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The legacy of cover crops on the soil habitat and ecosystem services in a heavy clay, minimum tillage rotation

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Abstract

Cover crops are grown as potential ways to improve soil fertility, soil structure, and biodiversity, while reducing weed/pest burdens. Yet, increased costs (in both time and fuel), farmer knowledge requirements, and yield uncertainty (green bridge effect and variable crop establishment) have led to hesitation among farmers. This study was conducted at the field scale (covering an area of nearly 20 hectares) to determine whether different cover crop mixtures affected soil properties and ecosystem services on a heavy clay soil. Measurements of soil chemistry, physics, biology, weed abundance, and subsequent crop performance were taken within a minimum tillage management system, across three cover crop mixtures (commonly sold to UK farmers). The cover crop mixtures included oats (*Avena sativa*), radish (*Raphanus sativus*), phacelia (*Phacelia tanacetifolia*), vetch (*Vicia sativa*), legumes, buckwheat (*Fagopyrum esculentum*) and a bare stubble control followed by a spring oat crop. Soil physics (penetrometer and bulk density) and chemistry (N, P, K, Mg, Ca, and organic matter) varied little across treatments, although there was significantly lower Mg in the cover crop including legumes and an increase in NO_3 within this treatment. Soil biology and botanical composition were also assessed, monitoring earthworm and mesofauna abundance; and sown and unsown (weed) biomass. Epigeic earthworms were found to have significantly larger abundance in cover crop mixtures with radish present, although other meso- and macrofauna did not differ. Significant weed suppression was found during both the cover crop growing period and as a legacy in the subsequent crop, leading to significant yield increases and economic benefits in some treatments. Our study confirms that cover crops are providing benefits, even on heavy clay soils, including improvements in nutrient leaching risk reduction, weed suppression, and crop yield, coupled with wider ecosystem benefits. We therefore consider cover crops to have a role in sustainable management of arable rotations.

KEYWORDS
cover crops, soil health, sustainable intensification, weed suppression, earthworms, heavy clay soil

1 | INTRODUCTION

Cover crops have been highlighted as a method to reduce nutrient losses (Cooper et al., 2017), increase soil organic carbon (Ladoni, Basir, Robertson, & Kravchenko, 2016), and change fauna abundance and diversity (Blubaugh, Hagler, Machtley, & Kaplan, 2016; Frasier et al., 2016) as well as reduce anthropogenic inputs (Wittwer, Dorn, Jossi, & Heijden, 2017). However, proving to the average farmer their usefulness has not been achieved to date (Bouma, 2018). The importance of sustainability in intensive agriculture has grown in prominence in recent years (Garnett et al., 2013). Incorporating legumes, widening crop rotation, reducing tillage, and utilizing cover crops are all potential ways to improve the profitability and sustainability of farming (Ball, Bingham, Rees, Watson, & Litterick, 2005; Dabney, Delgado, & Reeves, 2001; Rochon et al., 2004), through improvements in soil quality. Soil quality has been defined as "the capacity of a soil to function, within natural or managed ecosystem to sustain plant and animal production" (Creamer et al., 2010).

Crop monoculture and winter fallows are known to cause physical, chemical, and biological soil degradation (Bedano, Dominguez, Arolfo, & Wall, 2016). Monocultures and a lack of rotation (e.g., wheat after wheat) have been shown to lead to yield losses at the farm scale (Mazzilli, Ernst, Mello, & Pérez, 2016), reducing the sustainability of the farm business as a whole, in comparison with farms that increase diversity. Cover crops (sometimes referred to as catch crops) are plants that are grown when the soil would otherwise remain fallow (Ball et al., 2005; Dabney et al., 2001; Snapp et al., 2005; White, Holmes, Morris, & Stobart, 2016); commonly, this is the period between growing an "autumn-sown crop" harvested late summer and a "spring-sown crop" sown in mid-spring to late spring the following year and harvested that summer. However, this can also include crops grown between an early harvest and subsequent autumn-sown crop (Rücknagel et al., 2016). The terms catch and cover crop are used interchangeably. Cover and catch crops can also be referred to as the more general term "green manure" (Poeplau & Don, 2015).

Diversified cropping systems that incorporate year-round ground cover are known to maintain healthy soils (Benitez, Taheri, & Lehman, 2016). Yet, to implement cover crops there will be time, labor, and fuel costs, as well as education/training needed by the farmer. Implementation of cover crops also has yield uncertainty in the performance of the following crop—partly due to the green bridge effect (Acharya et al., 2016; a living host for plant herbivores and/or plant pathogens, where they can reside over the winter, ready to take over in the spring crop), as well as difficulties in the timing of establishment (and variability in establishment) of the subsequent crop. These problems are exacerbated on a heavy clay soil that is more prone to waterlogging, takes longer to dry out and warm up in the spring, reducing the time available to establish the spring crop. These factors have contributed to the limited use of cover crops among farmers in the UK.

Traditionally, arable agriculture on heavy clay soils in the UK utilizes conventional tillage within an autumn-sown crop rotation. However, due to increasing black-grass (*Alopecurus myosuroides*) problems (a highly competitive weed), this farming pattern may have to be adapted (Chauvel, Guillemin, Colbach, & Gasquez, 2001). By introducing spring cropping into the rotation, this provides an opportunity to control black-grass; black-grass will germinate throughout the autumn/winter outside the cropping period, enabling greater efficacy of a broad-spectrum herbicide prior to germination of the spring crop. However, leaving the soil bare over the winter can lead to increased soil erosion and waterlogging (Posthumus, Deeks, Rickson, & Quinton, 2015), increasing nutrient leaching and greenhouse gas emissions (Oertel, Matschullat, Zurba, Zimmermann, & Erasmi, 2016), hence the encouragement to use cover crops as part of a sustainable rotation. However, proof that cover crops provide these ecosystem benefits for farming systems in the UK particularly on heavy clay soils is needed, particularly to the farming community at the field scale.

Cover crops are grown as one way to build resilience into the soils system and are utilized to fulfill at least one of the following four objectives: (a) to improve soil fertility, (b) to benefit soil structure, (c) to reduce weed or pest populations, and (d) to provide other ecosystem services for the general environment (White et al., 2016). For example, ecosystem services provided by cover crops could include reduced leaching of nitrate and movement of soil to watercourses (Dabney et al., 2001; Gabriel, Garrido, & Quemada, 2013); increasing overwintering habitat provision (White et al., 2016); and increasing biodiversity on the farm (Bedano et al., 2016). In relation to current UK government policy and the benefits cover crops can provide, this could lead to paying farmers "public money for public goods" that will enhance the environment, rather than agricultural payments based on land area (DEFRA, 2018). The extent to which different cover crops meet these objectives is dependent on the cover crop species which can be grouped into one of four general categories—grasses and/or cereals, brassicas, legumes, and "other"—plant species not part of the rotation (White et al., 2016).

Cereals and grasses include oats (*Avena sativa*), rye (*Secale cereale*), and ryegrass (*Lolium perenne*), which generally produce more biomass (ground cover and rooting system) than other cover crop types (Maltais-Landry, Scow, & Brennan, 2014). Brassicas, such as radish (*Raphanus sativus*), mustards, and turnips, also provide a good ground cover and have been found to reduce nitrate leaching due to the deep rooting system which is able to scavenge more nutrients from depth (Cooper et al., 2017). Legumes, including vetch (*Vicia* *sativa*), crimson and berseem clover (*Trifolium incarnatum*; *T. alexandrinum*), and lucerne (*Medicago sativa*), fix nitrogen from the atmosphere and have been found to improve litter quality (due to their lower C:N ratios) (Frasier, Quiroga, & Noellemeyer, 2016) leading to increases in soil organism biodiversity (Crotty, Fychan, Scullion, Sanderson, & Marley, 2015) and mineralization (Frasier et al., 2016). While "other" cover crops include plants like buckwheat (*Fagopyrum esculentum*) and phacelia (*Phacelia tanacetifolia*), these are from different plant families taxonomically to other crops in a normal arable rotation and can therefore provide a disease break as well as other benefits. Buckwheat is very susceptible to cold temperatures and frost (Welch, Behnke, Davis, Masiunas, & Villamil, 2016). However, due to buckwheat's' deep penetrating root system, it can assimilate insoluble phosphorus (P) compounds lying deep within the soil profile and enrich the upper horizons for future crops (Masilionyte et al., 2017). Phacelia has been found to be effective at reducing soil waterlogging and nitrate leaching (Wyland et al., 1996), increasing P uptake in the following crop, and P concentrations within the soil itself (Eichler-Löbermann, Köhne, Kowalski, & Schnug, 2008).

Despite a number of studies on cover crops in recent years, few have focused their research on heavy clay soils, which are widespread in arable areas of the UK, but constrain timing of field operations, leading to reductions in available time for cover crop growth, therefore limiting the benefits arising from cover crops. For example, it is more difficult to achieve good seed to soil contact on heavy clay soils, thereby reducing establishment options (White et al., 2016), while adoption is sometimes limited due to a lack of environmental education, awareness, and a reluctance to change (Sastre, Barbero-Sierra, Bienes, Marques, & García-Díaz, 2017). However, improving soil structure, soil biology, and overall soil health is vital to maintain sustainability in arable systems.

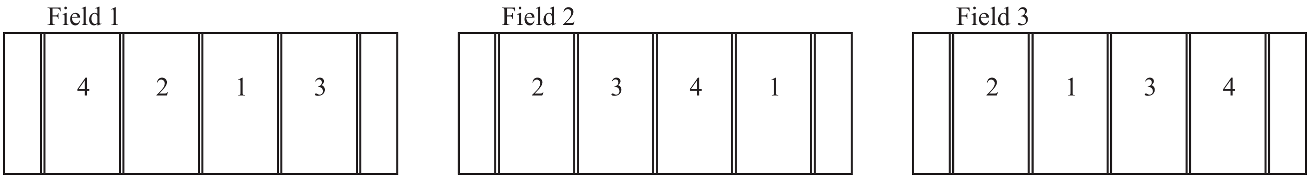
Here, we compare three cover crop mixes, which are commonly sold to UK farmers, with a bare stubble control (no cover crop) and assessed how soil chemistry, physics, and biology were affected by the different cover crops, along with weed biomass and the subsequent cash crop yield. We hypothesize that all cover crops will show a benefit (in soil structure, biology, weed abundance, and crop yields) in comparison with the bare stubble. We hypothesize that the most diverse cover crop mix will have the greatest effect, as it is made up of components from all four cover crop categories (White et al., 2016) in comparison with the other mixes which only have components from two or three categories. The mixtures used within this experiment are sold through seed companies either to meet ecological focus area (EFA) greening requirements (a mix with at least one cereal and one noncereal plant species, e.g., oats and phacelia); or to improve the soil habitat while also meeting EFA requirements, for example, as a soil structure building mix (oats, rye, phacelia, and radish) or as a biodiversity increasing mix (oats, phacelia, radish, legumes, and buckwheat); but whether these mixtures do improve soil structure or increase biodiversity has yet to be shown. The investigation will also consider whether cover crops are an economically viable option on a heavy clay soil in a temperate climate.

2 | MATERIALS AND METHODS

2.1 | Experimental site, plot establishment, and maintenance

The experimental area was set up in September 2015 at the Allerton Project—a 300 hectare mixed arable and livestock Research, Demonstration and Education Farm (Game & Wildlife Conservation Trust), in Loddington, Leicestershire, UK (N 052°36′53″ W 00°50′31″; 186 m a.s.l). The Allerton Project historically had a wheat–rape rotation with a "break" spring crop. Over the last ten years, there has been a reduction in cultivation, going from a plow-based system to direct drilling. Soils are predominantly a heavy clay loam, from the Denchworth series (Hodgson, 1997): texture 45% clay, 35% silt, and 20% sand. Winter wheat was harvested across three fields (totaling an area of ~20 hectares) on 7 September 2015 using a combine harvester ("CR9080," New Holland), following standard procedures (DEFRA, 2010). Four different cover crop mixes were established on 8 September 2015, in large "field-scale plots" (covering an area of nearly 20 hectares), replicated across three fields in a randomized block design (Figure 1). Each plot was 24 meters wide and up to 200 meters long, set out between the tramlines within each field. Each mixture was sown over an area of around a half hectare per field. During the cover crop period (September 2015–March 2016), 389 mm of rainfall was recorded, just over half the long-term annual average (664 mm [1961–1990, based on the Standard Average Annual Rainfall (SAAR) 1-km grid dataset from the Met Office]) and nearly 100 mm more than the 10 year average for the same location and time period (Figure 2). Weather data recorded on site (Figure 2) indicated that over the experimental period, December, March, and June were very wet months and overall temperatures were warmer than average (Met Office, 2018).

The four cover crop mixes were planted at the manufacturer's recommended seed rates for mixtures (Figure 1) using a direct drill ("Eco M," Dale Drills), rolled with a segmented ridged roller (Cambridge rolled) to flatten land, with no fertilizer applied at this stage. Cover crop mixes were either C + P—oats (*Avena sativa*) and phacelia (*Phacelia tanacetifolia*) (EFA Greening mix); C + P + R—oats, rye (*Secale cereale*), phacelia, and radish (*Raphanus sativus*) (Soil Structure mix); C + P + R + L—oats, phacelia, radish, buckwheat (*Fagopyrum esculentum*) and the legumes, vetch (*Vicia sativa*), crimson clover (*Trifolium incarnatum*), and berseem



Three fields split into four treatments, in a randomised block design
Measurements taken in duplicate from each rep ($n = 6$)
Each plot 24 m wide and around 200m long
Mix name refers to C - cereal; P - Phacelia; R - radish; L - legume

Mix	Mix name	Plant species vs. (variety) with seed rate	Cost (£/ha)
1	C+P	Oats vs. Mascani (50 kg/ha) + Phacelia vs. Angelia (1.5 kg/ha)	13.15
2	C+P+R	Oats vs. Mascani (12.5 kg/ha) + Rye vs. Protector (6.25 kg/ha) + Phacelia vs. Angelia (0.4 kg/ha) + Oil Radish vs. Baracuda (3.35 kg/ha) + Tillage Radish vs. Early Mino (2.5 kg/ha)	37.80
3	C+P+R+L	Oats vs. Mascani (11 kg/ha) + Phacelia vs. Angelia (1 kg/ha) + Oil Radish (6 kg/ha) + Vetch vs. Alexandros (2.5 kg/ha) + Crimson Clover vs. Cicero (0.5 kg/ha) + Berseem Clover (1.5 kg/ha) + Buckwheat (2.5 kg/ha)	34.00
4	Control	Bare stubble – no cover	0.00

FIGURE 1 Field-scale cover crop experiment layout—three fields located within 500 m of each other, at the Allerton Project (N 052°36′53″ W 00°50′31″). Four treatments sown in a randomized block design, each plot is 24 m wide (between tramlines) and up to 200 m long

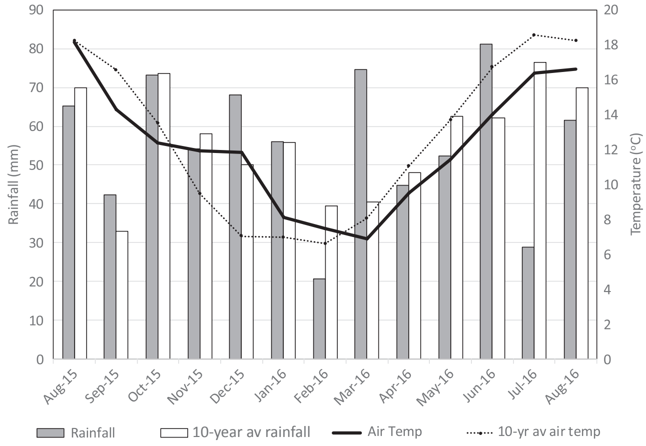


FIGURE 2 Loddington average monthly temperature (°C) and total rainfall (mm) per month from harvest 2015 to harvest 2016, including 10-year average for Loddington monthly temperature (°C) and total rainfall (mm)

clover (*T. alexandrinum*) (Biodiversity mix); or a "no cover" control that was left as bare stubble (there was no herbicide applied, so natural regeneration did occur). The cover crops were left undisturbed to grow over the autumn and winter before all cover crops were terminated on 5 April 2016 with 360 g/L glyphosate at 3.5 L/ha (Azural, Monsanto) and more applied 28 April 2016 at 1.5 L/ha allowing the cover crops (and weeds) to die back, prior to planting the spring oats.

Spring oats (*A. sativa vr. Canyon*, Frontier Agriculture) were sown on 20 April 2016 using an "Eco M" direct drill and rolled; diammonium phosphate fertilizer was applied on 30 April 2016 at a rate of 87.2 kg/ha (15.7 kg N, 40.1 kg P_2O_5/ha), and ammonium nitrate fertilizer was applied on 13 May and 25 May 2016 at rates of 130 and 116 kg/ha (YaraBela, Prilled N, 34.5% N, Yara), respectively, as per standard practice in UK agriculture following government guidelines (DEFRA, 2010). Growth regulators, herbicides, and fungicides were applied as standard practice and included two foliar applications of cyproconazole (Centaur, Bayer CropScience Ltd) on 28 May and 11 June. The broadleaved weed herbicides, 200 g/L fluroxypyr at 0.72 L/ha (Hurler, Barclay Ltd) and 200 g/kg metsulfuron-methyl at 28.8 g/ha (Jublilee, Dupont), were applied on 23 June 2016; and 360 g/L glyphosate at 3 L/ha (Azural, Monsanto) on 14 August 2016, to desiccate the oats ready for harvest, consistent with standard practice in UK agriculture. Spring oats were harvested on 2 September 2016, using a combine harvester and the grain and straw removed; yield data were recorded from the "Intelliview IV Display" ("CR9080," New Holland; ±10 kg accuracy) on board sensor within the combine at time of harvest for the individual replicates ($n = 6$). Economic impacts were also assessed calculating the gross margin and net margin in relation to yield. Gross margin equates to yield multiplied by oat grain sale price (£122 per tonne; Defra, 2017) minus variable costs (including tractor diesel costs, fertilizer, and pesticides; £223.57 per ha). Net margin equates to gross margin minus cultivation cost (cover crop seed cost (Figure 1), cover crop drilling and rolling, termination, and drilling and rolling spring oats).

2.2 | Soil chemical and physical composition

All measurements described herewith (for chemistry, physics, and biology analyses) were carried out throughout February 2016, thus allowing five months of plant growth/residency and was prior to them being destroyed by herbicide application.

2.3 | Soil chemistry

Soil samples were taken of the top 0–10 cm soil depth in a W-formation across each replicate plot and bulked keeping each plot separate; samples were stored at 4°C in the dark prior to analysis. All bulked soil samples were roughly broken up and homogenized by hand, before being subsampled for multiple analytical procedures, including organic matter content, pH, and mineral analysis (P, K, Mg). Organic matter content was determined by loss on ignition (Schulte & Hopkins, 1996), where dried samples were subsequently heated in a furnace at 360°C for 16 hr and reweighed. Soil pH was determined after mixing 10 g of soil with deionized water to make a slurry, prior to measurement with a pH probe. Mineral soil analysis (phosphorus [P], potassium [K], and magnesium [Mg]) and soil N being determined as nitrate (NO_3-N) and ammonium (NH_4-N) followed the methods described in Crotty et al. (2014). Briefly, soil P was determined as bicarbonate extractable (Olsen) P and 0.01 M $CaCl_2$ extractable P while the other minerals were extracted from the soil using acetic acid and measured using atomic absorption spectroscopy. Ammonium-N and nitrate-N were extracted using a 2 M KCl solution and available N calculated. Nitrate was determined by a reduction of nitrate to nitrite using a cadmium column followed by colorimetric measurement at 520 nm. Ammonium-N was determined colorimetrically at 660 nm. Soil N was determined for the 0–30 cm soil depth.

2.4 | Soil physics

To determine soil structure, bulk density, moisture content, and porosity were assessed. Bulk density was determined from intact soil cores (diameter 60mm, height 53mm; $n = 6$) collected at a depth of 0–10 cm, using a steel corer of known volume. The corer was forced into the soil and then soil and corer removed, and soil was trimmed with a knife to the corer length. Cores were weighed fresh and reweighed after oven-drying at 105°C for 48 hr. Soil moisture content and bulk density were calculated from measurements of the sample volume and dry weight (Carter & Gregorich, 2008). Soil porosity was also calculated from the bulk density results, using a particle density value of 2.7 g/cm^3. Soil compaction was assessed across each plot by taking 20 random point measurements across the center of each plot, using a soil compaction meter (Fieldscout SC900, Spectrum Technologies). The penetration resistance (kPa) was measured at 2.5-cm intervals down to 45 cm. The measurements for each plot and treatment were averaged ($n = 60$), and the KPa for each of the different soil layers was compared between treatments.

2.5 | Soil biology

The abundance of key functional groups in the soil food web, including earthworms and mesofauna, was quantified. Two soil cores were taken from random points within each plot for each of the faunal groups in February 2016 ($n = 6$).

2.6 | Earthworm population assessment

Earthworm abundance (per m^2), biomass (g/m^2), and diversity were quantified following Crotty et al. (2015). Briefly, a square of soil (20 cm by 20 cm) excavated to a depth of 20 cm, two per plot ($n = 6$) and taken from the field to the laboratory to be hand-sorted and identified. To ensure deep-burrowing earthworms were also counted, after excavation, mustard solution (10 g Colman's® mustard powder in 1 L of water) was added to the pit to expel any earthworms located below, and these were removed, washed, and added to the respective sample. Live earthworms were sorted into adults and juveniles, and identified to species using the taxonomic key by Sherlock (2012) and functional groups following Roarty, Hackett, and Schmidt (2017). Other macrofauna abundance and diversity were also quantified from the soil block taken for earthworm sampling as per Crotty et al. (2016) ($n = 6$), with macrofauna found identified to order and counted per block. This included centipedes, millipedes, beetles (adults and larva), fly larva, spiders, woodlice, slugs, and snails. This method follows a modified version of Bohan et al. (2000), allowing an absolute local density of slugs (and other macrofauna) to be quantified and has few of the problems of bait/pitfall trapping.

2.7 | Mesofauna sampling

Mesofauna was sampled from two intact soil cores (6 cm diameter, 7 cm depth) collected randomly from each plot ($n = 6$) and placed upside down on a Tullgren funnel for extraction over seven days. Due to the temperature gradient created by the suspended light bulb, invertebrates migrate through each core and are collected in 70% alcohol in a collecting jar beneath the funnel, prior to counting and identification (Crotty, Adl, Blackshaw, & Murray, 2012).

2.8 | Sward composition cover crops, spring oats, and spring oat yields

Sward compositions and biomass were assessed during the spring prior to the cover crops being destroyed (February 2016) and in the summer prior to the spring oats being harvested (June 2016). The composition was assessed by manually harvesting the plant material, cutting to ground level, from two randomly placed 50 cm^2 quadrats per plot ($n = 6$), and hand-sorting into different plant species. The fresh plant material was separated into sown (cover crop or spring oat) and unsown species (broad-leaf weeds and weed grasses), the separated material was dried (105°C for 24 hr), and the composition of sward was calculated on a dry matter per m^2 basis. Spring oat yield data were recorded from the "Intelliview IV Display" on board sensor within the combine at time of harvest for the individual replicates ($n = 6$).

2.9 | Statistical analysis

Analysis of variance (ANOVA) was used to assess differences between treatments. All data (collected in a randomized block design) were analyzed in GenStat® (Payne, Murray, Harding, Baird, & Soutar, 2014). Data were verified for normality and homoscedasticity prior to analysis and transformation applied (log10 + 1) if necessary. When $p < 0.05$, multiple comparisons were made using the Tukey HSD post hoc test. Multivariate analysis of variance (MANOVA) was performed to assess differences between treatments and multiple variables (grouped as biology, chemistry, and botanical composition). Canonical variate analysis was used to illustrate MANOVA results and to differentiate the cover crop mixtures (canonical variate means) based on the environmental parameters (canonical latent vector loadings). Simpson's index of diversity (1-D, Equation 1 below) was used to measure community composition of earthworm species diversity and mesofauna (separately). Equation 1 was used to calculate 1-D, where N is the total number of organisms of all species (s) within each treatment and the number of organisms (n_i) of each species (i). The results of which were analyzed by ANOVA.

$$1-\sum_{i=1}^{s} n_i\left(n_i-1\right)\Big/N\left(N-1\right) \tag{1}$$

3 | RESULTS

3.1 | Soil chemistry

Comparisons of soil chemistry across the different cover crop treatments and bare stubble control, after autumn and winter growth but prior to termination, showed that there was very little variability across treatments or fields (Table 1 for treatment averages) over all averages: P 18.1 (±0.5) mg/L; K 184.3 (±6.9) mg/L; or available N 15.3 (±1.02) mg/L, in the top soil layer. However, the concentration of Mg did differ between treatments ($p = 0.042$), with lower concentration in the C + P + R + L treatment in comparison with the control and C + P treatments (C + P + R intermediate). NO_3 was numerically higher in the C + P + R + L treatment ($p = 0.073$) and also available N in comparison with the other treatments (Table 1) although not statistically significant. The pH and organic matter content did not differ between treatments (over all averages: pH 7.3 (±0.06); OM% 3.4 (±0.23) Table 1 for treatment averages). However, combining all data variables (P, K, Mg, NO3, OM% pH, and bulk density) and

TABLE 1 Soil chemical and physical parameters under the different cover crop treatments (C + P [oats and phacelia], C + P + R [oats, phacelia, and radish], C + P + R + L [oats, phacelia, radish, and legumes], and bare stubble control). Analysis of results using ANOVA with Tukey HSD superscript letters to signify $p < 0.05$ differences between cover crop treatments. For full treatment details, see Figure 1

Measure	Depth	C + P	C + P + R	C + P + R + L	Control	*P*-value
NO_3 (mg/L)	0–30cm	9.5^a (±2.03)	10.1^a (±1.89)	12.1^b (±1.96)	10.7^{ab} (±1.77)	**0.073**
NH_4 (mg/L)	0–30cm	4.6 (±0.18)	4.6 (±0.84)	4.6 (±0.80)	4.9 (±0.25)	0.980
Available N (mg/L)	0–30cm	14.1 (±2.16)	14.7 (±2.57)	16.7 (±2.39)	15.6 (±2.02)	0.173
P (mg/L)	0–10cm	18.3 (±1.33)	17.3 (±1.33)	17.7 (±1.20)	19.0 (±0.00)	0.349
K (mg/L)	0–10cm	184.7 (±11.72)	190.3 (±18.68)	177.7 (±15.06)	184.7 (±17.46)	0.884
Mg (mg/L)	0–10cm	99.0^b (±11.53)	93.3^{ab} (±10.09)	88.0^a (±7.77)	98.7^b (±8.41)	**0.042**
pH	0–10cm	7.55 (±0.062)	7.27 (±0.104)	7.11 (±0.078)	7.28 (±0.121)	0.115
Organic matter (%)	0–10cm	3.43 (±0.528)	3.20 (±0.481)	3.41 (±0.590)	3.62 (±0.538)	0.108
Bulk density (g/cm^3)	0–10cm	1.10 (±0.049)	1.06 (±0.051)	1.06 (±0.050)	1.04 (±0.032)	0.549
Soil moisture (%)	0–10cm	43.9 (±2.08)	43.5 (±2.73)	42.7 (±2.91)	45.5 (±2.04)	0.658
Soil porosity (%)	0–10cm	59.3 (±1.81)	60.8 (±1.88)	60.6 (±1.84)	61.7 (±1.19)	0.565

Note: Bold indicates a significant difference between treatments.

analyzing (MANOVA) showed significant differences between treatments ($p < 0.001$), suggesting the different variables are more meaningful analyzed together than when considered separately (see Section 3.7).

3.2 | Soil physics

Bulk density, soil porosity, and soil moisture content did not differ among treatments ($p > 0.05$; Table 1). There was no difference in soil penetration resistance in the top 0–2.5 cm among treatments, but significantly increased resistance was found in the three cover cropped treatments compared to the bare stubble control between 5 and 12.5 cm soil layers (Figure 3). After 12.5 cm soil layer, there was no statistical difference between the control and the three cover crop treatments. Also after 22.5 cm, the control did not have the least soil compaction (as indicated by having higher soil penetration resistance measurements) and there were no significant differences between treatments.

3.3 | Soil biology

Assessing soil biology data together (mesofauna [Collembola, mites, and other mesofauna] and macrofauna [epigeic earthworms, endogeic earthworms, anecic earthworms, centipedes, and millipedes] through MANOVA showed significant differences between treatments ($p < 0.001$), showing there are differences between these independent groups dependent on cover crop treatment (see Section 3.7).

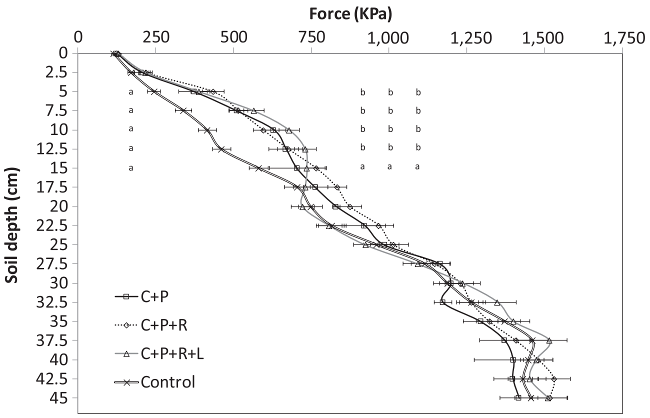


FIGURE 3 Soil penetration resistance measurements (average ± *SE*, $n = 60$). The results of soil penetration resistance (KPa) measurements among treatments (C + P [oats and phacelia], C + P + R [oats, phacelia, and radish], C + P + R + L [oats, phacelia, radish, and legumes], and bare stubble control) from depths 0–45 cm (for full treatment details, see Figure 1). Significant differences ($p < 0.005$) according to the Tukey HSD post hoc test indicated by different letters in the soil layers, where no letters are indicated the analysis of variance results were not significant

3.4 | Earthworm community composition

Overall, 740 (±65) earthworms per m^2 were found across all treatments—this was much higher than expected for arable soils (the benchmark of a healthy soil being above 400 per m^2 [van Groenigen et al., 2014]). No differences were found in total abundance of earthworms or biomass across treatments (Table 2). However, there were significant differences within the community assemblage assessed for the three earthworm functional groups. Epigeic earthworms had significantly higher abundances ($p = 0.010$) in both C + P + R and C + P + R + L treatments in comparison with C + P, with the control having intermediate abundances (Table 2). The abundances of endogeic and anecic earthworms did not differ between treatments though ($p = 0.892$ and $p = 0.495$, respectively) (Table 2). The same pattern was found for biomass of the three earthworm functional groups—with epigeics being significantly heavier ($p = 0.003$) in the C + P + R + L cover crop treatment compared to C + P and the control (Table 2), while in the C + P + R cover crop, epigeic earthworms were only heavier than C + P (with the control intermediate). The biomass of endogeics and anecics did not differ between treatments ($p = 0.716$ and $p = 0.571$, respectively; Table 2).

Around 30% of the earthworms extracted were adult specimens, from which eight earthworm species were identified. The most commonly found were the endogeic species *Aporrectodea caliginosa* and *Murchieona muldali*, as well as the epigeic species *Lumbricus rubellus* (Table 2). Both *L. rubellus* and *A. caliginosa* were found to be significantly affected by the different cover crop treatments (Table 2). *L. rubellus* (epigeic) had higher abundances in the two radish treatments in comparison with the C + P and the control treatment. While *A. caliginosa* (endogeic) had higher abundances in C + P + R only, with significantly lower abundances in the C + P + R + L and control treatments (C + P intermediate). Analyzing the earthworm species composition with Simpson's index of diversity, significant differences were found between treatments—with the C + P + R treatment having a greater diversity of species compared to the control (bare stubble) (Table 2). Assessments of the macroarthropods also collected during earthworm sampling found there to be a higher abundance of millipedes in the C + P + R treatment in comparison with the C + P and C + P + R + L treatments (with the control intermediate) (Table 2); beetles were also numerically greater in the C + P + R + L treatment ($p = 0.084$; Table 2). Slugs and snail abundance did not differ between treatments ($p = 0.434$; Table 2).

3.5 | Mesofauna community composition

An average of 37,600 (±5,000) mesofauna per m^2 was extracted across all treatments; over 73% were mites and 22% Collembola, while the other 5% were identified as "other"

TABLE 2 Overall abundance of earthworms and other macrofauna in relation to the different cover crop treatments (C + P [oats and phacelia], C + P + R [oats, phacelia, and radish], C + P + R + L [oats, phacelia, radish, and legumes], and bare stubble control; mean ± standard error [$n = 6$] individuals per m^2 unless otherwise stated) and ANOVA results ($df_{3,15}$ for all results; VR is variance ratio; $: too many zeros for statistical analysis). Significant differences ($p < 0.05$) according to the Tukey HSD test are indicated by different letters. For full treatment details, see Figure 1

Measure	C + P	C + P + R	C + P + R + L	Control	VR	*P*-value
Earthworm abundance	688 (±115.6)	829 (±157.4)	725 (±126.5)	721 (±142.5)	0.24	0.870
Epigeic abundance	13^{a} (±8.5)	133^{b} (±59.4)	113^{b} (±29.4)	42^{ab} (±19.0)	5.38	**0.010**
Endogeic abundance	596 (±108.3)	621 (±107.7)	525 (±105.3)	625 (±129.9)	0.20	0.892
Anecic abundance	54 (±16.4)	38 (±10.7)	50 (±11.2)	38 (±15.5)	0.83	0.495
Earthworm biomass (g m^2)	106 (±30.7)	112 (±19.4)	104 (±12.4)	98 (±22.6)	0.09	0.963
Epigeic biomass (g m^2)	3^{a} (±2.4)	19^{bc} (±9.2)	20^{c} (±3.9)	5^{ab} (±2.3)	7.21	**0.003**
Endogeic biomass (g m^2)	43 (±7.1)	52 (±8.7)	39 (±6.0)	46 (±11.7)	0.46	0.716
Anecic biomass (g m^2)	58 (±27.4)	31 (±11.7)	39 (±9.4)	47 (±20.1)	0.69	0.571
Simpson's Index of diversity: Earthworm species (1-D)	0.4^{ab} (±0.05)	0.6^{b} (±0.05)	0.6^{ab} (±0.05)	0.3^{a} (±0.11)	4.07	**0.027**
Lumbricus castaneus (epigeic)	8 (±5.3)	25 (±15.8)	17 (±8.3)	13 (±8.5)	0.39	0.761
Lumbricus rubellus (epigeic)	4^{a} (±4.2)	83^{b} (±55.4)	67^{b} (±27.1)	13^{a} (±8.5)	4.15	**0.025**
Allolobophora chlorotica (endogeic)	8 (±5.3)	21 (±11.9)	13 (±5.6)	8 (±8.3)	0.42	0.742
Aporrectodea caliginosa (endogeic)	25^{ab} (±20.4)	42^{b} (±5.3)	8^{a} (±5.3)	8^{a} (±8.3)	3.33	**0.048**
Murchieona muldali (endogeic)	133 (±22.0)	96 (±26.9)	96 (±23.6)	133 (±43.6)	0.52	0.674
Aporrectodea rosea (endogeic)	8 (±5.3)	4 (±4.2)	4 (±4.2)	8 (±5.3)	–	$
Satchellium mammalis (endogeic)	0	0	(±8.3)	0	–	$
Aporrectodea longa (anecic)	4 (±4.2)	4 (±4.2)	8 (±5.3)	8 (±8.3)	–	$
Epigeic immatures	0	25 (±12.9)	21 (±11.9)	17 (±10.5)	1.44	0.271
Endogeic immatures	421 (±92.1)	458 (±88.4)	404 (±109.8)	467 (±92.3)	0.13	0.940
Anecic immatures	50 (±15.8)	33 (±10.5)	42 (±8.3)	29 (±10.0)	1.45	0.267
Other macrofauna (all)	196 (±52.6)	204 (±63.1)	175 (±61.6)	196 (±34.4)	0.11	0.956
Slugs and snails	54 (±18.7)	58 (±24.7)	21 (±4.2)	33 (±12.4)	0.97	0.434
Coleoptera (all)	25 (±11.2)	50 (±17.1)	113 (±39.1)	75 (±21.4)	2.69	0.084
Millipedes (*Julidae* & *Polydesmidae*)	8^{a} (±8.3)	58^{b} (±20.1)	8^{a} (±8.3)	25^{ab} (±11.2)	3.47	**0.043**
Centipedes (*Geophilomorpha & Lithobiomorpha*	0	21 (±16.4)	13 (±12.5)	25 (±20.4)	–	$

Note: Bold indicates a significant difference between treatments.

mesofauna (including Coleoptera, Diptera, and centipedes). Total mesofauna abundance, total Collembola (and collembolan superfamilies), and total mites (and the main mite lineages) did not differ in abundance among treatments (Table 3). However, there were differences found in the "other" mesofauna ($p = 0.044$), with higher abundances in the C + P and C + P + R + L treatments in comparison with the C + P + R treatment (with the control intermediate) (Table 3). This is mainly due to the abundances of Diptera found within the C + P treatment, which when analyzed separately was also significantly higher ($p = 0.010$) than the C + P + R and control treatments (C + P + R + L was intermediate) (Table 3). Simpson's Index of diversity was found not to differ between treatments for mesofauna.

3.6 | Sward composition

In February, sown cover crop dry matter did not differ among the three cover crop treatments ($p = 0.119$). Although the proportion of the individual plant species did differ with significantly more cereal (oats) biomass in the C + P treatment compared to the other two mixes ($p < 0.001$), with C + P + R treatment having significantly more cereal (oats and rye) biomass than the C + P + R + L treatment, phacelia biomass did not differ between the three cover crop mixes ($p = 0.102$). There were significant differences in the amount of weed dry weight per m^2 harvested ($p = 0.001$) (Figure 4a); the majority was grass weed. The highest biomass of weeds was found in the control (bare stubble) treatment, which showed a large amount of natural regeneration, with significantly greater weed biomass compared to all the cover crop treatments; with the C + P + R treatment having significantly less weed biomass than the C + P + R + L treatment, and with C + P intermediate, Figure 4a (Tukey HSD letters).

In June, spring oats had been growing for 8 weeks, when plant composition assessments were made. Spring oat dry matter yields differed among the cover crop treatments ($p = 0.001$) (Figure 4b), with higher yields in both of the previously radish treatments (C + P + R and C + P + R + L) in comparison with the control (C + P intermediate to C + P + R + L). There were also significant differences in the amount of grass weed biomass ($p = 0.048$), with higher grass weed dry matter yields in the control treatment in comparison with the C + P + R + L treatment (the other two were intermediate) (Figure 4b). Broad-leaved weed biomass did not differ between treatments ($p = 0.619$; data not shown) although ranged from 5% to 35% of total weed biomass. In September when the spring oats were harvested, grain weight (at 15% moisture content) was found to differ significantly between treatments ($p = 0.018$), with around 1.5 tonnes per hectare greater yield in the most biodiverse treatment (C + P + R + L) compared to the control treatment (with the other two cover crop mixtures intermediate; Figure 4c). Economic impacts of the different cover crops did differ in relation to gross margin ($p = 0.020$) but not net margin ($p = 0.117$); the C + P + R + L treatment equated to £285.13 (±58.47) per hectare gross margin (£146.13 net) compared to C + P + R £207.67 (±38.27) (net £64.87), C + P £114.45 (±29.56) (net £17.06), and £98.63 (±28.84) (net £42.63) for the control.

3.7 | Multivariate analysis

Cover crop mixtures were examined in relation to soil biology, chemistry, physics, and botanical parameters using a canonical variate analysis, which explained 89.2% of the total variance (Figure 5), axis one 58.9% variation and axis two 30.3% variation. The cover crop treatments separated distinctly (canonical variate means) by abiotic variables (pH, NO_3, P, and bulk density), which explained most of the total variation (canonical latent vector loadings), with the biotic variables (mesofauna, macrofauna, and botanical composition) explaining little. However, when combining all data variables as either soil biology, chemistry, or botanical composition and analyzing (MANOVA) showed significant differences between treatments ($p < 0.001$) for each group, MANOVA takes into account the intercorrelation between the variables.

4 | DISCUSSION

Sustainable soil management is key to conserving ecosystem services while having resilient and economically

TABLE 3 Overall abundance of mesofauna in relation to the different cover crop treatments (C + P [oats and phacelia], C + P + R [oats, phacelia, and radish], C + P + R + L [oats, phacelia, radish, and legumes], and bare stubble control; mean ± *SE*) and ANOVA results ($df_{3,15}$ for all results; VR is variance ratio; \$: too many zeros for statistical analysis), most abundant groups only (found in more than five samples [$n = 24$]). Significant differences ($p < 0.05$) according to the Tukey HSD test are indicated by different letters. For full treatment details, see Figure 1

Measure	C + P	C + P + R	C + P + R + L	Control	VR	*P*-value
Total mesofauna	33,743 (±8,694)	28,341(±6,388)	39,397(±15,768)	49,246 (±9,145)	0.72	0.555
Total Collembola	9,961 (±4,551)	5,612 (±1,528)	5,893 (±3,215)	10,873 (±3,274)	0.58	0.637
Entomobryomorpha	8,909 (±4,379)	5,051 (±1,510)	5,135 (±3,257)	9,751 (±3,167)	0.69	0.572
Poduromorpha	281 (±140.3)	140 (±88.7)	337 (±224.0)	210 (±143.8)	0.20	0.895
Symphypleona	772 (±690.9)	421 (±153.7)	421 (±121.5)	912 (±412.6)	0.29	0.833
Total Mites	21,326 (±6,806)	21,817 (±6,554)	31,231 (±12,486)	36,549 (±7,080)	0.75	0.543
Astigmata	1,964 (±860)	3,718 (±1,415)	4,377 (±1,606)	5,121 (±1,527)	1.00	0.420
Mesostigmata	842 (±217.4)	421 (±266.2)	926 (±658.8)	912 (±453.5)	0.48	0.702
Oribatida	1,613 (±716)	2,666 (±1,307)	3,872 (±2,500)	2,105 (±941)	0.30	0.827
Prostigmata	16,906 (±5,839)	15,012 (±4,679)	22,055 (±8,299)	28,411 (±5,343)	1.16	0.361
Total other mesofauna	2,455^{b} (±201)	912^{a} (±427)	2,273^{b} (±335)	1,824^{ab} (±335)	3.51	**0.044**
Coleoptera (larvae and adults)	210 (±143.8)	–	168 (±94.1)	210 (±94.1)	–	\$
Diptera (larvae and adults)	1,333^{b} (±200.9)	281^{a} (±88.7)	1,010^{ab} (±260.6)	491^{a} (±168.9)	5.54	**0.010**
Centipedes	-	140 (±88.7)	168 (±153.7)	210 (±94.1)	–	\$
Enchytraeid worms	772 (±275.3)	421 (±343.7)	758 (±372.5)	421 (±343.7)	0.69	0.573
Simpson's Index of diversity: all mesofauna	0.46 (±0.097)	0.21 (±0.101)	0.33 (±0.141)	0.53 (±0.066)	0.18	0.909

Note: Bold indicates a significant difference between treatments.

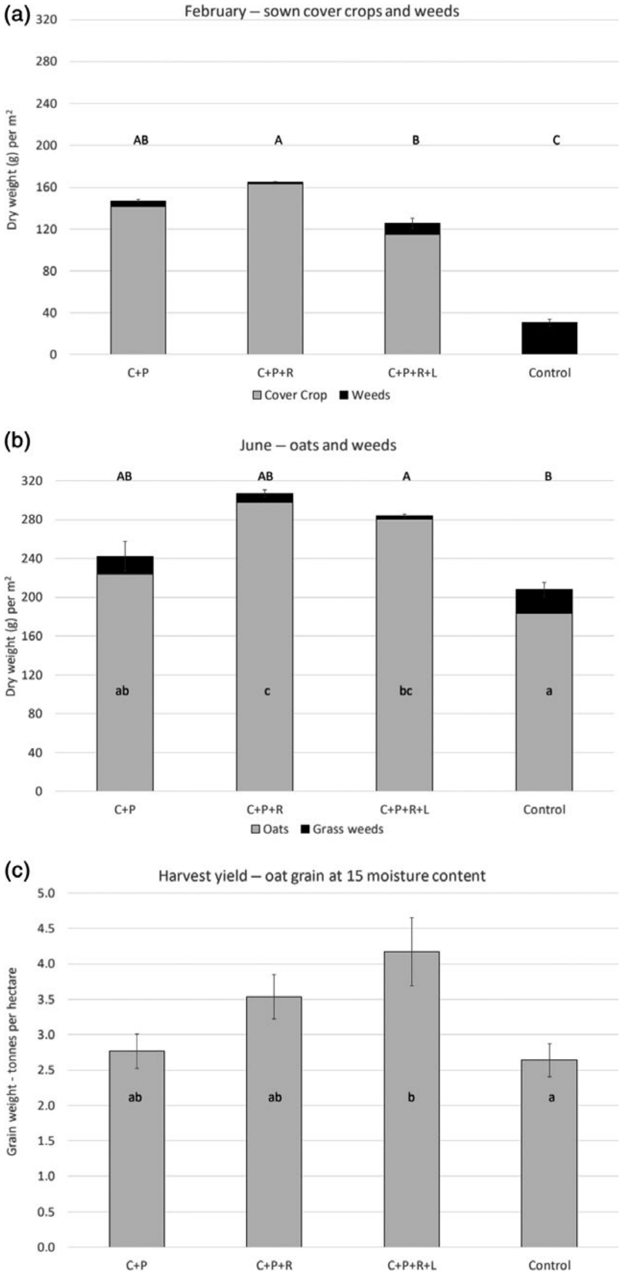


FIGURE 4 Plant composition assessments (a) February—sown cover crop biomass ($p = 0.119$) and weed biomass ($p = 0.001$) (dry weight per m^2); (b) June—oat biomass ($p = 0.001$) and weed biomass ($p = 0.048$) (dry weight per m^2); and (c) Harvest yields—oat grain at 15% moisture content ($p = 0.001$) (tonnes per hectare). Where significant differences ($p < 0.05$) were found between treatment (C + P (oats and phacelia), C + P + R (oats, phacelia, and radish), C + P + R + L (oats, phacelia, radish, and legumes), and bare stubble control), the Tukey HSD post hoc test was used, indicated by different letters (CAPITALS for significance in weed data; lowercase for significance in sown data). For full treatment details, see Figure 1

productive agricultural systems (Kibblewhite, Ritz, & Swift, 2008). Cover crops are often promoted as a possible way to improve the sustainability of cropping systems (Lehman et al., 2015). The aim of this experiment was to recreate standard farm practice while measuring the effect of a selection of cover crops on the overall soil health (chemistry, physics, and biology) as well as the subsequent crop yield in comparison with a bare stubble control, at the field scale. We hypothesized that the three cover crop treatments would show a benefit in comparison with the bare stubble, with the most diverse cover crop mix having the greatest effect as it contained the greatest range of plant species (from all four of the main groups of cover crops; White et al., 2016). During this field-scale experiment, the measurement of many soil and crop parameters has found that the cover crops did change the soil chemistry, physics, and biology to a certain extent, and had weed suppression effects, contributing to significant differences in the following crop yields, and gross margin although not in net margin. However, margin is the most relevant variable to a farmer interested in utilizing cover crops within their rotation (and £100 more per hectare for the most diverse mix (C + P + R + L) compared to a bare stubble (control) would be considered significant to them, even if it is not statistically significant).

Overall, there was very little variability across treatments or fields for soil nutrients; however, the multivariate analysis showed that when soil chemistry data were combined there were significant differences ($p < 0.001$). Canonical analysis showed these slight differences together were important, distinctly separating the cover crop treatments across both the *x*-axis and the *y*-axis (Figure 5), with pH, NO_3, P, and bulk density having the greatest effect. The larger amount of nitrate in the soil in the C + P + R + L cover crop treatment in comparison with the other cover crops was expected, as nonleguminous cover crops remove NO_3 more effectively from the soil than leguminous cover crops (Kuo & Sainju, 1998). Legumes are also known to increase available soil N through biological nitrogen fixation, hence the larger amounts found in the C + P + R + L treatments. One of the main ecosystem services cover crops provide is to reduce nitrate leaching (Dabney et al., 2001; Gabriel et al., 2013); this is particularly important in nitrate vulnerable zones. The weeds (and volunteers) growing in the bare stubble control treatment may have acted as a nonleguminous cover crop, utilizing excess nitrate within the soil, although it is more likely nitrogen leached out of the soil, due to the high amounts of rainfall in December (Figure 2). Nutrient use inefficiencies can cause environmental pollution through leaching and run-off, as well as the release of greenhouse gases to the atmosphere (Dungait et al., 2012); reducing this overwinter risk is crucial for environmental protection within sustainable agriculture. Mg uptake has been found to be enhanced where nitrate and available N are increased (Mulder, 1956), consistent with the findings here, as the C + P + R + L treatment had both the highest N available and the least Mg

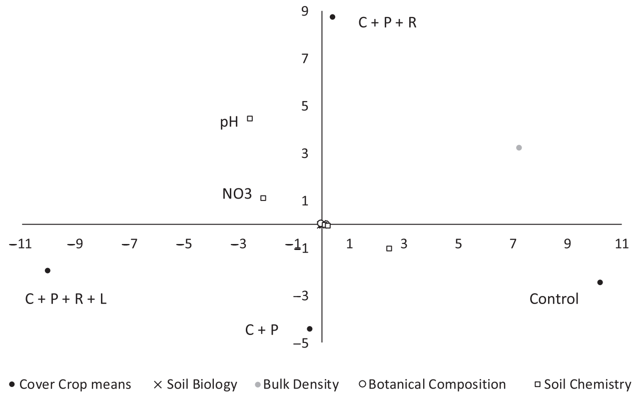


FIGURE 5 Canonical variate analysis to quantify the relationship between the cover crop mixtures (C + P [oats and phacelia], C + P + R [oats, phacelia, and radish], C + P + R + L [oats, phacelia, radish, and legumes], and bare stubble control) and environmental parameters. Soil chemistry parameters (K, P, Mg, NO_3, OM%, and pH), soil physics (bulk density), soil biology (macrofauna—epigeic earthworms, endogeic earthworms, anecic earthworms, centipedes, and millipedes; mesofauna—Collembola, mites, and other mesofauna), and botanical composition (weed biomass—February, grass weed biomass—June, and oat biomass—June) were included. Variables that have the greatest effect have been named on the figure

within the soil (Table 1), compared to the other treatments. A reduction in Mg within the soil has the potential to improve flocculation and therefore soil structure (Rengasamy & Marchuk, 2011), as well as increasing aeration and decreasing soil water content (Gransee & Führs, 2013), all beneficial to crop production in a heavy clay soil in areas with high rainfall. There was also a trend for less K and a slightly lower pH in the C + P + R + L treatment, indicating C + P + R + L has had a greater effect on soil chemistry than the other cover crop mixes.

Winter wheat was harvested in September, and the cover crops were sown using a direct drill. There was minimal soil disturbance during this time as the fields were "no-till"; however, the drilling occurred after a period of heavy rainfall in early September. The earlier a cover crop is sown, the greater amount of growth that can occur before the winter; within this experiment, the wheat was harvested at the earliest opportunity following a wet August (Figure 2). This late harvest and timing of cover crop sowing are indicative of the difficulties of farming in a temperate climate on a heavy clay soil, which has a tendency to become waterlogged. If a soil is waterlogged, there is a greater risk of compaction. There were significant differences between the three cover crop treatments compared to the bare stubble control in resistance to penetration for the 5–12.5 cm of soil depth (Figure 3), with the control having a lower resistance. This difference in penetration is likely due to the movement of the direct drill seeding the three cover crop treatments, after rainfall on heavy clay soils, and should be an important consideration in future experiments performed at the field scale on a working farm (and in real farming practice). The reduction in farm machinery passes across the bare stubble plots in comparison with the cover crop treatments was enough to reduce soil compaction. This is the first time that a difference in penetration resistance can be attributed to just one field movement by farm machinery. However, the limiting penetration resistance for root growth is 3,600 KPa (Ehlers, Kopke, Hesse, & Bohm, 1983) dependent on plant species and soil type, which is more than double all measurements taken across treatments; indicating that although there were differences between treatments, cover crop root growth would not have been detrimentally affected (and neither were the succeeding oat yields). One of the cover crop mixtures (C + P + R) was sold as a "soil structure building" mix, but our results show that there were no differences in soil structure compared to the other mixtures.

Cover crops are grown over the autumn and winter period, so the expected impact on soil biology was small, due to the timescale of the experiment and the seasonality of mesofauna (Olejniczak, 2007) and macrofauna (Eggleton, Inward, Smith, Jones, & Sherlock, 2009) populations. Earthworm abundance was higher than expected for arable fields (with over 700 per m^2 across treatments and fields) and was similar to those normally found in pasture (Chan, 2001), rather than conventional or no-till arable fields in the UK and across Europe (Dinter et al., 2013). Reducing soil disturbance through minimum tillage, cutting straw rather than baling, and being a heavy clay soil are all likely to have contributed to increasing earthworm numbers. Although total abundance and biomass of earthworms did not differ across treatments, there were significant differences in species diversity of earthworms, with the greatest number of species in the C + P + R treatment in comparison with the control (Table 2). One of the cover crop mixtures (C + P + R + L) was sold as a biodiversity increasing mix, but our results show that there were no differences found between mixtures although there was in comparison with the bare stubble control. Conventional agriculture (intensive tillage, pesticide use, and long periods of bare soil) usually reduces earthworm diversity (Peigné, Ball, Roger-Estrade, & David, 2007); any treatment which promotes an increase in diversity may lead to an improvement in soil health, even if some of the other conventional agriculture factors remained (e.g., tillage).

Differences were found in the abundance of the three earthworm functional groups (epigeics being significantly affected by treatments) across treatments and for two individual species abundances when analyzed separately (Table 2). Significant differences in abundance were found dependent on the cover crop mixture for two species of earthworm; however, *L. rubellus* (epigeic) was found to be higher in the two radish mixes while *A. caliginosa* was significantly more in the C + P + R treatment and significantly less abundant in the C + P + R + L treatment—this confliction is likely to be why the total abundance of earthworms was found not to differ between treatments. These two species are from different functional groups (*L. rubellus* epigeic while *A. caliginosa* is an endogeic). These differences in function may have influenced the variation in abundance between treatments. Endogeic earthworms feed on highly decomposed plant matter within the soil profile and are also known as "soil feeders" (Eggleton et al., 2009), whereas epigeics eat recently fallen plant litter at the soil surface (Sherlock, 2012). Hendriksen (1990) found that epigeic earthworms were selective feeders directly influenced by litter quality, while Schon, Mackay, Yeates, and Minor (2010) considered quantity of litter inputs to be a driving factor changing abundance. It is likely that it is a combination of these factors, earthworm species interactions, and the carrying capacity of the soil environment has led to the results here, as well as migration from less favorable areas (Table 2). Over all multivariate analysis showed significant differences in soil biology across the treatments; changes in earthworm abundance of functional groups, species, and diversity were also found. Earthworms are considered to be an important indicator of soil health (Doran & Zeiss, 2000), these results highlight the potential cover crops have for maintaining soil biodiversity and improving soil health.

Millipedes were the only other macrofaunal group to show differences between treatments, again with higher numbers in the C + P + R treatment (Table 2). This is likely to be due to a greater provision of food resources as the majority of millipede species are detritivores (Martens, Alphei, Schaefer, & Scheu, 2001). The abundance of slugs and snails did not differ between treatments, including the bare stubble control. The highest abundance was found in the C + P + R treatment, while the lowest was in the C + P + R + L treatment, disputing the assertion that radish as a cover crop increases slug numbers (Cooper et al., 2017). Few differences were found between treatments for the mesofauna (Table 3). This is likely to be due to the scale of measurements, in both time and space (Collins et al., 2011) and to the similarity between treatments (Bedano et al., 2016). However, there were differences in the "other" group of mesofauna, due to the increase in Diptera abundance in the C + P treatment. Further investigation is needed to explain this increase. Both plant species within the C + P (oats and phacelia) mix were present (in lower proportions) in all other cover crop treatments; therefore, it is unlikely to be a plant species-related increase in Diptera abundance.

Biomass of sown cover crops which were measured in February did not differ among the three cover crop treatments (Figure 4a, although the cereal biomass found in all three mixes did differ). The proportion of cereal sown (kg/ha) was C + P > C + P + R > C + P + R + L (Figure 1), which reflected the grown biomass results (data not shown). In C + P + R and C + P + R + L, radish had the largest proportion of grown biomass (66%–72%), which was not reflected in sowing rates (24%, Figure 1). The effectiveness of cover crops as weed control depends on the vigor of the cover crop and the time required to achieve a complete ground cover (Wilson, Lal, & Okigbo, 1982); therefore, it is unsurprising that the bare stubble control had significantly higher biomass of weeds in comparison with the three cover crop treatments. However, a different suppressive ability was found among the cover crop treatments—C + P + R had significantly less weed biomass than the C + P + R + L treatment with C + P intermediate (Figure 4a). This is likely to be due to the combination of plant species (oats, rye, phacelia, and radish) and seed rate of these species when compared with the other cover crop treatments (C + P + R + L had 28% of seed sown as legume or buckwheat seeds, but the proportion of grown biomass this equated to was <5%). It is likely that the C + P + R treatment had the right proportion of seeds sown leading to a faster covering of the soil (den Hollander, Bastiaans, & Kropff, 2007) and the largest sown biomass. The cover crops grew well over the autumn and winter, and it was a mild winter with temperatures above average (Figure 2) leading to buckwheat being present in the C + P + R + L mixture until at least 1 December; however, when the botanical composition assessments were made in February, no buckwheat was found to remain growing in those field plots.

The cover crops were terminated in April; however, the weed suppression effects were still visible in the following spring oat crop in June. Several studies have shown the weed suppressive effects of cover crops (Campiglia, Mancinelli, Radicetti, & Caporali, 2010; Finney, White, & Kaye, 2016; Hayden, Ngouajio, & Brainard, 2014) in winter annual weeds. However, here we have shown that cover crop weed suppression is carried over into the following spring cereal crop. There were still significantly more weeds in the area that had previously been the bare stubble control treatment in comparison with C + P + R + L in June (Figure 4b) and significantly larger quantities of spring oat crop biomass in the C + P + R and C + P + R + L treatments in comparison with the control (Figure 4b). As a no-till based system usually increases the weed burden (at least in the initial years of management; Holland, 2004), this legacy of weed suppression from the cover crops has large implications relating to the sustainable management of farming systems.

Grain yield analysis found there were economic benefits growing cover crops in comparison with leaving the ground bare over the winter within this experiment, with almost 1.5 tonnes per hectare greater yields in the most diverse treatment (C + P + R + L) compared to the bare stubble control (Figure 4c). Other studies that have assessed following crop yields have not found these significant differences (e.g., Welch et al., 2016; Wilson et al., 1982; Wyland et al., 1996). However, these significant yield differences were only noticeable in comparison between the most diverse cover crop mix C + P + R + L and the bare stubble control. Although net margin differences were not found to be statistically significant, an extra £100 per hectare from the C + P + R + L treatment would be considered a significant financial benefit by a farmer. Overall oat yields were low in relation to the average for 2016 (2.6 t/ha for the bare stubble control treatment compared to 4.2 t/ha for C + P + R + L treatment (Figure 4c)); however, the spring oats from the C + P + R + L treatment were within the range of oat yields (4.0–8.2 t/ha) harvested across the UK (ADAS, 2016). These lower yields were likely due to the above average rainfall that occurred in June (pre-anthesis and grain filling period; Figure 2) (Finnan & Spink, 2016; Met Office, 2018) and lower temperatures.

Prior to commencing this experiment, the costs and benefits of cover crops were relatively vague, with some improvements in soil physics and chemistry (Campiglia et al., 2010; Lehman et al., 2015) but limited when a whole farm analysis was implemented (Cooper et al., 2017; Schipanski et al., 2014). Our results confirm potential benefits of cover crops, even on clay soils, although only in a more diverse cover crop mix (including radish) where the benefits were significant and economically interesting. The benefits found here included improvements in nutrient leaching risk reduction, weed suppression, and crop yield. Coupled with wider ecosystem services associated with reduced soil erosion and nutrient leaching, we suggest that cover crops have a role in sustainable management of arable rotations, although uptake by farmers will depend on buoyant and stable crop prices allowing farmers to invest in a more diverse rotation.

5 | CONCLUSIONS

Overall, this study compared the use of three different mixes of cover crops in comparison with a bare stubble control, in a replicated field-scale experiment across 20 hectares. Soil chemistry, physics, and biology were assessed, along with plant composition and subsequent crop yields. The results showed that cover crops can change soil chemistry, physics, and biology, and these slight differences between measured variables when combined were significant. The cover crops were also shown to have a weed suppressive effect that lasts during the growth of the cover crops and has a legacy in the subsequent crop. This legacy has the potential to provide enhanced yields and profitability, dependent on cover crop mixes and commercial crop prices, when compared to a bare stubble control in a no-till system, even on a heavy clay soil. This has the possibility to future-proof agriculture within the UK and reduces the decline in yields that has occurred over the last 20 years.

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CONFLICT OF INTEREST

None declared.

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