Earthworm populations in a cool and wet district as affected by tractor traffic and fertilisation

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Received 21 September 1998; received in revised form 3 June 1999; accepted 8 June 1999

Abstract

In a field trial (1985–1996) on a sandy loam soil the effects of tractor traffic and fertilisation on earthworm populations were investigated. The tractor traffic treatments compared normal farm practice (‘normal’) with reduced tractor traffic (‘low’).

In the fertilisation treatments, three different cattle-manure management methods were compared. The cattle manure was applied as diluted slurry, as aerated slurry, or as separated manure with the composted faeces being applied to tilled land, while the urine was applied to ley. The different cattle manure management methods were compared at two different application levels. In addition, there were an unfertilised control and a higher application level with diluted slurry and mineral fertiliser treatments.

The endogeic species, \textit{Aporrectodea caliginosa} and \textit{A. rosea} constituted 67\% and 7\% of the population density, respectively, and 78\% and 3\% of the mass in the period 1993–1996. The epigeic species, \textit{Lumbricus rubellus}, constituted 25\% of the population density and 19\% of the mass.

The population density, but not the species composition, was strongly affected by tractor traffic. In the years 1987–1989, there was an average of 160 earthworms/m\textsuperscript{2} after normal, and 680 earthworms/m\textsuperscript{2} after low, tractor traffic. During the experimental period, the earthworm population decreased in treatments with low tractor traffic. Important reasons for the reduction in earthworm population are likely to be soil acidification and reduced manure application. In 1995, the differences in population density and mass between treatments with normal, and low, tractor traffic were no longer statistically significant (140 and 250 earthworms/m\textsuperscript{2}, respectively). In 1996, when there was no tractor traffic or fertilisation carried out, the corresponding population densities were 200 and 280 earthworms/m\textsuperscript{2}.

The population density and mass of earthworms were highest in manured soil. Increasing the amount of slurry applied was associated with a higher earthworm population in some years and a lower population in others. Increasing slurry application was most favourable for endogeic species and most destructive for epigeic species.

Neither the average total population density nor mass of earthworms was affected by whether the manure was treated as slurry, or separated. However, more earthworms were found after addition of solid manure than of urine. Aerated slurry did not result in a higher earthworm population than diluted slurry. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Acidification; Aerated slurry; Cattle manure; Mineral fertiliser; Organic farming; Soil compaction

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1. Introduction

Earthworms play an important role in the turnover of organic matter in soil and in building and maintaining a good soil structure (Lavelle, 1988). They, therefore, are essential for improved utilisation of added organic matter and, thus, for plant growth, especially in an extensive agricultural system, such as organic farming, which is based on nutrient release from turnover of organic matter.

Three ecological classes of earthworms have been identified (Bouche, 1977; Lee, 1985). Epigeic species, such as *Lumbricus rubellus*, live near the surface and feed on surface litter. Anecic species (deep burrowing species), such as *Aporrectodea longa* and *Lumbricus terrestris* also feed on surface litter, at least partially, but pull the organic material into vertical channels in the soil. Endogeic species, such as *A. caliginosa*, *A. rosea* and *Allolobophora chlorotica* feed on mineral and humus particles within the soil and move more horizontally in the soil.

Only a few investigations on earthworm species in agricultural soils have been carried out in Norway (Haraldsen and Engelstad, 1994; Haraldsen et al., 1994a, b). It is, therefore, of interest to examine what earthworm species are found in Norwegian agricultural soils under different conditions.

In Surnadal (Northwest Norway), a high population density and large mass of earthworms were found in an organic dairy farm from 1987 to 1989 (Hansen, 1996). Both, the population density and mass of earthworms were strongly reduced by tractor traffic in the loamy sand soil of this farm. A corresponding reduction in earthworm populations as a result of soil compaction has been found in many investigations (Aritajat et al., 1977b; Boström, 1986; Pizl, 1992; Söchtig and Larink, 1992). However, when traffic is removed, earthworm populations seem to recover quite quickly (Aritajat et al., 1977a; Haraldsen et al., 1994a). To our knowledge, no previous investigation has followed the effects of tractor traffic on earthworm populations over many years in the same field. Therefore, in this paper we present data on the long-term effects of tractor traffic on earthworm populations in an organic dairy farm in Surnadal and the development of earthworms after the tractor traffic ended.

Additions of organic matter in the form of farmyard manure have been found to increase earthworm populations under favourable soil conditions (Curry, 1976; Marshall, 1977; Andersen, 1979; Lofs-Holmin, 1983; Hansen, 1996). On the other hand, both cattle slurry and urine have been found to be transiently toxic to earthworms as a result of ammonia, benzoic acid and sodium sulphide content (Curry, 1976). The overall effects of long-term cattle slurry applications and treatments are, therefore, of interest. Aeration of slurry has been proposed as a strategy for, among other things, decreasing the toxicity of the slurry to earthworms (Nebiker, 1974; Bauchhenss, 1981), but this does not always seem to succeed (Bieri and Besson, 1987; Hansen, 1996).

The findings reported by Hansen (1996) are followed up in the present investigation by measurements of the long-term effects of manure management on earthworm species. We report the effects of ten years of tractor traffic and fertilisation treatments on the population density, mass and species composition of earthworms in a loamy sand soil in a cool, wet district. The tractor traffic treatments compared normal farm practice with reduced tractor traffic. In the fertilisation treatments, three different cattle manure-management methods were compared. The cattle manure was applied as diluted slurry, as aerated slurry, or as separated manure with solid composted manure applied on tilled land and urine on ley. The manure was added at different levels and was compared with unfertilised and mineral fertiliser treatments.

2. Material and methods

2.1. The experimental site

The field experiment was established in 1985 in Surnadal, Norway (63° 00′N, 8° 88′E) on an organic dairy farm. The previous crop rotation had a high proportion of ley, the manure was evenly distributed over the whole farm with small amounts applied each year, no chemical nitrogen fertilisers or pesticides were used, and the farmer had tried to avoid soil compaction as much as possible.

The climate in this region is fairly humid and cold, with an average normal yearly precipitation of 1360 mm and mean April–October temperature of 8.2°C. Monthly precipitation and temperature from 1985 to 1990 are given by (Hansen, 1996) and from...
The soil was mostly covered with snow during the winter and frost never occurred for a long period when there was no snow layer.

The soil was a naturally drained loamy sand developed on fluvial deposits (Typic Udorthents, USDA System of soil classification). The average bulk density at 7–11 cm depth was 1.25 g/cm³, with a pore volume of 52% (SE = 0.3) in 1985.

The soil is moderately rich in organic matter (organic carbon 2.1–2.2%, organic nitrogen 0.15–0.17%) and low in potassium and magnesium.

2.2. Experimental design

A split-plot factorial design with two replicates was used, with tractor traffic treatment on the main plots (28 × 8 m²) and fertilisation on the subplots (2.8 × 8 m²; sample area for yields 1.5 × 6.5 m²).

The trials were run for two five-year periods. Hansen (1996) presented details on crops, fertilisation, tractor traffic, experimental design, climate, and statistical analysis in the first crop rotation (1985–1990). The second crop rotation period (1991–1996) followed the same principles as the first, with some adjustments. The experimental site was the same throughout the investigation period and there was only one crop each year, as determined by the crop rotation.

The crop rotation was: Year 1, green fodder consisting of rape (Brassica napus), barley (Hordeum vulgare), peas (Pisum arvense) and field beans (Vicia faba); Year 2, barley with ley undersown; Years 3–5, ley containing timothy (Phleum pratense), red clover (Trifolium pratense), white clover (T. repens) and alsike clover (T. hybridum). In 1990 (oats) and 1996 (ley), no fertilisation or tractor traffic treatments were applied in order to test residual effects of previous treatments. In the present paper 1996 is called the after effect year.


In the first crop rotation (Hansen, 1996) there were two field trials, whereas in the second one, there was only one. The data presented here are only from the trial that was continued.

2.3. Tractor traffic

There were two tractor traffic treatments: normal and low. In both these treatments, a tractor was used for soil tillage (ploughing, two harrowings, rolling) and sowing. These passes were made across the experimental plots with tractors similar to those used for the normal tractor traffic treatment. Cereal harvesting was done with a lightweight experimental combine harvester. Green fodder and ley were cut with a two-wheel reaper and raked out of the field by hand. This was the only traffic in the treatment with low tractor traffic.

In the normal tractor traffic treatment, there was one additional pass of a tractor wheel-by-wheel once each spring, starting in 1986, and two passes shortly after each harvest. This was done all over the experimental plots in the normal tractor traffic treatment, which means that each spot was covered five times. Five
passes each year are comparable to normal dairy farm practice. From 1985–1989, a three-tonne tractor (2.5 tonnes on rear wheels, inflation pressure 150 kPa, tire width 32 cm) was used. From 1991 to 1995, the tractor weight was four tonnes. The tractor had dual settings and a total tyre width of 140 cm at the rear wheels (inflation pressure of 57 kPa). In front there were low-pressure tyres with a total width of 100 cm.

2.4. Fertilisation

The fertilisation levels (FL) one, two and three were intended to represent three different levels of farming intensity, with FL3 being the most intensive. FL1 corresponded to an organic farm where only the manure from the farm’s own cattle was used; at FL2, 35% more manure was added, while FL3 corresponded to the nutrients applied in conventional agricultural practice (Hansen, 1996). In addition, there was an unfertilised control (UNF).

There were three manure management methods: stored diluted slurry (DS), aerated slurry (AS), or separated manure [SM, solid composted manure on tilled land (1985, 1986, 1991, 1992) and diluted liquid on ley (1987–1989, 1993–1995)]. These methods were compared at FL1 and FL2.

DS was slurry, diluted with water to twice its original volume, shortly before use. The slurries were stored for four-to-six months prior to application in spring and after the first harvest.

AS was cattle slurry aerated with a submersible pump. In the first rotation (1985–1989), the aeration was done in a manure cellar (Hansen, 1996). In the second rotation, the slurry was aerated in a closed cylindrical container (radius and height = 2 m) with an ABS AGRO 75-4, 7.5 kW pump. The aeration started shortly after the container was filled. In the beginning, the pump was run continuously, but when the temperature reached 30°C (after ~5 days) the slurry was aerated for 10 min, fourteen times per day, for six weeks. The temperature was 28–32°C in 1993 and 1994, and 19–25°C in 1995. The AS used in spring was stored for only a few days after aeration, and the AS used after the first herbage cut was stored for ca. two months.

SM was separated by free drainage in the stable in 1985 and from 1991 to 1996. From 1986 to 1989 a Key Dollar slurry separator was used (Morken, 1987) and the liquid applied to ley from 1987 to 1989 came from the slurry separator. From 1993 to 1995, the liquid was diluted urine.

At FL3, DS was the only manure management. In addition, mineral fertiliser (18-3-15 from HYDRO—17.6% N as ammonium nitrate, 2.6% P and 14.6% K) was used either alone (NPK) or as DS plus NPK (DSN), where DS corresponded to FL1. NPK and DSN followed the fertiliser guidelines of conventional agriculture. In 1995 the NPK-fertilised treatments, but only those, were limed because of low soil pH. Manure samples were frozen (−20°C) for analyses, following the method described by (Horwitz, 1980).

Slurries were spread using cans (10 l) with a spraying plate, compost by dung fork, and mineral fertiliser by hand, spreading lengthways and crosswise. On ley, fertilisation was mostly done in cold and rainy weather.

At FL1 and FL2, the amounts of manure applied in the second crop rotation were only 70% of the amounts applied in the first crop rotation period. This was in order to adjust the manure level to the common practice on organic farms in the area. Hansen (1996) gives the amounts of nitrogen, phosphorus and potassium applied in the first crop rotation. The total amounts of manure, dry matter and nitrogen applied in the second crop rotation are presented in Table 1.

2.5. Sampling and measurements

Earthworms were sampled in ley years, after the second ley cut in 1987 (9 September) and after the first cuts in 1988, 1989, 1993, 1995 and 1996 (end of June to beginning of July). One soil sample from a 10 × 20- 

\text{cm}^2 \text{ area was taken from each plot (0–15 cm depth in 1987, and 0–20 cm depth in 1988–1996). The earthworms were hand sorted, washed, counted and weighed (fresh weight 1987–1989; after storage 1993–1996). At a depth of 15–20 cm, very few earthworms were found in this shallow soil. In the whole investigation no anecic species were found. Therefore, there are likely to be very few earthworms below 20 cm. From 1993 on, the sampled earthworms were killed in 96% ethanol with 0.7% diethylphthalate, and stored either in 96% ethanol (1993 and 1995) or in 4% formalin (1996).

From 1993 to 1996, the species and developmental stages were determined. Determination of earthworm
<table>
<thead>
<tr>
<th>Year</th>
<th>TA (tonne/ha)</th>
<th>DM (kg/ha)</th>
<th>Total N (kg/ha)</th>
<th>NH$_4$-N (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FL1 (mean of DS,AS,SM)</td>
<td>25 16 33 33 33 140</td>
<td>3112 1509 1635 1635 1326 9217</td>
<td>112 45 70 70 81 378</td>
<td>29 9 39 39 47 164</td>
</tr>
<tr>
<td>FL2 (mean of DS,AS,SM)</td>
<td>34 21 44 44 44 187</td>
<td>4164 2018 2183 2232 1773 12370</td>
<td>150 60 108 79 108 505</td>
<td>39 13 64 50 63 228</td>
</tr>
<tr>
<td>DS, mean of FL1 and FL2</td>
<td>35 28 59 59 59 239</td>
<td>2208 1247 2879 2925 2797 12056</td>
<td>95 40 116 88 117 455</td>
<td>58 17 64 53 64 256</td>
</tr>
<tr>
<td>AS, mean of FL1 and FL2</td>
<td>18 17 25 26 25 111</td>
<td>1373 1254 2195 2312 1179 8313</td>
<td>71 40 81 71 90 352</td>
<td>40 15 37 32 47 171</td>
</tr>
<tr>
<td>SM, mean of FL1 and FL2</td>
<td>36 11 31 31 31 140</td>
<td>7334 2789 653 618 673 12066</td>
<td>226 78 72 49 76 501</td>
<td>4 1 54 45 54 158</td>
</tr>
<tr>
<td>FL3, DS</td>
<td>70 44 80 140 140 475</td>
<td>4416 1936 3930 7015 6711 24008</td>
<td>189 62 128 210 281 870</td>
<td>116 26 64 126 154 487</td>
</tr>
<tr>
<td>FL3, NPK</td>
<td></td>
<td>137 83 120 209 176 725</td>
<td>73 44 63 110 93 383</td>
<td></td>
</tr>
<tr>
<td>FL3, DSN</td>
<td></td>
<td>1884 1065 2460 2500 2390 10299</td>
<td>160 68 125 209 203 765</td>
<td>91 33 64 116 109 413</td>
</tr>
</tbody>
</table>

Note: Fertilisation levels one and two (FL1, FL2) are given as means for the manure treatments diluted slurry (DS), aerated slurry (AS) and separated manure (SM). DS, AS and SM are given as means of FL1 and FL2. At fertilisation level three (FL3) the fertilisation treatments are diluted slurry (DS), NPK-fertiliser (NPK) and a combination of DS and NPK (DSN).
species was carried out on stored material according to Sims and Gerard (1985). The presence of clitellum and/or tubercula pubertatis was used to classify the earthworms as adults or juveniles.

Soil physical determinations were made with low and normal tractor traffic in selected fertilisation treatments. Soil porosity was determined in undisturbed soil samples (7–11 cm depth) taken by means of four 100-cm³ cylinders in autumn each year from 1985 to 1989 and in 1991, 1993, 1995 and 1996. Particle density, used to calculate material and pore volume, was determined according to De Boodt et al. (1967). Penetration resistance was measured in 1995 and 1996 with a fully automated penetrometer that followed the ASAE S13.2 standard (ASAE, 1987).

Soil samples (0–20 cm) for determinations of pH (H₂O), ammonium-acetate lactate-soluble calcium, phosphorous and potassium (Ca-AL, P-AL, K-AL, Égner et al., 1960), acid soluble potassium (K-HNO₃, Reitemeier et al., 1951) and ignition loss, were taken from all plots after the last harvest in autumn in 1985, 1986, 1987, 1988, 1990, 1993, 1995 and 1996. The organic carbon and total nitrogen concentrations were determined in the soil samples from 1995 and 1996 with a Perkin–Elmer 2400 analyser.

2.6. Statistical analyses and calculations

Tractor traffic and the interactions between tractor traffic and fertilisation were tested with analyses of variance (ANOVA). The mean square difference of the interaction effect (replicate × compaction) was used as an error term to test the effect of compaction. Contrasts and least significant differences were used to separate the effects of the different fertilisation treatments. Correlations of population density and mass of earthworms with soil pH, Ca-AL and ignition loss, organic carbon and total nitrogen concentrations were determined in the soil samples from 1995 and 1996 with a Perkin–Elmer 2400 analyser.

3. Results

3.1. Earthworm populations

From 1987 to 1989, the population densities ranged from 50 to 1200 earthworms/m², with a mean of 420 ± 30/m² (SE); earthworm mass ranged from 8 to 360 g/m², with a mean of 130 ± 10 g/m² (Table 2). There was a close correlation between the population density and mass of earthworms (r = 0.87, p <0.001).

From the first crop rotation (1987 to 1989) to the second (1993 to 1996), the population density and mass of earthworms decreased. The average total population density in the latter period was 260 ± 20/m² and the average mass was 70 ± 4 g/m². From 1993 to 1996, the earthworm species were determined. Aporrectodea caliginosa constituted 67% of the population density and 78% of the mass. The corresponding figures were 25% and 19% for Lumbricus rubellus, and 7% and 3% for Aporrectodea rosea. In addition, small numbers of Dendrodrilus rubidus and Allolobophora chlorotica were present.

The endogeic species Aporrectodea caliginosa, A. rosea and Allolobophora chlorotica dominated in 1993 and 1995, with 90% and 80% of the population density, respectively. In the aftereffect year (1996), when no cattle slurry was spread, the population densities of the epigeic species, L. rubellus and D. rubidus, increased and endogeic species decreased so that the epigeic species constituted 50% of the total.

3.2. Effect of tractor traffic

The population density responded strongly to tractor traffic (p <0.001). An average of 500 earthworms/m² was found with low tractor traffic, compared with 180 earthworms/m² with normal tractor traffic. The corresponding values for earthworm mass were 140 and 60 g/m². The difference in earthworm populations between normal and low tractor traffic treatments, was greatest at the beginning of the study period. In 1987 there was an average of 720 earthworms/m² after low, and 180/m² after normal, tractor traffic. During the study period, the earthworm populations decreased in treatments with low tractor traffic (Fig. 2). In 1993, the difference was still statistically significant (p <0.001 for mass, p <0.01 for population density), but not in 1995 and 1996.
The lower population density in the treatment with heaviest tractor traffic coincided with denser soil and lower porosity (Fig. 3). Since inflation pressure in tractor wheels was lower in the second crop rotation, the soil was less dense in the normal tractor traffic treatment in the second crop rotation than in the first one (Fig. 3). There was a close correlation between the volume of pores and the population density in 1988.

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3.3. Effect of fertilisation treatments

3.3.1. Effect of mineral fertiliser

In total, there were fewer earthworms in soil fertilised with mineral fertiliser only (NPK-fertilised) than in manured soil (Table 2, \( p < 0.002 \)), but the liming of NPK-fertiliser treatments in spring 1995 led to an immediate increase in earthworm populations in these treatments (Fig. 4).

3.3.2. Effect of increased manure application

Increasing the manure application from FL1 to FL2 increased the population density \( (p < 0.02) \) and the mass \( (p < 0.01) \) of endogeic but not of epigeic species (Fig. 5). Therefore, for all earthworms together, the increases in the population density and mass from FL1 to FL2 were not statistically significant (Table 3). A further increase in the manure application in the diluted slurry management (DS) increased both, the total population density and mass of earthworms in 1988, 1993 and 1996. This increase was due to an increased endogeic population in 1993 (Fig. 6). In 1989 and 1995, there was a tendency towards fewer earthworms with increasing manure level.

3.3.3. Cattle slurry vs. separated manure application

The total population density of earthworms was not significantly affected by whether the manure was treated as slurry or separated with solid composted manure applied to tilled land and urine to ley. Since most of the organic matter under separated manure treatments was added with the solid manure in tillage years (1985, 1986, 1991, 1992), there was less food from the added manure for the earthworms late in the ley period. In the years following the application of the solid manure (1987, 1988, 1993), there was a tendency towards more earthworms where separated manure was applied than in the plots that received slurry, but significantly fewer earthworms late in the second crop rotation period (1995, 1996) (Table 3 and 4). From 1993 to 1996, in the separated manure treatment, there was a large decrease in endogeic species (Fig. 7), but not in the epigeic species.

Table 3

<table>
<thead>
<tr>
<th>Population density</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contrast DS–AS</td>
<td>0.4</td>
</tr>
<tr>
<td>Contrast FL1–FL2</td>
<td>0.2</td>
</tr>
<tr>
<td>Contrast SM—DS, AS</td>
<td>0.7</td>
</tr>
</tbody>
</table>
3.3.4. Aerated vs. diluted cattle slurry

Whether the slurry was aerated or diluted did not significantly affect either the total population density or mass of earthworms in the treatment years (1987–1995, Table 3). In 1993 and 1995, there was a significantly lower mass of epigeic ($p<0.05$) but not of endogeic species of earthworms with aerated slurry than with diluted slurry (Fig. 7). Less organic matter was added with aerated slurry than with diluted slurry. From 1991 to 1995, the mean addition of organic

![Graphs showing earthworm mass and content of readily available calcium (Ca-AL) in soil with fertilisation treatments](image-url)
matter in the FL1 and FL2 diluted slurry management was 240 g/m² (dry matter basis) vs. 170 g/m² in the aerated management. This is a result of the breakdown of organic matter during composting of the aerated slurry.

### 3.4. Changes and correlations during the treatment period

During the treatment period there was a decline in earthworm populations with low tractor traffic in all fertilisation treatments, except high additions of diluted slurry (DS3) (Fig. 4).

Simultaneously with this decline, acidification of soil in the research field occurred and both, the soil pH and Ca-AL were quite low at the end of the experiment (Fig. 4). In treatments with low tractor traffic, the mass of earthworms was closely correlated with soil pH ($r = 0.95, p < 0.004$) and Ca-AL ($r = 0.96, p < 0.003$), but not with ignition loss. There was also a close correlation with herbage yields ($r = 0.92, p < 0.02$), which declined during the study period. With normal tractor traffic there were no significant correlations.
3.5. Residual effects of previous treatments

Correlation analysis showed that the amount of dry matter added with manure in 1991–1995 was the environmental factor that was most closely correlated with the total population density ($r = 0.61, p < 0.001$) and mass ($r = 0.49, p < 0.002$) of earthworms in the aftereffect year (1996). The main reason for this was the close correlation between the previously added manure and the population density and mass of juvenile earthworms ($r = 0.61, p < 0.001$ and $r = 0.50, p < 0.001$). Previously added manure was also correlated with the population density of *A. caliginosa* ($r = 0.44, p < 0.005$) and *L. rubellus* ($r = 0.54, p < 0.001$). Mass was not significantly correlated with previously added manure for *A. caliginosa*, but for *L. rubellus*, it was ($r = 0.50, p < 0.001$).

The total population density of adult earthworms was not significantly correlated with previously added manure, but was correlated with soil pH ($r = 0.33, p < 0.05$). For *A. rosea*, the population density of earthworms was correlated with soil pH ($r = 0.39, p < 0.05$), but not with previously added manure. The total population densities of *A. caliginosa* and *L. rubellus* were not correlated with soil pH.

Neither the mass nor the population density of any component of the earthworm population was correlated with ignition loss, organic carbon or total nitrogen in 1996.

4. Discussion

4.1. Earthworm populations

The number of earthworms found in the present field trial are relatively high compared with other Nordic sites (Andersen, 1979; Andersen et al., 1983; Boström, 1986; Christensen et al., 1987, Nuttinen, 1992; Haraldsen et al., 1994a, b). All the present species are commonly found in Norwegian soil (Haraldsen et al., 1994b). Their ecological traits ensure their survival in spite of regular ploughing. A combination of agricultural practice and occasional waterlogging of the soil may cause the absence of anecic species.

4.2. Effects of tractor traffic

The destructive effects of tractor traffic on earthworms are not surprising, and agree with the result of other investigations (e.g. Boström, 1986; Söchtig and Larink, 1992).

The very destructive effects of tractor traffic on earthworms and soil porosity in the present investigation probably occurred because, in this cool and wet climate, the soil often is moist and thus vulnerable to damage. In addition, the structure of this loamy sand easily deteriorates (Hansen et al., 1993). The tractor traffic also led to large yield declines (Hansen, 1996).

We expected tractor traffic to be more harmful to epigeic species than to endogeic species, as found by Pizl (1992), since earthworms near the surface are more vulnerable to direct pressure from the tractor wheels. This could not be confirmed in the present investigation, however. One reason might be the high density and penetration resistance in the soil with normal tractor traffic in the present investigation. In dense soil, the endogeic earthworms have to eat their way through the soil and cannot push it aside as easily as they can in looser soil (Dexter, 1978). As the tractor traffic treatment lowered the soil porosity most in the first crop rotation period (Fig. 3), the very harmful effect of tractor traffic on endogeic earthworms found in the second crop rotation period could be a consequence of the first crop rotation period.

The lack of a statistically detectable effect of previous tractor traffic on the earthworm population, a year after the last tractor traffic (1996), is in accordance with the results of Aritajat et al. (1977a) and Haraldsen et al. (1994a).

4.3. Effect of fertilisation treatments

4.3.1. Effect of mineral fertiliser

Our finding of fewer earthworms in soil fertilised with mineral fertiliser only (NPK-fertilised), than in manured soil agrees with the results of other investigations (Lofs-Holmin, 1983; Haraldsen et al., 1994a). The direct adverse effects of mineral fertilisers on earthworm populations seem to be most pronounced in light soils and with the nitrogen applied in acidifying compounds (Lofs-Holmin, 1983; Ma et al., 1990). In the present investigation, the soil is light (sandy loam) and the nitrogen fertiliser has an acidifying effect on earthworms.
The likelihood of a direct adverse effect of NPK-fertiliser on earthworms is indicated by the fact that, in the first part of the investigation period (1987–1993), there was a tendency for fewer earthworms in NPK-fertilised than in unfertilised soil (Table 2). However, this tendency was significant only in 1989.

Some investigators have found a positive long-term effect of adding mineral nitrogen (Edwards and Lofty, 1982; Boström, 1986). This is likely to be the result of increased crop growth and, thus, more organic material added to the soil. Liming of the soil in NPK-fertilised treatments may explain why there were no differences between earthworm populations in NPK-fertilised and manured treatments in 1995.

4.3.2. Effect of increased manure application

The significant correlation between the amount of organic matter added with manure and the population density of earthworms in the aftereffect year (1996) shows the importance of manure as a source of food for earthworms, as previously observed, for example, by Uhlen (1953); Edwards and Lofty (1977); Lofs-Holmin (1983) and Standen (1984).

The reason for a tendency towards fewer earthworms with increasing manure level in 1989 and 1995 may have been a toxic effect of cattle slurry on earthworms, as observed by (Curry, 1976). The fact that many dead earthworms were observed on the soil surface shortly after the slurry was spread in those years and the large increase in epigeic species in the aftereffect year 1996, supports this hypothesis.

4.3.3. Cattle slurry vs. separated manure application

A decrease in the earthworm population late in the ley periods in the separated manure treatment, when only the liquid fraction was being applied, can partially be explained by the fact that the effect of solid manure (FYM) does not last very long (Lofs-Holmin, 1983). This seems most evident for the endogeic species (Fig. 7). Because endogeic species feed mostly on mineral and humus particles within the soil, whereas epigeic species feed on plant residues and microorganisms at the surface, this is reasonable.

4.3.4. Aerated vs. diluted slurry

The main reason we did not get a positive effect of aerating the slurry on earthworm density, is likely to be reduced availability of food for the earthworms in the aerated slurry treatment compared with the diluted slurry. This hypothesis is supported by the fact that, in the aftereffect year (1996), there were fewer earthworms ($p < 0.05$) and less earthworm mass in the aerated that in the diluted slurry treatment. Haraldsen et al. (1994b) also found a tendency towards fewer earthworms in the aftereffect year in the treatments previously manured with aerated compared with diluted slurry. This is consistent with the field results of Bieri and Besson (1987).

In addition, it seems that we did not achieve reduced toxicity of the cattle slurry as a result of aeration as Nebiker (1974) and Bauchhenss (1981) did following more intense aeration which reduces the ammonia content; rather, a tendency to the opposite. This is indicated by the fact that, in plots where aerated slurry was applied, there was a lower mass of epigeic species than in plots with diluted slurry.

4.4. Reasons for the decline in earthworm populations in treatments with low tractor traffic

The close correlations between population density and mass and soil pH and Ca-AL that were observed with the low tractor traffic treatments suggest that acidification of the soil is an important reason for the reduction in earthworm populations in these treatments. Earthworm species differ in acid tolerance, and the tolerance seems to vary with environmental conditions. Lofs-Holmin (1986) found that A. caliginosa, A. rosea and L. rubellus, which were the dominant species in the present investigation, all were quite acid-tolerant. On the other hand, Lofs-Holmin (1983) found increased population density of A. caliginosa in a sandy soil when the pH was increased from 5 to 6.6. Satchell (1955), Piearce (1972) and Nordström and Rundgren (1974) also found positive correlations between pH and mass of A. caliginosa, as did Standen (1984) for the total earthworm mass in a meadow.

As the decline in earthworm populations was most pronounced at fertilisation level 1 (FL1), and because there was a close correlation between previously added manure and the earthworm populations in the aftereffect year, the reduction in the amount of manure applied at FL1 and FL2 in the second crop rotation (1991–1996) to 70% of that in the first crop rotation...
(1985–1990), may also be an important reason for the earthworm decline.

Changing weather conditions theoretically could have been a reason for the decline in earthworm populations. As the soil was covered with snow during cold periods, no drought occurred during the investigation period and the earthworm sampling (except 1987) was done mostly at the same time each year, this is not likely to be a major factor in the earthworm decline. Neither should the crop rotation be important, as the samplings were done in ley in both the crop rotations with the rotations being very similar.

5. Conclusions

When other conditions were favourable for earthworms, the near absence of tractor traffic led to a high population density of earthworms in this loamy sand. The highest population density and mass of earthworms were found in the manured soil. Increasing the amount of cattle slurry and urine decreased the population density and mass of earthworms transiently in some years, but not all. Aerated slurry application did not result in a higher earthworm population compared with diluted slurry.

Both, tractor traffic and soil acidification were found to depress the earthworm populations in this soil. The dominant earthworm species were the endogeic species *Aporrectodea caliginosa* and the epigeic species *Lumbricus rubellus*.

Acknowledgements

We would like to thank K. Myhr for suggesting the earthworm investigations, J. Andersen for penetrometer measurements, B.R. Ertvaag for his assistance during the research period, A.-K. Løes and V. Nuutinen for valuable comments and Professor W. Lockeretz for valuable comments and language correction.

References


