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RESEARCH ARTICLE

Can pasture-fed livestock farming practices improve the ecological condition of grassland in Great Britain?

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Abstract

1. Livestock farming in Great Britain (GB) faces multiple pressures. Yet, grassland managed for livestock is the most extensive habitat in GB and is key to cultural landscapes and their biodiversity and soil health.
2. This study analysed a nationally representative dataset of over 940 large (200 m^2) Neutral (agriculturally semi-improved) and (agriculturally) Improved Grassland plots from the GB Countryside Survey (CS) to assess relationships between key grassland sward and soil variables. Analysis also looked at how these variables changed over time as plots switched between these grassland types. Data from grassland plots managed by Pasture-Fed Livestock Association (PFLA) farmers were compared to CS plot data to assess the impacts of their practices on these variables.
3. Plant species richness in Neutral grassland types in CS plots was positively associated with total soil invertebrate abundance (total taxa) and soil N and C and negatively associated with soil P. There were negative relationships between the covers of *Lolium* sp. (Neutral only), legumes and forbs and soil C and moisture variables.
4. Grassland swards on PFLA member farms were characteristic of Neutral grassland. PFLA plots were more species rich and contained more legume and forb species and lower proportions of *Lolium perenne* than those on Improved Grassland. Vegetation height was greater in PFLA plots than in CS plots of either Improved or Neutral Grassland. Unlike CS Neutral Grassland plots, soil properties in PFLA plots were not significantly different from those for Improved Grassland for any measured variable (soil carbon concentration [C], bulk density, pH, nitrogen [N], phosphorus [P]).
5. Higher species richness in grasslands is associated with positive measures of soil health. PFLA plant communities contain relatively high species richness and tall vegetation, which is positive for biodiversity. Lack of positive measures of soil health associated with higher species richness recorded in PFLA grassland (as opposed

to CS grassland) may reflect time lags in soil responses to management, as evidenced through an analysis of the impacts of land-use change over time on CS plot characteristics. Our findings indicate that pasture-fed livestock approaches may be beneficial for grassland and wider ecosystems.

KEYWORDS
above-/below-ground interactions, pasture-fed, soil properties, sward composition, vegetation height

1 | INTRODUCTION

Livestock farming currently faces multiple pressures. A strong global environmental lobby on the climate impacts of meat and dairy production (Happer & Wellesley, 2019; Willett et al., 2019), low income levels (Wray, 2019), the potential impacts of leaving the European Union (EU), and land pressure for tree planting mean that livestock farmers in Great Britain (GB) are under pressure. Paradoxically, as GB's most extensive land cover type (Carey, Wallis, Chamberlain, et al., 2008), grassland and grassland farming are hugely significant for both farmers and the wider public, both in terms of the food produced and the multiple ecosystem functions and services which grassland provides (UKNEA, 2011). Grasslands play an important role in anchoring stable and productive soils and have been part of the GB landscape (along with associated grazing animals) for millennia (Sandom et al., 2014). Grassland soils absorb and filter water, cycle nutrients and store carbon on a large scale (Hewins et al., 2018). Grasslands provide habitats and food sources for a wide range of biota (Bullock et al., 2011), and are important at both field and landscape scales for the provision of cultural (Herrero et al., 2016) and other supporting and regulatory services (Sollenberger et al., 2019). Across large parts of rural GB, grassland livestock farming underpins rural communities, including income from tourism. In 2020, as it was coming out of the EU, the United Kingdom had the largest number of sheep and the third largest number of cattle of all EU countries. GB's agricultural grasslands and their management are also significant for the (primarily EU) countries to which GB meat is exported (Defra, 2020), both in terms of displacing emissions relating to livestock food products and potentially allowing grasslands in those countries to be less intensively managed.

In natural grassland systems, the co-evolution of plants and herbivores results in highly resilient grazed ecosystems that can support very high levels of herbivory (Du Toit & Cumming, 1999; Frank, 1998). Key elements of these grazed ecosystems include spatial and temporal variation in plant diversity and forage supply, topography, soils and rainfall, as well as variability amongst grazers. GB grasslands have been shaped by farming for thousands of years (UKNEA, 2011). Grazed grasslands in GB fall into one of four Broad Habitat classifications: Acid, Calcareous, Neutral and Improved grasslands (Jackson, 2000). These grasslands vary in terms of 'naturalness', with those classified according to underlying soil conditions (including Neutral Grassland) less impinged upon by agricultural management (including soil pH and fertility amendments) than intensively managed Improved Grassland. The term 'Improved' refers to the agricultural status of the grassland having been 'Improved' for productivity, rather than to an ecological measure of improvement.

In GB, as elsewhere globally, grassland 'improvement' has been arrived at through intensive management. In GB, farming advisory bodies advise farmers to reseed grassland swards regularly, in order to improve pasture yield and quality (McConnell, 2019) with benefits lasting between 5 and 10 years over those of an existing sward. Perennial ryegrass (*Lolium perenne*) is the forage species most widely sown (sometimes alongside a clover species) in temperate pastures due to its adaptability, yield and ease of establishment (McDonagh et al., 2016). It has also been the most commonly encountered plant species across GB in the last three Countryside Surveys (CSs) (1990, 1998 and 2007) (Carey, Wallis, Emmett, et al., 2008). CS is an ecological survey of GB which in 2007 consisted of a randomly stratified representative sample of 591, 1-km squares sampled in detail. An average of 32 plots are recorded in each 1 km, including five large random plots (200 m^2) representing large parcels of land (e.g. agricultural fields), data from which form part of this study. These plots are revisited in each survey, thereby enabling an analysis of change in vegetation and soils over time.

The prevalence of perennial ryegrass as a forage 'crop' is highly linked to significant loss of biodiversity, greenhouse gases emissions (particularly methane from livestock systems), land degradation and long-term degradation of rivers and seas from excess phosphorus (Herrero et al., 2016; IPBES, 2019; IPCC, 2019; Withers et al., 2019). Ryegrass responds well to high N fertility (King et al., 2012), with much of grassland research over recent decades focused on breeding of this (and related) species for enhanced yield in response to mineral fertilizers, and only more recent emphasis on forage quality and (to a lesser extent) persistence (Marshall et al., 2016). Little investment has been made into the development of resilient, productive and diverse swards for grassland.

Farmers across the GB livestock sector are recognizing the need to both highlight the positive aspects of livestock production as part of wider farming systems and to improve their agro-ecological performance. One farmer group, the Pasture-Fed Livestock Association (PFLA), is actively pursuing relevant research to evidence their practices. The PFLA has its own set of certification standards (as set out on the pastureforlife.org website) that address a wide range of environmental and animal health concerns including effective management and monitoring of soil health. The standards also (a) prohibit the use of monocultures and promote diverse and species-rich pastures and (b) state that pasture management must encourage biodiversity and reflect the importance of herbs and other native species within grass swards. The standards build on research by farmers and researchers that has shown the positive benefits of diverse swards for biodiversity, animal and soil health and for resilience of production (Balvanera et al., 2006; Hooper et al., 2005).

In this research, we sought to explore the large nationally representative CS grassland dataset to better understand relationships between soil and vegetation metrics and to investigate how shifts to or from more or less intensively managed grasslands between surveys in 1990 and 2007 (potentially mirroring a shift from intensive to PFLA production methods) were linked to those metrics.

These analyses provided a context and a counterfactual for evidencing how grassland is managed by PFLA farmers compared to grassland in the wider GB countryside. The study included data from 56 PFLA farmers (collected in 2018), who either are or intend to become certified producers. Common methodologies were used to enable results to be compared to those from the CS dataset (referred to above) in 2007. Relationships between soil and vegetation measures (as above for CS) were also analysed.

2 | MATERIALS AND METHODS

Farmer members of the PFLA were recruited to take part in the study. All were livestock farmers with over 95% farming beef. Farmers were recruited through two methods: (1) an internet (Google) forum to which all members have access, and (2) direct e-mail contact through the PFLA organization. Farms across GB (Figure 1) were sampled between May and September in 2018. In total, 56 farms took part in the survey, 28 of the farms were fully certified, four were provisionally certified and the remaining 24 were members only, with intentions to become certified producers in the near future. Farmers were interviewed about their farming practices, to help establish the type and longevity of pasture management, fertilizer use and grazing management. On-farm sampling included soil and vegetation using methods from the CS 2007 (see Emmett et al., 2008; Maskell, Norton, Smart, Scott, et al., 2008; Wood et al., 2017). CS samples a large number of 'typically managed' grassland fields across GB, and specific management information is not collected for every field surveyed. In each field, a large (200 m^2) randomly positioned plot (marked pre-visit) is sampled for plant species presence and cover, vegetation height and locational information, all of which are recorded in a series of nested quadrats. Soil characteristics are sampled using a soil core (15 cm length and 7 cm diameter). Plots were assigned to a Broad Habitat (Jackson, 2000) in the field using the CS vegetation key (Maskell, Norton, Smart, Carey, et al., 2008). Vegetation sampling included recording all species present and their visually estimated canopy cover (cover) within nested subplots within the 200 m^2. Vegetation height category was recorded as a modal value for each plot in the following categories (0–5 cm, >5–15 cm, >15–40 cm, >40 cm–1 m, >1 m). A single soil core (15 cm depth and 7 cm diameter) was taken from within each sampling plot. Soil cores from PFLA farms were tested for a range of properties in line with soil analysis protocols from CS (Emmett et al., 2008) (but excluded some measures made in CS). Measured properties on soils from PFLA farms included bulk density, soil C, total N, pH, Olsen and total P. Additional measures for CS soils (included in the analysis comparing soil and vegetation properties) were soil moisture and total soil invertebrate abundance in the sample. These were not included in the PFLA sample due to cost. CS soils and vegetation data are available through the NERC Environmental Information Data Centre (Bunce et al., 2014; Emmett, Reynolds, Chamberlain, Rowe, Spurgeon, Brittain, Frogbrook, Hughes, Keith, et al., 2016; Emmett, Reynolds, Chamberlain, Rowe, Spurgeon, Brittain, Frogbrook, Hughes, Lawlor, et al., 2016). Whilst there is a clear temporal disparity between PFLA and CS datasets, the scale (over 940 large plots on grassland) and spatial representativeness (GB) of CS make it a very robust and suitable dataset for comparison, with only minor changes in the variables compared here recorded between previous surveys in 1998 and 2007, for example a change in species richness of <1 (0.4) species in Improved Grassland across that time period (Carey, Wallis, Chamberlain, et al., 2008). Management, in terms of grassland inputs, changed little across the period 2007–2019 (Defra, 2019).

Where possible, plot location on the PFLA farms was determined pre-visit (using maps provided by the farmer) and validated on site (to check that an atypical field had not been selected). Where maps had not been provided, locations were chosen on the farm prior to seeing the field. Surveyors recorded information on the field characteristics as per CS (i.e. Broad Habitat, vegetation height etc.) and collected data from the farmer during the visit regarding current and historic field management practices including data on sward longevity, grazing management type (set-stocking, rotational etc.) and inputs.

No permissions, beyond those provided by farmers, were required.

2.1 | Analysis

2.1.1 | Vegetation/soil relationships

Generalized Additive Modelling (GAM) (Hastie & Tibshirani, 1990) in R (R Core Team, 2019) was used to analyse relationships between soil and vegetation variables for CS Improved and Neutral grasslands separately and for the PFLA plots (see Section 3.3). Species richness was log-transformed and cover data square root-transformed. In the CS analyses, the 1-km square was added as a random effect to account for spatial autocorrelation between plots within squares. Where species richness was the response variable, a Poisson distribution was used. GAMs were plotted to assess the shape and direction of the curve (as reported in Table 2). GAMs were used in this analysis as they allow for unconstrained and smooth nonlinear relationships. The ranges of the covariates used in the analysis were comparable for all three grassland types with the exception of soil carbon concentration, where the

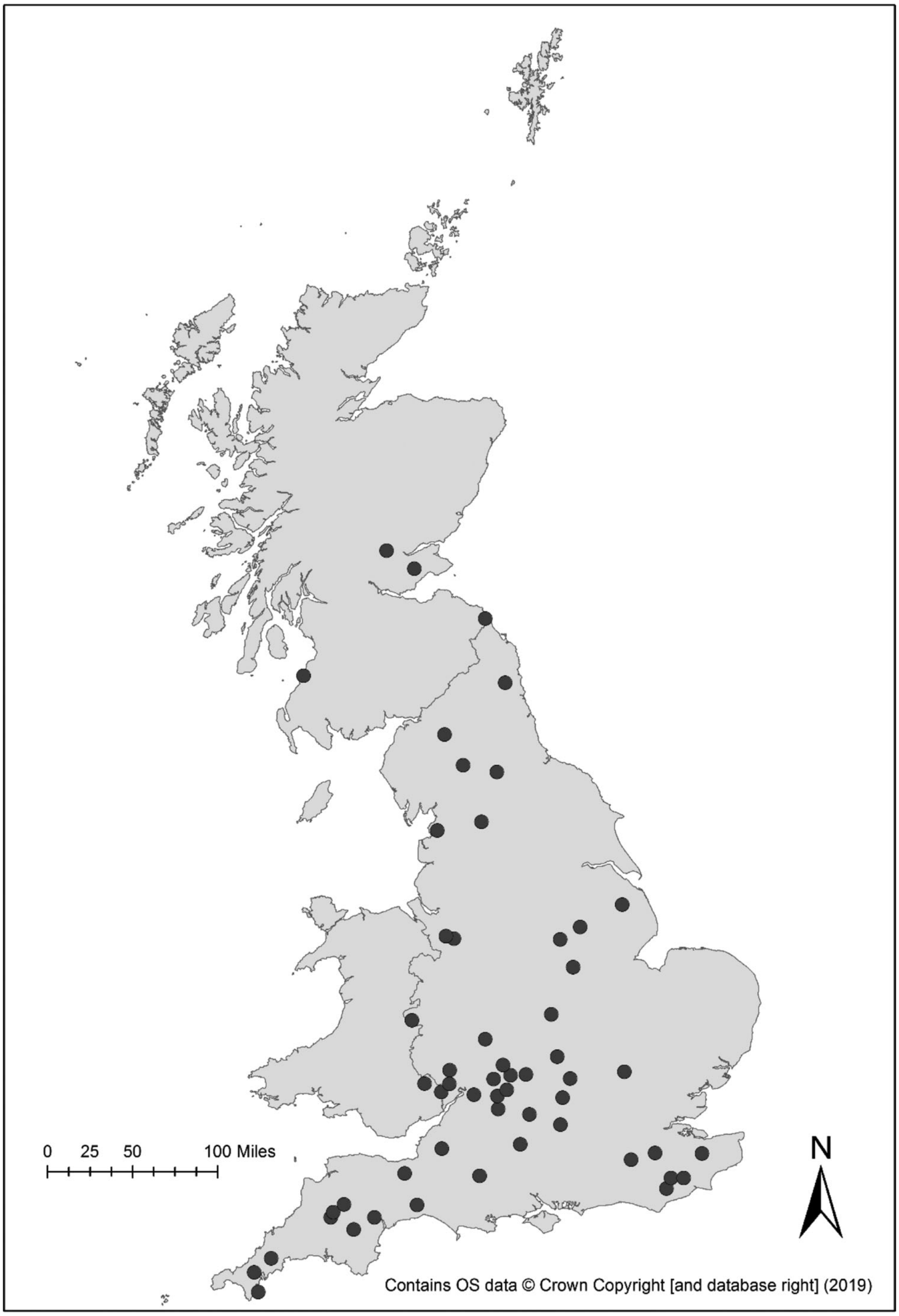

FIGURE 1 Locations of PFLA member farms sampled in 2018

maximum for the PFLA soils was only around one third of that of the Improved and Neutral Grassland sampled in CS.

Because the height data were categorical rather than continuous (i.e. GAM's not appropriate), linear mixed-effects models in R package nlme (Pinheiro et al., 2007; R Core Team, 2019) were carried out to investigate the relationships between vegetation height and other vegetation and soil variables for CS Improved and Neutral grasslands and for the PFLA plots (see Section 3.3).

2.1.2 | PFLA farms in context

PFLA data were initially screened on the basis of Broad Habitat types to establish adequate sample sizes for comparison with CS data. The majority of PFLA plots fell into either Neutral (n = 42) or Improved (n = 9) Grassland categories, with a small number of plots recorded as either Calcareous (n = 4) or Acid (n = 1) grassland. Because of their limited representation in the sample and potential impact on the analysis (in particular, calcareous soils generally have high levels of plant diversity and are very uncommon in the CS sample), samples from Acid and Calcareous grasslands were excluded from all subsequent analyses.

A number of metrics were derived from the vegetation plot data including total plant species richness, forb (herbaceous flowering plant) and legume richness; canopy covers of forbs, legumes, all grasses (including *Lolium* sp.), ryegrass only (*L. perenne* and *Lolium multiflorum*, hereafter referred to as *Lolium* sp.) and the number of grassland indicator species. Grassland indicator species were identified from Common Standards Monitoring guidance produced by the UK government advisory body on conservation and the Joint Nature Conservation Committee and refined in consultation with the Botanical Society of the British Isles to create a list of plants indicative of habitats of high conservation value (see Maskell et al., 2019). Each quadrat was also given a cover-weighted mean Ellenberg indicator value for fertility (N), light (L), moisture (F) and pH (R) based on Hill et al. (2004).

To enable comparisons between PFLA farms and the wider context of GB grasslands, comparable data on vegetation and soils in CS were extracted for all plots recorded in both Improved and Neutral grassland types. Analysis was carried out with plots from the 2007 survey, as these represent the most spatially representative set of plots that are closest in time to the PFLA sample. The total number of plots from CS was considerably higher than that in the PFLA sample (618 Improved, 323 Neutral).

A multivariate ordination analysis (Principal Components Analysis (PCA)) of the relationships between plant and soil metrics was undertaken using Canoco (ter Braak and Smilauer, 2002) for both datasets. The vegetation characteristics were used as response variables with soil variables, presence of livestock (from CS data) and survey identity (PFLA or CS) all superimposed as supplementary variables.

Differences in vegetation and soil variables between CS Improved and Neutral Grassland plots and the PFLA plots were analysed using linear mixed-effects models in the R package nlme (Pinheiro et al., 2007; R Core Team, 2019). Post hoc comparisons were carried out to test the differences across the different groups/treatments with a Tukey correction used to account for multiple testing.

2.1.3 | Impacts of land-use change over time on soil/vegetation characteristics (CS plots)

We tested for differences in the soil and vegetation characteristics (analysed above) of groups of CS grassland plots which either (i) changed between Neutral and Improved Grassland, (ii) remained the same or (iii) were converted from arable to Neutral or Improved Grassland between 1990 and 2007. Data were extracted and analysed using similar methods as above (linear mixed-effects models in the R package nlme [Pinheiro et al., 2007; R Core Team, 2019] with a Tukey correction).

3 | RESULTS

3.1 | Field management (S3)

Farmer interviews revealed that 47 of the 56 PFLA fields were managed as permanent pasture; the remaining nine were managed as temporary leys. Permanent pastures tended to be long term, with around a third over 50 years as pasture (with no re-sowing) and the remaining having been pasture for over 10 years. Forty-seven of the 56 fields were not fertilized with mineral fertilizers in the year of the survey and 18 were fertilized with organic fertilizers, primarily manure. On the nine fields on which mineral fertilizers were used, levels of nitrogen application were low, varying from 2 to 65 kg/ha. A higher proportion of farmers managing Improved Grassland used mineral fertilizers (30%) than those managing Neutral Grassland (14%). Except for one farmer (certified for 1 year only), farmers using mineral fertilizer were not certified PFLA practitioners (S3). Thirty of the sampled fields involved the use of a grazing system which involved dividing fields into grazing units (paddock, strip, mob) as opposed to the 24 fields on which set stocking, variable grazing (changing livestock types and densities) or rotational grazing was practised (no information was given for the further two fields).

3.2 | Vegetation/soil relationships

The results of analyses to investigate relationships between co-located soil and vegetation variables for CS plots in Improved and Neutral Grassland (in 2007) and PFLA plots are shown in Table 1.

3.2.1 | CS Improved and Neutral

CS improved

Results indicated negative relationships between the covers of legumes and forbs and soil C and moisture variables, a positive unimodal relationship between *Lolium sp.* cover and soil P and a negative U-shaped relationship between species richness and soil P. Indicator species richness was positively associated with soil C, but negatively associated with soil P. Higher overall species richness was positively associated with soil moisture. Vegetation height was positively associated with soil moisture, C, N and total invertebrate abundance (S1).

CS Neutral

Results were broadly similar to those for Improved grassland. Notable exceptions included a significant negative relationship between the cover of *Lolium* sp. and soil C and a significant positive relationship between total species richness and soil C (Table 1). Total plant species richness was also positively associated with soil N and total soil invertebrate abundance (numbers of invertebrates present) in soils.

TABLE 1 Vegetation–soil relationships for CS and PFLA plots in Improved and Neutral Grassland analysed using Generalized Additive Models

	Lolium cover		Legume cover		Forb cover		Legume species richness		Total species richness		Indicator species richness	
Logged	*F*	Dir	*F*	Dir	*F*	Dir	*F*	Dir	*F*	Dir	*F*	Dir
CS Improved												
Carbon concentration	ns		4.4*	–	5.6*	–	n s		Ns		12.5***	+
Soil moisture	4.4*	–	3.8*	–	4.1**	–	n s		4.8*	+	Ns	
Soil P	7.8***	∩	n s		ns		31.6***	–	11.3***	u	18.9***	–
Soil N	ns		n s		ns		4.8*	(–)	Ns		ns	
Total taxa	ns		ns		ns		s		Ns		ns	
CS Neutral												
Carbon concentration	12.1***	–	4.9*	–	4.8*	–	ns		9.5**	+	14.6***	+
Soil moisture	4.4*	–	11.1***	–	9.95**	–	ns		ns		ns	
Soil P	ns		5.9*	–	ns		12.8***	–	22.8***	–	16.6***	–
Soil N	ns		ns		ns		ns		5.4*	+	11.9***	+
Total taxa	ns		ns		ns		ns		5.3*	+	ns	
PFLA												
Carbon concentration	ns ($p = 0.07$)	(–)	ns		ns		ns		ns		ns	
Soil P	10.5**	+	3.8 ($p = 0.06$)	–	6.8*	–	15.6***	–	10.4**	–	20.5***	–
Soil N	ns		5.7*	–	ns				ns		ns	

Abbreviations: Total taxa, total soil invertebrate abundance. Dir, direction of response (+ positive, - negative); ns, non significant
Significance: ∩, U, shape of the relationship, $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

Since results relating to forb cover were somewhat surprising, that is higher forb cover associated with low soil C and moisture, analyses were carried out excluding agriculturally undesirable 'weed' species (*Cirsium vulgare*, *Rumex* sp.) to test whether these species were affecting the relationships between soil variables and forb cover. Results (not shown) indicated no effects of these species on the relationships shown in Table 1. Vegetation height was positively associated with soil moisture, soil N and total soil invertebrate abundance (S1).

3.2.2 | Pasture-Fed Livestock Association

As for CS plots, results indicated a significant positive relationship between soil P and the cover of *Lolium* sp. and significant negative relationships between soil P and a range of vegetation metrics consistent with higher biodiversity. Results also included a near significant negative relationship between *Lolium* cover and soil C (as found in the CS Neutral grassland plots) and a significant negative relationship between soil N and legume cover not found for the CS grassland types. Forb richness was higher in PFLA plots with vegetation between 40 cm and 1 m high than in plots with shorter vegetation (5–15 cm) (S1). A positive relationship between vegetation height and species richness was not significant.

3.3 | PFLA farms in context

The majority (82%) of PFLA plots (excluding those in Acid and Calcareous Grassland) were classified as Neutral Grassland. In CS 2007, almost twice as many plots were recorded in Improved than Neutral Grassland. On average, farmers with Improved Grassland had been PFLA members (2.8 years) and/or practitioners (0.7 years) for around a year less than farmers with Neutral Grassland (3.8 years members, 1.7 years practitioners) (S3). Figure 2 shows an ordination of the PFLA and CS plots which were classified as either Improved or Neutral Grassland, together with key plant and soil variables. There is a great deal of overlap between plots on PFLA fields and plots on both Neutral and Improved Grassland in CS. Axis 1 indicates a gradient between more intensively managed Improved Grassland on the left and more neutral higher diversity grassland on the right. Axis 2 is associated with soil pH, with more acid, high C soils towards the top and more alkaline soils with higher forb and legume cover towards the bottom.

Lolium perenne was the most commonly found species, found in 100% of PFLA plots and 90% of CS plots. *Lolium perenne* also had the highest species cover in both PFLA (30%) and CS plots (Improved 47%, Neutral 20%). *Trifolium repens* was present in ~80% of grassland plots in CS (85% in Improved and 75% in Neutral) covering ~10% of the plot area and *Trifolium pratense* was present in 14% of Improved and 26% of Neutral plots at low covers (~3%). In PFLA farms, *T. repens* was present in 75% of plots covering ~12% of the plot area and *T. pratense* was present in 45% of Neutral plots at low covers (~ 1%) and in <1% of plots

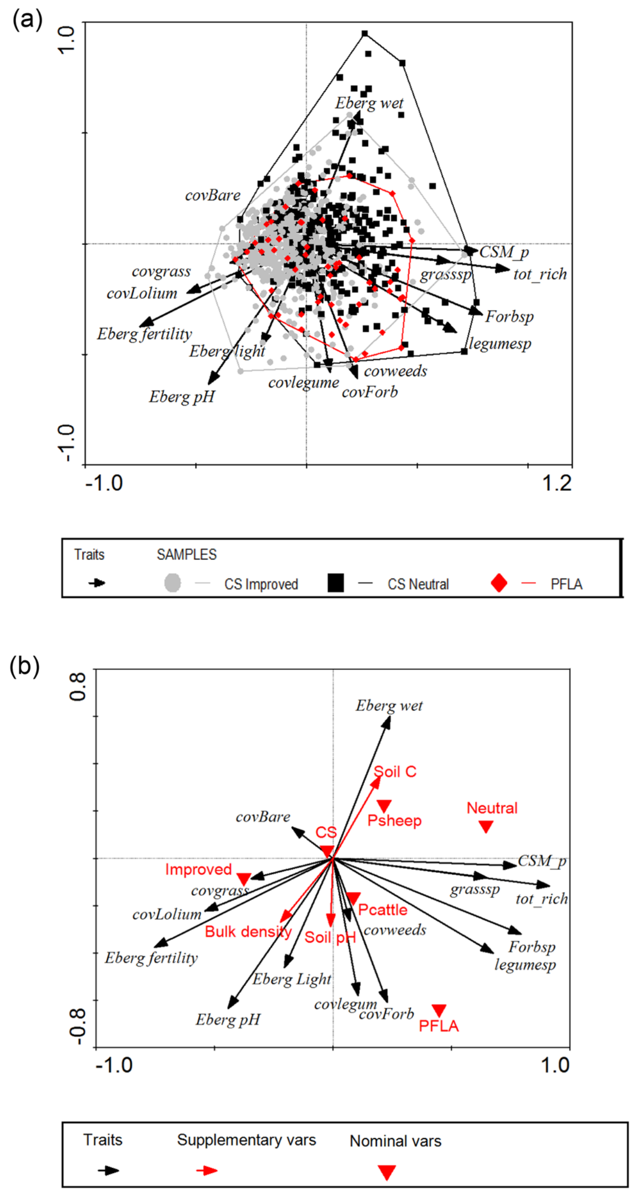

FIGURE 2 A multivariate analysis (PCA) of the spatial relationships between plant and soil metrics for Countryside Survey (CS) and PFLA plots. Response variables—plant characteristics (blue arrows and text), soil characteristics (red arrows and text) and management variables (red triangles and text)—have been added as supplementary variables. Panel (a) includes sample sites coloured by survey and habitat type and grouped into envelopes; panel (b) shows species and supplementary variables only. Variable labels: Eberg wet, Ellenberg wetness score; Eberg fertility, Ellenberg fertility score; Eberg pH, Ellenberg pH score; Eberg L, Ellenberg light score; covBare, cover of bare ground; covLolium, cover of Lolium; covgrass, cover of grass; covlegume, cover of legumes; covForb, cover of forbs; covweeds, cover of weeds; grasssp, grass species richness; legumesp, legume species richness; Forbsp, forb species richness; Tot_rich, total species richness; CSM_P, presence of grassland Condition Standards Monitoring species. Additional variables: covLolpe, cover of Lolium perenne; CS, CS plots; PFLA, PFLA plots; soil C conc, soil carbon concentration; Improved, Improved grassland (CS); Neutral, Neutral grassland CS; Psheep, presence of sheep; Pcattle, presence of cattle

TABLE 2 Results of tests for differences between soil and vegetation parameters in plots on (a) Improved grassland in CS (Imp), (b) Neutral grassland in CS (Neu) and (c) PFLA fields

	CS Improved	CS Neutral	PFLA	Significance
Vegetation				
Eberg N	5.6***	5.1*	5.41**	All different to one another
Eberg L	7.05	6.98***	7.07	CS Neutral different to CS Imp and PFLA
Eberg Wet	5.39	5.51***	5.34	CS Neutral different to CS Imp and PFLA
Eberg pH	6.03	5.82***	6.1	CS Neutral different to CS Imp and PFLA
Legume richness	1.14***	1.64	1.94	CS Improved different to CS Neu and PFLA
Forb richness	8.33***	11.73	10.1	CS Improved different to CS Neu and PFLA
Total richness	14.74***	21.74	20.78	CS Improved different to CS Neu and PFLA
CSM	0.27***	1.07	1.2	CS Improved different to CS Neu and PFLA
Grass cover	81.44***	72.89	74.5	CS Improved different to CS Neutral
Lolium cover	43.33***	14.25***	29.8***	All different to one another
Forb cover	17.2	19.2	33.5***	PFLA different to CS Imp and CS Neu
Bare ground	5.54	5.78	6.65	ns
Vegetation height	15.4***	28.9	34.9	CS Improved different to CS Neu and PFLA
Soil				
Soil pH	6.25	6.16	6.18	ns
Soil carbon conc.	57.8	66.9*	52.6	CS Neutral different to CS Imp
Soil bulk density	0.96	0.89***	0.96	CS Neutral different to CS Imp
Soil % N	0.45	0.48	0.51	ns
Soil P	29.9	23.1*	21.9	CS Neutral different to CS Imp

Note: Tests for significance were carried out using linear mixed-effects models.
Abbreviations: Eberg N, Ellenberg fertility score; Eberg L, Ellenberg light score; Eberg wet, Ellenberg wetness score; Eberg pH, Ellenberg pH score; CSM, presence of grassland Condition Standards Monitoring species.
Significance: *$p \leq 0.05$, **$p \leq 0.01$, and ***$p \leq 0.001$.

at 50%. One of the most common herb species recorded in CS was *Plantago lanceolata*, which was recorded in <20% of plots at a cover of <5%. In PFLA plots, cover was also <5%, but it was present in 47% of plots.

Table 2 summarizes the results of linear mixed models on soil and vegetation variables between the PFLA farms and CS data for Improved and Neutral Grassland. There were significant differences between the PFLA plots and CS Improved Grassland plots for many of the measured vegetation variables. These included a measure of the response of vegetation to soil fertility (Ellenberg N) and the cover of *Lolium* sp. (both higher in Improved Grassland); legume, forb and total species richness; vegetation height; forb cover and the number of positive grassland indicators present (CSM), all of which were higher in PFLA plots (see Figure 3) than in CS Improved Grassland plots. There were no differences between PFLA plots and Improved Grassland for the cover of grass species and for the other Ellenberg vegetation measures or the extent of bare ground. Vegetation height and forb cover were also greater in PFLA plots than in CS Neutral Grassland plots. Overall, although PFLA plots were mainly Neutral grassland, there were more differences between CS Neutral and Improved Grassland plots than there were between PFLA plots and Improved Grassland plots. It is worth noting, however, that the number of PFLA plots was considerably lower than that of CS plots, decreasing the likelihood of significant differences between PFLA plots and CS grassland plots, even where averages for PFLA were comparable to those for Neutral Grassland. For soil variables (C, bulk density, N, pH, P), there were no significant differences between the PFLA plots and CS Improved Grassland plots (although differences for soil P were almost significant, with P levels lower in PFLA plots than they were in Neutral Grassland plots) (Table 2; Figure 3). Differences between Neutral and Improved Grassland plots for swards and soils were, as would be expected, indicative of agricultural intensity being higher on Improved than on Neutral Grassland including higher grass cover, soil P and bulk density and lower soil C (Table 2; Figure 3).

3.4 | Impacts of land-use change over time on soil/vegetation characteristics (CS plots)

Analysis of these variables in CS plots which moved between Neutral and Improved Grassland or stayed in the same grassland types across the period 1990–2007 revealed that whilst variability within these groups of plots was high (as indicated in box plots with confidence intervals in S2), in general, the starting point in 1990 had a continuing influence on plot characteristics in 2007. Hence, plots that stayed

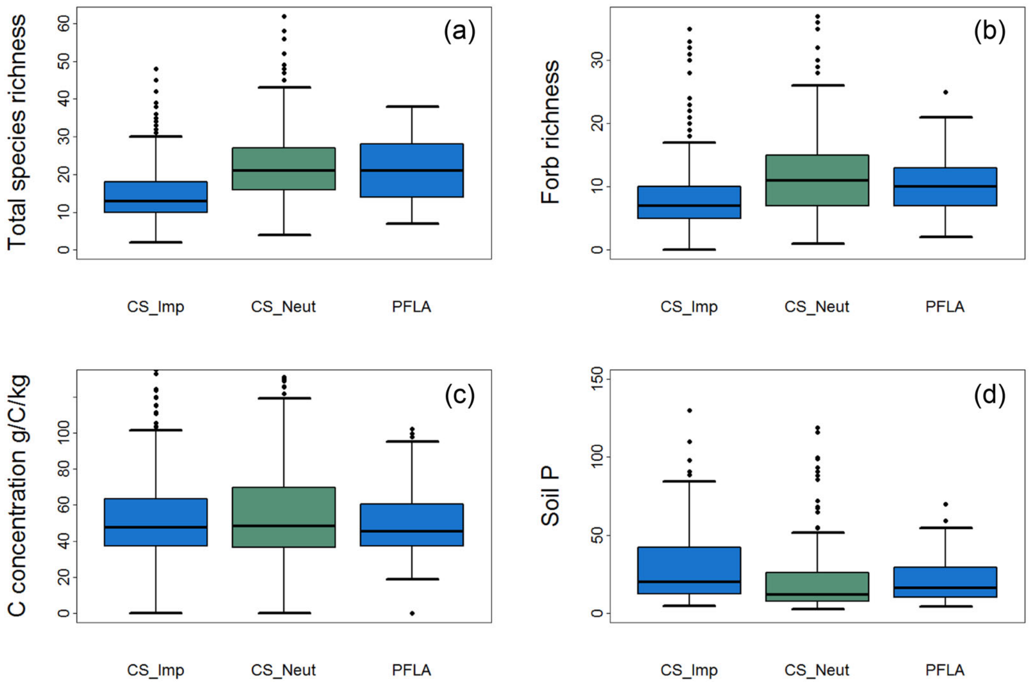

FIGURE 3 Boxplots comparing CS (Countryside Survey) Improved grassland, CS Neutral grassland and PFLA (Pasture Fed Livestock Association) grassland plots for (a) total species richness (plants), (b) forb (i.e. non-grass species) richness, (c) soil carbon (C) concentration (g/kg) and (d) soil phosphorus measured as Olsen P mg/kg (soil P)

as Neutral Grassland or changed from Neutral to Improved Grassland between 1990 and 2007 tended to have higher soil C concentration (S2) and higher species richness than plots that either stayed Improved or went from Improved to Neutral Grassland.

4 | DISCUSSION

This study reveals significant relationships between above- and below-ground variables in grassland and provides important findings for a comparison of grassland managed by PFLA farmers to a national sample of grassland.

4.1 | Vegetation/soil relationships

4.1.1 | Phosphorus

Soil P was the only soil variable at PFLA sites correlating with multiple vegetation measures. Significant positive relationships between soil P and *Lolium* cover for both the PFLA plots and the CS Improved Grassland plots (where the relationship was unimodal) indicated that some of the PFLA member farms may retain characteristics of conventional systems, perhaps reflecting a recent transition and legacy effects on existing swards and soils or, in some cases, continued management with P fertilizers. The relationship reflects positive (and agriculturally desirable) impacts of soil P on *Lolium* growth established decades ago (Nowakowski et al., 1977). Despite similarities in these relationships, *Lolium* cover was significantly lower in PFLA grassland than in CS Improved Grassland.

The competitive advantage of *Lolium* in high-P environments (over all other species) led to negative relationships between soil P and a range of plant diversity measures, for all plot types. These findings reflect similar results found for functional diversity in semi-natural grasslands in France (Goulnik et al., 2020) and for vegetation composition on comparable organic and conventional farms (van Dobben et al., 2019). Importantly, negative associations between soil P and legume cover and diversity indicate that Improved Grasslands are receiving levels of fertilizers that do not sustain or enhance the benefits of legumes sown into mixes. Given the fertility and forage benefits of legumes (Dewhurst et al., 2009; Lüscher et al., 2014) as well as their broader positive impacts on animal products and profitability (Schaub et al., 2020), this is of concern.

4.1.2 | Carbon, nitrogen, and moisture

Increases in soil C are a key goal for PFLA farmers. Relationships between soil C and sward components on PFLA farms were, however, not significant in this study. Higher covers of *Lolium* sp. were associated with low soil C in Neutral Grassland. The same was true for both legume and forb cover in both CS grassland types. Both *Lolium* sp. and legume species are shallow rooted, especially where nutrients are readily available (e.g. through inputs), contributing to low root depth and density (Bolinder et al., 2002; Crush et al., 2005). The negative relationships between forb cover and soil C imply that the forbs with high cover in these grassland types are also shallow rooted and indeed the two forb species with the highest cover in CS plots (*Ranunculus repens* and *Cerastium fontanum*) are shallow-rooted species. Positive relationships between vegetation diversity measures and soil C in both CS grassland types are likely to reflect the positive impacts of the presence of species with more extensive/dense roots or greater inputs from above-ground biomass on soil C as has been found even for moderately diverse pastures (McNally et al., 2015) and relatively simple mixtures (Cong et al., 2014). Likewise, positive relationships between soil N and total species richness/CSM species richness in Neutral Grasslands reflect those found in numerous grassland experimental studies (Cong et al., 2014).

For both Improved and Neutral Grassland, vegetation height was positively associated with soil moisture and soil N content. For Improved Grasslands, soils under vegetation over 1-m tall also contained significantly higher soil C than plots with shorter vegetation. These relationships indicate that vegetation height as well as being important for above- and below-ground biodiversity (see below) may also be very important for key soil properties. Soil moisture results in the CS Grassland plots tended to mirror the results for soil C. Whilst these findings may indicate a potential relationship between root structure and soil moisture retention (Lal, 2020), it seems that vegetation height (which may itself be related to rooting depth) could also play a key role in enhancing these soil quality parameters.

4.1.3 | Total soil invertebrate abundance (total taxa)

There was a significant relationship between the total plant richness of the sward and the total number of individual invertebrates recorded in the soil samples for Neutral Grassland plots only. Similarly, vegetation height was also related to total soil invertebrate abundance for both Neutral and Improved Grassland plots. Whilst the soil core method used in CS may not be ideal for capturing representative samples of all types of soil macrofauna (due to its relatively small size), these positive relationships between aboveground plant diversity and structure and total soil invertebrate abundance at scale (see Hooper et al., 2000) are rare examples of measured interactions which suggest the importance of vegetation characteristics for soil function (Wardle et al., 2004).

4.2 | PFLA farms in context

The results indicate that swards and, to a lesser extent, soils managed by PFLA farmer members are in better ecological condition than a large representative random sample of production-oriented Improved Grassland across GB. The fact that only around half of the farmers were certified practitioners indicates that even farmer members (who have not become certified) are managing their grassland less intensively than many other farmers across GB. Whilst there was high variability across the PFLA farms, and a clear overlap across PFLA plots and those on Improved and Neutral Grassland in CS (Figure 2), most PFLA plots were allocated to Neutral Grassland. The majority of Neutral Grasslands are semi-improved (i.e. have been agriculturally improved at some time) and are used for production. A small proportion are species-rich grasslands managed for conservation. It should be noted that the CS dataset does not enable a direct comparison between PFLA farmers and other farmers producing beef in GB, but rather puts the PFLA production system into the context of wider livestock grassland management.

4.2.1 | Sward characteristics

Relatively low sample sizes (an order of magnitude lower than in CS) and high variability across farms (location, stocking, grazing and input practices, stage of conversion to PLFA practices etc.) all influence the ability to detect differences between PFLA and CS grassland plots. Despite this, PFLA plots were significantly more species rich than CS Improved Grassland plots (by around six species) and contained a variety of grasses, forbs and legumes more closely resembling Neutral Grassland (though with a higher cover of forb species). Studies have already shown how plant richness and/or diversity is linked to sward and ultimately livestock productivity. For example, a study by Schaub et al. (2020) indicated that plant diversity in intensively managed grasslands both increased yields as well as reduced production risks, and Roca-Fernández et al. (2016) showed that more diverse swards resulted in higher milk production. Hence, detected differences in sward diversity may be important for the productivity of PFLA systems.

Vegetation in PFLA plots was also taller than in either CS Improved or Neutral Grassland plots and whilst this was only significantly related to higher forb richness in PFLA plots, taller vegetation was positively related to important soil variables for other plot types (see Section 4.1.2). The presence of flowering species and taller vegetation have been shown to lead to an increased abundance of invertebrates including butterflies and bees (Kruess & Tscharntke, 2002; Milberg et al., 2016; Woodcock et al., 2014). Taller vegetation has also been shown to be important for predators, including invertebrates and mammals (Meyer et al., 2019) and bird species (Vickery et al., 2001). Given the concerns raised by Hallmann et al. (2017) on losses of invertebrates in the protected areas which sit within the agricultural matrix, practices which can increase invertebrates within the matrix itself are likely to be very significant for wider biodiversity.

Sward height may be indicative of reduced management or may reflect specific rotational grazing practices which include 'rest periods' enabling grass swards to grow without continuous grazing pressure (Voisin, 1959). A recent review (McDonald et al., 2019) revealed that whilst extended rest periods, as advocated by Voisin as far back as the 1950s, do not themselves result in increased plant richness, they do positively impact biomass and animal production. In this study, farmer management information indicated that more than half of the PFLA farmers employed split-field practices, as opposed to continuous grazing across the whole field, which may have resulted in the differences detected in sward height between the CS and PFLA plots. Further work will report on the influence of specific grazing practices employed by PFLA farmers on soil and above-ground vegetation.

4.2.2 | Soil characteristics

Whilst sward characteristics showed clear differences between PFLA plots and Improved Grassland, soil characteristics were not markedly different. Average levels of P in PFLA soils were, however, even lower than those in Neutral Grassland, but high levels of variability (levels varied by almost a factor of 10 across PFLA sites) led to non-significant differences. Lower levels of P on PFLA farms and significantly lower P levels in Neutral Grassland (compared to Improved Grassland) are likely to be partly due to low levels of fertilizer applications, although soil P may persist in soils long after application (McDowell et al., 2020). Another key impact on soil P includes indirect cycling of P through livestock, either through high levels of P in forage or more usually from imported high-energy, concentrate feeds on intensive livestock holdings (Rothwell et al., 2020; Withers et al., 2001). In general, only small amounts of concentrates may be used on all-grass systems (Dentler et al., 2020) and regulations prevent certified PFLA producers from using them. Farming methods (e.g. PFLA practices) which avoid importing feed and limit fertilizer usage will lead to more sustainable phosphorus and food systems (Jacobs et al., 2017) and potentially a healthier soil microbiome (see Ikoyi et al., 2018).

Differences between soil C, bulk density and P measures on CS Neutral and Improved Grassland are likely to be due to differences in management type and intensity. Bulk density is related to soil organic matter; hence, soils with higher organic matter tend to be less dense. Results for lower bulk densities and higher soil C in Neutral than in Improved Grassland and negative relationships between these soil variables were similar to the results of Emmett et al. (2010) and are in line with other studies (Keller & Håkansson, 2010) and with modelling describing the impacts of ploughing/reseeding over time (Reinsch et al., 2018). They do, however, differ from studies that indicate that increasing the management intensity of grasslands through planting more productive species or increasing fertilizer inputs generally increases soil organic C accumulation (Sollenberger et al., 2019). Potentially, this inconsistency results from the short-term nature of many experimental studies as opposed to data from sites which form part of a long-term survey.

The fact that PFLA farms did not exhibit the same soil characteristics as Neutral Grasslands in terms of soil C and bulk density despite having vegetation compositions typical of Neutral Grassland may reflect high variabilities in these measures across the relatively small sample of 51 spatially dispersed farms on which comparisons were made. Alternatively, it may be due to the time lag over which these properties change (see below), or it may indicate that PFLA practices do not increase soil C. Variability is likely to be due to soil texture (Augustin & Cihacek, 2016) and climate (Hewins et al., 2018) as well as longevity and level of commitment to novel practices (with only half of the farms that are certified producers). The results from the analysis of plots that changed between grassland types in the period 1990–2007 indicated that both soil (soil C) and sward characteristics (forb richness) typical of Neutral Grassland were retained over time even in plots where management had been intensified and vice versa for plots in Improved Grassland. Hence, PFLA farms moving from practices more typical for Improved Grassland may take some time for levels of soil C, bulk density and P measures to approach those for Neutral Grassland.

5 | CONCLUSIONS

Grassland is an extensive highly managed component of GB ecosystems. Results from long-term monitoring data on GB grasslands show that management of sward species for biodiversity also contributes to soil health.

There are clear signs that grassland management, as practiced by PFLA members, is already improving the ecological condition of some UK grassland. CS data indicate that there is likely to be a time lag in terms of soil and vegetation responses to transitions from more improved nutrient-rich, species-poor Improved Grassland to Neutral Grassland.

The role of grazing in enhancing soil and vegetation properties is well documented (Sollenberger et al., 2019). Our findings indicate that pasture-fed livestock approaches may be particularly beneficial for grassland and wider ecosystems. A shift towards these approaches is being led by practitioners themselves which is likely to make their adoption at a scale far more likely than if implemented through top-down mechanisms (Thomas et al., 2020). However, also crucial to their uptake is an understanding of how the ecological characteristics of swards and soils relate to productivity (both quantity and quality of the sward and animals using it) and economic/business viability (Teague and Kreuter, 2020). This system-level understanding will be explored in future work with these farmers.

AUTHOR CONTRIBUTIONS

Lisa Norton conceived the ideas and designed the methodology for the study. Claire Wood designed the data collection and databases for the study. Lisa Norton and Markus Wagner collected the data for the study. Adam Pinder and Michele Brentegani analysed the soil samples in the labs. Lindsay Maskell and Lisa Norton analysed the data. Lisa Norton led the writing of the manuscript with input from Lindsay Maskell. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

CS soils and vegetation data are available through the NERC Environmental Information Data Centre: https://doi.org/10.5285/57f97915-8ff1-473b-8c77-2564cbd747bc (Bunce et al., 2014), https://doi.org/10.5285/fccd86b0-f5b6-4716-b4f7-f43ad82daeee (Emmett, Reynolds, Chamberlain, Rowe, Spurgeon, Brittain, Frogbrook, Hughes, Keith, et al., 2016) and https://doi.org/10.5285/79669141-cde5-49f0-b24d-f3c6a1a52db8 (Emmett, Reynolds, Chamberlain, Rowe, Spurgeon, Brittain, Frogbrook, Hughes, Lawlor, et al., 2016). The data that support the findings of this study are openly available at: https://doi.org/10.5285/78ca9a01-107b-4f33-8561-9c3e64db7e02 (Norton et al., 2021).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

S1. Relationships between vegetation height and soil and vegetation variables for CS (Improved and Neutral grassland plots combined) (NA = not available due to lack of data). CSM = presence of grassland Condition Standards Monitoring species, Tot_rich = total species richness, Forb sp = forb species richness, Legume sp = legume species richness, Total taxa = numbers of individuals recorded across all taxa, Soil biodiversity = total species richness of soil inverts, NA = not available, ns = not significant. Significance (*P<0.05, **P<0.01, ***P<0.001).

S2. Boxplots showing a) carbon concentrations and b) total plant species richness in plots which changed habitat types between CS 1990 and CS 2007. Table S2a shows the estimated difference (Est_Diff) and the significance of testing between Land use change categories, (e.g. 2-1 tests the change between Stayed as improved and Stayed as neutral) (*p<0.05, **p<0.01, ***p<0.05)

S3. PFLA status, farm area and field management practices for the PFLA sample. PFLA mem (yrs) = years as a PFLA member; PFLA prod (yrs) = years as a certified PFLA practitioner (Prov = provisionally certified); Pasture type (P-permanent, T-temporary), grazing type (SS-set stocked, R- rotational, M- mob, P/S – paddock/strip, VS – variable stocking); Mineral fertiliser (y-yes, n-no); Organic inputs (n-none, c-compost tea, m-manure, dw – dirty water, s-slurry).

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