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The effects of soil compaction mitigation on below-ground fauna: how earthworms respond to mechanical loosening and power harrow cultivation

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Highlights

- There was a negative effect of mechanical loosening on anecic earthworms.
- The effects of treatments on earthworm abundance and biomass were broadly similar.
- Mechanical loosening of grassland soil can negatively impact soil macrofauna.

Abstract

Soils are one of the most biologically diverse habitats within the terrestrial ecosystem. Although soils are vital to the provision of important ecosystem services, their direct protection and sustainable management are often lacking within conservation policy. Many grassland soils have undergone considerable management intensification and are subject to degradation pressures. Soil compaction is an important form of soil degradation that can reduce soil productivity and crop yields, although the impacts can be reversed through natural processes and mitigated through management interventions. While commonly used, substantial knowledge gaps exist regarding the impact of soil compaction mitigation techniques on key soil macrofauna; many of these organisms are essential to soil function. A complete split-plot design was used to investigate the impacts of mechanical loosening (subsurface soil disturbance using tines or radial blades without significant soil mixing or inversion) and power harrow cultivation (shearing and mixing of soil to prepare a seedbed for the establishment of a deep-rooting forb and legume mix) on the abundance and biomass of earthworms up to two years post-treatment. Mechanical loosening was undertaken at two depths, c. 20 cm and c. 35 cm as two separate treatments. There was a negative effect of mechanical loosening at both depths on the abundance and biomass of anecic earthworms, lasting up to two years post-treatment. There was no significant effect of power harrow cultivation on the abundance or biomass of earthworms. These negative effects are consistent with other studies that have shown mechanical loosening to be a source of earthworm mortality. Although these findings resulted from a single episode of power harrow cultivation and mechanical loosening at a single site, the results

indicate that the mechanical loosening of grassland soil can have a negative impact on important soil macrofauna and should possibly only be undertaken when the soil is in the most severely degraded conditions. Further work is needed to determine whether the negative impact of mechanical loosening is common to multiple sites and soil types and to link the reduction in earthworm number and biomass to future soil function.

Keywords: soil compaction; ecosystem services; grasslands; intensification; *Lumbricus terrestris*

1. Introduction

The effects of soil management on soil biodiversity and function are not as well understood in grassland systems as they are in arable systems (Vickery et al., 2001). Grasslands provide multiple benefits to society, including food production, water regulation, carbon storage and the provision of important habitats for a wide range of taxa. These include invertebrates (Hendrickx et al., 2007), in particular lepidopterans (Bourn and Thomas, 2002); mammals (e.g. brown hare *Lepus europaeus* (Hutchings and Harris, 1996)); and birds (Vickery et al., 2001) (e.g. corncrake *Crex crex* (Green and Stowe, 1993)). Many of the species supported by grasslands are experiencing serious population declines due to a combination of factors including habitat loss, increases in stocking rates and intensification of management practices (Allan and Bossdorf, 2014). While the above-ground biodiversity of grasslands is of increasing conservation concern, soils are one of the most species-rich habitats within the terrestrial ecosystem (Bardgett, 2005; Heywood, 1995) and are often overlooked within conservation policy (Giller, 1996; Haygarth and Ritz, 2009). Soil biodiversity is likely to play an important role in the provision of important ecosystem services such as regulating water quality, maintaining food security and providing carbon storage (Millennium Ecosystem Assessment, 2005). Facilitative interactions between functionally diverse groups of soil organisms drive ecological processes, such as litter decomposition, nutrient cycling and bioturbation (Bradford et al., 2002; Heemsbergen et al., 2004).

72 Grasslands account for 40 % of global land cover, excluding Greenland and Antarctica (White et al.,
73 2000). UK grasslands contribute 5% of Europe's permanent grassland (Smit et al., 2008) and within
74 the UK, permanent and temporary grasslands account for approximately 65 % of agricultural land
75 (DEFRA, 2014). However, intensification of management practices has led to 17 % of vegetated lands
76 experiencing human-induced soil degradation since 1945 (Bilotta et al., 2007; Oldeman, 1994).
77 Compaction is an important form of physical soil degradation (DEFRA, 2009; European Parliament
78 Council of the European Union, 2013) that threatens soil function and agricultural productivity.
79 While mitigation methods to alleviate compaction are a field of current interest, significant
80 knowledge gaps exist as to how best to identify high risk areas due to data scarcity and the difficulty
81 in interpreting the often complex interactions that drive soil processes (Trolldborg et al., 2013). Soil
82 compaction is a global problem, is widespread in Europe (Jones et al., 2003; Trautner et al., 2003)
83 and is not as visually recognisable as other forms of soil degradation, such as erosion. Several
84 assessment techniques exist to quantify soil condition (Mueller et al., 2009; Peerlkamp, 1967;
85 Shepherd, 2000). Newell-Price et al., (2013) reported on the use of such visual evaluation techniques
86 to assess soil structural condition in 300 grassland fields in England and Wales. They found that c.
87 10 % of grassland soils were in poor condition and c. 60 % were in moderate condition.

88 Soil compaction arises through repeated compressive forces from heavy farm vehicles (Defossez and
89 Richard, 2002; Håkansson et al., 1988) or from livestock trampling that can be exacerbated by high
90 stocking densities or extended grazing periods (Mulholland and Fullen, 1991; Warren et al., 1986).
91 However, the potential risk of compaction can depend as much on the water content and structural
92 strength of the soil as it does on the magnitude of the applied force (Batey, 2009) with compaction a
93 greater risk in soils with higher moisture contents (MAFF, 1970). This change in the spatial
94 arrangement of soil aggregates reduces soil permeability and macroporosity, leading to a reduction
95 in overall soil function. Severe soil compaction can lead to a reduction in soil productivity and
96 ultimately crop yields (Whalley et al., 1995); degraded soils are less able to provide essential
97 ecosystem services (Matson et al., 1997) and maintain soil diversity.

Although there are several soil compaction mitigation techniques that can improve the structure of compacted soils, sustainable soil management should aim to avoid compaction through good practice. Methods such as mechanical loosening (subsurface soil disturbance using tines or radial blades without significant soil mixing or inversion) often cannot fully compensate for the impacts of soil structural degradation and the treated soils can be susceptible to recompaction (Spoor et al., 2003). The three main types of equipment used to mitigate soil compaction in grassland soils vary in terms of their mode of action and the depth of effective operation: aerators can loosen soil to c. 10 cm depth; sward-lifters to c. 35 cm depth; and subsoilers c. 45 cm depth. Aerators or slitters consist of a series of radial blades or spikes, on a horizontal transverse non-powered rotor, that cut through the grass sward into the upper horizon of the topsoil. The nature and angle of the blades (or tines) will affect the degree of disturbance caused by the machine, as does forward speed, soil type and soil moisture level at the time of operation. By contrast, sward lifters and subsoilers work by lifting or fracturing the soil to alleviate the compacted area. Biological approaches to soil compaction mitigation also exist. For example, deep-rooted herb and legume species can have an observable effect on soil compaction by improving soil structure and macroporosity (Głąb, 2008; Latif et al., 1992; Lesturgez et al., 2004).

Any soil disturbance event, such as power harrow cultivation (shearing and mixing of soil to prepare a seedbed) or mechanical loosening, will alter not only the soil structure, but also the physical environment for soil organisms. Earthworms are an important group within soil macrofauna. They create burrows while mixing, ingesting and excreting soil material, thereby modifying the physical structure and availability of soil resources, and fulfilling the role of 'ecosystem engineers' (Lavelle, 2012; Lavelle et al., 1997; Pulleman et al., 2012). Earthworms are grouped into three ecological groups or ecotypes that exhibit different behaviours and provide different functions: anecics, endogeics, and epigeics. Anecic species, such as *Lumbricus terrestris*, create large vertical or subvertical permanent burrows from the surface down into the soil, a process that aids litter decomposition and nutrient cycling by pulling leaf-litter down into the soil. These burrows also

increase water infiltration rates and root development by creating macropores that improve soil structure and porosity. Endogeic species feed on mineral soil enriched with organic matter and also improve soil structure by creating a netlike system of smaller subsurface burrows. Epigeic species are found in the hummus layer and feed on plant litter.

This paper investigates the null hypothesis that mechanical loosening, power harrow cultivation, or the addition of deep-rooted forbs, have no effect on the abundance and biomass of earthworms. Although other studies (Emmerling, 2001; Ernst and Emmerling, 2009; Wyss and Glasstetter, 1992) have investigated the impacts of different tillage systems, and land use type and intensity (Boag et al., 1997; Smith et al., 2008) on the taxonomic diversity of earthworms in arable systems; the effect of mechanical loosening on earthworm ecotypes in grassland has not been studied. The experimental results from this study provide an indication of the extent to which mechanical loosening of degraded grassland soils can improve soil function and health.

2. Methods

We tested two methods known to alleviate soil compaction: mechanical loosening, and power harrow (PH) cultivation with the establishment of deep rooting forbs, including legumes. We investigated the effect these treatments had on the abundance and biomass of earthworms up to two years post-treatment. A collective analysis was firstly performed on all earthworm data, before separately analysing how anecic earthworms responded to treatments. Endogeic earthworms were not analysed separately due to the low numbers observed. Only adult earthworms were identified to species level due to uncertainty in the species identification of juveniles.

2.1. Study site and data collection

Field experiments were carried out at Nafferton Farm, northern England (54°98'57 N, 001°90'04 W). The soil was a sandy clay loam and was historically in a grassland-arable rotation; seven years grassland, followed by four years arable production. Arable production consisted of three years in

winter wheat and one year in spring barley (undersown). In the seven years preceding the start of the treatments the study site had been in continuous grassland under an organic dairy production system and was cut for silage two to three times per year. It was grazed by adult dairy cows between September and October each year and 100 ewes were overwintered. Dairy slurry was applied annually and dirty water twice annually amounting to approximately 15 machinery passes per year.

Initial treatments were applied on the 2nd September 2010 and earthworm sampling was undertaken one year after treatment, in October and November 2011 (over 22 days), and in September and October 2012 (over 15 days) two years post-treatment. Sampling was carried out between 0800 and 1400 hrs; data were not collected in adverse weather conditions or when frost or snow covered the ground. The mean monthly soil temperature and precipitation for the duration are presented in Fig. 1. Soil physical measurements (Anon, 1982); maximum penetration resistance (MPR) (0 - 15 cm and 15 - 30 cm depth) and bulk density (BD) (0 - 10 cm depth) were recorded for each plot ($n = 36$) in 2010 (pre-treatment), 2011, 2012 and 2013.

2.2. Experimental design

The effects of different soil compaction mitigation techniques were tested using a split-plot, randomised block experimental design; there were nine treatment combinations (Table 1) with four replicate plots of each treatment ($n = 36$ plots in total). Mechanical loosening was the complete block variable (24 x 16 m). Blocks were divided into three subplots each with a different treatment in terms of PH cultivation (surface cultivation/undisturbed) and the introduction (or not) of deep-rooting herbs and legumes (8 x 16 m). There was 6-12 m between each complete block and 10-12 m headlands.

Table 1. Summary of experimental treatments (see Table 2 for details of forb species). *n* shows the number of soil samples (for earthworms) used in the analysis. Sampling was randomised across the four replicates of each treatment.

Treatment	Mechanical	Power harrow cultivation /	<i>n</i> 2011	<i>n</i> 2012
	loosening	forb species introduction		
1	Unloosened	Grass sward undisturbed	8	4
2	Shallow (c.20 cm)	Grass sward undisturbed	8	4
3	Deep (c.35 cm)	Grass sward undisturbed	8	4
4	Unloosened	Power harrow, without forb species	8	4
5	Shallow (c.20 cm)	Power harrow, without forb species	8	4
6	Deep (c.35 cm)	Power harrow, without forb species	8	4
7	Unloosened	Power harrow, with forb species	8	4
8	Shallow (c.20 cm)	Power harrow, with forb species	8	4
9	Deep (c.35 cm)	Power harrow, with forb species	8	4

Prior to treatments the grass was cut with a Kuhn mower and McHale baler. Mechanical loosening was undertaken at a depth of c. 20 cm and c. 35 cm using a McConnell Shakaerator. Power harrowing was carried out using a standard agricultural PTO-driven power harrow that consisted of a series of bladed rotors that counter-rotated around a vertical axis. The natural vegetation of all plots was dominated by *Lolium perenne* and *Trifolium repens*; *Poa trivialis*, *Poa annua*, *Agrostis capillaris* and *Stellaria media* also occurred frequently. The power harrow treatment (treatments 4 - 9) was designed to create at least 50% bare ground within the sward as suitable regeneration niches for the deep-rooting forb and legume mix (Table 2) (RDS, 2004). The seed mix was broadcast by hand and then rolled using a Watson roller. The seed mix included three grass species (Table 2) to ensure that complete vegetation cover established, even if some of the forbs failed to germinate. Between

December and February in the months following mechanical loosening, sheep were introduced to the plots for short single grazing periods (c. 12-24 hrs) to control sward height and avoid shading out of introduced species (Table 3).

Table 2. Deep-rooting forbs and legume mix used in treatments 7- 9. Grass species are marked*

Scientific name	Common name
<i>Achillea millefolium</i>	Yarrow
<i>Centaurea nigra</i>	Common Knapweed
<i>Cichorium intybus</i>	Chicory
<i>Hypochaeris radicata</i>	Catsear
<i>Lotus corniculatus</i>	Birdsfoot Trefoil
<i>Plantago lanceolata</i>	Ribwort Plantain
<i>Sanguisorba minor subsp. muricata</i>	Forage Burnet
<i>Trifolium pratense</i> var. <i>pratense</i> (wild)	Wild Red Clover
<i>Trifolium pratense</i> var. <i>sativum</i> (commercial)	Commercial Red Clover
<i>Trifolium repens</i> (small-leaved)	Small-leaved White Clover
<i>Trifolium repens</i> (large-leaved)	Large-leaved White Clover
<i>Agrostis capillaris</i>	Common Bent*
<i>Anthoxanthum odoratum</i>	Sweet Vernal-grass*
<i>Cynosurus cristatus</i>	Crested Dog's-tail*

Table 3 Grazing periods and stocking densities

Livestock	Grazing periods	Density
Ewes	13/01/2011 – 25/01/2011	6.2 LU/ha

	01/12/2011 – 23/01/2012	1.9 LU/ha
	December 2012 – February 2013	1.9 LU/ha
Dairy heifers	July – October 2011	2.0 LU/ha
	July – October 2012	2.0 LU/ha
	Summer 2013	2.0 LU/ha

190

191 Treatment replicates were sampled in a random order using 30 x 30 cm metal quadrats. Quadrats
192 were randomly placed five times within each plot and sunk to a depth of approximately 3 cm; a
193 maximum of nine plots were sampled in a day. A non-destructive sampling method was used to
194 avoid impeding additional data collection within plots. Each quadrat was treated with two litres of
195 0.33% mustard solution (Gunn, 1992); the same batch of Suma Wholefoods organic ground yellow
196 mustard powder was used throughout. Before treatment the vegetation within the quadrat was cut
197 to approximately 3 cm to aid the detection of emerging earthworms. Subsequently each quadrat
198 was observed for 15 minutes while the solution percolated into the soil. All adult earthworms that
199 emerged after the solution was applied were identified to species level (Jones and Lowe, 2012; Sims
200 and Gerald, 1999) and weighed on site using a portable balance. After 15 minutes another
201 application of two litres of mustard solution was applied and the process repeated for another 15
202 minute period. All earthworms were washed and released within the same plot once sampling was
203 complete. Mean abundance and biomass were calculated from the combination of earthworm
204 counts from the five quadrats summed across each plot. Mean daily soil temperature at 15 cm depth
205 was calculated from data recorded at 15 min intervals by the permanent weather station at
206 Nafferton Farm.

207 2.3.Data analysis

208 All statistical analyses of earthworm data were performed using R version 3.0.2 (R Core Team, 2013).
209 Soil physical measurements were analysed using two-way ANOVAs between treatments and

between mechanical loosening and year. Predictor variables for the earthworm analyses included mechanical loosening, PH cultivation, year, and soil temperature at 15 cm depth. Soil temperature data were missing between the 17th and 21st of October 2012, replacement values were calculated as a mean of the previous seven days measurements. Mechanical loosening, PH cultivation and year were specified as fixed factors; soil temperature was the only continuous variable, included to account for possible diurnal patterns within earthworm activity.

Due to additional project aims the sampling of replicates was unbalanced. To achieve balanced sampling replicates that had been sampled more than twice in 2011, or more than once in 2012, were randomly subsampled prior to analysis (Table 1). A preliminary analysis was completed for both earthworm abundance and biomass that included all earthworms, i.e. adults and juveniles of all species. Abundance data were analysed using generalized linear mixed models (GLMMs) using the package *lme4 1.1-8* (Bates et al., 2015) and a negative binomial error structure (*glmer.nb*) to account for overdispersion. Biomass data were Box-Cox transformed to fulfil model assumptions prior to analysis using linear mixed models (LMMs) in the package *nlme 3.1-120* (Pinheiro et al., 2015). The random effect (1|block/PH cultivation) was included in both models to account for spatial variation within the data and to acknowledge the hierarchal design of the experiment. Main effect models with and without the random effect were compared using AIC (abundance 757.4 GLMM vs 753.41 GLM and biomass 528.3LMM vs 525.74LM). Due to an extremely low level of spatial variation (abundance $\sigma^2 = 1.77^{-12}$ and biomass $\sigma^2 = 1.61^{-8}$) and small n , the random effect was dropped from the final analyses to avoid models that were over-parameterised. Therefore, generalized linear models (GLMs) were used to model abundance data and were fitted with a negative binomial error structure (*glm.nb*) using the package *MASS* to account for overdispersion; linear models (LMs) were used to analyse the biomass data. The significance of main effects and interactions were assessed using likelihood ratio tests to compare nested models.

3. Results

Seven earthworm species were observed within the study site: two anecic species (lob worm *L. terrestris* and black-headed worm *Aporrectodea longa*), four endogeic species (green worm *Allolobophora chlorotica*, blue-grey worm *Octolasion cyaneum*, grey worm *Aporrectodea caliginosa* and rosy-tipped worm *Aporrectodea rosea*) and one epigeic species (redhead worm *Lumbricus rubellus*) (Table 4). Adult anecic earthworms represented 33.6 % of the total number of earthworms and 75.0 % of the total biomass sampled. Endogeic species represented 24.1 % of the total number of earthworms and 4.8 % of the total biomass. Juvenile worms accounted for 40.6 % of the total number and 19.9 % of the total sampled biomass. The remaining earthworms were adult *Lumbricus rubellus*.

3.1. Physical soil structure

There was no significant effect of PH cultivation ($F = 0.02$, d.f. = 2, $p = 0.980$) on MPR (0- 15 cm), or evidence of an interaction between treatments ($F = 0.01$, d.f. = 4, $p = 1.000$). There was a significant interaction between mechanical loosening and year ($F = 6.49$, d.f. = 6, $p < 0.001$). Shallow loosened plots had lower MPR (0 – 15 cm) compared to unloosened plots in 2011 and 2012 ($p < 0.001$ and $p = 0.030$, respectively, TukeyHSD) (Fig. 2A). There was no significant difference between deep loosened plots and unloosened plots in 2011 ($p = 0.057$, TukeyHSD) or 2012 ($p = 0.992$, TukeyHSD), or between shallow and deep loosened plots (2011, $p = 0.725$ and 2012, $p = 0.441$, TukeyHSD). The MPR (0 – 15 cm) variance was significantly heterogeneous between years and within treatments, however, sampling was balanced. There was no significant effect of PH cultivation ($F = 0.33$, d.f. = 2, $p = 0.723$) or of an interaction between treatments ($F = 0.12$, d.f. = 4, $p = 0.975$) on MPR (15-30 cm), but there was a significant interaction between mechanical loosening and year ($F = 3.69$, d.f. = 6, $p = 0.002$). MPR (15-30 cm) was significantly lower in 2011 in deep loosened plots compared to unloosened plots ($p < 0.001$, TukeyHSD) and compared to shallow plots ($p = 0.018$, TukeyHSD) (Fig. 2B). There was no significant difference between shallow loosened plots and

unloosened plots in 2011 ($p = 0.559$, TukeyHSD). There was significantly lower MPR (15 – 30 cm) in shallow and deep loosened plots compared to unloosened plots in 2012 (both $p < 0.001$, TukeyHSD), but no significant difference between shallow and deep loosened plots ($p = 1.000$, TukeyHSD). There was a significant interaction between mechanical loosening and year ($F = 3.06$, d.f. = 6, $p = 0.007$) on BD (0 – 10 cm); however, there were no significant post-treatment differences between treatments in the same year. There was a significant effect of loosening on BD (0 – 10 cm) ($F = 4.22$, d.f. = 2, $p = 0.017$) (Fig. 2C); BD on shallower loosened plots was significantly lower than on unloosened plots ($p = 0.02$, Tukey HSD). There was no significant difference between loosening treatments or between deeper loosened and unloosened plots. There was no significant effect of PH cultivation on BD (0 – 10 cm) ($F = 1.38$, d.f. = 2, $p = 0.256$) or of an interaction between treatments ($F = 0.17$, d.f. = 4, $p = 0.953$).

3.2. All earthworms

3.2.1. Abundance

There were significant interactions between mechanical loosening and PH cultivation ($X^2 = 12.22$, d.f. = 4, $p = 0.016$), mechanical loosening and year ($X^2 = 10.61$, d.f. = 2, $p = 0.005$), and mechanical loosening, PH cultivation and year ($X^2 = 26.71$, d.f. = 4, $p = 0.008$). There was no significant interaction between PH cultivation and year ($X^2 = 0.31$, d.f. = 2, $p = 0.857$). A model containing an interaction between mechanical loosening, PH cultivation and year was not significantly different from a model containing an interaction between mechanical loosening and year ($X^2 = 16.10$, d.f. = 10, $p = 0.097$) or an interaction between mechanical loosening and PH cultivation ($X^2 = 14.49$, d.f. = 8, $p = 0.070$). The interaction between mechanical loosening and year was chosen over the interaction between mechanical loosening and PH cultivation using AIC (746.80 and 749.19, respectively). Earthworm abundance was not significantly different on shallow loosened compared to unloosened ($p = 0.281$, TukeyHSD), or deep loosened plots in 2011 ($p = 0.827$, TukeyHSD), but they were significantly lower compared to unloosened plots ($p < 0.001$, Tukey HSD), and deep

loosened plots in 2012 ($p = 0.023$, Tukey HSD) (Fig. 3A). Deep loosened plots had significantly lower earthworm abundance compared to unloosened plots in 2011 ($p = 0.012$, TukeyHSD). There was no significant effect of PH cultivation ($p = 0.050$) when included as a main effect.

3.2.2. Biomass

There was a significant interaction between mechanical loosening and year ($X^2 = 10.34$, d.f. = 2, $p = 0.006$). There were no other significant interactions; mechanical loosening and PH cultivation ($X^2 = 3.82$, d.f. = 4, $p = 0.431$), PH cultivation and year ($X^2 = 0.13$, d.f. = 2, $p = 0.936$), and mechanical loosening, PH cultivation and year ($X^2 = 19.23$, d.f. = 12, $p = 0.083$). Earthworm biomass was significantly lower in 2012 compared to 2011 in unloosened plots ($p = 0.033$, Tukey HSD) (Fig. 3B) and shallow loosened plots ($p < 0.001$, Tukey HSD). Shallow and deep loosened plots both had significant lower earthworm biomass than unloosened plots in 2011 ($p = 0.005$ and $p < 0.001$ Tukey HSD, respectively). However, only biomass in shallow loosened plots was significantly lower compared to unloosened plots in 2012 ($p = 0.001$ and $p = 0.989$ Tukey HSD, respectively). Shallow and deep loosened plots did not differ from each other in 2011 ($p = 0.998$, Tukey HSD), but did differ significantly in 2012 ($p = 0.012$, Tukey HSD). There was no significant effect of PH cultivation on earthworm biomass when included as a main effect ($X^2 = 4.51$, d.f. = 4, $p = 0.105$).

3.3. Anecic earthworm species

3.3.1. Abundance

There was a significant interaction between mechanical loosening and year ($X^2 = 15.32$, d.f. = 2, $p < 0.001$) and between mechanical loosening, PH cultivation and year ($X^2 = 26.23$, d.f. = 12, $p = 0.01$). There was no significant interaction between mechanical loosening and PH cultivation ($X^2 = 4.54$, d.f. = 4, $p = 0.337$) or between PH cultivation and year ($X^2 = 1.41$, d.f. = 2, $p = 0.493$). A model containing an interaction between mechanical loosening, PH cultivation and year was not significantly different from a model containing an interaction between mechanical loosening and

year ($X^2 = 10.91$, d.f. = 10, $p = 0.364$). The model containing the interaction between loosening and year was deemed the best fit. There was no significant difference in anecic earthworm abundance between shallow loosened and unloosened plots in 2011 ($p = 0.054$, Tukey HSD) (Fig. 4A), but earthworm abundance was significantly lower in shallow loosened plots compared to unloosened plots in 2012 ($p < 0.001$, Tukey HSD). Earthworm abundance was significantly lower in deep loosened plots in 2011 compared to unloosened plots ($p = 0.003$), but was not significantly different in 2012 ($p = 0.920$, Tukey HSD). There was no significant effect of PH cultivation on anecic earthworm abundance when included as a main effect ($X^2 = 2.69$, d.f. = 2, $p = 0.260$).

3.3.2. Biomass

There was a significant effect of an interaction between mechanical loosening and year ($X^2 = 11.71$, d.f. = 2, $p = 0.003$) on the abundance of anecic biomass. There were no other significant interactions; mechanical loosening and PH cultivation ($X^2 = 2.38$, d.f. = 4, $p = 0.665$), PH cultivation and year ($X^2 = 0.17$, d.f. = 2, $p = 0.920$), and mechanical loosening, year and PH cultivation ($X^2 = 18.73$, d.f. = 12, $p = 0.095$). Anecic earthworm biomass was significantly lower in 2012 compared to 2011 in unloosened plots ($p = 0.022$, Tukey HSD) and shallow loosened plots ($p < 0.001$, Tukey HSD) (Fig 4B). There was significantly lower anecic biomass on shallow and deep loosened plots compared to unloosened plots in 2011 ($p = 0.016$ and $p = 0.003$ Tukey HSD, respectively); in 2012 only shallow plots had significantly lower biomass compared to unloosened plots ($p < 0.001$ and $p = 0.900$ Tukey HSD, respectively). Anecic earthworm biomass was not significantly different between shallow loosened and deep loosened plot in 2011 ($p = 0.995$), but anecic earthworm biomass was significantly lower in shallow loosened plots compared to deep loosened plots in 2012 ($p = 0.005$, Tukey HSD). There was no significant effect of PH cultivation on anecic earthworm biomass when included as a main effect ($X^2 = 4.61$, d.f. = 2, $p = 0.100$).

4. Discussion

4.1. Soil physical measurements

A range of physical parameters were impacted by soil mechanical loosening, for example: shallow loosening (c. 20 cm) had a significant effect for at least two years post-treatment on MPR at 0 – 15 cm depths; and there was a significant effect of deep loosening (c. 30 cm) on MPR (15 cm -30 cm) in 2011 and 2012.

The addition of deep-rooting forbs, including legumes, is an effective method for increasing sward diversity (Spehn et al., 2000) and first became available as an Entry Level Stewardship (ELS) agri-environment option in England in early 2013 (EK21- Legume and herb-rich swards). Other studies have found improved soil structure (Latif et al., 1992) and increased macroporosity (Lesturgez et al., 2004) when deep-rooted legumes were included in maize cropping systems. However, in this study they had no significant effect on soil physical measurements or on the abundance and biomass of earthworms. Unfortunately it was not possible to disentangle the effects of power harrowing on vegetation cover from the addition of sown forbs because they were necessarily combined in the same treatment to ensure successful establishment of the sown forbs.

4.2. Earthworms

The negative effect of mechanical loosening on earthworms varied between years when all earthworms were analysed collectively and when anecic earthworms were analysed separately; there was no significant effect of PH cultivation identified by either the collective analysis, or the separate anecic analysis. Patterns across treatments were similar for both abundance and biomass.

4.2.1. Anecic species

Most of the worms sampled belonged to the deeper burrowing anecic earthworms. The effect of mechanical loosening on anecic earthworm abundance and biomass appeared to be greatest on

shallow loosened plots in 2012. The apparent delayed recovery in abundance and biomass may have been due to the disruptive nature of shallow mechanical loosening in the upper topsoil layers. As anecic species dig very deep burrows (up to six feet in length) it may be that shallow loosening treatments impacted them more than deep loosening, as shallow loosening can disrupt the surface layer and prevent access to the soil surface. Deep loosening, while initially causing disruption (i.e. in 2011), will most likely retain the upper part of burrows intact, thereby providing access to the soil surface and allowing earthworm populations to recover more rapidly. The particularly heavy rainfall in 2012 (Centre for Ecology and Hydrology, 2012) (Fig. 1B) may have caused the surface soil layer to slump thereby exacerbating the initial effect of shallow mechanical loosening. Deep loosened plots on the other hand had significantly lower abundance in 2011 compared to unloosened plots, but did not differ significantly in 2012. This suggests a potential recovery in anecic earthworm abundance two years post-mechanical loosening in deep loosened plots. The reduction in abundance and biomass may have been due to mortality of large bodied anecic earthworms linked to loosening treatments and the destruction of permanent anecic earthworm burrows (Wyss and Glasstetter, 1992).

4.3.Sampling methodology

Due to repeat sampling and additional data collection within plots, destructive sampling methods were not possible. Mustard extraction (Gunn, 1992), was chosen for its ease of preparation in the field and non-lethal effects. The same batch of mustard was used throughout to standardise the chemical composition and extractive properties of the solution between sampling attempts. The numbers of earthworms observed in this study was lower than would be expected in temperate grassland (Table 2.3 p45 (Curry, 1994)). Mustard solution may have extracted fewer earthworms than other forms of chemical extraction (Pelosi et al., 2009; Zaborski, 2003); although the efficiency of these methods may depend on soil type (Iannone III et al., 2012; Pelosi et al., 2009). There is however, general agreement that a combination of hand-sorting and chemical expulsion has the

highest efficacy (Pelosi et al., 2009). Mustard extraction is potentially biased towards anecic species (Bartlett et al., 2006; Chan and Munro, 2001) and the number of endogeic earthworms in this study may have been underestimated. The large vertical burrows created by anecic earthworms may provide greater connectivity and water infiltration at the soil surface (Edwards et al., 1992) resulting in greater exposure to the mustard solution. In comparison, horizontally burrowing endogeic earthworms may take longer to be exposed to the mustard solution and may also respond by migrating horizontally through the soil rather than to the surface (Bartlett et al., 2006).

4.4. Management implications

Mechanical loosening is a potentially useful method to alleviate soil compaction (Burgess et al., 2000; Soane et al., 1986) and maintain a range of ecosystem services, such as increased water absorption (Jin et al. 2007). However, our findings indicate that the use of mechanical loosening should be considered with the potential negative impacts on some earthworm species in mind. The experimental results reported in this paper indicate that the negative impact on earthworm populations can last for at least two years.

The aims and objectives of the Environmental Stewardship scheme in England, and its successor Countryside Stewardship (Natural England, 2015), include: to conserve wildlife including farmland birds (biodiversity) and to protect natural resources by improving water quality and reducing soil erosion and surface run-off. To meet the standards of Good Agricultural and Environmental Condition (DEFRA, 2015) soil compaction has to be avoided, while in Countryside Stewardship there is a requirement to 'remove soil compaction' when buffer strips are established by reseeding intensive grassland. The establishment of threshold values for the effects of physical and biological soil parameters associated with soil compaction on soil fauna have proved difficult (Beylich et al., 2010). This is due not only to the high variability of soil processes, but also to the variability of experimental approaches making between study comparisons, and therefore generalised recommendations, difficult (Beylich et al., 2010). However, this study suggests that mechanically

loosening a soil that is in moderate condition could have detrimental effects on local earthworm populations and further threaten the provision of important soil processes. When earthworm populations have been reduced due to conventional and minimal tillage, populations were slow to recover and affected areas were not effectively recolonised by earthworms in adjacent undisturbed field margins (Roarty and Schmidt, 2013). Where recolonisation is limited, population recovery will be through reproduction by surviving individuals.

Mild to moderately compacted soil can improve through natural climatic processes and the presence of earthworms can further improve soil structure and alleviate compaction (Capowiez et al., 2012; Joschko et al., 1989). However, soil restoration is a slow process and this ability will differ between species (Bottinelli et al., 2014). While different soils and ecological communities may respond to disturbance events differently (Ernst and Emmerling, 2009) if sustainable soil management is to be further encouraged, unjustified mechanical loosening should be avoided as it may do more harm than good.

4.5. Implications for other species

Although trends vary between regions, depending on whether arable or pastoral systems dominate, improved permanent grassland, temporary grassland and rough grazing have all declined since the 1960s (Chamberlain et al., 2000). Modern agricultural practices (Atkinson et al., 2005; Galbraith, 1988; Shrubbs, 1990) and agricultural intensification (Chamberlain et al., 2000; Donald et al., 2001) are often cited as major causes of farmland bird declines. Many species have undergone serious declines in the last 20-30 years (Gregory et al., 2004) and changes in grassland management, such as the reduction in ley grass, rough grazing, and increased stocking density are associated with declines of species closely associated with grassland (Chamberlain and Fuller, 2000; O'Brien and Smith, 1992). Management practices such as conventional and conservation tillage (Capowiez et al., 2012; Chan, 2001; Ernst and Emmerling, 2009; van Capelle et al., 2012), and intensive grazing regimes (Curry et

al., 2008) can often result in changes in the abundance, distribution and community composition of earthworms. As soil macroinvertebrates, including soil-dwelling larvae, constitute an important foraging resource for many vertebrate species (e.g. the European badger *Meles meles* (da Silva et al., 1993; Kruuk and Parish, 1981) and the red fox *Vulpes vulpes* (Macdonald, 1980)), including numerous ground probing birds (e.g. song thrush *Turdus philomelos* (Gruar et al., 2003), northern lapwing *Vanellus vanellus* (Ausden et al., 2003) and European starling *Sturnus vulgaris* (Dunnet, 1955; Rhymer et al., 2012; Whitehead et al., 1995)), these changes could have a further indirect impact on above-ground predators that may experience a change in the availability and accessibility of important below-ground prey.

5. Conclusion

This study shows a significant negative effect of mechanical loosening on the abundance and biomass of anecic earthworms. Although limited to one site and mechanical loosening in a single year, these results only support the mechanical loosening of soil in severely degraded conditions due to the potential negative impact on important soil macrofauna that could impede future soil function, as well as indirect effects for earthworm predators.

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References

- Allan, E., Bossdorf, O., 2014. Interannual variation in land-use intensity enhances grassland multidiversity. *PNAS* 111, 308–313. doi:10.1073/pnas.1312213111
- Anon, 1982. Techniques for Measuring Soil Physical Properties., Ministry of Agriculture Fisheries and Food (MAFF) Reference Book 441.
- Atkinson, P.W., Fuller, R.J., Vickery, J.A., Conway, G.J., Tallowin, J.R.B., Smith, R.E.N., Haysom, K.A., lings, T.C., Asteraki, E.J., Brown, V.K., 2005. Influence of agricultural management, sward structure and food resources on grassland field use by birds in lowland England. *J. Appl. Ecol.* 42, 932–942. doi:10.1111/j.1365-2664.2005.01070.x
- Ausden, M., Rowlands, A., Sutherland, W.J., James, R., 2003. Diet of breeding Lapwing *Vanellus vanellus* and Redshank *Tringa totanus* on coastal grazing marsh and implications for habitat management. *Bird Study* 50, 285–293. doi:10.1080/00063650309461321
- Bardgett, R.D., 2005. The biology of soil : a community and ecosystem approach. Oxford University Press, New York.
- Bartlett, M.D., Harris, J.A., James, I.T., Ritz, K., 2006. Inefficiency of mustard extraction technique for assessing size and structure of earthworm communities in UK pasture. *Soil Biol. Biochem.* 38,

2990–2992. doi:10.1016/j.soilbio.2006.04.036

Bates, D.M., Maechler, M., Bolker, B.M., Walker, S., 2015. lme4: Linear mixed-effects models using Eigen and S4.

Batey, T., 2009. Soil compaction and soil management a review. *Soil Use Manag.* 25, 335–345. doi:10.1111/j.1475-2743.2009.00236.x

Beylich, A., Oberholzer, H.-R., Schrader, S., Höper, H., Wilke, B.-M., 2010. Evaluation of soil compaction effects on soil biota and soil biological processes in soils. *Soil Tillage Res.* 109, 133–143. doi:10.1016/j.still.2010.05.010

Bilotta, G.S., Brazier, R.E., Haygarth, P.M., 2007. The Impacts of Grazing Animals on the Quality of Soils, Vegetation, and Surface Waters in Intensively Managed Grasslands, in: *Advances in Agronomy*. pp. 237–280. doi:10.1016/S0065-2113(06)94006-1

Boag, B., Palmer, L.F., Neilson, R., Legg, R., Chambers, S.J., 1997. Distribution, prevalence and intensity of earthworm populations in arable land and grassland in Scotland. *Ann. Appl. Biol.* 130, 153–165. doi:10.1111/j.1744-7348.1997.tb05791.x

Bottinelli, N., Capowiez, Y., Ranger, J., 2014. Slow recovery of earthworm populations after heavy traffic in two forest soils in northern France. *Appl. Soil Ecol.* 73, 130–133. doi:10.1016/j.apsoil.2013.08.017

Bourn, N.A.D., Thomas, J.A., 2002. The challenge of conserving grassland insects at the margins of their range in Europe. *Biol. Conserv.* 104, 285–292. doi:10.1016/S0006-3207(01)00193-8

Bradford, M.A., Tordoff, G.M., Eggers, T., Jones, T.H., Newington, J.E., 2002. Microbiota, fauna, and mesh size interactions in litter decomposition. *Oikos* 99, pp. 317–323. doi:10.1034/j.1600-0706.2002.990212.x

Burgess, C.P., Chapman, R., Singleton, P.L., Thom, E.R., 2000. Shallow mechanical loosening of a soil under dairy cattle grazing: Effects on soil and pasture. *New Zeal. J. Agric. Res.* 43, 279–290. doi:10.1080/00288233.2000.9513428

Capowiez, Y., Samartino, S., Cadoux, S., Bouchant, P., Richard, G., Boizard, H., 2012. Role of earthworms in regenerating soil structure after compaction in reduced tillage systems. *Soil Biol. Biochem.* 55, 93–103. doi:10.1016/j.soilbio.2012.06.013

Chamberlain, D.E., Fuller, R.J., 2000. Local extinctions and changes in species richness of lowland farmland birds in England and Wales in relation to recent changes in agricultural land-use. *Agric. Ecosyst. Environ.* 78, 1–17. doi:10.1016/S0167-8809(99)00105-X

Chamberlain, D.E., Fuller, R.J., Bunce, R.G.H., Duckworth, J.C., Shrubbs, M., 2000. Changes in the abundance of farmland birds in relation to the timing of agricultural intensification in England and Wales. *J. Appl. Ecol.* 37, 771–788.

Chan, K.-Y., 2001. An overview of some tillage impacts on earthworm population abundance and diversity - implications for functioning soils. *Soil Tillage Res.* 57, 179–191.

Chan, K.-Y., Munro, K., 2001. Evaluating mustard extracts for earthworm sampling. *Pedo* 278, 272–278.

Curry, J.P., 1994. *Grassland invertebrates: ecology, influence on soil fertility and effects on plant growth*. Chapman and Hall, London.

Curry, J.P., Doherty, P., Purvis, G., Schmidt, O., 2008. Relationships between earthworm populations and management intensity in cattle-grazed pastures in Ireland. *Appl. Soil Ecol.* 39, 58–64. doi:10.1016/j.apsoil.2007.11.005

da Silva, J., Woodroffe, R., Macdonald, D.W., 1993. Habitat, food availability and group territoriality in the European badger, *Meles meles*. *Oecologia* 95, 558–564. doi:10.1007/BF00317441

518 Defossez, P., Richard, G., 2002. Models of soil compaction due to traffic and their evaluation. Soil
519 Tillage Res. 67, 41–64. doi:10.1016/S0167-1987(02)00030-2

520 DEFRA, 2015. Cross compliance in England: soil protection standards.

521 DEFRA, 2014. Structure of the agricultural industry in England and the UK at June [WWW
522 Document]. Annu. time Ser. 1984 to 2014. URL
523 [https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/403045/stru](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/403045/structure-june-uktimeseries-11feb15.xls)
524 [cture-june-uktimeseries-11feb15.xls](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/403045/structure-june-uktimeseries-11feb15.xls) (accessed 5.18.15).

525 DEFRA, 2009. Safeguarding our Soils: A Strategy for England.

526 Donald, P.F., Green, R.E., Heath, M.F., 2001. Agricultural intensification and the collapse of Europe's
527 farmland bird populations. Proc. Biol. Sci. 268, 25–9. doi:10.1098/rspb.2000.1325

528 Dunnet, G.M., 1955. The breeding of the starling *Sturnus vulgaris* in relation to its food supply. Ibis
529 (Lond. 1859). 97.

530 Edwards, W.M., Shipitalo, M.J., Traina, S.J., Edwards, C.A., Owens, L.B., 1992. Role of *Lumbricus*
531 *terrestris* (L.) burrows on quality of infiltrating water. Soil Biol. Biochem. 24, 1555–1561.
532 doi:10.1016/0038-0717(92)90150-V

533 Emmerling, C., 2001. Response of earthworm communities to different types of soil tillage. Appl. Soil
534 Ecol. 17, 91–96. doi:10.1016/S0929-1393(00)00132-3

535 Ernst, G., Emmerling, C., 2009. Impact of five different tillage systems on soil organic carbon content
536 and the density, biomass, and community composition of earthworms after a ten year period.
537 Eur. J. Soil Biol. 45, 247–251. doi:10.1016/j.ejsobi.2009.02.002

538 European Parliament Council of the European Union, 2013. Decision No 1386/2013/ on a General
539 Union Environment Action Programme to 2020 “Living well, within the limits of our planet”.
540 Official Journal of the European Union L354/171 of 20 November 2013.

541 Galbraith, H., 1988. Effects of agriculture on the breeding ecology of lapwings *Vanellus vanellus*. J.
542 Appl. Ecol. 25, 487–503. doi:10.2307/2403839

543 Giller, P.S., 1996. The diversity of soil communities, the “poor man”'s tropical rainforest? Biodivers.
544 Conserv. 5, 135–168. doi:10.1007/BF00055827

545 Głąb, T., 2008. Effects of tractor wheeling on root morphology and yield of lucerne (*Medicago sativa*
546 L.). Grass Forage Sci. 63, 398–406. doi:10.1111/j.1365-2494.2008.00647.x

547 Green, R.E., Stowe, T.J., 1993. The decline of the corncrake *Crex crex* in Britain and Ireland in relation
548 to habitat change. J. Appl. Ecol. 30, 689–695. doi:10.1016/0006-3207(95)90036-5

549 Gregory, R.D., Noble, D.G., Custance, J., 2004. The state of play of farmland birds : population trends
550 and conservation status of lowland farmland birds in the United Kingdom. Ibis (Lond. 1859).
551 146, 1–13.

552 Gruar, D., Peach, W., Taylor, R., 2003. Summer diet and body condition of Song Thrushes *Turdus*
553 *philomelos* in stable and declining farmland populations. Ibis (Lond. 1859). 145, 637–649.

554 Gunn, A., 1992. The use of mustard to estimate earthworm populations. Pedobiologia (Jena). 36, 65–
555 67.

556 Håkansson, I., Voorhees, W.B., Riley, H., 1988. Vehicle and wheel factors influencing soil compaction
557 and crop response in different traffic regimes. Soil Tillage Res. 11, 239–282. doi:10.1016/0167-
558 1987(88)90003-7

559 Haygarth, P.M., Ritz, K., 2009. The future of soils and land use in the UK: Soil systems for the
560 provision of land-based ecosystem services. Land use policy 26, S187–S197.
561 doi:10.1016/j.landusepol.2009.09.016

562 Heemsbergen, D.A., Berg, M.P., Loreau, M., van Hal, J.R., Faber, J.H., Verhoef, H.A., 2004.
563 Biodiversity effects on soil processes explained by interspecific functional dissimilarity. *Science*
564 (80-.). 306, 1019–1020. doi:10.1126/science.1101865

565 Hendrickx, F., Maelfait, J.P., Van Wingerden, W., Schweiger, O., Speelmans, M., Aviron, S.,
566 Augenstein, I., Billeter, R., Bailey, D., Bukacek, R., Burel, F., Diekötter, T., Dirksen, J., Herzog, F.,
567 Liira, J., Roubalova, M., Vandomme, V., Bugter, R., 2007. How landscape structure, land-use
568 intensity and habitat diversity affect components of total arthropod diversity in agricultural
569 landscapes. *J. Appl. Ecol.* 44, 340–351. doi:10.1111/j.1365-2664.2006.01270.x

570 Heywood, V., 1995. *Global Biodiversity Assessment*. Cambridge University Press.

571 Hutchings, M.R., Harris, S., 1996. The current status of the brown hare (*Lepus europaeus*) in Britain.

572 Iannone III, B. V., Umek, L.G., Wise, D.H., Heneghan, L., 2012. A simple, safe, and effective sampling
573 technique for investigating earthworm communities in woodland soils: implications for citizen
574 science. *Nat. Areas J.* 32, 283–292. doi:10.3375/043.032.0305

575 Jin, H., Hongwen, L., Kuhn, N.J., Xuemin, Z., Wenying, L., 2007. Soil loosening on permanent raised-
576 beds in arid northwest China. *Soil Tillage Res.* 97, 172–183. doi:10.1016/j.still.2007.09.016

577 Jones, D.T., Lowe, C.N., 2012. Key to common British earthworms of amenity grasslands. *OPAL F.*
578 *Guid.*

579 Jones, R.J.A., Spoor, G., Thomasson, A.J., 2003. Vulnerability of subsoils in Europe to compaction: A
580 preliminary analysis. *Soil Tillage Res.* 73, 131–143. doi:10.1016/S0167-1987(03)00106-5

581 Joschko, M., Diestel, H., Larink, O., 1989. Assessment of earthworm burrowing efficiency in
582 compacted soil with a combination of morphological and soil physical measurements. *Biol.*
583 *Fertil. Soils* 8, 191–196. doi:10.1007/BF00266478

584 Kruuk, H., Parish, T., 1981. Feeding Specialization of the European Badger *Meles meles* in Scotland. *J.*
585 *Anim. Ecol.* 50, 773. doi:10.2307/4136

586 Latif, M.A., Mehuys, G.R., Mackenzie, A.F., Alli, I., Faris, M.A., 1992. Effects of legumes on soil
587 physical quality in a maize crop. *Plant Soil* 140, 15–23. doi:10.1007/BF00012802

588 Lavelle, P., 2012. Soil as a habitat for organisms, in: Walls, D.H. (Ed.), *Oxford Handbook of Soil*
589 *Ecology and Ecosystem Services*. Oxford University Press, pp. 7–21.

590 Lavelle, P., Bignell, D., Lepage, M., Wolters, V., Roger, P., Ineson, P., Heal, O.W., Dhillion, S., 1997.
591 Soil function in a changing world : the role of invertebrate ecosystem engineers. *Eur. J. Soil Biol.*
592 33, 159–193.

593 Lesturgez, G., Poss, R., Hartmann, C., Bourdon, E., Noble, a., Ratana-Anupap, S., 2004. Roots of
594 *Stylosanthes hamata* create macropores in the compact layer of a sandy soil. *Plant Soil* 260,
595 101–109. doi:10.1023/B:PLSO.0000030184.24866.aa

596 Macdonald, D.W., 1980. The red fox, *Vulpes vulpes*, as a predator upon earthworms, *Lumbricus*
597 *terrestris*. *Z. Tierpsychol.* 52, 171–200.

598 MAFF, 1970. *Modern Farming and the soil*. Report for the Agricultural Advisory Council on Soil
599 *Structure and Soil Fertility*. London.

600 Matson, P.A., Parton, W.J., Power, A.G., Swift, M.J., 1997. Agricultural Intensification and Ecosystem
601 *Properties*. *Science* (80-.). 277, 504–509. doi:10.1126/science.277.5325.504

602 Millennium Ecosystem Assessment, 2005. *Ecosystems and Human Well-being: Biodiversity Synthesis*.
603 *World Resources Institute*, Washington, DC. doi:10.1196/annals.1439.003

604 Mueller, L., Kay, B.D., Hu, C., Li, Y., Schindler, U., Behrendt, A., Shepherd, T.G., Ball, B.C., 2009. Visual
605 assessment of soil structure: Evaluation of methodologies on sites in Canada, China and
606 Germany. *Soil Tillage Res.* 103, 178–187. doi:10.1016/j.still.2008.12.015

607 Mulholland, B., Fullen, M.A., 1991. Cattle trampling and soil compaction on loamy sands. *Soil Use*
608 *Manag.* 7, 189–193.

609 Natural England, 2015. Countryside Stewardship Manual.

610 Newell-Price, J.P., Whittingham, M.J., Chambers, B.J., Peel, S., 2013. Visual soil evaluation in relation
611 to measured soil physical properties in a survey of grassland soil compaction in England and
612 Wales. *Soil Tillage Res.* 127, 65–73. doi:10.1016/j.still.2012.03.003

613 O’Brien, M., Smith, K.W., 1992. Changes in the status of waders breeding on wet lowland grasslands
614 in England and Wales between 1982 and 1989. *Bird Study* 39, 165–176.
615 doi:10.1080/00063659209477115

616 Oldeman, L.R., 1994. *Soil Resilience and Sustainable Land Use*. CAB International, Wallingford.

617 Peerlkamp, P.K., 1967. Visual estimation of soil structure. *West European Methods for Soil Structure*
618 *Determination*, vol. 2 (11).

619 Pelosi, C., Bertrand, M., Capowiez, Y., Boizard, H., Roger-Estrade, J., 2009. Earthworm collection from
620 agricultural fields: Comparisons of selected expellants in presence/absence of hand-sorting.
621 *Eur. J. Soil Biol.* 45, 176–183. doi:10.1016/j.ejsobi.2008.09.013

622 Pinheiro, J.C., Bates, D.M., DebRoy, S., Sarkar, D., 2015. nlme: linear and nonlinear mixed effects
623 models. R package version 3.1–120.

624 Pulleman, M., Creamer, R., Hamer, U., Helder, J., Pelosi, C., Pérès, G., Rutgers, M., 2012. Soil
625 biodiversity, biological indicators and soil ecosystem services—an overview of European
626 approaches. *Curr. Opin. Environ. Sustain.* 4, 529–538. doi:10.1016/j.cosust.2012.10.009

627 R Core Team, 2013. *R : A Language and Environment for Statistical Computing*.

628 RDS, 2004. Sward enhancement: diversifying grassland by over-sowing and slot seeding. Rural
629 Development Service. Rural Dev. Serv. Tech. Advice Note 29, 4.

630 Rhymer, C.M., Devereux, C.L., Denny, M.J.H., Whittingham, M.J., 2012. Diet of starling *Sturnus*
631 *vulgaris* nestlings on farmland : the importance of Tipulidae larvae. *Bird Study* 59, 426–436.

632 Roarty, S., Schmidt, O., 2013. Permanent and new arable field margins support large earthworm
633 communities but do not increase in-field populations. *Agric. Ecosyst. Environ.* 170, 45–55.
634 doi:10.1016/j.agee.2013.02.011

635 Shepherd, T.G., 2000. *Visual Soil Assessment. Volume 1. Field Guide for Cropping and Pastoral*
636 *Grazing on Flat to Rolling Country*. horizons.mw & Landcare Research, Palmerston North,.

637 Shrubbs, M., 1990. Effects of agricultural change on nesting Lapwings *Vanellus vanellus* in England
638 and Wales. *Bird Study* 37, 115–127. doi:10.1080/00063659009477047

639 Sims, R., Gerald, B.M., 1999. *Synopses of the British Fauna: Earthworms*. Fields Studies Council.

640 Smit, H.J., Metzger, M.J., Ewert, F., 2008. Spatial distribution of grassland productivity and land use
641 in Europe. *Agric. Syst.* 98, 208–219. doi:10.1016/j.agsy.2008.07.004

642 Smith, R., McSwiney, C., Grandy, A., Suwanwaree, P., Snider, R., Robertson, G., 2008. Diversity and
643 abundance of earthworms across an agricultural land-use intensity gradient. *Soil Tillage Res.*
644 100, 83–88. doi:10.1016/j.still.2008.04.009

645 Soane, G.C., Godwin, R.J., Spoor, G., 1986. Influence of deep loosening techniques and subsequent
646 wheel traffic on soil structure. *Soil Tillage Res.* 8, 231–237. doi:10.1016/0167-1987(86)90336-3

647 Spehn, E., Joshi, J., Schmid, B., Alpehi, J., Körner, C., 2000. Plant diversity effects on soil
648 heterotrophic activity in experimental grassland ecosystems. *Plant Soil* 224, 217–230.
649 doi:10.1023/A:1004891807664

650 Spoor, G., Tijink, F.G.J., Weiskopf, P., 2003. Subsoil compaction: Risk, avoidance, identification and

alleviation. *Soil Tillage Res.* 73, 175–182. doi:10.1016/S0167-1987(03)00109-0

Trautner, A., Van Den Akker, J.J.H., Fleige, H., Arvidsson, J., Horn, R., 2003. A subsoil compaction database: Its development, structure and content. *Soil Tillage Res.* 73, 9–13. doi:10.1016/S0167-1987(03)00095-3

Troldborg, M., Aalders, I., Towers, W., Hallett, P.D., McKenzie, B.M., Bengough, A.G., Lilly, A., Ball, B.C., Hough, R.L., 2013. Application of Bayesian Belief Networks to quantify and map areas at risk to soil threats: Using soil compaction as an example. *Soil Tillage Res.* 132, 56–68. doi:10.1016/j.still.2013.05.005

van Capelle, C., Schrader, S., Brunotte, J., 2012. Tillage-induced changes in the functional diversity of soil biota – A review with a focus on German data. *Eur. J. Soil Biol.* 50, 165–181. doi:10.1016/j.ejsobi.2012.02.005

Vickery, J.A., Tallowin, J.R., Feber, R.E., Asteraki, E.J., Atkinson, P.W., Fuller, R.J., Brown, V.K., 2001. The management of lowland neutral grasslands in Britain: effects of agricultural practices on birds and their food resources. *J. Appl. Ecol.* 38, 647–664. doi:10.1046/j.1365-2664.2001.00626.x

Warren, S.D., Thurow, T.L., Blackburn, W.H., Garza, N.E., 1986. The influence of livestock trampling under intensive rotation grazing on soil hydrologic characteristics. *J. Range Manag.* 39, 491–495. doi:10.2307/3898755

Whalley, W.R., Dumitru, E., Dexter, a. R., 1995. Biological effects of soil compaction. *Soil Tillage Res.* 35, 53–68. doi:10.1016/0167-1987(95)00473-6

White, R., Murray, S., Rohweder, M., 2000. Pilot analysis of global ecosystems: Grassland ecosystems, World Resources Institute. Washington, D.C. doi:10.1021/es0032881

Whitehead, S.C., Wright, J., Cotton, P.A., 1995. Winter field use by the European starling *Sturnus vulgaris*: habitat preferences and the availability of prey. *J. Avian Biol.* 26, 193–202.

Wyss, E., Glasstetter, M., 1992. Tillage treatments and earthworm distribution in a Swiss experimental corn field. *Soil Biol. Biochem.* 24, 1635–1639. doi:10.1016/0038-0717(92)90162-Q

Zaborski, E.R., 2003. Allyl isothiocyanate: An alternative chemical expellant for sampling earthworms. *Appl. Soil Ecol.* 22, 87–95. doi:10.1016/S0929-1393(02)00106-3

Figure 1. A) Mean monthly soil temperature at 15 cm depth, B) Mean month rainfall, error bars are ± 1 SE.

Figure 2: Evidence that the treatments used in this experiment did alter soil compaction through changes in maximum penetration resistance: A) Maximum penetration resistance N cm^{-2} 0-15 cm depth, B) Maximum penetration resistance N cm^{-2} 15-30 cm depth, C) Bulk density g cm^{-3} 10 cm depth. 2010 to 2013 data combined, error bars are ± 1 SE. Light grey = 2010, light blue = 2011, white = 2012 and dark grey = 2013.

Figure 3. The effect of loosening treatments between years on: A) all earthworm abundance, B) all earthworm biomass. Error bars are ± 1 SE. Grey = 2011, white = 2012.

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695 Figure 4. The effect of loosening treatments between years on: A) anecic earthworm abundance, B)

696 anecic earthworm biomass. Error bars are ± 1 SE. Grey = 2011, white = 2012.

Table 4: Mean earthworms per m² sampled in each treatment, ± 1 SE.

Species	Year	Treatments								
		1	2	3	4	5	6	7	8	9
<i>L. terrestris</i>	2011	15.54 $\pm$ 2.41	10.82 $\pm$ 3.12	11.10 $\pm$ 2.18	19.43 $\pm$ 2.65	11.38 $\pm$ 2.39	8.33 $\pm$ 0.81	13.60 $\pm$ 2.24	8.88 $\pm$ 1.97	9.44 $\pm$ 2.04
	2012	9.44 $\pm$ 1.06	2.22 $\pm$ 0.91	6.66 $\pm$ 1.28	8.83 $\pm$ 1.06	2.22 $\pm$ 0.91	9.44 $\pm$ 2.10	9.99 $\pm$ 3.33	1.67 $\pm$ 1.06	3.33 $\pm$ 0.64
<i>A. longa</i>	2011	1.67 $\pm$ 0.91	6.66 $\pm$ 2.30	3.89 $\pm$ 1.67	4.44 $\pm$ 1.26	3.89 $\pm$ 1.17	1.11 $\pm$ 0.73	5.27 $\pm$ 2.26	0.83 $\pm$ 0.41	0.83 $\pm$ 0.58
	2012	3.33 $\pm$ 1.11	0.55 $\pm$ 0.56	4.44 $\pm$ 1.57	3.33 $\pm$ 0.64	2.22 $\pm$ 1.28	2.22 $\pm$ 2.22	4.99 $\pm$ 2.92	2.78 $\pm$ 1.67	5.00 $\pm$ 1.06
<i>A. chlorotica</i>	2011	5.83 $\pm$ 1.51	8.60 $\pm$ 2.12	6.11 $\pm$ 1.91	6.11 $\pm$ 2.04	6.11 $\pm$ 1.31	5.27 $\pm$ 2.10	7.22 $\pm$ 1.31	3.61 $\pm$ 0.93	4.16 $\pm$ 1.59
	2012	7.77 $\pm$ 1.11	6.11 $\pm$ 3.06	9.44 $\pm$ 2.78	10.55 $\pm$ 3.89	5.55 $\pm$ 2.13	9.44 $\pm$ 3.55	9.44 $\pm$ 2.92	1.11 $\pm$ 0.64	11.10 $\pm$ 1.28
<i>O. cyaneum</i>	2011	0.28 $\pm$ 0.28	0	0.28 $\pm$ 0.28	0.83 $\pm$ 0.58	0.55 $\pm$ 0.55	0	0.83 $\pm$ 0.83	0	0
	2012	0	0	0.55 $\pm$ 0.55	2.78 $\pm$ 1.40	0.55 $\pm$ 0.55	0.55 $\pm$ 0.55	0	0	0
<i>A. caliginosa</i>	2011	0.63 $\pm$ 0.41	0.55 $\pm$ 0.36	1.11 $\pm$ 0.84	0.83 $\pm$ 0.58	1.94 $\pm$ 1.06	0.55 $\pm$ 0.55	0.55 $\pm$ 0.55	0.28 $\pm$ 0.28	0
	2012	0	0.55 $\pm$ 0.55	0	2.78 $\pm$ 2.10	0	0	1.67 $\pm$ 1.06	0	0
<i>A. rosea</i>	2011	3.30 $\pm$ 1.76	3.03 $\pm$ 1.17	0.28 $\pm$ 0.28	3.30 $\pm$ 1.10	1.65 $\pm$ 1.08	1.65 $\pm$ 0.81	0.83 $\pm$ 0.83	0.83 $\pm$ 0.58	1.65 $\pm$ 0.91
	2012	1.10 $\pm$ 0.64	1.65 $\pm$ 1.05	1.65 $\pm$ 1.05	2.75 $\pm$ 1.65	1.10 $\pm$ 0.64	3.30 $\pm$ 2.11	3.30 $\pm$ 1.10	1.10 $\pm$ 1.10	1.65 $\pm$ 1.05
<i>L. rubellus</i>	2011	0	0.83 $\pm$ 0.41	0.83 $\pm$ 0.58	1.67 $\pm$ 1.09	0.83 $\pm$ 0.41	1.39 $\pm$ 0.93	1.94 $\pm$ 0.78	0.55 $\pm$ 0.36	0.55 $\pm$ 0.36
	2012	0	0	0	0.55 $\pm$ 0.55	0.55 $\pm$ 0.55	0.55 $\pm$ 0.55	0	0	0
Unidentified	2011	12.49 $\pm$ 3.41	15.54 $\pm$ 2.78	13.32 $\pm$ 2.91	22.76 $\pm$ 5.07	16.65 $\pm$ 3.96	11.10 $\pm$ 2.41	16.10 $\pm$ 4.11	8.88 $\pm$ 1.73	14.43 $\pm$ 4.34
juveniles	2012	24.98 $\pm$ 5.39	14.99 $\pm$ 1.40	21.09 $\pm$ 4.67	18.87 $\pm$ 4.20	18.32 $\pm$ 2.78	19.43 $\pm$ 8.66	22.20 $\pm$ 7.74	8.88 $\pm$ 0.91	19.98 $\pm$ 3.74