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NITROGENOUS FERTILIZERS AND EARTHWORM POPULATIONS IN AGRICULTURAL SOILS

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Summary—The influence of various inorganic and organic fertilizers was assessed in three long-term "classical" experiments and two short-term field experiments, one on grass and one on wheat. The long-term experiments included Broadbalk which had grown continuous wheat since 1843, Barnfield, continuous root crops since 1843 and Park Grass, continuous grass since 1836. Annual fertilizer treatments were farmyard manure (48 and 96 kg N ha^{-1}), various forms of inorganic nitrogen (48, 96, 144 and 192 kg N ha^{-1}), liquid and solid sewage sludge and sewage cake in a wide range of doses.

In the three arable experiments, all species of earthworms were more numerous in plots treated with organic fertilizers than in untreated plots.

There was a strong positive correlation ($r = 0.9825$) between amounts of inorganic N applied and populations of earthworms. Plots receiving both inorganic and organic N had the largest populations of earthworms.

The effects of both inorganic and organic N were much less on earthworm populations in grassland than on those in arable crops, even in the long-term experiments, and there was some evidence of adverse effects when an excessive amount of liquid sludge was applied in a single dose.

Effects of organic fertilizers were greater on populations of *Lumbricus terrestris* than on those of *Allolobophora longa*, *A. caliginosa* or *A. chorotica*.

INTRODUCTION

The importance of earthworms in breaking down organic matter and incorporating it into soil, thereby improving soil structure, aeration and drainage is well established (Darwin, 1881; Edwards and Lofty, 1977; Edwards, 1981). With recent development of minimal cultivation and direct drilling of crops into uncultivated soil, after the use of a broad spectrum herbicide, earthworm activity may be even more important in maintaining soil productivity (Edwards and Lofty, 1978, 1980).

There is evidence that earthworm populations are influenced greatly by availability of organic matter for food and this may come from plant residues or from animal or human waste applied to the land.

Traditionally, large quantities of farmyard manure (FYM) were used in agriculture but as the housing of pigs and cattle has intensified widespread use of FYM has been superseded by inorganic fertilizers. Even more recently, there has been a trend to apply increasing amounts of pig and cattle solids, sludges and slurries to agricultural land and, at present, 46% of human sewage in the form of activated sludges or sewage cake is applied to arable soils. In 1978, 29% of all agricultural land in the U.K. was treated with organic materials (Table 1).

Considering the extensive use of organic fertilizers, little is known about their effects on the soil fauna and particularly earthworms. Such information as is available was reviewed by Marshall (1977). The effects of organic matter on earthworms in arable crops have been studied only by Morris (1922, 1927) and Atlavinyte (1975). There is more information on how organic fertilizers affect earthworm populations in grassland (Jefferson, 1955, 1956; Zajonc, 1975; Curry, 1976; Edwards and Lofty, 1975; Cotton and Curry, 1980a and b). The only data on the effects of nitrogenous inorganic fertilizers on earthworm populations in the field are from Zajonc (1975), Edwards and Lofty (1975) and Gerard and Hay (1979).

METHODS

Earthworm populations were assessed in three "classical" experiments at Rothamsted and two short-term experiments where different forms of organic and inorganic fertilizers were used (see Rothamsted Annual Reports).

Long-term experiments

The Broadbalk experiment began in 1843, growing continuous wheat and comparing the effects of farmyard manure with inorganic fertilizers supplying the elements N, P, K, Na and Mg in various combinations. There have been many modifications but the basic treatments have continued on some plots. Earthworm populations in some of these plots were sampled in September 1979 by pouring dilute formalin on to sixteen 0.25 m^2 quadrats and collecting the worms that were brought to the surface (Raw, 1959). These were stored in 5% formalin until they could be identified. The plots sampled measured 48 × 6.3 m and the regular annual treatments were: (i) 35 t ha^{-1} farmyard manure, (ii) 35 t ha^{-1} farmyard manure plus from 1968 onwards 96 kg N ha^{-1} ("Nitro-chalk"), (iii) 192, (iv) 144, (v) 96 and (vi) 48 kg N ha^{-1} and (vii) no fertilizers.

The Barnfield experiment has grown root crops continuously on some plots since 1843 although there have been many modifications to the treatments and cropping. Earthworm populations were sampled in

Table 1. Agricultural land receiving organic fertilizers 1978

Crop	Proportion of total crop area receiving organic fertilizer (%)	Proportion (%) of area treated with organic fertilizers receiving particular forms: FYM	Slurry	Sewage sludge	Other organic
Spring cereals	19	76	19	3	2
Winter cereals	13	81	11	4	4
Potatoes	42	84	8	1	7
Grass	46	65	30	2	3
All crops and grass	29	72	24	2	2

October 1959 by the formalin method, ten 0.25 m^2 quadrats being used on each treatment investigated. The fertilizer treatment applied annually were: (i) 35 t ha^{-1} farmyard manure, (ii) farmyard manure + 96 kg N ha^{-1}($(NH_4)_2SO_4$), (iii) farmyard manure + 96 kg N ha^{-1}($NaNO_3$), (iv) 96 kg N ha^{-1} $NaNO_3$) + 35 kg P ha^{-1}, as granular super phosphate, (19% P_2O_5), 225 kg K ha^{-1} K_2SO_4 15 kg Na ha^{-1} Na_2SO_4 10 kg Mg ha^{-1} $MgSO_4$ and (v) no fertilizers.

The Park Grass experiment has compared regular fertilizer applications to grassland since 1856. Earthworm populations were sampled in May 1974 in plots that had received organic fertilizers every fourth year (35 t ha^{-1} farmyard manure and fish meal to supply 63 kg N ha^{-1}) and those that had no fertilizers. Sixteen 0.25 m^2 quadrats were sampled on each of the two treatments using the formalin method after the grass had been cut short.

Short-term experiments

An experiment in a newly-ploughed field at Rothamsted (Delharding) was started in February 1978. After winter ploughing, farmyard manure (200 kg N ha^{-1}) and sewage cake (200 kg N ha^{-1}) were each applied to four plots 9.0 × 1.4 m with four plots left untreated. All plots were sown to spring wheat (Minden). Treatments were repeated in November 1978 and plots sown to spring beans in 1979. Earthworm populations were assessed in four 0.25 m^2 quadrats per plot using the formalin method in March and November 1979.

The effects of applications of different forms of sewage to grassland on earthworm populations were assessed at Kings Walden, Herts. Plots were 16 × 2.3 m, and the treatments were: liquid sewage sludge at 402 kg N ha^{-1}, solid sewage sludge at 536 kg N ha^{-1} compared with no sludge treatment. The sludges were applied in spring and autumn 1978 and 1979 (half the total annual dose was applied on each occasion). There were four replicates of each treatment. Earthworm populations were assessed in October 1980 from four 0.25 m^2 quadrats per plot, using the formalin method.

RESULTS

Long-term experiments

In the Broadbalk continuous cereals experiment, progressively more earthworms occurred with increasing rates of inorganic and organic N (Table 2, Fig. 1) and there was a strong positive correlation between earthworm populations and amounts of nitrogen added (Fig. 2). Data on the percentage of organic carbon in the plots is available (Johnston, 1969) and when plotted against numbers of earthworms also showed a strong positive correlation (Fig. 3).

The results from the sampling in the Barnfield experiment on the long-term application of nitrogenous fertilizers to root crops (Table 3) also show increasing numbers of earthworms in plots treated with larger annual doses of fertilizer.

The increased numbers of earthworms resulting from the long-term application of organic manure to grassland in the Park Grass experiment were smaller than those on arable sites (Table 4).

Population of earthworms in the short-term arable experiment with farmyard manure and sewage cake (Table 5, Fig. 4) were larger in all plots in spring than in autumn; although both organic fertilizers increased

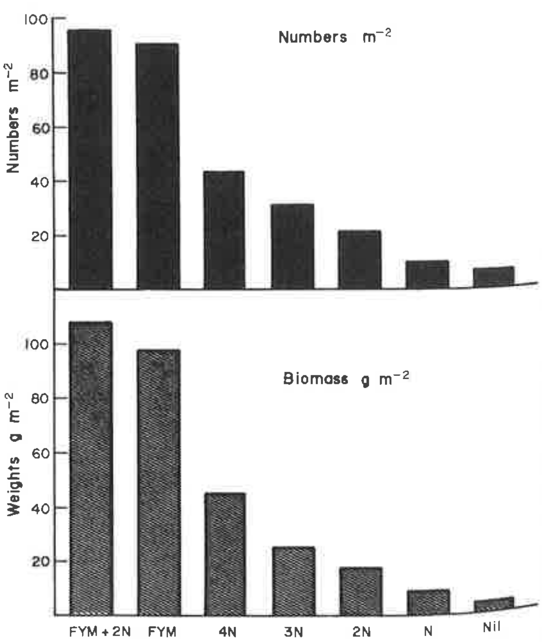

Fig. 1. Effects of long-term treatments with organic and inorganic fertilizers on earthworm populations in plots growing continuous cereals since 1843 (Broadbalk) (Solid columns—Numbers m^{-2}; Crosshatched columns—Biomass g m^{-1}).

Table 2. Effects of long-term organic and inorganic fertilizer treatments on earthworm populations in plots growing continuous cereals since 1843 (Broadbalk)

Species	Treatments FYM +2N	FYM only	4N (+PKMg)	3N (+PKMg)	2N (+PKMg)	1N (+PKMg)	Nil (+PKMg)	Nil (No fertilizers)	Standard error of mean	Degrees of freedom. Error mean square	F	F-test
L. terrestris												
No m^{-2}	36.4	23.1	10.7	7.1	3.3	2.7	4.0	2.7	1.113	88	34.224	sig < 0.01
Wt g m^{-2}	51.4	27.3	17.9	8.3	2.0	2.5	7.1	2.2	2.042	88	18.945	sig < 0.01
A. longa												
No m^{-2}	11.8	6.9	4.2	2.4	1.6	1.6	1.3	0.9	0.501	88	14.909	sig < 0.01
Wt g m^{-2}	8.6	5.0	2.9	2.5	1.4	1.3	1.6	0.3	0.545	88	6.635	sig < 0.01
A. caliginosa												
No m^{-2}	13.6	19.6	5.3	5.8	4.7	1.3	0.4	0.4	0.885	88	24.006	sig < 0.01
Wt g m^{-2}	3.1	3.7	1.0	0.8	0.8	0.2	0.0	0.0	0.274			
A. chlorotica												
No m^{-2}	32.4	39.8	22.7	15.3	11.3	4.4	1.8	1.6	1.761	88	18.772	sig < 0.01
Wt g m^{-2}	7.5	7.6	4.1	2.1	2.0	0.7	0.2	0.2	0.599			

(N = 48 kg N ha^{-1}).

earthworm numbers, sewage cake had the greatest effect.

The very large doses of sewage sludges applied to grassland in the Kings Walden experiment did not increase earthworm populations greatly (Table 6).

DISCUSSION

All the forms of nitrogenous fertilizers used in our field experiments increased total populations of earthworms. However, the effect of the fertilizers upon numbers of earthworms in arable land was much greater than in grassland. Morris (1922, 1926) reported from 2 to 2.5 times as many earthworms in plots receiving farmyard manure as in those to which no fertilizer was applied, but effects on different species were not identified. In a 2-yr study J. Anderson (personal communication) compared the effects on earthworms of 250, 500, 1000 and 2000 kg N ha^{-1}, applied as farmyard manure and animal slurry to a field cropped with a cereals, sugar beet and grass rotation. Both forms of manure in organic matter increased *L. terrestris* and *A. caliginosa* populations, but *A. longa* increased only in response to farmyard manure. The highest doses of organic N tended to decrease populations of most species of earthworms.

Apart from comments by Ogg and Nicol (1945) and Jacob and Wiegland (1952), the only other investigation into the effects of inorganic nitrogenous fertilizers on earthworms in arable land, other than those reported here, is that by Gerard and Hay (1979) who assessed the effects of 0, 50, 100 and 150 kg inorganic N ha^{-1} applied annually on populations in a barley field 2 yr and 5 yr after treatments began, and found the largest numbers in plots treated with 100 kg N ha^{-1}, although differences between 100 and 150 kg N ha^{-1} were not significant. Our results confirm these findings and provide a basis for speculation upon the ways in which fertilizers increase earthworm populations.

The organic fertilizers probably act directly by providing food for the earthworms. This was most obvious for populations of *L. terrestris* which increased more than those of other species probably because it feeds directly upon surface organic matter. Probably the influence of organic matter on all species is mainly through increasing their food supply, whether they feed directly upon the organic matter or upon microorganisms growing upon it. It is less clear how inorganic nitrogenous fertilizers favour the build-up or earthworm populations. However, in the long-term fertilizer experiment, on continuous wheat, there was a strong correlation between the amount of organic matter (% organic C) in the soil and the amount of N that had been applied annually (Figs 3 and 4) (Johnston, 1969). This suggests that the higher concentrations of N influence earthworms by increasing the amount of plant material and when this dies, in turn, the amount of decomposing organic matter increases. There was evidence that in terms of amounts of N applied per ha, organic matter N had a greater effect than inorganic nitrogen (Fig. 2).

The form of the inorganic nitrogen can also affect earthworm populations. In the Barnfield root crop

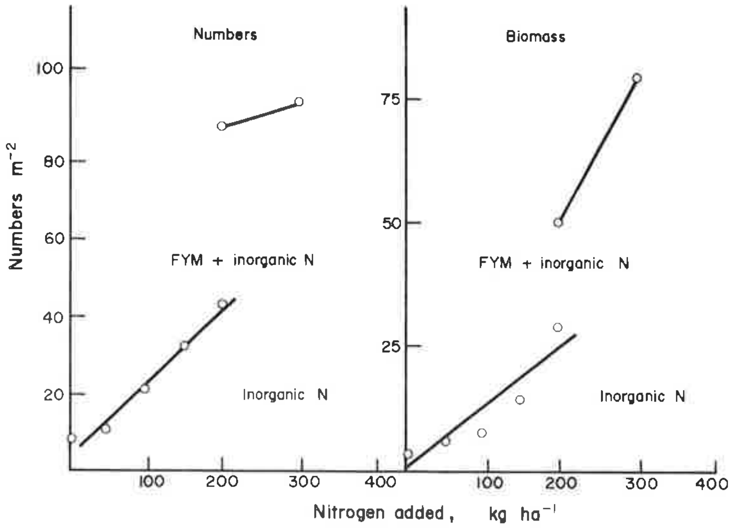

Fig. 2. Correlations between nitrogen and earthworm populations (Broadbalk).

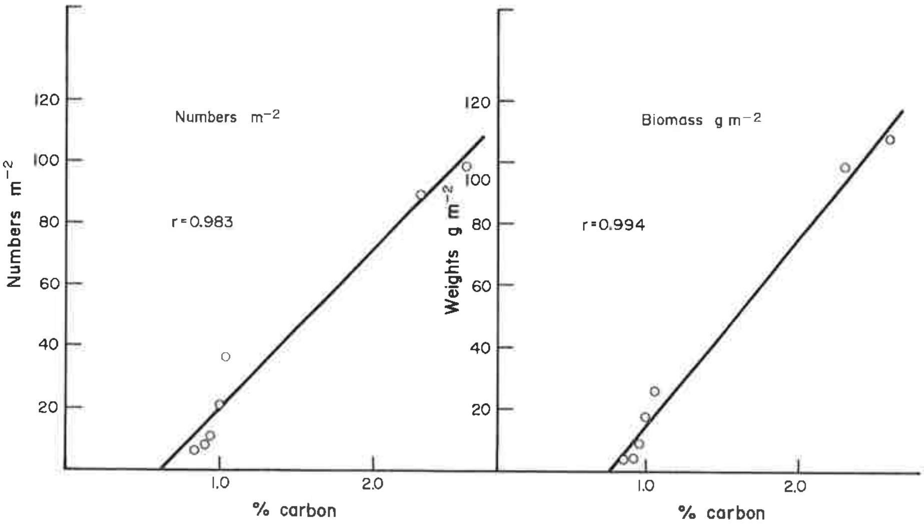

Fig. 3. Correlations between organic matter (% carbon) and earthworm populations (Broadbalk).

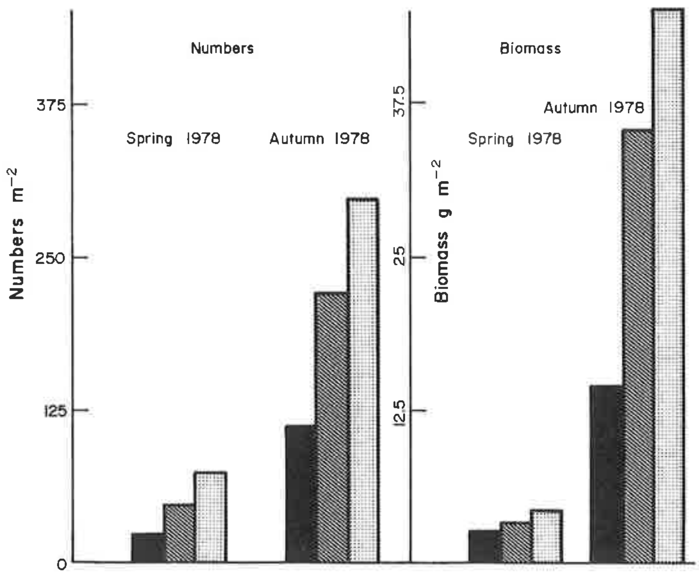

Fig. 4. Effects of sewage cake and farmyard manure on earthworm populations (Solid columns—no organic matter; Cross-hatched columns—farmyard manure; Dotted columns—sewage cake).

Table 3. Effects of long-term organic and inorganic fertilizer treatments on earthworm populations in plots growing continuous root crops since 1843 (Barnfield)

Table 3. Effects of long-term organic and inorganic fertilizer treatments on earthworm populations in plots growing continuous root crops since 1843 (Barnfield)

Species		Treatments: +2N ($[NH_4]_2SO_4$)	2N ($NaNO_3$)	FYM only	($NaNO_3$) +PKMgNa	No fertilizer	Standard error of mean	Degrees of Error mean square	F	F-test
L. terrestris	No m^{-2}	17.1	13.3	7.1	11.6	0.2	1.247	45	7.142	sig < 0.01
	Wt g m^{-2}	25.7	9.6	7.8	13.2	0	2.142	45	7.388	sig < 0.01
A. longa	No m^{-2}	4.4	0	2.2	0.4	0.4	0.420	45	5.132	sig < 0.01
	Wt g m^{-2}	2.6	0	1.8	0.2	3.4	0.374			
A. caliginosa	No m^{-2}	32.2	9.6	17.8	3.8	0.9	1.268	45	28.262	sig < 0.01
	Wt g m^{-2}	10.0	3.0	5.5	1.2	0.3	0.393			
A. chlorotica	No m^{-2}	23.1	12.9	51.6	13.1	9.1	2.012	45	24.918	sig < 0.01
	Wt g m^{-2}	8.1	4.5	18.6	4.6	3.2	0.684			

(N = 48 kg N ha^{-1}).

experiment farmyard manure plus ammonium sulphate increased populations more than farmyard manure plus sodium nitrate. This is surprising because several workers have claimed that ammonium sulphate can be harmful to earthworms (Escritt and Arthur, 1948; Rodale, 1948; Jefferson, 1955). However, the deleterious effect of ammonium sulphate may have been because large doses of this fertilizer cause soil acidity but there is no evidence that this occurred on Barnfield.

The fastest increases in total earthworm populations in arable land were in response to the sewage cake applications in the short-term Delharding arable experiment (Table 5). However, the greatest effects of the sewage cake treatments were upon *A. chlorotica*, and *L. terrestris* was influenced more by farmyard manure, which probably contains organic matter in a more acceptable form.

In Broadbalk continuous wheat, the increases in organic N had the greatest effect upon *A. chlorotica*, followed in turn by *L. terrestris*, *A. caliginosa* and *A. longa* (Fig. 2b). There was also some evidence that the elements P, K and Mg produced a small increase in earthworm numbers additional to that of nitrogen (Table 2).

Thus, although the available evidence is slender, it adds credence to results obtained in our experiments which show that organic fertilizers applied to arable land increase earthworm populations much more than inorganic nitrogenous fertilizers.

The effects of organic matter on earthworm populations in the two grassland experiments were very much less than in the arable experiments. Similar results have been obtained by other workers. For instance, Cotton and Curry (1980a) found a 62% increase in earthworm populations from the use of pig slurry (125–250 kg N ha^{-1}) and a slightly smaller increase in another study (Cotton and Curry, 1980b). Curry (1976) reported a 43% increase from the use of cattle slurry (225 kg N ha^{-1}) and a 46% increase after using poultry slurry (478 kg N ha^{-1}). Curry (1976) also reported that very high doses of slurry (2400 kg N ha^{-1}) decreased earthworm populations. Zajonc (1975) tested the effects of inorganic and organic nitrogenous fertilizers on grassland at doses from 100 to 300 kg N ha^{-1} and found the greatest increases in response to 100 kg N ha^{-1}.

In our Park Grass experiment, total earthworm populations were increased by only 11% by the farmyard manure, although those of *L. terrestris* were 184% more (Table 4). Sewage sludges in the Kings Walden grassland experiment increased total populations by 52% although numbers of *L. terrestris* nearly doubled. Populations increased more in response to solid than to liquid sludges (Table 6).

Sometimes liquid slurries had an initial detrimental effect on earthworm populations, dead worms appearing on the surface after treatment. Similar effects were noted by Curry (1976) who found, in laboratory tests, that slurries could be toxic to earthworms. Hence, any increase in populations occur only after this initial setback. The small effects of organic manures on populations of earthworms in grassland are due probably to the large amounts of organic matter already present in the form of root litter. Under such conditions, the avilability of food is unlikely to be limit-

Table 4. Effects of long-term organic fertilizer treatments on earthworm population in plots down to grass since 1843 (Park Grass)

Species		Treatment FYM	No fertilizer	Standard error of mean	Degrees of freedom. Error mean square	F	F-test
			1973 Sampling				
L. terrestris	No m^{-2}	20.5	7.2	0.920	30	28.796	sig < 0.01
	Wt g m^{-2}	33.9	8.2	1.639	30	33.590	sig < 0.01
A. longa	No m^{-2}	18.0	11.9	0.934	30	5.803	sig < 0.05
	Wt g m^{-2}	15.1	10.0	0.813			
A. caliginosa	No m^{-2}	6.4	6.6	0.670	30	0.009	NS
	Wt g m^{-2}	2.0	2.0	0.208			
A. rosea	No m^{-2}	4.4	3.9	0.682	30	0.076	NS
	Wt g m^{-2}	1.1	0.98	0.171			
O. cyaneum	No m^{-2}	6.4	15.3	1.872	30	3.131	NS
	Wt g m^{-2}	9.8	13.8	1.692			
			1974 Sampling				
L. terrestris	No m^{-2}	28.7	12.6	1.540	30	15.188	sig < 0.01
	Wt g m^{-2}	46.6	26.4	2.650	30	7.952	sig < 0.05
A. longa	No m^{-2}	11.6	8.7	1.214	70	0.678	NS
	Wt g m^{-2}	9.7	7.3	1.080			
A. caliginosa	No m^{-2}	4.9	5.7	0.847	30	0.136	NS
	Wt g m^{-2}	1.5	1.8	0.263			
A. rosea	No m^{-2}	1.8	3.4	0.557	30	1.020	NS
	Wt g m^{-2}	0.5	0.9	0.139			
O. cyaneum	No m^{-2}	5.4	18.8	2.070	30	5.273	sig < 0.05
	Wt g m^{-2}	9.7	16.9	2.827			

Table 5. Short-term effects of organic fertilizers on earthworm populations (Delharding)

Species		Treatments Sewage cake	FYM	Nil	Standard error of mean	Degrees of freedom. Error mean square	F	F-test
			Spring Sampling 1979					
L. terrestris	No m^{-2}	1.6	0.9	0.2	0.182	45	2.132	NS
	Wt g m^{-2}	1.9	0.3	0.1	0.387	45	2.052	NS
A. longa	No m^{-2}	0.0	0.6	0.0	0.111	45	1.901	NS
	Wt g m^{-2}	0.0	0.4	0.0	0.110	45	1.733	NS
A. caliginosa	No m^{-2}	15.7	8.1	6.5	0.890	45	4.774	sig < 0.05
	Wt g m^{-2}	4.9	2.5	2.0	0.276			
A. chlorotica	No m^{-2}	48.0	31.4	14.6	1.570	45	17.134	sig < 0.05
	Wt g m^{-2}	16.3	10.7	5.0	0.534			
			Autumn sampling 1979					
L. terrestris	No m^{-2}	2.4	4.2	2.0	0.562	33	0.455	NS
	Wt g m^{-2}	2.4	6.1	1.2	0.758	33	3.152	NS
A. longa	No m^{-2}	2.0	2.4	1.1	0.364	33	0.454	NS
	Wt g m^{-2}	3.1	4.2	1.1	0.758	33	1.176	NS
A. caliginosa	No m^{-2}	74.7	58.7	39.1	4.760	33	2.210	NS
	Wt g m^{-2}	23.2	18.2	12.1	1.476			
A. chlorotica	No m^{-2}	194.7	131.8	56.7	6.800	33	16.442	sig < 0.01
	Wt g m	66.1	44.8	19.3	2.312			

Table 6. Effects of short-term applications of sewage sludges on earthworm populations in grassland (Kings Walden)

Species		Treatment Solid sludge N3	Liquid sludge N2	No sludge	Standard error of mean	Degrees of freedom. Error mean square	F	F-test
L. terrestris	No m^{-2}	23.2	19.1	12.3	0.946	149	6.413	sig < 0.01
	Wt g m^{-2}	21.2	27.3	18.9	1.401	149	5.273	sig < 0.05
A. caliginosa	No m^{-2}	2.4	5.6	3.6	0.354	149	6.324	sig < 0.05
	Wt g m^{-2}	0.7	1.7	1.1	0.113			
A. chlorotica	No m^{-2}	5.2	6.3	4.3	0.551	149	4.953	sig < 0.01
	Wt g m^{-2}	1.8	2.1	1.5	0.187			

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