1. PROJECT OBJECTIVES

1. To characterise population variation in typical conventional and organic systems, monitoring changes in i) population biomass and abundance, ii) species composition and iii) the balance of different life stages within species.
2. i) To relate population variations to farming practices; ii) to estimate the quantity, form and pattern of significant organic inputs; and iii) to evaluate direct effects of cultivation.
3. i) To quantify the extent and location of earthworm burrowing and casting activity and; ii) to determine whether differences in earthworm activity between farming systems relate to variations in population characteristics or behavioural modifications in response to agronomic practices.
4. To estimate the soil benefits arising from earthworm activity in respect of i) burrowing and infiltration and ii) the contribution of casting to stable aggregation, microbial activity and nutrient mineralisation.
5. To assess the agronomic options available within organic systems for optimising the contribution of earthworms to soil fertility with particular emphasis on the role of ley frequency and duration.

2. PROGRESS TOWARDS OBJECTIVES

The numbering system used here refers to that in the above listing of objectives.

1. Earthworm populations were sampled extensively on three pairs of organic and conventional farms over two full annual cycles. In addition, further sampling was carried out on a single occasion at selected rotation stages on several additional organic-conventional pairings.
2. i and iii) Population data from the main survey allowed the beneficial effects of leys in arable rotations and the importance of tillage/reseeding practices to be evaluated. ii) This objective was modified (see Interim report 3008/3 and notes from project review, April 1st, 1996) by agreement to place the emphasis on estimating relative levels of fresh organic inputs to soils and assessing how these relate to population levels.
3. i) Cast numbers and burrow openings at the surface and at 25 cm depth were recorded on each sampling occasion allowing comparisons to be made between different farming systems/rotational stages. ii) Relationships between earthworm population and activity data were compared for different farming systems.
4. i) Infiltration through burrows was estimated by comparison of paired sites with blocked and unblocked burrow openings. Difficult weather/soil conditions restricted this assessment to Spring 1998 and the procedure was subject to very large inconsistencies. ii) Comparisons of source soil and cast materials were carried out on a number of occasions throughout the study. The very low levels of cast production during arable phases restricted these assessments to ley phases of rotations.
5. Data collected during the general surveys indicated several features of organic farming practice having a marked influence on earthworm populations.

3. METHODS

3.1 Site details

Three pairs of organic and conventional farms were selected in the main comparison to represent a gradation from arable to mixed farming (Table 1). The organic and conventional pairs at each locality were matched for similar soils and, where appropriate, crop rotations. However, crop rotations at each locality varied to some degree due to intrinsic system differences and individual farmer's decisions. In any one locality, organic systems tended to have proportionately longer periods of ley in rotations due to the need for fertility building.

A standard system of abbreviations have been used in all Tables as follows: O = organic and C = conventional; C1 = first year cereal, C2 = second year cereal, L1 = first year ley L2 = second year ley, L3 = third year ley and PP = permanent pasture; ND = no data. Statistical notations include NS = non-significant difference; * = significant difference $P < 0.05$ ** = significant difference $P < 0.01$ and *** = significant difference $P < 0.001$.

Table 1. Location, **c**rop rotation and soil texture class for farms in the main study.

Site	Farm	Location	Basic crop rotation (years cereal : ley)	Texture class

1	EFRC (O)	Berkshire	3 : 1 (stockless)	Sandy loam
1	Sutton Estate (C)	Berkshire	continuous arable	Sandy loam
2	Rushall's Fm. (O)	Wiltshire	2-3 : 2	Silty clay
2	Falkner's Fm. (C)	Wiltshire	3 : 1-2	Silty clay
3	Eastbrook Fm. (O)	Wiltshire	2 : 3	Clay
3	Manor Fm. (C)	Wiltshire	2 : 2	Clay
3	Rectory Fm. (C)*	Wiltshire	2-3 : 4	Clay

* after cropping changes on Manor farm, an adjacent farm was used in year two.

In selecting farms for the study, preference was given to those with well established crop rotations. Where possible, selected farms had examples of each rotational phase in more than one field within a single soil type. This approach aimed to minimise the risk of losing comparisons through short-term changes in farming practice. Whilst this aim was broadly successful, the third pairing was disrupted in year 2 of the project.

In Autumn 1996, Manor farm abandoned a long standing dairy enterprise due to the poor trading situation in livestock farming arising from the BSE crisis. As a result second cereals were not put down to leys. Rectory farm, on the same soil series and adjoining both the conventional and organic farm, was brought into the comparison. This new farm had a higher proportion of ley and a longer crop rotation than the original conventional farm.

The extended survey, carried out in Spring 1998, included four further organic-conventional farm pairings, in addition to the three original pairings. Details of these additional sites are given in Table 2. The main aim of this part of the research programme was to assess whether conclusions reached based on intensive sampling of a limited number of sites were supported by data from a wider survey. On some sites rotations included crops other than grass and cereals, for example potatoes. The pairings selected included one where the conventional farm had a greater proportion of grass than the organic farm.

Table 2. Site location, crop rotation and soil texture class for additional farms in the extended survey.

Site	Farm	Location	Basic crop rotation (years arable : ley)	Texture class
4	ADAS (O)	Norfolk	4 : 2	Silty clay loam
4	ADAS (C)	Norfolk	Continuous arable	Silty clay loam
5	CWS (O)	Leicestershire	3 : 2	Medium-heavy
5	CWS (C)	Leicestershire	3 : 2	clay loam
6	Little Pencoed (O)	Dyfed	1 : 3	Clay loam
6	Creswell Barn (C)	Dyfed	1 : 2	
7	Shepton (O)	Somerset	2 : 3	Silty clay loam
7	Godminster (C)	Somerset	2 : 5	Silty clay loam

3.2 Procedures

In the main study, sampling was carried out at four replicate points per phase of rotation, three times (autumn, spring and early summer) over each of two crop years. Earthworms were collected by handsorting blocks of soil (30 x 30 cm^2 to 25 cm depth). Deep burrowing species, below the blocks removed for handsorting, were brought to the surface using 0.5 - 1.5 l of a weak (0.5 %) formaldehyde solution. The quantity of extractant used varied with point infiltration rates.

Earthworms were identified using the keys and descriptions of Sims and Gerard (1985). At each point sampled surface cast numbers, and burrow openings at the surface and at 25 cm depth, were recorded.

For the purposes of presenting population data, the 10 species of earthworm found on individual farms were grouped into three functional classes as outlined in Figure 1. These groupings are based on species feeding habits, life cycles and suggested benefits for soil fertility. Since biomass and abundance data generally followed similar patterns, only the former are presented here although both sets of data were fully analysed. Although three life stages were recorded for each species, these data are not presented here because of limited space.

Figure 1. Earthworm species recorded in surveys and their characteristics.

	<u>**Characteristics**</u>	
large	**Size**	small
deep burrowing	**Habit**	surface dwelling
long	**Life span**	short
low	**Reproductive Rate**	high
great	**Soil benefits**	few
intolerant	**Stress**	tolerant
	<u>**Species**</u>	
Deep	**Intermediate**	**Shallow**
Aporrectodea longa	*Aporrectodea caliginosa*	*Allolobophora chlorotica*
Lumbricus terrestris	*Aporrectodea rosea*	*Lumbricus castaneus*
Octolasion cyaneum	*Octolasion tyrt. tyrt.*	*Lumbricus festivus*
		Lumbricus rubellus

A range of measurements were taken at each earthworm sampling point in order to establish factors influencing the size and composition of earthworm populations. Three organic matter assessments - loss on ignition, water soluble organic carbon and light fraction organic carbon (Wander *et al*., 1994) - were made. Field moisture content and soil pH were also measured. Agronomic and crop factors, such as time since cultivation and crop cover, were recorded.

Earthworm benefits were quantified in terms of microaggregate stability (Scullion, 1984), microbial biomass carbon (Vance *et al*., 1987) and, available P and K concentrations (MAFF, 1986). Properties of surface earthworm casts were compared with the underlying soil. Casts were collected on five occasions from phases of rotation that were common to organic and conventional systems, during autumn and spring when casting was most abundant. Only leys produced sufficient casting to allow materials to be collected in this way.

Rates of infiltration through earthworm burrows were also measured across a range of rotational phases using using 40 cm diameter, falling-head, single infiltration rings (Logsdon *et al*., 1993). Pairs of infiltration rings were sealed 3 cm into the soil surface. The number of earthworm burrow openings per ring was recorded and burrows in one of the rings blocked by smearing the soil. The difference in infiltration between paired rings was attributed to the infiltration through earthworm burrows.

3.3 Statistical analysis

Data were compared by analysis of variance for phases of rotation that were common between individual pairs of organic and conventional farms. Analysis of variance, with the proportion of ley in the rotation as a covariate, was carried out for cereal phases across all three main farm pairings.

Simple and multiple regression analyses were employed to evaluate relationships between earthworm population data and soil/agronomic factors. Earthworm population-activity relationships within single farm pairings were compared by parallel regression analysis.

Data analyses were carried out using Statgraphics Version 7 (1993) and Minitab Version 11.2 (1996) statistical packages.

4. RESULTS

Each sub-section of the Results is related to Objectives as numbered in Section 1. Where selected results are given these are representative of the full data set.

4.1 Earthworm population surveys

4.1.1 Organic-conventional system comparisons - main sites **(**Objectives 1i-iii, 2i-2iii and 5)

Analyses of variance of earthworm biomass data were carried out on phases of rotation that were common between systems, over the three sample occasions in each of the two crop years. Means in Tables 3-5 are based on 4 sample points per phase of rotation and 3 sampling occasions within each 'year', unless stated otherwise.

Interactions between farm and crop rotation phase for earthworm indices were highly significant ($p < 0.01$) in most cases. Generally, these interactions resulted from there being a greater range in earthworm biomass between phases over the organic compared with the conventional rotations. Further comparisons were carried out within farm pairings to evaluate differences between these farms for individual phases of the rotation (Tables 3-5).

Before describing results from individual farm pairings, a number of general points can be made. Across the three farm pairs, year two biomass was generally lower (30-40 %) than that for year one. This reflected the prolonged dry conditions encountered prior to and during sampling. There was also some evidence that the benefits of grass leys were less pronounced in year two; soil moisture appeared to be a limiting factor for earthworms in the second year and higher annual evapotranspiration under grass led to these soils becoming drier than those under cereals.

<u>4.1.1.1. EFRC plots and Sutton Estate.</u>

In year one (Table 3), there was a progressive decrease in earthworm biomass from the first to third cereal after ley on the organic stockless plots. In contrast, there was a large decrease in earthworm biomass in year two from the first to second year cereal and a small increase from the second to third year cereal. In year two there was a progressive decrease in earthworm biomass from the first to third cereal after break crop on the conventional farm but this was not observed in year one where earthworm biomass was very similar between first, second and third year cereals. In year two, earthworm biomass was significantly greater on the organic compared to the conventional system in the first cereal, the third cereal and winter beans whereas in year one, only the first and second cereal had significantly greater earthworm populations than corresponding conventional fields. Also in year two, earthworm biomass was similar under beans and cereals but in year 1, it was consistently higher under beans for both systems.

Table 3 Means (g m^{-2}) of total and functional group earthworm biomass on EFRC (O) and Sutton (C) farms for common stages of the rotation in 1995-6 and 1996-7.

		'95-6				'96-7			
farm	crop	surface	shallow	deep	total	surface	shallow	deep	total
O	Beans	12 **	46 **	36 NS	94 NS	7 *	38 *	14 NS	59 *
C	Beans	6	24	25	69	3	21	8	32
O	C1	29 ***	81 ***	43 NS	154 ***	20 ***	77 ***	40 *	137 ***
C	C1	7	15	22	43	3	28	26	57
O	C2	9 **	45 ***	42 NS	98 ***	6 **	25 **	12 NS	44 NS
C	C2	6	17	23	45	2	9	15	26
O	C3	7 ***	31 NS	16 NS	54 NS	7 **	27 **	29 **	64 ***
C	C3	0	47	11	58	2	10	2	14
O	PP	11	142	204	365	9	135	214	358

Although each species group followed a similar trend to that of the overall population, differences between systems in the biomass of deep burrowing species were less consistent than those of the other two groups.

4.1.1.2. Rushall's and Falkner's farms

With the exception of the first cereal in year 2, systems differences for total earthworm biomass were not significant in either year for the Rushall’s-Falkner’s comparison (Table 4). In this comparison, rotations differed between the two years with a greater proportion of cereal cropping in year two of the study. On Rushall’s Farm, the failure of a ley undersowing of the second cereal in year one resulted in no second year leys in year two. In year two, there was no clear pattern to differences within rotations, whereas in year one there was a progressive decrease in earthworm biomass from the first cereal to the beginning of the first year of ley on the organic farm. Again species groupings followed the same general pattern to that of total biomass, although there was some evidence of the organic system favouring shallow and intermediate groups compared with the conventional system, at the expense of deep burrowing species.

Table 4 Means (g m^{-2}) of total and functional group earthworm biomass on Rushall's (O) and Falkner's (C) farms for selected stages of rotation in 1995-6 and 1996-7.

		‘95-6				‘96-7			
farm	crop	surface	shallow	deep	total	surface	shallow	deep	total
O	C1	16 NS	34 NS	43 NS	95 NS	5 NS	14 NS	12 NS	31 *
C	C1	12	25	46	82	5	17	51	73
O	C2	18 **	26 NS	29 NS	73 NS	7 NS	20 NS	42 NS	69 NS
C	C2	7	24	59	90	3	11	12	26
O	L1	4 NS	18 NS	38 NS	60 NS	8 **	20 *	10 NS	38 NS
C	L1	5	19	32	56	3	12	25	40
O	L2	10 NS	20 NS	33 NS	63 NS	ND	ND	ND	ND
C	L2	6	15	25	46	ND	ND	ND	ND
O	PP	15 NS	65 NS	115 NS	195 NS	4 NS	36 NS	123 ***	163 **
C	PP	17	41	87	145	5	28	55	88

4.1.1.3 Eastbrook and Manor (Rectory) farms.

First year conventional leys in years one and two are not directly comparable because the two conventional farms used had different rotations.

Total biomass data for the first survey year tended to favour the organic system, although differences were not always statistically significant. In year two this trend was less consistent, with the second cereal only giving a significant system difference. In year two, the rotation on Eastbrook organic farm was compared with corresponding phases from two different conventional farms. In terms of proportions of cereals to ley, the conventional rotation involving the year two leys was closer to the rotation on Eastbrook farm than that comprising the year two cereals. The greater similarity in populations between systems in year two suggests that differences in duration of the ley were an important factor affecting the overall systems difference obtained in year one. Average population data on Eastbrook farm were affected by particularly large populations on one field (C1 year 1 and C2 year 2). As with the other two farm pairings, trends in each species group largely followed those of the overall population.

Table 5 Means (g m^{-2}) of total and functional group earthworm biomass on Eastbrook (O) and Manor/Rectory (C) farms for selected stages of rotation 1995-6 and 1996-7.

		‘95-6				‘96-7			
farm	crop	surface	shallow	deep	total	surface	shallow	deep	total
O	C1$	41 ***	160 ***	121 **	326 ***	3 NS	28 NS	28 ***	60 NS

C	C1	10	56	29	95	7	38	0	45
O	C2	14 ^{NS}	37 ^{NS}	3 ^{NS}	55 ^{NS}	29 ***	78 ***	96 ***	203 ***
C	C2	7	35	7	50	4	12	15	31
O	L1	ND	ND	ND	ND	9 ^{NS}	61 ^{NS}	8 ***	78 ^{NS}
C	L1	4	32	4	41	9	55	44	108
O	L2	36 **	38 ^{NS}	34 **	107 *	ND	ND	ND	ND
C	L2	8	33	5	46	ND	ND	ND	ND
O	L3	ND	ND	ND	ND	16 ^{NS}	37 ^{NS}	39 ^{NS}	92 ^{NS}
C	L3	ND	ND	ND	ND	9	65	64	137
O	PP	28 ^{NS}	68 ^{NS}	78 ^{NS}	175 ^{NS}	16 ***	44 *	66 ^{NS}	125 *
C	PP	24	57	68	150	2	26	55	83

$ C1 year 1 after 4 grass; C1 year 2 after 3 years grass

4.1.2 Overall system comparison for main sites (Objectives 1i-iii)

Analyses of variance, with and without the ley covariate, were carried out on transformed earthworm biomass and abundance data across the 3 main system pairings for the common, cereal phases of rotations. These analyses were performed on field means since covariate values could not vary within fields. Full analysis of variance tables are given the Annex with only a summary provided here.

System differences (Table 6) were statistically significant for biomass ($P < 0.002$) and abundance ($P < 0.001$) of earthworms when the covariate was excluded from the analysis. When differing proportions of ley in rotations were taken into account, there was no significant system difference for biomass ($P = 0.50$), although there remained a system effect for abundance ($P = 0.034$).

Table 6. Mean (m^{-2}) population biomass and abundance over first and second year cereals (1996-7 data) across all organic and conventional farm pairings.

System	Biomass g	Abundance nos
Organic	78.5	230.9
Conventional	35.9	71.7

The above findings indicate that the proportion of ley in rotations is a key factor determining differences in earthworm populations between the organic and conventional systems compared. However, all system differences could not be explained fully by this factor

4.1.3 Extension of survey (Objectives 1i-iii)

A total of seven organic-conventional pairs were sampled in this phase of the work, including the three original pairings. Earthworm biomass and abundance data are given in Table 7 and are consistent with those of the more detailed, earlier study.

The original pairings will be discussed first. In the EFRC-Sutton pairing (1), earthworm populations were larger in the organic system and this was mainly due to greater numbers of deep burrowers. However, this effect did not persist into the second cereal. The Rushall's-Faulkner's pair (2) showed higher populations in the first cereal after the ley for the conventional farm, particularly of deep burrowers, but this difference was not carried through into the second cereal. For the Eastbrook-Rectory pairing (3), where the proportion of ley was greater, populations of surface species in the first cereal were higher in the conventional farm than in the organic but the reverse was the case for deep burrowing species. In the second year ley there was a similar pattern although here the conventional system favoured shallow species at the expense of deep burrowers. Following the longer period of conventional cereals, populations were consistently lower in the first ley of the conventional farm for all species groups.

Of the four new pairs of farms surveyed, the ADAS organic-conventional pairing (4) was similar to that of EFRC-Sutton, with the organic system having a ley phase compared with the all arable conventional system. As with the EFRC-Sutton comparison, populations on the ADAS organic site were very much larger than those on the conventional site, especially under the first arable crop of potatoes. The CWS site (5) had very similar rotations for organic and conventional systems and generally few earthworms; populations were slightly higher under the final conventional arable crop, perhaps as a result of the minimum tillage practised for this system, but the reverse was the case for the second year of the ley phase. The practice of establishing organic leys by undersowing the final cereal may explain this reversal. For the Dyfed pair (6), the organic system, with an extra year of ley in the cereal-ley rotation, had higher populations in the shallow grouping but fewer deep burrowers in the first cereal phase; differences between the two systems were small in the ley phase. In the final pairing (7) the conventional farm had a higher proportion of ley in the rotation than the organic farm and this was reflected in higher population abundance over both rotational phases in the former system.

Table 7 Earthworm biomass (g m^{-2}) and numbers (m^{-2}) for 7 sites sampled in Spring 1998.

$ Pairing, system &			Biomass				Numbers			
stage in rotation			surface	shallow	deep	total	surface	shallow	deep	total
1	O	C1	14 NS	76 *	66 NS	156 *	67 NS	236 NS	25 *	328 NS
1	C	C1	11	36	16	63	36	86	4	126
1	O	C2	12 NS	47 NS	27 NS	86 NS	122 NS	256 *	27 NS	405 *
1	C	C2	13	38	31	82	60	126	8	194
2	O	C1	5 NS	38 NS	18 *	61 *	44 NS	181 *	10 *	235 NS
2	C	C1	8	44	88	140	40	108	49	198
2	O	C2	7 **	15 NS	48 NS	70 NS	51 *	82 NS	31 NS	164 NS
2	C	C2	19	23	42	84	106	110	28	243
3	O	C1	36 **	61 NS	166 NS	263 NS	168 *	168 NS	124 **	460 NS
3	C	C1	122	62	158	343	326	86	36	449
3	O	L1	16 *	60 NS	23 NS	101 NS	111 **	311 ***	35 *	457 ***
3	C	L1	2	37	22	62	8	81	8	97
3	O	L2	10 NS	21 *	60 *	92 NS	69 NS	140 NS	57 NS	267 NS
3	C	L2	10	55	31	96	75	221	42	337
4	O	A1	0 NS	125 ***	231 ***	356 ***	0 NS	429 ***	126 ***	556 ***
4	C	A1	0	2	0	2	0	7	0	7
4	O	A2	0 NS	45 NS	147 *	192 NS	0 NS	144 NS	103 NS	247 NS
4	C	A2	5	44	38	87	28	131	40	199
5	O	A3	<< 1 **	4 NS	1 *	6 *	1 *	13 NS	2 NS	15 *
5	C	A3	1	3	11	15	6	14	4	24
5	O	L2	1 NS	6 *	12 **	20 ***	5 NS	26 NS	10 *	40 NS
5	C	L2	1	2	4	7	11	21	6	37
6	O	C1	4 NS	107 ***	62 NS	173 **	28 NS	235 **	63 **	326 NS
6	C	C1	6	16	81	103	36	121	189	346
6	O	L2	18 *	27 NS	201 NS	246 NS	83 *	179 NS	186 NS	449 NS
6	C	L2	3	38	155	196	14	178	190	382
7	O	A1	13 NS	46 NS	115 NS	174 NS	56 **	208 NS	100 NS	363 *
7	C	A1	26	76	110	211	149	324	121	594
7	O	L2	9 NS	43 NS	51 *	103 *	47 NS	160 NS	31 *	237 *
7	C	L2	11	46	180	237	57	178	83	317

$ Details of rotations in farm pairings are given in Tables 1 and 2.

*4.1.4. Tillage effects (*Objective 2.iii*)*

Where cropping changes within a rotation, differences between May and November samplings indicate a combination of tillage and seasonal effects. The effect of seasonal changes alone can be estimated by reference to trends occurring on undisturbed, permanent pasture controls. Additional responses to cultivation, residue incorporation and cropping on rotational fields may be indicated where population changes differ markedly from those on control sites.

Data (Table 8) are given for the 1996 sampling year only since population patterns were similar for both the main sampling years. It should be noted that surveys were carried out during particularly dry years, a situation which may have influenced population response. For example, under dry conditions the larger deep burrowing species, normally at greatest risk of direct mechanical damage, would have retreated below the tillage depth. Prevailing weather conditions also precluded sampling closer to cultivation because of difficulties in carrying out reliable surveys in very dry soils.

Table 8 Earthworm biomass before and after cultivation: May-Oct 1996

Pair, system &		— surface —		— shallow —		— deep —		— total —	
stage in rotation		May	Nov.	May	Nov.	May	Nov.	May	Nov.
2 O	C1→C2	10^{NS}	7	14^{NS}	22	29*	87	53*	116
2 C	C1→C2	6^{NS}	3	26*	7	5^{NS}	12	37^{NS}	22
2 O	C2→L1$^{\alpha}$	20*	7	29*	15	15^{NS}	6	64*	28
2 C	C2→C3	2^{NS}	0	10^{NS}	11	33^{NS}	44	45^{NS}	56
2 O	L2→C1	4^{NS}	7	21*	10	23*	8	49*	25
2 C	L2→C1	5^{NS}	5	8^{NS}	15	14**	112	27**	132
2 O	PP	2^{NS}	4	65*	21	171^{NS}	162	238^{NS}	187
2 C	PP	21**	1	38*	19	61^{NS}	53	120^{NS}	73
3 O	C1→C2	45^{NS}	27	152*	89	112*	50	308*	166
3 C	C1→C2	5^{NS}	3	81**	13	41^{NS}	22	128**	38
3 O	C2→L1$^{\alpha}$	13^{NS}	7	31^{NS}	35	3^{NS}	7	48^{NS}	49
3 C	C2→C3	7^{NS}	2	29^{NS}	18	0	3	36^{NS}	23
3 O	L4→C1	13	0	63**	14	172	0	249***	14
3 C	L2→C1	5	0	31^{NS}	18	14	0	49^{NS}	18
3 O	PP	23^{NS}	16	65^{NS}	42	81*	37	170*	94
3 C	PP	18	0	39^{NS}	14	74^{NS}	73	132*	87

Notes:

$^{\alpha}$ undersown therefore not cultivated in Autumn.

For both of the farm pairings reported in Table 8, total biomass and that of individual species groupings on control sites declined between May and November regardless of farming system. There was some variation in the extent of this decline which was probably due to the very dry conditions prevailing over this period leading to mortality, particularly amongst the adult population. Fields subjected to tillage and cropping changes failed to show any consistent pattern of change either in total or species grouping biomass; in some cases marked increases in biomass were recorded whilst in other cases there were very marked declines. Overall, there was no evidence of a large and persistent adverse effect of tillage/crop change on any section of the earthworm population. Populations changes appeared to be determined by factors specific to individual fields.

4.2 Soil organic indices. (Objective 2.ii)

As noted in section 3, three measurements of soil organic matter were carried out. Water soluble (WSOC) and light fraction (LFOC) organic carbon measurements were intended to indicate the biologically active fraction of the total (LOI) organic pool. It was thought that these active fractions were more likely to affect earthworm population size.

Although WSOC and LFOC indices followed a predictable trend within rotations, with values lowest after several years of arable cropping and highest in permanent pasture, both indices exhibited very high variability within field replicates. Permanent pasture soils generally had significantly higher WSOC and LFOC values than rotational soils, but there were no statistically significant differences between farm systems or rotation phases.

Relationships between these organic indices and earthworm populations will be discussed further in a later section (4.6).

4.3 Earthworm activity - surface casting and burrowing (Objective 3)

Earthworm casting and burrowing were recorded at each sampling point and on every sampling occasion. Data for the Spring 1996 sampling occasion are given in Table 9 and represent a period of high earthworm activity.

Surface cast weights and numbers were positively correlated ($P < 0.0001$) with crop cover, probably because of protection against weathering. This factor and the impact of treading by livestock need to be considered when interpreting data. Also, there is some confounding of cast and surface burrowing records in that surface casts obscure the presence of an underlying burrow opening. This last point is well illustrated by data for permanent pasture controls which typically had very high rates of surface casting compared with rotational leys but few surface burrow openings.

Recorded cast numbers were very low on most arable phases of rotations, regardless of farming system. Slaking of unprotected casts and increased sub-surface casting within the loosened tillage layer probably explain this finding. Within ley phases, there was no consistent pattern differentiating casting in organic and conventional systems. For individual rotational phases, organic fields had higher densities of surface burrow openings than conventional fields in all but one case; the organic field in this exceptional comparison had been grazed before the survey was carried out so that treading damage may have caused openings to be obscured. Burrow densities at 25 cm depth varied much less than those at the surface between rotational phases. This may indicate that they persist, and perhaps are re-used, after death of the earthworm which created them. Numbers of deep burrowing species recorded at the same time as burrows varied markedly between rotation phase and farming system; there were no significant correlations between densities of deep burrowing earthworms and deep burrows. This conclusion is supported by work of Lighart (1996) who estimated deep burrow half lives of several years. Where there were significant system differences in deep burrow density these tended to favour the conventional system, particularly under cereals.

Reasons for variations in earthworm activity will be discussed further in a later section (4.4)

Table 9 Cast numbers/weights and burrow openings (m^{-2}) for the farms surveyed in Spring 1996. Data are the means of four replicates.

Pairing, system & stage in rotation			Casts numbers	Casts dry weights (g)	Burrow openings - surface	Burrow openings - 25 cm depth
1	O	B1	0	0	705**	36 ^{NS}
1	C	B1	0	0	183	28
1	O	C1	83	56	1853*	33^{NS}
1	C	C1	0	0	1100	33
1	O	C2	0	0	975 ^{NS}	22 ^{NS}
1	C	C2	0	0	825	22
1	O	C3	0	0	406*	31*
1	C	C3	8	6	306	47
1	O	PP	139	212	50	58
2	O	C1	8 ^{NS}	4*	680**	31*
2	C	C1	8	14	200	44

2	O	C2$	ND	ND	ND	28*
2	C	C2	36	89	1578	47
2	O	L1	50	82	644**	50*
2	C	L1	ND	ND	222	36
2	O	L2	39 NS	50 NS	625***	50 NS
2	C	L2	47	65	28	53
2	O	PP	108 NS	186a	0	75*
2	C	PP	139	134b	0	42
			~~	~~~~~~~~~~~~~~~~~~~~	~~~~~~~~~~~~~~~~~~~~	
3	O	C1	8 NS	2	1550***	64*
3	C	C1	6	0	125	100
3	O	C2$	ND	ND	ND	36*
3	C	C2	3	0	78	56
3	O	L2	17**	16*	8**	56 NS
3	C	L2	92	41	36	56
3	O	PP	94**	76**	3**	56*
3	C	PP	22	14	28	69

$ ploughed shortly before sampling. Where zeros occur, means were not compared statistically.

4.4 Earthworm population-activity relationships (Objective 3ii)

Population-activity relationships in conventional and organic systems were compared for each sampling occasion using data from individual farms. Grassland and arable rotational phases were assessed separately, because of the marked effect of tillage on activity. Sufficient cast data were available for the Eastbrook-Manor pair alone, since in this pair the proportion of grass in the rotation was greater. As noted in Section 4.3, there were no significant relationships between population and deep burrow density. For this reason, data presented here relate to surface activity only.

A selection of regression equations are given (Table 10) for the Spring 1996 sampling occasion when levels of earthworm activity were generally high. Where close ($P < 0.01$ or better) linear relationships were obtained for similar activity indices and rotational phases in both organic and conventional systems, the regressions were compared for differences in slope and intercept.

Although many of the activity-population relationships did not differ significantly between farming systems, there was a general tendency for numbers of burrow openings at a given population density to be higher on organic systems, and for numbers of casts to be higher in conventional leys.

Table 10 Comparisons of activity-abundance relationships for different farming systems - Spring 1996 data.

Pairing & system	Regression equations	R^2	P^{α}	Differences between systems: slope	intercept
Pair 1, all arable crops					
O	bs^{β} = 9.3 surface (A+S) + 30.5	41	**	NS	NS
C	bs = 7.4 surface (A+S) + 26.7	27	**		
O	bs = 3.7 total (A+S) + 18.0	36	**	NS	*
C	bs = 3.7 total (A+S) + 3.7	37	**		
Pair 2, leys greater than 1 year old and permanent pasture					
O	$casts^{\phi}$ = 0.29 shallow (A+S) + 2.0	71	***	NS	NS
C	casts = 0.57 shallow (A+S) + 3.9	71	**		
O	casts = 0.23 shallow + deep (A+S) + 2.1	64	**	NS	**
C	casts = 0.55 shallow + deep (A+S) + 2.7	82	**		

O	casts = 0.17 total (A+S) + 2.1	65	**	NS	NS
C	casts = 0.40 total (A+S) + 2.4	83	**		
Pair 3, all cereals and leys less than 1 year old					
O	bs = 7.6 surface (A) + 15.7	73	**	*	NS
C	bs = 4.4 surface (A) + 1.5	60	**		

Notes:
$^{\alpha}$ significance of regression $^{\beta}$ bs = nos. surface burrows $^{\phi}$ casts = nos. at the surface

The above findings suggest that population size is a major factor determining differences between systems in earthworm activity. However there is also some indication of modifications to earthworm behaviour between systems, with higher levels of surface activity in organic cereals.

4.5 Burrowing and infiltration (Objective 4i)

Early work on water infiltration through earthworm burrows (1995-6 Annual Report) indicated that the proposed methodology provided a means of assessing the significance of earthworm activities this process. An extensive survey of infiltration rates was carried out in March 1998 under moist soil conditions on two of the farm pairs; conditions on the third pair were considered unsuitable for the procedure.

Earthworm burrows were found to make an important contribution to infiltration only at certain stages of rotations. For example, the loosening effects of cultivation on infiltration remained large and highly variable in fields cultivated in Autumn and the additional inflow via burrows was insignificant. In leys infiltration was much lower than that in cereals and here burrows accounted for between 10 and 50% of recorded infiltration. Given the high level of within field variation, there were no significant differences between farming systems.

4.6 Soil-agronomic factor - population relationships (Objective 2ii-iii)

Stepwise multiple regression analyses were carried out to establish soil and agronomic factors affecting population indices across a rotation. These analyses also assessed the extent to which population characteristics could be predicted on the basis of regression models. Three broad categories of factor were included in the analyses - food supply (standing herbage/cover; soil organic matter indices - section 4.2), physical limitations (soil temperature and moisture content) and agronomic practices (time since cultivation).

Within individual farm pairs, multiple regressions accounted for between 30 and 40% of population variation. However, factors explaining variation in these regressions varied between farm pairs/soil types and between sampling years (see Table 11 for examples).

Table 11a Analysis of variance for regressions of biomass and soil/agronomic factors.

Eastbrook-Manor pair (1995-6 data)

SOURCE	F	*p*
Regression	4.27	0.013
Predictor	t-ratio	*P*
constant	-1.19	0.246
LOI	-1.57	0.127
moisture	2.25	0.033
system	-2.55	0.016

Rushall's - Falkner's (1995-6 data).

SOURCE	F	*p*
Regression	4.09	0.005
Predictor	t-ratio	*P*
constant	2.54	0.016
cover	-0.99	0.329
LOI	-0.49	0.629
months plough	-1.96	0.058
herbage	3.59	0.001

Further analyses suggested that water soluble organic carbon (WSOC), but not light fraction organic carbon, was a good predictor of population size when population indices were related to organic carbon measured in soils collected from the previous sampling occasion. This finding is consistent with the view that WSOC reflects recent organic inputs and that there is a lag time for population responses to these inputs. One limitation to the use of past WSOC values in predicting populations in the present study was that mean data had to be used for individual fields, thus reducing the number of data points in regressions.

4.7 Comparison of soil and surface cast properties (Objective 4ii)

Casts were collected over two years but dry conditions restricted cast collection to 5 occasions during Spring and Autumn. Clearly identifiable surface cast material under cereals and leys less than one year of age was negligible, at least in part because of slaking. In order to collect sufficient material for analyses, all samples were taken from second or third year leys, which precluded sampling from the EFRC-Sutton pair. Variations within farm systems, as indicated in Table 12, may be due in part to differences in the age of leys sampled.

Microbial biomass and nutrient data are presented in Table 12. Whereas casts from the Falkner's leys had a consistently higher microbial biomass than Rushall's organic leys, in the other pairing these differences were generally small and non-significant. Eastbrook organic ley soil had a significantly larger microbial biomass than that for Manor but not for Rectory leys. Overall, casts had significantly greater microbial biomass than soil, although on several occasions soil and cast data on organic leys were similar. The overall mean for the conventional farms was significantly greater than that of the organic farms (Table 12).

Table 12 Microbial biomass and nutrient contents for the leys on organic (O) and conventional (C) farms.

Sample period	Farm	Material	mic. biomass mg C g^{-1}soil	Available P μg g^{-1} soil	Available K μg g^{-1} soil
Nov. '95	Rushall's (O)	casts	0.73 *	18.7 **	268**
Nov. '95	Falkner's (C)	casts	0.99	69.4	574
Nov. '95	Rushall's (O)	soil	0.38 NS	16.3 NS	167 NS
Nov. '95	Falkner's (C)	soil	0.38	21.5	195
Apr. '96	Rushall's (O)	casts	0.13 *	2.4 ***	394 NS
Apr. '96	Falkner's (C)	casts	0.29	11.7	493
Apr. '96	Rushall's (O)	soil	0.12 NS	2.5 NS	153*
Apr. '96	Falkner's (C)	soil	0.10	4.2	232
Apr. '96	Eastbrook (O)	casts	0.16 NS	69.5 *	571 NS
Apr. '96	Manor (C)	casts	0.29	88.3	535
Apr. '96	Eastbrook (O)	soil	0.18 **	37.3 **	193 NS
Apr. '96	Manor (C)	soil	0.08	15.4	119
May. '97	Eastbrook (O)	casts	0.30 NS	14.6 NS	423 **
May. '97	Rectory (C)	casts	0.48	11.0	968
May. '97	Eastbrook (O)	soil	0.50 NS	0.9 **	120 *
May. '97	Rectory (C)	soil	0.48	8.1	71
Nov. '97	Eastbrook (O)	casts	0.47 NS	4.7 *	399 ***
Nov. '97	Rectory (C)	casts	0.58	18.1	670
Nov. '97	Eastbrook (O)	soil	0.17 *	4.3 NS	148 *
Nov. '97	Rectory (C)	soil	0.30	4.2	213
GRAND -	CASTS		0.45 ***	30.8 ***	530 ***
MEANS	SOIL		0.30	10.8	161
	ORGANIC		0.33 *	17.1 ***	284 ***
	CONVENTIONAL		0.43	24.5	407

Differences between casts and source soil in available P and K were consistently greater in the conventional compared to the organic systems (Table 12). Available P and K concentrations were very similar in the soils of Rushall's and Falkner's leys whereas available P was significantly greater in the organic soil on two out of three sample occasions for the Eastbrook organic - conventional farms comparison. Overall, the concentration of available P and K was about 3 times larger in casts compared to soil. Concentrations of P and K were also significantly greater (mean of casts and soils) in the conventional compared to the organic systems.

Although differences in cast LOI and stability between conventional and organic leys were often statistically significant (Table 13), these differences favoured the organic system in some instances and the conventional in others. With the exception of the Eastbrook - Manor comparison, there were no significant differences in LOI between organic and conventional soils. Overall, LOI was about 30 % greater in casts compared to soil, with this trend more pronounced in conventional systems, and 10 % greater for conventional versus organic leys.

Both clay and clay plus silt stability were greater in casts than in soil (Table 13). With the exception of the November 1997 sampling occasion, differences in clay stability between farms were non-significant. As with LOI, several significant system differences in clay+silt stability were obtained, but these favoured either system depending on sampling occasion and appeared to reflect LOI values. Overall, micro-aggregate stability was slightly greater in the conventional compared with organic systems.

Table 13 Loss on ignition (LOI), clay and clay+silt stability for cast and soil samples from leys on conventional (C) and organic (O) farms.

Sample period	Farm	Material	LOI %	Clay Stability %	Clay + Silt Stability %
Apr. ‘96	Rushall's (O)	casts	23 *	89 NS	64 NS
Apr. ‘96	Falkner's (C)	casts	31	87	64
Apr. ‘96	Rushall's (O)	soil	10 NS	74 NS	41 NS
Apr. ‘96	Falkner's (C)	soil	13	70	44
Apr. ‘96	Eastbrook (O)	casts	14 *	84 NS	47 ***
Apr. ‘96	Manor (C)	casts	11	82	24
Apr. ‘96	Eastbrook (O)	soil	9 **	77 NS	29 ***
Apr. ‘96	Manor (C)	soil	6	76	15
May. ‘97	Eastbrook (O)	casts	14 **	87 *	48 NS
May. ‘97	Rectory (C)	casts	16	90	51
May. ‘97	Eastbrook (O)	soil	10 NS	77 NS	37 NS
May. ‘97	Rectory (C)	soil	10	78	39
Nov. ‘97	Eastbrook (O)	casts	9 *	83 **	17 *
Nov. ‘97	Rectory (C)	casts	12	88	28
Nov. ‘97	Eastbrook (O)	soil	8 NS	72 **	10 **
Nov. ‘97	Rectory (C)	soil	9	79	25
GRAND -	CASTS		11.9 ***	86 ***	36 ***
MEANS	SOIL		8.3	77	28
	ORGANIC		9.6 *	81 *	31 NS
	CONVENTIONAL		10.6	83	33

5. DISCUSSION

5.1 Reliability of results

Considerable efforts were made to match farming systems in terms of soils and rotations. These efforts were largely successful although the lack of control over farm practices meant that there were several instances where data could not be obtained from intended rotational phases or where different rotational phases were compared from those originally intended. Where such problems arose, they were taken into account in interpreting results and do not undermine the reliability of the conclusions reached.

All of the sampling of the main study sites was carried out under abnormally dry conditions. These conditions meant that the timing of sampling had to be altered from the original plan and the frequency with which various assessments (e.g. infiltration) were carried out was less than that intended. On the basis of results obtained, it is unlikely that the broad conclusions reached would have been altered by sampling during different climatic conditions. However, it is possible that the extent and detailed nature of some findings (e.g. tillage effects) may have been influenced by the high soil moisture deficits prevailing.

Dry soil conditions also meant that surface casting was below ‘normal’ levels. Partly for this reason, but also because of soil-earthworm characteristics (section 4.3), quantities of cast material on cereal phases were too low for their collection to be practicable. If the paucity of surface casting under cereals could be taken to indicate very low levels of soil processing by earthworms then the absence of data from such sites would not be important. However, it is likely that much soil was voided within the tillage layer, a process observed in the field, and that much of the material cast on the surface slaked on rainfall impact. Although slaked materials would not contribute to aggregate stability, there may have been residual effects on microbial and nutrient dynamics which could not be assessed directly.

On a more general level, organic farms in any one locality tended to have a higher proportion of ley in their rotation than conventional farms. This was regarded as a difference inherent to organic-conventional comparisons rather than a weakness in farm selection. In practice, a range of ley-arable rotations were included in the study and data analysis allowed comparisons of system differences with and without the period of ley as a factor.

5.2 Main findings

Although there are some indications of secondary factors affecting earthworm populations, data from the main comparisons and the extended survey emphasise the importance of the ley phase, and its duration, in maintaining large earthworm populations in organic rotations. Leys had a similar role to play in conventional systems, even though there were differences in the nature and management of conventional (e.g. less clover) of this phase; it has been argued that clover is particularly beneficial to earthworms because of its high protein content (Edwards and Bohlen, 1996). These findings are broadly consistent with other studies. For example, Berry and Karlen (1993) found much higher populations of earthworms on ‘organic’ as compared with conventional stockless systems in comparisons very similar to those carried out for the EFRC-Sutton pairing. In contrast, Yeates *et al*. (1997) found markedly greater earthworm biomass in conventional rather than organic grassland soils. Although there were examples in the present study of larger populations on conventional leys, permanent pasture populations favoured, if anything, the organic system.

The pattern of population increase during ley phases and decrease during arable phases was apparent for biomass and abundance of the overall population and for individual species groups. It is consistent with other similar (e.g. Fraser *et al*., 1996). In most cases, the benefits of leys did not persist much beyond the first year of arable cropping. Also, there were examples where the ley conferred little benefit in terms of population size, often where initial earthworm densities were very low. The data available suggest that population size and composition approach those of permanent pasture sites only after three to four years of ley.

Various factors associated with leys have been put forward to explain their benefits to earthworms. Carbon inputs under leys have been estimated at between 3000 and 5000 kg ha^{-1} y^{-1}, compared with around or 3500 800 kg ha^{-1} y^{-1} for cereals where straw is removed or incorporated (Jenkinson & Raynor, 1977; Lynch, 1981). Straw was removed in all of the farms studied here. Although there was little evidence of a marked effect of tillage on earthworms in the present study, the lack of disturbance in leys is also considered to favour earthworms, particularly deep burrowing species.

There was some evidence of differences in species composition between organic and conventional systems, with indications of higher densities of smaller surface and shallow dwelling species in organic systems. These findings on two of the farm pairs were consistent with higher densities of surface burrows in organic systems.

It is generally agreed that repeated tillage causes a decline in earthworm abundance, particularly for larger deep-burrowing species (e.g. Edwards & Bohlen, 1996). However, it has been shown that populations recover quickly from mechanical damage and predation following tillage if their environment is favourable (e.g. Scullion *et al*., 1988). There was no consistent evidence of adverse, short-term population responses to tillage in the present study which could not be explained by seasonal factors. However, as noted earlier, prevailing weather conditions may have influenced this outcome. Reductions in populations as a result of direct mortality may have been compensated, in the short-term, by increased food supply through incorporated organic residues.

Differences between systems in surface activity of earthworms may be explained by a combination of factors including variations in population size and species composition. However, even allowing for these differences there were indications that individual earthworms may be more active at the surface of soils under organic rather than conventional cereals. Although Scullion & Ramshaw (1988) found reduced surface activity with increased fertiliser usage, their findings were obtained at rates of fertiliser input higher than those used on cereals. Crop protection chemicals in conventional systems may, however, have deterred surface activity.

Earthworm excreta contained higher levels of available phosphorus and potassium than the underlying soil. This differential tended to be greater for organic compared with conventional systems. High P availability in cast material has been noted in several previous studies (e.g. Sharpley & Syers, 1976). There may be several reasons for these increases in nutrient content. In the case of phosphorus, higher organic contents and microbial populations in casts would be expected to lead to enhanced mineralisation of organic-P; there is also evidence of enhanced phosphatase activity in casts (Satchell and Martin, 1984). Earthworms feed on organic residues and soil rich in organic matter so that it is not clear whether the results obtained represent an additional release of nutrients or simply their concentration in excreted materials. Enhanced K availability in casts cannot be attributed to mineralisation of organic matter. Increases in potassium availability has been attributed to selective feeding on plant litter rather than to any active mechanism affecting its availability (e.g. Lee, 1985). If this is the case, then phosphorus results reported here could be explained by a similar mechanism since the proportional increase was similar for P and K.

The more pronounced increase in cast nutrient contents in conventional systems was associated with a similar effect on LOI, although increases in organic content were generally much smaller than those for available P and K. The amount of plant residues present in soil handsorted for earthworms was highly variable and did not differ significantly between farm systems. Therefore, differences in cast organic matter content cannot be attributed to this factor. Although residue nitrogen concentrations were significantly higher in conventional compared with organic systems, there were no consistent system differences for residue P or K. Higher N availability may, however, have allowed for greater increases in microbial biomass.

Aggregate stability was higher in casts compared with soils in leys. Field evidence suggested that earthworm contributions to this aspect of soil fertility were greater in leys than in cereals. Recently voided materials are in the form of a slurry and will only remain to form aggregates if they are able to dry before direct rainfall impact. Leys are more likely to provide fresh casts with some protection from rainfall impact than cereals, since cereals provide little cover during the Autumn and Spring periods of maximum casting. Also, casts produced in leys are likely to be inherently more stable than those in cereals because of higher inputs of fresh organic residues.

The method used for measuring infiltration through burrows was effective where soils were undisturbed as in older leys but not where there had been recent cultivation. Given the increased densities of burrows openings in organic compared with conventional cereals, a greater contribution to infiltration might be inferred. However, it has been found that the majority of water flux occurs through a few, effective burrows (Ela *et al*., 1992) direct measurements of infiltration through burrows were so variable that system differences were non-significant. It appears, therefore, that infiltration rings were not large enough to adequately sample these effective burrows.

Efforts to develop a broad ranging, empirical model to predict earthworm populations on the basis of soil and agronomic factors proved difficult. Although a high proportion of population variation within an individual site and year could be accounted for by multiple regressions, the importance and strength of particular factors varied with site and year suggesting that factors controlling population variation were, to a degree, site specific.

IMPLICATIONS

Earthworm populations, and deep burrowing species in particular, are good biological indicators of soil quality. Their activities aid in the decomposition of organic matter and release of nutrients, mix and aerate soil, and create drainage channels. They represent an important link in the food chain, as a key food resource for several species of mammals and birds (e.g. MacDonald, 1983). There are clear benefits, for the maintenance of soil fertility and promotion of the broader agricultural ecosystem, in encouraging systems of farming which favour earthworms.

The major feature of such farming systems should be the inclusion of a significant proportion of ley within the rotation. Organic farming offers a clear option for achieving this objective. However, there is clearly some potential for set aside 'leys' in maintaining population levels within stockless systems and for conventional mixed farming systems in achieving much of the benefit of organic systems. It should be noted here, that that on some sites earthworm populations appeared to be too low to respond quickly to the favourable conditions of short-term leys.

Within organic rotational systems, the ley performs a key role in fertility building and weed control. The way in which leys are broken up for arable cropping, and the management of nutrient release, are of equal importance. Findings reported here indicate that earthworms are similarly affected.

Increased nutrient availability on the soil surface in the form of casts may be viewed as beneficial or adverse from an environmental or agronomic viewpoint. Loss of nutrient rich, fine cast materials through erosion may be greater under conventional compared with organic cereals where much of the surface cast material fails to achieve stability.

FUTURE WORK

Differences in the characteristics of cast materials, between organic and conventional systems, may have broader implications for C and nutrient turnover in agricultural soils. Further work will be required to elucidate links between these processes, organic nutrient composition/deposition and population characteristics.

Further work needs to be done in evaluating agronomic options within organic systems as to their effect on earthworms. For example, ley management or composition might be considered with the aim of maximising populations. Also, bi- or multi-cropping might offer the possibility of maintaining populations into arable phases.

At a more detailed level, findings have indicated that earthworms may influence the availability and disposition of nutrients, but the effect on plant uptake is not clear. Also, their activities are likely to interact with the behaviour and dynamics of other soil biota. There is for example, clear evidence of such interactions with mycorrhizal fungi which have a particularly important role in organic farming systems.

A range of previous studies have demonstrated plant productivity benefits resulting from the presence of large earthworm communities (e.g. Stockdill, 1982; Scullion, 1994). However, it is not clear whether particular species are essential to this process nor is it clear whether there is a progressive benefit with increasing population size. There is evidence of severe population decline and species impoverishment in certain soil-cropping combinations, and a depleted capacity for recovery. In these circumstances, some indication should be obtained of the minimum population required to deliver fertility and environmental benefits, and to respond effectively to favourable management, as part of measures to ensure the sustainable use of soil resources.

PUBLICATIONS/PRESENTATIONS

Progress reports. EFRC Bulletins June 1996, September 1997 & February 1998
Neale S. 1997. A comparison between organic and conventional farming systems with respect to earthworms and their effects. Organic Farming - Science into Practice. Royal Agricultural Society of England, Nov 1997.
Neale S and Scullion J 1998. A comparison between organic and conventional farming systems with respect to earthworm biomass and its effects. *In Proceedings of Conference on Mixed Farming Systems* in Europe (ed H van Keulen *et al*), pp 85-90.
Scullion J 1998. Earthworms and agricultural soils. *New Farmer and Grower* Spring 1998, pp 14-17.
Poster produced for Royal Agricultural Show 1998.

A paper has been offered for the Organic Farming Conference at Cirencester, January 1999. A series of papers will be submitted for publication in scientific journals.

REFERENCES

Berry EC and Karlen DL (1993). Comparison of alternative farming systems II. Earthworm population density and species diversity. *American Journal of Alternative Agriculture* 8, 21-26

Edwards CA and Bohlen PJ (1996). *Biology and Ecology of Earthworms*. Chapman & Hall, London.

Ela SD, Gupta SC and Rawls WJ (1992). Macropore and surface seal interactions affecting water infiltration into soils. *Soil Science Society of America Journal* 56: 714-721

Fraser PM, Williams PH and Haynes RJ (1996). Earthworm species, population size and biomass under different cropping systems across the Canterbury Plains, New Zealand. *Applied Soil Ecology* 3, 49-57.

Jenkinson DS and Raynor JH (1977). The turnover of soil organic matter in some of the Rothamsted classical experiments. *Soil Science* 123: 298-305.

Logsdon SD, Radke JK and Karlen DL (1993) Comparison of alternative farming systems. I. Infiltration techniques. *American Journal of Alternative Agriculture* 8 (1): 15-20.

Lee KE (1985). *Earthworms: Their Ecology and Relationships with Soils and Land Use*. Academic Press, Sydney.

Lighart TN (1996). *Development of Earthworm Burrow Systems*. Landbouwuniversiteit te Wageningen.

Lynch JM (1991). Sources and fate of soil organic matter. *In Advances in Soil Organic Matter Research* (ed. WS Wilson), pp 231-238. The Royal Society of Chemistry, London.

MacDonald DW (1983). Predation on earthworms by terrestrial invertebrates. In *Earthworm Ecology* (ed. JE Satchell), pp 393. Chapman & hall, London.

MAFF (1986) *The Analysis of Agricultural Materials*. Technical bulletin 427, HMSO, London.

Satchell JE and Martin K (1984). Phosphatase activity in earthworm faeces. *Soil Biology and Biochemistry* 16: 191-194.

Scullion J (1984) *The Assessment of Experimental Techniques Developed to assist the Rehabilitation of Restored Opencast Mining Land*. Ph.D. thesis, University of Wales, Aberystwyth.

Scullion J and Ramshaw GA (1988). Factors affecting surface casting behaviour in several species of earthworm. *Biology and Fertility of Soils* **7**: 39-45.

Scullion J Mohammed ARA and Ramshaw GA (1988). Changes in earthworm populations following cultivation of grassland on undisturbed and former opencast coal mining land. *Agriculture, Ecosystems & Environment* **20**: 289-302.

Scullion J (1994). *Restoring Farmland after Coal*. British Coal Opencast Executive, Mansfield.

Sharpley AN & Syers JK (1976). Potential role for earthworm casts for the phosphorus enrichment of runoff waters. *Soil Biology and Biochemistry* 8: 341-346.

Sims R.W. and Gerard B.M. (1985) Earthworms, keys and notes for the identification and study of the species. Synopsis of the British Fauna (New Series) No. 31, Linnean Society of London.

Stockdill SMJ (1982). Effects of introduced earthworms on the productivity of New Zealand pastures. *Pedobiologia* 24, 29-35

Vance ED, Brookes PC and Jenkinson DS (1987) An extraction method for measuring microbial biomass. *Soil Biology and Biochemistry* 19: 703-707.

Wander MM, Traina PC, Stinner BR and Peters SE (1994). Organic and conventional management effects on biologically active soil organic matter pools. *Soil Science Society of America Journal* 58: 1130-1139

Yeates GW, Bardgett RD, Cook R, Hobbs PJ, Bowling PJ and Potter JF (1997). Faunal and microbial diversity in three Welsh grassland soils under conventional and organic management regimes. *Journal of Applied Ecology* 34, 453-470.