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To cite this article: Robyn Nicolay, Simon Jeffery & Nicola Randall (2021) Comparison of three soil health indicators between different vegetative strip compositions, African Journal of Range & Forage Science, 38:sup1, S104-S109, DOI: [10.2989/10220119.2021.2001570](https://doi.org/10.2989/10220119.2021.2001570)

To link to this article: <https://doi.org/10.2989/10220119.2021.2001570>



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Research Note

Comparison of three soil health indicators between different vegetative strip compositions

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Contemporary evidence shows biotic factors play a prominent role in the soil health and the provision of soil functions. Herbaceous grassland species differ in their modulation of soil communities, effects on soil components, as well the processes they interact with or regulate. In this study, we aimed to investigate the impact of different plant species communities on soil health, as quantified by soil physical (water infiltration), chemical (soil organic matter) and biological (Collembola community data) indicators. Data was collected from an existing long-term field trial in the UK, planted to either forb-dominated composition, grass species dominated composition or a multipurpose mixture of forb and grass species. Results showed that plant community can determine soil water infiltration rates, particularly with observed increased soil organic matter (SOM) and epigeic Collembola abundances. The results presented here add evidence that plant communities planted as vegetative buffer strips can be specifically tailored to support soil health development and maintenance.

Keywords: bioindicators, Collembola, infiltration, soil function, soil organic matter

Supplementary material: available at <https://doi.org/10.2989/10220119.2021.2001570>

The intensification of agricultural land use has brought about increased diffuse source pollution within water catchments, the breakdown of natural biogeographical barriers and reduced landscape heterogeneity within agroecosystems (Macfarlane and Bredin 2017; Cresswell 2018). The introduction and management of vegetative strips around agricultural fields (hereafter termed field margin strips) in these agricultural systems have been highlighted as a mitigation measure to prevent such impacts (Stutter et al. 2012; Petersen et al. 2020).

A complex of forbs and grasses make up the composition of planted field margin strips, with numerous studies highlighting their effectiveness in mitigating both surface and groundwater quality, as well as the regulation of ecological functions (Gregory et al. 1991; Lind et al. 2019). Although previous studies have tested species combinations designed to advance of aboveground ecosystem service complementarities in field margin strips (Cresswell et al. 2018), there is limited field-based information on the belowground ecosystem services these plants support. Evidence suggests plant species compositions play a prominent role in the overall health of soil biomes in that their edaphic network of multitrophic interactions correspond with ecosystem functioning (Bünemann et al. 2018; Rinnot et al. 2019).

Field margin strips can perform a wide range of functions, such as flood attenuation, eutrophication prevention,

as well as provision of organic matter to support food webs in riparian zones (Macfarlane and Bredin 2017). It is within this context that riparian buffer zones have the potential to positively influence soil health, and in turn below ground ecosystem services. Soil health comprises biological, chemical, and physical attributes (Rinot et al. 2019). In this study, we assess the effects of the plant species composition of planted field margin strips on one indicator for each soil health attribute: 1) the diversity and composition of the Collembola community (biological), 2) soil organic matter (SOM) content (chemical) and 3) soil water infiltration (physical).

All three indicators are established measures of soil health. Collembola communities are an important component of edaphic mesofauna (Parisi et al. 2005), whereas SOM is a key factor in the sustainability of biological functions through the provision of energy and supporting edaphic biological diversity and activity (Buckley and Schmidt 2001; Franzluebbers 2002). Water infiltration measures the soil's capacity to accept, hold and release water, which can be linked with aggregate stability, effecting soil health either positively or negatively (MacEwan and Fitzpatrick 1996).

We explored these three soil health indicators in existing multifunctional field margin strips established in a field experiment in April 2015 by Cresswell (2018). The experiment tested five different plant species compositions

for field margin strips (Table 1), selected by using published and grey literature between 1983 and 2017 to link plant traits with target ecosystem services (Cresswell et al. 2018). Treatments consisted of 1) 100% forb dominated communities intended for pollinator and parasitoid support, 2) 100% grass dominated communities (Cresswell 2018) proposed as buffers for water quality protection, 3) multifunctional vegetative strips consisting of 50% forbs and 50% grasses (Cresswell 2018) suitable for all soil types, 4) a similar mix designed specifically for Sandy Loam Soils, and 5) an example of a commercially available seed mix. Additional information on species and selection is described by Cresswell (2018).

Species richness was monitored over time by Cresswell (2018), considering successional changes often result in grasses outcompeting less-competitive wildflowers to become dominant (Grime et al. 2007). Grass-dominated field margin strips showed an average of 26% forb incursion over three years. 50% Forb 50% grass multifunctional vegetative strips showed an average of 60% forb incursion over three years. Despite these changes in composition, all initially planted species were still present at the time of sampling for this study.

The experimental site was located in Shropshire, England (52°46'32" N, 2°25'40" W), on sandy loam soils. Mean monthly maximum and minimum temperatures range from 20 °C in July to 1 °C in January, respectively. The mean annual rainfall is 105 mm, most of which falls in the summer months, with snow experienced in winter. The different

field-margin strip-composition treatments were planted in 4 m by 4 m plots (separated by 1 m grass buffer strips) in a randomised block design with five replicates. All treatments were sown at 2 g m⁻² and during initial establishment the site was hand weeded for non-sown species.

Sampling of the three soil-health indicators was undertaken in April 2019, four years following establishment. To assess the Collembola community, soil core samples were collected using 5 cm diameter bulk density rings to a depth of 10 cm, accounting for depths that present the most active collembolan population densities (Mayvan et al. 2015). Three random samples were collected from each experimental plot and extracted via Berlese-Tullgren funnels. Specimens were collected in 20 ml 75% ethyl alcohol. An extraction period of fifteen days was used. Samples were examined under a stereomicroscope at low magnifications and indexed using the Qualita Biologica del Suolo ('Biological Soil Quality') Collembola (QBS-c) method described by Parisi et al. (2005) and Parisi and Menta (2008). This method offers a rapid means of characterising edaphic microarthropod populations without the requirement of taxonomic understanding of observed Collembola species. This QBS-c is based on the concept that Collembola samples with high ecomorphological index scores (EMI) correlate positively with soil health and positive edaphic functionality (Parisi et al. 2005). Collembola present within each sample were assigned an EMI according to the different adaption levels relative to their soil environment (antenna length, furca,

Table 1: Community composition and sowing rate of seed mixes of the different treatments

		All soil types	Sandy loam soils	Water quality protection	Pollinator support	Commercial mix
Forb species	Common Cats Ear	<i>Hypochaeris radicata</i>	✓	✓	✓	
	Common Bird's-foot-trefoil	<i>Lotus corniculatus</i>	✓	✓		
	Common Knapweed	<i>Centaurea nigra</i>	✓	✓	✓	✓
	Dandelion	<i>Taraxacum</i>	✓	✓	✓	
	Devils bit scabious	<i>Succisa pratensis</i>		✓		
	Germander Speedwell	<i>Veronica chamaedrys</i>	✓	✓	✓	
	Hogweed	<i>Heracleum</i>		✓	✓	
	Hedge Bedstraw	<i>Galium mollugo</i>				✓
	Hedge Woundwort	<i>Stachys sylvatica</i>	✓			✓
	Meadow Buttercup	<i>Ranunculus acris</i>	✓		✓	✓
	Oxeye Daisy	<i>Leucanthemum vulgare</i>	✓		✓	✓
	Primrose	<i>Primula vulgaris</i>	✓		✓	
	Red Campion	<i>Silene dioica</i>	✓		✓	✓
	Red Clover	<i>Trifolium pratense</i>	✓	✓	✓	✓
	Rough Hawkbit	<i>Leontodon hispidus</i>			✓	
	Tufted Vetch	<i>Vicia cracca</i>				✓
	White Clover	<i>Trifolium repens</i>	✓	✓	✓	
	Wild Carrot	<i>Daucus carota</i>	✓			✓
	Wild Strawberry	<i>Fragaria vesca</i>		✓		
Yarrow	<i>Achillea millefolium</i>	✓	✓		✓	
Grass species	Common Bent	<i>Agrostis capillaris</i>	✓	✓	✓	
	Cock's Foot	<i>Dactylis</i>	✓	✓	✓	✓
	Crested Dogs Tail	<i>Cynosurus cristatus</i>		✓		
	Meadow Fescue	<i>Festuca pratensis</i>	✓	✓		✓
	Meadow Foxtail	<i>Alopecurus pratensis</i>			✓	
	Red Fescue	<i>Festuca rubra</i>	✓	✓		✓
	Tall Fescue	<i>Festuca arundinacea</i>			✓	✓
	Timothy	<i>Phleum pratense</i>			✓	✓

presence of hair or scales, and pigmentation). Collembola were then classified according to a particular EMI category, based on phenological characteristics according to their ecomorphological forms; epigeic, hemiedaphic or euedaphic (Supplementary Figure S1).

Water infiltration into the soil in each field margin strip treatment was determined using the falling-head method with a double ring infiltrometer to determine *in situ* field saturated hydraulic conductivity (K_{fs}), following methods described by Elrick and Reynolds (2002). K_{fs} was calculated using the following equation (Equation 1) adapted from Reynolds (2008):

$$K_{fs} = \frac{\alpha \cdot q_s \cdot AR1}{a(\alpha \cdot H1 + 1) + (q_s \cdot \pi a^2)} \quad (\text{Equation 1})$$

where $\alpha = 0.12 / \text{cm}$ is a predetermined site soil structure parameter assigned according to categories described by Elrick et al. (1989), $q_s = Q_s / \pi a^2$ is the measured quasi-steady infiltration rate from the inner ring, Q_s is the corresponding quasi-steady flow rate using quasi-empirical constant $C_1 = 0.316_{\tau}$ and $C_2 = 0.184_{\tau}$ applied for $d \geq 3 \text{ cm}$ and $H \geq 5 \text{ cm}$, $a = 5 \text{ cm}$ is the radius of the inner ring, $H1 = 6 \text{ cm}$ is the steady depth of ponded water in inner ring, $d = 3 \text{ cm}$ is the depth of ring insertion into soil, $A = \pi a^2$ is the cross-sectional area, and $R1$ is the steady-state infiltration rate.

To assess SOM, three random soil core samples were collected from each experimental plot, air-dried and sieved together, using a 2 mm sieve to give a composite sample was determined as the value of loss on ignition (LOI) at 550 °C (Equation 2), expressed as a percentage of weight (wt.at) lost after 105 °C moisture loss according to Heiri et al. (2001):

$$LOI = \frac{(wt.at_{105^\circ C}) - (wt.at_{550^\circ C}) \times 100}{(wt.at_{105^\circ C})} \quad (\text{Equation 2})$$

Differences in mean Collembola abundances, water infiltration and SOM between different field-margin strip-compositions were assessed using Analysis of Variance (ANOVA). Response data were log10 transformed and assumptions of normality in the residuals were satisfied using a Shapiro–Wilk test and histograms. Homogeneity of variances was satisfied using Bartlett's test and Q–Q plot of residuals presented no significant outliers. Data are assumed independent. For SOM and water infiltration, a one-way ANOVA was used to detect differences between the treatment means, with block included as a grouping factor. Microarthropod abundances often have skewed frequency distributions; for that reason generalised linear models (GLMs) with a Poisson distribution were used to estimate the mean abundance of Collembola in each of the three EMI categories. Treatment was the explanatory variable and abundance of (1) epigeic Collembola, (2) abundance of hemiedaphic Collembola, (3) abundance of euedaphic Collembola, (4) water infiltration and (5) SOM as interacting variables. An ANOVA was then performed to detect whether means differed between treatments. Models were described using a blocking factor to account for main

effects of blocking structure. Principal Component Analysis (PCA) was used to explore the variables associated with observed discrimination between the samples. Data were analysed with R Studio 3.6.1 (R Development Core Team 2020) using the *FactoMineR* package.

Our analyses indicated significant differences between different field margin strip composition treatments in mean water infiltration and Collembola abundances. SOM averaged between 1.85% and 2.67%; however, no significant differences were observed ($F = 1.655$, $p = 0.20$, $df = 4$). For water infiltration, the Pollinator Support and the All Soil Types treatment showed significantly higher rates than other treatments (respectively, mean = 0.058 cm s^{-1} , mean = 0.039 cm s^{-1} , $F = 3.15$, $p = 0.03$, $df = 4$) (Figure 1).

Collembola from ecotypes identified in the QBS-c method were present in every treatment. Epigeic

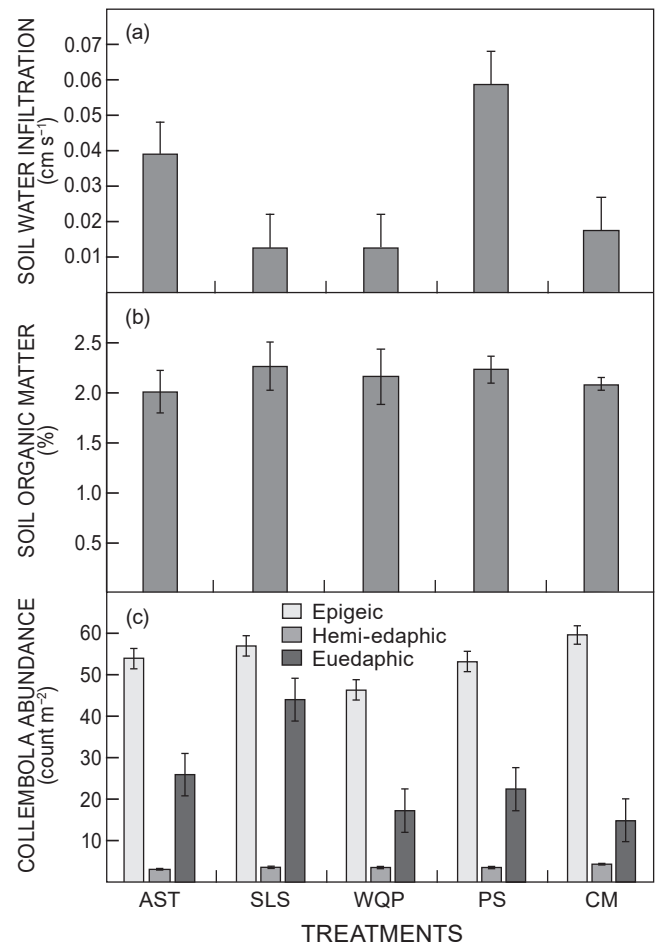


Figure 1: Bioindicators shown within each treatment; (a) Average field saturated hydraulic conductivity (K_{fs}) by treatment. Columns shown rate, bars show standard errors ($n = 15$), (b) Soil Organic Matter (SOM) by treatment, Columns shown content, bars show standard errors ($n = 15$), (c) mean Collembola counts by ecomorphological forms (epigeic, hemiedaphic and euedaphic), within each treatment. Bars shows standard errors ($n = 15$). Where AST = Multifunctional seed mix for all soil types, SLS = Multifunctional seed mix for sandy loam soils, WQP = Water quality protection seed mix, PS = Pollinator support seed mix, CM = Commercially available multifunctional seed mix

Collembola indicated the greatest abundance across all treatments ($z = 3.578, p < 0.01, df = 24$). Hemidaphic Collembola suggested statistical significance in treatments planted to Pollinator Support ($z = -2.098, p = 0.03, df = 24$). Euedaphic Collembola abundances indicated statistical significance in treatments planted to Pollinator Support ($z = -5.419, p < 0.001, df = 24$), Commercial Mix ($z = -4.334, p < 0.001, df = 24$), and Water Quality Protection ($z = -3.870, p < 0.001, df = 24$).

When using a PCA to explore relationships between the three soil health indicators, the first two Principal Components accounted for approximately 52% of the variation (Figure 2). Most discrimination that is observed between treatments occurs in PC1 as All Soil Type mixes vs Sandy Loam Soil mixes. The main factors driving this discrimination are field saturated hydraulic conductivity (K_{fs}) ('x: All Soil Type mixes = 0.039 cm s^{-1} and Sandy Loam Soil mixes = 0.012 cm s^{-1}); SOM ('x: All Soil Type

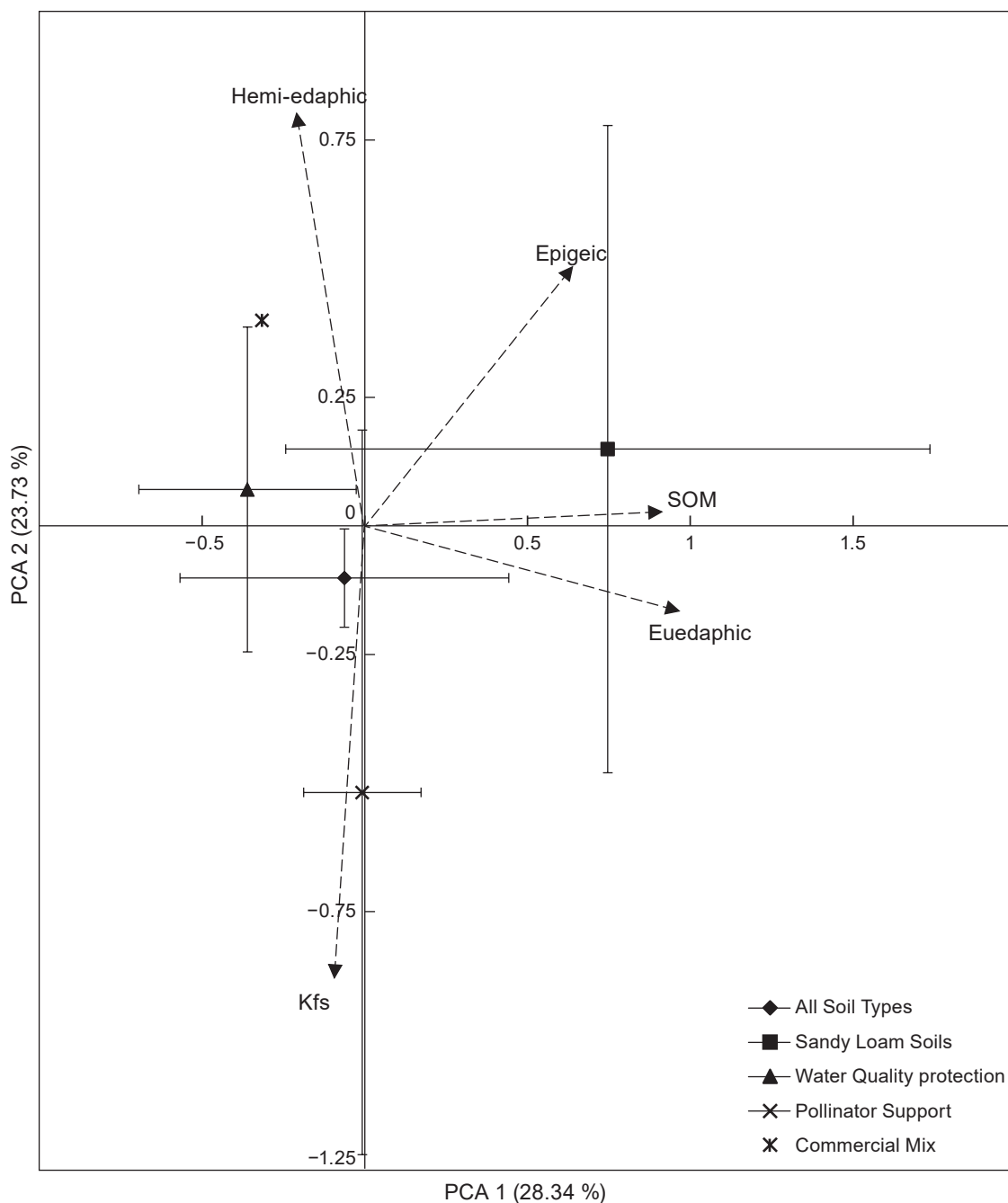


Figure 2: Treatment variables factor map Principal Components Analysis (PCA) of the treatment scores of the 25 field plots. Included as well are the sample scores for diagnostic soil health indices (Collembola: epigeic, hemiedaphic and euedaphic, SOM, Field saturated conductivity)

mixes = 2.00% SOM dry weight and Sandy Loam Soil mixes = 2.6% SOM dry weight); Epigeic (‘x: All Soil Type mixes = 64 m⁻² and Sandy Loam Soil mixes = 57 m⁻²); Hemiedaphic (‘x: All Soil Type mixes = 3 m⁻² and Sandy Loam Soil mixes = 4 m⁻²); and Euedaphic (‘x: All Soil Type mixes = 26 m⁻² and Sandy Loam Soil mixes = 44 m⁻²). Some discrimination can also be observed in PC2 as Pollinator Support mixes ≠ Water Quality Protection mixes = the Commercial Mix. Collembola ecotype and SOM are the variables that most contribute to this observed discrimination (Figure 2).

A key finding of this study is that the plant community composition can influence soil-water infiltration rates. Contrary to expectations, forb dominated Pollinator Support treatments and mixed compositions planted for All Soil Types, rather than grass dominated Water Quality treatments, showed a significantly higher water infiltration function; these observations could aid in field-margin strip selection for improved infiltration in vulnerable zones, adding to existing ecosystem services. This supports studies by Su et al. (2018) showing natural restoration of soils with a greater plant diversity and forb ratio increased soil infiltration rates and cumulative infiltration. The outcomes of this study suggest that planting forb-dominated or mixed grass-forb communities in field margin strips or riparian buffer zones can be beneficial for water protection-based ecosystem services in agricultural landscapes, as well as slow the flow-catchment management concepts (Collentine and Futter 2018).

The statistical and PCA analysis suggested Collembola ecotype contributed to observed discrimination between treatments. High abundances of epigeic Collembola across all field margin strip compositions, particularly when observing increased SOM, is consistent with findings by de Oliveira Filho et al. (2015) where the density of Collembola changed significantly with land use varying soil disturbance. With the site having not been disturbed for four years, Collembola abundance was expected to demonstrate high richness of these edaphic fauna. Salamon et al. (2004) suggested that high epigeic Collembola abundance could be attributable to increased soil microbial and fine root biomass within treatments within plant functional groups. With the addition of aforementioned plant communities in previously degraded landscapes, changes in Collembola abundance can provide long term ecosystem services, consequently aiding in the promotion of land functionality (de Oliveira Filho et al. 2015). Consistently low hemiedaphic Collembola across treatments may be attributable to microarthropod seasonal fluctuations. Possible observed higher species evenness and diversity may be seen in soils with consistent soil moisture levels or frequently irrigated soils measured seasonally (Tsiafouli et al. 2016).

The presence of relatively high abundances of euedaphic Collembola is usually indicative of high levels of soil health (Parisi and Menta 2008). The plant communities used in this study had been established in 2015, without mechanical soil disturbance or intervention since that time, with the result that the belowground Collembola community had time to develop; it being the most sensitive ground to disturbance and the longest to subsequently recolonise (Parisi and Menta 2008).

Despite the wide range of plant species used in the different treatments, and although quantified SOM demonstrated higher percentages within the soil (Figure 1), no independent statistically significant differences were observed between treatments rhizosphere (four years after planting). Treatments were however seen to show significance when observed with interacting factors (Collembola abundance and water infiltration) suggesting SOM levels influence hydrological functioning in relation to soil functioning and aggregation (Franzluebbers 2002), indicated as such by elevated Collembola abundances.

The results of this study demonstrate that different herbaceous forb or grass compositions had different relative effects on the soil health indicators investigated in this study. In particular, the forb-dominated Pollinator Support composition and the mixed forb-grass All Soil Types composition improved water infiltration. High abundances of epigeic and euedaphic Collembola may indicate high levels of soil health, suggested to be attributable to minimal land disturbance and could contribute to ecosystem services. Low abundances of hemiedaphic Collembola may be attributable to environmental causes. Integration of spatiotemporal variation and prolonging the sample period to attain time series data may be valuable in understanding whether different field margin compositions could result in different ecosystem service provision over time, as the edaphic ecosystem stabilises.

Acknowledgements — Research at the trial sites and laboratories was aided and authorised by Harper Adams University, Shropshire, including assistance by Dr Claire Cresswell, Grace Milburn and Ana Natalio. RE Nicolay was supported by the Elizabeth Creek Charitable Trust, facilitated via the Harper Adams Development Trust.

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