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Influence of earthworms on soil properties and grass production in reclaimed cutover peat

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Abstract The effects of earthworms on grass growth and soil structure in reclaimed peat were studied in a glasshouse bucket experiment. Cumulative grass yields from 13 cuts taken over a period of 20 months were 89% higher in organically fertilized and 19% higher in inorganically fertilized buckets with earthworms than in similarly fertilized buckets without earthworms. When fertilizers were withheld from some buckets after 7 months grass growth during the remainder of the study was significantly greater in the presence of earthworms under both organic (+222%) and inorganic (+114%) regimes. It is considered that grass growth responses were mainly due to enhanced organic matter decomposition and mineralization.

Soil subsidence rates, hydraulic conductivity, moisture characteristics, bulk density, porosity, fibrosity, and soil morphology and micromorphology were significantly influenced by earthworm activity. The results show that earthworm activity can significantly accelerate the process of maturation and profile development in reclaimed peat soils.

Key words Earthworms · Grass yields · Reclaimed peat · Soil maturation · Soil properties · Moisture characteristics · Organic matter decomposition · Micromorphology

Introduction

The influence of earthworms on soil structure and fertility, and their contribution to the maturation and development of reclaimed mineral soils, is well documented (Stockdill 1982; Hoogerkamp et al. 1983; Curry and Cotton 1983; Syers and Springett 1983), but less is known of their role in organic soils. Earthworm are scarce in acid peats, but when such soils are drained and reclaimed for agriculture significant populations can become established (Kajak et al. 1985; Curry and Boyle 1995). Their presence has been linked with A1 horizon development in long-reclaimed Dutch organic soils (de Bakker 1982), while their role in humification and stabilization of soil physicochemical conditions was emphasized by Kajak et al. (1985).

Extensive areas of deep peat in central Ireland have recently been reclaimed for grassland following industrial peat mining. The reclamation process involves deep ploughing to bring to the surface a 15- to 20-cm layer of underlying mineral soil. This material is mixed with residual peat, levelled and graded, limed to pH ~ 7 in the top 20-cm layer, fertilized and seeded with perennial ryegrass *(Lolium perenne)* and clover *(Trifolium repens)*.

Microplot studies in one such reclaimed site at Clonsant, Co. Offaly, indicated that introduced earthworms could significantly influence herbage yield (Curry and Boyle 1987), but critical study of their impact on soil structure proved impossible because of site heterogeneity. The object of the present study was to assess, under controlled conditions, the role of earthworms in the structural development of reclaimed peats and their influence on sward productivity.

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Materials and methods

Effects of earthworms on grass growth

Peat and mineral soil were collected from a recently cutover site at Clonsant, Co. Offaly, which had been deep ploughed 1 year previously. The peat was of mixed forest origin, and the underlying relict mineral soil was derived from limestone till. The pH of the peat was 4.5; it contained 5.2% ash and 1.5% N, and its bulk density was 0.18 g cm^{-3}. The subpeat mineral soil had a pH (H_2O) of 5.8; its ash content was 31.2%, the N content was 0.05% and its bulk density was 1.45 g cm^{-3}. The mineral soil was separated into three size categories by sieving through 50-mm, 25-mm and 5-mm aperture screens, and the peat was sieved through a 10-mm aperture screen. The peat and mineral components were mixed in the ratio 3 kg peat: 2 kg of each mineral size category (dry mass basis) and 75 g ground limestone was added 9 kg^{-1} peat/mineral mix to mimic field reclamation practice.

Table 1 Grass cutting dates and dates of fertilizer application

Date	Grass cuts	Fertilizer application per bucket [a]	
		Inorganic	Organic
7/5/84		2.0 g urea [b] 5.0 g 0.7.30 [d]	100 g CM [c] 5 g 0.7.30
19/6/84	x		
20/6/84			100 g CM
10/7/84		1.0 g urea	
13/7/84	x		
10/8/84	x		
14/9/84	x		
8/10/84			100 g CM
6/11/84	x		
9/12/84 [e]		2.0 g urea	100 g CM
10/1/85	x		
6/3/85	x		
28/3/85	x	2.0 g urea 5.0 g 0.7.30	100 g CM 5.0 g 0.7.30
27/4/85	x		
19/6/85	x		
13/8/85	x	2.0 g urea	100 g CM
30/9/85	x		
8/1/86	x		

[a] One gram per bucket = 70 kg ha^{-1}
[b] 48% N
[c] Cattle manure mixed with peat
[d] N:P:K
[e] Fertilizer witheld from five buckets per treatment after this date

Plastic buckets of internal diameter 297 mm tapering to 240 mm and 252 mm deep were filled with soil; six 5-mm-diameter holes were provided for drainage and the bottom of each bucket was covered with 0.25-mm nylon mesh to prevent earthworm escape. Perennial ryegrass seeds were allowed to germinate on moistened tissue paper and 50 seedlings were planted in each bucket after 1 week's growth. Field-collected earthworms expelled from grassland using a weak (0.2%) formalin solution were rinsed in water, kept overnight on damp tissue paper and added to half the buckets on 9 May 1984. Ten *Aporrectodea/Allolobophora* and seven juvenile *Lumbricus* with a combined biomass of 7 g were added per bucket, equivalent to a field population of 250 individuals and 100 g biomass m^{-2}. A second addition of earthworm was made on 1 October 1994, comprising seven *Aporrectodea/Allolobophora* and three *Lumbricus* (biomass 6–7 g) per bucket. The main species represented were *Lumbricus terrestris* L., *Aporrectodea caliginosa* (Sav.) and *Allolobophora chlorotica* (Sav.), common grassland species with complementary ecological roles in the soil. The buckets were assigned to four treatments with 15 replicates as follows:

1. Inorganic fertilizers with earthworms
2. Inorganic fertilizers without earthworms
3. Mainly organic fertilizers with earthworms
4. Mainly organic fertilizers without earthworms

The buckets were kept in a glasshouse and arranged in a completely randomized layout. They were watered 2–3 times $week^{-1}$. Maximum temperatures were maintained at 15°–20°C and minimum temperatures ranged from 4° to 10°C. The fertilizer regimes (Table 1) mimicked those used on grassland on reclaimed peat at Clonsant, although the frequency of application was about twice that used in the field to allow for more rapid growth under glasshouse conditions.

Grass was cut on 13 occasions from 19 June 1984 to 8 January 1986 (Table 1), dried to constant mass at 60°C and weighed.

Effects of earthworms on soil properties

At the end of the experiment, after 20 months, the following physical soil properties were measured in selected buckets:

Subsidence

Assessments were made of the degree of settling and compaction that had taken place throughout the experiment. Four measurements were made from points level with the rim of the bucket to the soil surface, crosswise, and 20 mm from the side of the bucket, and a fifth measurement was made at the centre. The mean of the five measurements was used as an index of subsidence.

Saturated hydraulic conductivity

A modification of the constant head method (Klute 1965) was used to measure hydraulic conductivity. In order to avoid disturbing the soils, the bases of the buckets were left intact and water flow was measured through the drainage holes. The soils were saturated by standing the buckets in a trough of water to a depth within 2 cm of the soil surface for 24 h. A ring 25 cm in diameter was pressed into the soil to a depth of approx. 2 cm to facilitate an even flow of water into the soil and to minimize flow between the side of the bucket and the soil. A reservoir of water was connected to the soil head ring by means of a siphon and water was collected below the bucket by means of a funnel and graduated cylinder. After the water level in the head had stabilized, the time taken for 500 ml to flow through the soil was recorded. Four measurements were made and the results were pooled to give a mean value. Hydraulic conductivity (K, cm h^{-1}) was calculated as $K=(Q/At)(L/\Delta H)$ where Q=volume of water, A=cross-sectional area of sample, t=time for Q to flow through the sample, L=length of sample (depth of soil) and ΔH=hydraulic head difference.

Bulk density

The clod method was used (Blake 1965b). Two 5×5×5-cm clods were cut from the soil profile at depths of 0–5 and 5–10 cm in each bucket. The clods were weighed in air, coated with paraffin wax, weighed again in air, weighed in water and then dried in an oven at 70°C. Bulk density (g cm^{-3}) was determined from the equation $Db=dw\ Wod/[Wsa-Wspw+Wpa-(WPa\ dw/dp)]$ where Db=bulk density, dw=density of water, Wod=oven dry weight of soil sample, Wsa=net weight of soil sample in air, $Wspw$=weight of soil sample plus paraffin in water, Wpa=weight of paraffin coating in air and dp=density of paraffin.

Total porosity was calculated from bulk density and particle density as $ST=100\ ((PD-BD)/PD)$, where ST=total porosity, BD=bulk density and PD=particle density. PD is the density of solid soil particles (g cm^{-3}). The mass is determined by weighing and the volume is calculated from the mass and density of water displaced by the sample (Blake 1965a, b).

Soil moisture characteristics

The moisture-holding capacities of earthworm-worked and unworked soils were determined at suction pressures 0.4, 1.0, 1.5 and 2.0 on the pF scale using the sand box method. Soil samples measuring 5 cm×5 cm×4 cm deep and coated on five sides with wax were used. A hole was cut at the top to allow moisture to flow out. The base of the soil sample in contact with the sand was covered with a piece of hydrophilic nylon cloth held in place by an elastic band. The sand box and samples were prepared, and pF curves were drawn, following the procedures outlined by Stakman et al. (1969).

Fibrosity

Fresh samples equivalent to 2.5 g DM were soaked overnight in 200 ml 2% sodium hexametaphosphate solution and, after shaking for 1 min, the contents were washed through a 150-µm sieve. The "rubbed-fibre" remaining on the sieve was dried at 105°C, weighed, then ashed at 450°C for 6 h in a muffle furnace so that the fibre content could be expressed on an ash-free basis.

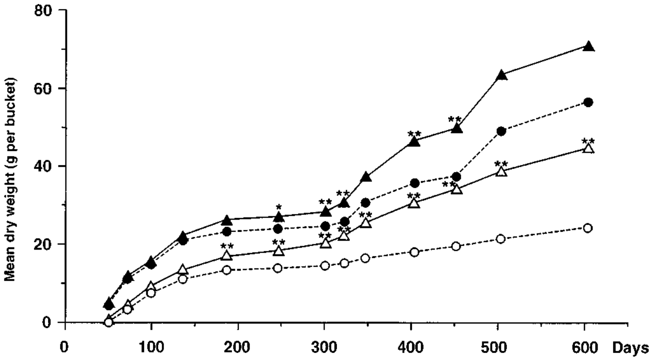


Fig. 1 Grass yields with and without earthworms under organic and inorganic fertilizer regimes. Harvest dates on which grass yields were significantly higher in the presence of earthworms are indicated (* $P<0.05$, ** $P<0.01$, $n=10$). –▲– earthworms, inorganic fertilizer, –△– earthworms, organic fertilizer, - -●- - no earthworms, inorganic fertilizer, - - ○- - no earthworms, organic fertilizer

Morphology and micromorphology

The influence of earthworms on soil morphology was assessed by photographic examination of vertical soil sections from buckets with and without earthworms. In addition, subsamples measuring 40×40×70 mm were impregnated with resin, sectioned and the sections were mounted on glass slides for microscopic examination and photography.

Results

Effects of earthworms on grass growth

Cumulative grass yields in the series of buckets which were fertilized throughout are shown in Fig. 1. The total grass yields over the 13 cuts were 89% higher in organically fertilized buckets with earthworms than in similarly fertilized buckets without earthworm, and this difference was highly significant, based on ANOVA (Table 2). Total grass yields were 19% greater in inorganically fertilized buckets with earthworms than in similarly fertilized buckets without, but this difference was just short of being significant at the 95% level (Table 2).

Cumulative yields in buckets which were not fertilized after the 7th month are shown in Fig. 2. The total yield from buckets with earthworms was 86% higher under the organic regime, and 38% higher under the inorganic, compared with buckets without earthworms. In both cases the earthworm effect was significant (Table 2). Harvest dates on which yields were significantly higher in the presence of earthworms are indicated in Figs. 1 and 2. This was the case on five dates under continued inorganic fertilization, and on nine dates under the continued organic regime. In the series of buckets where fertilizer application was discontinued the earthworm effect was significant on three dates in the inorganic, and on seven dates in the organic treatments.

The influence of earthworms on grass yields was relatively less during the initial 8-month period (cuts 1–6) than it was during the remaining 12 months of the study

Table 2 Grass yields (g DM±SE) from buckets with and without earthworms. The *F* values were derived from ANOVA with repeated measurements

	Earthworms present	Earthworms absent	*F*	*P*
Cuts 1–6, $n=15$				
Inorganic	26.5 (0.9)	23.9 (0.7)	5.1	0.03
Organic	18.4 (0.7)	13.9 (0.5)	27.5	<0.001
Cuts 7–13, fertilizers continued, $n=10$				
Inorganic	42.0 (4.7)	32.4 (3.4)	2.7	0.12
Organic	27.0 (1.2)	9.9 (0.5)	175.2	<0.001
Cuts 7–13, fertilizers discontinued, $n=5$				
Inorganic	9.2 (1.7)	4.3 (1.2)	5.5	0.47
Organic	16.1 (2.5)	5.0 (1.4)	15.2	0.005
Total yields fertilizers continued, $n=10$				
Inorganic	67.7 (4.4)	56.9 (3.3)	3.8	0.07
Organic	45.6 (1.8)	24.1 (0.9)	114.6	<0.001
Total yield fertilizers discontinued, $n=5$				
Inorganic	37.2 (0.9)	26.9 (1.7)	28.2	<0.001
Organic	33.9 (2.8)	18.2 (1.5)	23.9	0.001

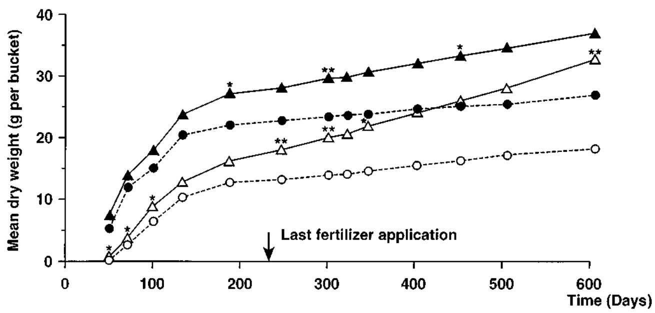


Fig. 2 Grass yields with and without earthworms under conditions of declining fertility. Harvest dates on which grass yields were significantly higher in the presence of earthworms are indicated (* $P<0.05$, ** $P<0.01$, $n=5$). –▲– earthworms, inorganic fertilizer, –△– earthworms, organic fertilizers, - -●- - no earthworms, inorganic fertilizer, - -○- - no earthworms, organic fertilizer

(cuts 7–13). This was particularly the case in the organic treatments, where yields from cuts 1–6 combined were 32% higher in buckets with earthworms than in buckets without, while the yield responses to earthworm in cuts 7–13 were +173% when fertilizer application was continued and +222% when it was discontinued (Table 2). A small (+11%) but statistically significant yield response in the presence of earthworms was recorded in cuts 1–6 under the inorganic regime, while in the later period (cuts 7–13) a significant yield response (+114%) to earthworm was only recorded under conditions of declining fertility, following cessation of fertilizer application.

Table 3 Effects of earthworms on soil properties in a glasshouse bucket experiment

		Earthworms present	n	Earthworms absent	n
Soil depth (mm)					
Organic		162.8[b]	13	184.1	16
Inorganc		147.1[b]	12	163.7	13
Bulk density (g cm^{-3})					
Organic	0–5 cm	0.72	13	0.64	15
	5–10 cm	0.71	13	0.68	15
Inorganic	0–5 cm	1.08[b]	16	0.66	17
	5–10 cm	0.97	16	0.87	17
Total porosity (%)					
Organic		70.5	4	74.9	4
Inorganic		61.7[a]	4	70.1	4
Organic matter (%)					
Organic		13.1	16	13.9	16
Inorganic		11.2	16	13.2	16
Fibrosity (%)					
Organic		4.6[b]	16	8.3	16
Inorganic		6.4	12	6.7	12
Ksat. (cm ha^{-1})					
Organic		36.9[b]	13	115	15
Inorganic		64.7	12	87.6	10

Significant earthworm effects: [a] $P<0.05$, [b] $P<0.01$

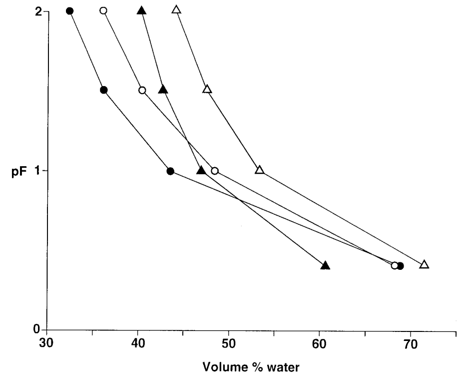


Fig. 3 Water retention curves for soils with and without earthworms. ▲ earthworms, inorganic fertilizer, △ earthworms, organic fertilizers, ● no earthworms, inorganic fertilizer, ○ no earthworms, organic fertilizer

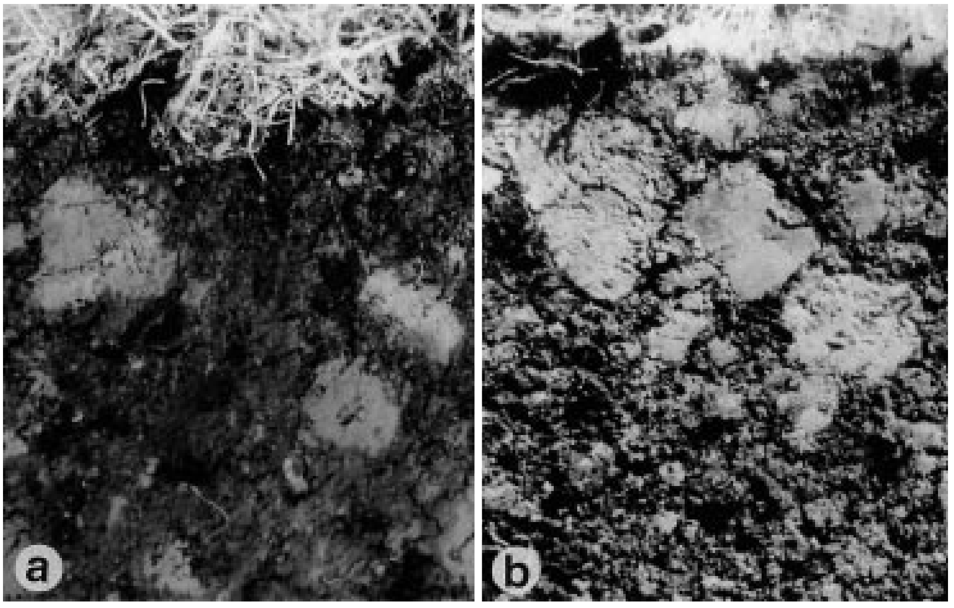
Effects of earthworms on soil properties

Mean depths of soil in buckets where earthworms had been present were significantly less than in buckets without earthworms under both fertilizer regimes (Table 3), indicating a significant effect of earthworms on the degree of subsidence of these disturbed soils. The rate of water movement through the soils (saturated hydraulic conductivity, *Ksat.*) was correspondingly lower in the earthworm-worked soils, although this effect was only significant under the organic fertilizer regime. Earthworm activity significantly increased bulk density and reduced total porosity in the top 5-cm layer of inorganically fertilized soil but not in organically fertilized soil. Earthworm did not influence the percentage organic matter (mass loss on ignition) content of the peat/soil mixtures, but they did significantly reduce the percentage fibrosity in organically fertilized buckets (Table 3).

Moisture retention curves for soil sample from the four treatments are shown in Fig. 3. The curves indicate that soil from the organic treatment with earthworms held the greatest volume of water (73% at pF 0.4, 48% at pF 2.0) over the range of suctions applied, the water being retained mainly in pores of smaller diameter than would be drained by a suction pressure of pF 2.0.

The inorganic treatment with earthworms had the lowest soil water volume percentage at pF 0.4, indicating a lower volume of large-diameter pores reflecting the relatively high bulk density of this soil (Table 3). At other pF

Fig. 4 a, b Vertical sections of soils from inorganically fertilized buckets with (**a**) and without (**b**) earthworms, ×0.4



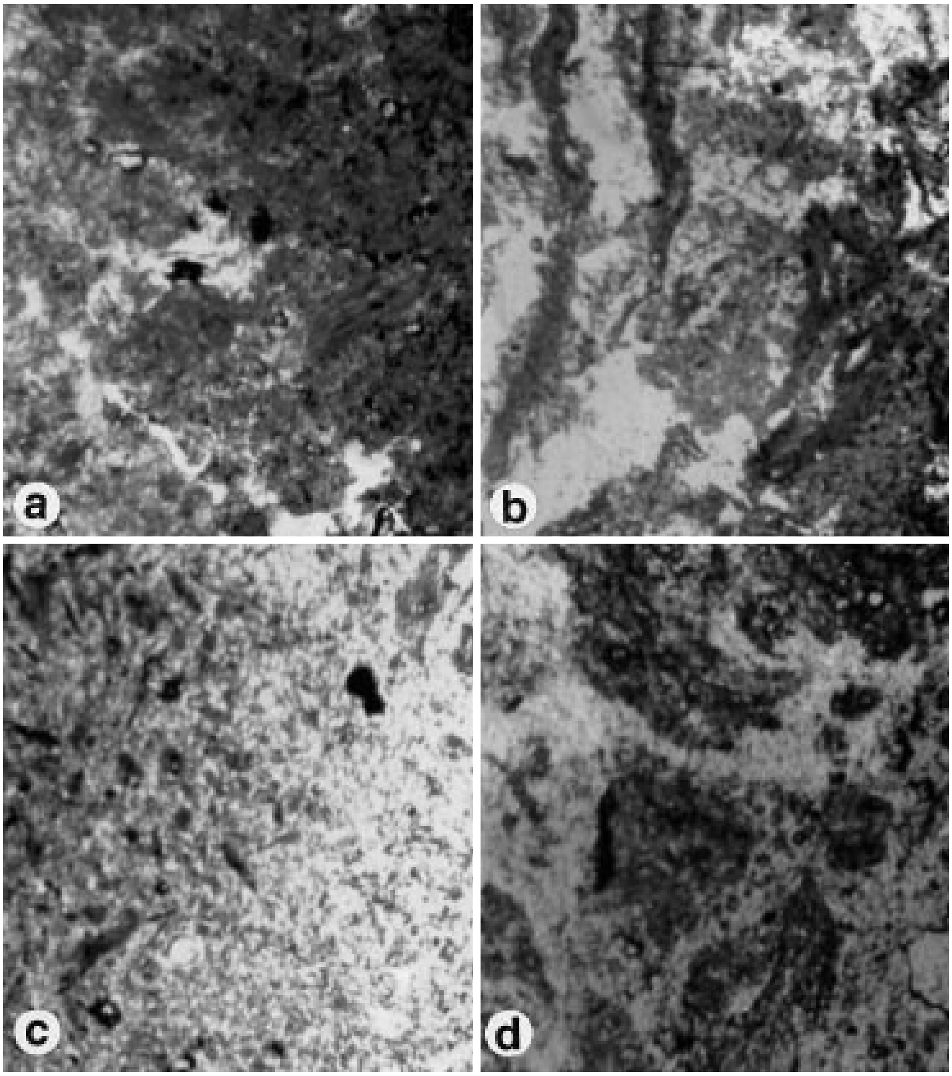


Fig. 5 a, b Thin sections (×17.5) from soils with and without earthworms: **a** with earthworms, organic fertilizer, **b** without earthworms, organic fertilizer, **c** with earthworms, inorganic fertilizer, **d** without earthworms, inorganic fertilizer

values moisture retention characteristics paralleled those of the worm-worked organic soil, with 60% of the water volume being retained at pF 2. The moisture retention curves for both fertilizer treatments without earthworms followed similar trends, with relatively high moisture retention at pF 0.2 reflecting large-diameter pore volumes comparable with those in earthworm-worked, organically fertilized soils. Only 33–40% of the water volume was retained at pF 2, indicating lower percentage volumes of smaller-diameter pores than in worm-worked soils, while a higher proportion of their water-holding pores fell within the pF 0.4–2.0 range compared with worm-worked soils.

The contrast between worm-worked and unworked soil profiles was marked (Fig. 4). The worm-worked soil presented a smooth surface resulting from smearing with mineral soil, and the presence of earthworm channels was marked by lines of dark, finely divided organic matter. There is evidence of intimate mixing of organic and inorganic materials around the larger mineral clods, and some clods showed signs of earthworm tunnelling. The worm-free soil, by contrast, had a loose-textured appearance and there was little sign of mixing of mineral and organic components. Thin sections examined under high magnification show further evidence of earthworm activity (Fig. 5). Sections from worm-worked soil were dominated by finely divided organic plasmic material, with faecal material being much in evidence. In the worm-free soil, by contrast, the organic material retained more of its original fibrous nature.

Discussion

The enhanced plant growth recorded in the presence of earthworms accords with the results of a number of similar studies conducted with mineral soils (e.g. Hopp and Slater 1948; Van Rhee 1965), although clear-cut positive responses have not always been reported. Plant growth responses are usually attributed to earthworm-induced improvements in soil physical and chemical characteristics and enhanced nutrient supply (Stockdill 1982; Lavelle et al. 1992; Bohlen and Edwards 1995). In the present case the more pronounced response under the organic regime suggests that the main benefit of earthworm activity may have been enhanced organic matter mineralization and increased nutrient supply. This conclusion is supported by the data from the inorganic regime, where the most pronounced earthworm effect was recorded when fertilizer application was discontinued and soil fertility declined. Earthworms were found to increase the amounts of mineral nitrogen released in leachate from afforested peat soils in Cumbria, UK (Robinson et al. 1992), and it is likely that the yield response to earthworms in the absence of fertilizer was mainly due to enhanced mineralization of peat. The substantially greater earthworm effect in soil previously amended with cattle manure probably reflects continuing mineralization of this material. However, the moderate yield response observed under the continued inorganic regime where nutrient supply was unlikely to have been limiting suggests that plant growth may also have been influenced by an earthworm-mediated improvement in soil structure. A grassland herbage yield response to the presence of earthworms had also been recorded in field microplots receiving organic manure, but no such response had occurred in inorganically fertilized microplots (Curry and Boyle 1987).

When peat soils are drained and reclaimed for agriculture the characteristics of their surface horizons change rapidly. These changes include a reduction in moisture content, an increase in ash content, bulk density and pH, enhanced humification and structural development and reduced water infiltration rates (Hammond 1981; Van der Linden 1982; Williams et al. 1985). Microbial activity increases enormously following drainage and is probably the main agency responsible for these changes in the initial stages, while larger invertebrates such as earthworms are considered to play an important part in A1 horizon development at a later stage (de Bakker 1982; Kajak and Okruszko 1987). However, the results of the present study confirm the ability of earthworms to bring about very significant changes in the characteristics of reclaimed soils within a relatively short period of time. The overall physical appearance of the soils without earthworms at the end of the plant growth experiment was of a very loosely bound mixture of peat and mineral materials, bound only by plant roots. In comparison with the earthworm-worked soils, little structural development had taken place. With such poor moisture retention capacity at relatively low suction pressures these soils would tend to be drought-prone in dry weather. By contrast, earthworm-worked soils were more compact and tended to be less fibrous, more dense, and to have lower infiltration capacity and improved water retention properties. They presented visual evidence of significant structural modification compared with unworked soils, the nature and extent or this modification being quite strongly influenced by fertilizer regime. The reduction in fibrosity and water infiltration was most pronounced under the organic regime, while bulk density was hardly altered at all. Any tendency for bulk density to increase as a result of earthworm activity was probably countered by incorporation of the organic fertilizer which when deposited as earthworm faeces within the soil volume would contribute to the development of a small-diameter pore system and reduced *Ksat*. values. The thin sections provided evidence for the presence of large amounts of finely divided organic matter in the profile, while the relatively high volume percentage of water held at pF 2.0 further reflects this finely structured nature.

Where cutover peats have been deep ploughed, the potential role of earthworms in mixing mineral and organic constituents is of particular interest. The soil sections confirm that earthworms can contribute to this process through their normal feeding activities, while field observations suggest that some earthworms may utilize large mineral clods as aestivation sites to avoid the effects of dry summer weather. Burrowing into the clods in this way could hasten their disintegration and accelerate soil mixing and development.

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