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Relations between Agronomic Practice and Earthworms in Norwegian Arable Soils

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ABSTRACT

This paper presents Norwegian studies of earthworms (density, biomass, burrows density, species, juvenile to adult ratios) in arable soil in Norway conducted during the last 20 years. The effects of crop rotations, fertilization, soil tillage and compaction on earthworms are presented, based on various field experiments. Geophagous (soil eating) species such as *Aporrectodea caliginosa* and *A. rosea* dominate the earthworm fauna in Norwegian arable soil. *Lumbricus terrestris* is also present; in our studies even frequently found in an all-arable crop rotation with annual ploughing. In southern Norway, *L. rubellus*, and *A. longa* are commonly found. Earthworm density, recorded in autumn varied between 30 and 350 individuals m^{-2} in different studies, with the lowest values found in conventional all-arable farming systems. One year of ley in the crop rotation increased earthworm burrow density, earthworm density and biomass. Even short-term leys for green manure had a positive effect, likely due to high clover content. Application of animal manure increased earthworm density and biomass. Because geophagous species prefer the upper soil layer, shallow ploughing (15 cm depth) was expected to be detrimental. However, the earthworm density and biomass was not lower with shallow as compared to deep ploughing (25 cm depth). With earthworm densities such as those found in farming systems with ley and animal manure, an estimated amount of 221 tonne of topsoil per hectare passes through the earthworm digestion system within one year. Field-collected geophagous earthworm casts had considerably higher concentrations of plant nutrients than bulk soil (28% higher concentration of Tot-N, 36-53% for P_{AL}, 40-59% for K_{AL}). Hence, earthworm casts are significant natural sources of plant nutrients, also in soils with high dominance of geophagous earthworm species.

Keywords: casts, crop rotation, fertilization, manure, ploughing, soil tillage

Abbreviations: ANE, average nutrient enrichment; **DM**, dry matter; **JAR**, juvenile to adult ratio; **SE**, standard error

INTRODUCTION

The background to and aim of this paper

Until about 1990, very few studies of earthworms in arable soil had been conducted in Norway. In parallel to an increasing interest in organic farming methods since then, several studies of earthworm fauna and activity have been carried out and published by various authors, referred to in **Table 1**. In addition to this, the authors of this paper have participated in several studies where earthworm investigations have been complementary to the main agronomic topics such as yield levels and weed management. Over the years, this work has accumulated into a body of material worthy of an overall presentation.

The purpose of this paper is to present relations between agronomic practice and earthworms (density, biomass, burrow density, juvenile to adult ratio) in arable soil in Norwegian field experiments. We discuss these results in a context where the principles of organic farming constitute the background. An introduction is describing the ecology of earthworm species, soils and agriculture in Norway and the principles of organic farming. Then Norwegian studies of earthworm species in arable soil are presented, focusing on the geographical distribution and dominant species. This is done to substantiate the results presented in the main results and discussion section. This latter section initially presents results on how earthworm activity was influenced by agronomic means such as crop rotation and fertilization in two long-term experiments. Thereafter we focus on the impact of soil tillage and compaction, and relations between earthworm activity and decomposition of organic matter, which were studied in short term experiments. Finally, we present the nutrient content in earthworm casts collected in field. The outcome is an overview of what we know about earthworms in arable soil in Norway by 2009.

Detritivorous and geophagous earthworm species

The significance of earthworms to promote soil fertility has been acknowledged for a long time. Charles Darwin was probably the first to examine scientifically the effect of earthworms on soil morphology, in his classical work “The Formation of Vegetable Mould through the action of worms with observations of their habits” (Darwin 1881). The largest species found under north European conditions, the dew worm (*Lumbricus terrestris* Linneaus), has received much attention for its activities, mixing plant residues and soil and living in the same permanent deep burrow for several years (Edwards and Bohlen 1996; Butt and Nuutinen 2005). Their large size, and their production of small, but striking heaps of manure and plant residues on the soil surface, have made more scientists than Darwin interested in this species. The dew worm is detritivorous, meaning that this species eats fresh and decomposing plant residues, and its favourite habitat is pastures, lawns and gardens where plant residues are available and where deep soil tillage seldom occurs. In regularly ploughed soil this species is less frequently found, and smaller, soil eating (geophagous) species, with more temporary burrows usually dominate the earthworm fauna (Rasmussen 1999; Chan 2001). The geophagous species seem to cope better with disturbances such as soil tillage and compaction. The field worm (*Aporrectodea caliginosa* Savigny) and the pink worm (*Aporrectodea rosea* Savigny) are such geophagous species frequently found in Scandinavian arable soils. Geophagous earthworm

Received: 29 April, 2009. Accepted: 3 December, 2009.

Original Research Paper

Table 1 Earthworm species found in arable soil in Norway in scientific studies since 1987, sites ranked by increasing latitude. Xb= dominant species by biomass, Xn= dominant species by number/density, Xbn = dominant species by both biomass and number/density. X without extra letter = second most common species, x = common species, but found in lower amounts than the dominating species, * = less than three individuals found or less than 1 g m^{-2}.

Species/ Site, year, latitude	***A. caliginosa***	***A. rosea***	***A. longa***	***L. rubellus***	***L. terrestris***	***A. chlorotica***	***O. cyaneum***	***D. rubidus***	***L. castaneus***	**Reference**
Landvik, 1993 58°20´N	Xn	*	Xb	x	x	X				Sveistrup *et al*. 1997
Landvik, 1996	Xb	x	X	X	x	X	*			Bakken *et al*. 2006
Landvik, 2000	Xb	*	X	x	x	*				Bakken *et al*. 2006
Voll, Ås, 1993 59°40´N	Xbn	x	x	x		X				Sveistrup *et al*. 1997
Voll, 1996	Xb	x	*	X	*	X				Bakken *et al*. 2006
Voll , 2000	X	x	X	Xb		X				Bakken *et al*. 2006
Apelsvoll, 1994 60°42´N	Xn	x	*		x					Engelstad (pers. obs.)
Apelsvoll, 2004	Xn	X		x	x			*		Pommersche (pers. obs.)
Møystad, 2006 60°47´N	Xn	x		x	Xb					Pommeresche (pers. obs.)
Surnadal1987-89 63°00´N	Xbn	x		X		*		*		Hansen and Engelstad 1999
Skjetlein,1991 63°20´N	Xbn	x	*	X	*					Haraldsen *et al*. 1994
Kvithamar, 1993 63°30´N	Xbn	x		X	*	*		*	*	Sveistrup *et al*. 1997
Kvithamar, 1996	Xb	x		X		*				Bakken *et al*. 2006
Kvithamar, 2000	Xb	x		X	x	X		*	*	Bakken *et al*. 2006

species eat their way through the soil and consume organic matter included in the soil they eat. Animal manure as well as small particles of partly decomposed plant residues are consumed, but these species do not prefer fresh plant residues (Edwards and Lofty 1977). The geophagous species are usually found in the upper soil layer, in the growing season seldom below 25 cm (Rundgren 1975). The usual ploughing depth is Scandinavia is 20-25 cm.

In addition to the geophagous/detritivorous distinction, several other schemes have been proposed to classify earthworm species into major ecological categories. The ecological groups of Bouché (referred by Edwards and Bohlen 1996) differentiate earthworms into epigeic, anecic and endogeic species, based on combinations of morphology, behavior and habitat preference. The epigeic species are mainly litter dwellers, living in surface litter and composts, and frequently found in changeable temporary microhabitats. Epigeic species found in arable soil and composts in Scandinavia are generally heavily pigmented, and comprise the species *Lumbricus rubellus* (Hoffmeister), *Lumbricus castaneus* (Savigny), *Dendrodrilus rubidus* (Savigny) and the compost worms *Eisenia fetida* (Savigny) and *Eisenia andrei* (Bouché). The anecic group covers deep-burrowing species with vertical permanent burrows, emerging – usually at night – to feed on plant residues and litter on the soil surface. *L. terrestris* and *Aporrectodea longa* (Ude) are anecic earthworm species commonly found in Scandinavian arable soil. Endogeic species inhabit the mineral soil. They are often less pigmented, and commonly geophagous. They produce temporary burrows and leave their casts in the soil rather than on the soil surface. *A. caliginosa*, *A. rosea* and *Octolasion cyaneum* (Savigny) are endogeic species commonly found in Scandinavian agricultural soil.

Earthworms and agronomic means

Earthworms and their activity are important to improve and maintain soil fertility, soil structure and aggregate stability (Edwards and Lofty 1977; Clements *et al.* 1991; Marinissen 1994). That earthworms influence plant growth positively by their presence in soil, is shown in several studies, but still much is unclear about the earthworm-plant interrelationships in the soil (Scheu 2003). An experimentally induced absence of earthworms in a grass sward was found to increase soil compaction and more litter was accumulated on the soil surface (Clements *et al.* 1991). The absence of earthworms also greatly reduced soil organic matter, soil moisture and infiltration rate in the same study.

Systems with grass and clover in the rotation often host higher biomass and numbers of earthworms compared with all-arable systems (Edwards and Lofty 1977; Schmidt *et al.* 2003). Organic cropping systems have shown higher earthworm biomass and density than conventional systems (Mäder *et al.* 2002), but this is not always so (Scullion *et al.* 2002). Animal manure provides food and increases the biomass of earthworms (Curry 1976; Andersen 1979: Hansen and Engelstad 1999), but slurry may be toxic in the short term (Curry 1976). Similarly, ammonium-based inorganic fertilizers may be harmful to earthworms, especially in sandy soils (Lofs-Holmin 1983; Hansen and Engelstad 1999). Mineral fertilizers may have a positive effect on earthworms by increasing the amount of plant biomass, thereby increasing their food supply (Edwards and Lofty 1982).

Ploughing of established grassland increases earthworm populations, but continuous cultivation usually lowers them (Lee 1985). Positive effects on earthworms are often found under reduced tillage systems (Rasmussen 1999; Chan 2001). The choice of tillage method affects the relative abundance of earthworm species. No tillage/direct drilling often favours night crawlers (*L. terrestris*), whilst ploughing favours field worms (*A. caliginosa*) (Chan 2001).

Earthworms are sensitive to soil compaction (Söchtig and Larink 1992; Hansen and Engelstad 1999), but the negative effects depend much on the soil type and the humidity in the soil at the time of driving. Earthworm channels in the deeper soil layers (below 25 cm) are less disrupted by ploughing and compaction and thus indicate a more long term effect of the cropping systems and other agronomic means than the density and biomass of earthworms found in the topsoil.

Norwegian soils and farming systems

Only 4% of the Norwegian land is arable soil, and the whole country was glaciated until about 10 000 years ago. The post-glacial land-uplift has unveiled marine sediments with loam and clay soil in former fjord bays, with good conditions for crop production. Relatively large areas of this soil are found around the cities of Oslo and Trondheim. In the valleys, fluvial sediments with sandy soils are common along river beds, often well suited for production of vegetables and potatoes. Above the upper marine limit, morainic soil is common, and forage the most common crop. Morainic soils are usually linked to a sloping landscape, whereas the fields with sedimentary soils are relatively flat.

The mean annual temperatures in the agricultural areas are between +4 to 6°C. The annual precipitation varies geographically, from about 400 mm year^{-1} in the eastern parts to about 3500 mm in the western parts of Norway. Stretching from 57° to 71°N, Norway has a relatively cold climate with a slow decomposition of organic matter. Hence the average content of soil organic matter is high as compared to regions with a warmer climate. A typical value for arable mineral soil, based on 291 samples from 6 counties in southern Norway, is 3.4% soil organic matter (Riley and Bakkegard 2006). Due to leaching, as the annual precipitation is larger than the evaporation, Norwegian soils are generally slightly acidic ($pH_{H2O} < 7$).

Norwegian agriculture is designed for supplying a population of 4.8 million people (in 2009) with important food such as milk, meat, eggs, cereals, potatoes and vegetables. Ruminants have traditionally been important because of the good access to pastures in mountainous areas. Cereal production is dominated by barley, oats and spring wheat. The yields and crops vary geographically, with one harvest of grass ley in the North and three times in the south. Larger and heavier tractors and machines are used on the fields now than only a few years ago. Organic farming is encouraged by the government, with a national goal of 15% organic production and consumption by 2015 (LMD 2009). By the end of 2008, 5.1% of the farm land was organically managed or under conversion (Debio 2009). Dairy cows and other ruminants are the dominating productions in both organic and conventional farming systems.

Organic farming principles

Organic agriculture is based on four principles, of health, ecology, fairness and care (IFOAM 2009). The ecology principle is of high relevance for a discussion of earthworms as it states that organic agriculture should be based on living ecological systems and cycles, work with them, emulate them and help sustain them. Organic production is based on ecological processes and recycling, refraining from the use of synthetic fertilizers and pesticides. Hence, soil fertility, quality and structure have a special attention, and crop rotations and fertilization strategies are designed to support a living and productive soil. With no use of synthetic nitrogen (N) fertilizers, organic systems are dependent on biological processes in plants and soil such as N_2-fixation and mineralization of manure and plant residues for the N supply. For other nutrients, recycling of animal manure is essential to supplement the mineralization from the local soil to maintain satisfactory crop yields. The prohibition of synthetic pesticides forces the organic farmer to focus on preventive strategies in relation to weed management and pest control. In addition to human power, mechanic and thermal measures are commonly used against weeds, and natural agents and predators against pests.

Organic farmers tend to feed and protect the soil to increase and maintain high soil fertility, instead of adding the required amount of nutrients for each crop at the beginning of each season. To favour soil structure and conserve plant nutrients, a sufficient content of soil organic matter is required. Hence, both the production of organic matter in the field, the recycling of organic residues and the processes in the soil linked to decomposition of organic matter are of special interest in organic farming systems.

Earthworm species in Norwegian arable soil

Stöp-Bowitz (1969) conducted a thorough survey and identified 18 earthworm species in Norway. His study was more focused on the (re)invading of species after the last glacial period than the frequency of earthworm species in arable soil. However, seven species were identified as being indifferent to soil cultivation, called hemerodiaphores, and nine to be favoured by cultivation, called hemerophiles. The author also mentioned that the hemerodiaphore species *A. caliginosa* and *A. rosea* become dependent on cultivated soil for their survival in the northern (colder) regions of the country. Haraldsen and Engelstad (1998) presented the geographical distribution of earthworms in Norway, emphasizing their influence on soil properties. In **Table 1**, the species identified in scientific studies of earthworms in arable soil in Norway since 1987, are listed.

The first Norwegian study of earthworm species in an agronomic context was probably conducted by K. Retvedt and G. Uhlen in 1946 and 1947, studying the effects of different types and amounts of fertilizers on earthworms in pot experiments and field trials (Uhlen 1953). About 25 years ago, focus was again set on earthworms in arable soil. In a 10 year field experiment, located at an organic dairy farm in Surnadal (63° 00′ N), differences in yield levels with various soil compaction and animal manure treatments and amounts were studied (Hansen 1996). The earthworm fauna was identified to species in this system by Hansen and Engelstad (1999), and *A. caliginosa* and *A. rosea* were the most abundant species (**Table 1**). Several authors studied the earthworm fauna in agricultural research projects in different parts of the country in the same period (**Table 1**). For details about crop rotations, sampling methods and results we refer to the original papers.

Based on the studies referred in **Table 1**, we conclude that the most common earthworm species in arable soils in Norway is *A. caliginosa*, followed by *A. rosea* and *L. rubellus*. In the southern part of the country, *A. longa* is common, but this species is rarely found north of the 60°N latitude. At most sites, *L. terrestris* and *Allolobophora chlorotica* (Savigny) were found, but in low numbers. *O. cyaneum*, *D. rubidus* and *L. castaneus* were only found in very low numbers at a few sites. A few Norwegian records are published on earthworms in Tromsø (69°38´N) and further North. *A. caliginosa* and *L. rubellus* have been found several times in farmed land in Finnmark, around 71°N (Haraldsen and Engelstad 1994a, 1994b). The most northern observations of *L. terrestris* and *A. rosea* by Haraldsen (pers. comm.) are in Tromsø. The agricultural land on these latitudes is commonly permanent pastures with no or infrequent shallow ploughing. **Fig. 1** shows representative examples of adult individuals of four common earthworm species in Norwegian arable soil.

Because geophagous earthworm species dominate in arable soil in Norway, it is the impact of their main activity – soil eating – that influences soil quality characteristics such as soil organic matter content and soil structure. By

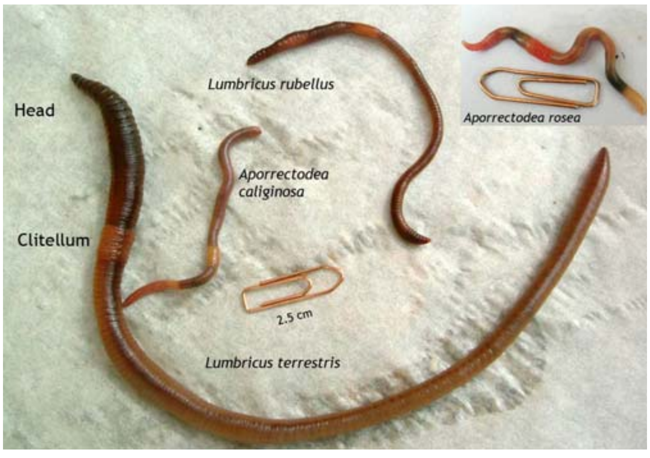

Fig. 1 Living individuals of adult earthworm species commonly found in arable soil in Norway. Note the differences in pigmentation, protecting the head of *L. terrestris* and the whole body of *L. rubellus* against the sun's rays. *A. caliginosa* and *A. rosea* are less pigmented and in *A. rosea*, even the gut content is visible. The two latter species do not so frequently visit the soil surface as the former ones. Photo by R. Pommeresche.

Table 2 Characteristics of six farming systems compared since 1990 at Bioforsk Arable Crops, research centre Apelsvoll. Abbreviations: Con = reference system of conventional practice as practiced in 1985; Opt = conventional practice optimized to reduce runoff; Org = organic practice. Ar = arable production system, Fo = fodder production system. Subscript numbers (0, 25, 50, 75) indicate percentage of ley in the crop rotation. To illustrate the intensity of fertilization, the average annual amount of nitrogen (N) applied in mineral fertilizer and/or cattle slurry, and fixed by legumes (estimated) is shown (from Korsæth 2008).

System	Crop rotation	Fertilization	Soil tillage	Pesticides used
ConAr$_0$	Potato	Mineral fertilizer	Autumn ploughing,	Cereal retardants, potato vine killer.
	Spring wheat	123 kg N ha^{-1}y^{-1}	spring harrowing	Herbicide
	Oats			Insecticide
	Spring barley			Fungicide - not in oats.
OptAr$_0$	Potato	Mineral fertilizer	Two times spring harrowing,	Oat retardant, potato vine killer.
	Spring wheat $_{CC}$[1]	121 kg N ha^{-1}y^{-1}	weed harrowing in cereals	Herbicide in potatoes.
	Oats $_{CC}$			Insecticide
	Spring barley $_{CC}$			Fungicide - not in oats.
OrgAr$_{25}$	Spring barley $_{U}$[1]	Only green manure	Spring ploughing,	None
	Grass-clover ley	N fixation	weed harrowing in cereals	
	Spring wheat $_{CC}$	46 kg N ha^{-1}y^{-1}		
	Oats and peas			
OptFo$_{50}$	Spring barley $_{U}$	Mineral fertilizer and cattle slurry	Spring ploughing,	Herbicide in spring barley.
	1st year ley	151 kg N ha^{-1}y^{-1}	weed harrowing in wheat	Insecticide and fungicide in cereals.
	2nd year ley	N fixation		Glyphosate before ley ploughing in 2004.
	Spring wheat $_{CC}$	23 kg N ha^{-1}y^{-1}		
OrgFo$_{50}$	Spring barley $_{U}$	Cattle slurry	Spring ploughing,	None
	1st year ley	63 kg N ha^{-1}y^{-1}	weed harrowing in wheat	
	2nd year ley	N fixation		
	Spring wheat $_{CC}$	63 kg N ha^{-1}y^{-1}		
OrgFo$_{75}$	Spring barley $_{U}$	Cattle slurry	Spring ploughing	None
	1st year ley	81 kg N ha^{-1}y^{-1}		
	2nd year ley	N fixation		
	3rd year ley	61 kg N ha^{-1}y^{-1}		

[1] Ryegrass as catch crop (CC)
[2] With undersown (U) grass-clover ley

their cast production and loosening and aeration of the soil, soil quality is positively influenced by earthworms. Equally, agronomic means such as crop rotation, fertilization, soil tillage and soil compaction influence the earthworm fauna. This will now be discussed based on studies in arable soil in Norway, in farming systems ranging from organic to conventional management.

METHODOLOGY

Effects of crop rotation and other agronomic means - the farming systems at Apelsvoll

1. Farming systems comparison

In order to assess long-term effects on productivity, environmental impacts and soil fertility of contrasting agronomic practices, six farming systems have been compared since 1990 on a loam soil at Bioforsk Arable Crops, research centre Apelsvoll (Eltun 1994; Korsaeth 2008; Riley *et al.* 2008). The location of Apelsvoll (latitude) is shown in **Table 1**. The experiment mimics systems ranging from conventional cash crop production without livestock to organic dairy production with mostly grass-clover ley (**Table 2**). Three systems are classified as arable (Ar), and three as fodder (Fo) production systems. All systems have a 4-year crop rotation with each crop present every year in two replicate plots. In addition to crop rotation and fertilization, main factors varying between the systems are the use of catch crops, soil tillage and pesticide use. Some changes in rotations and fertilizer levels were made in 2000, but the main features, such as manure use and incidence of ley in the rotation have been maintained since 1990 (Eltun 1994; Korsaeth 2008). One exception is the organic fodder system with 75% clover-grass ley (OrgFo$_{75}$), which was a conventional fodder production system with 50% ley until 1999, receiving both animal manure and some mineral fertilizer.

The experimental site comprises 12 blocks (30 m × 60 m) separated by 7.5 m wide grass border zones. The two blocks of each of the six systems are randomly distributed on the site. The ploughing depth is 22-23 cm. The amount of cattle slurry in each system is calculated from the theoretical number of cows sustained. The percentage of clover seed is 25% in the ley in organic arable system (OrgAr$_{25}$ see **Table 2**) composed of 15% red clover (*Trifolium pratense* L.) and 10% white clover (*Trifolium repens* L.). In all other leys, 10% of red clover is included in the seed mixture. With respect to earthworms, the main differences between the six farming systems are the amount of ley in the crop rotation, the use of cattle slurry and/or mineral fertilizers, the use of pesticides, and soil tillage.

2. Earthworm sampling

Earthworm density, biomass and burrow density were recorded in each farming system in October 1994 and again in late September - early October 2004. In all systems except OrgFo$_{75}$, plots used for sampling of earthworms had been used to grow spring wheat (*Triticum aestivum* L.), which was harvested two weeks before the sampling. In OrgFo$_{75}$, the sampling plots had been used for a third year ley. The sampling was destructive, and hence applicable only in plots which would be ploughed subsequently. The crop previous to the spring wheat was potatoes (*Solanum tuberosum* L.) in the conventional arable systems (ConAr$_0$, OptAr$_0$), and ley in all other systems (**Table 2**). In the OptFo$_{50}$ system, this ley was treated with Glyphosate in spring to kill all plants before ploughing.

From each plot, three soil blocks (50 cm × 50 cm × 25 cm depth) were dug out and the worms were removed by hand from the blocks and collected. These samples were merged to one composite sample from each cropping system. The worms were then identified to species according to Stöp-Bowitz (1969) and Sims and Gerard (1999), and into adults and juveniles within species. Earthworm density was recorded as the number of individuals m^{-2} of various species. The biomass was recorded as fresh weight (g m^{-2}) of various earthworm species, after some weeks of storage in 75% alcohol solution. The alcohol storage may reduce the weight slightly due to extraction of water, but most of the gut content is kept inside the worms by this storage method. Hence the measured fresh weight of earthworms is fairly comparable to field conditions. The density of earthworm burrows was recorded in the field on a horizontal face (50 × 50 cm) as the number of holes m^{-2}, just below ploughing depth at 25 cm, under each soil block. Holes over 2 mm were counted. No roots > 2 mm diameter were found at this depth, so all holes were made by earthworms. The juvenile to adult-ratio (JAR) was calculated. A high JAR indicates many juveniles and that the population is in growth.

The effects of systems on earthworm biomass, earthworm density and channel density were tested with ANOVA and the Ryan's test using the general linear model procedure in SAS (SAS Institute Inc. 1987). Contrasts were used to compare the systems with and without cattle manure and the systems with and without grass–clover ley. *t*-tests were used to compare the mean values for 2004 and 1994.

Effects of fertilization - the long-term fertilization trial at Møystad

1. The fertilization trial

At Møystad (latitude **Table 1**), a long-term fertilization trial has been running since 1922, measuring the effects on yield levels and soil characteristics of various fertilization practice on a fertile morainic loam soil. Various amounts and combinations of animal manure and mineral fertilizers are compared, in total 18 treatments with four replicates, each plot being 3.9 m × 7.7 m. From 1922 to 2006, the same seven-year crop rotation was followed, with three years of grass ley (no clover in the seed mixture), oats, potatoes, spring wheat and spring barley (*Hordeum vulgare* L.) undersown with grass ley seed. Each year, the same crop was grown on all experimental plots, which was in 2006 the third year of grass ley. The level of fertilization was increased (2 to 4 times more) in 1983 both for inorganic fertilizers and manure, to adapt to levels used in practical farming in Norway at that time. More details about the experimental treatments are provided by Riley (2006), e.g. the amounts of manure and mineral fertilizers before and after 1983, in addition to crop yields, nutrient balances and chemical analyses from 1983 to 2003.

2. Earthworm sampling

Earthworms were sampled in all replicate plots of four treatments with contrasting fertilization, in September/October 2006. The growing seasons from 2004 to 2006 were used to measure residual effects, with no nutrient application. The selected treatments were as follows: **Control**, unfertilized since 1922; **Mineral**, nitrogen (N), phosphorus (P) and potassium (K) in mineral fertilizer, 100-44-115 kg ha^{-1} y^{-1}, N applied as ammonium nitrate; **Manure low**, composted solid cattle manure, 20 tonne ha^{-1} y^{-1} equal to 80 kg total N ha^{-1} y^{-1}; and **Manure high**, composted solid cattle manure, 40 tonne ha^{-1} y^{-1} equal to 160 kg total N ha^{-1} y^{-1}. The fertilized treatments are roughly representative for the current fertilization level in conventional and organic farming in Norway.

Topsoil was sampled in one block (30 cm × 30 cm × 20 cm soil depth) dug out from each plot, in total 16 samples. Earthworms were removed by hand from the blocks, counted and sorted into juveniles and adults. Earthworms from deeper soil (below 20 cm) were sampled by pouring a mustard suspension (6 g mustard powder l^{-1} of water) into the holes where soil blocks had been removed. For topsoil worms, the total biomass was recorded as g m^{-2} after storage in 75% alcohol. The species of each worm was not determined, but the dominating earthworm species found on the experimental site were determined according to Stöp-Bowitz (1969) and Sims and Gerard (1999). For worms from the deeper soil, only *L. terrestris* were found, and classified into juvenile (with no clitellum) or adult (with clitellum) and weighed after storage in 75% alcohol. The JAR was calculated.

The effects of sampling depth and treatments on earthworm biomass were statistically tested by analysis of variance.

Effects of soil tillage and compaction - the soil tillage experiments at Apelsvoll and Kvithamar

1. The soil tillage experiment

In a study at Apelsvoll and Kvithamar (latitude in **Table 1**), the effects on earthworm activity of deep and shallow ploughing with light versus heavier tractors were investigated from 2003 to 2006 (Bakken *et al.* 2009). According to Rundgren (1975), the dominant species at both sites, *A. caliginosa*, is mostly found in the upper 10-15 cm of the soil in spring (April-May). Hence, shallow ploughing (15) cm was expected to cause more serious damage to the earthworms than deeper ploughing. By ploughing, the soil is cut and turned, and to prepare a seed bed, several tillage operations are added. Deeper ploughing will place the earthworm layer under a protecting layer of soil with few earthworms, which may decrease the risk of predation and damage by UV radiation and sun heat. It also increases the volume of tilled soil, which may reduce the risk of earthworms getting damaged by the soil tillage equipment. Being burried to a deeper soil layer was expected to be less damaging for *A. caliginosa*, which is adapted to a life within the soil and can eat its way back into its preferential layer.

The experiments were conducted in a three year arable organic crop rotation composed of green manure, spring wheat or barley with a catch crop of white clover and Italian ryegrass (*Lolium multiflorum* var. *italicum* Lam.), and oats (*Avena sativa* L.) with peas (*Pisum sativum* L.). The green manure was a mixture of common vetch (*Vicia sativa* L.), phacelia (*Phacelia tanacetifolia* Benth.), red clover and Italian ryegrass. All crops were grown in three replicates in all seasons during 2002-05. Residual effects were measured in spring barley in 2006. No fertilisers or manure were applied during the experiment. The soils were a well-drained loam at Apelsvoll with 3.4% soil organic matter, and a poorly drained silty clay loam at Kvithamar with 4.9% soil organic matter, measured in 0-20 cm depth.

Ploughing was performed each year in May (spring), when the topsoil moisture content was at or below field capacity, using single furrow ploughs that resulted in a complete coverage of the surface by wheels each year. This ploughing procedure induces about three times the normal coverage by wheels during ploughing as compared to a practical ploughing on farms. The light tractors weighed 2-3 Mg and the heavier tractors 5-7 Mg, with the heaviest tractors used at Apelsvoll. The shallow ploughing depth was 15 cm, and deep ploughing depth was 25 cm. Except for ploughing, all further operations on the experimental field were performed with light machinery.

2. Earthworm sampling

Earthworms were sampled in two layers in the topsoil, 0-13 and 13-25 cm, in 2003, 2004 and 2006 in September/October at both sites, from each plot in three replicates in all treatments with light and heavier tractor and shallow and deep ploughing. The experiment also contained a set of treatments where all tractor wheels were placed "on land" during ploughing. The earthworm studies were conducted only in the treatments with normal in-furrow placement of two wheels. The sampling occurred in plots where cereal residues mixed with catch crops had been ploughed in during the spring, and oats mixed with peas were grown. Soil blocks (20 cm × 20 cm × block depth, 0-13 and 13-25 cm) were dug out and earthworms removed by hand. The earthworm density, numbers of juveniles and adults within different species and juvenile to adult-ratio were recorded annually. The earthworm species were determined according to Stöp-Bowitz (1969) and Sims and Gerard (1999).

The data for earthworm number and biomass were analysed by ANOVA arranged as a split-split-plot design, using SAS (SAS Institute Inc. 1987).

Decomposition study in the soil tillage experiments

Using litterbags, the decomposition of barley straw was studied in arable soil at two experimental sites, Apelsvoll and Kvithamar, during 2004. The investigation was a part of the soil tillage experiment described above. The litterbag method was developed in 2003, and the photos shown are from that season. Nylon litter-bags were filled with 5 g dry, chopped (5 cm) straw of spring barley from the previous autumn, from each site respectively, collected in fields in spring (**Fig. 2A**). The barley straw had low nutrient content (1.4% N (DM) at Apelsvoll and 0.6% N at Kvithamar) and high content of slowly decomposable structures (cellulose, hemicelluloses and lignin). The latter was measured as Neural Detergent Fibres and comprised 82% of the total DM of the straw at

Fig. 2 Litterbag content at different stages of decomposition, photos from Apelsvoll. (**A**) Barley straw used to fill the litterbags. (**B**) Litterbag content after two months' placement in soil, aggregates of earthworm casts and straw are separated from the remaining straw material. (**C**) Litterbag content after four months' placement in soil. Note the increase in aggregates and change in straw colour and structure from A to C. Earthworm casts were usually attached to some straw material, resulting in aggregates with a spiky look. Photos by R. Pommeresche.

Apelsvoll and 86% at Kvithamar (Goering and van Soest 1970). The filled bag diameter was 7 cm. A mesh size of 5 mm allowed different kind of soil biota, including earthworms, to enter the content of the bags. The bags were moistened before placement in soil.

The bags were placed at both sites using a manual soil auger, in plots where oats with peas were grown, shortly after soil tillage and sowing, May 25 2004. Bags were placed in treatments where a light tractor (2-3 Mg) had been used for ploughing, in both shallowly (15 cm) and deeply (25 cm) ploughed plots, in three replicates. In all treatments the tractor wheels were placed "on land" during ploughing. In each plot five bags were randomly distributed and shallowly (centre of bag at 13 cm soil depth) or deeply (centre of bag at 25 cm soil depth) placed. Altogether, 240 litterbags were used.

From May to October 2004, altogether five sampling dates, one litterbag per experimental plot and depth were sampled. By each sampling the litterbag content was sorted by hand. The amount of straw and amount and numbers of aggregates were recorded (**Fig. 2B, 2C**). The aggregates were "soil crumbs" of varying size (3-10 mm). The aggregates were most likely earthworm casts, because no soil was included in the litterbags by placing and it is not likely that soil has fallen into the litterbags. The reduction in straw content during the season was used as an indicator of the decomposition rate. Any kind of soil fauna visible by eye collected in the litterbags were identified to group or species.

Nutrient content in earthworm casts

In 2005, litterbags with the same barley straw as used in the over described decomposition study was used to collect earthworm casts for chemical analysis. The bags were buried in the over described soil tillage experiments. Litterbags were placed in experimental plots with oats and peas, ploughed with a light tractor to two different depths (15 and 25 cm) in three replicates. In all treatments the tractor wheels were placed "on land" during ploughing. Four litterbags per replicate plot were randomly placed in two depths, with the centre of the bag placed at 13 or 25 cm soil depth on May 25, 2005.

From each plot, two litterbags per placing depth were gently sampled on August 23 and October 18, 2005. At the same time, bulk soil was sampled from 10-15 and 22-27 cm soil depth *ca*. 10 cm from the litterbag sites. Two soil samples were taken by auger and mixed to represent the bulk soil from one depth and litterbag plot.

The litterbag contents were dried at 35°C and divided into aggregates (= earthworm casts) and remaining straw (**Fig. 3**). All aggregates above ca 2 mm size were picked out using a forceps. All visible straw fragments were removed (**Fig. 3**). The casts were gently sifted (2 mm sieve) by hand, and any remaining straw fragments were removed during the sifting. Bulk soil was also dried and sifted before analysis. We did not expect the nutrient content

Fig. 3 Dried casts (on the paper) and remaining straw from one litterbag with a high content of casts, from Apelsvoll in 2005 (note mesh size of 2 mm of the sieve). Photo by R. Pommeresche.

in straw to have a significant impact on the nutrient content of the casts, because the straw was leached by lying in the field during the winter. The barley straw used in the litterbags was low in N content and high in slowly decomposable structures (see analyses above).

Each litterbag contained between 0.5 and 6 g dry weight (DW) of cast soil. The lowest amounts were found in the clay soil at Kvithamar. As the minimum amount of soil required for chemical analysis was 5 g, samples from all plots and both depths were bulked for each sampling date at Apelsvoll, resulting in four samples of cast soil for analysis. At Kvithamar, samples from both sampling dates were bulked, leaving us with one sample per soil depth.

In bulk soil and casts, concentrations of ammonium acetate-lactate (AL)-extractable P, K, Mg, Ca and Na were determined by ICP (Egnér *et al.* 1960) and total N and C by an autoanalyser. The AL-extraction is the common method to estimate plant available nutrients in Norwegian soils.

RESULTS AND DISCUSSION: EFFECTS OF CROP ROTATION, FERTILIZATION, SOIL TILLAGE AND COMPACTION ON EARTHWORMS

Effects on earthworms of crop rotation and other agronomic means in the farming systems at Apelsvoll

1. Earthworm burrows, biomass and density

In all systems with ley in the rotation and/or application of slurry, there was a significant increase in the density of earthworm burrows from 1994 to 2004 (**Fig. 4**). In 1994, after five experimental seasons, a positive effect of ley and animal manure on earthworm activity was already evident, but the differences were larger in 2004. A similar pattern as shown for burrows in 2004 was found for earthworm biomass (**Fig. 5**). The earthworm density was also higher in all systems with ley except OrgFo$_7$ (**Fig. 5**). For the OrgFo$_{75}$ system, no changes in earthworm density were found from 1994 to 2004 (Riley *et al.* 2008), and the 2004 values were lower than the number of burrows indicates (**Fig. 5**). One contributing factor to the unexpectedly low earthworm density in OrgFo$_{75}$ may be that the earthworms escaped during the digging of the blocks, which was more time consuming in the three-year old ley than in the wheat stubble plots. In 1994, and even more so in 2004, the conventional arable systems had much lower values for all recorded earthworm parameters than the other four systems. The main reason for this is likely that no ley was included and no animal manure was used in the all-arable rotation. Increased earthworm populations with leys in the rotations have also been shown by Edwards and Lofty (1977) and Scullion *et al.* (2002). For Norwegian conditions, Bakken *et al.* (2006) found an increased biomass of earthworms when a crop rotation was changed from all arable to partly ley, as a part of conversion to organic management. The two conventional systems at Apelsvoll may have shown especially low values of earthworm density and biomass because the crop in 2003 was potatoes, demanding much soil tillage and pesticide use, and leaving small amounts of plant residues to feed the next season's soil fauna. However, the number of burrows, which is a less dynamic parameter, was also clearly lower in these systems (**Fig. 4**).

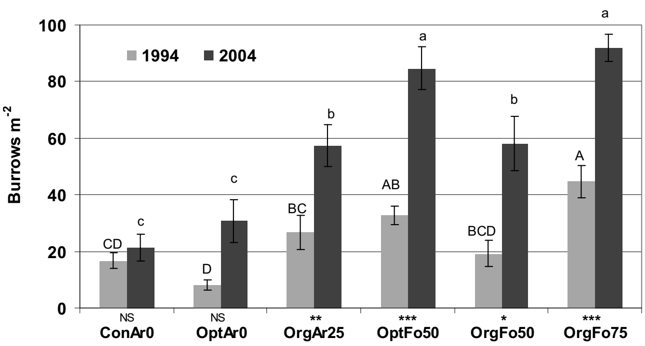

Fig. 4 Density of earthworm burrows (number m^{-2}) at 25 cm soil depth in six farming systems compared at Apelsvoll. The systems are explained in **Table 2**. Statistically significant differences among farming systems are shown by different capital letters in 1994 and small letters in 2004. Symbols under the bars indicate significance levels of the changes between 1994 and 2004 (NS=not significant, *= p< 0.05, ** = p< 0.01). Vertical lines show ± one standard error. Figure reprinted from **Riley H, Pommeresche R, Eltun R, Hansen S, Korsaeth A** (2008) Soil structure, organic matter and earthworm activity in a comparison of cropping systems with contrasting tillage, rotations, fertilizer levels and manure use. *Agriculture, Ecosystems and Environment* **124**, 275-284, ©2008, with kind permission from Elsevier.

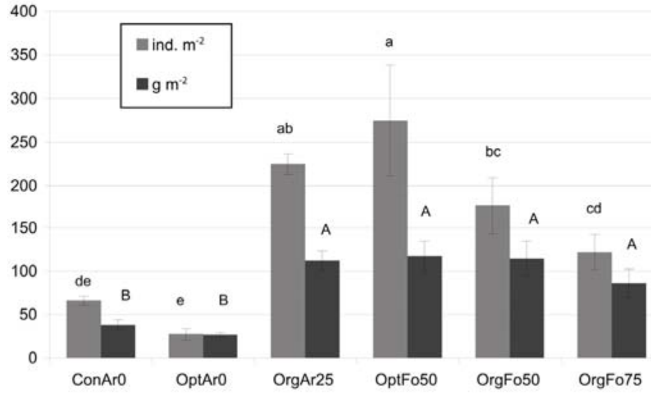

Fig. 5 Density (individuals m^{-2}) and biomass (g m^{-2}) of earthworms from 0-25 cm soil depth in 2004 in six farming systems compared at Apelsvoll, sum of all species and age groups. The systems are explained in **Table 2**. Statistically significant differences among farming systems are shown by different capital letters for biomass and small letters for density. Vertical lines show ± one standard error (SE). Figure modified from Riley *et al.* (2008).

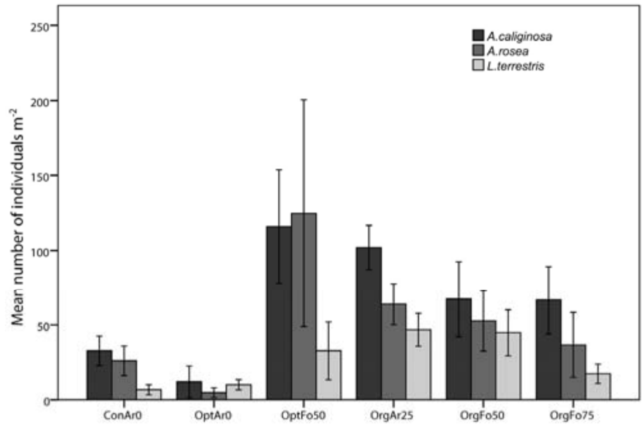

Fig. 6 Density (individuals m^{-2}) of selected earthworm species from 0-25 cm soil depth in 2004 in six farming systems compared at Apelsvoll, sum of juveniles and adult individuals within each species. The bars show ± two SE. The systems are explained in **Table 2**.

2. Earthworm species and juvenile to adult ratios

All earthworm species found in this study are referred in **Table 1**. Here we present data for the three dominant species, *A. caliginosa*, *A. rosea* and *L. terrestris* recorded in 2004. Ley in the crop rotation and the application of slurry seems to support not only the earthworm activity in general, but also the presence of *L. terrestris* (**Fig. 6**). Even in the OrgAr$_{25}$ system with only one year out of four with ley, relatively high densities of this species were found, and much higher values than in the OrgFo$_{75}$ system where sampling occurred in a third year ley. Chan (2001) found reduced tillage to cause less destruction of *L. terrestris* burrows. However, the absence of ploughing did not increase earthworm activity in the present study, as shown by the low number of *L. terrestris* and other earthworms in the OptAr$_0$ system. In general it seems that spring harrowing is even more detrimental to earthworms than spring ploughing, as shown by less earthworms in this system than in ConAr$_0$ (**Figs. 5, 6**).

The numbers of juveniles and adults, as well as the juvenile to adult ratios (JAR), varied between species (**Fig. 7, Table 3**). For the largest species *L. terrestris*, only a few adult worms were found, and the JAR was generally high (**Table 3**). The maximum JAR value was found in the OrgFo$_{75}$ system (**Table 3**). For the medium-sized species *A. caliginosa*, higher numbers of both adults and juveniles were found than for *L. terrestris* in most systems (**Fig. 7**). The numbers were again lowest in the conventional arable

Table 3 Ratios between the numbers of juvenile and adult individuals of the dominant earthworm species, *Aporrectodea caliginosa*, *Lumbricus terrestris* and *Aporrectodea rosea* in 2004 in the six farming systems compared at Apelsvoll. (Details of the systems are explained in **Table 2**).

System	*A. caliginosa*	*L. terrestris*	*A. rosea*
$ConAr_0$	1.14	- (no adults found)	0.63
$OptAr_0$	0.64	5.50	0.17
$OrgAr_{25}$	2.06	17.00	0.87
$OptFo_{50}$	3.27	4.33	1.67
$OrgFo_{50}$	1.42	5.44	0.44
$OrgFo_{75}$	1.25	20.00	0.77
Average	1.84	7.90	0.95

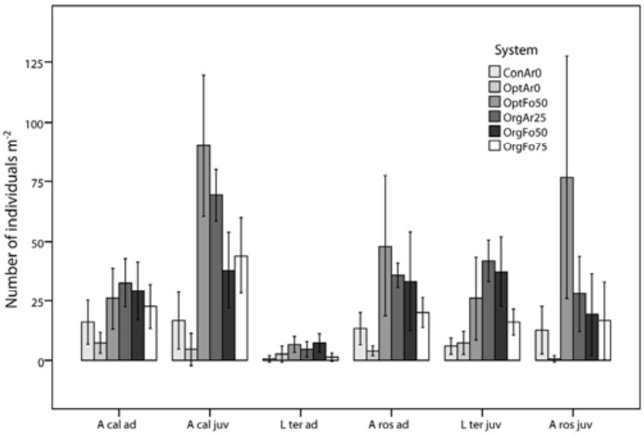

Fig. 7 Distribution of adult (ad) and juvenile (juv) individuals of various earthworm species from 0-25 cm soil depth in 2004 in six farming systems compared at Apelsvoll. A cal = *Aporrectodea caliginosa*, L ter = *Lumbricus terrestris*, A ros = *Aporrectodea rosea*. The bars show ± two SE. The systems are explained in **Table 2**.

systems, where the numbers of adults and juveniles were about equal (**Table 3**). Ley favoured the number of *A. caliginosa* in general, but the number of juveniles and hence the juvenile to adult ratios were especially high in the $OrgAr_{25}$ and $OptFo_{50}$ systems (**Table 3, Fig. 7**). A high JAR value indicates a high share of juveniles in the system and indicates a population in growth. For the small-sized species *A. rosea*, more adults than juveniles were found in all systems except $OptFo_{50}$ (**Table 3**). The high number of *A. rosea* juveniles in $OptFo_{50}$ indicated that this system was favourable for geophagous earthworms, as was also confirmed by high numbers of *A. caliginosa* juveniles and many *A. rosea* adults in this system. The yields, both of cereals and ley, in this system were significantly higher than in the organic systems (Korsaeth 2008), partly due to higher application of fertilizer and animal manure (**Table 2**). An increased availability of nutrients, also for earthworms, may be an explanation of the higher numbers of individuals and the high JAR of the geophagous species in $OptFo_{50}$.

3. Summarized discussion

In general, the earthworm studies in the farming systems comparison experiment at Apelsvoll have demonstrated that fodder production systems are favourable for earthworms. Systems with grass-clover leys and application of slurry, as well as green manure leys in arable organic systems that are cut and mulched during the season, are clearly more favourrable for earthworms than arable conventional systems. The effect was positive both for short-term and long-term leys, and for long-living, deep working species such as *L. terrestris* as well as for the smaller, geophagous species *A. caliginosa* and *A. rosea*. Further, leys are less tilled than cereals and row crops and hence give the earthworm population more time to develop.

It is somewhat surprising that the earthworm density and biomass in this experiment were not positively influenced by the growing of catch crops in $OptAr_0$, as compared to $ConAr_0$ with no catch crops. Schmidt *et al.* (2003) found a large positive effect of catch crops on earthworm density and biomass, but in that study the catch crop was white clover. The ryegrass catch crop used in the present study (*Lolium perenne* L. or *Lolium multiflorum* Lam.) did not have such a positive impact, underlining the importance of plant species for earthworm development.

The $OrgFo_{75}$ system was a third year ley at sampling, whereas stubble from spring wheat was the crop residue in all other systems at sampling. Due to the positive effect of ley on earthworm density, we expected to find the highest numbers of earthworms in this treatment, especially of *L. terrestris*. We also expected the numbers of adults to be higher in this system, but neither was found to be the case. In most instances (**Fig. 5**), lower numbers of earthworms were found in this system as compared to all other treatments where ley was included in the rotation.

In the present study, long-term leys did not favour the number of earthworms more than short-term leys. However, the earthworm burrows through the 0-25 cm layer seem to have been better developed in the third year ley plots than in the other plots.

The numbers of burrows on the face at 25 cm soil depth was high in $OrgFo_{75}$ (**Fig. 4**), confirming that the earthworm density and biomass (**Fig. 5**) may in fact have been underestimated in this system. Worms may have escaped during digging. The mustard suspension method was tested at Apelsvoll to study earthworms from the deeper soil. However, at this site the method was not useful because the suspension did not drain into the soil rapidly enough. Hence it was not possible to achieve data for earthworm populations from deeper soil from the farming systems comparison experiment at Apelsvoll.

Effects on earthworms of fertilization in the long-term experiment at Møystad

In the topsoil at Møystad, all common earthworm species in Norwegian arable soil were found; *A. caliginosa*, *A. rosea*, *L. terrestris* and a few individuals of *L. rubellus*. The density of worms were in general somewhat lower than in the farming systems with ley at Apelsvoll. In the deeper soil (below 20 cm), *L. terrestris* was the only species that was found (**Fig. 8**), mostly as adults, but there were also some juveniles. In the topsoil, only juveniles of *L. terrestris* were found.

In all treatments, the density of earthworms was much higher ($p < 0.001$) in the topsoil (0-20 cm) than in the deeper soil (**Fig. 9**). In the topsoil, the smaller, more numerous

Fig. 8 ***L. terrestris*** **emerging from their burrows about five minutes after a mustard suspension was poured on to a horizontal face at 20 cm soil depth.** The size of the hole is 30 cm × 30 cm. The grey color shows residues of the mustard suspension. Photo by R. Pommeresche.

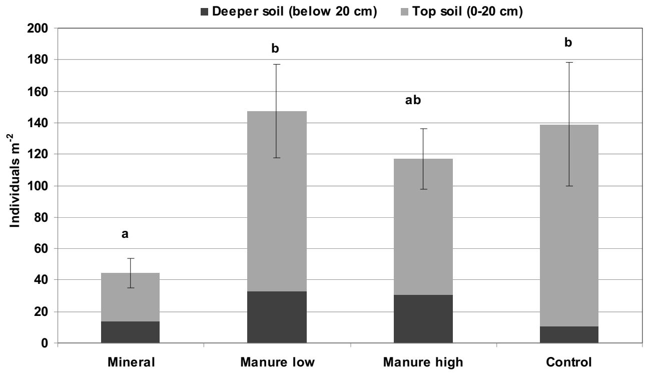

Fig. 9 Earthworm density in topsoil (0-20 cm) and deeper soil (below 20 cm) after four treatments of long-term fertilization at Møystad. Significant differences ($P < 0.05$) between treatments (across both depths) are shown by different letters. Vertical lines show ± one standard error (across both depths).

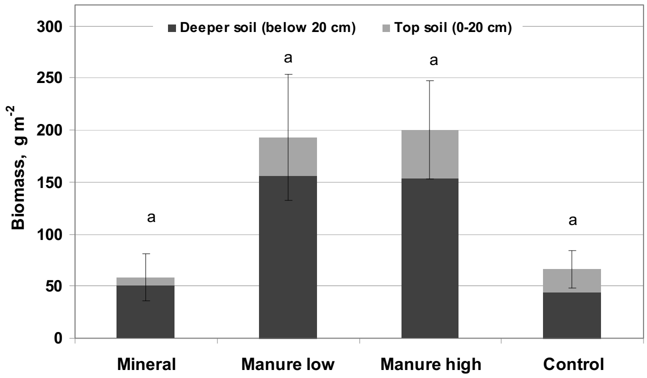

Fig. 10 Earthworm biomass in topsoil (0-20 cm) and deeper soil (below 20 cm) after four treatments of long-term fertilization at Møystad. Significant differences ($P < 0.05$) between treatments (across both depths) are shown by different letters. Vertical lines show ± one standard error (across both depths).

species *A. rosea* and *A. caliginosa* were dominant, together with juvenile *L. terrestris*. This resulted in a high earthworm density, but low biomass (**Fig. 10**). The earthworms found in the deeper soil were few, but much heavier, causing earthworm biomass to be much larger ($P < 0.01$) in the deeper soil than in the topsoil (**Fig. 10**).

The individual worm weight varied by a factor of 30, as the largest worm of *L. terrestris* weighed about 6 g, and the average adult weight of *A. rosea* was only 0.2 g. The distribution of adults and juveniles of *L. terrestris* in topsoil and deeper soil compares well with the way this species generally uses arable soil as habitat. Young *L. terrestris* often live in temporary burrows in the upper parts of the soil, and start to dig more permanent, deeper vertical burrows as they grow larger (Lowe and Butt 2002).

Total earthworm density across both soil depths was significantly lower in the Mineral treatment than in the Control and Manure low, and also lower ($P = 0.07$) than in the Manure high treatment (**Fig. 9**). With respect to earthworm biomass, there was a clear tendency ($P < 0.10$) for higher earthworm biomass in the Manure low and Manure high than in the Control and Mineral treatments (**Fig. 10**).

The mean individual weight of adult *L. terrestris* earthworms in the deeper soil varied from 4.8 g in the Mineral treatment to 6.3 g in Manure low, and for juveniles from 1.5 g in Manure low to 3.8 g in Manure high. Within each age group (juvenile or adults), the difference between the mentioned treatments was statistically significant. However, as the total number of records is low ($N = 20$ for adults, 12 for juveniles) the results must be interpreted with care. A larger variation among young individuals than older is to be expected due to their different age, and we emphasize most the results of the adults. Heavier adults in the Manure treatments confirm the results shown for earthworm density and biomass that animal manure has a positive impact on earthworms.

Although the whole experimental field had been under ley with no fertilization for three seasons, the effects of the former long-term use of animal manure were still clearly visible. A general positive effect of animal manure on earthworm density and biomass was also found by Uhlen (1953), who investigated some treatments in the Møystad experiment. The positive effect on earthworms was most evident in the application year and the subsequent season, but a statistically significant effect was found even six years after application in Uhlen's studies. Several authors (e.g. Haraldsen *et al.* 1994; Hansen and Engelstad 1999; Mäder *et al.* 2002) have found a significant increase in earthworm density and biomass by application of animal manure, but in these studies the time span between earthworm measurement and the last manure application was less than one year. Hence, the long-term effects of manure application were not assessed in these studies.

The long-term effects found at Møystad are somewhat surprising, especially since the effect was found after three seasons of ley (2006), which should have increased the earthworm parameters in all treatments. A possible explanation is that the applied manure was composted solid cattle manure, which may have a slower decomposition rate in soil than the more frequently used slurry. Another explanation may be that the clover content in the leys in 2006 differed between the treatments, with the largest proportions in treatments receiving animal manure. This difference occurred in spite of that no clover was used in the ley seed mixtures. Clover seeds may have followed the cattle manure, and clover may also have dispersed from field margins. Red clover constituted as much as 18 and 21% of the dry matter (DM) yield in the Manure low and Manure high treatments respectively, and white clover constituted 5% of the DM yield in the Control treatment. Clover as a sub crop is favourable for earthworms (Schmidt *et al.* 2003) as well as clover fed to earthworms in experiments (Shipitalo *et al.* 1988). No clover was recorded in the Mineral treatment plots, but this could be due to the lack of liming which may have hampered clover growth due to lower soil pH. The average soil pH_{H2O} in 2005 was 5.6 in the Mineral treatment, as compared to 6.3 and 6.4 in the Manure low and Manure high treatments and 6.0 in the Control. The somewhat lower soil pH after long-term use of mineral fertilizers may also have decreased the number of earthworms in the Mineral treatment. Hansen and Engelstad (1999) found a close correlation between earthworm biomass and soil pH as well as extractable calcium (Ca-AL) concentrations. In the Møystad experiment, the Ca-AL levels were lower in the Mineral treatment; 1600 mg kg^{-1} soil as compared to 2100-2700 mg kg^{-1} in the other treatments. However, most European species have a wide range of tolerance for varying pH, and for *A. caliginosa* and *A. rosea*, the optimum pH range has been reported to be between 5.0 and 6.0 (Edwards and Bohlen 1996). The earthworms should have coped well with the pH 5.6 in the Mineral plot.

In general, we conclude that the long-term application of cattle manure was favourable for earthworms. We also conclude that comparable amounts of N, P and K in mineral fertilizer cannot substitute animal manure application to support the earthworm fauna. The positive effect of animal manure sustains for several years subsequent to the manure application.

Effects on earthworms of soil tillage and compaction in the soil tillage experiment at Apelsvoll and Kvithamar

In the soil tillage experiment with different ploughing depth and tractor weight at Apelsvoll and Kvithamar, the density of earthworms varied much within the treatments. No general effect on earthworm density was found of tractor weight

Table 4 Composition of the earthworm population in the soil tillage experiment. Shares of individuals (sum of juveniles and adults) of various species. Average values across treatments.

Site	Apelsvoll			Kvithamar		
Year	2003 (%)	2004 (%)	2006 (%)	2003 (%)	2004 (%)	2006 (%)
Aporrectodea caliginosa	98	84	84	79.5	87	81.5
Aporrectodea rosea	2	13.5	11	4.5	8	6
Lumbricus rubellus	0	1	2.5	15.5	5	9.5
Lumbricus terrestris	0	1.5	2.5	0.5	0	3

Table 5 Ratios between the numbers of juvenile and adult individuals of the earthworm species found at the two sites in the soil tillage experiment. ind. = individuals, juv = juveniles

Site	Apelsvoll			Kvithamar		
Year	2003	2004	2006	2003	2004	2006
Ratio juveniles/adults in						
Aporrectodea caliginosa	3.3	4.2	4.7	2	3.6	2.4
Aporrectodea rosea	No adults	3.0	1.6	0.3	2.5	0.3
Lumbricus rubellus	No ind.	1.0	No adults	No adults	0.9	4.8
Lumbricus terrestris	No ind.	No juv.	No adults	1.9	No ind.	6.0

or ploughing depth. However, on the site with lightest soil and where heavier tractors were used (Apelsvoll), we found a negative effect of the heaviest tractor (Riley *et al.* 2009). Across both ploughing depths at Apelsvoll, the difference in earthworm density was statistically significant in 2006 (P =0.055). In this year, 315 earthworms m^{-2} were found in the topsoil (0-25 cm) where the light tractor was used for ploughing, and 210 m^{-2} with the heavy tractor. These numbers are high as compared to densities found in the farming system comparison study at Apelsvoll, especially because the experimental field was ploughed each year. The generally high earthworm density likely reflects the positive impact of the catch crop (white clover and ryegrass) ploughed in during spring, as was found by Schmidt *et al.* (2003). Across all treatments and years, the mean earthworm density was 222 m^{-2} at Apelsvoll and 235 m^{-2} at Kvithamar, out of which about 90% were found in the uppermost 13 cm.

At Apelsvoll, a higher proportion (P = 0.002) of the earthworm biomass was found in the upper topsoil (0-13 cm) after shallow than after deep ploughing in 2006. After shallow ploughing, 95% of the biomass was found in the upper topsoil. Deeper ploughing seemed to facilitate the distribution of earthworms into the deeper topsoil (13-25 cm). At Apelsvoll, 35% of the earthworm biomass was found in the deeper topsoil after deep ploughing. At Kvithamar, there was no significant effect of the treatments on earthworm biomass or the distribution between soil layers. Less clear results at Kvithamar may be due to lighter tractors used at that site, and that the soil structure was already heavily compacted when the experiment was established (Bakken *et al*. 2009).

Earthworms are sensitive to soil compaction, as shown by a study where earthworm density was four times higher (680 as compared to 160 worms m^{-2}) by reduced tractor traffic as compared to normal (Hansen and Engelstad 1999). In the reduced treatment, only soil tillage was carried out by tractor; fertilization and harvesting operations were by hand or light machinery for research purpose. The results in the study of Hansen and Engelstad (1999) were obtained in a loamy sandy soil with an easily deteriorating soil structure, and hence vulnerable for soil compaction. However, in a comparable study on a clay soil, the effect of reduced tractor traffic was less evident and only statistically significant for earthworm density (Haraldsen *et al.* 1994). Nevertheless, the results of Hansen and Engelstad (1999) as well as results referred to above for the treatment with reduced soil tillage at Apelsvoll (OptAr$_0$) indicate that soil tillage and other mechanical operations in the field impact the earthworm fauna.

The share of individuals of each earthworm species (**Table 4**) and JAR values within species (**Table 5**) are shown as averages of all treatments, due to minimal effects of treatments on these parameters. At Apelsvoll in particular, *A. caliginosa* dominated the earthworm fauna (**Table 4**). *L. rubellus* was more common at Kvithamar than at Apelsvoll. At Apelsvoll, the *Lumbricus* individuals represented a somewhat higher proportion in the last experimental year. At Kvithamar, all individuals of *L. terrestris* (seven out of 237) in 2006 were found in treatments where the light tractor was used.

For *A. caliginosa*, the JAR was comparable to the values found in the treatment most favourable to earthworms in the farming system comparison study at Apelsvoll, OptFo$_{50}$ (**Table 5** vs. **Table 3** and **Fig. 7**). That study also revealed high JAR values of *L. terrestris* in some systems, which compares well to the high ratio found at Kvithamar for this species in 2006 (**Table 5**). However, for *L. terrestris* the JAR variability is large due to the generally low numbers of individuals.

Our initial hypothesis that the earthworm fauna would suffer from annual ploughing and especially so with a shallow ploughing depth, was not confirmed in this study. Not only were the differences small between the treatments, but the earthworm density was, surprisingly, generally high. Hence, if shallow ploughing is demanded, e.g. to avoid mixing less fertile soil into a nutrient rich topsoil layer, this will probably not damage the earthworm fauna. However, by shallow ploughing there was a tendency that the earthworms restricted their distribution to the ploughed layer only, which may not be fortunate for plant growth. Deeper ploughing is also required in organic farming systems to control perennial weeds (Riley *et al.* 2009).

The results should not be interpreted that earthworms are insensitive to soil tillage and compaction. In fact he study showed a positive effect on earthworm density when a lighter tractor was used for ploughing. The results also show that earthworms may be frequent even in quite compacted soils, with an all-arable crop rotation and no application of animal manure. A possible explanation for the lack of significant differences between treatments in this study is that the ploughing, which was the only work operation in the field causing "extra" compaction, was always conducted at appropriate soil moisture conditions to avoid destructive management of the experimental field. The effects would likely have been more visible if the ploughing had been performed on wet soil, which is often impossible to avoid under practical conditions.

Decomposition of barley straw and amounts of earthworm casts

Earthworms play a major role in the breakdown of organic matter, and thereby in the mineralization of plant nutrients. They eat partially decomposed crop residues, fragment them, mix them with soil and transport organic matter from the surface to deeper soil layers. Geophagous species do not only eat to achieve energy and nutrients; they move around in the soil by eating their way through it, and hence they

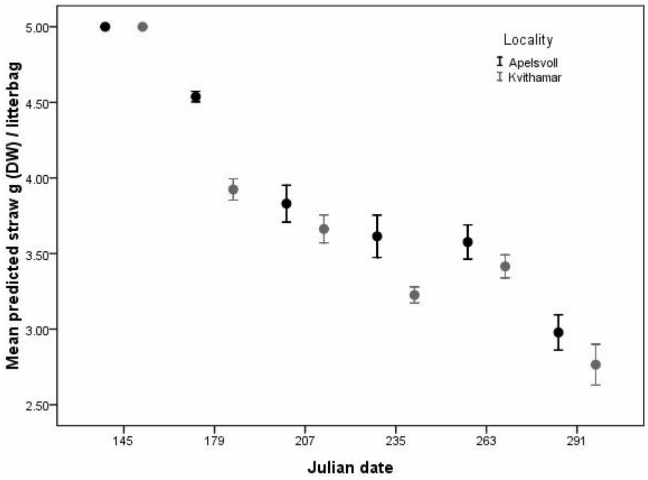

Fig. 11 Decomposition of barley straw in arable soil during the growing season of 2004, as reduction in dry weight of straw in litterbags buried in soil at two sites. Mean amount of reminding straw (± 2 SE) are plotted against date and adjusted for effects of ploughing depths and block effects (= predicted values). Mean values for two placement (13 and 25 cm) and ploughing depths (15 and 25 cm). Litterbags were buried on Julian date 145 (= 25 May) and sampled on subsequent dates until date 291 (= 18 Oct).

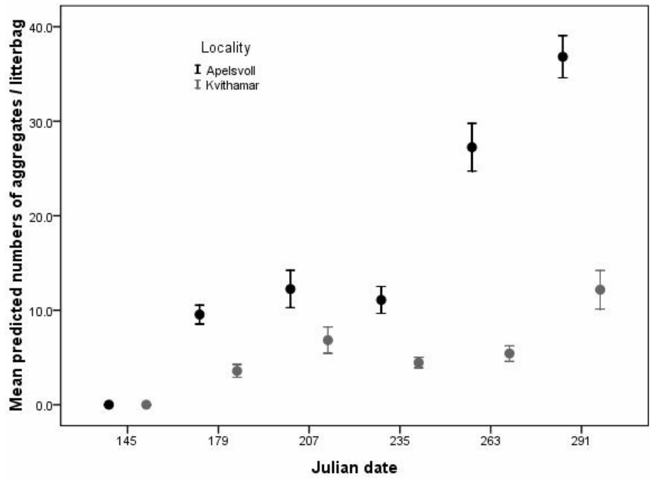

Fig. 12 Numbers of aggregates (see Fig. 2B) found in litterbags at two sites during the 2004 growing season. Mean number of aggregates (± 2 SE) are plotted against date and adjusted for effects of ploughing depths and block effects (=predicted values). Mean values for two placement (13 and 25 cm) and ploughing depths (15 and 25 cm). Dates are explained in **Fig. 11**.

produce a notable amount of casts (excrement heaps). At high earthworm densities, a significant part of the soil volume in an arable soil will pass through the earthworm digestive system each year. The decomposition study of barley straw illustrates the importance of earthworms for the breakdown of plant residues. At both sites there was a significant reduction ($P < 0.001$) in straw weight during the season. More straw was decomposed at Kvithamar than at Apelsvoll ($P < 0.001$) (**Fig. 11**). On average, 55% of the initial 5 g straw was left in litterbags in October at Kvithamar and 60% at Apelsvoll.

The ploughing depth did not significantly impact the decomposition of the straw, but there was an effect of placement depth. At Apelsvoll with less clayey soil, the decomposition was faster in the more deeply placed litterbags ($P < 0.05$). This indicates that decomposition may have been hampered by drought at Apelsvoll, as otherwise the decomposition would likely be faster with shallow placing due to higher availability of oxygen. In the clay soil at Kvithamar, the decomposition was faster in shallowly placed bags in the shallowly ploughed plots ($P < 0.05$), indicating good combination of moisture and oxygen availability. We may conclude that in lighter soil types, straw may be buried deeper and still become decomposed.

Some single earthworms, mainly juvenile specimens of *A. caliginosa*, were found within the content of the litterbags. Altogether, 11 such worms were found in litterbags from Apelsvoll and two from Kvithamar. Other soil fauna groups that were found were brown and white mites, enchytraeides, collembolas, beetle larvae and diplopods.

The activity of the earthworms were not measured by their presence, but by the excrements/casts left in the litterbags, counted as aggregates (**Fig. 2B, 2C**). During the season there was an increase in the numbers of aggregates found in the litterbags at both sites ($P < 0.001$), with a much larger number of aggregates at Apelsvoll than at Kvithamar by the end of the season ($P < 0.001$) (**Fig. 12**). The ploughing depth did not influence the number of aggregates. The placement depth had a slight impact on the number of aggregates. At Kvithamar, more casts were found in shallowly placed litterbags in shallowly ploughed plots ($P < 0.001$), which confirms the result described above for straw decomposition.

The earthworm density in the soil in autumn was comparable at both sites; 218 worms m^{-2} at Apelsvoll and 270 worms m^{-2} at Kvithamar, measured in late September 2004. At both sites, more than 80% of the population was comprised of *A. caliginosa*. The decomposition as measured by reduction in the amount of barley straw differed by only 5% between the two sites (**Fig. 11**). However, the number of aggregates in the litterbags was much higher at Apelsvoll (**Fig. 12**), indicating that the earthworms played a larger role in straw decomposition at that site. The average individual biomass of earthworms, calculated with the data from 2004 was 0.39 g (fresh weight) at Apelsvoll and only 0.24 at Kvithamar. The proportion of juveniles was almost equal, 76% at Kvithamar and 78% at Apelsvoll. Hence, the lower individual weight at Kvithamar is due to lighter worms at that site, which was also confirmed by visual assessment during the identification of species. We assumed that lighter worms could be due to colder and wetter soil at Kvithamar as compared to Apelsvoll. However, there were only minor differences in climatic characteristics such as soil temperature and precipitation. Average soil temperatures at 10 cm soil depth during the growing season (May-October) and accumulated precipitation for the same period were 12.9°C and 75 mm at Apelsvoll, and 12.2°C and 77.5 mm at Kvithamar. Due to the more clayey and less well drained soil, the oxygen availability was probably better in the more porous and hence drier soil at Apelsvoll. This may have contributed to higher consumption by and hence heavier earthworms at that site.

The litterbags were crammed full with moistened straw, and put into a hole which fitted the bag exactly. On top of the bags, soil was gently pressed. Hence, it is not likely that significant amounts of soil entered the bags via the mesh openings. With respect to the decrease in straw weight, we cannot exclude that various soil fauna may have transported straw fragments out of the bags. However, most of the straw decomposition has probably occurred in the bag, as shown by the large amount of straw debris mixed with straw pieces in the bag sampled late in the season (**Fig. 2C**). Several microorganisms, not least soil fungi, contribute to soften and fragment the straw. Soil fungi are a popular food source for earthworms, and early successional fungal species may function as a cue to lead the earthworms to feeding pools of decomposing organic matter (Bonkowski *et al.* 2000). The occurrence of earthworm casts in the litterbags clearly shows that the worms have been inside the bags. The reason for the worms to enter the bag is most likely to feed on fungi and degrading straw fragments, and by this eating activity they have participated in the decomposition process. The importance of earthworms for straw decomposition was also demonstrated by Curry and Bryne (1992), who found a significantly reduced decomposition rate when earthworms were excluded from the straw residues.

Nutrient content in geophagous earthworm casts

Feeding mostly on plant residues, detritivorous earthworms produce casts that are often rich in nutrients as compared to the bulk soil (e.g. Graff 1970; Buck *et al.* 1999; Haynes *et al.* 2003), with higher concentrations of carbon (C), N, P and sulphur (S). The casts of geophagous species tend to have lower nutrient concentrations (Buck *et al.* 1999; Haynes *et al.* 2003) even under the same laboratory conditions, due to less consumption of plant feed (Haynes *et al.* 2003) and relatively higher consumption of soil (Buck *et al.* 1999). However, the casts from the geophagous species also contained more nutrients than undigested soil.

Cast production by the geophagous species *A. caliginosa* is impressive (**Fig. 13**). Boström (1988) measured this in the laboratory and found a linear relation between body mass and cast production for juveniles of *A. caliginosa*. The daily fresh weight of casts per individual could be calculated as (0.14 + 2.61 × the individual body fresh weight (g)). The relation was temperature dependent, and for adult individuals, the relation between body mass and daily cast production was not linear; it stabilized around 1.9 g individual^{-1} day^{-1} at 15°C.

Transferred to field conditions, this constitutes an impressive amount of soil and indicates that in each season, a significant part of the topsoil passes through the digestive system of earthworms. Buck *et al.* (1999) discuss whether increased cast production by geophagous species is a consequence of demand for nutrients, such as described for juveniles of *A. caliginosa* above. Another option is that an increased nutrient availability will induce burrowing activity due to the extra energy available.

Earthworm casts from arable soil under Norwegian field conditions have not previously been analyzed. Because geophagous species dominate, *A. caliginosa* is the most common (**Tables 1, 4**), we did not expect the chemical composition of the casts to differ much from the bulk soil. On average for the two sites, the earthworm population over three years (2003, 2004 and 2006) was 229 worms m^{-2}. The average biomass was 73 g m^{-2}, and the individual fresh weight after storage in 75% alcohol suspension was 0.32 g. The dominant species in both soils was *A. caliginosa* (80-85% of the individuals), so the dominating proportion of the litterbag casts was likely produced by *A. caliginosa*. We assume earthworms to be active during the growing season, May-September, 153 days. At Apelsvoll, the average soil temperature at 10 cm soil depth during the growing season of 2005 was 13.5°C, and at Kvithamar it was 11.5°C. Calculated by the formula of Boström (1988), the individual daily cast production by 15°C was estimated to 0.14 + 2.61 × 0.32 g = 0.975 g DW. This amount is well below the average daily cast production recorded by Boström (1988) in the laboratory for adult individuals. For a careful estimate of individual daily cast production, we reduced this value to 65% due to lower temperature in the field = 0.63 g DW, and made no correction for an average higher cast production of adults. On an area basis, this amount corresponds to 22.1 kg m^{-2} y^{-1} or 221 tonne casts ha^{-1} DW, according to the following formula: 229 worms m^{-2} * (0.63 g/day * 153 days) = 22.1 kg m^{-2} y^{-1} (Pommeresche *et al*. 2009).

Fig. 13 Earthworm egestion (*Dendrodrilus rubidus*, small photo), and casts produced by the portrayed individual of *A. caliginosa* (large photo) during a stay in the laboratory. Photo by R. Pommeresche.

For all nutrients, the measured concentrations were higher in cast than in bulk soil (**Table 6**). The contents of P and K were 40-60% higher in the casts, whereas the contents of Ca and Mg were only 10-20% higher. For tot-N and C, the casts contained 30-50% more than the bulk soil. The differences were larger than we expected, but compare well to the laboratory studies of Haynes *et al.* (2003) and Buck *et al.* (1999). A likely reason for the higher concentrations of AL-extractable nutrients in the casts is that the earthworms do not only eat soil particles, but also fungi and debris of plant residues with higher nutrient concentrations than bulk soil. It may also be a digestible effect on the availability of the soil nutrients as they pass through the worms.

To discuss the practical impact of our results, we estimated the average nutrient enrichment (ANE) in casts as the difference between nutrient concentrations in casts and bulk soil converted to amounts per hectare (**Table 6**). On average for the two sites, these differences corresponded to amounts of kg ha^{-1} y^{-1}, 5.6 for P, 8.9 for K, 5.3 for Mg, 144 for tot-N and 2542 for C. The ANE is remarkably high for total C and N. A likely explanation is that the earthworms have fed on materials with a higher nutrient concentration than the bulk soil. However, much is still unknown about the earthworm-plant interrelationships, for instance free living N-fixing organisms in soil, and it is tempting to ask if such phenomena may have occurred, possibly in the intestine of the worms. Because the N availability in organic farming systems is restricted due to no use of mineral fertilizer N, the high N content and significant amounts of casts produced by geophagous earthworm constitutes an amount of N that is high enough to influence the nutrient supply to crops on

Table 6 Concentrations of AL-extractable nutrients and total (tot) N and carbon (C) in earthworm casts and bulk soil from two sites, means of two soil depths (13 and 25 cm). Mg = magnesium, Na= sodium. Values are shown for dry soil, ± SE. ANE= average nutrient enrichment, average across sites of the differences between nutrient concentration in casts and nutrient concentration in bulk soil, converted to kg ha^{-1} by multiplication of a factor of 221 tonne casts ha^{-1}y^{-1}.

Nutrient	P_{AL} (mg kg^{-1})	K_{AL} (mg kg^{-1})	Mg_{AL} (mg kg^{-1})	Na_{AL} (mg kg^{-1})	Ca_{AL} (mg kg^{-1})	Tot-C (g kg^{-1})	Tot-N (g kg^{-1})
Apelsvoll (site)							
Bulk soil	67.8 ± 6.4	76.3 ± 6.8	155 ± 5.8	8 ± 1.4	1588 ± 28.7	19.3 ± 1	1.7 ± 0.1
Casts	92.3 ± 14.1	121.0 ± 8.4	182.5 ± 9.6	12.5 ± 1.3	1818 ± 90.0	29.3 ± 4.0	2.2 ± 0.2
Paired t-test	p=0.022	p=0.007	p=0.002	p=0.006	p=0.005	p=0.025	p=0.022
Kvithamar (site)							
Bulk soil	49.5 ± 3.5	89 ± 5.7	165 ± 21.2	32.5 ± 0.7	1960 ± 14.1	40 ± 7.1	2.9 ± 0.4
Casts	75.5 ± 21.9	125 ±7.1	185 ± 7.1	43.5 ± 2.1	2265 ± 262	53	3.7
ANE (kg ha^{-1} y^{-1})	5.58	8.92	5.25	1.71	59.12	2541.50	143.65

field level. Hence, this topic is of large practical relevance, and deserves to be studied further.

These results show that earthworm casts are efficient and important natural sources of plant nutrients, also in soils with high dominance of geophagous (soil eating) earthworm species.

CONCLUSIONS

A positive effect of both short and long term leys on the earthworm fauna was demonstrated in the long-term comparison study of farming systems at Apelsvoll. Burrow densities, earthworm density and biomass were increased not only for long-living and deep working species such as *L. terrestris*, but also for the smaller, geophagous species *A. caliginosa* and *A. rosea*. Conventional, all-arable farming systems had much lower values of all the mentioned earthworm parameters. This is explained by a lack of ley in the rotation, but also by a lack of animal manure.

Long-term application of cattle manure was favourable for earthworm density and biomass, as shown by the long-term fertilization trial at Møystad. Effects were clearly visible several seasons after the last manure application. N, P and K applied as mineral fertilizer could not substitute for animal manure application to support the earthworm fauna.

The earthworm fauna tolerates annual ploughing, and shallowly ploughing (to 15 cm) was not detrimental to earthworms, even if they prefer the upper topsoil layer as their habitat. Only minor effects of tractor weight and ploughing depth were found on earthworm density and biomass, but at the least compacted site, more earthworms were found where the lighter tractor was used.

The decomposition of barley straw was influenced by soil properties. At the site with lighter and better drained soil (Apelsvoll), decomposition occurred faster in litterbags that were placed at 25 cm as compared to 13 cm. At the site with more clayey and less well drained soil (Kvithamar), decomposition was faster in shallowly placed bags. At Apelsvoll, we found the earthworms to be heavier, and more earthworm casts were found in the litterbags used to study decomposition. This indicates that earthworms were relatively more important for straw decomposition at that site.

Concentrations of important plant nutrients such as N, P, K, Ca and Mg were higher in earthworm casts collected in the field than in the bulk soil. The concentrations of total N and total C were remarkably high. Geophagous earthworms produce significant amounts of casts, and the amount of N in the casts is high enough to influence the nutrient supply to crops at a field level. This topic is of large practical relevance especially for organic farmers, and should be studied further. These results show that earthworm casts are significant natural sources of plant nutrients, also in soils with high dominance of geophagous earthworm species.

ACKNOWLEDGEMENTS

We are grateful to colleagues in Bioforsk and other institutes in Norway for the access to earthworm results from several projects and for help to collect earthworms. Financial support from the Research Council of Norway through the strategic programme 'Organic cropping systems for higher and more stable cereal yields' and from Bioforsk Organic Food and Farming, is acknowledged.

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