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Sustainable soil management in the United Kingdom: A survey of current practices and how they relate to the principles of regenerative agriculture

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Abstract

Sustainable soil management is essential to prevent agricultural soil degradation and maintain food production and core soil-based ecosystem services. Regenerative agriculture, one approach to sustainable soil management, is rapidly gaining traction in UK farming and policy. However, it is unclear what farmers themselves consider to be sustainable soil management practices, and how these relate to the principles of regenerative agriculture. Further, there is little insight into how sustainable soil management is currently promoted in agricultural knowledge and innovation services (AKIS). To address these knowledge gaps, we undertook the first national-scale survey of sustainable soil management practices in the United Kingdom and complemented it with targeted interviews. We found high levels of awareness (>60%) and uptake (>30%) of most sustainable soil management practices among mixed and arable farmers. Importantly, 92% of respondents considered themselves to be practising sustainable soil management. However, our analysis shows that farmers combine practices in different ways. Not all these combinations correspond to the full set of regenerative agriculture principles of reduced soil disturbance, soil cover and crop diversity. To better understand the relationship between existing sustainable soil management practices in the United Kingdom and regenerative agriculture principles, we derive a "regenerative agriculture score" by allocating individual practices among the principles of regenerative agriculture. Farmers who self-report that they are managing soil sustainably tend to score more highly across all five principles. We further find that sustainable soil management messaging is fragmented and that few AKIS networks have sustainable soil management as their primary concern. Overall, our study finds that there are multiple understandings of sustainable soil management among UK farmers and land managers and that they do not

Coline Jaworski and Anna Krzywoszynska are joint first authors of this work, having contributed equally to design, data collection, analysis and writing.

correspond to regenerative agriculture principles in a straightforward way. This diversity and variety in sustainable soil management needs to be taken into account in future policy and research.

KEYWORDS

conservation agriculture, regenerative agriculture, soil degradation, soil health, sustainable farming

1 | INTRODUCTION

The global soil degradation crisis in agriculture is threatening to undermine food and environmental security (Borrelli et al., 2017; Evans et al., 2020) and has been estimated to cost the global economy $10 trillion, which is more than the global expenditure on either healthcare or education (ELD, 2015). Sustainably managing soils is fundamental for the delivery of many of the Sustainable Development Goals, to which 193 countries have committed (Keesstra et al., 2016), and is recognized as a critical global issue. The urgency of this challenge is highlighted by a recent study by Evans et al. (2020), which found that a third of conventionally managed arable topsoils (in a sample of 255 international sites) had an estimated lifespan of less than 200 years.

Soil degradation comprises two components: loss of soil quantity and loss of soil quality. Sustainable soil management refers to land management practices that not only help to prevent soil erosion but also help to enhance the multi-functionality of the soil, which is often conceptualized as "soil health" (Ingram, 2008; Kibblewhite et al., 2008). No single definition of sustainable soil management exists, as different practices are required in different soil and agro-ecological contexts (Miner et al., 2020). However, there is increasing recognition that sustainable soil management needs to encompass practices that can simultaneously improve soil biology, soil structure and nutrient status (Berdeni et al., 2021; Guest et al., 2022) and reduce reliance on expensive chemical inputs (Austen et al., 2022; LaCanne & Lundgren, 2018). Widely used soil conservation measures including contour cultivation, terracing, cover cropping, conservation tillage (minimum disturbance tillage) and no-tillage (zero tillage or direct drilling) can extend soil lifespans, increasing these to over 10,000 years in 39% of soils (Evans et al., 2020). At the same time, many of these practices improve soil biology and health (Austen et al., 2022).

One model of sustainable soil management that has rapidly gained prominence in the last 5 years (Giller et al., 2021; Newton et al., 2020) is regenerative agriculture, which is a farmer-led approach to land management innovation aimed at restoring soil health (LaCanne & Lundgren, 2018; Sherwood & Uphoff, 2000; Tittonell et al., 2022). Regenerative agriculture is increasingly recognized as a movement or paradigm shift in modern agricultural practices (O'Donoghue et al., 2022). The movement has lacked consistent definitions and does not specify a particular set of practices. This is notably because its core value is the adaptation to local context (soil, farming system and climate) in order to regenerate agricultural resources with a special focus on soil, water and biota, to achieve positive environmental and soil health outcomes (O'Donoghue et al., 2022). The relatively loose definitions of regenerative agriculture have resulted in criticism of the concept and its potential to cause confusion, as it combines practices that have been understood to be associated with contrasted farming approaches such as agroecology and sustainable intensification (Giller et al., 2021; Newton et al., 2020). Despite this increased interest in soil health, the extent to which UK farmers are already using sustainable soil management practices, and the extent to which these practices correspond to the principles of regenerative agriculture, remains poorly understood.

While regenerative agriculture lacks a consistent definition, it is nonetheless being recognized as a potentially important pathway to greater sustainability of agri-food systems. This is shown by the peer-reviewed awards to major UK Research and Innovation-funded projects in the United Kingdom which explicitly explore regenerative agriculture (Doherty et al., 2022; Jackson et al., 2021), and by the mentioning of regenerative practices as an element of the forthcoming UK Environment Land Management scheme for England (Defra, 2020). The Scottish Government goes further, with an explicit focus on regenerative agriculture in its current vision for agricultural development (Scottish Government, 2022).

Many practitioners and advocates for regenerative agriculture now promote five commonly agreed principles for land management practice (Farm of the Future, 2022; Ritz, 2021). These are (i) minimize soil disturbance, (ii) maximize crop diversity, (iii) keep the soil covered all year round, (iv) maintain living roots all year round and (v) integrate livestock (this is primarily aimed at increasing soil organic matter through the use of grazing and manures, and fertility building with less chemical fertilizer). In accordance with regenerative agriculture, achieving sustainable soil management requires changes in practices in both conventional and organic farming systems to simultaneously address these five principles.

Rapid adoption of many sustainable soil management practices, including no-tillage, is taking place; however, Europe is lagging behind America and Australia (Kassam et al., 2019). No-tillage is now used widely in South America (>60% of cropped area), Australia and New Zealand (45% of cropped area) and North America (28% of cropped area). In Canada, more than 55% of cropped area since 2011 has been under no-tillage management, and with other soil conversion methods, this has substantially reduced soil erosion, as has the increased implementation of soil conservation measures in US agriculture (Baumhardt et al., 2015). While no-tillage cropping is among the most effective ways to reduce wind and water erosion of soil (Evans et al., 2020), in the European Community it accounted for only 5% of cropped area in 2015–2016, the United Kingdom having about 7.6% of its 4.7 million ha of cropland under this kind of management (Kassam et al., 2019). A review of tillage practices from 249 arable and mixed English farms indicated that in 2010, 60% of cropping area was plough-based, 32% used reduced intensity tillage and 8% used no-tillage (Townsend et al., 2016). Two more recent questionnaire surveys suggest a greater change away from ploughing. Dicks et al. (2018) found that 81% of 95 UK arable and mixed farmers interviewed in 2015 said that they already practised minimum- or no-tillage, while Alskaf et al. (2020) estimated from 371 English farms that in 2016, nearly 48% of arable land by area was cultivated using reduced tillage, but the adoption of no-tillage remained very low at 7% (Alskaf et al., 2020).

Low rates of adoption of soil conservation measures are of concern as the annual costs to the UK economy of soil degradation in England and Wales have been estimated to be £1.2 bn (Graves et al., 2015), which was more than 25% of total UK farm gate-income in 2015 (Defra, 2016). Most of this economic loss was not due to soil erosion but to loss of soil quality and functions, especially due to depletion of organic matter. Increasing awareness of the economic impacts of soil degradation (Graves et al., 2015) and intensified economic pressures on farmers arising from input costs and yield plateaus (which are likely due to soil constraints) provide impetus for change. Farmers using conventional intensive cropping in short rotations have been facing increasingly intractable weeds, pests and diseases (Austen et al., 2022), compounded by extreme weather events that have led, somewhat belatedly, to both UK farmers and policymakers to recognize the need for a wider uptake of sustainable soil management. This is reflected in the 25 Year Environment Plan, which sets an objective for all soils in England to be managed sustainably by 2030 (Defra, 2018). The development and introduction of the new Environmental Land Management scheme replacing the EU Common Agricultural Policy following the departure from the EU, along with the Net Zero and climate change adaptation targets, aims to deliver sustainable soil management founded on the principle of "public money for public goods" (Bateman & Balmford, 2018; Defra, 2021).

In spite of this increased attention among different stakeholder groups, the questions of what constitutes sustainable soil management, how this term is understood by farmers, how widely sustainable soil management techniques are used and what the barriers and enablers are to adoption remain important knowledge gaps. From a policy perspective, it is important to know how the increasingly influential principles of regenerative agriculture correspond with existing sustainable soil management approaches. Moreover, it is widely recognized that all forms of sustainable soil management are knowledge intensive and that knowledge networks are needed to ensure farmer adoption and adaptation of relevant practices (Ingram, 2008; Kibblewhite et al., 2008). Sustainable soil management-oriented farmer networks have emerged in the United Kingdom to encourage the uptake of soil-health-oriented farming and support farmers in adopting and adapting sustainable soil management practices through peer-to-peer learning (Krzywoszynska, 2019). However, to date, no evidence has been collected on the spread and influence of UK's soil-health-oriented farming and land management networks and the impact of network participation on sustainable soil management adoption.

This study addresses these important knowledge gaps through the first ever survey of sustainable soil management practices in UK farming and a series of interviews with sustainable soil management stakeholders. While the use of reduced tillage is increasing (Dicks et al., 2018; Townsend et al., 2016), in this paper we go beyond a focus on tillage. Achieving sustainable soil management depends on the adaptation and adoption of a set of combined practices by land managers. In regenerative agriculture, as well as conservation agriculture, combining minimal soil disturbance, crop diversification and maintenance of living and/or non-living soil cover are promoted as they increase the likelihood of achieving soil health improvements (Lal et al., 2007; Virto et al., 2015). Therefore, in order to shed light on the state of sustainable soil management in the United Kingdom at a time when regenerative agriculture is rising in prominence, we investigate here not only what practices are being used but also whether and how they are being combined.

2 | METHODS

We used a mixed method (quantitative and qualitative) approach. The study consisted of two phases: first, an online survey of UK farmers and land managers; and second, semi-structured interviews with 25 sustainable soil management stakeholders and industry experts, including farmers, advisers and organization representatives. This research study addressed the following questions:

1. To what extent is the general farming and land managing population in the United Kingdom aware of, and engaged with, sustainable soil management?
2. How do farmers combine sustainable soil management practices (if at all), and how does this relate to the five principles of regenerative agriculture?
3. Through what channels is sustainable soil management promoted in the United Kingdom?
4. What support is needed to enable wider adoption of sustainable soil management practices in the United Kingdom?

2.1 | Research phase 1: online survey

The online survey of farmers and land managers across the United Kingdom was designed to address research questions 1, 2 and 4. The survey was made up of 42 questions, provided in Data S1. These were largely closed response questions, with a smaller number of open questions. The survey responses were collected in February and March 2020. The survey was advertised in national farming media and on social media and promoted with the incentive of a single winner cash prize draw (£500).

The objective of the online survey was to understand what practices comprise "sustainable soil management" for UK farmers. The survey deliberately avoided explicit use of the concept "regenerative agriculture," in order to (i) engage with as wide a range of farmers and land managers as possible (not just those recognizing themselves as doing regenerative agriculture); and (ii) to gain insight into what practices are already widely used under the umbrella of "sustainable soil management." In order to understand the extent of the overlap between UK farmers' sustainable soil management practices and the increasingly popular regenerative agriculture concept, regenerative agriculture principles were subsequently used as organizing concepts in the analysis.

To investigate the awareness, nature and uptake of sustainable soil management in the present study, we established a list of the 14 most recognized and implemented practices. This was based on a review of current sustainable soil management policies and advice (Defra, Soil Association, NIAB) and validated by consulting a panel of soil scientists (including co-authors of the study). The 14 practices were no-tillage, minimum-tillage, cover crops, growing legumes as cash or cover crops, mob/holistic grazing, overwinter stubble, leys (including herbal), diversified rotation (four or more crops within a 6-year period, excluding cover crops), using compost, using slurry, using digestate, using manure, returning all crop residue to the field and adapting ploughing to topography (e.g. contour ploughing).

In order to shed light on the way in which farmers may be combining sustainable soil management practices, and especially the extent to which combinations correspond to regenerative agriculture, we classified the 14 practices in relation to the 5 regenerative agriculture principles discussed above (Ritz, 2021):

(i) Minimize soil disturbance: no-tillage, minimum-tillage and leys
(ii) Maximize crop diversity: diversified rotation, leys, growing legumes and cover crops
(iii) Keep the soil covered all year round: cover crops, leys, overwinter stubble and returning crop residue to the field
(iv) Maintain living roots all year round: leys and cover crops
(v) Increase soil organic matter through the use of non-chemical fertilizers: using compost, slurry, digestate or manure, returning crop residue to the field, leys and mob/holistic grazing

Note that (v), in a pure regenerative system would be "integrate livestock." However, for the purposes of the survey, we chose to investigate a range of organic matter additions, including manure, under the grouping (v) "increase soil organic matter." This is because the sustainable soil management practices most recognized and implemented in the United Kingdom currently do not explicitly include the integration of livestock in farming systems, and indeed many arable farmers lack the facilities, expertise or time investment required to maintain their own livestock (Cooledge et al., 2022). In the remainder of the text, these five analytical categories will be referred to as "the five regenerative agriculture principles."

In the survey, we first collected background data on respondent's demographic profiles, soil type, farming system, and professional training and knowledge networks (accreditations and agri-environmental schemes, memberships to farming networks and use of advisers). We then investigated the respondents' concerns about and awareness of sustainable soil management through a series of questions about their perceived role as a farmer, their concern around and perception of soil degradation, soil issues in their farm, their use of soil analysis tests and the importance given to sustainable soil management. We further investigated respondents' awareness and use of the 14 sustainable soil management practices (possible responses were aware of, currently or regularly implementing, currently experimenting or stopped using). We also asked if overall the respondents felt they were practising sustainable soil management. Finally, we asked open questions about their perceptions of the barriers to and enablers of the adoption of sustainable soil management practices.

2.2 | Qualitative interviewing

The second phase of the research focused on addressing research questions 3 and 4. This phase used semi-structured telephone interviews and desk-based research in order to: (i) map organizations and networks promoting sustainable soil management practices in the United Kingdom and generate an understanding of the level of connectivity between them and (ii) explore what support farmers and land managers feel is needed to enable wider adoption of combined sustainable soil management practices in the United Kingdom. The sample for this phase focused on two types of sustainable soil management stakeholders: (A) farmer-led organizations explicitly set up to promote and support the uptake of sustainable soil management practices and (B) sustainable soil management network experts, such as advisers providing soil-health-oriented advice. Networks and experts were identified through desk-based research and through snowballing.[1] The interviews were approximately 45 min in duration, conducted via telephone and followed a semi-structured format. A total of 24 interviews were completed with stakeholders with the field of sustainable soil management, including experts and advisers from key institutions (9), leaders of farming groups (9) and independent advisers and experts (6). Where permitted, these interviews were audio-recorded or (in one case) notes were taken. The interviews were transcribed, coded in relation to research questions and analysed thematically (Cope, 2009).

2.3 | Data analysis

A quantitative approach was used to identify the extent to which the general farming and land managing population in the United Kingdom are aware of, and engaged with, sustainable soil management and to explore the uptake of combined sustainable soil management practices in the United Kingdom, using the online survey data. Analyses involving the 14 sustainable soil management practices used data from respondents in arable and mixed-farming systems only, since many of these practices are mostly not applicable to livestock-only systems.

All statistical analyses were performed using R version 4.2.1. (R Core Team, 2022). To identify commonly used practices and combinations of practices, that is groups of farmers combining sustainable soil management practices in a similar way, we performed a hierarchical analysis clustering farmers based on the combination of practices currently or regularly used, applying the R function "hclust" (library stats; R Core Team, 2022) to a Euclidean-distance matrix and using Ward's minimum agglomeration method. We tested the significance of the clustering with the function "sigclust" (1000 simulations, covariance estimation based on original background noise threshold; R library "sigclust"; Huang et al., 2022). A heatmap was created using the emerged clustering of farmers and practices and the function "Heatmap" (library ComplexHeatmap; Gu, 2022).

We were also interested in comparing how the combinations of practices used followed the five regenerative agriculture principles. To do this, we calculated the proportion of practices associated with a given principle each respondent was using (see section 2.1). We used these proportions to derive a "regenerative agriculture" score. The score indicates the extent to which a given farmers' set of sustainable soil management practices corresponds with the regenerative agriculture principles. For instance, if a farmer was using minimum-tillage and no-tillage but not leys, their score for the first regenerative agriculture principle "minimize soil disturbance" was 2/3. The total farmer regenerative agriculture score was calculated as the sum of their five scores for each principle and ranges between 0 (no practices used) and 5 (all sustainable soil management practices used). Finally, the open responses were incorporated under the same coding framework as used for stakeholder interviews and analysed to identify the barriers to and enablers of adoption of sustainable soil management practices in the United Kingdom.

To explore respondents' understanding of the need for sustainable soil management (an aspect of Question 1), we statistically tested how perception of soil degradation varied across spatial scale categories ("the land you farm," "in the United Kingdom," "globally") among all respondents. To understand what sustainable soil management means for UK stakeholders (Question 1), and how this relates to the five regenerative agriculture principles (Question 2), we tested the relationship between respondents' self-assessment of whether they practised sustainable soil management ("yes" or "no") and their total regenerative agriculture score, for respondents in arable and mixed-farming systems only. The total regenerative agriculture score was treated as a continuous variable. To assess whether the farming system affected the total regenerative agriculture score, we tested the relationship between farmers' total regenerative agriculture score and the farming system (mixed vs. arable). To understand how soil characteristics and farmers' relations to soil are related to their engagement in sustainable soil management, we tested independently the relationships between the total regenerative agriculture score and their level of concern about soil degradation in relation to farming, soil characteristics (implemented separately as factors – dominant soil type: clay, clay loam, sandy loam or silty loam; altitude: below or above 50 m a.s.l.; topography: flat, gently sloping, undulating, or steeply sloping; perceived specific topography impacting land management), perceived soil issues (implemented separately as factors: insufficient organic matter, erosion, compaction, poor infiltration, low or unavailable nutrients, drainage, low pH, high pH, slaking, capping, high load of soil-borne diseases or pathogens, and insufficient earthworms) and the number of soil tests conducted. We also looked at whether soil type influenced the use of any specific practice, which could indicate whether underlying soil type limits a given farmer's ability to score highly across all five principles.

Since there is evidence that networking is key to the adoption of sustainable soil management practices (Krzywoszynska, 2019), we tested the relationships between the total regenerative score and the self-assessed level of connectedness to farming networks (continuous, 0–100) and between the total regenerative score and how far they estimated their agricultural adviser has assisted in the adoption of sustainable soil management practices (continuous, 0–100; Question 4). To assess whether the feeling of high connectedness to farming networks matched the declared connections to formal and informal networks, we tested the relationships between the self-assessed level of connectedness, engaging in a formal network ("yes" vs. "no") and engaging in an informal network ("yes" vs. "no"). Finally, to identify how potential barriers may impact the suite of sustainable soil management practices used, we tested whether the frequency of barriers reported by respondents differed among the five farmer groups identified by clustering reported practices.

To test associations between two categorical variables, we used χ^2-tests (function "chisq.test"; library stats; R Core Team, 2022). To test regressions between a continuous and a categorical variable, we used linear models (function "lm," library stats; R Core Team, 2022), followed by an ANOVA and a Fisher (vs. χ^2-test) test. The normality of residuals was tested in the best model using the "simulateResiduals" function (library DHARMa; Hartig, 2022). When significant associations were found between multi-level categorical variables, mean comparisons were performed using independent χ^2-tests between each pair and correcting *p*-values for multiple testing using the "*p*.adjust" function (library stats; R Core Team) with the Benjamini and Hochberg (1995) method. When significant relationships were found between a continuous and a categorical variable, mean comparisons between groups were performed using the "emmeans" function (library emmeans; Lenth, 2022). A *p*-value correction for multiple testing was also applied to suites of tests on the same data: relationships between farmer group structure and farmers' five regenerative agriculture scores and total regenerative agriculture score, relationships between total regenerative agriculture score and soil characteristics and relationships between total regenerative agriculture score and perceived soil problems. Finally, to test if the dominant soil type (only considering soil types with enough respondents: clay [$N=44$], clay loam [$N=65$], sandy loam [$N=63$], silty loam [$N=16$]) influenced the use of a specific practice, we performed an ANOVA test on a constrained canonical analysis (function "cca," library vegan; Oksanen et al., 2022) on the use of the 14 practices (0 not used, 1 used) using the soil type as factor.

3 | RESULTS

3.1 | Description of the respondents' population

The quantitative survey generated 473 responses, of which 297 were viable after removal of incomplete, non-farmer/land manager respondents and non-UK respondents (Figure 1). The final sample was predominately male, landowner-managers, aged 35–64 (Table 1) and working across different sectors of the agricultural industry (38% mixed farming, 31% livestock only and 31% arable including general cropping).

3.2 | Question 1: What is the awareness and engagement with sustainable soil management?

We first asked farmers about their role as farmers and their perception of soil degradation. In indicating the motivations for farming, respondents ranked equally high the roles of maximizing profit (mean 7.2 on a scale of 1: unimportant to 10: very important) and producing food and other goods (mean 7.5), but ranked looking after the environment significantly higher (mean 8.5, $df=2$, $\chi^2=8.94$, $p=.011$). In relation to motivations for sustainable soil

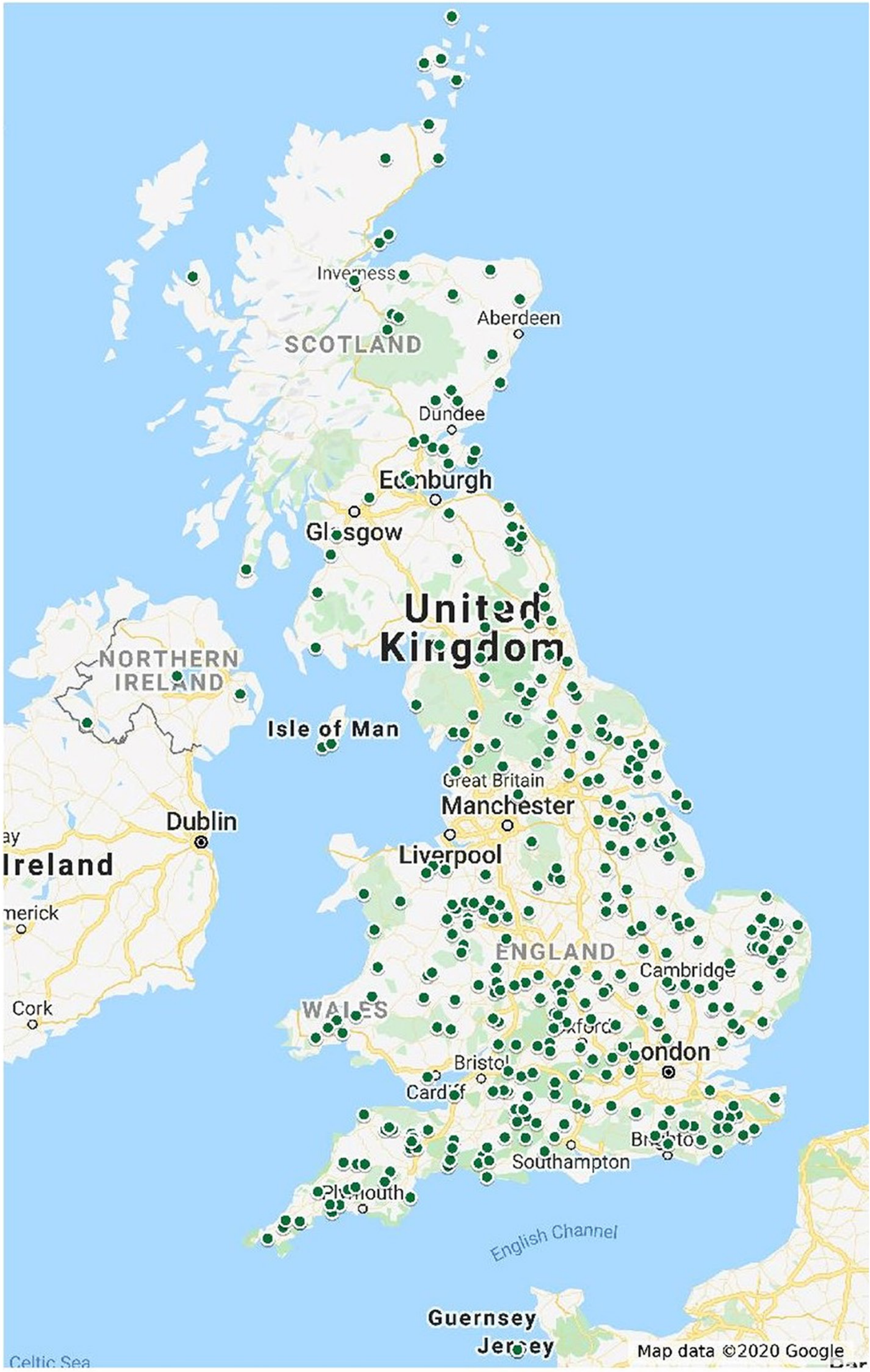

FIGURE 1 Geographical spread of respondents to the online quantitative survey ($N = 297$).

management, on a scale of 1 (not important) to 5 (extremely important), food security (mean 4.6), improving farming productivity (mean 4.6), enhancing biodiversity (mean 4.5), ensuring clean drinking water (mean 4.4), mitigating climate change (mean 4.3), preventing flooding (mean 4.1) and ensuring clean air (mean 4.0) were all seen as equally and highly important reasons to manage soils sustainably.

With regard to respondents' perceptions of land degradation, there was a significant variation across scales ($F_{2,888} = 282$, $p < .001$; Figure 2). Typically respondents perceived their land as only lightly degraded on a scale of 1–5 (mean score 2.08, 95 CI [1.99, 2.17]). Land on the national scale was perceived as significantly more degraded than respondents' own land (degraded; mean score 3.10, 95 CI [3.01, 3.19]). On a global scale, land was judged to be even more degraded and significantly more degraded than UK soils (heavily degraded; mean score 3.63, 95 CI [3.53, 3.72]). The majority of farmers who participated in the survey were strongly concerned about soil degradation within agriculture: almost half of them gave a score of 5 of 5 (most concerned) and another third gave a score of 4.

Our results indicate a broad awareness of the 14 sustainable soil management practices among mixed and arable farmers. Over 60% of these respondents were aware of no-tillage and minimum-tillage practices, as well as the use of herbal leys, cover crops, growing legumes, overwinter stubble, returning all crop residue to the field and using manure and mob/holistic grazing (Figure 3). Adapting ploughing to topography had the lowest awareness of 46%. Furthermore, terms associated with a systemic sustainable soil management approach (soil degradation, soil health, soil quality and soil organic matter) were largely known by over 92% of the respondents. The term "soil biota or soil biology or soil microbiome" was recognized by only 76% of participants. Only one of the 297 respondents was unaware of these five terms.

TABLE 1 Sample characteristics.

Characteristics	Number of respondents	Sample breakdown (%)
Status		
Landowner-manager	210	71
Tenant farmer	53	18
Land manager	34	11
Gender		
Male	256	86
Female	41	14
Age bracket		
18–24	4	1
25–24	26	9
35–44	56	19
45–54	73	25
55–64	90	30
65–74	38	13
75+	10	3

The most common soil analysis tests undertaken by respondents were walking the field and NPK nutrient tests, followed by "dig and look," observations of roots and compaction assessments with a spade or penetrometer (Figure 4). Finally, over half of the participants reported carrying out organic matter tests, Visual Evaluation of Soil Structure (VESS) scores (AHDB, 2018) and earthworm counts, while bulk density and slake tests remained barely used.

Moving from awareness to practice, the data suggested high levels of adoption of sustainable soil management techniques. While 92% of respondents reported doing sustainable soil management (from all systems and also from mixed and arable systems only), 98% of them were regularly implementing at least one of the 14 practices, and they were regularly using on average five sustainable soil management practices at the time of the survey. Those in arable and mixed-farming systems were implementing on average 5.8 practices. The practices most often (currently or regularly) used in arable and mixed-farming systems were using manure (52%), cover crops (44%) and a diversified rotation (40%).

We found that the respondents were quite active in relation to experimenting with new sustainable soil management-related practices: 48% of all respondents and 52% of respondents from mixed and arable systems reported to be currently experimenting with a new soil improvement technique. From those, 33% (30% of respondents from arable and mixed systems) were experimenting with more than one new technique at that time (most often no-tillage with cover crops and increasing crop diversity). The techniques most often experimented with in mixed and arable systems were cover crops (34% of farmers), no-tillage/direct drilling (25%), non-chemical fertilizers (19%), minimum-tillage (18%), increasing crop diversity (19%) and holistic grazing (including of winter cover crops, 11%).

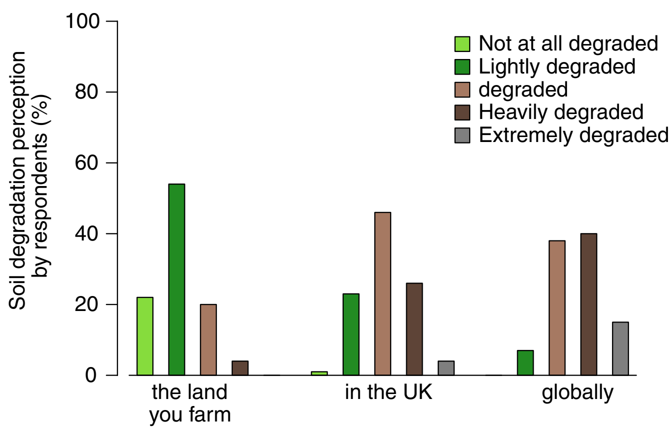

FIGURE 2 Perception of soil degradation at different spatial scales. $N = 297$ respondents from the online quantitative survey.

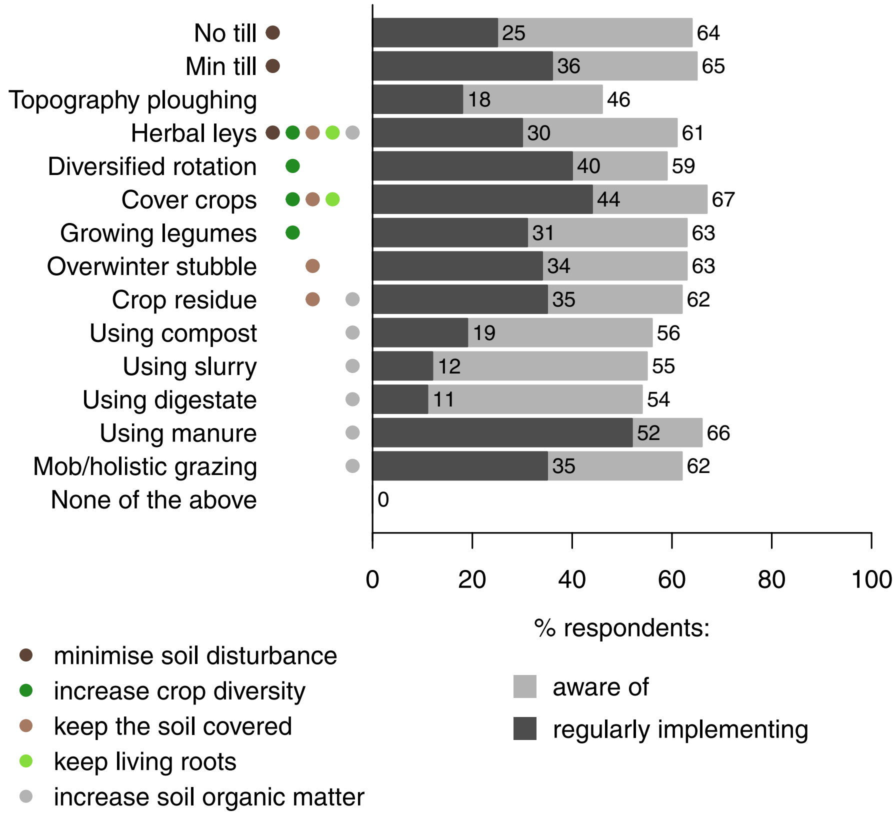

FIGURE 3 Awareness and regular implementation of the 14 sustainable soil management practices in mixed and arable farming systems. Light grey: percentage of respondents aware of the practice; dark grey: percentage of respondents implementing the practice as part of their current or regular soil management practices. All respondents were aware of at least one practice and using at least one practice. $N=206$ respondents (online quantitative survey; mixed and arable systems only). Numbers on the right side of bars show percentages. Coloured dots show the correspondence between practices and the five regenerative agriculture principles (see text, section 2.1). Crop residue, returning all crop residue to the field; Min till, minimum-tillage; No till, no-tillage.

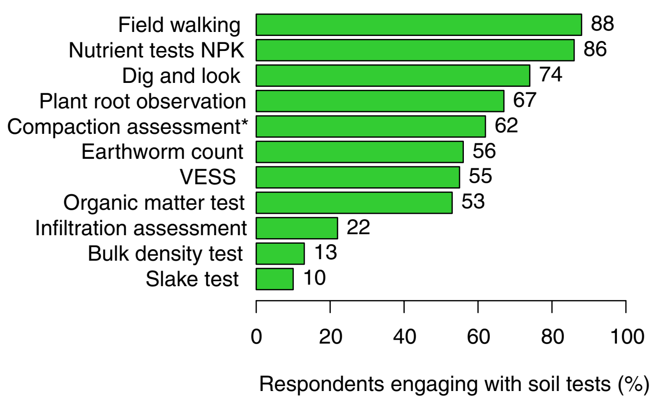

FIGURE 4 Soil analysis practices undertaken. $N=297$ respondents from the online quantitative survey. Numbers on the right side of bars show percentages. * using a spade or a penetrometer. VESS, visual evaluation of soil structure.

3.3 | Question 2: How do farmers combine sustainable soil management practices (if at all), and how does this relate to the five regenerative agriculture principles?

The hierarchical clustering of farmers based on the similarity of use of the 14 practices identified five groups of farmers implementing different combinations of practices (Figure 5 and Table 2), although such clustering was not statistically significant (mean cluster index 0.87, $p=.29$). Nonetheless, we used the identified farmer groups in addition to regenerative agriculture scores in subsequent analyses, because we found them to be an extremely useful heuristic for organizing the information. In addition to different main combinations of practices (Table 2 and Figure 5), we show below that the group structure is significantly associated with farmers' regenerative agriculture scores for each of the five principles (Table 3), farmers' total regenerative agriculture score (sum of the five scores for each farmer Table 3) and farmers' self-assessment of whether they are doing or not doing sustainable soil management (Figure 6).

Farmers' regenerative agriculture scores for each principle were significantly different across the five farmer groups (Table 3 and Figure 7). Groups 2 and 4 scored highest on combining practices linked with all five principles, due to the diverse suite of practices implemented in these two groups (Figure 5). Group 1 scored the highest on the principle of "minimize soil disturbance" due to the almost systematic use of no-tillage and minimum-tillage combined, but scored lower on the other four principles. Groups 3 and 5 had balanced, but low, scores across all five sustainable soil management principles. It should be noted that all groups present some level of internal variation, with Groups 1 and 5 being the most consistent and Groups 3 and 4 the most diverse.

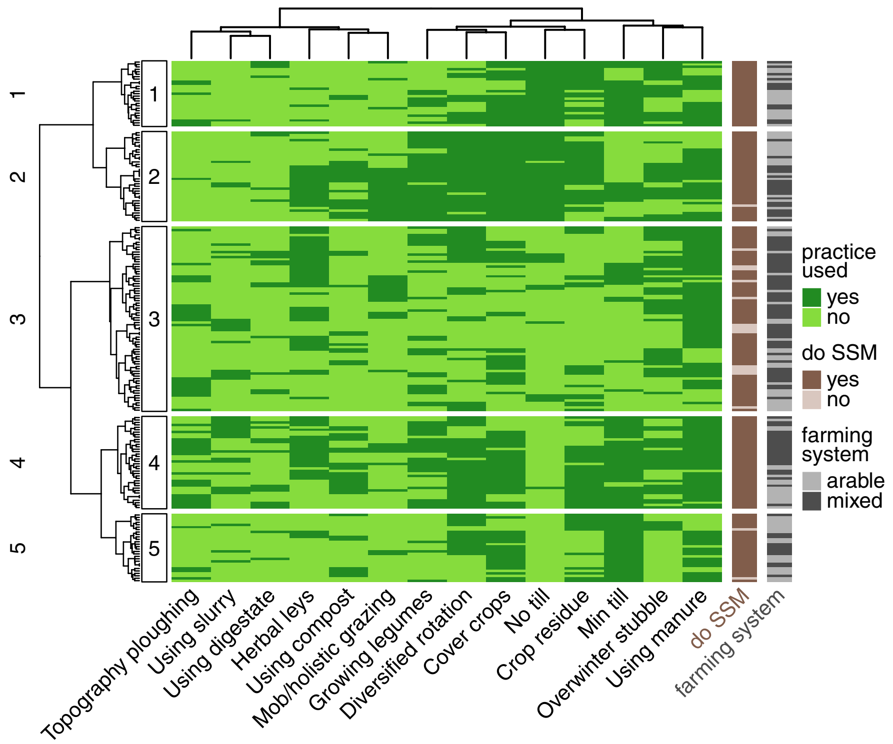

FIGURE 5 Heatmap showing the different combinations of practices used by respondents from mixed and arable systems in their regular or current soil management. Practices are shown in columns in dark green if used and light green otherwise, with individual farmers as rows. The top tree shows how practices are clustered – clustered practices are more often used together. The left tree shows how farmers are clustered: farmers' Groups 1–5 were identified based on the similarity of practices used calculated using hierarchical clustering: farmers in the same cluster tend to use the same combination of practices. The brown vertical bar to the right shows how each farmer answered the question "Is sustainable soil management something you do?" (do SSM), while the grey vertical bar shows the type of farming system (mixed or arable). $N = 206$ respondents from the online quantitative survey (from mixed and arable farming systems only). Crop residue, returning all crop residues to the field; Min till, minimum-tillage; No till, no-tillage.

TABLE 2 Main practices and combinations of practices used in each farmer group.

Group	Practice combination trend
1	This group tended to combine no tillage with cover crops, manure and minimum tillage.
2	This group combined practices the most consistently, all using cover crops, mostly combined with legumes, diverse rotation and no-tillage. Many also used herbal leys, mob/holistic grazing and manure.
3	This group combined practices the least consistently: a majority of them used manure and half of them used leys.
4	This group implemented a diverse range of practices including minimum-tillage, diverse rotation, manure, cover crops and returning crop residue for the majority, along with a good uptake of growing legumes, overwinter stubble and leys (>50%).
5	This group was characterised by a systematic use of minimum-tillage with cover crops, diverse rotation and manure for more than half of the respondents, but otherwise a very limited implementation of the other practices.

Farmers' total regenerative agriculture scores were also significantly different across the five farmer groups (Table 3 and Figure 6a): scores in Groups 2 and 4 where higher on average compared to Groups 1, 3 and 5. In addition, farmers' total regenerative agriculture scores were positively and significantly related to their self-assessment of whether they manage soil sustainably or not ($F_{1,204} = 8.33$, $p = .0043$; Figure 6b). In other words, answering "no" to the question "Is sustainable soil management something you do?" was associated with a lower total regenerative agriculture score on average ("no": mean 1.62, 95 CI [1.09, 2.16]; "yes": mean 2.44, 95 CI [2.28, 2.60]). The variation in respondents' self-assessment of whether they manage soil sustainably or not among the five farmer groups

TABLE 3 Relationships between the farmer group clustering and farmers' regenerative agriculture scores.

	F	df	Adjusted *p*	Estimates: group means [95 CI]				
				Group 1	Group 2	Group 3	Group 4	Group 5
Five regenerative agriculture scores								
1. Minimize soil disturbance	22.0	4, 201	<.001***	0.64 [0.56, 0.73] a	0.60 [0.52, 0.67] a	0.28 [0.23, 0.33] c	0.51 [0.44, 0.58] ab	0.37 [0.29, 0.45] bc
2. Increase crop diversity	33.5	4, 201	<.001***	0.40 [0.31, 0.49] c	0.85 [0.77, 0.93] a	0.39 [0.33, 0.44] c	0.70 [0.62, 0.77] b	0.36 [0.27, 0.45] c
3. Keep the soil covered	18.3	4, 201	<.001***	0.57 [0.48, 0.65] a	0.79 [0.61, 0.76] a	0.40 [0.35, 0.45] a	0.66 [0.59, 0.74] b	0.34 [0.25, 0.43] b
4. Keep living roots	10.4	4, 201	<.001***	0.44 [0.33, 0.56] bc	0.77 [0.37, 0.51] a	0.44 [0.37, 0.51] c	0.66 [0.56, 0.76] ab	0.39 [0.28, 0.51] c
5. Increase soil organic matter	20.4	4, 201	<.001***	0.27 [0.20, 0.33] b	0.47 [0.41, 0.52] a	0.31 [0.27, 0.35] b	0.52 [0.47, 0.57] a	0.24 [0.17: 0.30] b
Total regenerative agriculture score	26.3	4, 201	<.001***	2.31 [1.96, 2.67] b	3.37 [3.07, 3.67] a	1.82 [1.61, 2.03] b	3.05 [2.75, 3.34] a	1.69 [1.35, 2.04] b

Note: Different letters within a row show significantly different group means. *p*-Values before or after correction for multiple testing were all very small; we thus show only adjusted *p*-values here. ***$p < 0.001$.

was also significant ($\chi^2 = 17.8$, df = 4, $p = .0014$; Figure 5, brown right vertical bar). Group 3 had the lowest proportion of respondents self-assessing to be managing soil sustainably (82%), while in Groups 1 and 4 all respondents considered themselves to be doing sustainable soil management, with high levels also reported for Groups 2 (97%) and 5 (93%). Importantly, even in the groups with relatively low uptake of practices, respondents self-assessed to be managing soil sustainably (Figure 5, brown right vertical bar). Finally, the total regenerative agriculture score was significantly different between farming systems ($F_{1,204} = 10.7$, $p = .0012$): the mean score of respondents from mixed systems (mean 2.60, 95 CI [2.39, 2.80]) was roughly 20% higher than that of respondents from arable systems (mean 2.09, 95 CI [1.86, 2.32]). This was shown in the farmer groups by a roughly equitable distribution of arable and mixed-farming systems except in Group 3, which included twice as many mixed as arable systems (Figure 5, grey right vertical bar).

There was no significant relationship between farmers' total regenerative agriculture score and their concern about soil degradation in relation to farming (Table 4). In addition, the dominant soil type did not influence the use of any specific practice (Table 4). However, the total farmer regenerative agriculture score was related to respondents' self-reporting of existing specific topographical features impacting land management, although this was not significant after correction for multiple testing (Table 4). The most frequently reported soil issues among a list of soil problems were soil compaction, drainage and insufficient soil organic matter (Table 4). Most self-reported soil issues were not related with farmers' total regenerative agriculture score, except drainage and slaking, but these relationships were no longer significant after correction for multiple testing (Table 4). The number of soil analysis tests used by respondents was significantly related to their total regenerative agriculture score (Table 4): farmers doing 2 tests had a mean (±SE) total regenerative score of 2.0 (±0.4), while farmers doing 10 tests had a mean (±SE) score of 3.1 (±0.3). Finally, respondents gave similar scores on average across their perceived roles as farmers (make maximum profit, produce food and other goods, and look after the environment), but the scores were not related to their total regenerative agriculture score (Table 4).

3.4 | Question 3: Through what channels is sustainable soil management promoted in the United Kingdom?

Our semi-structured interviews revealed a wide network of organizations, platforms (online and offline) and groups who promote or engage with sustainable

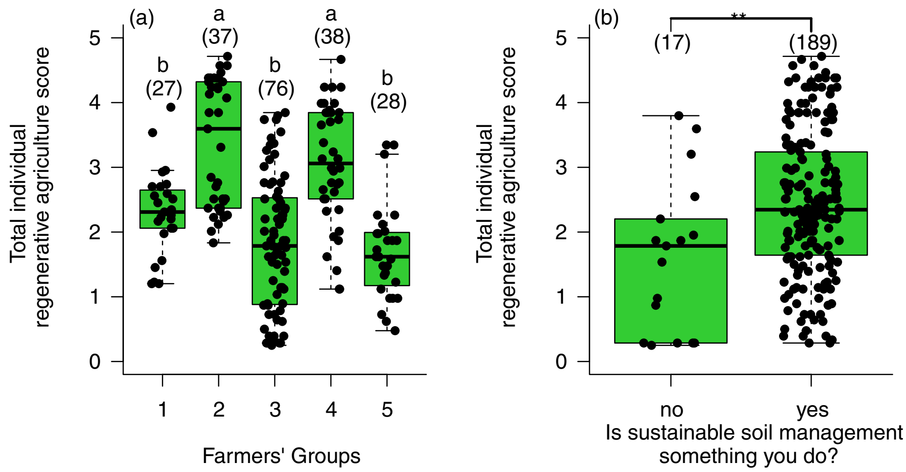

FIGURE 6 Relationships between farmers' total regenerative agriculture score and (a) farmers' groups and (b) self-assessment of whether they manage soil sustainably or not. $N=206$ respondents from the online quantitative survey (from mixed and arable farming systems only).

soil management as part of their activities. However, we found that only one group places sustainable soil management as a central concern: BASE-UK (Biodiversity, Agriculture, Soil, and Environment – UK). We found that, typically, UK Advisory, Knowledge and Information System (AKIS) organizations and groups advocate the use of sustainable soil management practices as a way to achieve other objectives, for example, in Catchment Sensitive Farming. We identified that the promotion of sustainable soil management practices was primarily driven by:

- Championing experts (individual experts offering advice, e.g. specialized agronomists)
- Championing farmers (e.g. soil farmer of the year)
- Farmer networks
- Facilitated groups (formal/informal; public/privately funded)
- Specific online platforms (social media profiles and online forums)
- Accreditation or certifications schemes/organizations
- Farmer discussion groups focusing on best practice learning

A much smaller and tightly interlinked network of individuals, organizations and groups exists in the United Kingdom, which is specifically concerned with soil sustainability and/or soil health. This network includes the members of BASE-UK and clients of a small groups of agricultural advisers dedicated specifically to issues of soil health improvement. In this network, adoption of combined sustainable soil management practices, as advocated by conservation agriculture and soil health literatures (Lal et al., 2007; Virto et al., 2015), is promoted. Interestingly, our analysis showed that respondents feeling most connected and engaged in most formal and informal networks also had the highest total regenerative agriculture scores.

3.5 | Question 4: What support is needed to enable wider adoption of sustainable soil management practices in the United Kingdom?

The majority (52%) of the farmers taking part in the online survey were members of one or more formal networks (Figure 8). The most represented formal networks were BASIS (20%) and "Farmer Cluster" (12%), the latter describing place-based, cooperating groups of farmers often facilitated by a third party (Prager, 2022). Engagement with informal farming networks specifically discussing soils and soil-related issues was much higher (70%). The most used informal networks were local group meetings or one-to-one discussions (40%), following on Twitter or Instagram hashtags (28%), and farming forums (26%). Despite this, farmers felt only moderately connected to farmer networks (average score given to feeling connected of 49% on a scale of 0, not at all connected, to 100%, extremely connected). Among respondents from mixed and arable systems only, the levels of memberships were slightly higher (60% of farmers members of formal networks; 72% members of informal networks discussing soils and soil-related issues). The average score on how connected they felt was also slightly higher (50%). Engaging in formal networks was significantly associated with engaging in informal networks ($\chi^2=11.2$, df$=1$, adjusted $p<.001$) as well as feeling well connected ($F_{1,202}=28.6$, $p<.001$); that is, farmer members of a formal network were also engaging in informal networks and feeling well connected. The

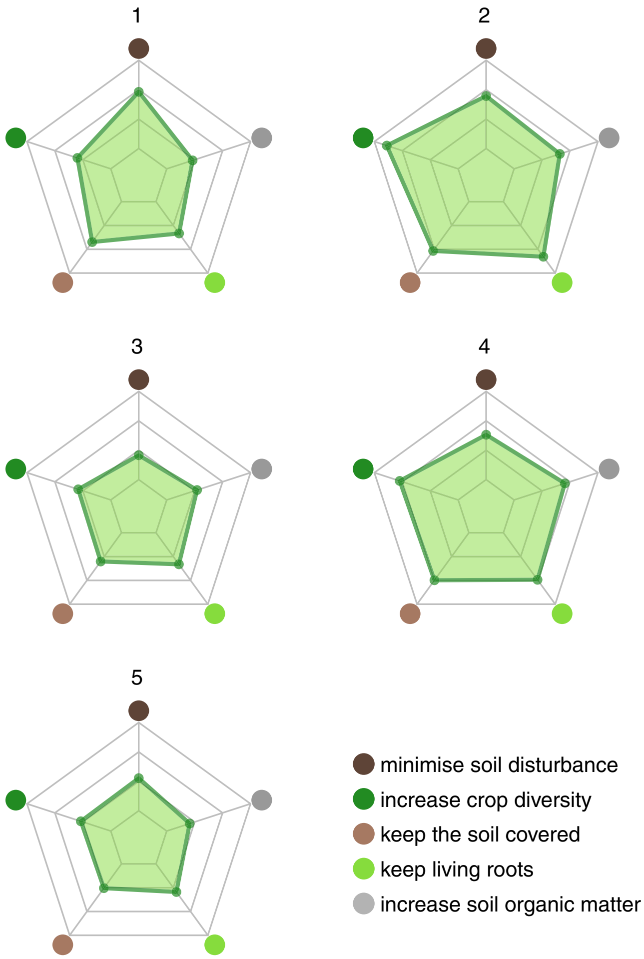

FIGURE 7 Mean regenerative agriculture scores for the five regenerative agriculture principles and the five farmers groups. Numbers 1–5 refer to farmers' Groups 1–5 on Figure 5. Farmers' regenerative agriculture scores for each principle were calculated as the proportion of practices associated with that principle being used. Small green dots on each axis of the radar plots show the mean values of the five regenerative agriculture scores within each farmer group. The green area shows the extent of the average uptake of practices following the five principles in each group. The wider and more symmetrical the area, the higher and more balanced the average uptake of the five principles.

score given to feeling well connected was also positively and significantly related to the total regenerative agriculture score ($F_{1,202}=5.82$, $p=.017$). For instance, respondents feeling the least (connectedness score < 20 versus the most connected score > 80) had a mean (±SE) total regenerative agriculture score of 2.0 (±0.2) and 2.6 (±0.2), respectively. The positive relationships between feeling connected, formal and informal farmer network membership and high total regenerative agriculture scores suggest that farmer networks help promote the adoption of sustainable soil management practice combinations.

When asked about agricultural advice, 72% of farmers in mixed and arable farming systems answered they had an agricultural adviser (against 34% in livestock-only farming systems). Interestingly, on average, arable and mixed farmers who said they had an agricultural adviser gave a moderate score (mean 56%) for how far their agricultural adviser had helped in adopting sustainable soil management practices. This score was not significantly related to farmers' total regenerative agriculture score ($F_{1,146}=0.392$, $p=.53$). This implies relatively neutral influence of agricultural advisers in promoting the adoption of sustainable soil management practices.

Respondents reported 12 main different types of barriers to the adoption of sustainable soil management practices (Table 5). The barriers most often reported were capital costs (24%), weather and climate (15%), profitability (14%), logistics (12%) and access to unbiased, tailored knowledge (11%). However, the prevalence of these main barriers was not different across the five farmers groups (capital costs: $\chi^2=8.80$, df = 4, $p=.066$; weather/climate: $\chi^2=3.05$, df = 4, $p=.55$; profitability: $\chi^2=6.02$, df = 4, $p=.20$; logistics: $\chi^2=1.03$, df = 4, $p=.90$; knowledge access: $\chi^2=2.83$, df = 4, $p=.59$).

Subsequently, our respondents reflected on the enablers of sustainable soil management adoption. Unsurprisingly, the most frequently mentioned mechanism was financial incentives (subsidies, commodities, access to equipment, free soil analysis testing, free training, etc.; 46% of arable and mixed farmers). The access to unbiased, locally tailored knowledge and advice was also frequently reported (24%) along with the need for better training (education, farmer-led trialling, etc.; 7%), and more research quantifying the benefits of local solutions (9%). Other infrequent enablers were access to soil analysis tests, clear soil performance indicators, a wider farmer network, larger farmed area/longer tenancy and support of farm relatives (farm team, landowner and family).

4 | DISCUSSION

Our study is the first to report the awareness and uptake of a full suite of sustainable soil management practices aligned with regenerative agriculture principles at the scale of the United Kingdom. Our quantitative online survey gathered 297 responses. Among the 206 responses from mixed and arable systems, we reported a high level or awareness of sustainable soil management methods (>60%), as well as a good uptake of these practices (>30%) and a fair number of respondents (30%) experimenting with sustainable soil management practices. A vast majority (92%) of respondents considered themselves to be practising sustainable soil management. We looked at how the combinations of practices regularly

TABLE 4 Statistical analyses of the relationships between farmers' total regenerative score and concern about soil degradation, soil characteristics, perceived soil problems, number of soil analysis tests and perceived role as farmers.

	Answer description	F	df	p	Adjusted p
Soil degradation concern in relation to farming		1.24	4, 201	0.30	NA
Soil characteristics					
Effect of dominant soil type:	clay 21%;				
- in relation to regenerative score	clay-loam 32%; sandy loam 31%; silty loam 8%	0.762	3, 184	0.52	0.520
- in relation to use of the 14 practices		1.37	3, 184	0.10	NA
Altitude (m above sea level)	<50 m: 42%; >50 m: 52%	2.81	1, 196	0.095	0.285
Topography	numeric 1 to 5[a]	1.48	1, 204	0.23	0.460
Specific topographic features impacting land management	yes 57%; no 43%	5.05	1, 204	0.026 *	0.104
Perceived soil problems	**% yes:**				
Insufficient organic matter	55	0.360	1, 204	0.55	1
Erosion	22	0.204	1, 204	0.65	1
Compaction	61	0.809	1, 204	0.37	1
Poor infiltration	37	1.55	1, 204	0.22	1
Low or unavailable nutrients	31	7.12	1, 204	0.0082 **	0.098
Drainage	59	0.238	1, 204	0.63	1
Low pH	28	0.0074	1, 204	0.93	1
High pH	26	5.73	1, 204	0.018 *	0.20
Slaking	3	0.0044	1, 204	0.95	1
Capping	34	0.102	1, 204	0.75	1
High load of soil-borne diseases or pathogens	4	0.804	1, 204	0.37	1
Insufficient earthworms	27	0.272	1, 204	0.60	1
Number of soil analysis tests	0–11 tests	46.0	1, 204	< 0.001 ***	NA
Perceived role as a farmer	**score 0–10 (mean ± SE):**				
Make maximum profit	7.6 ± 0.1	0.911	2, 610	0.40	NA
Produce food and other goods	7.6 ± 0.2	0.0553	2, 612	0.95	NA
Look after the environment	8.3 ± 0.1	4.98	1, 613	0.026 *	NA

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

[a] 1: flat; 2: flat-gently sloping; 3: gently-sloping; 4:undulating or varied from flat to steeply sloping; 5: steeply sloping.

used matched the five principles recommended in regenerative agriculture approaches, namely reduce soil disturbance, increase crop diversity, keep the soil covered, keep living roots all year round and increase soil organic matter using non-chemical fertilizers. Our clustering analysis found five farmer groups: Group 2 combining no-tillage with a large number of practices, Group 4 combining minimum-tillage with a large number of practices, Group 1 using no-tillage and minimum-tillage but otherwise few practices, Group 5 using minimum-tillage but otherwise few practices and Group 3 did not use either minimum-tillage or no-tillage. Group 3 had the lowest percentage (although very high – 87%) of respondents considering themselves to be doing sustainable soil management, suggesting a discrepancy between what farmers report as sustainable soil management and the way it is understood in academic literature. Also, Groups 3 and 5 had the lowest scores on the five regenerative agriculture principles. Overall, our findings confirm that in farmers' perception, taking care of soil health may be achieved

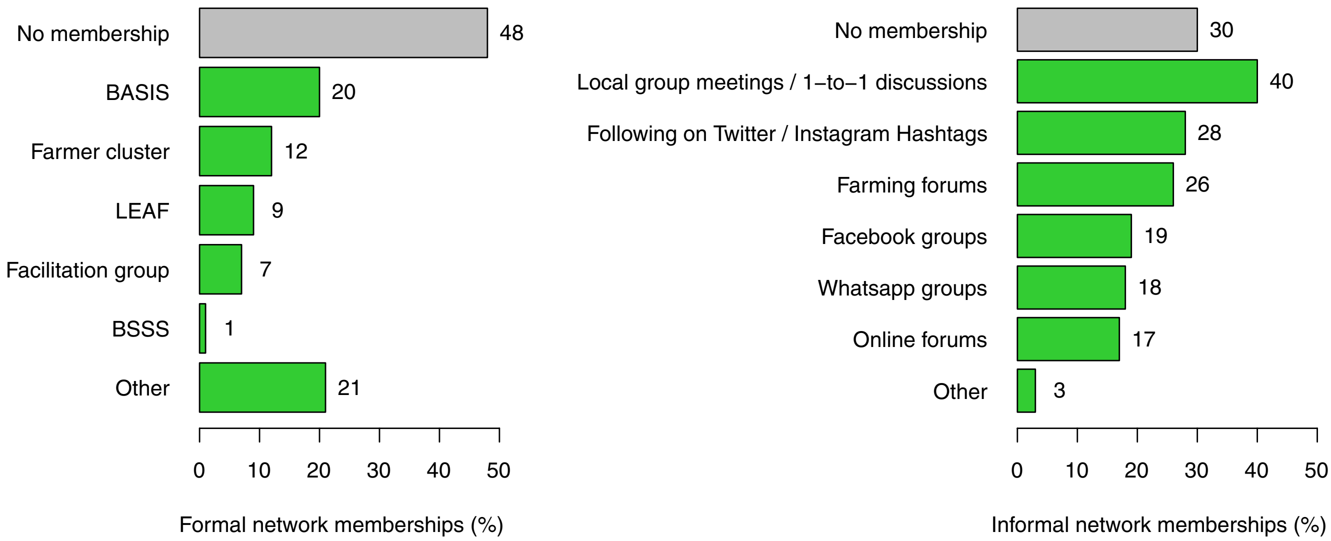

FIGURE 8 Memberships in formal farming networks (left) and informal farming networks specifically discussing soils and soil-related issues (right). $N=297$ respondents from the online quantitative survey. Numbers on the right side of bars show the corresponding percentages. BASIS https://basis-reg.co.uk; LEAF linking environment and farming (https://leaf.eco/farming/leaf-network); BSSS, British Society of Soil Science (https://soils.org.uk/).

TABLE 5 Barriers to the (further) adoption of sustainable soil management practices reported by respondents from arable and mixed-farming systems, and classified in main categories.

Barriers to adoption of sustainable soil management practices	% respondents
Capital costs of seeds, equipment and infrastructure	24
Weather, climate and climate change (increased variability of weather)	15
Profitability due to yield variability and increased costs	14
Logistics (animal health, labour, access to alternative inputs)	12
Access to unbiased, concise and locally adapted knowledge	11
Time constraints (implementing and trialling new practices under favourable weather)	10
Soil limitations (soil type, topography and soil problems)	7
Lack of research measuring the benefits of sustainable soil management practices	4
Changing rotations (to remove crops incompatible with sustainable soil management like maize and sugar beets)	3
Weed control	2
Lack of governmental incentive	1
Restrictions from regulations and certification schemes	1

through diverse practices and combinations of practices. Furthermore, we found that most farmers self-assess as practising sustainable soil management, regardless of the way in which they combine different sustainable soil practices (i.e. not necessarily following the principles of regenerative agriculture). Using outcomes of both our quantitative survey and qualitative interviews, we also found that on average our respondents were well connected to a network of organizations indirectly promoting sustainable soil management, but that a number of barriers to a wider uptake remains, including access to reliable and locally relevant information and the financial impact of implementing new practices. This suggests a need for tailored financial incentives and ways to promote locally relevant trials and farmer-to-farmer knowledge exchange.

4.1 | Representativeness of the respondent population

The population of respondents to our online quantitative survey was largely skewed towards male (86%), landowner-managers and who are aged 35–65 (Table 1). This broadly reflects the national picture with landholders and managers being 84% and 83% male, respectively, and 84% of farm holder-managers (Defra, June 2019 Census Data; the Evidence Compendium). However, these census data cover England and do not include Wales, Scotland and Northern Ireland, which we did in our online survey (Figure 1). The geographical spread of respondents across the United Kingdom in our sample was fairly even, with a balanced representation of farming systems (mixed, livestock only and arable – although terms proposed in the survey are not directly comparable to Defra's June 2019 Census data), suggesting a reasonably even representation of UK farming and agriculture. As such, our findings offer indicative insights which should be further investigated at scale.

The age range of the sample (Table 1) differs somewhat from the UK national picture, with an under representation of 65s and over (16% against the 35–40% national average) and an over representation of under 35s (10% against the 2% national average). The higher than average participation of younger land managers is possibly a reflection of the mode of surveying (online). It may also indicate that younger sectors of the farming population are interested in sustainable soil management, a relatively new concern, and linked with an overall shift in perceived farmer role from primarily producing food to also producing environmental goods (Bateman & Balmford, 2018). With the surprisingly high score of 9% respondents considering that they are doing sustainable soil management, it is very likely that the population is more biased towards these practices than the national average. Similarly, our sample shows an over-representation (10%) of certified organic holdings, compared with the national average of 2.9% organic classification (Defra, 2021).

4.2 | Awareness and uptake of sustainable soil management practices and relationship with the five regenerative agriculture principles

The respondents were concerned about soil degradation, but judged the degradation of the land in the United Kingdom overall to be much worse than the degradation of their own land, while land globally was judged to be even more degraded. This corresponds with previous research indicating that farmers are unlikely to recognize land degradation issues within their own farms (Schneider et al., 2010). Alternatively, it may reflect genuinely better soil on the land managed by the relatively young farmers in our respondent population, who are actively engaged in deploying sustainable soil management techniques. Either way, it indicates that in terms of public communication, we should not assume a shared urgency around concerns of UK land degradation, but it could reflect an over-representation of farmers already practising sustainable soil management – and hence, having improved their soils already – among the respondents.

While the awareness of sustainable soil management practices and of terms associated with soil health was very high (>95% in average among all participants, >60% in respondents from mixed and arable systems), the engagement with tests to monitor soil health (earthworm counts, VESS score, organic matter test, bulk density and slake test) remained low, except for root observations. This may be due to limited understanding of how the tests can inform sustainable soil management, the costs of having the soil analysed or limited knowledge of how to perform do-it-yourself tests (Rhymes et al., 2021). However, almost half of the respondents (48%) reported to be currently experimenting with a sustainable soil management practice. This is evidence of a paradigm shift happening when farmers are dissatisfied with conventional farming approaches and are looking for new, more sustainable ways of farming.

Regarding uptake of sustainable soil management practices, one obvious result of the survey is that in the view of the UK farming population of respondents, there is not a single way of sustainably managing the soil. While a vast majority of respondents considered themselves to be doing sustainable soil management, the clustering analysis highlighted five groups, differing in how sustainable soil management practices were combined, and the extent to which these combinations corresponded to the principles of regenerative agriculture (regenerative agriculture scores). This diversity can be seen to correspond to a core value of the regenerative farming movement: adaptation to the soil type and the wider local farming context (O'Donoghue et al., 2022; Ritz, 2021). In light of this necessary diversity, we argue that it is unlikely that regenerative farming in the United Kingdom can be defined by a precise set of practices as would be promoted, for example, by a certification scheme.

The match between sustainable soil management practices and the five regenerative agriculture principles was made based on evidence from the literature (Lal et al., 2007; Virto et al., 2015). Therefore, scientific evidence would only support combinations of practices corresponding to the highest and most balanced regenerative agriculture scores – that is, combinations of diverse sustainable soil management practices following all five regenerative agriculture principles – to be truly sustainable soil management. As such, there seems to be a discrepancy between what farmers report as sustainable soil management and the way it is understood in academic literature at least in some of the farmer groups (Groups 3, 1). From this online survey, it seems that farmers and land managers consider themselves to be employing sustainable soil management if they undertake any soil-health-related practice, but not necessarily a combination of practices following the regenerative agriculture principles. This needs to be taken into account in future research as there seem to be differences in the understanding of what constitutes sustainable soil management in different epistemic communities (e.g. farmers, researchers and policymakers).

The wide diversity in the way practices are being combined, reflected by the five groups as well a wide within-group variation, may also stem from variations in the understanding of terms used in the survey. The core question was "What practices do you currently or regularly use as part of your sustainable soil management?" and there may be differences among farmers between current or regular use due to, e.g., system conversions. Also, many farmers reported using both no-tillage and minimum-tillage; while it is unlikely that they combined the two practices simultaneously in the same field, they could use the two rotationally or in different parts of the farm with different farming requirements. Divergences in interpretations are likely to be found in each term used in the survey, since it is not possible to properly define every term in an unambiguous way. For this reason, even the quantitative results proposed in this study should be interpreted with caution.

We acknowledge that our simple scoring system does not capture all aspects of the regenerative agriculture movement. Regenerative agriculture involves adaptive management at farm and landscape scales, including monitoring of soil and other outcomes, peer-to-peer learning and long-term transformative, systemic change. We believe the proposed scoring system adds value, as a communication and analytical tool, to provide insight into how a systemic change, either towards sustainable soil management or towards regenerative agriculture, is taking place across farming regions and landscapes.

We also recognize the limitations of a single regenerative agriculture score calculated in this way. For instance, using both no-tillage and minimum-tillage would give a similar score on the first principle to using no-tillage and herbal leys, the latter is likely a more effective combination of practices for enhancing soil organic matter (Austen et al., 2022; Guest et al., 2022). Such limitations are inevitable when condensing complex "systems management" information into a simple, easy-to-interpret score. We could have weighted the practices, based on evidence of their actual contributions to specific goals of regenerative agriculture, such as enhanced carbon sequestration. We decided not to do this, partly in the interests of simplicity (ease of interpretation), but also, importantly, because the evidence itself is not equally distributed across practices or farming systems. This approach would bias the scoring system in favour of well-studied practices and systems.

4.3 | Through what channels is sustainable soil management promoted in the United Kingdom?

Farmer-driven networks are regularly recognized as being crucial to the circulation of knowledge in the farming community and the adoption of land management practices, technology and more (Ingram, 2008). We find that while there is a significant amount of knowledge exchange around sustainable soil management in the United Kingdom, this tends to be fragmented, with relevant education and innovation predominantly an add-on to other objectives. As a result, there is little attention to the need to approach sustainable soil management as a systemic practice, beyond specific groups and individuals.

Previous research findings suggest that participating in communities of practice (e.g. formal and informal farming groups) and peer-to-peer learning play a significant role in the adoption of new practices and are then crucial to farmers' uptake sustainable soil management as a systemic practice (Krzywoszynska, 2019). The results of the survey suggest that sustainable soil management as a systemic practice is supported by the participation in communities of practice for whom that is a central concern (e.g. BASE-UK). We also found that farmers feeling less connected had also the lowest total regenerative agriculture scores. This is evidence that networking is a key element of adopting sustainable soil management practices. However, we did not find evidence of significant influence of traditional farm advisers.

4.4 | What support is needed to enable wider adoption of sustainable soil management practices in the United Kingdom?

In line with previous research, this project confirmed the fragmented nature of knowledge exchange around sustainable soil management in the United Kingdom (Skaalsveen et al., 2020) and the appetite for greater researcher–farmer interaction around issues of soil (Krzywoszynska, 2019). As one interviewee reported, "these farmer training networks are a really good thing. We really need to explore that science, that art of helping farmers to learn on their own terms." Both in the interviews and in the open text sections of the online survey, our participants appealed for increased knowledge exchange, increased availability of evidence and more education and training. Participants expressed support of the collaborative learning model embraced, for example, by the Innovative Farmers initiative developed by the Soil Association (https://www.innovativefarmers.org/), and other farmer–researcher collaboration groups. Respondents called for more reliable, unbiased and locally tailored knowledge, as well as increased education and training (including through on-farm trials). Locally adapted research and evidence were also called for as mechanisms supporting the adoption of sustainable soil management practices. The other main perceived lever were financial incentives.

5 | CONCLUSION

We report moderate to high levels of awareness and uptake of some sustainable soil management practices in our relatively young sample of UK farmers. Our data show that some, but not all, sampled farmers are already combining these practices in a way that contributes to all five principles of regenerative agriculture, aiming to restore soil health by reducing soil disturbance, maintaining soil cover and crop diversity and increasing soil organic matter. Our results should inspire caution in assuming progress on sustainable soil management in the United Kingdom. Future sustainable soil management policies, the monitoring of sustainable soil management uptake and knowledge exchange programmes need to attend more closely to farmers' and land managers' own understandings of soil degradation and sustainable soil management, to avoid a false assumption of shared paradigms. As the divergence between the sustainable soil management framing in research and policy, and among practitioners, has been reported in other geographical contexts (Higgins et al., 2019; Schneider et al., 2010), clearly more research on this issue is needed. Progress towards achieving sustainable soil management in the United Kingdom has to take seriously the role of sustainable soil management-dedicated communities of practice, including those focused on "regenerative agriculture," and actively involve farmers in finding ways of developing sustainable soil management practices that work for specific places.

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CONFLICT OF INTEREST STATEMENT

Authors declare to have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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ENDNOTE

[1] Snowball sampling is a purposive sampling method where initial participants nominate other potential participants who fit the eligibility criteria (Given, 2008). It is commonly used in studies exploring expert networks.

REFERENCES

AHDB. (2018). Visual Evaluation of Soil Structure. https://media.ahdb.org.uk/media/Default/Imported%20Publication%20Docs/Healthy%20grassland%20soils%20factsheet.pdf

Alskaf, K., Sparkes, D. L., Mooney, S. J., Sjögersten, S., & Wilson, P. (2020). The uptake of different tillage practices in England. *Soil Use and Management*, *36*, 27–44. https://doi.org/10.1111/sum.12542

Austen, N., Tille, S., Berdeni, D., Firbank, L. G., Lappage, M., Nelson, M., Helgason, T., Marshall-Harries, E., Hughes, H. B., Summers, R., Cameron, D. D., & Leake, J. R. (2022). Experimental evaluation of biological regeneration of arable soil: The effects of grass-clover leys and arbuscular mycorrhizal inoculants on wheat growth, yield, and shoot pathology. *Frontiers in Plant Science*, *13*, 2900. https://doi.org/10.3389/fpls.2022.955985

Bateman, I. J., & Balmford, B. (2018). Public funding for public goods: A post-Brexit perspective on principles for agricultural policy. *Land Use Policy*, *79*, 293–300. https://doi.org/10.1016/j.landusepol.2018.08.022

Baumhardt, R. L., Stewart, B. A., & Sainju, U. M. (2015). North American soil degradation: Processes, practices, and mitigating strategies. *Sustainability*, *7*, 2936–2960. https://doi.org/10.3390/su7032936

Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society Series B*, *57*, 289–300. https://doi.org/10.1111/j.2517-6161.1995.tb02031.x

Berdeni, D., Turner, A., Grayson, R. P., Llanos, J., Holden, J., Firbank, L. G., Lappage, M. G., Hunt, S. P. F., Chapman, P. J., Hodson, M. E., Helgason, T., Watt, P. J., & Leake, J. R. (2021). Soil quality regeneration by grass-clover leys in arable rotations compared to permanent grassland: Effects on wheat yield and resilience to drought and flooding. *Soil and Tillage Research*, *212*, 105037. https://doi.org/10.1016/j.still.2021.105037

Borrelli, P., Robinson, D. A., Fleischer, L. R., Lugato, E., Ballabio, C., Alewell, C., Meusburger, K., Modugno, S., Schütt, B., Ferro, V., Bagarello, V., Van Oost, K., Montanarella, L., & Panagos, P. (2017). An assesustainable soil managementent of the global impact of 21st century land use change on soil erosion. *Nature Communications*, *8*, 1–13. https://doi.org/10.1038/s41467-017-02142-7

Cooledge, E. C., Chadwick, D. R., Smith, L. M., Leake, J. R., & Jones, D. L. (2022). Agronomic and environmental benefits of reintroducing herb-and legume-rich multispecies leys into arable rotations: A review. *Frontiers of Agricultural Science and Engineering*, *9*, 245–271. https://doi.org/10.15302/J-FASE-2021439

Cope, M. (2009). Transcripts: Coding and analysis. In R. Kitchin & N. Thrift (Eds.), *International encyclopedia of human geography* (pp. 350–354). Elsevier.

Defra. (2016). Farm household income and household composition 2014/15. Retrieved from https://www.gov.uk/government/collections/farm-business-survey

Defra. (2018). A Green Future: Our 25 Year Plan to Improve the Environment. [Online Document]. Retrieved from https://www.gov.uk/government/publications/25-year-environment-plan.

Defra. (2020). The Path to Sustainable Farming: An Agricultural Transition Plan 2021 to 2024. [Online Document]. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/954283/agricultural-transition-plan.pdf.

Defra. (2021). Policy paper: Sustainable Farming Incentive: Defra's plans for piloting and launching the scheme. [Online document]. Retrieved from https://www.gov.uk/government/publications/sustainable-farming-incentive-scheme-pilot-launch-overview/sustainable-farming-incentive-defras-plans-for-piloting-and-launching-the-scheme.

Defra. (2021). Organic farming statistics 2021. Retrieved from https://www.gov.uk/government/statistics/organic-farming-statistics-2021.

Dicks, L. V., Rose, D. C., Ang, F., Aston, S., Birch, A. N. E., Boatman, N., Bowles, E. L., Chadwick, D., Dinsdale, A., Durham, S., Elliott, J., Firbank, L., Humphreys, S., Jarvis, P., Jones, D., Kindred, D., Knight, S. M., Lee, M. R. F., Leifert, C., … Sutherland, W. J. (2018). What agricultural practices are most likely to deliver 'sustainable intensification' in the UK? *Food and Energy Security*, *8*, e00148. https://doi.org/10.1002/fes3.148

Doherty, B., Bryant, M., Denby, K., Fazey, I., Bridle, S., Hawkes, C., Cain, M., Banwart, S., Collins, L., Pickett, K., Allen, M., Ball, P., Gardner, G., Carmen, E., Sinclair, M., Kluczkovski, A., Ehgartner, U., Morris, B., James, A., … Connolly, A. (2022). Transformations to regenerative food systems – An outline of the FixOurFood project. *Nutrition Bulletin*, *47*, 106–114. https://doi.org/10.1111/nbu.12536

ELD Initiative. (2015). Report for policy and decision makers: Reaping economic and environmental benefits from sustainable land management. Retrieved from https://www.eld-initiative.org/fileadmin/ELD_Filter_Tool/Publication_Report_for_Policy_and_Decision_Makers__Reviewed_/ELD-pm-report_08_web_72dpi.pdf

Evans, D. L., Quinton, J. N., Davies, J. A., Zhao, J., & Govers, G. (2020). Soil lifespans and how they can be extended by land use and management change. *Environmental Research Letters*, *15*, 0940b2. https://doi.org/10.1088/1748-9326/aba2fd/meta

Farm of the Future: Journey to Net Zero. (2022). Report from the Royal Agriculture Society of England. Retrieved from https://www.rase.org.uk/news-article/RASE%20launches%20Farm%20of%20the%20Future:%20Journey%20to%20Net%20Zero%20report

Giller, K. E., Hijbeek, R., Andersson, J. A., & Sumberg, J. (2021). Regenerative agriculture: An agronomic perspective. *Outlook on Agriculture*, *50*, 13–25. https://doi.org/10.1177/0030727021998063

Given, L. M. (2008). Snowball sampling. In *The SAGE encyclopedia of qualitative research methods* (p. 816). SAGE Publications, Inc.. https://doi.org/10.4135/9781412963909.n425

Graves, A. R., Morris, J., Deeks, L. K., Rickson, R. J., Kibblewhite, M. G., Harris, J. A., Farewell, T. S., & Truckle, I. (2015). The total costs of soil degradation in England and Wales. *Ecological Economics*, *119*, 399–413. https://doi.org/10.1016/j.ecolecon.2015.07.026

Gu, Z. (2022). Complex Heatmap visualization. *iMeta*, *1*, e43. https://doi.org/10.1002/imt2.43

Guest, E. J., Palfreeman, L. J., Holden, J., Chapman, P. J., Firbank, L. G., Lappage, M. G., Helgason, T., & Leake, J. R. (2022). Soil macroaggregation drives sequestration of organic carbon and nitrogen with three-year grass-clover leys in arable rotations. *Science of the Total Environment*, *852*, 158358. https://doi.org/10.1016/j.scitotenv.2022.158358

Hartig, F. (2022). DHARMa: Residual diagnostics for hierarchical (multi-level / mixed) regression models. R Package Version 0.4.6. Retrieved from https://CRAN.R-project.org/package=DHARMa

Higgins, V., Love, C., & Dunn, T. (2019). Flexible adoption of conservation agriculture principles: Practices of care and the management of crop residue in Australian mixed farming systems. *AU International Journal of Agricultural Sustainability*, *17*, 49–59. https://doi.org/10.1080/14735903.2018.1559526

Huang, H., Liu, Y., & Marron, J. S. (2022). sigclust: Statistical significance of clustering. R package version 1.1.0.1. https://CRAN.R-project.org/package=sigclust

Ingram, J. (2008). Are farmers in England equipped to meet the knowledge challenge of sustainable soil management? An analysis of farmer and advisor views. *Journal of Environmental Management*, *86*, 214–228. https://doi.org/10.1016/j.jenvman.2006.12.036

Jackson, P., Cameron, D., Rolfe, S., Dicks, L. V., Leake, J., Caton, S., Dye, L., Young, W., Choudhary, S., Evans, D., Adolphus, K., & Boyle, N. (2021). Healthy soil, healthy food, healthy people: An outline of the H3 project. *Nutrition Bulletin*, *46*, 497–505. https://doi.org/10.1111/nbu.12531

Kassam, A., Friedrich, T., & Derpsch, R. (2019). Global spread of conservation agriculture. *International Journal of Environmental Studies*, *76*, 29–51. https://doi.org/10.1080/00207233.2018.1494927

Keesstra, S. D., Bouma, J., Wallinga, J., Tittonell, P., Smith, P., Cerdà, A., Montanarella, L., Quinton, J. N., Pachepsky, Y., van der Putten, W. H., Bardgett, R. D., Moolenaar, S., Mol, G., Jansen, B., & Fresco, L. O. (2016). The significance of soils and soil science towards realization of the United Nations

sustainable development goals. *The Soil*, *2*, 111–128. https://doi.org/10.5194/soil-2-111-2016
Kibblewhite, M. G., Ritz, K., & Swift, M. J. (2008). Soil health in agricultural systems. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*, 685–701. https://doi.org/10.1098/rstb.2007.2178
Krzywoszynska, A. (2019). Making knowledge and meaning in communities of practice: What role may science play? The case of sustainable soil management in England. *Soil Use and Management*, *35*, 160–168. https://doi.org/10.1111/sum.12487
LaCanne, C. E., & Lundgren, J. G. (2018). Regenerative agriculture: Merging farming and natural resource conservation profitably. *PeerJ*, *6*, e4428. https://doi.org/10.7717/peerj.4428
Lal, R., Reicosky, D., & Hanson, J. (2007). Evolution of the plow over 10,000 years and the rationale for no-till farming. *Soil and Tillage Research*, *93*, 1–12. https://doi.org/10.1016/j.still.2006.11.004
Lenth, R. (2022). emmeans: Estimated marginal means, aka least-squares means. R Package Version 1.8.1-1. Retrieved from https://CRAN.R-project.org/package=emmeans
Miner, G. L., Delgado, J. A., Ippolito, J. A., & Stewart, C. E. (2020). Soil health management practices and crop productivity. *Agricultural and Environmental Letters*, *5*, e20023. https://doi.org/10.1002/ael2.20023
Newton, P., Civita, N., Frankel-Goldwater, L., Bartel, K., & Johns, C. (2020). What is regenerative agriculture? A review of scholar and practitioner definitions based on processes and outcomes. *Frontiers in Sustainable Food Systems*, *26*, 194. https://doi.org/10.3389/fsufs.2020.577723
O'Donoghue, T., Minasny, B., & McBratney, A. (2022). Regenerative agriculture and its potential to improve Farmscape function. *Sustainability*, *14*, 5815. https://doi.org/10.3390/su14105815
Oksanen, J., Simpson, G., Blanchet, F., Kindt, R., Legendre, P., Minchin, P., O'Hara, R., Solymos, P., Stevens, M., Szoecs, E., Wagner, H., Barbour, M., Bedward, M., Bolker, B., Borcard, D., Carvalho, G., Chirico, M., De Caceres, M., Durand, S., … Weedon, J. (2022). vegan: Community Ecology Package. R package version 2.6-2. Retrieved from https://CRAN.R-project.org/package=vegan
Prager, K. (2022). Implementing policy interventions to support farmer cooperation for environmental benefits. *Land Use Policy*, *119*, 106182. https://doi.org/10.1016/j.landusepol.2022.106182
R Core Team. (2022). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/
Rhymes, J. M., Wynne-Jones, S., Williams, A. P., Harris, I. M., Rose, D., Chadwick, D. R., & Jones, D. L. (2021). Identifying barriers to routine soil testing within beef and sheep farming systems. *Geoderma*, *404*, 115298. https://doi.org/10.1016/j.geoderma.2021.115298
Ritz, K. (2021). The Groundswell 5 Principles and Soil Sense. Retrieved from https://groundswellag.com/karl-ritz-the-groundswell-5-principles-and-soil-sense/
Schneider, F., Ledermann, T., Fry, P., & Rist, S. (2010). Soil conservation in Swiss agriculture – Approaching abstract and symbolic meanings in farmers' life-worlds. *Land Use Policy*, *27*, 332–339. https://doi.org/10.1016/j.landusepol.2009.04.007
Scottish Government (2022) *Sustainable and regenerative farming – Next steps: Statement*. Agriculture and Rural Economy Directorate, Scottish Government ISBN 9781804351154. https://www.gov.scot/publications/next-step-delivering-vision-scotland-leader-sustainable-regenerative-farming/
Sherwood, S., & Uphoff, N. (2000). Soil health: Research, practice and policy for a more regenerative agriculture. *Applied Soil Ecology*, *15*, 85–97. https://doi.org/10.1016/S0929-1393(00)00074-3
Skaalsveen, K., Ingram, J., & Urquhart, J. (2020). The role of farmers' social networks in the implementation of no-till farming practices. *Agricultural Systems*, *181*, 102824. https://doi.org/10.1016/j.agsy.2020.102824
Tittonell, P., El Mujtar, V., Felix, G., Kebede, Y., Laborda, L., Soto, R. L., & De Vente, J. (2022). Regenerative agriculture – Agroecology without politics? *Frontiers in Sustainable Food Systems*, *2*, 6. https://doi.org/10.3389/fsufs.2022.844261
Townsend, T. J., Ramsden, S. J., & Wilson, P. (2016). How do we cultivate in England? Tillage practices in crop production systems. *Soil Use and Management*, *32*, 106–117. https://doi.org/10.1111/sum.12241
Virto, I., Imaz, M. J., Fernández-ugalde, O., Gartzia-bengoetxea, N., Enrique, A., & Bescansa, P. (2015). Soil degradation and soil quality in Western Europe: Current situation and future perspectives. *Sustainability*, *7*, 313–365. https://doi.org/10.3390/su7010313

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