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Short communication

Earthworms and weed seed distribution in annual crops

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Abstract

A field study was conducted to determine if earthworm activity would affect the abundance and composition of weed seed banks in annual row-crops. The abundance of weed seeds in surface-deposited earthworm casts was determined in continuous monocultures and rotations that included corn, soybean, and winter wheat, with or without cover crop. Casts were collected weekly over the growing season and the weed seed content determined by direct germination in a heated greenhouse. Weed seed composition in surface casts was compared to that in the seed bank (0–5 cm) and soil surface by the same method. Earthworm cast production varied temporally and among crops and was higher in winter wheat compared to corn or soybean. The effect of crop rotation on cast production was significant only in soybean, with the highest production in monocultures compared to three-crop rotations. Weed seed densities were significantly higher in casts collected from winter wheat than corn or soybean. Comparisons of the composition and relative abundance of seeds in earthworm casts with the surface soil layer and seed bank suggest that earthworms contribute to redistribution of weed seeds over the growing season.

Keywords: Cover crops; Crop rotation; Earthworms; Soil seed banks; Weed communities

1. Introduction

Much of the current work on seed banks in agroecosystems has focused on how mechanical factors such as tillage and the movement of farm machinery affect the distribution of seeds in the soil (Grundy et al., 1999; Buhler et al., 2001). However, biological factors such as seed predators (Marino et al., 1999; Menalled et al., 2000) and burrowing and foraging activity by small animals (Harper, 1977) can also influence the distribution of seeds in the soil. These, too, can vary with management (Brust and House, 1988).

Earthworms are capable of ingesting and excreting substantial numbers of seeds in their casts (Grant, 1983; Thompson et al., 1994; Willems and Huijsmans, 1994; Decaens et al., 2003). In a laboratory study, Grant (1983) showed that 75–90% of the seeds ingested by *Lumbricus terrestris* L. and *Allolobophora longa* Ude passed through their digestive tracts with little or no effect on seed viability. Studies of seed

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Table 1
Summary of the rotations sampled for earthworm cast production in 2002

Rotation[a]	Rotation sequence			Crop planting, 2002	Cultivations, 2002	Cover crop, 2001–2002
	2000	2001	2002			
M	Corn	Corn	Corn	23 May 2002	10 and 18 June	None
MC	Corn	Corn	Corn	23 May 2002	10 and 18 June	Red clover
R	Soybean	Wheat	Corn	23 May 2002	10 and 18 June	None
RC	Soybean	Wheat	Corn	23 May 2002	10 and 18 June	Red clover, cereal rye
M	Soybean	Soybean	Soybean	23 May 2002	10 and 18 June	None
MC	Soybean	Soybean	Soybean	23 May 2002	10 and 18 June	Cereal rye
R	Wheat	Corn	Soybean	23 May 2002	10 and 18 June	None
RC	Wheat	Corn	Soybean	23 May 2002	10 and 18 June	Cereal rye, crimson clover
M	Wheat	Wheat	Wheat	4 October 2001	None	None
MC	Wheat	Wheat	Wheat	4 October 2001	None	Red clover
R	Corn	Soybean	Wheat	4 October 2001	None	None
RC	Corn	Soybean	Wheat	4 October 2001	None	Red clover, cereal rye

[a] M: continuous monoculture; MC: continuous monoculture with one cover crop annually; R: three-crop rotation; RC: three-crop rotation with two cover crops annually.

dispersal by earthworms in European grasslands (Grant, 1983; Thompson et al., 1994; Willems and Huijsmans, 1994) and Colombian savannas and pastures (Decaens et al., 2003) have shown that earthworm activities, such as surface-casting, are important for the maintenance of plant community composition and species diversity in these systems.

The aim of this study was to determine how different crop rotations influenced the composition and abundance of weed seeds in surface-deposited earthworm casts in annually tilled row-crops managed without chemical inputs. Specific goals of the study were to determine: (1) if earthworm activity, measured as cast production, differed among continuous monocultures and three-crop rotations of corn, soybean and winter wheat, with and without cover crops and (2) if earthworm casts collected from these rotations contained germinable weed seeds.

2. Materials and methods

The study was conducted in 12 rotation manipulations that were part of the biodiversity experimental plots (BEP) at the long term ecological research (LTER) project in agroecology at the W.K. Kellogg Biological Station (KBS) of Michigan State University in southwestern Michigan, USA. Rotations were initiated in 2000 and consisted of corn, soybean, and winter wheat grown in continuous monocultures and three-crop rotations, with and without cover crops (Table 1). All rotations were managed without any fertilizer or pesticide and were chisel-plowed and soil-finished each year prior to planting. Rotations were replicated in four blocks and plots measured 9.1 m $\times$ 27.4 m. Soils were mainly in the Kalamazoo (fine-loamy, mixed, mesic Typic Hapludalfs) and Oshtemo (coarse-loamy, mixed, mesic Typic Hapladalfs) soil series (Whiteside et al., 1959). Earthworm species present in tilled-cropping systems at the LTER site included *Aporrectodea tuberculata* (Eisen), *A. turgida* (Eisen), and *L. terrestris* L. (Smith et al., unpublished data).

Earthworm casts present on the soil surface were collected at weekly intervals in two permanent 50 cm $\times$ 50 cm subplots in each replicate plot. Because of differences in harvesting dates among crops, casts were collected from mid-June through late August 2002 in corn and winter wheat, and through late-September 2002 in soybean. Following collection, each cast was air-dried for approximately 1 week, and then weighed to the nearest 0.01 g.

To determine the density and composition of weed seeds within casts, weighed casts were immediately placed in a plastic tray filled with sterile growing medium (Sunshine Germinating Mix #3, Sun Gro Horticulture, Bellevue, Washington, USA) in a temperature-controlled greenhouse. Trays were kept moist and watered from above, as needed using a mist sprayer. Seedling emergence from each cast was recorded at weekly intervals through mid-December 2002.

To determine if weed seed composition and abundance in worm casts reflected that of the soil surface or subsurface seed bank, parallel studies of the weed seed composition from these two sources were conducted. Soil seed bank composition was determined from samples taken in mid-May 2002. Ten soil cores (diameter 2 cm) were taken to a depth of 5 cm from a 25 cm × 25 cm area in three locations in each replicate. Each 10-core soil sample was composited and spread out onto sterile seedling mix and placed in the greenhouse. Seedling germination from these samples was assessed from 29 May to 24 September 2002. Additional soil samples were taken to determine the average dry mass of a 10-core sample. These samples were dried for 4 days at 60 °C and their weights averaged to allow determination of the density of seeds in the soil seed bank.

The composition of weed seeds in the surface soil was determined in all replicates planted to soybean and four randomly chosen replicates planted to corn and winter wheat on 26 September 2002. Soil was collected from a 25 cm × 25 cm area to a depth of 0.5 cm in four random locations within each replicate sampled. The four sub-samples were aggregated by replicate and weighed to determine the total soil mass sampled. Seedling emergence from the surface soil samples was monitored for three months and censused at regular intervals as described above. The number of seedlings emerged from earthworm casts and surface and subsurface soil was expressed kg^{-1} dry soil to allow comparisons from a similar soil mass.

One- and two-way ANOVA were used to detect significant crop species and crop rotation and cover crop effects on total earthworm cast production and seedling densities within casts and surface and seed bank samples. Because wheat and corn treatments were sampled for a shorter duration than the soybeans, crop species effects on cast production were only compared over the time period when all treatments were sampled. Crop rotation and cover crop effects on earthworm cast production were analyzed separately for each crop species. Means were compared using Fisher's protected LSD test. Linear regression was used to determine if there was a relationship between the timing of cast production or the mass of individual casts and the abundance of germinable weed seeds that emerged from casts. Cast production and seed density data were log and square root transformed, when necessary, to improve normality.

3. Results

Earthworm cast production varied seasonally in all crop species. At the beginning of the study, casts were only observed in winter wheat. Few casts were observed in any of the rotations from July to mid-August and then a sharp increase in cast production was observed in all crops in late August. By 27 August, the last date sampled for corn and wheat, cast production in the three crops was similar (number: $F_{2,9} = 1.156$, $P = \mathrm{NS}$; mass: $F_{2,9} = 0.285$, $P = \mathrm{NS}$). Cast production in soybeans declined over the remainder of the season.

Over the time period in which all rotations were sampled, cumulative earthworm cast production was significantly higher in winter wheat than corn or soybean (number: $F_{2,9} = 10.99$, $P = 0.004$; mass: $F_{2,9} = 4.427$, $P = 0.046$). Within crop species, the effect of crop rotation was only significant in soybean (number: $F_{1,12} = 10.71$, $P = 0.007$; mass: $F_{1,12} = 11.27$, $P < 0.001$) where total numbers and dry weight of earthworm casts were nearly two times higher in the monocultures than in either of the rotations. There was no effect of cover crops on cast production for any rotation.

Over 1000 earthworm casts were collected from the rotations over the course of the study. Twelve weed species were identified from the casts (Table 2). Seed sizes for the species ranged from 0.5 to 4.5 mm (Uva et al., 1997); however, two small-seeded weed species, *Arabidopsis thaliana* (L.) Heynh. and *Cardamine hirsuta* L., made up the majority (68%) of seeds that germinated from the casts. These two species were also abundant in surface soil samples (70%) but made up less than 3% of the soil seed bank (Table 2).

In general, weed seed densities were higher in earthworm casts than in samples collected from the soil surface and seed bank (Table 2). Germinable weed seed densities in earthworm casts differed among crop species and were significantly higher in casts collected from winter wheat than those in corn and soybean ($F_{2,9} = 6.47$, $P = 0.018$). Over 92% of the weed seeds that germinated from earthworm casts were from casts

Table 2
Composition and abundance of germinable weed seeds identified from earthworm casts and surface and seed bank soil samples

Weed species	Seed size[a] (mm)	Casts		Surface soil		Seed bank	
		Total	Number (kg^{-1})	Total	Number (kg^{-1})	Total	Number (kg^{-1})
A. thaliana (L.) Heynh.	0.7	149	340.3	40	51.1	25	1.0
C. hirsuta L.	1.0	86	196.4	3	3.8	11	0.4
Stellaria media (L.) Vill.	1.2	30	68.5	0	0	328	12.7
Veronica sp.	1.0	27	61.7	7	8.9	9	0.3
Mollugo verticillata L.	0.5	10	22.8	0	0	766	29.6
Digitaria sanguinalis (L.) Scop.	2.6	3	6.9	0	0	106	4.1
Conyza canadensis (L.) Cronq.	1.2	2	4.6	0	0	5	0.2
Oxalis stricta L.	1.2	1	2.3	0	0	4	0.2
Panicum dichotomiflorum Michx.	2.0	1	2.3	4	5.1	82	3.2
Poa sp.	3.0	1	2.3	0	0	4	0.2
Taraxacum officinale Weber in Wiggers	4.5	1	2.3	0	0	17	0.7
Sonchus oleraceus L.	3.2	1	2.3	0	0	1	0.0
Unknown/other[b]	–	34	77.6	7	8.9	573	22.1

[a] Seed size estimates are based on Uva et al. (1997) except for *A. thaliana* which was directly measured.
[b] Individuals that died before they could be identified and species not found in earthworm casts.

collected in winter wheat. Within winter wheat, germinable weed seed densities in earthworm casts differed in response to rotation ($F_{1,12} = 9.20$, $P = 0.010$) and were highest in casts collected from continuous wheat monocultures. Seed content of earthworm casts was related to cast size, with larger casts containing more weed seeds ($r^2 = 0.069$, $P < 0.001$).

Germinable weed seed densities in the surface and seed bank soil samples did not differ across crop species (surface: $F_{2,9} = 2.19$, $P = \mathrm{NS}$, seed bank: $F_{2,9} = 1.68$, $P = \mathrm{NS}$); however, trends were similar to that in earthworm casts, with higher seed densities (seeds/kg soil) in wheat compared to corn or soybean. Germinable weed seed densities in the wheat seed bank samples differed among rotations ($F_{1,12} = 6.71$, $P = 0.024$), and were higher in the two rotations than the monocultures.

4. Discussion

Both crop identity and management impacted surface cast production by earthworms. In soybean, the high rates of cast production observed in the continuous monocultures relative to rotations may have been due to a greater abundance of soybean residues. Soybean residue, because of its high N content, tends to be a higher quality food source than residue of corn or wheat (Curry, 1998). Schmidt et al. (2003) showed that earthworm abundance was higher under a cereal–legume intercrop than a cereal monoculture and attributed this effect to residues provided by the legume.

All three earthworm species present in tilled systems at the LTER have been observed to produce surface casts (Lee, 1985) and at least one species, *L. terrestris*, has been shown to ingest seeds (Grant, 1983). Differences in the densities of weed seeds in casts collected from different crop species were unexpected, and may have been due to variation in the abundance of weed seeds suitable for earthworm ingestion in fall versus spring-sown crops. While other studies have demonstrated substantial vertical dispersal of seeds by earthworms (Thompson et al., 1994; Willems and Huijsmans, 1994), results of this study suggest that a large component of seed dispersal by earthworms in annual row-crops is horizontal, resulting in aggregation in casts of seeds from the soil surface. This conclusion is supported by the observed similarity in weed seed composition and density among earthworm casts and surface soil (Table 2). *A. thaliana* was the most abundant weed species in the earthworm casts and accounted for a much higher percentage of the total weed seeds in surface soil than seed bank samples. Winter annuals such as *A. thaliana* and *C. hirsuta* are common in the emergent weed communities in fall-sown crops and seeds of these species would have been relatively abundant on the soil surface in winter wheat over the duration of the study.

These results are consistent with other studies that show earthworms tend to ingest smaller-seeded species (Thompson et al., 1994; Willems and Huijsmans, 1994). The ecological implications for small-seeded weed species in annual row-crop systems will depend on how earthworm ingestion and subsequent aggregation in surface casts impact seed survival.

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References

Brust, G.E., House, G.J., 1988. Weed seed destruction by arthropods and rodents in low-input soybean agroecosystems. Am. J. Alter. Agric. 3, 19–25.

Buhler, D.D., Kohler, K.A., Thompson, R.L., 2001. Weed seed bank dynamics during a five-year crop rotation. Weed Technol. 15, 170–176.

Curry, J.P., 1998. Factors affecting earthworm abundance in soils. In: Edwards, C.A. (Ed.), Earthworm Ecology. St. Lucie Press, Boca Raton, pp. 37–64.

Decaens, T., Mariani, L., Betancourt, N., Jimenez, J.J., 2003. Seed dispersion by surface casting activities of earthworms in Colombian grasslands. Acta Oecol. 24, 175–185.

Grant, J.D., 1983. The activities of earthworms and the fates of seeds. In: Satchell, J.E. (Ed.), Earthworm Ecology. Chapman & Hall, London, pp. 107–122.

Grundy, A.C., Mead, A., Burston, S., 1999. Modeling the effect of cultivation on seed movement with application to the prediction of weed seedling emergence. J. Appl. Ecol. 36, 663–678.

Harper, J.L., 1977. Population Biology of Plants. Academic Press, London.

Lee, K.E., 1985. Earthworms: Their Ecology and Relationships with Soils and Land Use. Academic Press, Sydney.

Marino, P.C., Gross, K.L., Landis, D.A., 1999. Weed seed loss due to predation in Michigan maize fields. Agric. Ecosyst. Environ. 66, 189–196.

Menalled, F.D., Marino, P.C., Renner, K.A., Landis, D.A., 2000. Post-dispersal weed seed predation in Michigan crop fields as a function of agricultural landscape structure. Agric. Ecosyst. Environ. 77, 193–202.

Schmidt, O., Clements, R.O., Donaldson, G., 2003. Why do cereal–legume intercrops support large earthworm populations? Appl. Soil Ecol. 22, 181–190.

Thompson, K., Green, A., Jewels, A.M., 1994. Seeds in soil and worm casts from a neutral grassland. Funct. Ecol. 8, 29–35.

Uva, R.H., Neal, J.C., DiTomaso, J.M., 1997. Weeds of the Northeast. Cornell University Press, Ithaca.

Whiteside, E., Schneider, I., Cook, R., 1959. Soils of Michigan. Michigan State University Agricultural Experiment Station Special Bulletin No. 402.

Willems, J.H., Huijsmans, K.G.A., 1994. Vertical seed dispersal by earthworms: a quantitative approach. Ecography 17, 124–130.