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Earthworms and enchytraeids in conventional and no-tillage agroecosystems: A biocide approach to assess their role in organic matter breakdown

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Summary. Earthworm and enchytraeid densities and biomass were sampled over an 18-month period in conventional and no-tillage agroecosystems. Overall, earthworm densities and biomass in the no-till system were 70% greater than under conventional tilling, and enchytraeid densities and biomass in the no-till system were 50%–60% greater. To assess the role of annelids in the breakdown of soil organic matter, carbofuran was applied to field enclosures and target (earthworm and enchytraeid biomass, standing stocks of organic matter) and non-target effects (bacteria, fungi, protozoa, nematode and microarthropod densities, litter decay rates, plant biomass) were determined in two 10-month studies. In the winter-fall study, carbofuran reduced the annelid biomass, and total soil organic matter standing stocks were 47% greater under no-till with carbofuran compared to control enclosures. Twelve percent of the difference could have been due to non-target effects of carbofuran, as determined from litterbag decay rates. In the summer-spring study, carbofuran again significantly reduced the annelid biomass, and treated pens in the no-till area had significantly greater standing stocks of fine organic matter (43%–45%). Although the densities of bacteria and nematodes were reduced in carbofuran-treated litterbags under a no-till system, the rates of decay were not reduced and estimates of the amount of organic matter processed could not be adjusted for non-target effects. A 76% difference in the standing stock of coarse organic matter between control and carbofuran-treated pens in the conventional-till system indicated further non-target effects. We concluded that our estimates of the amount of organic matter processed by annelids in no-till and conventionally tilled agroecosystems represented a maximum potential because of the confounding non-target effects of carbofuran.

Key words: Earthworm – Enchytraeid – Tillage – Organic matter – Biocide – Agroecosystems

No-tillage agriculture, characterized by minimal soil disturbance and the surface placement of crop residues, is becoming widely adopted in the United States (Christensen and Magleby 1983; Blevins 1984). In conventional tillage systems the soils are plowed and disked and crop residues are buried. Numerous studies have demonstrated greater earthworm densities under reduced or no-till systems compared to conventionally tilled systems (Teotia et al. 1950; McCalla 1953; Lal 1974, 1976; Barnes and Ellis 1979; Gerard and Hay 1979; Edwards and Lofty 1982; Edwards 1983; House and Parmelee 1985; Mackay and Kladivko 1985). Despite these observations little attempt has been made to quantify the role of earthworms in the breakdown of organic matter in the two systems. The potential importance of earthworms in the C cycle in no-till systems was illustrated by Hendrix et al. (1987), who estimated that earthworms accounted for 30% of the total heterotrophic respiration in a no-till system compared to 5% under conventional tilling during the cool season. The estimate from the no-till system exceeds the contribution to total soil respiration usually cited for earthworms in temperate undisturbed ecosystems (~10%; Lee 1985).

Earthworms can significantly affect the decomposition of organic matter in agroecosystems. Earthworms accelerate the decomposition of organic matter directly by consumption, and indirectly by incorporating organic matter into soil and stimulating microbial activity in casts and around burrows (Hamilton and Dindal 1983; Shaw and Pawluk 1986). Greater consumption of leaves and lower standing stocks of surface organic matter have been correlated with greater earthworm densities in orchards and grasslands (Raw 1962; Van Rhee 1963). In barley fields, earthworms accounted for 5%–21% (depending

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on the soil type) of the total mass loss from straw enclosed in litterbags (Jensen 1985). Mackay and Kladivko (1985) reported that *Lumbricus rubellus* increased the decomposition of soybean residues by 26% and maize by 33% in pot experiments. The result of these high consumption rates and low C assimilation efficiencies (Bolton and Phillipson 1976) of earthworms is that large quantities of litter are comminuted, mixed with the mineral soil, and excreted in casts. Casts generally have higher moisture, C and N contents, and often a higher C:N ratio than the surrounding soil, and thus provide a favorable habitat for microbial activity (Lee 1985; Shaw and Pawluk 1986).

Little information is available on the effects of cultivation on enchytraeids. Enchytraeids may exhibit short-term reductions in densities or shifts in taxa following cultivation (Kasprzak 1982). House and Parmelee (1985) reported higher enchytraeid densities in a conventionally tilled than a no-till system, based on a single spring sample. Lagerlof et al. (1989) found that when a grass ley was plowed, the enchytraeids increased from 4700 to 28000 m^{-2} in 2 months. They concluded that the advantages of an increased organic matter input outweighed the negative effects of mechanical damage.

Very little is known about the role of enchytraeids in decomposition and nutrient-cycling processes in agroecosystems. The contribution of enchytraeids to total soil respiration is small (Lagerlof et al. 1989), but can exceed that of earthworms in agroecosystems (Golebiowska and Ryszkowski 1977). In a litterbag study, Lagerlof and Andren (1985) concluded that less than 1% of the total C loss from buried straw could be attributed to enchytraeids, but Lagerlof et al. (1989) calculated that the enchytraeids consumed 3%–12% of the organic matter input. As proposed for other soil fauna, the main influence of enchytraeids in decomposition and nutrient-cycling processes may be indirect, involving their interaction with the microflora. Enchytraeid casts, like those of earthworms, provide a favorable microhabitat for microbial activity (Kasprzak 1982).

Chemical biocides have been used previously to assess the role of earthworms in litter decomposition (Malone and Reichle 1973; Syers et al. 1979; Broadbent and Tomlin 1982). However, only Malone and Reichle (1973) assessed the effects of biocides on non-target soil organisms. Broadbent and Tomlin (1982) considered the non-target effects of carbofuran on microarthropods only. Without quantifying the potential non-target biocide effects, the contribution of annelids to decomposition may be over- or underestimated. This is particularly important when using a biocide such as carbofuran which has insecticidal and nematicidal effects, and may also influence microbes or microbially-mediated processes (Ingham 1985). Results may be further confounded by indirect non-target effects following removal of the target organisms.

Hendrix et al. (1986) developed conceptual food web models for no-till and conventional-till agroecosystems to serve as a basis for investigations on how the food web structure influences decomposition and nutrient-cycling processes. The models predicted that earthworms would be a dominant component in the no-till decomposition processes, and that enchytraeids would be relatively more important in conventional-till decomposition processes compared to no-till. Based on these models, our objectives in the present study were to quantify the role of earthworms and enchytraeids in decomposition processes in conventional-till and no-till agroecosystems. We determined earthworm and enchytraeid densities and biomass over an 18-month period. To quantify the role of the earthworms and the enchytraeids in organic-matter processing, we used carbofuran to eliminate the earthworms and enchytraeids and then recorded changes in the standing stocks of particulate organic matter, biomass of target and densities of non-target organisms, and litter decomposition rates and plant biomass levels.

Methods

Site description

This study was conducted at the Horseshoe Bend Experimental Area near Athens, Georgia, USA. The floodplain soil is a well drained sandy clay loam with 66% sand, 13% silt, and 21% clay in the Hiwassee series (Typic Rhodudult). The organic C content of the top 15 cm was 1.2% and 1.4% for the conventional and the no-till systems, respectively. Other physical and chemical properties of this soil have been described elsewhere (Groffman et al. 1986).

The area has been under continuous conventional and no-till systems since 1978. Four 28-by 28-m plots were established for each treatment. The conventional-till plots were moldboard-plowed to a depth of 15 cm and disked or rotary-tilled prior to planting of the winter (small grain rye, *Secale cereali*) and summer crops (soybeans, *Glycine max*, or grain sorghum, *Sorghum bicolor*). For the present study, the plow dates were 15 November 1985, 20 May 1986, and 20 November 1986. The no-till plots were left undisturbed except for surface drilling of summer crops.

Before the initiation of this study in November 1985, the summer crop was soybeans which were fertilized with 0:9:27 NPK at 511 kg ha^{-1}. The summer crop in 1986 was grain sorghum which was fertilized with NPK at 103, 10 and 19 kg ha^{-1}. The winter cover crop in both 1986 and 1987 was rye. No insecticides have been used on the Horseshoe Bend Experimental Area since 1967. In the present study period, the use of herbicides was restricted to a single application of glyphosate (6 l ha^{-1} Round-up Monsanto Co., St. Louis, MO.) before planting of the summer crop. Dolomitic limestone (2300 kg ha^{-1}) was applied to all plots in May 1980. A complete site and treatment history was given by Groffman et al. (1987).

Density and biomass

The earthworms and enchytraeids were sampled with a 10-cm diameter by 15-cm deep soil core. The worms were sampled at approximately monthly intervals from November 1985 to April 1987. The sampling for the present study was conducted in conjunction with other ongoing experiments and the number of samples available for each tillage treatment varied as follows: $n = 8$ for November and December 1985, $n = 4$ from January to April 1986, $n = 3$ from July to September 1986, and $n = 12$ from October 1986 to April 1987.

The worms were extracted by wet-sieving over stacked screens; the top screen had a mesh of 2.38 mm and the bottom screen had a mesh of 0.79 mm. The earthworms and their cocoons were picked out by hand from the organic debris. The organic debris was then floated in water and the enchytraeids were picked out by hand.

Earthworms were identified as individuals when at least 75% of the body was present; smaller portions were not counted as individuals, but were included in biomass determinations. The cocoons were counted and included as earthworm biomass. Only whole enchytraeid specimens were counted. Both the earthworms and the enchytraeids were freeze-dried to avoid any biomass loss with formalin preservation. After freeze-drying, the worms were ashed at 500 °C for 4 h to determine the ash-free dry weight biomass.

Organic matter

The first experiment, the winter-fall study, was conducted from January 1986 to October 1986. On 11 December 1985, 2.0-by 2.0-m plexiglass enclosures were installed to a depth of 25 cm in conventional-till and no-till plots. The installation trenches were dug with a cable layer and disturbance within the enclosure was minimal. The enclosure walls extended 30 cm above the ground. Two enclosures were installed in each of the four conventionally tilled and no-till plots. On 3 January 1986, carbofuran (112.6 g Furadan 10G Mobay Corp., Kansas City, MO.) was applied as a vermicide to one set of the enclosures in each tillage treatment. Both the control and the carbofuran enclosures were given 18 l of tap water. The enclosures were given an additional 18 l of tap water on 19 February 1986. A second dose of carbofuran (100 g Furadan 15G) and water was applied to the enclosures on 25 June 1986.

Earthworms and enchytraeids were sampled for biomass on 12 January, 2 February, 1 March, 22 April, and 17 October 1986, corresponding to days 10, 31, 57, 108 and 286 following the initial carbofuran application. On 17 October 1986 (day 286) particulate organic material (>0.79 mm) was collected on the screens from the same soil cores used for the earthworm and enchytraeid sampling. Live roots were separated from the organic matter. The organic matter oven-dry weight was recorded, the material ground, and then ashed at 500 °C for 4 h to determine the ash-free dry weight. The above-ground plant biomass (crop + weeds) was harvested on 14 May 1986 from 1.0 m^2 in the enclosures and oven-dried for 48 h at 60 °C. The root biomass was determined from the cores collected on 22 April 1986 and oven-dried as above.

Approximately 2.0 g of oven-dried soybean leaves (collected from the soil surface after leaf fall) was placed in 10-by 10-cm (inside diameter) fiberglass-nylon litterbags with a mesh size of 1.8 mm. The bags were placed on the soil surface in the no-till enclosures and buried to 5 cm in the conventional-till enclosures. One bag per plot ($n = 4$ per treatment) was collected from each tillage type on days 10, 31, 59, 94 (6 April 1986), 122 (4 May 1986), and 286 following the initial carbofuran application. The litter was oven-dried for 48 h (50 °C) and the dry weight was recorded for calculation of the decomposition rates. The litter was then ground and subsamples were ashed at 500 °C for 4 h to determine the ash-free dry weight. The dry weight remaining percentages were corrected for soil infiltration into litterbags (Blair and Crossley 1988). Decay rates were determined by the single negative exponential decay model (Olson 1963).

The second experiment, the summer-spring study, was conducted between July 1986 and April 1987. A second set of identical enclosures was installed in the conventional and no-till plots on 19 June 1986. On 25 June 1986 carbofuran (100 g Furadan 15G) was applied to one set of enclosures. The control and carbofuran-treated enclosures were given 18 l of tap water. A second application of carbofuran and water was applied to the enclosures on 25 November 1986. All enclosures were given additional applications of tap water (18 l) on 5 September 1986 and 2 February 1987.

Earthworms and enchytraeids were sampled for biomass from three of the four enclosures on 4 July, 1 August, 5 September, and 29 September 1986, corresponding to days 10, 38, 73, and 97 following the initial carbofuran application. All four enclosures were sampled on 12 April 1987 (day 292). Particulate organic matter was collected from the earthworm cores on 10 November 1986 (day 139) and 12 April 1987 (day 292). The organic matter was separated into coarse (>2.38 mm) and fine fractions (>0.79 mm, <2.38 mm), and in contrast to the winter-fall study, these fractions were analyzed separately. The root biomass was sampled on 1 September 1986 and the above-ground plant biomass was collected on 7 November 1986, as described above.

Small-grain rye straw (2.5 g) was placed in litterbags and applied to the plots as described for the first experiment; two bags were collected from three of the four plots ($n = 6$ per treatment) on 6 July, 20 July, 3 August, 18 August, 2 September, 14 September, and 29 September 1986, and 26 April 1987, corresponding to days 13, 27, 41, 56, 71, 83, 97, and 307 following the initial carbofuran application. The litterbags were processed and the decay rates were determined as described above.

Two additional sets of litterbags were collected from the control and the carbofuran-treated plots (1 bag per plot, $n = 3$ per treatment). One set, collected on days 13, 41, 71, 97, and 307 following the initial carbofuran application, was analyzed for total bacteria (Babiuk and Paul 1970), total fungal hyphal lengths (Jones and Mollison 1948), and total protozoa (most probable number, Singh 1946). The second set, collected on days 13, 41, 56, 71, 83, 97, and 307 following the initial carbofuran application, was extracted on Baermann funnels for 48 h and the total nematodes were quantified (Parmelee and Alston 1986). Microarthropods were sampled only on 28 September 1986 (day 97) and 26 April 1987 (day 307), and were extracted on modified Tullgren extractors for 72 h from the same litterbags used to determine the decay rates. The abundance of each type of organism was expressed as the number per gram of ash-free dry weight of litter, since adhering soil was unavoidably included in the extraction process.

Differences between the earthworm and enchytraeid density and biomass in the no-till and conventionally tilled systems were determined with a two-sample *t*-test (unpaired). Bacteria, fungi, protozoa, and nematode densities were subjected to an analysis of variance using the Statistical Analysis System package (SAS Institute Inc. 1982) as part of larger study (Beare et al. unpublished data 1986–1987). Significant differences among means were determined using Tukey's (honestly significant difference) test. For all other variables, comparisons were limited to control vs. carbofuran within a tillage type, and a two-sample *t*-test (unpaired) was used to detect significant differences. A *t*-test was used to compare litter decay rates (slopes of the natural log-transformed control and carbofuran litterbag decomposition curves; Zar 1984). Differences were considered significant at $P \leq 0.05$, unless stated otherwise.

Results

Abundance and biomass

The two dominant earthworm species found at Horseshoe Bend were *Aporrectodea caliginosa* (Savigny 1826) and *Lumbricus rubellus* (Hoffmeister 1843). Other species present were *Aporrectodea rosea* (Savigny 1826), *Octolasion tyrtaeum* (Savigny 1826), *Eukerria saltensis* (Beddard 1895), *Diplocardia caroliniana* (Eisen 1898), and *Microscolex* sp.

The earthworm densities and biomass were greater in the no-till than the conventionally tilled plots throughout the 18-month study period, and both were significantly greater in the no-till plots on 10 out of 16 sampling dates (Fig. 1 a, b). Over the course of the study, the average earthworm densities were 611 and 176 m^{-2} and biomass values were 14.69 and 4.60 g ash-free dry weight m^{-2} for no-till and conventional-till, respectively, a reduction of 70% for both parameters under conventional tilling compared to no-till. The maximum density in the no-till plots was 892 m^{-2} and the maximum biomass was 29.94 g ash-free dry weight m^{-2}. In contrast, the maximum earthworm density was 589 m^{-2} and the maximum biomass was 16.21 g ash-free dry weight m^{-2} in the conventionally tilled system.

Enchytraeids were consistently more abundant in the no-till than the conventionally tilled plots, significantly so on 8 out of 15 sampling dates (Fig. 2 a). The biomass was usually greater in the no-till plots but was significantly so on only 5 out of 15 sampling dates (Fig. 2 b). However, the average weight of the individual enchytraeids was greater in the conventional (0.29 mg ash-free dry weight) than in the no-till plots (0.16 mg ash-free dry

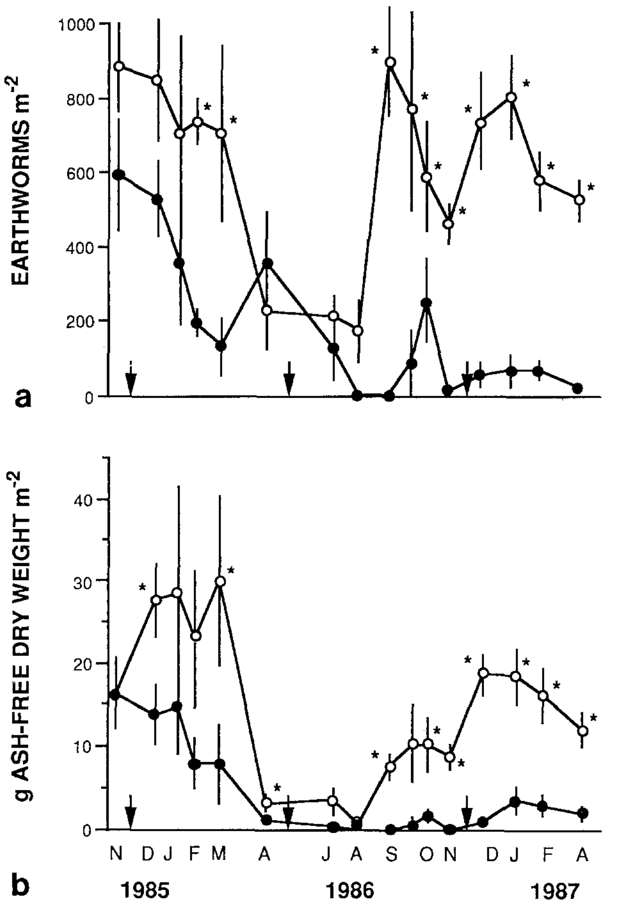

Fig. 1. Densities (**a**) and biomass (**b**) or earthworms from November 1985 to April 1987 in no-till (○) and conventional-till (●) plots. Values are x̄ ± 1 SE

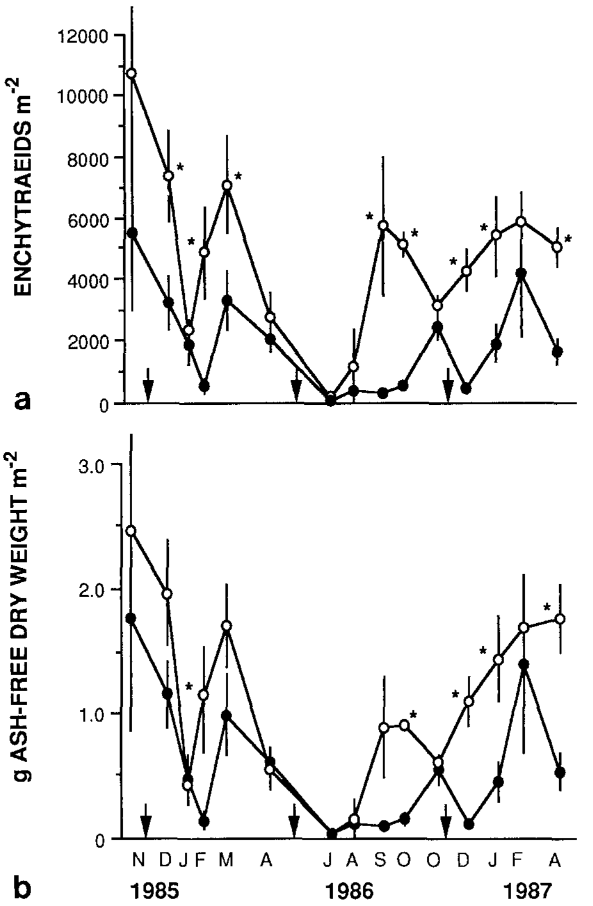

Fig. 2. Densities (**a**) and biomass (**b**) of enchytraeids from November 1985 to April 1987 in no-till (○) and conventional-till (●) plots. Values are x̄ ± 1 SE

weight). Overall, the average densities under conventional tilling (1902 m^{-2}) were only 40% of those in the no-till plots (4720 m^{-2}) while the conventional-till biomass (0.57 g ash-free dry weight m^{-2}) was 50% of the no-till biomass (1.12 g ash-free dry weight m^{-2}). The maximum enchytraeid abundance was 10749 and 5510 m^{-2} and the maximum biomass was 2.47 and 1.76 g ash-free dry weight m^{-2} in the conventional and no-till plots, respectively.

Biocide target effects

Carbofuran reduced the earthworm biomass in the no-till soils by 79% within the first 10 days in the winter-fall study, and the specimens extracted were moribund (Table 1). Significant reductions in the earthworm biomass were detected on days 57 and 286 after the initial carbofuran application. No earthworms were present in the carbofuran treated pens on days 57 and 108 and the biomass was obtained from cocoons only. After 286 days, the earthworm biomass was reduced by 98% in the no-till carbofuran-treated plots compared to the controls. The reductions in the no-till enchytraeid biomass were significant on days 108 and 286, and by day 286 the biomass in the carbofuran-treated plots had been reduced by 97% relative to the controls in the winter-fall study. The initial reductions in earthworm biomass in the conventional-till carbofuran-treated plots were not as great as in the no-till plots but the biomass steadily declined and by day 286 the conventional-till carbofuran-treated plots contained no earthworms. The enchytraeid biomass in the conventional-till carbofuran-treated treatments had been significantly reduced by days 108 and 286 compared to the controls, and was at or near zero in the carbofuran-treated plots.

After 10 months in the winter-fall study, there was significantly more total organic matter remaining in the no-till carbofuran-treated plots compared to the controls (Table 2). Expressed as a percentage of the no-till controls, there was 47% more organic matter in the no-till carbofuran-treated pens. Although there was 21% more organic matter in the conventional-till carbofuran-treated plots than in the control plots after 286 days, the difference was not significant.

Carbofuran was equally effective at reducing the earthworm and enchytraeid biomass in the summer-spring study (Table 3). Significant reductions in the no-till earthworm biomass were observed on days 73 and 292. Carbofuran had significantly reduced the no-till enchytraeid biomass by days 97 and 292, and by day 292 the carbofuran-treated enchytraeid biomass was only 2% of the no-till controls. The earthworm biomass was generally very low in the conventionally tilled plots throughout

Table 1. Winter-fall: Earthworm and enchytraeid biomass (g ash-free dry weight m^{-2}, $\bar{x} \pm 1$ SE) in no-tillage (NT) and conventional tillage (CT) agroecosystems in control and carbofuran-treated pens from January 3 1986 to October 17 1986

	Days after initial application of carbofuran				
	10 ($n = 4$)	31 ($n = 4$)	57 ($n = 4$)	108 ($n = 4$)	286 ($n = 12$)
NT					
Earthworms					
control	28.4 ± 13.2	23.0 ± 8.29	29.9 ± 10.2	3.28 ± 0.99	10.3 ± 3.17
carbofuran	5.94 ± 0.49	4.65 ± 2.67	0.50 ± 0.23*	1.46 ± 1.00	0.15 ± 0.11*
Enchytraeids					
control	0.43 ± 0.13	1.14 ± 0.42	1.70 ± 0.33	0.55 ± 0.16	0.60 ± 0.08
carbofuran	0.28 ± 0.09	0.95 ± 0.35	1.31 ± 0.67	0.01 ± 0.01*	0.02 ± 0.01*
CT					
Earthworms					
control	14.6 ± 5.43	7.91 ± 2.86	7.97 ± 4.63	1.14 ± 0.31	1.84 ± 0.81
carbofuran	10.3 ± 4.57	4.99 ± 2.71	1.89 ± 1.76	1.12 ± 0.42	0*
Enchytraeids					
control	0.47 ± 0.19	0.14 ± 0.07	0.99 ± 0.32	0.60 ± 0.13	0.54 ± 0.10
carbofuran	0.34 ± 0.19	0.18 ± 0.10	0.66 ± 0.43	0*	0.04 ± 0.02*

* Significantly different from control at $P = 0.05$

Table 2. Winter-fall: Standing stock (g ash-free dry weight m^{-2}) of total organic matter (>0.79 mm) to a depth of 15 cm in no-tillage (NT) and conventional-tillage (CT) control and carbofuran-treated pens 286 days (October 17 1986) after initial application ($n = 12$, $\bar{x} \pm 1$ SE)

	Organic matter		Difference (% of control)
	Control	Carbofuran	
NT	566.98 ± 34.89	836.09 ± 50.64*	47
CT	416.16 ± 54.74	503.74 ± 61.28	21

*Significantly different from control at $P = 0.001$

the summer-spring study, but following day 10, the biomass in the carbofuran-treated pens was lower, although not significantly so, than the controls on every sampling date. The enchytraeid biomass in the conventionally tilled carbofuran-treated plots was also less than the controls on all sampling dates, but was significantly lower only on day 292.

After 139 days in the summer-spring study, there were significantly greater standing stocks of organic matter in both size fractions from the no-till carbofuran-treated pens compared to the controls (Table 4). The carbofuran-treated no-till pens contained 45% more fine, 32% more coarse, and 34% more total organic matter than the control plots. There were no significant carbofuran effects on organic matter in the conventionally-tilled plots after 139 days in the summer-spring study. There was 17% more fine organic matter in the conventionally tilled carbofuran-treated pens than the controls, a non-significant difference. Standing stocks of coarse organic matter were actually slightly less in the conventionally till carbofuran-treated pens than in the controls, and the total amounts were similar.

By day 292 in the summer-spring study, there was 43%, 30%, and 32% more fine, coarse, and total standing stocks of organic matter, respectively, in the no-till carbofuran-treated pens compared to the controls (Table 4).

Table 3. Summer-spring: Earthworm and enchytraeid biomass (g ash-free dry weight m^{-2}, $\bar{x} \pm 1$ SE) in no-tillage (NT) and conventional-tillage (CT) agroecosystems in control and carbofuran-treated pens from June 25 1986 to April 12 1987

	Days after initial application of carbofuran				
	10 ($n = 3$)	38 ($n = 3$)	73 ($n = 3$)	97 ($n = 3$)	292 ($n = 12$)
NT					
Earthworms					
control	3.45 ± 1.57	0.61 ± 0.47	7.67 ± 1.40	10.40 ± 4.64	12.4 ± 1.91
carbofuran	1.25 ± 0.98	0.53 ± 0.08	1.26 ± 0.33*	2.17 ± 1.32	0.41 ± 0.41*
Enchytraeids					
control	0.03 ± 0.02	0.16 ± 0.16	0.89 ± 0.40	0.90 ± 0.03	1.09 ± 0.15
carbofuran	0.10 ± 0.06	0.03 ± 0.02	0.10 ± 0.08	0.03 ± 0.02*	0.02 ± 0.02*
CT					
Earthworms					
control	0.18 ± 0.10	0.31 ± 0.31	0.10 ± 0.10	0.69 ± 0.69	1.99 ± 1.38
carbofuran	0.54 ± 0.50	0	0	0	0.37 ± 0.37
Enchytraeids					
control	0.03 ± 0.03	0.12 ± 0.11	0.10 ± 0.04	0.16 ± 0.05	0.67 ± 0.10
carbofuran	0	0.01 ± 0.01	0.01 ± 0.01	0.05 ± 0.05	0.24 ± 0.08*

* Significantly different from control at $P = 0.05$

Table 4. Summer-spring: Standing stock (g ash-free dry weight m^{-2}) of fine (>0.79 mm, <2.38 mm), coarse (>2.38 mm) and total organic matter (fine + coarse) to a depth of 15 cm in no-tillage (NT) and conventional tillage (CT) control and carbofuran-treated pens 139 (November 10 1986) and 292 (April 12 1987) days after initial application ($n = 12$, $\bar{x} \pm 1$ SE)

	Organic matter		Difference (% of control)
	Control	Carbofuran	
November 10, 1986			
NT			
Fine	193.85 ± 12.01	281.76 ± 28.82*	45
Coarse	485.46 ± 43.33	639.39 ± 35.57*	32
Total	687.74 ± 52.75	921.30 ± 47.15*	34
CT			
Fine	248.57 ± 22.71	291.27 ± 19.13	17
Coarse	527.61 ± 118.67	478.03 ± 73.44	−9
Total	776.26 ± 126.32	779.83 ± 88.38	1
April 12, 1987			
NT			
Fine	119.11 ± 6.18	170.07 ± 16.27*	43
Coarse	595.55 ± 71.90	775.91 ± 134.01	30
Total	714.66 ± 75.16	945.98 ± 133.14	32
CT			
Fine	157.22 ± 8.38	170.24 ± 12.0	8
Coarse	266.88 ± 34.33	470.88 ± 46.48*	76
Total	424.10 ± 39.55	641.12 ± 52.22*	51

*Significantly different from control at $P = 0.05$

Although the differences were similar to those on day 139 for no-till, the only significant difference in the carbofuran-treated pens was with fine organic matter. In the conventionally tilled plots on day 292, fine organic matter levels were not significantly affected by the carbofuran treatment. However, coarse organic matter was significantly greater in the conventional-till carbofuran treatment (76% of controls). Total organic matter standing stocks in the conventional-till carbofuran-treated pens were also significantly greater than the controls.

Biocide non-target effects

In the winter-fall study, there was no significant difference between the percentage dry weight of soybean litter remaining in the no-till control and carbofuran-treated litterbags on any sampling date (Fig. 3a). However, the decay rate of soybean litter in the carbofuran-treated litterbags ($k = -1.46$ year^{-1}, $r^2 = 0.99$) was significantly slower than in the controls ($k = -2.24$ year^{-1}, $r^2 = 0.99$). Although the percentage dry weight remaining was greater in the conventional-till carbofuran-treated litterbags than in the controls on all sampling dates, the differences were not significant (Fig. 3b). The litter decay rates were also not significantly different between the conventional-till carbofuran-treated samples ($k = -1.37$ year^{-1}, $r^2 = 0.96$) and the controls ($k = -1.67$ year^{-1}, $r^2 = 0.92$).

In the summer-spring study, the rye-litter weight loss was not significantly affected by the carbofuran treatment under either no-till or conventional-till (Fig. 3c, d). There were no significant differences in the percentage dry weight remaining on any sampling date. Similarly, there were no significant differences in the decay rates between carbofuran-treated ($k = -0.95$ year^{-1}, $r^2 = 0.79$) and control ($k = -0.94$ year^{-1}, $r^2 = 0.67$) litter under no-till or between carbofuran-treated ($k = -1.33$ year^{-1}, $r^2 = 0.52$) and control ($k = -1.45$ year^{-1}, $r^2 = 0.48$) litter in conventionally tilled soils.

Significant non-target carbofuran effects were detected on several decomposer groups in the summer-spring study. Surface litter bacteria in no-till and buried litter

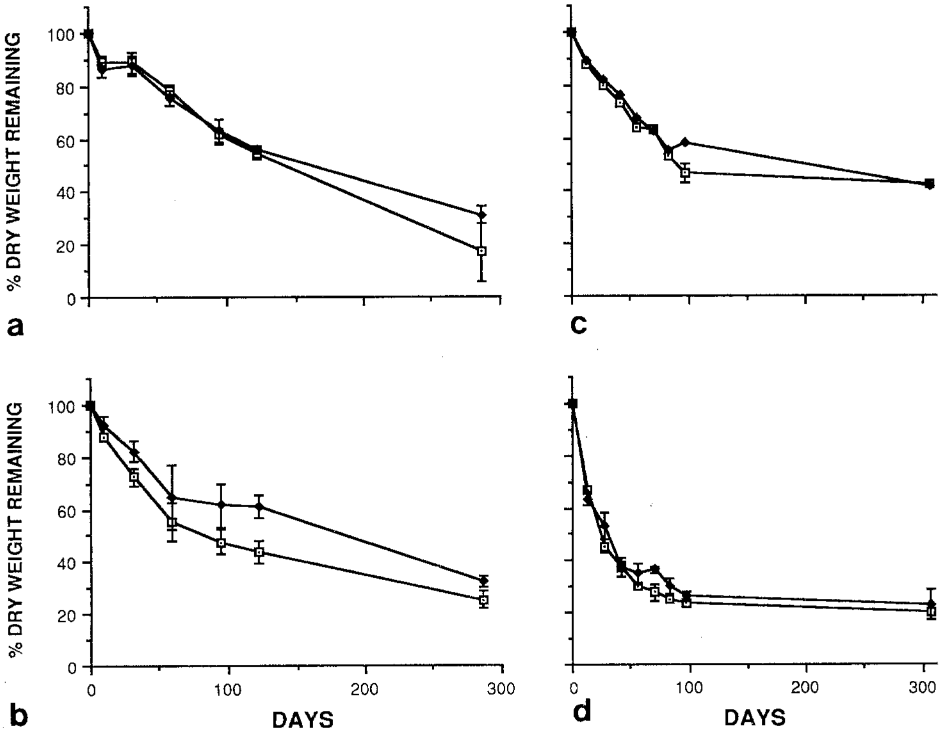

Fig. 3. Decomposition of soybean litter in (**a**) no-till (*NT*) and (**b**) conventional-till (*CT*) plots during the winter-fall study and decomposition of rye litter in (**c**) NT and (**d**) CT during the summer-spring study with control (□ – □) and carbofuran-treated (◆ – ◆) litter. Values are $\bar{x} \pm 1$ SE

bacteria in conventional-till samples were reduced significantly in the carbofuran-treated pens compared to the controls (Fig. 4a, b). Carbofuran also significantly reduced nematode densities in both no-till and conventional-till litter (Fig. 4g, h). Litter fungi and protozoa, however, were not significantly affected by carbofuran in either tillage treatment even though their densities were lower in the carbofuran-treated litter than in the controls on the final sampling date (Fig. 4c–f). The microarthropod abundance (no. g^{-1} ash-free dry weight $\bar{x} \pm 1$ SE) was similar in no-till surface litter from the carbofuran-treated (154±54) and the control (185±85) pens on day 97. On day 307, the microarthropod density was actually greater in the no-till litter from the carbofuran-treated (534±185) than the control (95±33) pens, although the difference was not significant. In contrast, the microarthropod density in the conventional-till buried litter on day 97 was significantly lower in the carbofuran-treated (321±54) compared to the control (777±126) pens. By day 307, however, there was no significant difference between treatments (carbofuran, 680±481; control, 287±92).

The plant biomass values were highly variable, and there were no significant carbofuran effects on the plant biomass (data not shown) either above or below the ground in either study. There was no difference in the no-till above-ground biomass input into the carbofuran-treated ($983 \pm 106\ \mathrm{g\,m}^{-2}$) and the control ($794 \pm 146\ \mathrm{g\,m}^{-2}$) pens in the winter-fall study. Similarly, the total above-ground plant biomass input was not different between the carbofuran-treated ($935 \pm 69\ \mathrm{g\,m}^{-2}$) and the control ($916 \pm 58\ \mathrm{g\,m}^{-2}$) pens with conventional tilling.

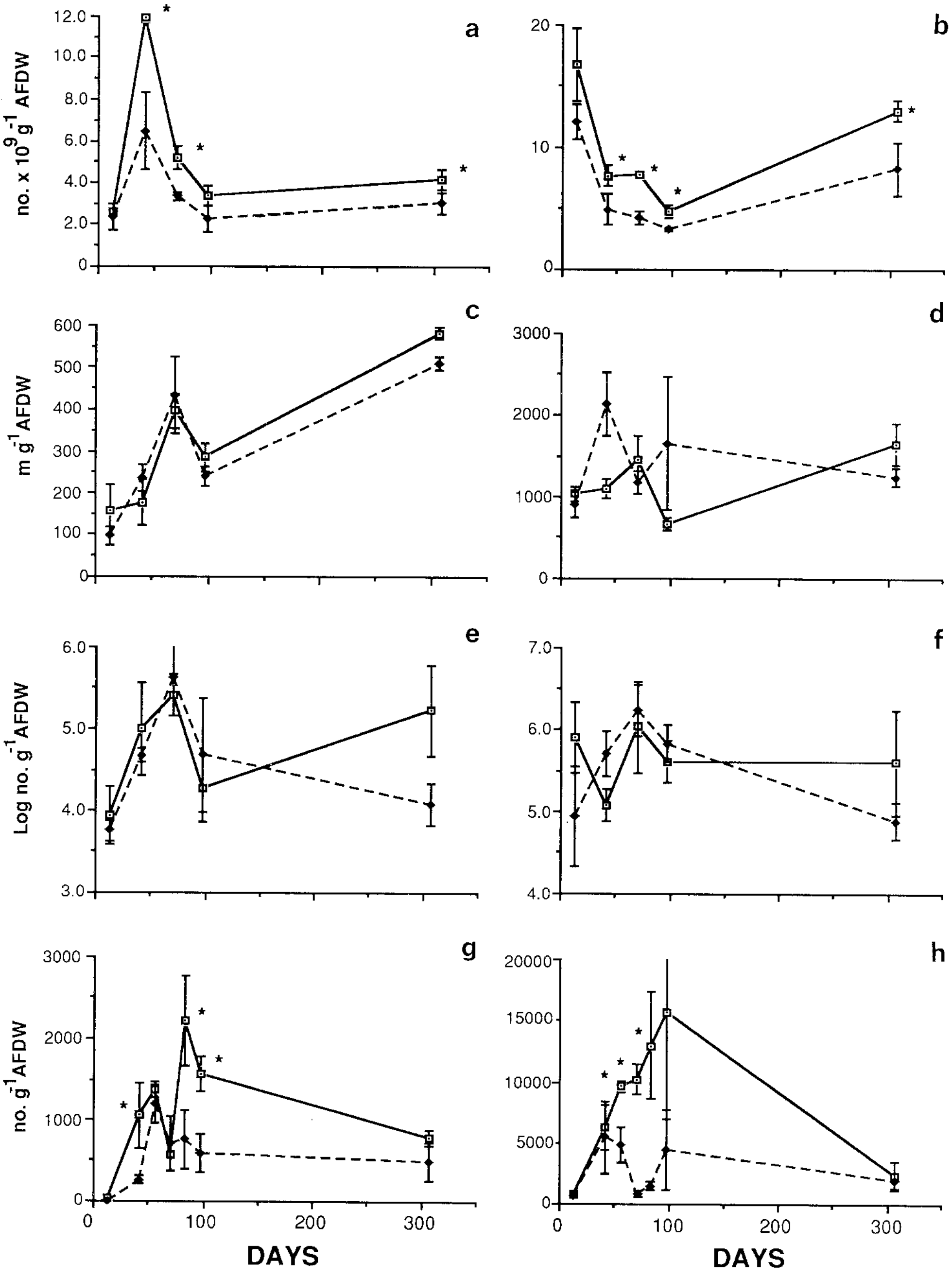

Fig. 4. Densities of bacteria (**a, b**), fungi (**c, d**), protozoa (**e, f**) and nematodes (**g, h**) on control (□ – □) and carbofuran-treated (◆ -- ◆) rye litter in no-till and conventional-till plots during the summer-spring study. **a, c, e, g** are NT; **b, d, f, h** are CT. *AFDW* ash-free dry weight. Values are $\bar{x} \pm 1$ SE

In the summer-spring study, there was no significant difference between the above-ground input to the no-till carbofuran-treated (755 ± 55 g m^{-2}) and the control (770 ± 46 g m^{-2}) pens. The above-ground input to the conventional-till carbofuran-treated (684 ± 149 g m^{-2}) and the control (866 ± 131 g m^{-2}) pens was also not significantly different.

Discussion

Abundance and biomass

Earthworm densities and biomass in the conventionally tilled soils were, on average, only 70% of the no-till values, and these results support the general conclusion that earthworm populations are greater in no-till than in conventional-till agroecosystems.

Edwards (1983) and Lee (1985) reviewed the possible adverse effects of cultivation on earthworm populations, and concluded that the most important factors may be the loss of surface litter and the consequent decline in soil organic matter that leads to a reduction in food resources. During the spring of 1986, Horseshoe Bend experienced a severe drought with rainfall 60% below the 100-year average for this period. Soil moisture in the top 5 cm of the no-till plots declined from 18% in January to 6% in May, and decomposition of no-till surface weed litter was reduced by drought conditions during this period (Parmelee et al. 1989). Both the no-till and the conventional-till earthworm populations crashed in April (Fig. 1). However, after the drought the no-till earthworm densities and biomass returned to near predrought levels, but the conventional-till populations failed to recover by the end of the study. Additionally, as the drought continued at Horseshoe Bend, the cocoon biomass in the no-till system increased (Parmelee and Crossley 1988). This may have reflected a normal cycle in the seasonal life history of the earthworms, or cocoon production may have increased in response to the adverse conditions and then contributed to re-establishing the population after the drought. Therefore, the greater resiliency of the no-till earthworm communities following adverse conditions may provide an additional mechanism that leads to relatively greater densities and biomass in long-term comparisons with conventional tillage.

The earthworm abundance and biomass in the no-till plots at Horseshoe Bend generally greatly exceeded the estimates reported for other no-till soils. Although Edwards (1983) observed densities approaching our maximum no-till densities, most no-till studies reported values of less than a few hundred per square meter. With the exception of some pastures and grasslands (Lee 1985), the earthworm abundance in our no-till system also approached or exceeded the densities reported for natural ecosystems. The high densities of earthworms at Horseshoe Bend may be partially explained by the relatively high fertility of the floodplain site (most recently flooded in 1966), liming (Syers and Springett 1984), and the absence of insecticide use. Moreover, wet-sieving is an efficient extraction method, and we recovered small earthworms that may not have been recovered if dry hand-sorting or formalin extraction techniques had been used.

Hendrix et al. (1986) proposed that enchytraeids were more important in conventional-till detrital food webs. Our current results demonstrated that, in fact, enchytraeid densities and biomass were consistently greater in the no-till system. Other tillage comparisons have not yet been reported. The densities of enchytraeids at Horseshoe Bend fall within the lower range of the densities reported from other agroecosystems (Kasprzak 1982). However, these densities were certainly underestimated at Horseshoe Bend. The extraction technique used here collected only the largest specimens. Preliminary extraction of enchytraeids by the O'Connor method (1967) indicated that our estimates may have been at least an order of magnitude low (Veikko, Huhta; personal communication 1987). The biomass values may be somewhat more reliable because of the greater contribution from the larger specimens.

Organic matter: winter-fall

In the winter-fall study, carbofuran reduced the large annelid biomass (particularly earthworms) and organic matter breakdown was inhibited in the no-till system. It was not possible to separate the effects of the earthworms and the enchytraeids on the breakdown, but our estimates of the organic matter processing rates in the no-till system were within the range reported for earthworms (Raw 1962; Mackay and Kladivko 1985; Hendrix et al. 1987). The potential contribution by enchytraeids should not be underestimated, however. For example, in a cultivated field, the amount of C respired by enchytraeids was much higher than that of earthworms even though the enchytraeid biomass was ten times lower (Golebiowska and Ryszkowski 1977).

Carbofuran significantly reduced the soybean litter decay rate in the no-till plots, and the reduction may have indicated non-target effects. The litterbag mesh size would have limited any access by large earthworms, but was large enough for small earthworms and enchytraeids to enter. However, during this study no earthworms or enchytraeids (visual inspection) were found in the litterbags. Assuming that the difference in decay rates was not due to the absence of annelid feeding in the carbofuran-treated litterbags, the difference could be attributed to non-target effects and litterbags could then provide a correction factor for the standing-stock organic matter estimates. The regression equations for the decay curves in the no-till soils predict that there would be a 12% difference between treatments after 10 months (compared to the 14% difference actually observed; Fig. 3 a). Therefore, we reduced the estimate of annelid-processed organic matter in the no-till plots over 10 months to 35% (47% – 12%).

Organic matter: summer-spring

In the summer-spring study, the no-till annelid biomass was significantly reduced and greater standing stocks of organic matter occurred after carbofuran application. The percentage differences in organic matter levels between the carbofuran-treated and control plots were similar to the differences observed in the no-till plots in the winter-fall study over a similar length of time. The effect of annelid removal was most evident on no-till fine organic matter standing stocks. *Aporrectodea caliginosa*, the most abundant earthworm at Horseshoe Bend, preferred finer particulate organic matter and exhibited faster growth when fed smaller sized food particles (Bostrom and Lofs-Holmin 1986). Thus, *Aporrectodea caliginosa* may have been partly responsible for the difference in fine organic matter breakdown. The other dominant earthworm species present at Horseshoe Bend, *Lumbricus rubellus*, consumed a larger proportion of coarse litter in its diet (Piearce 1978). Enchytraeids also consume fine organic matter (O'Connor 1967) and, therefore, may have preferentially impacted fine organic matter dynamics.

Carbofuran significantly reduced the numbers of bacteria and nematodes in the no-till litterbags during the summer-spring study, but these non-target effects were not expressed in a reduced litterbag decay rate or in the final remaining dry weight percentages. Therefore, it was not possible to adjust the estimates of annelid-processed organic matter for non-target effects. The 76% difference in coarse organic matter levels between the carbofuran-treated and control plots under conventional tillage in the summer-spring study, however, suggested that there were potentially major non-target effects. The difference did not appear to be an effect of the biocide on target groups as only the enchytraeid biomass was significantly reduced by carbofuran. The bacteria, nematode, and microarthropod densities were all significantly depressed in the conventional-till carbofuran-treated litterbags, but these reductions did not affect litter breakdown in the bags. We are not able to explain why these non-target effects were so apparent under conventional tilling in this one sampling period and not in others, and were only manifested in coarse litter. It is possible that the litterbags did not accurately reflect conditions that affect the decomposition of unconfined coarse litter, or that other unknown factors were present. If the results can be explained by non-target effects and not by target effects or error, then we can conclude, at least, that the decomposition of coarse organic matter in the conventional-till system is strongly dependent on biotic components. Hendrix et al. (1986) proposed that a bacterial-based food web may be relatively more important with conventional tillage compared to no-tillage. Our evidence of carbofuran effects on bacteria, coupled with the larger standing stocks of coarse organic matter in the conventional-till carbofuran-treated pens, provided support for their original hypothesis. Additionally, the no-till food web may be fungal-based (Hendrix et al. 1986), and if this hypothesis is correct, then the less obvious non-target effects in the no-till system may have been due to the decreased importance of bacteria in the no-till food web.

Conclusions

Our objectives were to assess the role of annelids in the breakdown of organic matter in no-till and conventionally tilled agroecosystems through use of a biocide. We demonstrated that when high levels of annelid biomass, as occurred in the no-till system, were reduced, there was significant inhibition of the breakdown of organic matter. The amount of organic matter processing that could be attributed to the annelids, however, was confounded by non-target effects. These non-target effects may have been due to the direct action of the biocide, but it was also possible that some of the non-target effects were due to the indirect result of annelid removal. Regardless of the cause of the non-target effects, our estimates of the amount of organic matter that was processed by annelids must be considered maximum potential estimates. Our results also demonstrate the critical importance of the biota (target or non-target) in regulating organic matter breakdown in both the no-till and conventional-till systems.

In the effort to develop sustainable agroecosystems, systems that rely less on conventional tillage practices will promote earthworm and enchytraeid activity. Our results and those of Parmelee and Crossley (1988) indicate that annelids can make major contributions to organic matter breakdown and N cycling in no-till systems. Whether or not annelids will contribute to the sustainability of these systems will depend on the balance between processes that promote retention and efficient use of nutrients and those that do not. For example, earthworms are known to increase aggregate size and stability (van Rhee 1969; Mackay and Kladivko 1985; Temirov and Valiakhmedov 1988), and to stimulate root biomass and depth of rooting, height and biomass of above-ground tissue, and yield (Edwards and Lofty 1977, 1978, 1980; van Rhee 1977). Annelids, however, may also contribute to the loss of nutrients from the system (Anderson and Ineson 1984; James and Seastedt 1986; Svensson et al. 1986). Further research is needed to assess the role of annelids in promoting long-term sustainability in agroecosystems.

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