April 2013 and October 2013. ORT=occasional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

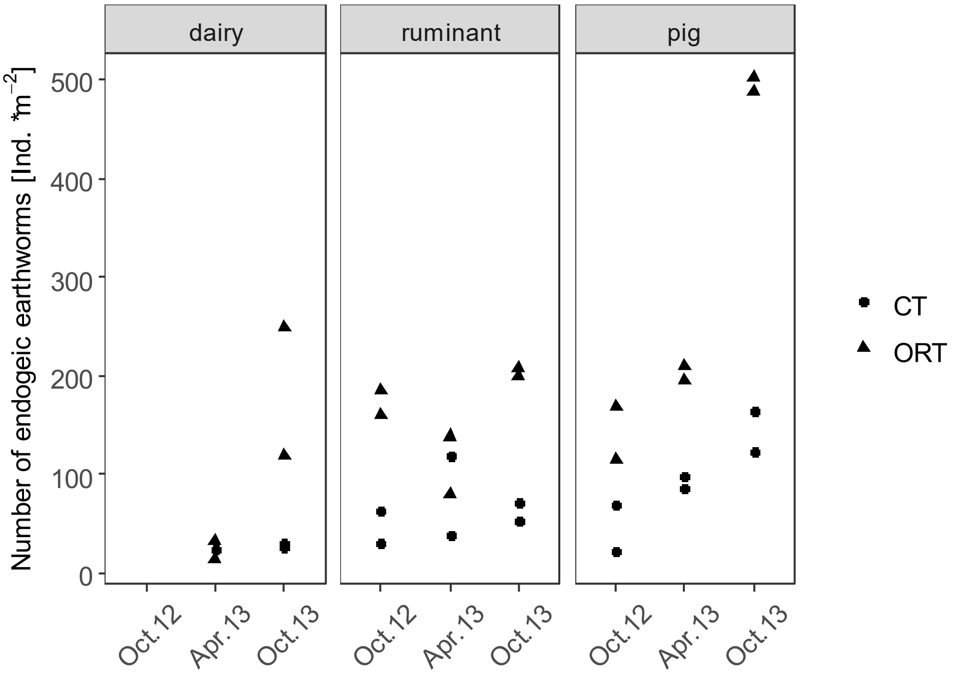

Figure 4: Number of endogeic earthworm individuals separated per field, month and management type. Each field belonging to one farming system serving the needs of one group of farming animals (dairy, ruminant II, pigs). Examinations were carried out in October 2012, April 2013 and October 2013. ORT=occasional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

The number of species was significantly different between the two tillage treatments in October 2012 (CT: 2.5 ± 0.1 Sp. m^{-2}; ORT: 5.3 ± 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 A 1).

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 A 1).

II.1.1.3.2 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).

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 12, April 2013 and October 2013. Variable Field with the factors dairy, pig and ruminant. Varaiable Transect with four transects within each field. Notation of model components is as follows: 1|Var2 -> random slope.

Model			Results LR-Test			Coefficients of determination R^2
Dependent variable	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 anecic individuals	1|Field	Number of anecic 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

$* p < 0.05$, $** p < 0.01$, $*** p < 0.001$

II.1.1.3.3 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 (Figure 5), the positive financial effects of ORT-treatment were offset, because the selling price of triticale was the most important factor in the calculation.

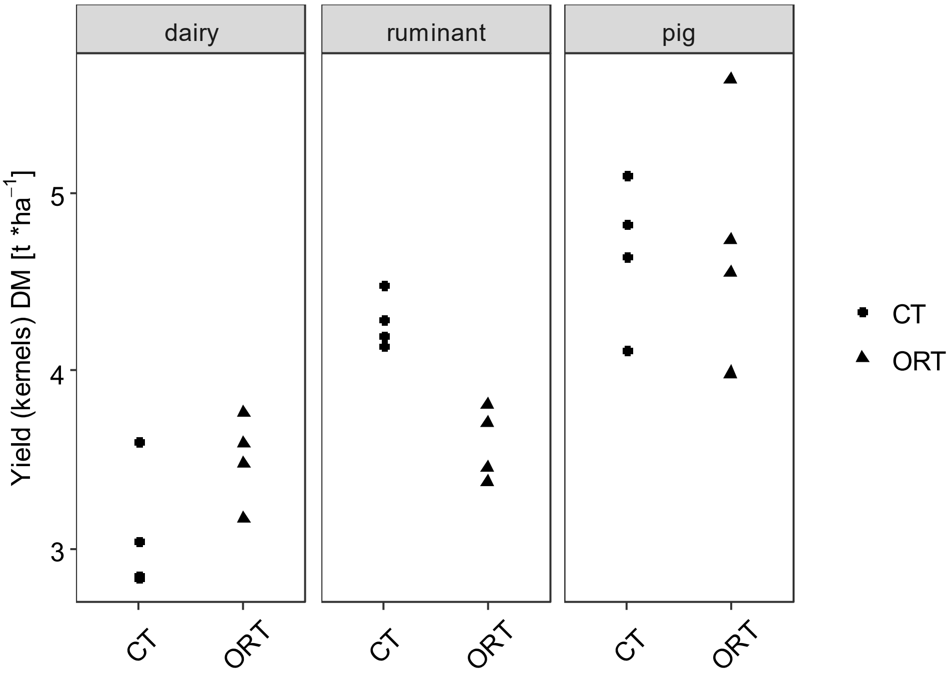

Figure 5: Kernel yield of triticale separated per field and management type. Each field belonging to one farming system serving the needs of one group of farming animals (dairy, ruminant II, pigs). Examinations were carried out in October 2012, April 2013 and October 2013. ORT=occasional reduced tillage, CT=conventional tillage. Trenthorst, Germany 2012/2013.

Table 5: Contribution margin of triticale production in the two tillage systems (CT vs ORT) in three different organic farming systems (dairy cow, ruminant, pig). DM = dry matter; ORT = occasional reduced tillage; CT = conventional tillage.

	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

II.1.1.4 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 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, 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 sensitivity 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.

II.1.1.5 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 *Lumbricus 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 economical outcomes.

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II.1.2 Reduced tillage enhances earthworm abundance and biomass in organic farming: A meta-analysis

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Abstract

Organic farming aims to support and utilise ecosystem services such as bioturbation and the mixing of organic materials into the soil. These services are provided by earthworms. Organic farmers therefore seek to provide the best possible habitats for earthworms. One possible way to support earthworm populations is to reduce tillage intensity.

The use of reduced tillage techniques has become more and more important in organic farming in recent years. While the positive effect of reduced soil tillage on earthworm population in conventional farming has been repeatedly described, there have been relatively few analyses focussed on organic farming systems. To address this gap in knowledge, we compiled and evaluated data on the influence of reduced tillage on earthworms in organic farming in temperate regions. Our analysis shows an overall significant positive effect of reduced tillage on earthworm abundance (+ 90 %) and earthworm biomass (+ 67 %). Reduced tillage includes shallow-inverting and non-inverting systems. The positive effects were only statistically significant for non-inverting systems. Reduced tillage used over several years results in a shift in earthworm communities to species characterised by higher mean individual biomass (*Lumbricus terrestris* (Linnaeus, 1758), *Aporrectodea longa* (Ude, 1885)).

Keywords: review; temporal change; no-till; shallow inversion tillage; *Lumbricidae*.

II.1.2.1 Introduction

In organic farming, organic materials are of utmost importance for the nutrient supply of crops. Organic fertilizers as well as plant residues must be mixed into the soil and their decomposition must be maintained. In temperate regions, earthworms, especially deep burrowing anecic species such as *Lumbricus terrestris* (Linnaeus, 1758) and *Aporrectodea longa* (Ude, 1885), are very important for the incorporation and decomposition of plant residues in the soil (Blume et al., 2010).

In their recent meta-analysis Briones and Schmidt (2017) showed that in general reducing tillage intensity promotes earthworm abundance and biomass confirming the results of previous reviews (Carr et al., 2013; Chan, 2001; van Capelle et al., 2012). However, some studies found results that contrast with these overall trends (Chan, 2001).

To our knowledge, there has been no attempt to systematically compile data on the influence of reduced tillage on earthworm abundance and biomass under organic farming. Examining the effect of reduced tillage on earthworm populations in organic farming is not straightforward as a wide range of management practices characteristic of organic farming such as the absence of agrochemicals, diversified crop rotations and the use of organic fertilizers may promote earthworms irrespective of the tillage methods used (Bertrand et al., 2015). The influence of the plant protection products (pesticides) used in conventional farming on earthworms is difficult to predict, as substances differ in how they are applied. Exposure pathways differ depending on earthworm species or ecological groups (Bertrand et al., 2015). Furthermore, substance dosages may be sub-lethal but impact on earthworm populations in terms of activity or reproduction (Datta et al., 2016). Overall, the absence of agrochemicals is unlikely to have negative effects on earthworms. In organic farming, farmyard manure, slurry, and plant residues are the main sources of organic amendments to the soil. While Leroy et al. (2008) could show that slurry and farmyard manure positively influenced earthworm communities under field conditions there is no reliable information on the influence of crop residues available (Bertrand et al., 2015). For wide organic crop rotations with considerable proportions of ley, Riley et al. (2008) reported positive effects on earthworm communities. Besides biotic and abiotic factors interacting with the effect of tillage on earthworm communities, the way reduced tillage is conducted (shallow soil inversion tillage *vs* non-inversion tillage *vs* no-till) and the time elapsed since the last conventional mouldboard plough-based cultivation may influence the outcome (Briones and Schmidt, 2017).

Against this background we conducted a meta-analysis of data in peer-reviewed publications. Our main question was about the effect of reduced tillage in organic farming on earthworm abundance and biomass. Our study was guided by three hypotheses:

H_1: There is an overall positive effect of reduced tillage on earthworm abundance and biomass in organic farming.

H_2: In terms of reduced tillage techniques to support earthworm populations, non-inverting tillage is more beneficial than shallow-inverting soil tillage.

H_3: The positive effect of reduced tillage practices increased with the time elapsed since the last use of the conventional mouldboard plough.

II.1.2.2 Material & Methods

We conducted a literature search via Web of Science (www.webofknowledge.com) in October 2016 using the following combination of search terms:

Earthworm* AND Tillag* AND (Eco* OR Organic*) AND (Farm* OR Agricul*)

We identified 177 relevant publications. We screened abstracts and full texts to include only those studies in our meta-analysis that met the following requirements:

1) different ecological groups of earthworms (anecic, endogeic, epigeic) considered;
2) data on earthworm abundance and/or biomass included;
3) conducted under organic farming standards;
4) reduced tillage as treatment;
5) the use of mouldboard ploughing as control;
6) conducted in the temperate zone.

These requirements were met with eight studies providing 19 datasets on earthworm abundance and seven studies providing 17 datasets on earthworm biomass. When necessary we recalculated data of single studies to obtain abundance and biomass values per m^2. Where data were presented in figures only, we contacted the authors to obtain the original data. Since only so few studies could fulfil our requirements, the results of individual comparisons can have considerable influence on the overall result of the meta-analysis. Therefore, we sought to reduce variance within the response variable with a robust statistical approach to reject outliers using a "Tukey fence" with all values outside the interquartile range being considered as outliers (Cooper et al., 2016). The range was defined as $Q_1\text{-}k*IQR$ to $Q_3+k*IQR$. With Q_1 lower quartile point, Q_3 upper quartile point, $IQR = Q_3\text{-}Q_1$ and $k = 1.5$. This process resulted in the inclusion of 19 datasets on abundance from eight studies and 15 datasets on biomass from six studies. It is obvious that some datasets are from the same study (Table 6 & Table 7). We always checked that each dataset represented a unique comparison. In addition to mean abundance and biomass we collected information on soil type, duration of the study, and sampling procedure and compiled this information in Table 6 & Table 7. We used relative change (RC) in earthworm abundance and biomass as response variables (Du et al., 2017). RC is defined as the change in abundance or biomass under reduced tillage relative to the abundance or biomass under conventional tillage and has been calculated as:

$$RC = (M_{RT}\text{-}M_{CT})/M_{CT}$$

where M_{RT} and M_{CT} are the mean abundance or biomass values under reduced (RT) and conventional (CT) tillage, respectively.

We followed the approach applied by Du et al. (2017) and checked for significant difference of means from zero by one-sample t-test or, in case of non-normality of the data, one-sample Wilcoxon signed rank test. Normality of data was checked using Shapiro-Wilk test. Like Cooper et al. (2016) we faced the problem that many studies did not give a measure of variance. Therefore, we followed the approach applied by these authors and Du et al. (2017) and conducted an unweighted meta-analysis. In terms of meta-analysis, weighting gives more influence to those datasets obtained from studies with higher numbers of replicates and/or lower variance. If unweighted analyses are conducted each dataset will influence the result in the same way. All statistical analysis were conducted using R 3.3.1 (R Development Core Team, 2016).

Table 6: Soil characteristics of the study sites and methods applied for earthworm sampling at the different study sites reported in the literature used. USDA TC: USDA texture classes according to Soil Survey Division Staff, 1993.

Study	Study site	Soil					Earthworm sampling	
		USDA TC	Sand	Silt	Clay	Type of soil	Excavation depth [cm]	(Additional) extraction
Moos et al. (2016)	Trenthorst/Wulmenau	Loamy	42	37	20	Stagnic Luvisols	0-15	Mustard-water extraction
Crittenden et al. (2014)	Lelystad	Light	66	12	23	Calcareous Marine Clay Loam	0-20	Formaldehyde extraction
Kuntz et al. (2013)	Frick	Heavy	22	33	45	Stagnic Eutric Cambisol	0-25	
De Oliveira et al. (2012)	Favrieux	NA	NA	NA	NA	Haplic Luvisol	0-30	Mustard solution
De Oliveira et al. (2012)	Villarceaux	NA	NA	NA	NA	Haplic Luvisol	0-30	Mustard solution
Peigné et al. (2009)	Rhone Alpes	Light	58	27	15	Fluvisol		Formalin extraction
Peigné et al. (2009)	Brittany	Loamy	34	46	20	Cambisol		Formalin extraction
Peigné et al. (2009)	Pays de la Loire	Loamy	25	57	14	Cambisol		Formalin extraction
Berner et al. (2008)	Frick	Heavy	22	33	45	Stagnic Eutric Cambisol	0-20	Mustard solution
Metzke et al. (2007)	Frankenhausen	Loamy	2	81	17	Luvisol		Formalin extraction
Emmerling (2001)	Eichenhof	NA	NA	NA	NA	Cambisol	0-30	Mustard solution

Table 7: Earthworm abundance and biomass values used in the meta-analysis. RT: reduced tillage. RT_NI: Reduced tillage with techniques not inverting the soil. RT_SI: Reduced tillage with techniques inverting the soil, but shallower than CT. CT: conventional tillage. RC: Relative change. Group: A (5-32 months since last ploughing); B (42 months since last ploughing); C (78-114 months since last ploughing).

Study	Study site	Tillage system RT	Working depth RT	Time since last ploughing in RT		Mean abundance RT (M_{RT})	Mean abundance CT (M_{CT})	Relative change in abundance (M_{RT}-M_{CT})/M_{CT}	Mean biomass RT (M_{RT})	Mean biomass CT (M_{CT})	Relative change in biomass (M_{RT}-M_{CT})/M_{CT}
			[cm]	Months	Group	[Individuals m^{-2}]	[Individuals m^{-2}]	%	[g m^{-2}]	[g m^{-2}]	%
Moos et al. (2016)	Trenthorst/Wulmenau	RT_NI	15	24	A	406	97	319			
Crittenden et al. (2014)	Lelystad	RT_NI	8	42	B	557	543	3	74	35	111
Crittenden et al. (2014)	Lelystad	RT_NI	8	42	B	446	543	-18	58	35	66
Kuntz et al. (2013)	Frick	RT_SI	5	114	C	262	157	67	77.1	50.2	54
De Oliveira et al. (2012)	Villarceaux	RT_NI	10	10	A	57	45	27			
De Oliveira et al. (2012)	Favrieux	RT_NI	10	5	A	314	145	117			
Peigne te al. (2009)	Rhone Alpes	RT_NI	0	42	B	5	2	150			
Peigne te al. (2009)	Rhone Alpes	RT_NI	15	42	B	6	2	200	2	1	100
Peigne te al. (2009)	Rhone Alpes	RT_SI	20	42	B	6	2	200	3	1	200
Peigne te al. (2009)	Pays de la Loire	RT_NI	0	30	A	37	13	185	37	23	61
Peigne te al. (2009)	Pays de la Loire	RT_NI	15	30	A	16	13	23	27	23	17
Peigne te al. (2009)	Pays de la Loire	RT_SI	20	30	A	31	13	138	26	23	13
Peigne te al. (2009)	Brittany	RT_NI	0	78	C	61	92	-34	40	19	111
Peigne te al. (2009)	Brittany	RT_NI	12	78	C	60	92	-35	40	19	111
Peigne te al. (2009)	Brittany	RT_SI	15	78	C	76	92	-17	28	19	47
Berner et al. (2008)	Frick	RT_NI	15	32	A	582	424	37	101	129	-22
Metzke et al. (2007)	Frankenhausen	RT_SI	10	24	A	28.5	32.8	-13	38.1	27.0	41
Emmerling (2001)	Eichenhof	RT_SI	15	42	B	28	22	27	26.6	16.6	60
Emmerling (2001)	Eichenhof	RT_NI	30	42	B	98	22	345	23.5	16.6	42

II.1.2.3 Results and discussion

Earthworm abundance was significantly higher (around 90 %) under reduced tillage when compared with mouldboard ploughing (Figure 6). From examination of specific reduced tillage systems, a doubling in the number of individuals (+ 99 %) was apparent where non-inverting soil tillage was conducted. Concerning earthworm biomass results wre similar. There was an overall significant positive effect of reduced tillage (+ 67 %; Figure 6). However, while non-inversion tillage significantly enhanced biomass compared with mouldboard ploughing (+ 65 %), shallow-inversion tillage and mouldboard ploughing did not differ significantly. These results support our first hypothesis (H_1) that in organic farming, reduced tillage can promote earthworm abundance and biomass. Furthermore, with regard to hypothesis two (H_2), a positive effect of non-inversion tillage is evident, while the positive effect was not significant in case of shallow-inversion tillage. The results support the view that reducing tillage depth alone does not significantly promote earthworms (Metzke et al., 2007). All tillage systems that invert the soil impact negatively on anecic earthworms as their vertical burrows are destroyed and the animals can be injured or killed (Jeffery et al., 2010).

All studies considered mouldboard ploughing as control treatment, but there were differences in the mouldboard ploughing depth. Therefore, we examined the dataset in an additional analysis to use only those studies applying mouldboard ploughing to more than 25 cm depth as control. Results from this analysis did not differ from that shown in Figure 6 and we therefore do not further describe or discuss them further.

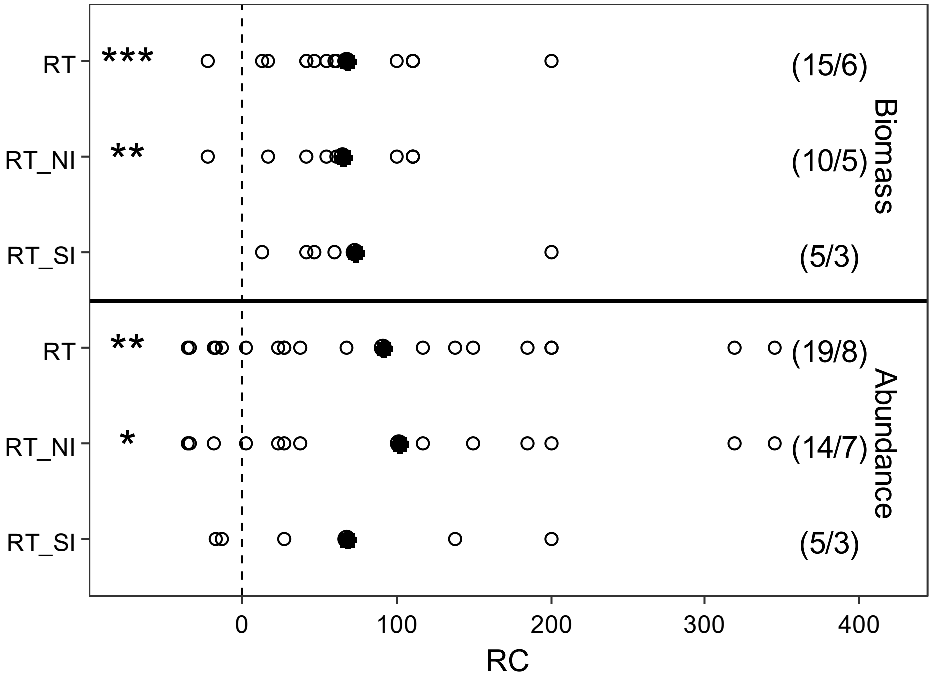

Figure 6: Influence of different types of reduced tillage on earthworm abundance (Individuals m^{-2}) and biomass (g m^{-2}) in organic farming. The relative change (RC, %) under measures of reduced tillage when compared with measures of conventional tillage is presented. Filled circles indicate mean values. The number of comparisons / number of studies are given in brackets. RT: reduced tillage. RT_SI: reduced tillage, shallow inversion tillage. RT_NI: reduced tillage, non-inversion tillage. RC = $(M_{RT}-M_{CT})/M_{CT}$; with M_{RT}: mean under reduced tillage; M_{CT}: mean under conventional tillage. Asterisks indicate significant difference of means/medians from zero (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$). P-values according to t-test or Wilcoxon-signed-rank tests (when data were not normally distributed).

Results of studies of changes in earthworm biomass due to reduced tillage as affected by the time elapsed since the last mouldboard ploughing are shown in Figure 7. While in the short term (5-32 months since last ploughing) the positive effect of reduced tillage was not significant, studies conducted 42 months or later after last ploughing showed a significant positive effect of reduced tillage on earthworm biomass. Earthworm abundance was influenced significantly positive in early (5-32 months) and medium (42 months) time period whereas later (78-114 months) no influence of reduced tillage could be revealed (Figure 7). Thus, our third hypothesis (H_3) could be confirmed for earthworm biomass only. We assume a cumulative effect over time for earthworm biomass as large and heavy anecic species are slowly reproducing and developing (Jeffery et al., 2010). Therefore, overall earthworm biomass increases over time when these species find favourable habitat conditions. Differences in earthworm abundance between conventional and reduced tillage decreased and seem to disappear with time since last ploughing. This could be due to the positive effect of tillage/ploughing on some endogeic species like *Aporrectodea caliginosa* (Savigny, 1826) (Ernst and Emmerling, 2009). Boström (1995) and Crittenden et al. (2014) found interactions between tillage systems and organic matter management. Increased organic matter availability in the topsoil due to ploughing positively affected endogeic species and here in particular *A. caliginosa*. Besides the increased availability of organic matter in the topsoil reduced competition of anecic earthworms due to mouldboard ploughing can be favourable for endogeic species (Eriksen-Hamel and Whalen, 2007). We assume a shift in earthworm assemblage under long-term reduced tillage from endogeic to anecic species dominating the communities. This is expressed by increasing biomass along with stable abundance values.

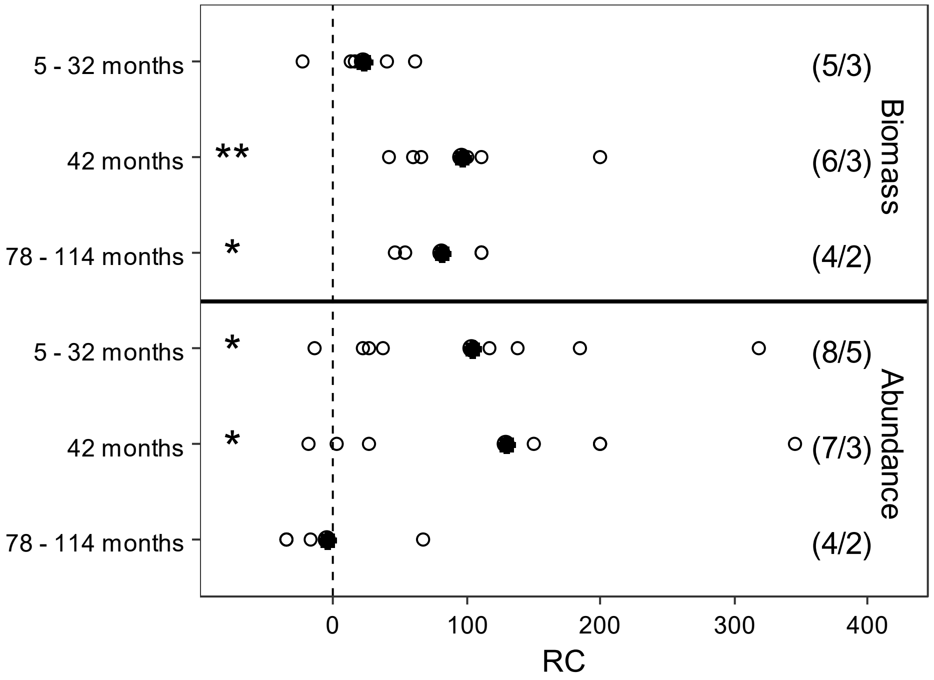

Figure 7: Influence of reduced tillage on earthworm abundance (Individuals m^{-2}) and biomass (g m^{-2}) in organic farming in relation to the last use of a mouldboard plough. Given is the relative change (RC, %) under measures of reduced tillage when compared with measures of conventional tillage. Filled circles indicate mean values. The number of comparisons / number of studies are given in brackets. RC = $(M_{RT}-M_{CT})/M_{CT}$; with M_{RT}: mean under reduced tillage; M_{CT}: mean under conventional tillage. Asterisks indicate significant difference of means/medians from zero (* $p < 0.05$, ** $p < 0.01$). P-values according to t-test or Wilcoxon-signed-rank tests (when data were not normally distributed).

II.1.2.4 Conclusions

Overall, there are few peer-reviewed publications on the influence of reduced tillage on abundance and biomass of earthworms in organic farming. Nevertheless, the available data show a positive effect of reduced tillage compared with mouldboard ploughing in the short-term. This result point to an opportunity to conduct a wide-ranging survey of earthworm communities under the preconditions described and to accompany this survey with an evaluation of ecosystem services provided by earthworms in these fields.

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II.2 Collembolans

II.2.1 Response of collembolan communities to different management practices in organic farming

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Abstract

Agricultural management systems have long lasting impacts on physical, chemical, and biological soil properties. Organic farming aims at reducing these impacts by implementing wide crop rotations and more recently by increased usage of reduced tillage. One feasible path to assess the impact of different crop rotations or tillage systems on soil is the investigation of soil fauna groups, which hold key position within the soil food web. A promising group are collembolans, which are secondary decomposers, feeding on fungi and microorganisms, and are thus closely linked to the soil environment. In this study we investigated the influence of different organic crop rotations (mixed arable *vs* stockless arable) and tillage systems (conventional tillage *vs* reduced tillage) on abundance and species richness of collembolan communities. Furthermore, species composition and composition of life forms were examined. At an organic-experimental farm in northern Germany, we sampled collembolans (i) in two crop rotations each managed consistently for 10 years and (ii) in an experiment comparing conventional with reduced tillage.

Species composition of collembolan communities turned out to respond to the impact of different crops or interannual effects rather than to management practices. Soil acidity and soil moisture were the most important factors. Furthermore, by trend, the proportion of euedaphic collembolan individuals increased in soil environments offering more stable habitat conditions in terms of resource availability and the absence of soil disturbance. These were those habitats with enhanced availability of organic matter or with reduced intensity of soil disturbance.

Keywords: soil biodiversity, life-forms, EMI, reduced tillage, dairy, stockless.

II.2.1.1 Introduction

Through a wide range of activities, humankind has remarkably influenced the soil environment and caused changes in soil fauna compositions. Agriculture is one of humans activities impacting on soil biodiversity most directly and severely (Orgiazzi et al., 2016b). Negative effects are especially expected in intensively managed systems with narrow crop rotations (Eisenhauer, 2016; Venter et al., 2016). To foster sustainability and soil biodiversity, organic farming uses wider crop rotations, which include different leguminous crops and rely on organic fertilization. In organic mixed farming systems nutrition of crops relies on recycling of livestock manure and the inclusion of forage and grain legumes. Besides, stockless arable cropping systems are common. Their fertilization is solely based on N-fixation of legumes and input of crop residues and green manure (Colomb et al., 2013; Smith et al., 2015). Like all soil organisms, collembolans rely on the availability of organic matter in the soil. As they are secondary decomposers, feeding on fungi and microorganisms, this dependence is mainly indirect. However, the exact influence of organic fertilizers on collembolan communities is still under debate. Platen and Glemnitz (2016) found a positive effect on collembolan abundance when applying digestate from biogas production in a two-year field experiment. Kautz et al. (2006) showed a positive effect of yearly application of straw and green manure. Also Kanal (2004) found a positive fertilization effect when applying cattle manure, but highlighted additional cyclic effects on abundance. On the contrary, Pommeresche et al. (2017) described negative short-term effects of slurry application on collembolan abundance, with more negative effects for epigeic than endogeic species. None of the studies found any consistent effect on collembolan community composition. Furthermore, Jagers op Akkerhuis et al. (2008) showed that the method of slurry application can alter the effect the fertilizer has. So the influence of organic fertilization on characteristics of collembolan communities is mediated at least by the type of organic matter, and timing and technique of application.

Several studies indicate positive effects of the presence of legumes on collembolan density and diversity in grassland due to increased microbial biomass, and higher litter quality (Sabais et al., 2011; Salamon et al., 2004). But no studies have been conducted so far showing these effects of legumes within arable crop rotations.

Recently, there have been different approaches to integrate reduced tillage into organic farming systems (e.g. Berner et al., 2008; Mäder and Berner, 2012; Moos et al., 2016). It is well known that reducing tillage intensity has a wide range of positive effects, but is hindered in organic farming through specific challenges like increasing weed pressure, restricted N-availability, or restricted crop choice (Peigné et al., 2007). Brennan et al. (2006) found that reduced tillage promotes collembolan abundance. Miyazawa et al. (2002) ascribed the negative effect of conventional tillage on collembolan abundance to modified soil temperature, humidity and pore size distribution. Contrary, van Capelle et al. (2012) found a significant overall reduction in abundance and species diversity (H’) with decreasing tillage intensity. The authors highlighted that this result was depending on interacting effects of soil texture and collembolan life-form. Negative effects of reduced tillage were shown for atmobiont and euedaphic species in loamy soils (van Capelle et al., 2012). Euedaphic species are well adapted to live within the soil but at the same time rely on the maintenance of stable habitat conditions (Jeffery et al., 2010). This refers especially to pore space within the soil, as collembolans are not burrowing. Because of reduced tillage, pore space can be reduced in loamy soils. Compared to euedaphic collembolans, hemiedaphic and atmobiont species are not so dependent on the soil structure, as they inhabit the upper soil layer, the litter layer, or the soil surface. Therefore other factors are influencing these life-form groups (see above, c.f. Pommeresche et al., 2017). Thus, specific shares of euedaphic, hemiedaphic and atmobiont species should indicate an impact of soil management intensity.

The investigation of widely distributed soil fauna groups, which hold key positions within soil food webs, can be an approach to shed light on the influence of management measures on soil systems. Collembolans are likely to be good indicators for soil conditions because they are widely distributed and at the same time not very mobile in the soil. This low mobility causes a lifetime exposition to potential stressors and responses of collembolan communities to changing abiotic and biotic factors might increase. Furthermore, due to short life cycles of the species composition and size of collembolan communities might respond rapidly to environmental changes. This response might be further enhanced through their function as secondary decomposers which links them closer to the environment than predatory or herbivorous animals (Greenslade, 2007).

Against this background, we examined how collembolan communities respond to management differences in organic arable farming under given environmental conditions. We analysed possible effects of tillage and crop rotation on species richness, abundance, as well as life-form and species composition of collembolan communities. It was hypothesised that differences in soil management (i) caused differences in the species composition of collembolans and (ii) influenced the share of the different collembolan life-forms.

II.2.1.2 Material and Methods

II.2.1.2.1 Study site

The study presented here was conducted at the experimental station of the Thuenen-Institute of Organic Farming in Trenthorst/Wulmenau, Schleswig Holstein, northern Germany (53°46’N, 10°31’E). The station was managed under the EU Organic Standards 2092/91 and 834/2007 since conversion from conventional farming in 2001. Soil types on the site are Stagnic Luvisols from boulder clay with silty-loamy texture and bulk densities of the topsoil between 1.3 – 1.5 Mg m^{-3}. 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). The atlantic climate, with a mean annual precipitation of 700 mm, well distributed throughout the year, and a mean annual temperature of 8.8 °C, offers favourable cropping conditions.

Within the experimental station, four farming systems have been established: dairy cow, ruminant II, pig, and stockless (Figure 1). Each system consists of fixed fields and one fixed crop rotation. The first three of the crop rotations are part of mixed farming systems and have been designed to serve the needs of particular farm animals. The respective farming systems and the crop rotations are named according to the related animals. In the fields of these rotations livestock manure with the same quality was applied (slurry and solid manure) as separated storage and application of farmyard manures was not carried out. The 'stockless' system differs from the 'mixed' systems in fertilization and organic matter application and backflow (c.f. II.2.1.2.2). Each field on the experimental station can be identified by a unique field-code. The farming area is nearly flat and soil conditions are rather similar. Furthermore, crop rotations comprise similar elements (Table 8). Therefore, fields from the three rotations of the 'mixed' systems can be seen as replicates when cultivated with identical crops. According to German fertilization recommendations, soils were sufficiently supplied with P, K, and Mg. The apparent soil pH of 6.3 – 6.5 was typical for arable land in temperate regions.

Each field on the station includes one or two long-term monitoring plots (LTM-plot) of one hectare. Generally, within each LTM-plot four geo-referenced long-term sampling points (LTM-point) are located in a square at a distance of 60 m. Monitoring plots are stretched to cover one hectare (rectangular) in narrow fields and the LTM-points are then located in a zigzag with distances of 30 m (c.f. Figure 1). 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).

The German Weather Service (DWD – Deutscher Wetterdienst) provided information about soil moisture for the years 2012 and 2014. Figure 8 shows values of %-available water under winter wheat in a depth of 0-30 cm as calculated for soil and weather conditions on the experimental station using the AMBAV model (Löpmeier, 1994).

Table 8: Crop rotation (dairy, ruminant II, pig, stockless) and average soil conditions in 2012 on the fields of the experimental farm in Trenthorst/Wulmenau. The crop rotations comprise five (ruminant II), six (dairy, stockless) or seven (pig) fields.

Farming system	Dairy	Ruminant II	Pig	Stockless
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	red clover winter wheat spring barley field pea winter rape triticale
pH	6.4 ± 0.1	6.4 ± 0.0	6.3 ± 0.1	6.5 ± 0.1
Nutrient content (mg $100g^{-1}$)				
P	7.0 ± 0.3	8.6 ± 0.4	6.1 ± 0.4	7.7 ± 0.3
K	11.9 ± 0.5	16.1 ± 0.8	13.0 ± 1.2	11.0 ± 0.4
Mg	10.3 ± 0.3	11.6 ± 0.2	11.8 ± 0.3	11.3 ± 0.3
Texture (g kg^{-1})				
Clay (< 2µm)	23 ± 1	18 ± 2	24 ± 3	23 ± 1
Silt (2-50 µm)	35 ± 1	33 ± 3	40 ± 3	37 ± 0
Sand (50-2000 µm)	42 ± 2	48 ± 4	35 ± 2	39 ± 1

P and K: CAL extract (Schüller, 1969), Mg: $CaCl_2$-extrakt (Schachtschabel, 1954). Mean ± standard deviation.

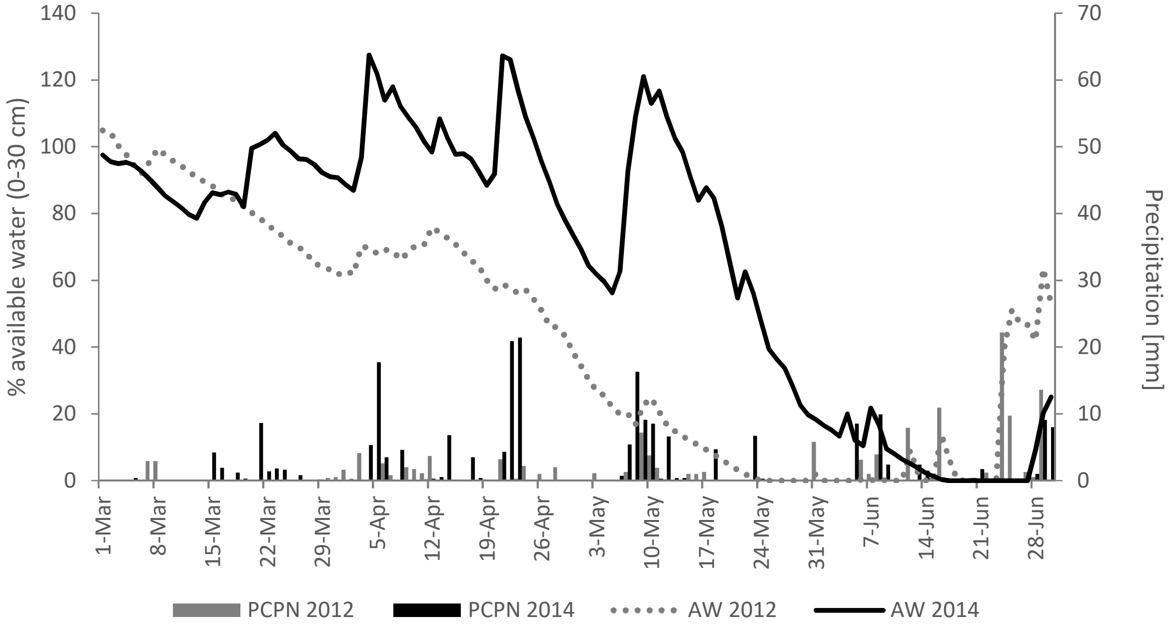

Figure 8: Precipitation (PCPN) and available water (AW) under winter wheat in Trenthorst/Wulmenau in 2012 and 2014 according to AMBAV model.

II.2.1.2.2 Study design

We conducted two comparisons to evaluate the influence of different management systems on collembolan communities in organic farming: (i) dairy rotation *versus* stockless rotation and (ii) conventional tillage with ploughing *versus* reduced tillage without ploughing.

The first comparison deals with the development in different crop rotations in organic farming. In May 2012, we sampled six fields of the dairy cow (DC) and six fields of the stockless (SL) rotation to evaluate the influence of one decade of these different organic farming systems. The management of these rotations mainly differed in the share of forage legumes, in the amount of remaining plant material (green mulch and straw) on the fields and in farmyard manure application (Table 9).

Besides this comparison of long-term management effects, we also studied collembolan communities within a short-term experiment. In summer 2012, three fields were halved, each belonging to one of the 'mixed' crop rotations. On each of these fields one half-field was managed with ploughing (CT: conventional tillage) and the other half without ploughing (RT: reduced tillage). Within our study CT and RT were defined according to ASAE (2005). Conventional tillage included the use of a two-sided mouldboard plough, with a working depth of 25-30 cm, whereas on the half-fields managed with RT no mouldboard plough was used and tillage depth was a maximum of 15 cm (no soil inversion). We conducted reduced tillage for two years; in 2012 before growing triticale and in 2013 before growing clover-grass.

Table 9: Characteristics of fertilization and crop residue management on the fields of the dairy and stockless rotation in the harvest years 2002 to 2012. For plant residue management the absolute number of appearances is given.

	Dairy	Stockless
N from organic fertilizers (kg ha^{-1} a^{-1})	39-62	-
Organic matter from organic fertilizers (kg ha^{-1} a^{-1})	954-1318	-
Liming (kg ha^{-1} a^{-1})	0-300	-
Plant residues remaining on the field (not clover-grass)	2-3	7-8
Years with clover-grass	2-4	1-2
Mulching of clover grass	0-3	1-4
Ploughing of clover-grass	1-2	1-2

The agricultural management measures carried out are summarized in Table 10. Table 11 shows the fertilization regimes. We sampled the half-fields in May 2012 (before introducing the different tillage systems) and again after two years in May 2014 to assess the influence of CT and RT on collembolan communities. Samples taken in 2012 from the half-field subsequently managed with CT in the dairy cow rotation have also been part of the dataset when comparing DC and SL.

Table 10: Agricultural measures applied for soil management on the three experimental fields, each belonging to one out of three farming systems (dairy, ruminant II, pig), in summer and autumn 2011, 2012, and 2013. CT: conventional tillage; RT: reduced tillage.

		2011			2012						2013					
Agricultural machinery used (ASABE, 2009)	Working depth (cm)	Dairy	Ruminant II	Pig	Dairy		Ruminant II		Pig		Dairy		Ruminant II		Pig	
					CT	RT	CT	RT	CT	RT	CT	RT	CT	RT	CT	RT
Chisel plough for stubble cultivation	10-15	x	x	x	x	x	x	x	x	x	x	x	2x	2x	x	x
Two way mouldboard plough (5-furrow)	25-30	x	x	x												
Two way mouldboard plough (5-furrow) with packer	25-30				x		x		x				x		x	
Two way mouldboard plough (4-furrow)	25-30										x					
Chisel plough	10-15							2x		2x	x	x	x	x	x	x
Spring teeth harrow	10-15	x	x				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	x	x	x
Land roller		x	x													

Table 11: Characteristics of fertilization and crop residue management in the harvest years 2002 to 2014 on the three fields that were part of the experiment on the influence of reduced tillage. For plant residue management the absolute number of appearances is given.

	Dairy	Ruminant II	Pig
N from organic fertilizers (kg ha^{-1} a^{-1})	52	63	51
Organic matter from organic fertilizers (kg ha^{-1} a^{-1})	1293	1675	1097
Liming (kg ha^{-1} a^{-1})	100	458	300
Plant residues remaining on the field (not clover-grass)	3	4	NA
Years with clover-grass	4	4	NA
Mulching of clover grass	3	6	NA
Ploughing of clover-grass	2	3	NA

II.2.1.2.3 Sampling and identification of collembolans

At four LTM-points per half-field/field (cf. Figure S1) two soil samples were collected with an auger (effective diameter 4 cm, depth 10 cm) resulting in eight samples per half-field/field. Collembolans were extracted from the whole samples using a MacFadyen high-gradient extractor (MacFadyen, 1961). After collecting the collembolans in monoethylenglycol they were transferred to 96 % ethanol for storage. Collembolans from all sampling points were mounted on a glass microscope slide and counted using a binocular microscope (max. magnification 50x). Finally, as we had to identify many specimens per sample, two samples out of eight were selected randomly. Attention was payed to always select samples from two different LTM-points. From these two samples collembolans were identified to species level (max. magnification 400x) according to Hopkin (2007). If necessary additionally identification keys by Gisin (1960), Bretfeld (1999), Potapow (2001), Thibaud et al. (2004), Dunger and Schlitt (2011), or Jordana (2012) were used. The nomenclature used follows the system proposed by Hopkin (2007).

Heterosminthurus bilineatus Gr.*, Protaphorura armata* Gr., *Sminthurinus aureus* Gr., and *Sminthurus viridis* Gr. are keyed out by Hopkin (2007) as conglomerates of species. Furthermore, when discussing the genera *Desoria* and *Isotomurus* Hopkin (2007) mentions difficulties in separating some species from these genera. Therefore, he summarizes them into species groups *Desoria tigrina* Gr. and *Isotomurus palustris* Gr., which we adopted in the identification process.

When using autecological information on collembolan species to characterise gradients uncovered with NMDS (II.2.1.2.5) geographical differences have to be considered. Fjellberg (1998, 2007) characterizes *Protaphorura armata* (Tullberg, 1869) and *Sminthurus viridis* (Linnaeus, 1758) as preferring rather dry or mostly dry habitats which is in contrast to other authors. While Hopkin (1997) describes poor drought resistance for *Protaphorura armata*, Bretfeld (1999) states for *Sminthurus viridis* to prefer the vegetation of moister grasslands and herbaceous fields. We suppose that these different ratings of species are due to the fact that the assessments of Fjellberg (1998, 2007) are more valid for boreal and alpine regions with lower mean temperatures. Individuals of some collembolan species are able to tolerate reduced humidity compared with individuals of the same species living under climatic conditions with higher mean temperatures (Snider and Butcher, 1972 as cited in Hopkin, 1997). In case of *P. armata* and *S. viridis* we did not adopt the view of Fjellberg (1998, 2007).

II.2.1.2.4 Life-form traits of collembolans

We used the method proposed by Martins da Silva et al. (2016) to sort collembolan species according to their adaptation to living within the soil by calculating an eco-morphological index (EMI). This enabled us to calculate a weighted mean EMI value for each collembolan sample. This value is called mean trait value (EMI mT) (Vandewalle et al., 2010).

In addition to using the EMI mT-values for describing collembolan communities, we aimed at visually comparing the composition of collembolan life-forms from different collembolan communities by using ternary diagrams (c.f. II.2.1.2.5). Thus, we used publications by Stierhof (2003), Chauvat et al. (2007), Sticht et al. (2008), and Salamon et al. (2011) to assign the calculated EMI values of species to life-forms (Table 12). We assume that species with the same EMI score belong to the same life-form type. Using 0.7 as upper threshold for the hemiedaphic type is supported by studies of Dittmer and Schrader (2000), Salamon et al. (2004), and Querner (2008). Additionally, this threshold separates species with and without ocelli. Studies by Caravaca and Ruess (2014); D'Annibale et al. (2015); Dombos et al. (2017); Gillet and Ponge (2004); Leinaas and Bleken (1983); Lindberg and Bengtsson

(2005); Ponge (2000); and Sterzynska and Kuznetsova (1995) justify to separate between hemiedaphic and atmobiont at 0.3. As we followed the system proposed by Gisin (1943) we combined species described as epigeic and atmobiont under the term atmobiont.

Furthermore, we derived our results from adult individuals. We would like to promote the strictly systematic approach presented here, as it is easily reproducible. Oliveira Filho et al. (2016) used a similar approach with slightly different threshold values for separation of life-forms. However, the authors did not explain their determination of thresholds.

Table 12: Life-forms (LF) of collembolan species as derived from eco-morphological index (EMI) and publications of Stierhof (2003), Chauvat et al. (2007), Sticht et al. (2008), and Salamon et al. (2011). EMI (eco-morphological index) scores according to Martins da Silva et al. (2016). at: atmobiont; ep: epedaphic; he: hemiedaphic; eu: euedaphic.

	Abbreviation	Ocelli	Antenna	Furca	Scales/hairs	Pigmentation	**EMI according to Martins da Silva et al. (2016)**	Life-form after Chauvat et al. (2007)	Life-form after Sticht et al. (2008)	Life-form after Stierhof (2003)	Life-form after Salamon et al. (2011)	**Derived Life-form**
Isotomurus palustris Gr.	Isot.palu	0	2	0	0	0	**0.1**	ep	he	he		**at**
Tomocerus minor (Lubbock, 1862)	Tomo.mino	0	0	0	0	2	**0.1**			he		**at**
Heteromurus nitidus (Templeton, 1835)	Hete.niti	0	2	0	0	2	**0.2**		he	eu	he	**at**
Lepidocyrtus cyaneus (Tullberg, 1871)	Lepi.cyan	0	2	0	0	2	**0.2**	ep	at	he	ep	**at**
Lepidocyrtus lanuginosus (Gmelin, 1788)	Lepi.lanu	0	2	0	0	2	**0.2**	ep	at	he	ep	**at**
Lepidocyrtus lignorum (Fabricius, 1775)	Lepi.lign	0	2	0	0	2	**0.2**			he		**at**
Heterosminthurus bilineatus Gr.	Hete.bili	0	2	0	4	0	**0.3**		at			**he**
Lipothrix lubbocki (Tullberg, 1872)	Lipo.lubb	0	2	0	4	0	**0.3**			he		**he**
Deuterosminthurus bicinctus (Koch, 1840)	Deut.bici	0	4	0	4	0	**0.4**					**he**
Pseudosinella alba (Packard, 1873)	Pseu.alba	0	4	0	0	4	**0.4**	he		eu	he	**he**
Pseudosinella decipiens (Denis, 1925)	Pseu.deci	0	4	0	0	4	**0.4**					**he**
Pseudosinella denisi (Gisin, 1954)	Pseu.deni	0	4	0	0	4	**0.4**					**he**
Pseudosinella fallax (Börner, 1903)	Pseu.fall	0	4	0	0	4	**0.4**					**he**
Pseudosinella immaculata (Lie Pettersen, 1896)	Pseu.imma	0	4	0	0	4	**0.4**		he			**he**
Sminthurides malmgreni (Tullberg, 1876)	Smin.malm	0	4	0	4	0	**0.4**					**he**
Sminthurides parvulus (Krausbauer, 1898)	Smin.parv	0	4	0	4	0	**0.4**			he		**he**
Cryptopygus thermophilus (Axelson, 1900)	Cryp.ther	0	4	0	4	2	**0.5**		he	he	he	**he**
Desoria tigrina Gr.	Deso.tigr	0	4	0	4	2	**0.5**					**he**
Deuterosminthurus pallipes (Bourlet, 1843)	Deut.pall	0	4	0	4	2	**0.5**		at		ep	**he**
Deuterosminthurus sulphureus (Koch, 1840)	Deut.sulp	0	4	0	4	2	**0.5**					**he**
Isotoma viridis (Bourlet, 1839)	Isot.viri	0	4	0	4	2	**0.5**	ep	he	he	ep	**he**
Parisotoma notabilis (Schäffer, 1896)	Pari.nota	0	4	0	4	2	**0.5**	he	he		he	**he**
Sminthurinus aureus Gr.	Smin.aure	0	4	0	4	2	**0.5**	he	he	he	ep	**he**
Sminthurinus concolor (Meinert, 1896)	Smin.conc	0	4	0	4	2	**0.5**					**he**
Sminthurinus niger (Lubbock, 1867)	Smin.nige	0	4	0	4	2	**0.5**			he	ep	**he**
Sminthurus viridis Gr.	Smin.viri	0	4	0	4	2	**0.5**					**he**
Sphaeridia pumilis (Krausbauer, 1898)	Spha.pumi	0	4	0	4	2	**0.5**	he	he	he	he	**he**
Stenacidia violacea (Reuter, 1881)	Sten.viol	0	4	0	4	2	**0.5**					**he**
Vertapogus westerlundi (Reuter, 1897)	Vert.west	0	4	0	4	2	**0.5**					**he**

Table 12 continued.

	Abbreviation	Ocelli	Antenna	Furca	Scales/hairs	Pigmentation	**EMI according to Martins da Silva et al. (2016)**	Life-form after Chauvat et al. (2007)	Life-form after Sticht et al. (2008)	Life-form after Stierhof (2003)	Life-form after Salamon et al. (2011)	**Derived Life-form**
Ballistura schoetti (Dalla Torre, 1895)	Ball.scho	0	4	2	4	2	**0.6**					**he**
Ceratophysella denticulata (Bagnall, 1941)	Cera.dent	0	4	2	4	2	**0.6**			he	he	**he**
Cryptopygus bipunctatus (Axelson, 1903)	Cryp.bipu	0	4	0	4	4	**0.6**		he		he	**he**
Folsomia brevicauda (Agrell, 1939)	Fols.brev	0	4	2	4	2	**0.6**					**he**
Folsomia manolachei (Bagnall, 1939)	Fols.mano	0	4	2	4	2	**0.6**	he		he		**he**
Folsomia sexoculata (Tullberg, 1871)	Fols.sexo	0	4	2	4	2	**0.6**					**he**
Parisotoma ekmani (Fjellberg, 1977)	Pari.ekma	0	4	0	4	4	**0.6**					**he**
Proisotoma minuta (Tullberg, 1871)	Proi.minu	0	4	2	4	2	**0.6**		he	he		**he**
Proisotoma tenella (Reuter, 1895)	Proi.tene	0	4	2	4	2	**0.6**					**he**
Folsomides parvulus (Stach, 1922)	Fols.parv	0	4	2	4	4	**0.7**			eu	he	**he**
Proisotoma minima (Absolon, 1901)	Proi.mini	0	4	2	4	4	**0.7**			he		**he**
Xenylla boerneri (Axelson, 1905)	Xeny.boer	0	4	4	4	2	**0.7**					**he**
Cryptopygus garretti (Bagnall, 1939)	Cryp.garr	4	4	0	4	4	**0.8**					**eu**
Cyphoderus albinus (Nicolet, 1842)	Cyph.albi	4	4	0	4	4	**0.8**	he		eu		**eu**
Isotomiella minor (Schäffer, 1896)	Isot.mino	4	4	0	4	4	**0.8**	eu	eu	eu		**eu**
Magalothorax minimus (Willem, 1900)	Mega.mini	4	4	0	4	4	**0.8**	eu	eu	eu		**eu**
Oncopodura crassicornis (Shoebotham, 1911)	Onco.cras	4	4	0	4	4	**0.8**			eu		**eu**
Folsomia candida (Willem, 1902)	Fols.cand	4	4	2	4	4	**0.9**		he	eu		**eu**
Folsomia inoculata (Stach, 1947)	Fols.inoc	4	4	2	4	4	**0.9**		eu			**eu**
Folsomia spinosa (Kseneman, 1936)	Fols.spin	4	4	2	4	4	**0.9**		he	eu		**eu**
Isotomodes productus (Axelson, 1906)	Isot.prod	4	4	2	4	4	**0.9**		eu	eu	eu	**eu**
Neotullbergia crassicuspis (Gisin, 1944)	Neot.cras	4	4	4	4	4	**1**		eu	eu		**eu**
Paratullbergia callipygos (Börner, 1902)	Para.call	4	4	4	4	4	**1**	eu	eu	eu		**eu**
Protaphorura armata Gr.	Prot.arma	4	4	4	4	4	**1**	eu		eu	eu	**eu**
Stenaphorura denisi (Bagnall, 1935)	Sten.deni	4	4	4	4	4	**1**	eu	eu	eu	eu	**eu**
Supraphorura furcifera (Börner, 1901)	Supr.furc	4	4	4	4	4	**1**					**eu**
Willemia anophthalma (Börner, 1901)	Will.anop	4	4	4	4	4	**1**	eu	eu	eu	eu	**eu**
Mesaphorura spec.	Mesa.spec	NA	NA	NA	NA	NA	**NA**	NA	NA	NA		**NA**

II.2.1.2.5 Statistics

Statistical models

For detecting differences in the number of individuals or the number of species depending on the type of crop rotation generalized linear mixed models (GLMMs) were used including 'crop rotation' (DC *vs* SL) as fixed and 'field-code' as random intercept effect.

When analysing the influence of tillage on the number of individuals the 'tillage regime' (CT *vs* RT) was used as fixed effect in GLMM. 'Sampling date' (May 2012, May 2014) and the interaction of 'sampling date' and 'tillage regime' were used as additional fixed effects to check for temporal variability within the data. The 'crop rotation' (dairy cow, ruminant II, pig) was used as random intercept effect. The same set-up was used when modelling the number of species depending on changes in the tillage regime.

Mean trait values (EMI mT-values) were evaluated using linear mixed models (LMMs). The model evaluating the influence of 'crop rotation' used 'crop rotation (Dc *vs.* SL) as fixed effect and 'field-code' as random intercept effect. After applying a backward selection procedure the model describing the influence of 'tillage regime' on EMI mT-values used 'sampling date' (May 2012, May 2014) as fixed effect and 'crop rotation' as random intercept effect (dairy cow, ruminant II, pig).

Statistical analyses were conducted using R 3.2.2 (R Development Core Team, 2016). All GLMMs were calculated for negative-binomial distributed count data. We used the R-package glmmADMB (Fournier et al., 2012; Skaug et al., 2015) for calculating GLMMs. For negative-binomial models the package uses the log as standard link-function. The estimation method used in glmmADMB is Laplace. Linear mixed models were calculated using the R-package lme4 (Bates et al., 2015a). After setting up models LS-Means and pairwise comparisons were obtained using the R-package lsmeans (Lenth, 2016). Abundance, species richness and EMI mT-values presented in the results section will be LS-means.

Non-metric multidimensional scaling

Non-metric multidimensional scaling (NMDS) and associated analyses were conducted using the R-package vegan (Oksanen et al., 2015). After conducting NMDS, differences between centroids for factor levels were statistically compared using vegan::adonis. As homogeneity of multivariate spread is a prerequisite for using adonis, vegan::betadisper was applied. The adjustment of p-values obtained from pairwise comparisons of centroids by adonis was conducted using stats::p.adjust with Bonferroni correction. NMDS were calculated using abundance values. The final NMDS analysis for the comparisons between crop rotations and tillage regimes both used three dimensions and had stress values of twelve and eleven, respectively. When displaying species in the NMDS plots they had to be weighted. Only the main species were displayed to avoid overlapping of species labels. Species weighting was done as follows: (1) calculating the share of each species in every sample; (2)

calculating the share of samples in which the share of a species was greater than or equal to 3.2 %; (3) weighting of species according to this share of samples. The threshold of 3.2 % was chosen according to Engelmann (1978) who proposed this level for separation of main and other species of soil arthropod communities.

Ternary diagrams

Ternary diagrams illustrate compositions of three components and we used them to visualise the composition of collembolan life-forms. We calculated the share of atmobiont, hemiedaphic, and euedaphic collembolan individuals in each sample. For creating ternary diagrams the R-package compositions was used (van den Boogaart et al., 2014). The share of each component is 100 % in the corner labelled accordingly and 0 % at the line opposite to this corner.

II.2.1.3 Results

II.2.1.3.1 Comparison of crop rotations dairy cow (DC) *versus* stockless (SL)

In 2012 neither collembolan abundance nor species richness differed significantly between DC and SL (Table 13). On fields of the DC system 22 species and on those of the SL system 29 species were identified. There was no significant difference between EMI mT-values of crop rotations in May 2012 (DC: 0.50 ± 0.06; SL: 0.54 ± 0.06; p=0.664). When visually comparing the proportions of life-forms between the fields under DC and SL rotation in May 2012 a higher share of euedaphic individuals under DC could be revealed, while the share of hemiedaphic individuals was higher under SL (Figure 9). Because the 95 % CIs overlap, these differences have to be assessed as tendencies.

In May 2012 the main gradient within the data on collembolan communities in DC and SL along the first NMDS-axis was spanned by *Protaphorura armata* Gr. and *Sphaeridia pumilis* (Krausbauer, 1898) and the gradient along the second axis was spanned by *Heterosminthurus bilineatus* Gr. and *Willemia anophthalma* (Börner, 1901) (Figure 10a).

No significant differences between the centroids for the two crop rotations could be revealed (p=0.105). It became clear, that there is no difference along the first axis and only little along the second (Figure 10b). When using crop-classes rather than crop rotations as grouping variables some differentiation is possible (Figure 10c). Collembolan communities differ between crops cultivated in autumn (winter crops) and those cultivated in spring (spring crops). However, none of the centroids differed significantly (Table 14).

Table 13: Results of statistical modelling to reveal the influence of different crop rotations (DC vs SL) on abundance and species richness of collembolans. Least square means (LSM) as well as lower (LCL) and upper (UCL) confidence levels are given.

Response	p	Effect Level	LSM	Asymptotic LCL	Asymptotic UCL
Abundance (Individuals m^{-2})	0.4384	DC	19,126	8,015	45,645
		SL	31,107	13,033	74,244
Species richness (Species per sample)	0.2131	DC	5	3	7
		SL	7	5	10

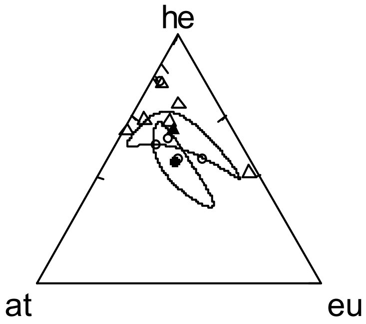

Figure 9: Ternary diagram representing the relative proportions of life-forms (eu: euedaphic, he: hemiedaphic, at: atmobiont) in the collembolan communities on the fields of the dairy cow (DC) and stockless (SL) rotation in 2012. Data from SL marked with triangles and data from DC with circles. Solid markings represent the geometrical means. Ellipses indicating 95-% CI.

Table 14: Results of pairwise comparison of centroids from the collembolan dataset in DC and SL in May 2012. SGrain: spring grown grain; WGrain: winter grown grain; F-LEG: fodder legumes (clover-grass mixture); G-LEG: grain legumes; LEG-Mix: mixtures of grain legumes and grains; MA: maize

	Adjusted p
F-LEG - G-LEG	1
F-LEG - LEG-Mix	0.9
F-LEG - MA	NA
F-LEG - SGrain	0.675
F-LEG - WGrain	0.345
G-LEG - LEG-Mix	NA
G-LEG - MA	NA
G-LEG - SGrain	NA
G-LEG - WGrain	1
G-LEG-Mix - MA	NA
LEG-Mix - SGrain	NA
LEG-Mix - WGrain	1
MA - SGrain	NA
MA- WGrain	NA
SGrain - WGrain	0.285

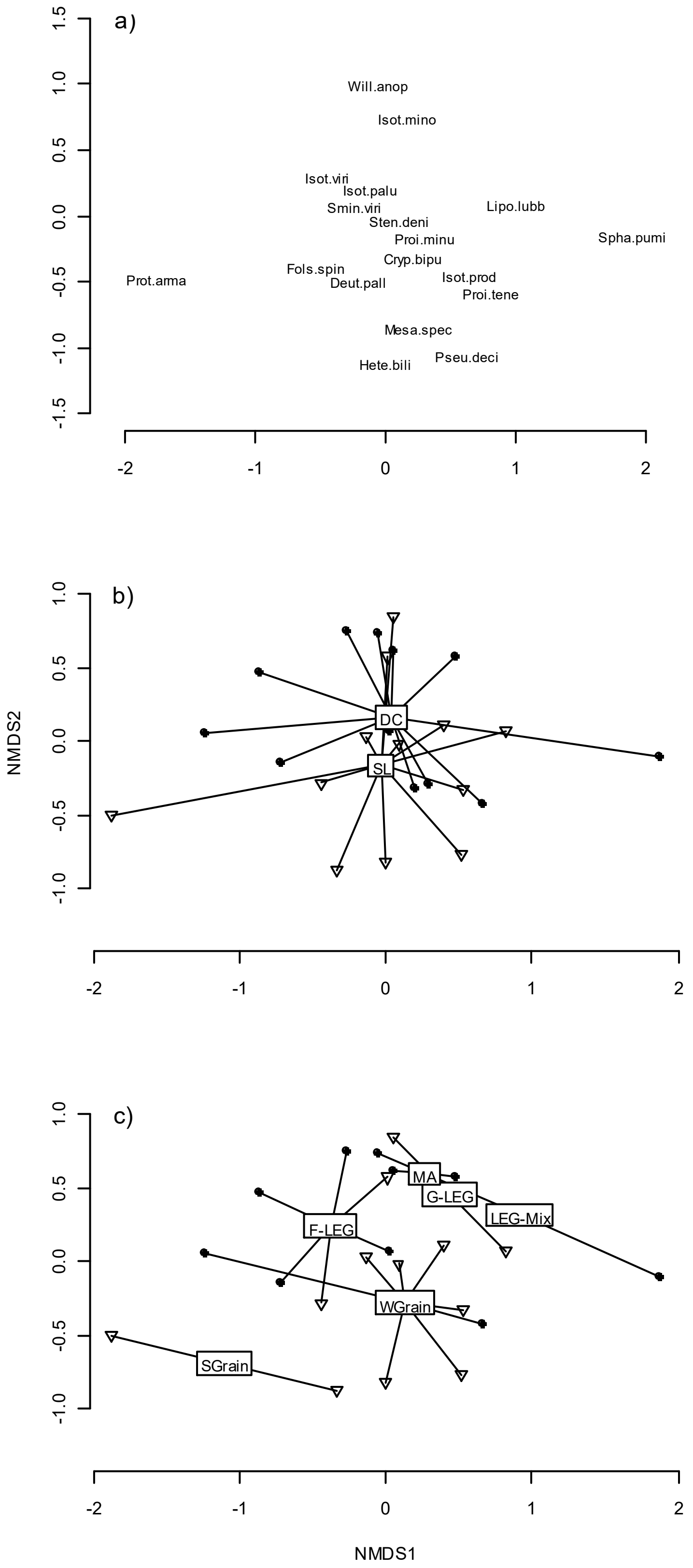

Figure 10: Figure 3: NMDS for the collembolan data from May 2012 for the two crop rotations dairy cow (DC) and stockless (SL). a) Ordination showing main species within the dataset (Abbreviations according to Table 5). b) Sampling points grouped according to farming systems (SL marked with triangles and DC with circles). c) Sampling points grouped according to crop classes (SGrain: spring grown grain; WGrain: winter grown grain; F-LEG: fodder legumes (clover-grass mixture); G-LEG: grain legumes; LEG-Mix: mixtures of grain legumes and grains; MA: maize).

II.2.1.3.2 Comparison of tillage regimes: conventional (CT) *versus* reduced (RT)

Neither in 2012, before setting aside the plough, nor in 2014, after two years of reduced tillage, any significant difference in collembolan abundance or species richness could be revealed when comparing CT and RT (Table 15). However, collembolan abundance was significantly higher in 2014 in both tillage regimes.

Table 15: Results of statistical modelling to reveal the influence of different tillage regimes (CT vs RT) on abundance and species richness of collembolans. Least square means (LSM) as well as lower (LCL) and upper (UCL) confidence levels are given.

Response	Grouping	p	Effect Level	LSM	Asymptotic LCL	Asymptotic UCL
Abundance (Individuals m^{-2})	2012	0.0514	CT	8,220	5,317	12,708
			RT	12,046	7,762	18,693
	2014	0.4821	CT	29,067	18,804	44,933
			RT	25,357	16,419	39,161
	CT	**<0.0001**	2012	8,220	5,317	12,708
			2014	29,067	18,804	44,933
	RT	**0.0002**	2012	12,046	7,762	18,693
			2014	25,357	16,419	39,161
Species number (Species per sample)	2012	0.8995	CT	5	3	8
			RT	5	3	8
	2014	0.8206	CT	6	4	10
			RT	6	4	9
	CT	0.2881	2012	5	3	8
			2014	6	4	10
	RT	0.476	2012	5	3	8
			2014	6	4	9

Irrespective of the tillage regime, the EMI mT-value was significantly higher in May 2012 than in May 2014 (2012: 0.61 ± 0.04; 2014: 0.43 ± 0.04; $p < 0.01$). Using ternary diagrams a visual comparison of the proportions of life forms under CT and RT in May 2012 (Figure 11a) and May 2014 (Figure 11b) was possible. In the diagram for the data from 2012 the 95 % CIs are overlapping considerably, so that the higher share of euedaphic individuals under CT and the higher share of hemiedaphic individuals under RT could not be considered being significant. In May 2014, it turned out that under CT the share of atmobiont individuals was higher than under RT whereas under RT the share of euedaphic individuals was higher (Figure 11b). The 95 % CIs only overlap slightly for the data from May 2014.

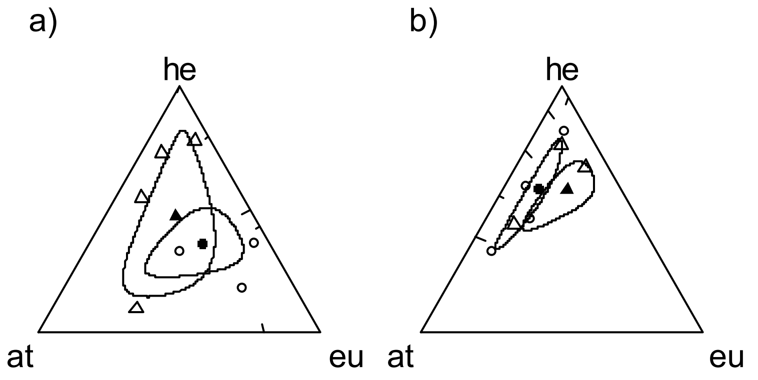

Figure 11: Ternary diagram representing the relative proportions of life-forms (eu: euedaphic, he: hemiedaphic, at: atmobiont) in the collembolan communities on the fields under CT and RT in May 2012 (a) and May 2014 (b). Data from RT marked with triangles and data from CT with circles. Solid markings represent the geometrical means. Ellipses indicating 95-% CI.

The first axis of an NMDS on the collembolan data of fields under CT and RT was spanned by *Sminthurides malmgreni* (Tullberg, 1876), *Cyphoderus albinus* (Nicolet, 1842) and *Pseudosinella alba* (Packard, 1873) on the one side and *Deuterosminthurus pallipes* (Bourlet, 1843) and *Neotullbergia crassicuspis* (Gisin, 1944) on the other side (Figure 12a). NMDS-Axis 2 was spanned by *Sminthurides parvulus* (Krausbauer, 1898), *P. armata* Gr., *Supraphorura furcifera* (Börner, 1901) and *I. palustris* Gr. on the one side and *P. alba*, *Cryptopygus thermophiles* (Axelson, 1900) and *Sminthurus niger* (Lubbock, 1867) on the other side. It became apparent that there was no difference between centroids of CT and RT, neither in May 2012 nor in May 2014. Although the centroids differed between May 2012 and May 2014 (Figure 12b) no test for significance of this difference was possible as the condition of homogeneity of multivariate spread was not satisfied. Significant differences between spring grain crops (grain legume/cereal mixtures; LEG-Mix) and fodder legumes (red clover-grass; F-LEG) ($p=0.003$) and between grain legumes (G-LEG) and fodder legumes (F-LEG) ($p=0.003$) could be shown (Figure 12c). In May 2012, all fields were cultivated with G-LEG or LEG-Mix, respectively. In May 2014, all fields were cultivated identically with F-LEG.

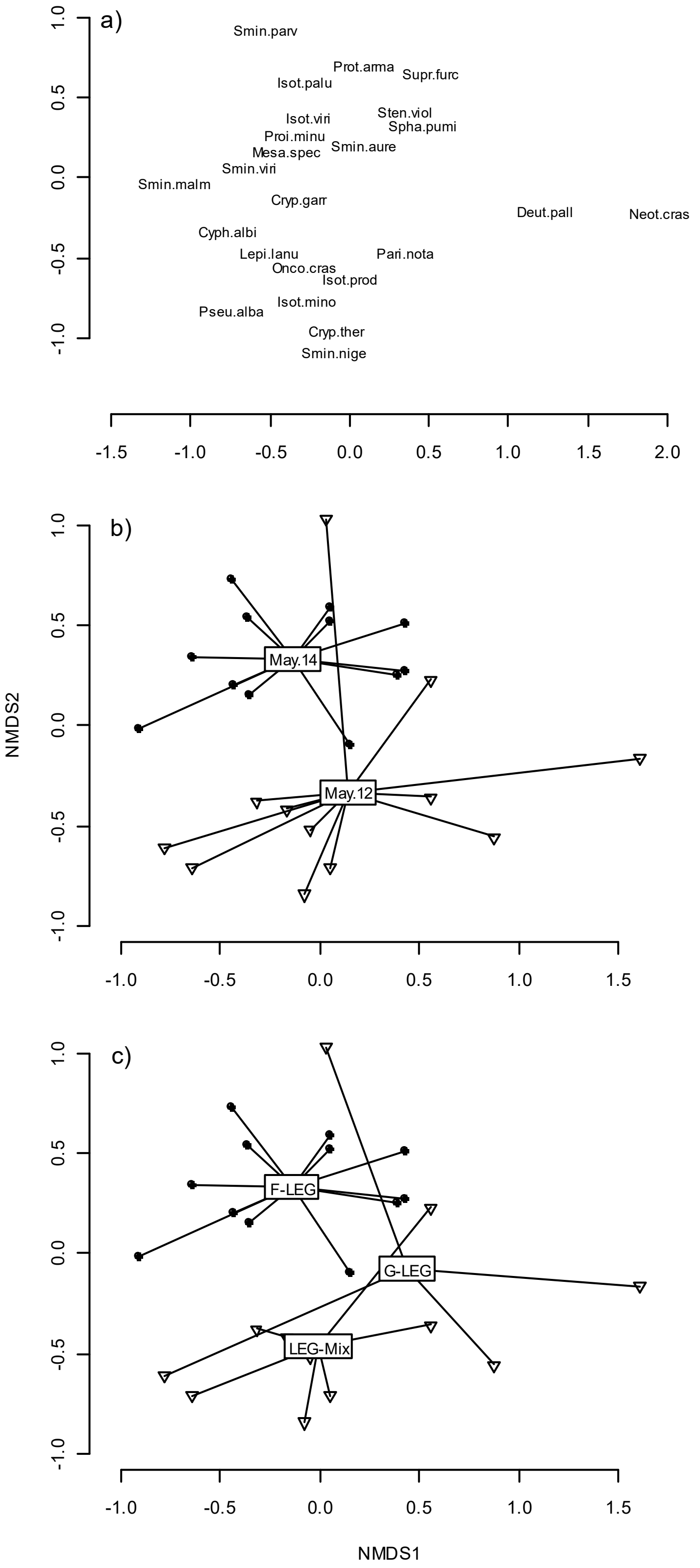

Figure 12: NMDS for the collembolan data from May 2012 and May 2014 under the different management systems CT (conventional tillage) and RT (reduced tillage) a) Ordination showing main species within the dataset (Abbreviations according to Table 5). b) Sampling points grouped according to sampling month (May 2012 marked with triangles and May 2014 with circles). c) Sampling points grouped according to crop classes (F-LEG: fodder legumes (clover-grass mixture); G-LEG: grain legumes; LEG-Mix: mixtures of grain legumes and grains).

II.2.1.4 Discussion

II.2.1.4.1 Crop rotations

We did not find significant differences in terms of abundance and species richness between the dairy cow and stockless rotation. Noteworthy in our dataset are the partly high abundance values under winter crops in 2012. The year 2012 was rather dry, and it is expected that drought negatively affects most collembolan species except for those specifically adapted to desiccation (Hopkin, 1997). There was no difference in EMI mT-values between the dairy cow and stockless rotation but the by trend higher share of euedaphic individuals in the dairy cow rotation in 2012 was accompanied by a higher C content of the soil (Table 16). Therefore, collembolan life-forms seem to indicate differences in resource availability when comparing organic stockless farming systems against those integrating animal husbandry.

Table 16: Content of C and N, and C:N ratio and pH on the field belonging to the rotations dairy cow (DC) and stockless (SL) in 2012. p values as obtained by Wilcoxon Rank Sum Test.

	Median		p	
	DC	SL		
C [g kg^{-1}]	12.93	11.21	0.006251	**
N [g kg^{-1}]	1.24	1.15	0.1254	
C/N	10.4	9.9	0.03467	*
pH	6.4	6.5	0.413	

II.2.1.4.2 Tillage systems

No differences in abundance and species richness between tillage systems could be revealed. Like in our study, Petersen (2002) did not find differences in collembolan density when comparing conventional ploughing and non-inverting deep tillage in a one-year case study. Sabatini et al. (1997) supported this results for the long run when studying fields managed constantly for 15 years prior to sampling. In contrast, House and Parmelee (1985) and Miyazawa et al. (2002) revealed a positive effect of reduced tillage on collembolans. Though, van Capelle et al. (2012) showed an overall positive effect of conventional tillage on collembolan abundance and diversity (H’) when evaluating twelve datasets from nine German studies. In their review, van Capelle et al. (2012) highlighted the fact that this overall effect does not hold true for all combinations of soil type and life-form. For instance, species of all life-form types were promoted by reduced tillage of silty soils.

Abundance was higher in 2014 irrespective of the tillage regime. We ascribe these results to higher soil moisture in 2014 and the different crops under study in 2012 (spring grown grain-legume cereal mixtures or pure grain-legumes) and in 2014 (winter grown clover-grass). Annual effects, based on differences in soil moisture, rather than management effects were also shown by D'Annibale et al. (2017).

Like for collembolan abundance we could also show significant differences between EMI mT-values when comparing May 2012 and May 2014 irrespective of the tillage system, with higher values in

2012. Higher EMI mT-values indicate a higher share of euedaphic individuals, which we assume is due to the dry weather conditions in 2012 decreasing the share of hemiedaphic and atmobiont individuals.

In 2014, after two years of reduced tillage, the share of euedaphic individuals was by trend enhanced under reduced tillage indicating a starting stabilization of habitat conditions (Martins da Silva et al., 2016). While euedaphic collembolans are favoured by habitats offering stable conditions in terms of resource availability, soil moisture, or disturbance, the proportion of atmobiont species is higher in less stable, regularly changing, habitats (Martins da Silva et al., 2016). In line with this, the half-fields under conventional tillage showed by trend a higher share of atmobiont individuals.

II.2.1.4.3 Collembolan communities

In the NMDS comparing the dairy cow and stockless rotation the species at the ends of axis 1 (Figure 10) can be differentiated according to their life-form. *P. armata* is a euedaphic species, a “true soil-dweller” (Bauer and Christian, 1993), with only poor drought resistance (Hopkin, 1997). On the other hand, *S. pumilis* lives in the litter layer of soils of different humidity (Bretfeld, 1999; Ponge, 2000) and is a mobile epigeic species (Salamon et al., 2004). As the centroids of the dairy cow and stockless rotation were not separated along this axis both crop rotations, after ten consistent years of different organic farming practices, host collembolan communities consisting of a balanced mixture of species of different life-forms. The second axis follows a gradient of soil acidity. *Pseudosinella decipiens* (Denis, 1925) is characterised as not occurring under acid conditions (Ponge, 1993), while *W. anophthalma* prefers acidic habitats like peat, mor, or moder (Chauvat and Ponge, 2002; Salmon et al., 2014). Therefore, data on collembolan communities indicate more acidic conditions under the dairy cow rotation when compared to the stockless rotation.

The differentiation between collembolan communities of different crop classes was more pronounced than between the two crop rotations. Differences became apparent between winter and spring crops along axis 1. As sampling took place in May, the time elapsed since tillage differed markedly between these two groups. Different crops were in different development status causing different degrees of soil coverage. As Salmon et al. (2014) found convergence of species traits for epigeic (atmobiont) species and those living in open habitats the gradient along the first axis reflects differences in habitat openness. Along the second axis, legumes and maize can be differentiated from cereals. Here the collembolan communities might uncover lower pH values in the rhizosphere of legumes (Li et al., 2007; Maltais-Landry, 2015) and maize (Kamh et al., 2002). Kamh et al. (2002) found enhanced excretion of protons from *Zea mays* under P-deficient conditions. To what extent proton excretion of young maize plants to dissolve P influenced soil pH was not within the scope of our study, but cannot be ruled out as a reason (Ohm et al., 2015). Therefore, the higher share of legumes and maize in the dairy cow rotation might have influenced the differentiation of the dairy cow and stockless rotation along the second NMDS-axis. Nevertheless, differences in soil acidity could not be revealed through measuring pH (Table 16). This disparity between pH measurements and conclusions drawn from collembolan data might be because the differences in pH values were below the measurement resolution. Furthermore, measurements of pH were done in February while collembolans were sampled in May.

We could not reveal any gradient along the first NMDS axis when comparing conventional and reduced tillage (Figure 12). Species at both ends of the axis are xerothermophil and prefered dry and open habitats (*C. albinus* (Bockemühl, 1956 as cited in Dekoninck et al., 2007), *P. alba* (Filser, 1995), *D. pallipes* (Bretfeld, 1999; Fjellberg, 2007; Querner, 2004), *N. crassicuspis* (Stierhof, 2003)). Along the second axis, a humidity gradient is spanned. *S. parvulus*, *P. armata*, *S. furcifera*, and *Isotomurus palustris* (Müller, 1776) prefer wet or damp habitats (Bretfeld, 1999; Fjellberg, 1998, 2007; Hopkin, 1997, 2007) whereas *P. alba* and *C. thermophilus* are adapted to dry habitat conditions (Detsis, 2009; Filser, 1995; Kautz et al., 2006; Potapow, 2001). Therefore, data on collembolan communities suggest moister soil conditions in 2014 when compared to 2012.

Like for the data obtained when comparing the dairy cow and stockless rotation a differentiation of collembolan communities between crop classes, rather than between management systems, was possible. In this case, the differentiation seems to be interlinked with the year of sampling. While in 2012 spring grown crops were cultivated the grass-clover-mixture present on all fields in 2014 was a winter crop. Thus, increased soil cover of vegetation in 2014 consequently lead to higher soil moisture. Alvarez et al. (2001) also discussed a positive effect of higher soil moisture due to higher weed densities as possibly influencing collembolan communities. Furthermore, general data on soil moisture revealed higher water content in the soil in 2014.

Overall, it turned out that different crop rotations and tillage regimes in organic farming did not influence collembolan abundance, species richness, or EMI mT-values. Species abundance and composition rather reacted to different crops cultivated and interannual effects. These factors seem to overlay the expected general management-induced changes in the medium to long term. Shifts in the share of the different life-forms showed some weak reactions, with the share of euedaphic individuals indicating stabilizing habitat conditions depending on resource availability (organic matter supply) and absence of soil disturbance (reduced tillage).

II.2.1.5 Conclusion

Characterising changes in collembolan communities caused by differences in soil management remains challenging. On this issue, the well-known high variability in collembolan abundance mainly hinders the use of density measures. The usage of data on the structure of collembolan communities seems to be more promising. The proportions of-life forms within collembolan communities revealed response to management changes, mainly in terms of the proportion of euedaphic individuals. Other studies showed that the proportion of euedaphic individuals can be used as an indicator for stable habitat conditions. We conclude that soil habitats in organic farming systems with manuring as well as under reduced tillage are more stable, than in systems without manuring or under conventional tillage, respectively. Furthermore, we showed the influence of different crops and annual variations on the structure of collembolan communities. Differences in soil acidity and moisture were elucidated by evaluating the structure of collembolan communities. When focussing on the assessment of management systems through evaluating collembolan communities one has to bear in mind that site conditions, mainly related to soils and annual variations, can have important influence.

Acknowledgements

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II.2.2 Short-term effects of reduced tillage on soil collembolan communities

Moos et al. (2017), Conference Paper, Wissenschaftstagung Ökologischer Landbau, Campus Weihenstephan, Freising-Weihenstephan, 07.-10. März 2017.

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Abstract

Collembolans, a widespread group of soil fauna, could potentially be used as indicators of management changes in (organic) farming systems. In this study we investigated the short term effects of reduced compared to conventional tillage on collembolan communities. Results of a two-year field trial showed that collembolan communities are likely influenced by different tillage systems. These effects, however, were not significant. Furthermore, interannual variations seem to strongly influence the composition of collembolan communities. We assign these effects to different crops cultivated during our study period.

Keywords: tillage, NMDS, soil biodiversity, springtails

II.2.2.1 Introduction and Objective

Because of their function as secondary decomposers collembolans are linked to the soil food-web in several ways. Therefore, they can potentially be used as valuable indicators for soil health. Soil tillage influences the soil properties as habitat and impacts on the dynamics of the abundance of soil fauna (van Capelle et al., 2012). However, changes in the soil fauna caused by management changes can often only be detected with a certain delay. In this study we evaluated short-term effects of reduced tillage on the composition of collembolan communities. Furthermore, we investigated whether characteristic species for different tillage systems can be identified.

II.2.2.2 Methods

The study was conducted on the experimental station of the Thünen-Institute of Organic Farming (Soil types: Stagnic Luvisols from boulder clay with silty-loamy texture; mean annual precipitation: 700 mm; mean annual temperature: 8.8 °C). In the summer of 2012 three fields at the experimental station, which had been identically managed before, were halved. Subsequently, in 2012 and 2013 on one half of each field a mouldboard plough was used for cultivation (CT: conventional tillage;

inverting the soil; working depth 25-28 cm) and the other half was cultivated without using the plough (RT: reduced tillage; not inverting the soil; working depth: max. 15 cm). Further details of the study design can be found in Moos et al. (2016). There were four geo-referenced sampling points on each half-field, which have been used for long-term monitoring since 2003 (Schaub et al., 2007). In autumn 2012 triticale and in 2013 clover-grass was planted on all fields.

Soil sampling was conducted in November 2012, in May and October 2013, and in May 2014. Eight samples were collected per half-field (depth: 0-10 cm; diameter: 4 cm: volume: 126 cm^3) and collembolans were extracted by using a MacFadyen-Extractor (MacFadyen, 1961). Two out of eight samples were randomly selected from which collembolans were identified to species level according to Hopkin (2007).

Data were analysed by non-metrical multidimensional scaling (NMDS). This multivariate statistical method finally produces figures from which the similarity of two samples can be derived. The further two points are separated from each other in the coordinate system, the less species they have in common (Leyer and Wesche, 2007). Statistical analyses were conducted using R 3.2.2 (R Development Core Team, 2016) with the R-package vegan (Oksanen et al., 2015). Data from the harvest years 2013 and 2014 were analysed together to identify shifts in the species composition of collembolans during this period. Mean species composition (centroids) were determined for tillage regimes (CT vs. RT), month of sampling (November vs. May and October vs. May), and the interaction of these factors. For statistical comparison of centroids vegan::adonis was used.

II.2.2.3 Results

In both harvest years centroids for RT and CT differed more in autumn (November and October) than in spring (May). However, none of these differences was significant. While for the harvest year 2013 tillage regimes differed significantly (Figure 13a; p=0.041) there was no significant difference for the sampling months (November 2012 vs. May 2013). For the harvest year 2014 results were the reverse (Figure 13b; p=0.003): The sampling months (October 2013 vs. May 2014) differed significantly while no significant difference could be identified between tillage treatments.

II.2.2.4 Discussion

For both harvest years data indicate an alignment of collembolan communities between CT and RT with time since tillage. However, this alignment seems to be more pronounced in the harvest year 2014 which is supposed to be caused by the different crops cultivated in 2013 and 2014. When cultivating clover-grass (2014) the different effects of CT and RT on the collembolan community are aligned sooner as when triticale (2013) is cultivated. Clover-grass produces a closed ground cover rapidly and therefore homogenizes the habitat conditions, irrespective of the tillage treatment.

Lepidocyrtus lanuginosus (Gmelin, 1788) and *Parisotoma notabilis* (Schäffer, 1896), located near the CT-centroid (Figure 1a), are characterised as typical species of arable fields (Chauvat et al., 2007; Ponge et al., 2013; Potapow, 2001). Nevertheless, the knowledge regarding the autecology of many collembolan species is still limited.

Many species found in this study are furthermore characterised as generalist species with wide ecological niches. For this reason, it was not possible to derive ecological demands of the different collembolan communities through assigning single species to their centroids.

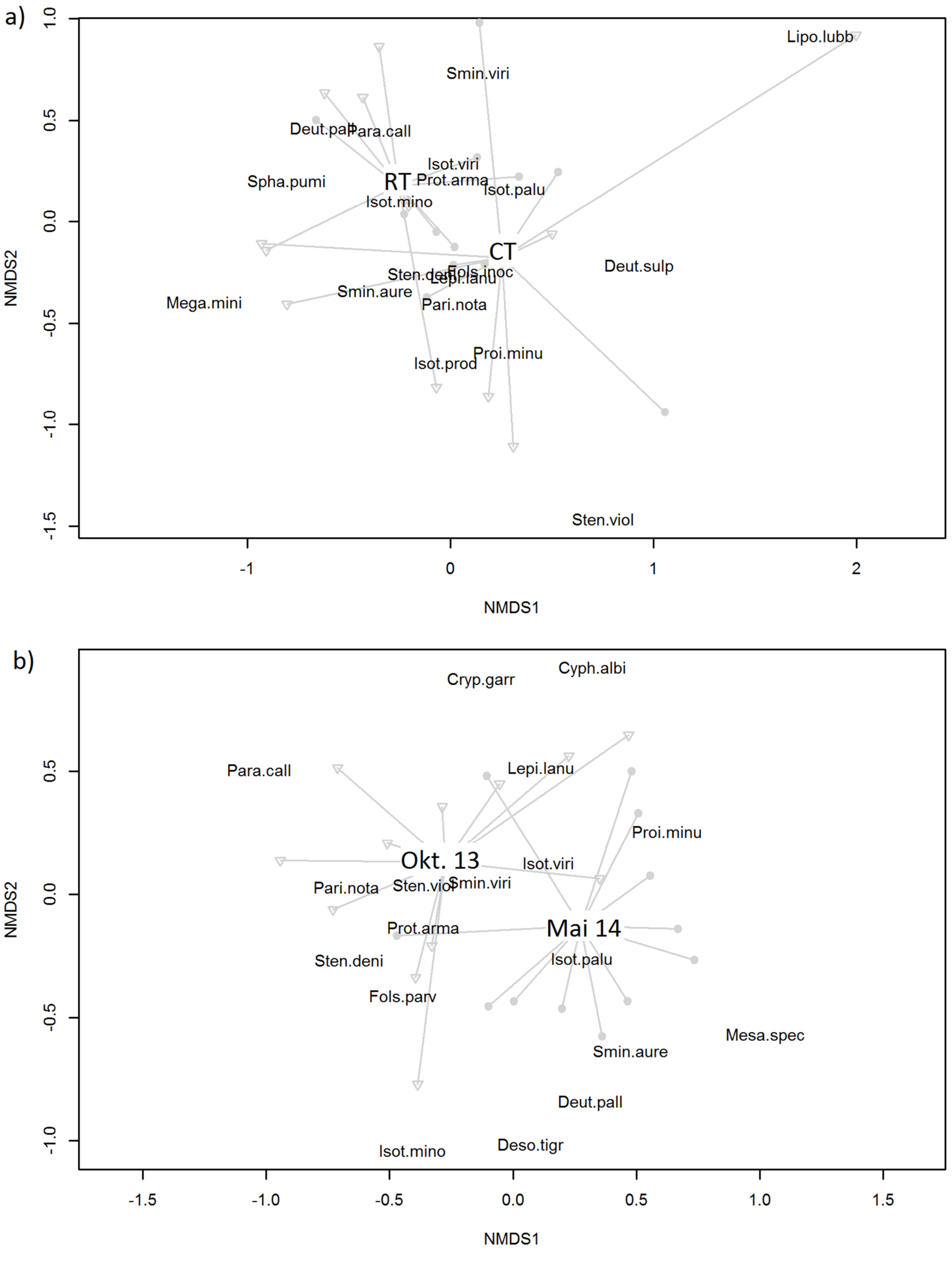

Figure 13: a) NMDS of the data from the harvest year 2013 with centroids for tillage systems (CT vs. RT); b) NMDS of the data from the harvest year 2013 with centroids for sampling months (October 2013 vs. May 2014).

Cryp.garr: *Cryptopygus garretti*; Cyph.albi: *Cyphoderus albinus*; Deso.tigr: *Desoria tigrina* Gr.; Deut.pall: *Deuterosminthurus pallipes*; Deut.sulp: *Deuterosminthurus sulphureus*; Fols.inoc: *Folsomia inoculate*; Fols.parv: *Folsomides parvulus*; Isot.mino: *Isotomiella minor*; Isot.palu: *Isotomurus palustris* Gr.; Isot.prod: *Isotomodes productus*; Isot.viri: *Isotoma viridis*; Lepi.lanu: *Lepidocyrtus lanuginosus*; Lipo.lubb: *Lipothrix lubbocki*; Mega.mini: *Megalothorax minimus*; Mesa.spec: *Mesaphorura* spec.; Para.call: *Paratullbergia callipygos*; Pari.nota: *Parisotoma notabilis*; Proi.minu: *Proisotoma minuta*; Prot.arma: *Protaphorura armata* Gr.; Smin.aure: *Sminthurinus aureus* Gr.; Smin.viri: *Sminthurus viridis* Gr.; Spha.pumi: *Sphaeridia pumilis*; Sten.deni: *Stenaphorura denisi*; Sten.viol: *Stenacidia violacea.*

II.2.2.5 Conclusions

From our two-year field trial we conclude that collembolan communities are sensitive to changes in the upper soil caused by agricultural management. However, tillage induced effects are overlaid by effects induced by the cultivated crop.

Acknowledgement

We would like to thank Daniel Baumgart, Regina Grüning, Magdalena Langer, Rainer Legrand and Meike Reimann for valuable support in the laboratory.

Part III General discussion

III.1 Main results

The first Paper in Part II of this thesis (II.1.1) presents the results of a case study on the influence of occasional reduced tillage (ORT) on earthworm communities and the economic performance of triticale cultivation. The ORT treatment was compared to conventional tillage (CT). In total, seven earthworm species were identified in this study. The data revealed that earthworm biomass was significantly reduced under CT both four weeks and about seven months after tillage. The same effect could be observed 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). Earthworm abundance aligned within half a year on the half-fields treated with CT and ORT. 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 (SG I). 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 study earthworm communities, it was investigated whether the number of surface casts could help estimate earthworm performance. It was shown that the number of surface casts cannot be used as a general predictor of earthworm performance. Only the number of individuals of *L. terrestris*, the number of anecic individuals and the total earthworm biomass can be estimated reliably by counting surface casts (SG IV).

Section II.1.2 condenses information from peer-reviewed papers on the influence of reduced tillage on earthworms in organic farming in a meta-analysis. The analysis showed an overall significantly positive effect of reduced tillage on earthworm abundance (+ 90 %) and biomass (+ 67 %) (SG II). Methods of reduced tillage have to be divided into shallow-inverting and non-inverting systems as positive effects were only significant for non-inverting systems. When methods of reduced tillage are applied for several years, a shift appears in the composition of earthworm communities. The share of species with higher mean individual biomass increases (*L. terrestris*, *A. longa*).

Sections II.2.1 and II.2.2 focus on the influence of different tillage regimes (CT *vs* ORT) and crop rotations (high *vs* low input of organic matter) on collembolan communities. Overall, the collembolan communities were highly variable in space and time. Therefore, only very few significant differences could be detected. After ten years of consistent management, neither collembolan species richness nor their abundance nor eco-morphological index (EMI) differed significantly between a crop rotation of a mixed farm and a crop rotation of a stockless farm (II.2.1, SG III, SG V). While in the medium term (two years) no influence of tillage on collembolan communities could be found (II.2.1), it turned out that the composition of collembolan communities differed four weeks after tillage (SG I). However, these differences were not significant and aligned within six to seven months (II.2.2). Species composition of collembolan communities responded to the impact of different crops or annual effects rather than to management measures. Soil acidity and soil moisture were important factors for the composition of collembolan communities. A positive but not significant trend of euedaphic collembolan species gaining more importance in soil environments that offer more stable habitat conditions (SG V) was found. These concerns habitats with enhanced availability of organic matter or with reduced tillage intensity.

III.2 The influence of (occasional) reduced tillage on soil fauna in organic farming

Differences in the recovery time of earthworm abundance and biomass after ploughing are most likely caused by the fact that different ecological groups are involved in the recovery. While faster-reproducing endogeic species mainly account for abundance values, biomass is mainly determined by slowly-reproducing anecic species (Bertrand et al., 2015; Jeffery et al., 2010; Pelosi et al., 2009). Furthermore, since larger soil organisms (adult anecic individuals) tend to be more sensitive to anthropogenic disturbance (Pulleman et al., 2012), a delayed increase of earthworm biomass after ploughing is expected.

Similarly to previous findings in the case of conventional farming (Briones and Schmidt, 2017; van Capelle et al., 2012), tillage intensity reduction overall positively influences earthworm abundance and biomass also in organic farming. It was shown that the same mechanisms act as discussed for the field study in Trenthorst/Wulmenau. The positive effects of tillage intensity reduction on anecic earthworms develop with some delay due to their longer generation time of approximately nine months (Jeffery et al., 2010) and thus slower reaction to changing abiotic conditions.

Tillage influences soil conditions in various ways. Soil temperature and moisture are altered, and the distribution of organic matter within the soil profile is modified (van Capelle et al., 2012). These tillage-induced changes affect collembolans as well as all other organisms of the soil biota. Nevertheless, the equalisation of the community composition of collembolans under CT and ORT within half a year indicates that tillage-induced differences are overlaid by the influence of weather conditions and properties of the cultivated crops. These factors mainly influence soil moisture and acidity. It has been shown before that collembolans are sensitive to differences in soil acidity (van Straalen and Verhoef, 1997) and soil water content (Hasegawa et al., 2015), and Lindberg et al. (2002) pointed out that it is mostly drought that induces changes in the soil fauna (oribatid mites and collembolans). In a pan-European study, Salmon et al. (2014) showed the overall importance of soil acidity and moisture in the distribution of collembolan species, at least indirectly through humus forms. In general, collembolans are favoured by intermediate levels of soil moisture (Jeffery et al., 2010), although it is nowadays recognised that specialised species can survive desiccation as well as flooding (Hopkin, 1997). Soil acidity influences collembolan communities either directly or indirectly by changing the food availability (Ponge, 1993).

Salmon et al. (2014) pointed out the importance of "habitat openness" for the composition of collembolan communities on a large geographic scale and across a broad range of ecosystems. In the study presented in Section II.2.1, the ground cover of vegetation was clearly different between May 2012 (field bean/oat, field pea/spring barley, field bean) and May 2014 (clover-grass). Therefore, "habitat openness" also likely induces differences in collembolan communities on the smaller spatial scale. The share of euedaphic collembolan individuals was by trend, but not significant, higher after two years of reduced tillage, what supposedly shows a stabilization of habitat conditions (Martins da Silva et al., 2016). In this case, stability is mainly linked to the absence of regular disturbance by ploughing.

III.3 The influence of organic crop rotations on the structure of collembolan communities

The field study comparing different crop rotations indicated that the share of euedaphic individuals can be used as an indicator for stabilizing habitat conditions (Martins da Silva et al., 2016). Here, "habitat stability" is supposed to be related to a continuous availability of organic matter provided by farmyard manure and a higher proportion of fodder and grain legumes. Collembolans prefer habitats with a continuous supply of organic matter (Vreeken-Buijs et al., 1998), which was ensured in the mixed farming system by the regular application of farmyard manure and slurry. On the contrary, in the stockless system, organic matter was only returned to the soil as grain straw and mulch of clover leys. Organic matter from green manure, grain straw, and farmyard manure differs strongly in their influence on soil properties (Mohanty et al., 2011). While manuring with straw has positive effects on soil structure and soil physical properties (Kautz et al., 2006), farmyard manure has a particularly positive effect on the C and N content of the soil (Tirol-Padre et al., 2007). Organic inputs are known to enhance soil microbial activity (Gomiero et al., 2011) but different types of organic matter may lead to different microbial community composition (Bowles et al., 2014). Since collembolans, in turn, rely on the microbial community, organic matter may have an indirect effect on their community composition.

III.4 Indicators for soil biodiversity

Because of the importance of soil biodiversity in human well-being, particular attention should be paid to its status and development. Biological indicators are important in supporting sustainable management, as well as policy and decision-making. However, describing and evaluating the status of the soil fauna is difficult because of the high temporal and spatial variability of soil organisms. To sufficiently describe effects of different land uses, a set of indicators is necessary (Griffiths et al., 2016).

III.4.1 Earthworms

It was shown in this thesis, that well-known indicators to describe the status of earthworm communities like abundance and biomass (Turbé et al., 2010) can also be used to discriminate between earthworm communities under different tillage systems in the short-term (II.1.1). However, the time interval between the impact of interest (in this case tillage) and earthworm sampling has to be considered. In spring, the different tillage measures taken in autumn could not be discriminated by evaluating earthworm abundance. This effect may be the cause for the earthworm abundance sometimes not being rated as a valuable indicator for agricultural pressures (Cluzeau et al., 2012). Whether tillage can significantly influence species diversity of earthworms is debatable. The study on earthworms under occasional reduced tillage did not show differences in species numbers. This is in line with Pulleman et al. (2012), who found species composition to be rather stable, while abundance and biomass varied more depending on environmental factors. In contrast, a review by Chan (2001) showed that conventional tillage can significantly alter the species composition of earthworms. However, these changes in species composition could only be shown when comparing earthworm communities under conventional tillage to those of perennial leys or permanent grasslands.

Until now, studies on earthworm surface casts have mainly dealt with the physico-chemical properties of casts or their overall influence on soil characteristics (e.g. Abail et al., 2017; Singh et al., 2017; Vidal et al., 2017). Some investigations regarding the use of surface casts as indicators for the status of earthworm communities have been conducted in Africa (Birang et al., 2003; Hauser et al., 2012). However, in these studies, forests or fallows were compared with cropped fields. In agricultural fields, the number of earthworm casts has been used as a proxy for overall earthworm activity (Perreault et al., 2007; Thakuria et al., 2009) or, in particular, for the activity of *L. terrestris* (Sharpley et al., 2011). However, none of these studies except for the study of Scullion et al. (2007) tried to establish a numerical relationship between the characteristics of earthworm communities, such as abundance or biomass, and the number of surface casts. Scullion et al. (2007) did some calculations and found significantly positive correlations between casts and earthworm abundance when evaluating data from leys or from leys and arable fields simultaneously. Nevertheless, the authors did not show any significant correlations when only data from arable fields were considered.

In this thesis, a positive correlation between the number of earthworm surface casts and the abundance of *L. terrestris* could be found. Since *L. terrestris* is an important ecosystem engineer in Central Europe and, consequently, its abundance is a valuable indicator of biological soil conditions

(Paoletti, 1999), counting surface casts can be used to provide an estimate for the functioning of the ecosystem.

Since earthworm casts can be easily detected in the field without expert knowledge and special equipment, they could be increasingly used as indicators for the abundance of *L. terrestris.* Surface cast counting could be used to assess and improve soil health in the field (Guidotti et al., 2017). Farmers and agricultural consultants could use the number of earthworm surface casts to give the first estimate of soil biological conditions on single fields. To promote this method, efforts should be made to establish thresholds or target figures under different soil and climatic conditions (Havlicek, 2012). Since ancient pastures and meadows can be used as a reference for complete earthworm communities of a certain region (Paoletti, 1999), these ecosystems could also be used as a reference system for the potential number of earthworm surface casts.

III.4.2 Collembolans

The results of this thesis showed that collembolan communities were most sensitive to the types of crops cultivated and the related changes in soil moisture and acidity (c.f. II.2). On the contrary, different crop rotations and tillage regimes did not strongly influence the community composition in the long-term.

The fact that collembolan communities, that were studied for this thesis, differed in terms of species composition four weeks after tillage and then aligned (II.2.2) shows that they can be used to assess inertia (the relative resistance of community structure to perturbation) and elasticity (the required time to return to the undisturbed state) of soil ecosystems (Migliorini et al., 2005). The soils and their collembolan communities studied here have been treated under agricultural management for many years, have therefore adapted to the regular disturbance through tillage, and react in a periodic manner.

One of the major problems in using collembolans as indicators are the taxonomic challenges within this group (Gerlach et al., 2013). As many traits of collembolan species can be linked to environmental variables (Salmon et al., 2014), it might be valuable to use mean species traits values to derive environmental indicators. One method is to deduce an eco-morphological index (EMI) from some important traits (Martins da Silva et al., 2016; Vandewalle et al., 2010). This approach was applied (II.2.1) and combined with the use of collembolan life-forms (Gisin, 1943). In addition to the mean trait value of EMI (EMI mT) the shares of euedaphic, hemiedaphic, and epigeic individuals can be displayed in ternary diagrams. This allows to intuitively compare different collembolan communities. The share of different life-forms showed some potential as relatively easy-to-use bioindicators. Significant differences between management schemes, however, could not be established. In terms of EMI mT-values, the yearly effects showed the only significant differences.

Differences in the share of collembolan life-forms in different soils as trait based approaches are promising (Turbé et al., 2010) and might be subject to further investigations. Studies on more sandy soils may be especially interesting as there the relative importance of collembolans increases (Blume et al., 2010).

In contrast to earthworms, the investigations giving a first estimate of the status of collembolan communities directly in the field are not feasible. The high technical effort required to extract collembolans from soil samples prevents the use of this group in agricultural consultancy. Nevertheless, eco-morphological indices and other trait-based approaches can be used in drafting expert opinions. The use of collembolan communities as soil fauna indicator can be further optimised by using gel-based sub-sampling (Jagers op Akkerhuis et al., 2008; Mulder and Elser, 2009). This approach is based on the evaluation of only 70 individuals from each sample, which provides a higher predictability of how many samples can be routinely assessed in a certain timeframe.

III.4.3 Soil fauna indicators: General remarks

The studies conducted for this thesis were all undertaken on the experimental station of the Thuenen-Institute of Organic Farming. The soils on the farm are Stagnic Luvisols characterised as loamy according to Soil Survey Divison Staff (1993). This has to be considered as the soil type is known to influence the soil fauna. While the mesofauna (collembolans, mites, enchytraeids) is more adapted to living in sandy soils with stable structure, anecic earthworms like *L. terrestris* are not able to sustain their burrows in coarsely textured soils and therefore can be found more frequently in loamy soils (Blume et al., 2010). Furthermore, enchytraeids, collembolans, and mites tolerate more acidic soil conditions than earthworms (Blume et al., 2010). The different influence of soil types on soil biota is of particular interest in soil monitoring as the soil types also show specific reactions to agricultural management. For instance, Peigné et al. (2018) found increased soil compaction under conservation tillage on sandy soils, which in turn influenced the earthworm communities. Consequently, the usability of biological indicators has to be verified for light, loamy, and heavy soils (Soil Survey Divison Staff, 1993).

Soils are highly complex habitats, and soil biota are influenced by a wide range of abiotic (e.g. temperature, moisture, soil compaction) and biotic (e.g. inter- and intraspecific competition) factors. Therefore, the utilisation of soil fauna to monitor soil health is complex. Evaluating the influence of management measures on soil fauna can only be reliable when a set of preconditions is met. Indicators can only give trustable results based on only one influencing factor to avoid further interactions (e.g. fertilisation x tillage). The communities of soil organisms run through periodic changes throughout the year, based on differences in soil temperature and soil moisture. Therefore, the sampling of soil organisms should only be conducted during periods of the year with in general optimal abiotic conditions for the respective group. Comparisons can only be conducted within similar soil types as these strongly influence habitat conditions of soil organisms.

Different characteristics of soil organism groups have a different potential as indicators. Therefore, a graduated use of information could be useful. Measurements with only a few manifestations, like life-forms of collembolans, could be used for general comparisons of different ecosystems like meadows and arable fields. Conversely, differences in arable fields at the same site may be only detectable by evaluating collembolan data with methods of multivariate statistics, which can potentially reveal a broad spectrum of differences. However, to deviate ecological gradients from multivariate collembolan data, autecological information on single species is required. Unfortunately, such information is scarce (c.f.II.2.1).

This thesis focussed on the use of soil biodiversity indicators in an agricultural context to identify and optimise sustainable soil management strategies. Moreover, soil biodiversity indicators have the potential to raise awareness of the capacity of soil resources to support human well-being. Furthermore, these indicators could also be used to develop guidelines for decision makers regarding future strategies to counteract negative trends in soil health (Pulleman et al., 2012). Despite the potential for soil biodiversity monitoring to improve decision-making processes, it is currently not part of any European legislation (Römbke et al., 2016). Römbke et al. (2016) have identified the control of cross-compliance rules, of sewage sludge, compost and bio-waste application, and the evaluation of the use of pesticides or genetically modified organisms as potential scopes for soil biodiversity indicators on the European level. Pulleman et al. (2012) highlighted that indicators have to facilitate communication with and between various end users and therefore have to be as simple and clear as possible.

The pan-European EcoFINDERS project showed that molecular biological methods are becoming more and more important in monitoring soil biodiversity and ecosystem functions (Lemanceau et al., 2016). A ranking of potential indicators by Stone et al. (2016) revealed that out of their top ten indicators, seven made use of molecular methods. Regarding higher organisms, DNA-barcoding gains more importance, for example, with the German GBOL initiative (German Barcode of Life, 2017) and its worldwide umbrella system, the BOLD System (Barcode of Life Data Systems, 2017). Portable devices for conducting DNA-barcoding in the field are available nowadays (NANOPORE, 2017; Pomerantz et al., 2017), which will influence monitoring of soil biodiversity. Besides DNA-barcoding, next-generation sequencing will markedly change soil biodiversity research and monitoring. Between 2001 and 2014, the cost of sequencing genomes was reduced by the factor 100,000. At the same time, it became possible to provide more than 12 million sequences within one day with an accuracy of 99.9 % (Orgiazzi et al., 2016a).

Nevertheless, with the current state of the art, indicators based on soil fauna abundance, biomass, and morphological species diversity are still very important. For earthworms, counting surface casts or the spade test (Beste, 1997) are easy to use low-priced methods to quickly derive information on soil health. Although the extraction and determination of collembolans is more time consuming than the study of earthworms, the technical requirements are still acceptable. Moreover, several soil chemical gradients can be derived from collembolan species data, and information derived from the share of different life-forms can be used to give an overall estimate of the soil conditions at the time of sampling. In general, using species traits as indicators is supposed to foster generalisation across eco-regions and make the use of indicators independent of taxonomy (Pulleman et al., 2012).

Part IV Summary

IV.1 Summary (in English)

Soil health is defined as the ability of soils to maintain ecosystem functions in the long-term and subsequently provide ecosystem services. Arable farming relies on several ecosystem services, and many of these services are largely dependent on an abundant and diverse soil fauna. Earthworms are the most important representatives of the soil macrofauna in central Europe. They are loosening the soil through their burrowing activity, incorporate organic material, and mix mineral and organic soil components. These activities initiate and promote decomposition by other soil microorganisms. Besides earthworms, the members of the soil mesofauna (mainly collembolans and acari) mediate the decomposition process. They are secondary decomposers feeding on soil microorganisms. Decomposition of organic matter in the soil is an important part of natural nutrient cycles and provides plants with nutrients.

While in conventional farming the use of artificial chemical fertilizers has largely replaced nutrient provisioning from organic matter, organic farming strongly relies on decomposition and cycling of organic fertilizers. Therefore, organic farmers aim at fostering an abundant and diverse soil fauna. To evaluate efforts seeking to make progress to that end, indicators are needed to describe the status of soil biodiversity.

This thesis aimed to further develop easy-to-use indicators that are used to describe the status of the soil fauna. In particular, characteristics of earthworm and collembolan communities and their suitability as soil biodiversity indicators were analysed.

In this thesis, the impact of different organic crop rotations and different tillage regimes on these organism groups was investigated. The suitability of data on earthworm and collembolan communities to distinguish between different management practices was investigated. The use of reduced tillage systems is currently discussed both in science and practice, and the evaluation of the effects (and suitability) of occasional reduced tillage in organic farming is an important part of this thesis.

Occasional reduced tillage (ORT) positively influenced earthworm performance already in the short-term. In the same study, it was shown that besides earthworm diversity, biomass, and abundance the number of earthworm surface casts can be used to describe earthworm communities. The short-term positive response of earthworm performance to reduced tillage could be verified for organic arable farming in general. A meta-analysis showed that reducing tillage intensity positively influenced earthworm abundance and biomass in organic farming.

Collembolan species richness and abundance could not be used to distinguish different management practices. In terms of the species composition, it was observed that it differed between conventional and reduced tillage immediately after implementing but aligned under the different practices within

half a year. The share of euedaphic collembolan individuals showed some potential to serve as an indicator for discriminating between different management practices. This was shown when comparing crop rotations and tillage systems. The proportion of euedaphic individuals increased when habitat conditions started to stabilise. Stable habitat conditions refer to constant resource availability, constant soil moisture conditions, and the absence of soil disturbance.

However, different crop classes and interannual variations in soil conditions influenced the community composition of collembolans. Soil acidity and soil moisture were identified as determining factors for differentiation.

Overall, the count of earthworm surface casts was shown to be an easy-to-use indicator for abundance and biomass of anecic earthworm species, especially *L. terrestris*. Concerning collembolans, no indicator that can be used as easily as the count of earthworm casts, could be detected. Nevertheless, collembolan life-form traits showed some potential as indicators for discerning between different management practices and are at the same time relatively easy to identify.

Advanced technological methods like DNA-barcoding will change the monitoring of soil fauna in the future. Nevertheless, easy-to-use indicators will, at least in the medium-term, continue to be used.

IV.2 Zusammenfassung (in German)

Böden gelten als gesund, wenn sie langfristig in der Lage sind, Ökosystemfunktionen und daraus resultierend Ökosystemdienstleistungen bereitzustellen. Ackerbausysteme nutzen eine Vielzahl von Ökosystemdienstleistungen, die maßgeblich von einer arten- und individuenreichen Bodenfauna abhängen. Regenwürmer sind in Mitteleuropa die wichtigsten Vertreter der Bodenmakrofauna. Durch ihre Grabaktivität sorgen sie für Durchlüftung und Lockerung des Bodens. Sie arbeiten organisches Material in den Boden ein und sorgen für eine Durchmischung von mineralischen und organischen Bodenbestandteilen, wodurch sie auch die weitere Zersetzung der organischen Substanz durch Bodenmikroorganismen fördern. Die Vertreter der Bodenmesofauna (hauptsächlich Collembolen und Milben) beeinflussen als Sekundärzersetzer die Nährstoffkreisläufe, indem sie sich von Mikroorganismen ernähren und dadurch deren Abundanz und Aktivität verändern können. Die Zersetzung organischer Substanz im Boden ist ein wichtiger Bestandteil aller natürlichen Nährstoffkreisläufe und Grundlage der Nährstoffversorgung der Pflanzen.

Während in konventionellen Ackerbausystemen mineralische Dünger für einen Großteil der Nährstoffversorgung der Kulturen verantwortlich sind, ist im ökologischen Pflanzenbau der möglichst optimale Umsatz organischer Düngemittel im Boden von großer Bedeutung. Aus diesem Grund ist die Förderung einer individuen- und artenreichen Bodenfauna ein wichtiges Ziel im ökologischen Landbau. Um einschätzen zu können, wie der Zustand der Bodenfauna ist und wie sich unterschiedliche Managementmaßnahmen auswirken, werden aussagekräftige Indikatoren benötigt.

Ziel dieser Dissertation war es, solche Indikatoren weiterzuentwickeln. Hierzu wurden Effekte unterschiedlicher Bodenbewirtschaftungsverfahren analysiert.

Ein besonderes Augenmerk sollte dabei auf der einfachen Anwendbarkeit der Indikatoren liegen.

Als potentielle Indikatoren wurden die Eigenschaften von Regenwurm- und Collembolengemeinschaften untersucht.

Im Rahmen der vorliegenden Dissertation wurden unterschiedliche Fruchtfolgen des Ökolandbaus und unterschiedliche Bodenbearbeitungssysteme hinsichtlich ihrer Auswirkungen auf diese Organismengruppen verglichen. Daraus wurde abgeleitet, welche Charakteristika der Gemeinschaften sich eignen, um die unterschiedlichen Managementmaßnahmen voneinander zu unterscheiden. Da die Eignung von Verfahren der reduzierten Bodenbearbeitung im ökologischen Landbau derzeit in Wissenschaft und Praxis diskutiert wird, war die Analyse des vorübergehenden Pflugverzichts ein wichtiges Thema der Dissertation.

Es zeigte sich, dass sich schon der einmalige Verzicht auf den Pflug (occasional reduced tillage - ORT) positiv auf die Regenwurmbiomasse und -abundanz auswirken kann. In derselben Untersuchung zeigte sich weiterhin, dass sich neben der Regenwurmdiversität, -biomasse und -abundanz auch die Zahl der an der Bodenoberfläche abgelegten Losungshaufen eignet, um Regenwurmgemeinschaften

zu beschreiben. Darüber hinaus konnte in einer Meta-Analyse gezeigt werden, dass sich reduzierte Bodenbearbeitung im ökologischen Landbau allgemein positiv auf die Biomasse und Abundanz von Regenwürmen auswirkt.

Es stellte sich heraus, dass sich Abundanz und Artenzahl von Collembolen nicht eignen, um Managementunterschiede nachzuweisen. Beim Vergleich des konventionellen mit dem reduzierten Verfahren der Bodenbearbeitung unterschied sich die Artenzusammensetzung zwar vier Wochen nach der Bodenbearbeitung, nach circa einem halben Jahr waren aber keine Unterschiede mehr nachweisbar.

Der Anteil eu-edaphischer Collembolenindividuen zeigte einiges Potential als Indikator für Managementunterschiede. Unterschiede traten sowohl beim Vergleich der Fruchtfolgen, als auch beim Vergleich der unterschiedlichen Bodenbearbeitungssysteme auf. Der Anteil eu-edpahischer Individuen war tendenziell höher, wenn sich die Habitatbedingungen stabilisierten. Von einer Stabilisierung wird bei gleichbleibender Nährstoff- und Wasserverfügbarkeit bzw. dem Fehlen regelmäßiger Störungen ausgegangen.

Die Artenzusammensetzung der Collembolen reagierte zwar nicht auf Managementunterschiede, zeigte aber Unterschiede in Abhängigkeit von der angebauten Kulturart oder des Untersuchungsjahres. Bodenfeuchte und pH-Wert waren hier die bestimmenden Faktoren.

Insgesamt stellte sich heraus, dass die Zahl von Regenwurmlosungshaufen an der Bodenoberfläche ein sehr einfach anzuwendender Indikator für die Abundanz und Biomasse anezischer Regenwürmer und besonders für L. terrestris ist. Für Collembolen konnte kein vergleichbar einfach anzuwendender Indikator abgeleitet werden. Dennoch zeigten die Lebensformtypen der Collembolen einiges Potential als Indikatoren und diese sind deutlich leichter zu bestimmen als Collembolenarten.

Das Monitoring im Bereich Bodenfauna wird sich in Zukunft durch Methoden des DNA-Barcodings verändern. Dennoch werden einfach anzuwendende Indikatoren ihre Bedeutung weiterhin behalten.

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Appendix

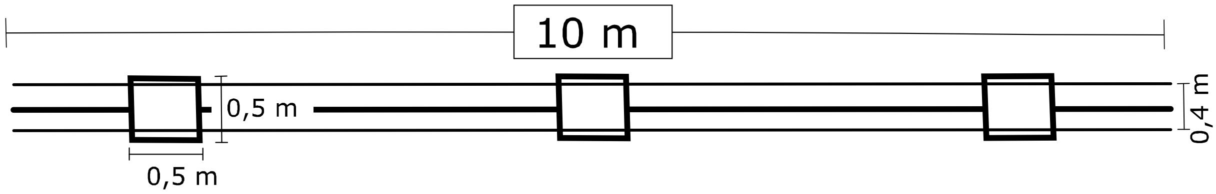

Figure A 1: Sketch of the sampling transects used within the study for examination of earthworm performance. Two transects were set up per half-field in October 2012, April 2013 and October 2013.

Table A 1: Earthworm biomass (total) and abundance (total and species specific number of individuals [Ind. m-2]) in different organic farming systems (dairy, ruminant II, pig) and under different tillage systems (CT vs. ORT). ORT: occasional reduced tillage; CT: conventional tillage; sub.: subadult; ND: no data.

Farming system	Date	Transect	Type	Casts per Transect	Biomass [g m^{-2}]	Number of Ind. per m^2	Aporrectodea caliginosa	Allolobophora chlorotica	Aporrectodea rosea	Sum endogeic	Lumbricus terrestris	Lumbricus terrestris sub.	Aporrectodea longa	Aporrectodea longa sub.	Sum anecic	Lumbricus rubellus	Lumbricus castaneus	Sum epigeic	Epilob (endogeic) juv	Tanylob (anecic or epigeic) juv	Not determined
Dairy	10.2012	T1	CT										ND								
	04.2013	T1	CT	2	8.21	26		12	1	13				1	1				11		1
	10.2013	T1	CT	10	14.07	46	3	12	1	16			1		1				15	13	1
	10.2012	T3	CT										ND								
	04.2013	T3	CT	14	25.65	31	3	5	4	12	1	1	1	3	7				12		
	10.2013	T3	CT	10	21.87	40	7	8		15			4		4				12	9	
Dairy	10.2012	T4	ORT										ND								
	04.2013	T4	ORT	6	20.55	41	1	7	11	19			3	4	7				13		3
	10.2013	T4	ORT	27	ND	156	3	11	12	25	7	1	1	3	12				95	21	3
	10.2012	T6	ORT										ND								
	04.2013	T6	ORT	13	14.08	19	3		7	9	1			1	3				4	1	2
	10.2013	T6	ORT	42	144.41	331	57	24	7	88	5	7	8	1	21				160	55	7
Ruminant II	10.2012	T1	CT	9	25.01	37	4	1		5	4				4				25	3	
	04.2013	T1	CT	9	46.67	63	11	1	1	13		5	5	3	13				25	7	4
	10.2013	T1	CT	28	43.23	78	12	4	3	19		7	4	3	13				35	7	5
	10.2012	T3	CT	23	51.19	95	5			5	4	1	3		8				59	20	3
	04.2013	T3	CT	20	78.32	150	28	19	7	53	4	4	1		9				67	17	3
	10.2013	T3	CT	53	56.25	102	13		1	15		12	1	4	17				57	9	3
Ruminant II	10.2012	T4	ORT	19	103.37	245	23	19	1	43	5		5	4	15		1	1	143	29	14
	04.2013	T4	ORT	33	73.64	115	12	28	3	43	3	21		1	25				37	3	7
	10.2013	T4	ORT	43	ND	277	59	16	17	92	5	5	1	5	17				116	47	5
	10.2012	T6	ORT	21	91.17	204	19	17	1	37	5		4	11	20		1	1	123	17	5
	04.2013	T6	ORT	18	103.55	177	48	17	5	71	3	5	4	7	19				68	9	10
	10.2013	T6	ORT	66	122.39	289	35	29	12	76	4	17	1	5	28				124	49	12

Table A 1 (continued)

Farming system	Date	Transect	Type	Casts per Transect	Biomass [g m^{-2}]	Number of Ind. per m^2	Aporrectodea caliginosa	Allolobophora chlorotica	Aporrectodea rosea	Sum endogeic	Lumbricus terrestris	Lumbricus terrestris sub.	Aporrectodea longa	Aporrectodea longa sub.	Sum anecic	Lumbricus rubellus	Lumbricus castaneus	Sum epigeic	Epilob (endogeic) juv	Tanylob (anecic or epigeic) juv	Not determined
Pig	10.2012	T1	CT	0	16.21	31				0				1	1				23	5	1
	04.2013	T1	CT	11	43.80	108	17	25		43				4	4				56	1	4
	10.2013	T1	CT	39	34.25	144	33	5		39				4	4				85	12	4
	10.2012	T3	CT	16	12.13	83	3		1	4			1	1	3				67	1	9
	04.2013	T3	CT	2	37.60	99	7	8		15				3	3	4		4	72		5
	10.2013	T3	CT	8	45.64	181	31	15		45			1		1				120	12	2
Pig	10.2012	T4	ORT	8	32.48	143	9	8		17				4	4	3	4	7	97	5	12
	04.2013	T4	ORT	36	140.16	229	83	23	3	108	5	1	3	1	11				101	3	6
	10.2013	T4	ORT	47	152.56	617	75	57	3	135		1	9	1	12	13	5	19	367	80	5
	10.2012	T6	ORT	27	77.22	196	53	8	1	63	3			11	13				105	5	9
	04.2013	T6	ORT	29	154.36	235	63	35		97	3		8	7	17	1		1	97	8	13
	10.2013	T6	ORT	28	157.01	574	95	49	12	156	1	4	12	1	19				332	56	11

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