Soil Use and Management

RESEARCH ARTICLE OPEN ACCESS

The Effect of Long-Term Underlying Management on Soil Faunal Communities of a Newly Established Herbal Ley

N. D. Cannon[1] | Y. Booyse[1] | P. J. Murray[1] | F. V. Crotty[1,2]

[1]School of Agriculture, Food and Environment, Royal Agricultural University, Cirencester, Gloucestershire, UK | [2]Agriculture and Land Team, Ricardo Energy and Environment, The Gemini Building, Didcot, UK

Correspondence: N. D. Cannon (nicola.cannon@rau.ac.uk)

Received: 14 March 2025 | **Revised:** 7 October 2025 | **Accepted:** 14 October 2025

Funding: This project was kindly funded by The John Oldacre Foundation.

Keywords: cultivations | direct drill | earthworms | reduced tillage | soil biodiversity | soil fauna | tillage

ABSTRACT

Soil ecosystems support a diverse range of life essential for a functioning soil. However, agricultural establishment methods like tillage intensity have been shown to directly affect soil fauna populations. Soil fauna diversity and abundance were investigated following a 10-year experiment testing different crop establishment systems in an arable crop rotation. Large plots (30 × 100 m) within a randomised block design were established using either a plough-based system, minimum tillage or no tillage using a direct drill. Significant differences were found between the cultivation systems for several biological groups together with seasonal differences. Overall, total mesofauna was greatest in minimum and no till plots having greater numbers of cari, total Collembola and collembolan superfamilies *oduromorpha* and *Symphypleona*. Nematode abundance was also greater in the minimum and no till plots. Although total earthworm abundance did not differ between cultivations, there were differences between functional groups with anecic species being more prevalent in the least disturbed soils. Overall, findings demonstrated that the effects of long-term tillage treatments are visible across the whole soil food web. This could have long term impacts on ecosystem services even when land management has changed to a conservation focus. Further analysis did not find any clear linkage between soil physical assessments which could be useful as soil biological indicators.

1 | Introduction

Intensification of agriculture in order to improve yields has been a focus of government policies and therefore a priority for many farmers since the Second World War, with an increase in the use of mechanical and chemical solutions and the enhancement of human control over natural processes (Tilman et al. 2011). This intensification of production systems has been responsible for soil degradation, loss of natural fertility, impaired soil functionality, biodiversity loss, and contributing towards climate change (Hatfield et al. 2017; Springmann et al. 2018; Stergiadi et al. 2015; Tivet et al. 2013). In an attempt to mitigate against soil organic carbon (SOC) loss, some farmers have adopted no-till techniques to reduce soil and crop residue disturbance, minimize erosion risks and sequester carbon, while reducing energy requirements to grow the crop (Lal et al. 2007).

Reduced tillage generally forms part of a wider agronomic practice which includes residue management, diverse crop rotations, as well as the addition of cover crops (Busari et al. 2015; Zibilske et al. 2002). Reducing tillage intensity, such as minimum tillage and direct drilling (no till), has been shown to increase crop resilience to extreme weather events (Dicks et al. 2019; Rial-Lovera et al. 2017; Cannon and Rial-Lovera 2025). Despite the proven environmental benefits of reduced tillage techniques (Alvarez and Steinbach 2009; Benito et al. 1999; Celik et al. 2020; Cerdà et al. 2020), a global meta-analysis by Pittelkow et al. (2015) found that no till reduced yield on average by 5.1% across a wide range of crops and many farmers still choose to use plough-based systems due to their reliability and greater yield potential. However, several studies have shown that intensive ploughing leads to compaction and soil erosion by leaving soil bare and exposed, resulting in lower productivity and soil quality (El Titi 2002; Lal et al. 2007).

Biodiversity loss, especially of the fauna, can lead to a simplification of the soil food web which is a major threat to soil ecosystem functionality. The impacts of intensive agriculture on overall soil biodiversity are highly variable depending on region, crop and soil physical characteristics (FAO, ITPS, GSBI, SCBD, & EC 2020). It is however evident, that conventional agricultural practices can reduce biodiversity within the soil (Briones and Schmidt 2017; House and Parmelee 1985; Lori et al. 2025; Mathew et al. 2012) leading to a reduction in ecosystem stress resilience (Balvanera et al. 2014; Byrnes et al. 2014; Loreau et al. 2002; Soliveres et al. 2016; Wagg et al. 2014).

Since being described as ‘nature's plough’ by Charles Darwin in 1881, earthworms have been referred to as keystone species and ‘ecosystem engineers’ within soil ecosystems and are considered a key bioindicator of soil health (Le Bayon et al. 2017; Liu et al. 2019; Van Groenigen et al. 2014). Intensive farming practices such as conventional tillage and agrochemical inputs (Chan 2001) have consistently shown a reduction in both population size and diversity of earthworms (Kemper et al. 2011). The loss of these ecosystem engineers can have impacts on other trophic levels altering populations of mesofauna, nematodes, and protozoa.

Functional and species diversity is more important than simply numerical abundance. Earthworms, for example, fulfill different ecological functions. Each ecological group (endogeic, epigeic and anecic) has distinct burrowing, feeding and casting (excretion) habits and is impacted by agricultural management in different ways (Crotty 2020). Endogeic species are least sensitive to disturbances and most prevalent across agricultural landscapes (Briones and Schmidt 2017) having short life cycles, high fecundity rates and fast recovery after disturbance (Van Groenigen et al. 2014). Epigeic and anecic species are more sensitive to disturbances due to their proximity to the soil surface, burrowing habit and size.

Invertebrates including Collembola (springtails) and Acari (mites) form a crucial link in the soil food web by activating microflora, fragmenting organic matter and enhancing available nutrients (FAO, ITPS, GSBI, SCBD, & EC 2020). Acari are an integral part of soil food webs, and span several trophic levels including fungivores, bacterivores, detritivores and (top) predators (Crotty et al. 2011). Collembola are among the most diverse, abundant and functionally important soil organisms (Potapov et al. 2020) and are an equally integral part of the soil food web (Crotty et al. 2016). Collembolans are good indicators of soil conditions because they are widely distributed, have short life cycles and can rapidly adapt to and reflect environmental changes (George et al. 2017). This response is further enhanced through their function as secondary decomposers, feeding on fungi and microorganisms (Crotty et al. 2016).

Nematodes are an important group for community indicator analysis due to more information existing on their taxonomy and feeding roles than for any other microfauna (Gupta and Yeates 1997). Furthermore, they form a central part of the food web as they represent multiple trophic levels including primary (plant-parasitic herbivores), secondary (bacterivores and fungivores) and tertiary (predators and omnivores) feeders (Yeates et al. 1993). The composition of these communities provides valuable information regarding the soil's health, since nematodes are predominantly specific in their food preferences and abundant in decomposition habitats (Bongers and Bongers 1998).

Here we hypothesize that over the long term, the effect of greater soil disturbance will negatively impact soil faunal communities and populations. This study explores the impact of tillage on soil faunal communities by determining the impact of long-term tillage treatments on soil mesofauna and earthworm abundances. We consider if prior cultivation methods (plough, minimum tillage and direct drill) and the effect of seasonality have an impact on soil fauna abundance during the establishment of a herbal ley.

2 | Materials and Methods

2.1 | Experimental Site

The field experiment was established in September 2010 at the Royal Agricultural University's Harnhill Manor Farm, Cirencester, UK (51°42′ N, 01°59′ W; 135 m a.s.l.) in clay texture soil (22% sand, 38% silt and 40% clay) with the aim of determining the effect of management practice on crop yields (Cannon and Rial-Lovera 2025). The baseline soil data at the start of the long-term experiment reported 4.4% organic matter, pH 7.4–7.7, phosphorus content of 13–15 mg kg^{-1} of soil or index 1, magnesium content of 19–21 mg kg^{-1} or index 0 and potassium of 200–220 ppm or index 2 (Vijaya Bhaskar et al. 2013). The index value ratings were based on the DEFRA (2010) assigned values.

The experiment followed a randomised block design replicated six times. Each block (90 × 100 m) was divided into three tillage treatments of 30 × 100 m with three treatments of either conventional plough-based tillage (PT), minimum tillage (MT) and direct drilling (DD). Individual plot cultivation treatments remained constant across all the years. Crop management practices and cultivation system treatments are described in Table 1. When the field received agronomic inputs, all plots received the same amount of nitrogen (N), phosphorus (P) and potassium (K), adapted to the specific requirement of each crop under conventional management according to AHDB Nutrient Management Guide RB209 (AHDB 2023). Herbicides, fungicides and insecticides were also applied to the whole experimental site following conventional management practices.

After 10 years of management the opportunity was taken to investigate the effects on soil biodiversity. During the 10 cropping seasons from 2010/11 to 2019/20 which proceeded the soil sampling to evaluate soil changes, crops of winter and spring wheat (*Triticum aestivum* L.), winter barley (*Hordeum vulgare* L.) and

TABLE 1 | Cultivation treatment specifications, crop type and key dates.

Year	Drilling date	Crop	Treatment			Harvest date
			CT	MT	DD	
2010/11	05/11/2010	Winter wheat	Plough to 20 cm and power harrow combination drill (8 cm) and then roll	Cultivated to 30 cm and the drilled and rolled	Direct drill to 8 cm and rolled	25/08/2011
2012	14/03/2012	Spring wheat				22/08/2012
2013	10/04/2013	Spring wheat				27/08/2013
2014	18/04/2014	Spring wheat				31/08/2014
2015	21/04/2015	Spring wheat				16/08/2015
2015/16	04/10/2015	Winter wheat				17/08/2016
2016/17	06/10/2016	Winter barley				14/07/2017
2017/18	26/08/2017	Winter oilseed rape				17/07/2018
2018/19	22/10/2018	Winter wheat				14/08/2019
2019/20	23/10/2019	Winter barley				29/07/2020
2020/24	07/09/2020	Herbal ley				Grazing

winter oilseed rape (*Brassica napus* L.) were grown (Table 1). Winter cereal crops were sown between the end of September until the beginning of November depending on the season, whilst spring cereals were sown between March and April. Oilseed rape was sown at the end of August and harvested in July (Table 1). The management system of the experimental site was initially organic for the first two cropping seasons, but subsequently managed conventionally for the following eight cropping seasons. It was then returned to organic management as a herbal ley for the conversion period, and during the experimental soil evaluation period.

Weather data was collected at the Royal Agricultural University weather station in Cirencester (51° 42′33.6′′ N 1° 59′ 40.7′′ W), 3 miles away from the trial site which records daily local rainfall and atmospheric temperatures (Figure 1).

Soil assessments were carried out in triplicate during the growing season, with assessments being made in the autumn, winter and spring (see Table 2).

2.2 | Soil Indicators

Sampling intervals were divided into three stages in the autumn, winter and spring. Environmental factors such as field activity, average temperature and rainfall were recorded (Table 2). Three samples were systematically taken from each of the 18 plots using the same pattern for each block. During sampling all variables were taken from the same 1 m^2, selected at random from pre-determined segments (top left, middle right and bottom left).

2.3 | Soil Physical and Chemical Parameters

Soil organic matter content was determined using the loss on ignition method (Heiri et al. 2001; Nelson and Sommers 1996). Oven-dried samples were subsequently heated in a muffle furnace at 550°C for 4 h and reweighed. Soil moisture at the time of sampling was recorded as part of this process. Soil temperature was carried out in triplicate during macrofauna sampling using a digital thermometer (TenmaTP101) which was inserted 10–12 cm deep into the soil.

Visual evaluation of soil structure (VESS; AHDB 2022) was used to assess the topsoil for compaction. Three random samples of undisturbed soil blocks (20 × 20 × 20 cm) were extracted using a spade and each layer within them was scored from 1 (loose, crumbly, porous soils) to 5 (compact, dense, solid).

2.4 | Macrofauna

Earthworm (and other macrofauna) abundance (m^{-2}) was quantified following Crotty and Stoate (2019). Briefly, at each sampling, three soil block samples (20 × 20 × 20 cm) were excavated randomly within each plot using a spade, and each soil block was hand sorted in the field and all macrofauna removed for further identification in the laboratory. While the soil block was being sorted, a solution of two tablespoons of mustard powder

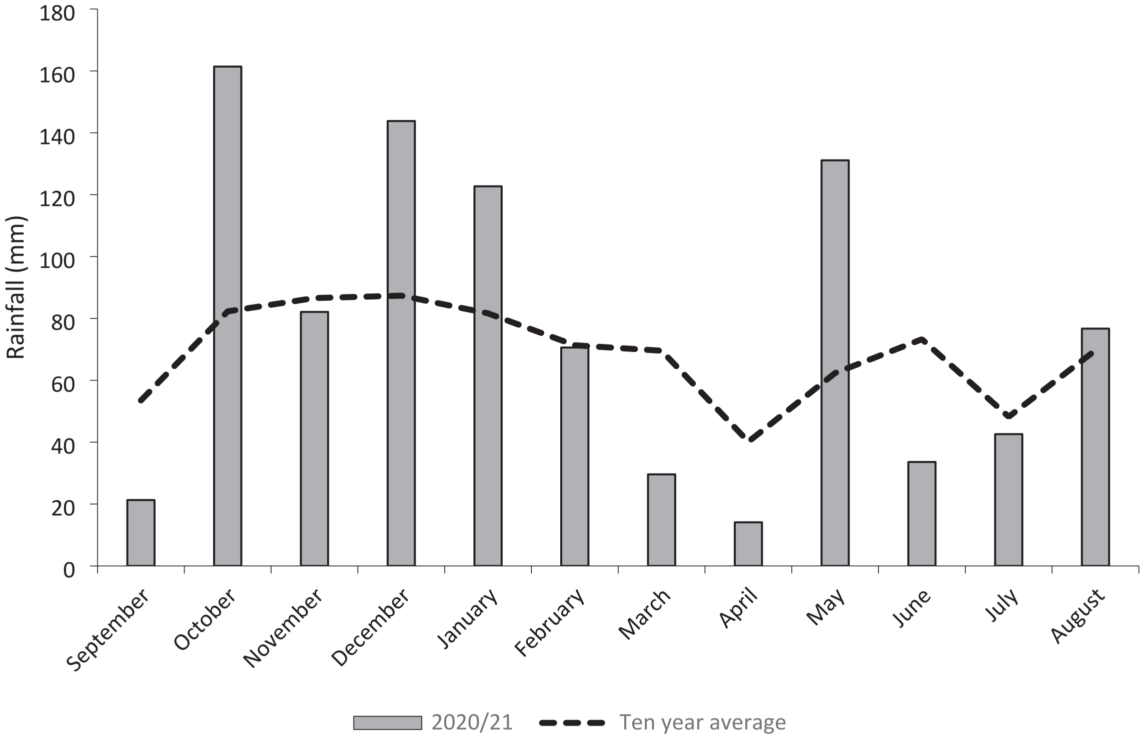

FIGURE 1 | Annual rainfall (mm) during the soil macro- and meso- fauna data collection period compared to the 10 year mean monthly rainfall.

TABLE 2 | Assessment periods.

	Sampling dates	Field status	Rainfall (mm)	Temp (°C)
Autumn	Mid-October	Post drilling of herbal ley	160	10.6
Winter	Late November	Tillering grasses and good herbal establishment	82	3.75
Spring	Mid-May	Post sheep grazing	130	7.7

and 1 L of water was poured evenly across the extraction quadrat and observed for 20 min. All emerging earthworms were removed. Extracted juvenile earthworms were counted and recorded, adult earthworms were identified to functional group (Sims and Gerard 1985) and other invertebrates identified according to Wheater and Read (1996).

2.5 | Mesofauna

Microarthropods were extracted using Tullgren funnels (Burkard Scientific Ltd., Rickmansworth, England). Soil cores (100 mm diameter × 50 mm deep) were extracted and transferred to the funnels and left for 7 days. Microarthropods move away from heat generated by a light bulb (20 W) placed above the core, through the soil into a preservative solution (70% ethanol). Organisms were then identified and grouped according to mites (Krantz and Walter 2009) or Collembola super families (Hopkin 2007).

2.6 | Microfauna—Nematodes

The wet tray extraction method was used as described by Whitehead and Hemming (1965), and adapted by Crotty et al. (2011) to isolate nematodes from cored soil samples (100 g) using an intact soil corer. Briefly, nematodes moved out of the soil into the water-filled tray; this was followed by settlement and reduction of the water solution over a period of 7 days, to obtain a concentrated nematode sample. Nematode abundance counts were conducted on 3 × 250 μL samples using an inverted microscope.

2.7 | Community Change

An assessment of the relative response of the different functional groups to the different cultivation regimes was done using the change equation:

$$V = \left[2\mathrm{Mx}/(\mathrm{Mx}+\mathrm{Mct})\right] - 1$$

based on the equation by Wardle (1995) where Mx is the abundance of organisms in either the direct drilled (DD) or minimum tillage (MT) treatments and Mct the abundance in the conventionally ploughed treatment The index ranges from −1 (functional groups extremely inhibited by CT) to +1 (functional groups extremely stimulated by DD or MT), with 0 indicating relatively equal abundances under both systems.

2.8 | Decomposition

Decomposition was used as a proxy for measuring biological function in the soil. Decomposition assay tests were conducted using cotton strips simulating labile and wooden sticks to represent more recalcitrant substrates. The cotton strips were prepared by cutting the material to 9.5 ×14.5 cm with the selvedge remaining at the top of each strip to ensure samples were consistent. The wooden sticks were pre-prepared (100 ×10 mm) lollipop sticks. Samples were numbered clearly using a permanent marker before being dried, weighed and recorded. Using a spade, the cotton strips were inserted vertically into the soil using the back of a spade to ensure the strip was fully inserted and flush with the soil surface. The wooden sticks were placed 100 mm away from cotton strips. On 26th August 2021, after 60 days of incubation, the sticks and the cotton were carefully removed, using a ruler to check that all the organic material was removed. Sticks and strips were cleaned by hand to remove adhered soil and plant residues before being washed carefully without detergent in order to retain the integrity of the samples. Sticks and strips were dried and brushed carefully to retain sample integrity. The tensile strength of the wooden sticks and the cotton strips was measured using a Force gauge (PCB Instruments Ltd. Force Gauge PCE-FB Series). The wooden sticks were secured rigidly over two pieces of 8 cm wide and 10 cm high wood to ensure there was enough room for the sticks to bend under the downward pressure of the force gauge. The cotton strips were pulled tightly over a circular tube and clamped using a slotted stainless steel hose clamp to ensure the cotton was under tension. The sticks and the cotton under tension were then subjected to a downward force with a sharp point attached to the force gauge until the cotton or stick was punctured. Once punctured, the force gauge measured and recorded the maximum amount of force, in kilograms, required to puncture the wooden sticks and cotton strips, respectively.

2.9 | Soil Compaction

At the spring sampling period a Spectrum Field Scout 900 (Spectrum Technologies Inc., Illinois, USA) digital compaction meter (penetrometer) was used as an ultrasonic depth sensor capturing resistance readings measured in KPa in 2.5 cm increments up to 45 cm depth. Three measurements were taken from each plot adjacent to the soil sampling zone.

2.10 | Statistical Analysis

Repeated measures analysis of variance (ANOVA) was used to assess differences between treatments and sampling periods. Data (collected in a randomised block design) was analysed in GENSTAT (GenStat, 24th ed., 2024, VSN International Ltd., Hemel Hempstead, UK). Where required the data was normalised before univariate and multivariate analyses of variance. Where $p < 0.05$, multiple comparisons were made using Tukey's HSD post hoc test to identify differences between treatments. Both the soil physical and biological characteristics then underwent a correlation analysis.

The penetrometer readings were analyzed using a general ANOVA as this measure was only taken during the spring sampling period and a correlation matrix was performed on the soil physical and biological measures assessed.

3 | Results

3.1 | Soil Organic Matter and VESS

Following 10 years of diverse cultivation systems, PT (4.64%) had significantly ($p < 0.001$) lower levels of organic matter than MT (4.96%) or DD (5.14%) (Table 3). There was also a significant difference in VESS with the MT (2.90) and DD (2.91) having significantly ($p < 0.05$) lower scores (showing least compaction), compared to the PT plots (3.31) (Table 3).

3.2 | Soil Temperature and Moisture

Significant differences were observed across the season for soil temperature ($p < 0.001$), with the highest recorded in the autumn (16.7°C), then the winter (13.3°C) followed by the spring (8.7°C). The PT system impacted soil temperature, providing a significantly ($p = 0.05$) lower (12.7°C) temperature than MT (13.1°C), with DD (13.0°C) being intermediate (Table 3).

Soil moisture content also significantly changed throughout the assessment period (Table 3), with the soil being significantly wetter in the autumn (28.7%) than in winter (23.4%) or spring (22.4%) ($p < 0.001$). Furthermore, the cultivation system also influenced the amount of water in the soil, with PT having significantly ($p < 0.05$) lower water content than MT (DD being intermediate).

3.3 | Macrofauna–Earthworms

Table 4 shows the earthworm abundance in the three cultivation treatments. No significant differences were found in the abundance of the total number of earthworms between any of the cultivation treatments. However, there were significant differences within functional groups, where the anecic earthworms were found in significantly ($p = 0.031$) greater numbers in the MT (33.3 m^{-2}) and DD (31.5 m^{-2}) systems compared to PT (9.6 m^{-2}) (Table 4). Nevertheless, sampling time did influence earthworm abundance, with winter sampling (1063 m^{-2}) having a significantly ($p < 0.001$) greater total earthworm population compared to autumn (470 m^{-2}) or spring (557 m^{-2}). The seasonal effect on total earthworms was primarily due to the endogeic group having a significantly greater population than either the epigeic or anecic populations ($p < 0.001$) in the winter with (770 m^{-2}) autumn (257 m^{-2}) and spring (409 m^{-2}) sample periods. The population of epigeic worms had significantly greater ($p = 0.023$) abundance in the autumn (27.8 m^{-2}) than in the winter (5.6 m^{-2}) or spring (7.4 m^{-2}). Meanwhile, the anecic group had significantly lower ($p = 0.031$) numbers in the winter (9.3 m^{-2}) compared to the autumn (27.8 m^{-2}) and spring (37.0 m^{-2}). Juvenile earthworm numbers were also significantly greater ($p < 0.001$) in the winter (278 m^{-2}) than in the autumn (157 m^{-2}) or spring (104 m^{-2}).

TABLE 3 | Impact of cultivation on soil organic matter, temperature (°C), VESS score and soil moisture. Analysis using ANOVA with repeated measures for season and Tukey's HSD post hoc test (superscript letters signify $p < 0.05$ differences between cultivation treatments and season of sampling).

		Cultivation (C)							Within cultivation
	Season (S)	**PT**	**MT**	**DD**	**Mean**	**Effect**	**FProb**	**SED**	**SED**
Soil organic matter	Autumn	4.57	5.03	5.14	4.91	C	**<0.001**	0.1112	
(%)	Winter	4.58	4.94	5.11	4.88	S	0.515	0.0742	
	Spring	4.78	4.93	5.17	4.96	C × S	0.528	0.1529 (84.98)	0.1285
	Mean	4.64^{a}	4.96^{b}	5.14^{b}					
Soil temperature	Autumn	16.42	17.16	16.66	16.75^{a}	C	**0.05**	0.192	
°C	Winter	8.21	8.89	8.96	13.34^{b}	S	**<0.001**	0.313	
	Spring	13.36	13.38	13.29	8.69^{c}	C × S	0.735	0.482 (90.7)	0.542
	Mean	12.66^{a}	13.14^{b}	12.97^{ab}					
Visual assessment	Autumn	3.25	2.99	3.03	3.09^{b}	C	**<0.001**	0.0807	
	Winter	3.54	2.99	2.93	3.15^{b}	S	**0.001**	0.0753	
	Spring	3.14	2.72	2.77	2.88^{a}	C × S	0.307	0.1336 (99.43)	0.1303
	Mean	3.31^{c}	2.90^{a}	2.91^{b}					
Volumetric water	Autumn	25.62^{ab}	31.42^{b}	29.14^{b}	28.73^{b}	C	**0.049**	1.063	
(θ)	Winter	22.91^{a}	24.84^{a}	22.32^{a}	23.36^{a}	S	**<0.001**	0.861	
	Spring	23.34^{a}	21.69^{a}	22.07^{a}	22.37^{a}	C × S	**0.06**	1.616 (84.19)	1.492
	Mean	23.34^{a}	25.99^{b}	25.13^{ab}					

Note: FProb in bold are statistically significant.

TABLE 4 | Earthworm abundance (m^{-2}) in a newly established herbal ley after 10 years of different cultivation systems. Analysis using ANOVA with repeated measures for season and Tukey's superscript letters to signify $p < 0.05$ differences between cultivation treatments and season of sampling.

	Cultivation					Season				
	PT	**MT**	**DD**	**FProb**	**SED**	**Autumn**	**Winter**	**Spring**	**FProb**	**SED**
Endogeic (m^{-2})	452	461	524	0.501	66.7	257^{a}	770^{c}	409^{b}	**<0.001**	16.68
Epigeic (m^{-2})	14.8	11.1	14.8	0.887	8.35	27.8^{b}	5.6^{a}	7.4^{a}	**0.023**	8.35
Anecic (m^{-2})	9.6^{a}	33.3^{b}	31.5^{b}	**0.031**	10.03	27.8^{b}	9.3^{a}	37.0^{b}	**0.031**	10.03
Juvenile earthworms (m^{-2})	183	169	187	0.820	31.1	157^{a}	278^{b}	104^{a}	**<0.001**	31.1
Total earthworms (m^{-2})	659	674	757	0.496	89.2	470^{a}	1063^{b}	557^{a}	**<0.001**	89.2

Note: FProb in bold are statistically significant.

3.4 | Mesofauna

For all cultivation treatments and seasons, a mean of 21,050 mesofauna m^{-2} was extracted; 18% were Acari and 82% were Collembola. The abundance of total Collembola (m^{-2}) did not differ between seasons. Symphypleona had significantly ($p < 0.001$) higher numbers in winter (4047 m^{-2}) compared to spring (889 m^{-2}) and autumn numbers (370 m^{-2}). Entomobryomorpha were unaffected by the season of sampling (Table 5). However, the Acari were more prevalent ($p < 0.001$) in spring (5549 m^{-2}) after increasing from winter (3385 m^{-2}) which had significantly more than in autumn (2749 m^{-2}).

The total number of mesofauna m^{-2} was significantly greater at lower tillage intensity (MT [25,600 m^{-2}] and DD [24,370 m^{-2}])

($p = 0.007$) in comparison with PT (13,178 m^{-2}). Collembola superfamilies all showed significant differences between cultivation systems (Table 5). Poduromorpha were significantly ($p = 0.003$) more prevalent in DD (5778 m^{-2}) than in MT (4593 m^{-2}), which had significantly more than PT (2222 m^{-2}). The Symphypleona were significantly ($p = 0.003$) fewer in both PT (1185 m^{-2}) and MT (889 m^{-2}) systems in comparison to DD (3259 m^{-2}).

3.5 | Nematodes

MT (17,808 n/100 g) and DD (16,960 n/100 g) had significantly greater ($p < 0.001$) nematode abundance per 100 g of soil in comparison to PT (9968 n/100 g). There were also significant seasonal effects, with lower ($p = 0.003$) abundance of nematodes in the autumn (12,288 n/100 g) compared to winter (17,744 n/100 g) and spring numbers (14,688 n/100 g) being intermediate (Figure 2).

3.6 | Change Index

The change index indicates that most of the biota are positively influenced by the reduced tillage, the exceptions being the epigeic earthworms and the Symphylopleona (Figure 3).

3.7 | Decomposition

The highest mean tensile strength of the cotton strip assays was in the PT (1.167 kg), which was significantly higher than both MT (0.613 kg) and DD (0.490 kg) respectively, indicating the least decomposition had occurred in PT. In the wooden stick decomposition test, the highest mean tensile strength was observed under PT (4.476 kg) which was significantly higher than the MT (3.593 kg) and DD (2.370 kg), again indicating that the least decomposition had occurred in PT.

TABLE 5 | Total mesofauna abundance (per m^2), superfamilies and nematodes after 10 years of different cultivation systems in the autumn, winter and spring in a newly established herbal ley. Analysis using ANOVA with repeated measures for season and Tukey's superscript letters to signify $p < 0.05$ differences between cultivation treatments and season of sampling.

	Cultivation				Season				SED
	PT	MT	DD	FProb	Autumn	Winter	Spring	FProb	148 df
Total Acari (m^{-2})	2734^a	4267^b	4593^b	**0.010**	2749^a	3385^b	5459^c	**< 0.001**	647
Total Collembola (m^{-2})	$10,444^a$	$21,333^b$	$19,778^b$	**0.013**	12,667	20,519	18,370	0.121	3923
Total mesofauna (m^{-2})	$13,178^a$	$25,600^b$	$24,370^b$	**0.007**	15,415	23,904	23,830	0.080	4304
Collembola superfamilies									
Entomobryomopha (m^{-2})	7037^b	$15,852^a$	10741^b	**0.042**	7781	10,963	14,889	0.127	3483
Poduromorpha (m^{-2})	2222^a	4593^b	5778^c	**0.009**	4519^{ab}	5481^b	2593^a	**0.044**	1166
Symphypleona (m^{-2})	1185^a	889^a	3259^b	**0.003**	370^a	4074^b	889^a	**< 0.001**	743

Note: FProb in bold are statistically significant.

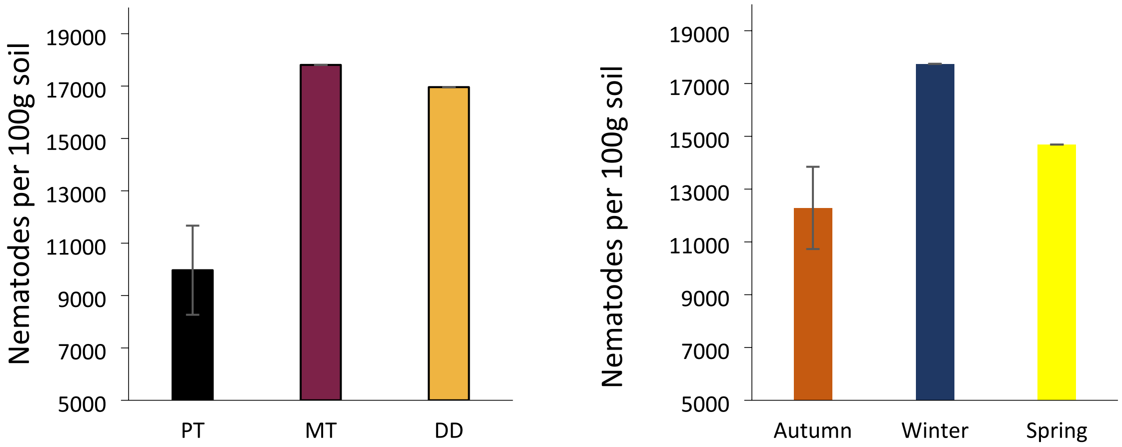

FIGURE 2 | Nematode abundance per 100 g of soil under differing cultivation regimes and a different sampling season.

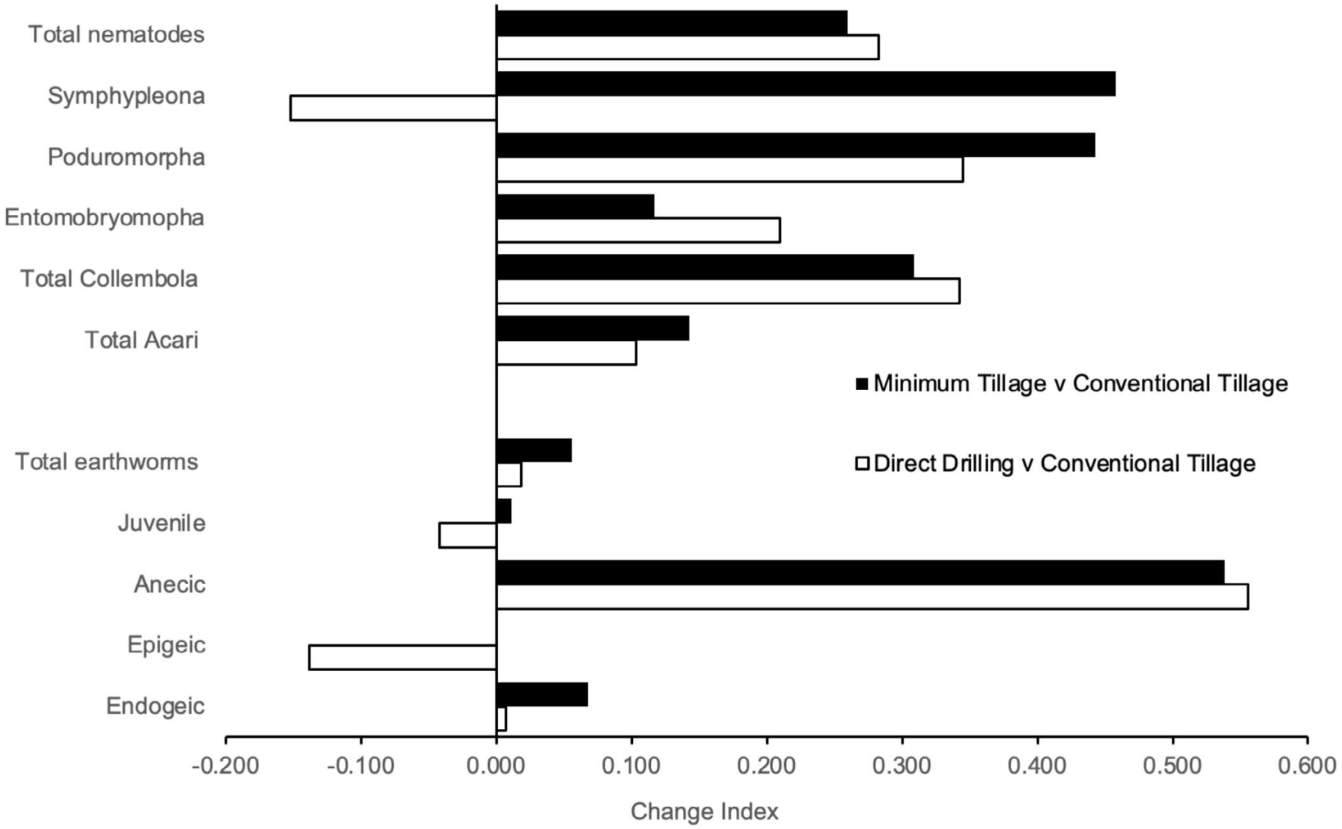

FIGURE 3 | Change Index calculated for the main invertebrate groups where the index ranges from −1 (functional groups extremely inhibited by PT) to +1 (functional groups extremely stimulated by DD or MT), with 0 indicating relatively equal abundances under both systems.

3.8 | Soil Compaction

There was no significant difference between the three different crop establishment techniques in the force required to penetrate through the soil profile (Figure 4). From 35 cm depth there were more false readings due to the presence of stone.

3.9 | Correlation Analysis

Correlation of the biological data with the soil physical parameters did not reveal any significant relationships. There were, however strong correlations between the total numbers of Acari and the number of Entomobryomorpha, endogeic worms, juvenile worms and soil temperatures all at $p < 0.001$ (see Supporting Information for the correlation table).

4 | Discussion

A functioning soil delivers multiple ecosystem services such as water quality, plant productivity and soil nutrient recycling (Karlen et al. 2019; Menta and Remelli 2020) and the abundance, diversity and activity of the edaphic fauna directly and indirectly affect a soil's ability to deliver these services (Tahat et al. 2020). Studying soil fauna alongside the soil parameters provides an assessment of the impact of different cultivation practices on elements of soil health. As biodiversity is in decline globally (IPCC 2023), and the greatest concentration of organisms in agricultural systems is in the soil (Plaas et al. 2019), it is essential to understand how management decisions made by farmers can influence biodiversity within our soils.

4.1 | Impact of Crop Establishment Techniques on Soil Organic Matter and VESS

Soil compaction and declining organic matter are major agricultural concerns. Conventional plough-based tillage has traditionally been employed to alleviate topsoil compaction and aerate the soil, facilitate seed establishment and dislodge weeds thus increasing yields. This practice has, however, led to an actual increase in compaction due to aggregate displacement, heavy machinery loading, particularly in wet conditions, exacerbated by an already low organic matter content (Hamza and Anderson 2005).

The amount of SOM within the soil has been found to change the water holding capacity, with greater water retention where there is more organic matter (Rawls et al. 2003), Benito et al. (1999), reported that less intensive tillage methods conserved water, particularly in dry years. In our study DD and MT had significantly greater organic matter levels than PT (Table 3). However, these differences did not impact soil water content over the period of the study potentially due to within-season rainfall patterns. We also observed an interaction between cultivation system and season of sampling,

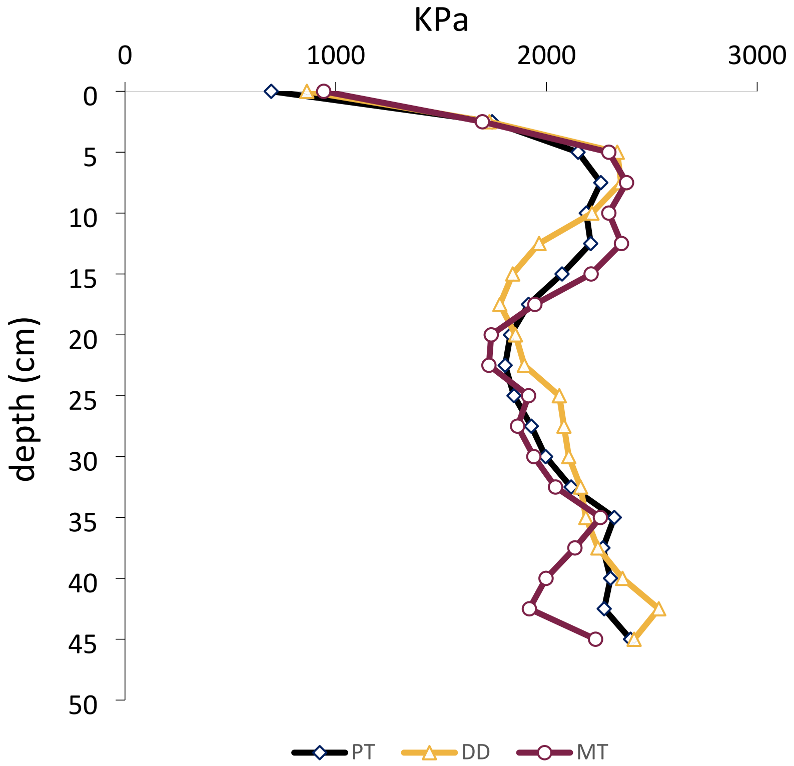

FIGURE 4 | The impact of cultivation system on the mean penetrometer readings taken in the spring and analysed using ANOVA.

demonstrating drier soils in the autumn following crop establishment. These changes in soil moisture have the potential to impact crop yields.

VESS scoring provides a measure of the quality of soil structure that is often used by farmers as it is relatively low-tech, with higher scores indicating a poorer soil structure. Within this investigation PT had relatively high VESS scores compared to the reduced tillage systems (Table 3), which may impact root penetration. It may also indicate a reduction in biotic activity, specifically the earthworm species that burrow (macro- and mesofauna) and break up soil aggregates (Oades 1993).

4.2 | Cultivation Effects on Earthworms

Earthworms are often considered to be an important indicator of soil health (Fründ et al. 2011). Earthworm abundance has been linked to increased organic matter in soils (Ke and Scheu 2008) but this was not directly observed in this study. Although there were no significant differences found for total earthworm numbers within the different cultivation systems (Table 4) in contrast to findings from other researchers (Chan (2001), Hangen et al. (2002), Peigné et al. (2009), van Capelle et al. (2012)), who reported a greater abundance in less intensive tillage systems. There were significantly greater numbers of anecic earthworms in the less intensive tillage systems (MT and DD) (Table 3). This is in agreement with the global meta-analysis by Briones and Schmidt (2017), where they found that epigeic and anecic functional groups displayed the greatest sensitivity to ploughing, particularly *Lumbricus terrestris* which responded most positively to MT.

Anecic earthworms are known to be deep burrowing and to move organic matter throughout the soil profile as part of their feeding ecology (Crotty 2020). Thus, the increased organic matter found within the MT and DD soils could be attributed to their presence. Conventional tillage directly reduces earthworm numbers particularly for the larger anecic species. As well as increasing the mortality rate of earthworms, the impact of tillage changes the soil structure and decimates earthworm burrows, affecting their food availability and location, increasing the risk of predation, and changing the soil microclimate (Crotty 2020). However, the intensity of ploughing (depth, axle load), the time of tillage (spring or autumn i.e., dry or wet conditions), soil and crop type all affect the impact of this land management practice (Gerard and Hay 1979) which can therefore lead to inconsistent findings between studies.

4.3 | Effects on Mesofauna

Intensive tillage can induce high levels of stress including microclimatic conditions and physical damage to soil organisms, including mesofauna, often resulting in less diverse but more stress-adapted communities (Chauvat et al. 2007; Marx et al. 2016; Carlesso et al. 2022). This may be why total mesofauna, total Collembola and total acari were observed in greater numbers in MT and DD treatments (Table 5), when compared to PT plots.

There were also seasonal differences for the Collembola superfamilies Symphypleona and Entomobryomorpha, as well as the Acari, but these were likely due to different stages in lifecycles or environmental conditions at sampling (Crotty et al. 2015) or soil moisture changes. Moisture content in soil is a predominant factor when determining distribution; low moisture levels are often serious resulting in desiccation (Christiansen et al. 2009) among the Collembola. Collembola resist desiccation by moving into microenvironments of higher humidity and thus may have moved between cultivation treatments as time progressed through the sampling period, although there is little evidence of populations or individuals moving relatively large distances, Carlesso et al. (2022) showed that heavy disturbance inhibited the development of stable mesofaunal communities in arable systems.

4.4 | Collembola Superfamilies

Symphlypleona species were significantly higher in DD plots (not MT) when compared to PT in the spring (Table 5). This is when the organic ley had reached maturity and livestock (sheep) had been introduced to graze (pre-sampling). These are a small group with much more uniform habits (DeWalt and Resh 2019) such as being active jumpers, residing in the superficial litter layer and vegetation dwellers, with a predominant diet of fungi and plant tissue (Malcicka et al. 2017). Due to the proliferation of above-ground, and indeed, below-ground vegetation in the spring, it can be argued that this led to an increased abundance of this superfamily. Poduromorpha Collembola showed a similar pattern, although this group was most abundant in the DD plots in the winter. Poduromorpha are decomposers, thus likely to have increased in abundance as a greater amount of senesced and fallen foliage would have been present during this period. These results agree with a number of other studies monitoring Collembola abundance in relation to tillage (Bokova et al. 2023; Coulibaly et al. 2017).

4.5 | Nematodes

Nematodes live in the water-filled pore spaces within the soil and are likely to increase in population size when conditions are most suitable for their requirements (Neher 2001). Investigations can provide highly valuable information relating to the functional changes within arable soils (Freckman 1988), as they show clear preferences for certain food sources (Ruess et al. 2000), as well as being highly sensitive to soil moisture content (Kaya and Gaugler 1993). Therefore, cultivation methods that alter these soil conditions would likely impact nematode community composition, and may result in promoting or inhibiting specific soil processes and functions (van Capelle et al. 2012). Variability in nematode abundance between the different sampling seasons may be explained by Elfstrand et al. (2008) who observed that seasonal variations affected feeding rates.

The increased abundance of nematodes in the MT and DD treatments supports the findings of Fu et al. (2000) who reported greater numbers under DD than PT-based systems. Treonis et al. (2010) reported that the abundance of nematodes decreased when tillage intensity was reduced, but the study separated trophic groups and observed greater numbers of bacterial-feeding nematodes compared to lower numbers of fungal-feeding nematodes in tilled systems. D'Hose et al. (2018), found only two studies relating to non-inversion tillage impacts on nematode abundance and community composition. In both investigations, no significant differences were reported for different nematode functional groups. Although trophic levels were not assessed in this study, this explains the observed variability in abundance over time. As van Capelle et al. (2012) suggested, differences in nematode abundance under varying tillage intensities resulted in different nematode feeding groups and shifts in species composition depending on cultivation system and crop residue mixing.

4.6 | Decomposition Rates

Overall, there were significant differences in the tensile strength of cotton strips and wooden sticks dependent on cultivation treatment. These results are a proxy for variation in microbial activity across the treatments, with both the labile (cotton strips) and recalcitrant (wooden sticks) SOC pools represented showing changes in decomposition over time. For both the cotton strips and wooden sticks there was a decrease in tensile strength with disturbance, showing the microbial community was more active under less disturbance and turnover. These results are in agreement with a number of studies showing changes to the microbial community dependent on tillage management (e.g., Li et al. (2020); Schmidt et al. (2018); Mbuthia et al. 2015), although often these relationships are also influenced by fertiliser input, which was maintained the same across cultivation treatments in these experiments.

4.7 | Soil Faunal Diversity at Different Scales

By analysing these different scales of sized organisms as well as the decomposition tests using cotton strips and wooden sticks it has enabled a detailed view of the soil food web, which has enabled an overview of the effect of agricultural management on each faunal group. Overall, there is an accumulation of evidence from this study showing that maintaining an intensive form of cultivation for over 10 years (tillage), causes long-term changes to the community composition of the soil. Results indicated that depending on the earthworm functional group, different impacts were observed with the larger anecic group showing the greatest benefit in community numbers when the intensity of tillage was reduced. Nematodes and certain Collembola superfamilies revealed increased abundances when tillage intensity was reduced. Changes in abundance are probably due to physical destruction, soil moisture levels and the availability of different food sources (including soil organic matter), possibly adapting to the environmental conditions experienced.

There are two potential reasons for differences observed between the lower intensity tillage system and the intensive plough-based system. Firstly, reduced physical disturbance on soil aggregates, and secondly, deeper burial of crop residues which may have altered the faunas' food source. Nevertheless, reduced tillage intensity created a more favorable habitat for organism reproduction and longevity. The long-term nature of this study and the large-scale plots have helped to reduce the risk of dispersal from neighboring plots, and suggests more stable populations, although seasonal variations were still experienced due to feeding activity and reproduction influences.

Biodiversity loss, especially the fauna, has led to a simplification of the soil food web which is a major threat to soil ecosystem functionality. For example, the greater abundance of anecic earthworms which make vertical burrows in the soil can help plant rooting (Rowe and Crotty 2024), redistribute crop residues and improve soil aggregation. The benefits from anecic earthworms can help overcome some of the major challenges facing future cropping systems by improving soil structure, reducing the impacts of compaction and improving the soil nutrient balance (Crotty et al. 2016). Sandhu et al. (2008) demonstrated economic benefits by increasing earthworm populations and improving soil health leading to increased agricultural profitability.

It was predicted that following 10 years of different intensity tillage treatments, a greater effect on soil faunal populations would have been observed due to annual disturbances from arable management practices. Despite some groups appearing to be unaffected by tillage intensity, the investigation has demonstrated that different crop establishment systems influence soil biodiversity and abundance. Still, plant–soil interactions and the connectedness and interactions between the different faunal trophic levels require further consideration to determine the impact of agricultural systems on the soil food web. Our results confirm our hypothesis, that the intensity of tillage impacts soil fauna abundance for most of the groups studied.

5 | Conclusion

This study compared the impact of different cultivation intensities on the soil food web by measuring soil faunal abundance and diversity at three different scales (micro, meso and macro) after 10 years of crop establishment treatments. Findings suggest that the abundance and diversity of mesofauna were greatly influenced by the cultivation system, with increased abundance in total mesofauna, Acari, and total Collembola (Poduromorpha and Symphyleona superfamilies). Overall earthworm abundance was not impacted by tillage intensity, but anecic earthworms were significantly less abundant following plough-based cultivation compared to the other treatments. Here we have demonstrated that reducing cultivation intensity has helped to improve soil biodiversity, which impacts the sustainability of different crop establishment techniques. Thereby supporting the initial hypothesis that the long-term effect of greater soil disturbance negatively impacts communities and populations within the soil.

Acknowledgements

The authors would like to thank the John Oldacre Foundation for funding this work. We would also like to thank Rijk Dipeveen and Susan Coe-Martin for assisting in sampling and laboratory analysis and to Ampney Brook Farms for allowing this long-term study to continue. Thanks are expressed to Tony Norris for helping to facilitate the field operations for this trial and to the laboratory technicians in supporting practical work.

Disclosure

Synopsis: Ten years of different crop establishment systems led to greater soil fauna diversity and abundance when tillage intensity was reduced.

Ethics Statement

Fully ethical approval was given by the RAU Ethics Committee.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All data are available on request from the corresponding author.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** sum70143-sup-0001-TableS1.xlsx.