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Future proofing a long-term agricultural experiment for decades to come: Relocation and redesign

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ABSTRACT

We took land encroachment for urban development that threatened a 60-year-old field experiment as an opportunity to transport and redesign an entire experiment to more effectively address contemporary challenges. The field experiment comprised long-term pH plots, established for agronomic demonstration in 1961, but used over the years for both applied and fundamental research. We redesigned the experimental layout to add strength to the statistical design through randomisation. Continuation and enrichment of the long-term pH experimental platform lends a unique resource for microbiome research *per se*. Here we have provided a rationale for why the decision was made to move the soils from the former Woodlands Field pH experiment. Moving soil on the scale of a field experiment requires costs and benefits to be weighed up in that the realisation of the transfer costs and the costs for the ongoing maintenance can outweigh the costs of a new experimental set up or indeed closing the experiment and walking away. It is important to recognise that much of the value is in assets that are not monetary. Considerations include the availability of a site suitable from a biophysical perspective but also considering ownership and future access. The topsoil (0–20 cm to plough depth) was moved to a new location in a similar environment and within the same soil association. The soil was disturbed under very dry conditions and placed back into the earth in the new location within 90 minutes, and thus as near to normal cultivation as possible. Additional plots were added to the experiment that will be amended to the pH treatments in the long-term experiment providing an exciting opportunity to assess how soil microbial communities change over time. Soil samples taken 2 years after the relocation of the soils indicate that the soil pH gradient (4.5–7.5) has been maintained. Safeguarding this long-term resource on soil pH helps us to predict the impacts of changed practice with regard to liming on productivity and also to address wider contemporary and future issues surrounding net zero, food security and soil protection.

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1. Introduction

It is well recognized that perhaps the greatest flaw in all research undertaken on the environment, on soils and in agronomy, is a failure to capture the effect of time. Typically, soil and environment research projects run for a few years and report on that time scale. This presents a significant limitation to the value of the research findings, as some processes can take over a decade for the impacts to materialise and reach a new 'steady-state'. Long-term experiments offer a unique opportunity to understand the impacts of crop management on food production, crop quality, soil development, carbon (C) storage and biodiversity over time as well as to understand the interactions between agricultural productivity and climate change (Macdonald et al., 2020; Rasmussen et al., 1998; Richter et al., 2007; van Oort et al., 2022). Long-term experiments can provide insight into the long-term sustainability of agricultural systems that can be obtained in no other way (Berti et al., 2016). They can also allow the exploration of resilience of agricultural systems to climate change (e.g. Addy et al., 2020; Li and Tao, 2023). Long term field experiments such as those at Rothamsted, UK, provide very rare examples of resources which address the deficiency of time-scale endemic to most environmental and agricultural research. Johnston and Poulton (2018) note that the value of well-designed and documented experiments increases with time. They note also that appropriate changes to both the experimental design and management can increase their relevance to current and future food production and wider sustainability issues. Historic data from groups of long-term experiments in diverse environments are increasingly being used to understand how factors like crop diversification can contribute to climate change resilience (Bowles et al., 2020), crop yields (Smith et al., 2023) and ecological intensification (MacLaren et al., 2022). The value of such experiments increases where there are archived samples available (Richter et al., 2007), either for new analysis, reanalysis as analytical techniques change or for reanalysis to help understand data anomalies (Debreczeni and Körschens, 2003). Ostler et al. (2023) described archived samples as "unique snapshots in time" to be used for future research often for purposes that were not even devised when the archiving commenced.

While many long-term experiments outlive both those who design them and their original purpose, many others are closed down after relatively short periods. The cost of maintenance is always a factor in this, but other reasons include experimental designs that are no longer fit for purpose and subjects that are no longer relevant and breach regulatory changes or cannot endure land ownership issues. Some are closed because they have answered the question they set out to answer. Other reasons cited for closure include shifts in research priorities and societal instability (Richter et al., 2007). It is hard to estimate total numbers of long-term agricultural experiments existing, closed or relocated but Grosse et al. (2021) identify 186 experiments outside Germany of which 16 have been closed. They also report 140 ongoing long-term experiments out of 205 recorded in Germany using a definition of 20 years (Grosse et al., 2020). The reasons for these closures are not well documented but development threats from housing, highways and infrastructure and institutional development (universities and research institutes) are all well-known factors. However, these are unique resources, and when faced with the prospect of losing land, it is important to consider what can be salvaged from such a long-term investment. Aside from the use of the data, this could include archiving large quantities of soil to provide soils of known history and characteristics as a resource for glasshouse or laboratory experiments.

When a long-term field experiment is threatened, a more radical and challenging approach is to relocate the soils from different treatments and continue the experiment. This can provide an opportunity to redesign plot layout, or to start a new experiment using that soil. This has been done occasionally but rarely fully documented. For example, half of the long-term Woburn Market Garden Experiment (https://gn.org/experiments/47), UK that had treatments with sewage sludge, compost and FYM, against controls was moved in 2005, but this has yet to be documented in the literature (Steve McGrath, Rothamsted Research. Personal communication 2023). Topsoil was also relocated in a long-term experiment exploring the use of organic manures at ADAS Gleadthorpe, UK as a result of the construction of a reservoir in 1997 (Anne Bhogal, ADAS. Personal communication 2023). At SLU in Sweden one experiment from a set of 10 in the Swedish long-term soil fertility experiment series (R3–9001) started in 1957, was moved approximately 3 km from Örja to Borgeby in Southern Sweden in 2010 (https://glten.org/experiments/400). One replicate of a second experiment in the same series were also moved within one field at Orup. There is little documentation of either move and nothing has been published since moving (Sabine Braun, SLU. Personal communication 2023). Perhaps the best-documented example of an experiment being moved, and the subsequent data analysed and published is from the Magruder Plots, USA moved in 1947, to make way for a new dormitory on the Oklahoma A & M College campus. Surface and sub-surface soils from six of the original 10 plots were moved 1.6 km West of the original location to a similar sub-soil (Girma et al., 2007). The surface 40.6 cm soil, comprising approximately 450 tonnes of soil, were moved to preserve the biological integrity of the soils (Girma et al., 2007). Yield trends reportedly remained similar post-relocation (Harper, 1953).

These examples of moving long-term field experiments allow study of fertiliser or organic amendment impacts to crops and soils. Such experiments are abundant across the globe as they address the major challenges of fertility and soil carbon management. Some observe soil pH to be a major driver of treatment differences, and other research exploring pH gradients across geologically contrasting soils has found it to drive microbial (Shen et al., 2013) and plant communities (Basto et al., 2015), and even compaction resistance (Woldeyohannis et al., 2022). There are very few long-term, controlled field experiments exploring soil pH on one soil type, but these are needed to remove confounding factors like mineralogy, vegetation and soil carbon that affect interpretation of regional studies.

In this paper, we aim to explain the decision-making processes used to decide on whether, and how to, capitalise on the legacy of soils managed using different pH or fertiliser regimes over a period of up to 100 years in 2 long-term experiments. These were based at Woodlands Field, Craibstone Estate SRUC, Aberdeen UK and threatened by urban development. Woodlands Field comprised two long term experiments, one set up in 1922 (the Craibstone Long-term Fertiliser Experiment), and the other (pH Experiment) established in 1961. By documenting the decision-making process, and the methodology for relocating large quantities of soil without compromising its biological integrity, we aim to provide others faced by similar dilemmas over the future of long-term experiments, with a process which will guide and help them in redesigning, repurposing and relocating unique resources for future agricultural and environmental research. We then describe the experimental redesign and relocation of top soil from one experiment that met the criteria for this action.

2. Woodlands Field as a case study for relocating long-term experiments

In 2021 it became apparent that the Woodlands Field experimental platform at Craibstone near Aberdeen (57.19°N, 2.21°W) would be lost to urban development. Without substantial intervention, this would mean the end of two long-term experiments. The Long-term Fertiliser Experiment was established in 1922 to demonstrate to farmers and students the impact of newly available nitrogen (N), phosphorus (P) and potassium (K) fertilisers on crop production. The pH experiment, also set up for demonstration/educational purposes, was established as a formal experiment in 1961. The Woodlands Field experiments were designed following the principle of a fixed term rotation with all courses of the rotation applied in every year (space for time substitution) (Preece, 1986) and, because they were both set up as educational resources for use with farmers and students, the applied treatments (either pH or fertiliser or crop within rotation, Figures S1 & S2) were not randomised. Whilst this set up, particularly the pH gradient from 4.5 to 7.5 in half pH units, was visually striking and therefore excellent for teaching, the lack of randomisation and any within-season replication provided challenges in terms of analysis and use of the plots for research purposes. Nonetheless, the continual treatments still had the effect of conditioning the soil in specific ways. In both experiments, the rotation treatment was in phase order in the criss-cross design. As a consequence of the design, the assessment of the treatment effect requires aggregation of the responses either across plots within a year or across years within a plot. The experimental design, without randomization or within-season replication, was however typical of many field experiments set up in the early 20th Century (Grosse et al., 2020) and there is ongoing development of statistical methods to allow the robust use of data from such experiments (e.g. Macholdt et al., 2020).

The plan to build on the Woodlands Field left the experimental team with a decision to make as to whether the value of these long-term experiments could be enhanced by continuing their existence in any way. At the time the original Woodlands Field experiments were designed, the focus was entirely about food production and the available information suggests the focus was very much on food quantity rather than environmental quality. Future agricultural experiments need to be able to quantify the impacts of management on multiple ecosystem services including soil health and above and belowground biodiversity as well as production (Li et al., 2023). Both experiments had crop rotations which were still relevant to mixed farming in Northern Britain but did not give the opportunity to explore novel crop combinations or crop diversity for enhanced resilience, for example through the introduction of cover crops. Thus, from the outset, in considering the option to relocate and repurpose the experiments the focus was on use of the soil microbiomes and physicochemical environments developed during the previous 60–100 years rather than on a continuation of the agronomic treatments per se. Soil microbiomes are fundamental because they are directly tied to nutrient recycling, especially C, nitrogen (N), phosphorus (P) and sulphur (Suman et al., 2022). Plant development is built largely on symbiotic relationships with microorganisms in the soil, allowing the plants to nourish themselves more effectively, and allowing the microbiota to develop populations with large nutrient stores (Kumar et al., 2019; Santos and Olivares, 2021). This interaction generally leads to an improvement of the soil characteristics (Lehman et al., 2015). In general, most soil bacteria do better in neutral pH soils that are well oxygenated. Soil pH is also a key factor in soil borne diseases (Zhang et al., 2022a) and the microbiota can contain soilborne plant pathogens that can be variably aggressive and persistent, depending on soil conditions and interactions with other members of the microbial community.

Also affected by soil pH over long time periods are physicochemical properties, such as exchange sites and carbon-mineral associations (Goulding, 2016). This depends on soil type. The experiments described here have a sandy loam textured soil with a relatively shallow topsoil (approximately 20 cm), classified as an iron podzol (locally referred to as Countesswells series) with free drainage (Glentworth et al., 1962) and a soil organic matter content of approximately 10.4% by loss on ignition.

2.1. The Craibstone Long-term Fertiliser Experiment

The Long-term Fertiliser Experiment comprised a 3 year grass/white clover ley (Perennial Ryegrass [*Lolium perenne L.]*), Timothy grass [*Phleum pratense L.]* and white clover [*Trifolium repens L.*]) followed by spring oats [*Avena sativa* L.], a root course (originally subdivided into potatoes [*Solanum tuberosm* L.], swedes (*Brassica napus* L.) and turnips (*Brassica rapa*) but with only potatoes only in recent years) and finally an undersown spring barley [*Hordeum vulgare* L.] crop. The first-year grass was cut for hay, with the 2nd and 3rd years cut and mulched to simulate grazing. There were 6 fertiliser treatments. All received farmyard manure (25 t ha^{-1}) supplying approximately (Total N 150 kg ha^{-1}, Total P 35 kg ha^{-1}, and Total K 195 kg ha^{-1} (AHDB, 2023)) once every 6 years, prior to ploughing the ground in readiness for the root phase of the rotation. The control treatment received no other fertiliser inputs. The remaining treatments were N (as ammonium nitrate), P as triple superphosphate (TSP), potassium (K), NPK (with P as ground mineral phosphate (GMP)), NP_{TSP}, NK and $P_{TSP}K$ only. The original trial design is given in Figure S1. Crop protection chemicals were applied as needed based on typical agronomic practice for each crop for the region. The fertiliser treatments are shown in Table S1. Experiments with similar treatments were catalogued by Smith et al. (2002) at Nahrstoffmangelversuch in Germany (started 1938), and 2 experiments in the Ukraine (started 1929 and 1967) but all with arable-only rotations. Other examples of such “replacement experiments” include the nutrient deficiency experiments at Thyrow (Ellmer et al., 2000) and at Giessen in Germany (Macholdt et al., 2019) with 3 course arable rotations. There are many good examples of long-term ley/arable experiments at different levels of N fertilisation including those at Woburn, UK (Johnston et al., 2017) and the Swedish soil fertility experiments (Carlgren and Mattsson, 2001). The latter includes P and K levels which vary independently but there is no treatment equivalent to the NK and NP treatments in the Woodlands Field Long-term Fertiliser Experiment.

2.2. The pH Experiment

There are several long-term experiments in Europe that include soil pH treatments but as far as we know the pH Experiment in Woodlands Field at SRUC Craibstone, Aberdeen, was unique in including both a pH gradient (4.5–7.5) and a ley/arable crop rotation (3 years of grass/white clover, winter wheat (*Triticum aestivum* L.), potatoes, spring barley, swedes and undersown spring oats). As with the Long-term Fertiliser Experiment, the 1st grass/white clover ley was cut for hay, while the 2nd and 3rd year leys were mulched to simulate grazing. The original trial design in given in Figure S2 and the fertiliser application rates in Table S2. Crop protection chemicals were applied as needed and written records kept. The pH was maintained on the basis of annual soil testing using aluminium sulphate (1961–2012) and then iron sulphate (2013 onwards) to decrease the pH and calcium oxide or calcium carbonate to increase the pH. Pietri and Brookes (2008a) noted that pH gradient experiments on single soil types are rare worldwide. In the UK, there is continuous winter wheat on the Hoosfield acid strip at Rothamsted, UK with pH from 3.7 to 8.3 created accidentally by liming in the mid-19th century (Pietri and Brookes, 2008b). There are several experiments with liming treatments in crop rotations, for example, Stackyard Field at Rothamsted (Woburn 1962–1996) and Sawyers Field which ran for the same period and has now been reinstituted with cereals (rye, triticale and wheat in 2023) and 4 levels of liming (Andy Gregory, Rothamsted Research. Personal communication 2023). At Jyndevad in Denmark a replicated trial established in 1942 aims at target pH values of 3.7 (native pH), 5.4, 6.2, and 6.7 (as measured in 0.01 M $CaCl_2$ extracts) but this has been in continuous barley since 1985 (Abalos et al., 2020). Similarly in Spain a continuous rye experiment with 4 levels of different types of lime was maintained for 10 years (Olego et al., 2021). There is also a replicated long-term pH experiment at the University of Wisconsin-Madison Spooner Agricultural Research Station, USA where corn, soy and alfalfa have been grown for 25 years at 5 different pH levels (4.7–6.7) on excessively well drained soils with 2.15% organic matter (Braus and Whitman, 2021). Most of these experiments have very different cropping and soil organic matter levels to the Craibstone long-term experiments with an average soil organic matter content of 10.4% (loss on ignition). One unusual feature about the pH Experiment is that in 60 years the rotation was not changed unlike many other experiments e.g. Rothamsted ley arable experiments (Johnston et al., 2017) and Askov, Denmark (Christensen et al., 2022). The fertiliser treatment was also maintained over 60 years. The intention was to maintain varieties as far as possible, but records were kept of when and why they were changed.

3. The decision-making process

A scheme to aid decision making was developed, each step in Fig. 1 is effectively a gate. The steps (1–5) in the left-hand side boxes can be met through the evidence described in the right-hand side boxes. Relocating an experiment requires passing through all these gates and finally having the financial and logistical resources available to allow relocation. The following section works through the process for the pH Experiment and the Long-term Fertiliser Experiment from Woodlands Field.

3.1. Step 1: Have past manipulations created a unique soil resource?

Step 1 asks the question as to whether the long-term experiment has developed a unique soil resource or whether the experiment could be stopped and restarted elsewhere. Molecular analysis of soils samples collected from the Long-term Fertiliser Experiment in 2018 and the pH Experiment in 2019 was used to address this. Microbial taxonomic compositions (metabarcoding with high-throughput MiSeq® sequencing of bacterial and fungal rRNA and Internal Transcribed Spacer (ITS) sequences respectively) was carried out in order to compare and quantify the size and effects of management on soil bacterial and fungal biodiversity (details of the method are given in Fernández-Huarte et al., 2023). The pH value consistently affected both bacterial and fungal taxa in the soils, while fertiliser gave weaker results influencing only certain types or abundance of bacteria and fungi (Fernández-Huarte et al., 2023). The effect size of the pH treatment range was also greater than that of location when tested against 6 other UK locations/soil types. Figs. 2 and 3 illustrate the impact of pH on species richness and community structure, respectively. The pH of the soil consistently affected both bacterial and fungal taxa (merged amplicon sequence variants) using these three different biodiversity metrics. This impact was not shown in any of the other 7 long-term experiments, these other long-term experiments were set up to investigate a range of organic amendments (green waste compost, manure, cover crops), fertilisers and tillage (Fernández-Huarte et al., 2023).

At Step 1 the evidence would suggest that either experiment could be relocated but the evidence is stronger for the pH Experiment.

3.2. Step 2: Is there management and experimental data to categorise it as a long-term experiment?

Data and sample archives from long-term experiments provide a living laboratory for future science (Ostler et al., 2023). A data archive requires that good records are kept of the management, experimental data and the environmental conditions (Ostler et al., 2023). These records should abide by the FAIR principles which "ensure an experiment and its data are sufficiently well stewarded to remain findable, accessible, interoperable and re-usable over time" (Wilkinson et al., 2016). An archive of crop and soil samples enables new or re-analysis. Both the Long-term Fertiliser Experiment and the pH Experiment were set-up originally as demonstrations, with the yield being the prime focus. Except for the 1940 s, primarily the period of the Second World War, the records of yield for the Long-term Fertiliser Experiment are largely complete. The records of yield for the pH Experiment are complete for over 50 years. Detailed data is also available on the fertiliser application rates for both long-term experiments (Tables S1 & S2). Data on cereal varieties grown is largely complete for both experiments; however, there are gaps in the information for the root crops (Tables S3 & S4). Until the last 10 years, the management information on the experiments indicates the month of the activity. However, soil analysis data are sparse, although soil pH data is available for many years of the pH experiment. Daily temperatures have been recorded at the site since 1931, and precipitation since 1961. Since the early 2010 s, soil samples have been archived from the pH Experiment on an annual basis. However, there

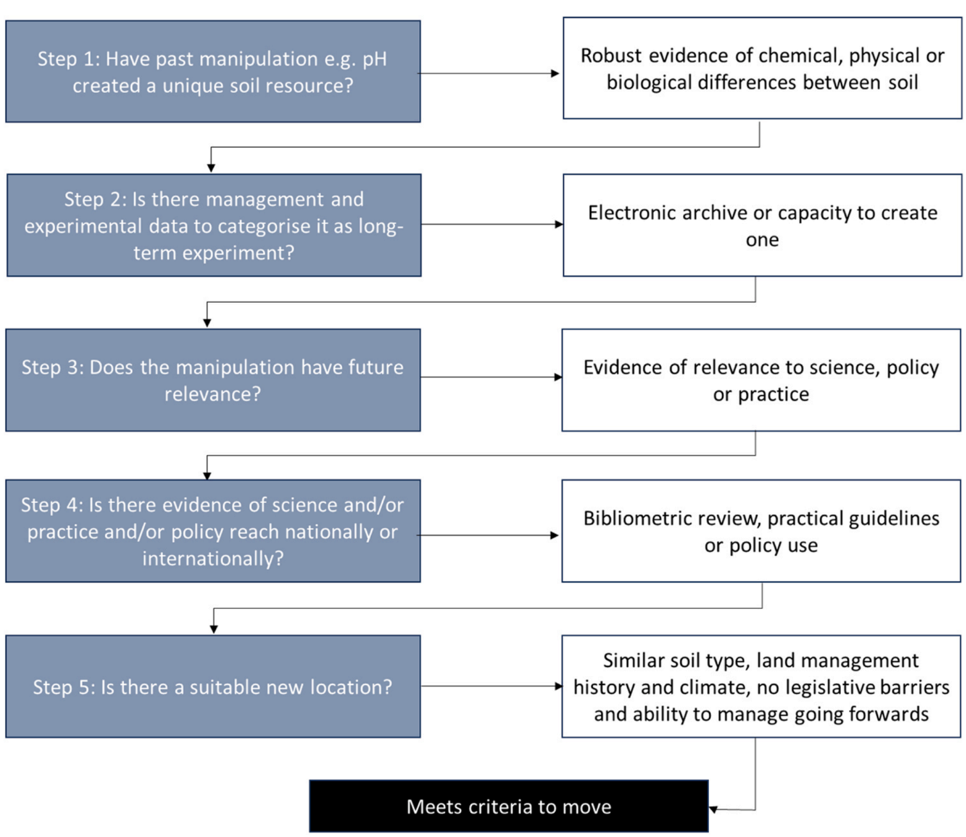

Fig. 1. Schematic decision-making process.

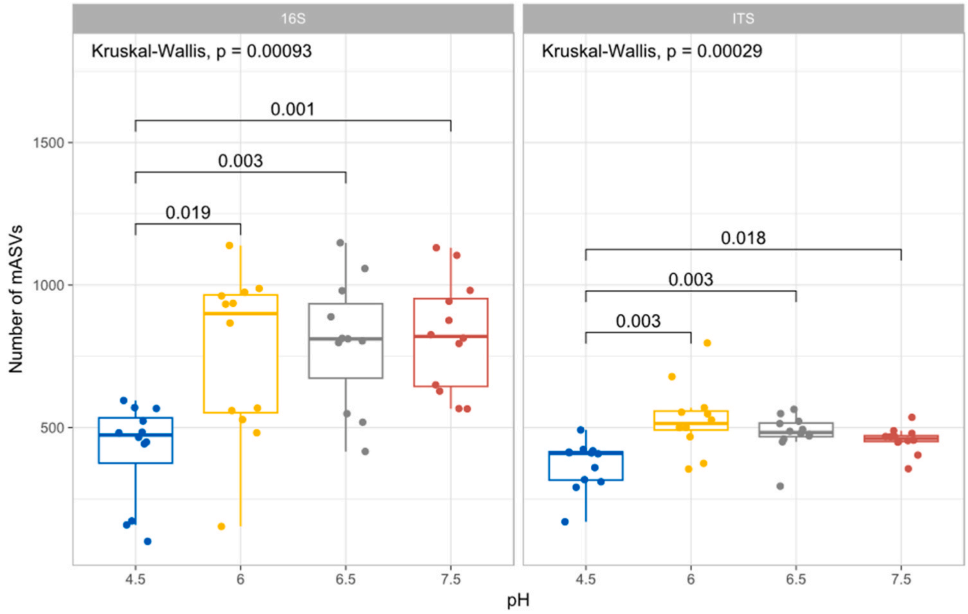

Fig. 2. Box plots showing significant general and pairwise differences in richness of bacterial (16 S) and fungal (ITS) barcodes from soils managed at 4 different pH values, measured from the number of sequence variants. Significant differences in numbers of taxa between trial sites as revealed by Wilcoxon pairwise tests are shown as variation in the numbers of bacterial (left) and fungal (right) merged amplicon sequence variants (mASVs) identified by metabarcoding.

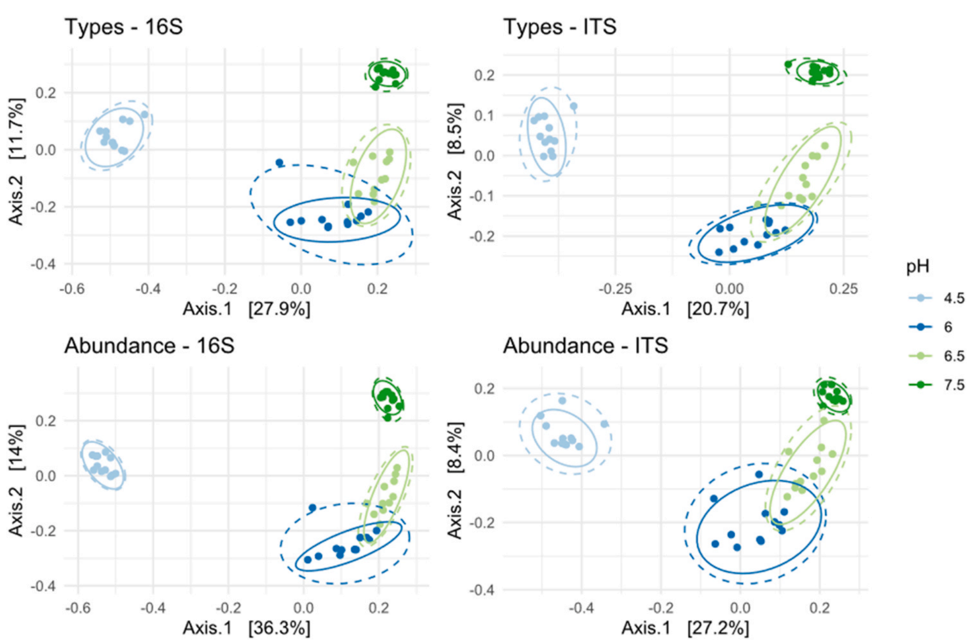

Fig. 3. Principal Coordinate Analysis (PCoA) of the types (top) and abundances (bottom) of 16 S and ITS mASVs. Colours represent replicated soil samples at each pH level. The percent variance explained by each PCoA axis is indicated.

are very few archived soil samples from the Long-term Fertiliser Experiment or crop samples from either rotation.

At Step 2 the evidence would suggest that either experiment could be relocated.

3.3. *Step 3: Does the manipulation have future relevance?*

To be successful, the redesigned experiment needs to function as an outdoor living laboratory that continues to provide a resource to the wider research community, contribute to knowledge exchange activities and provide a teaching resource which has enduring relevance. To ensure these requirements were met, a number of online stakeholder events were held that involved representatives of these communities from research, academic and knowledge transfer organisations across Europe. At these events the “big” research questions that will potentially be asked over the next two decades were explored. These were focused on the sustainability of agricultural systems (achieving Net Zero, enhancing soil health and increasing diversity of systems) and the potential use of new research technologies, e.g., metagenomics. It was also recognised that redesigning an experiment offers the opportunity to add more treatments allowing a wider variety of questions to be asked which build on the original design.

3.3.1. Long-term Fertiliser Experiment

Nitrogen (N) is the primary limiting factor on plant, and therefore crop, growth globally, this constraint was largely removed with the advent of the Haber-Bosh process and the subsequent large-scale application of synthetic nitrogen in agricultural settings worldwide. However, many areas are still severely nitrogen limited due to inherently infertile soils and the inaccessibility of commercial fertilisers. In regions with fertile soils or abundant access to fertilisers, more efficient fertiliser use is a contemporary challenge to address the high cost of this input and its environmental impacts. One threat of N fertiliser application is soil acidification.

A recent review of fertiliser use, food security and environmental sustainability on a global scale draws together evidence that suggests N application could be reduced by approximately 35% with a production loss of only 1% in some countries (Penuelas et al., 2023). These reductions can be affected in multiple ways including legume-based intercropping (Jensen et al., 2020), maintaining appropriate plant counts to prevent leaching and use of N sensors for appropriate dosing (Colaço and Bramley, 2018). Whereas in other areas where N inputs are typically low, these could be increased with concomitant yield increases without exceeding regional N runoff maxima (Penuelas et al., 2023). This work also considered the agronomic use and sustainability of P and K but all 3 nutrients were assessed individually (Penuelas et al., 2023), whereas recent work has found that the stoichiometry of the system (particularly the balance of N and P) can result in co-limitation of plant growth (Craine and Jackson, 2010; Schleuss et al., 2020; Ringeval et al., 2021). Given the recognised importance of understanding fertiliser applications and their interactions, myriad fertiliser field experiments exist globally; the GLTEN network lists 264 out of 342 registered experiments as having a fertiliser component (GLTEN network www.glten.org). Fertiliser omission experiments are common enough, particularly when considering crop breeding work, but many have changed rotations over time. The Dikopshof experiment (Ahrends et al., 2020; Seidel et al., 2021) has maintained a consistent rotation since 1953 but, the Long-term Fertiliser Experiment in Woodlands Field at Craibstone has existed without rotational change for a century.

The Long-term Fertiliser Experiment was established in 1922, 9 years after the invention of the Haber-Bosh process and was designed to demonstrate to farmers in north-east Scotland the agronomic value of modern fertilisers to increase yields at a time of population expansion and the prospect of food shortage. Over the past 9 decades this experiment has primarily been used for education and have demonstrated increased crop productivity. In recent years however, the experiment has been a source of information not only on how modern cultivars respond to different N, P, K applications but also to contemporary questions on how fertiliser applications influence soil C pools (Tshering, 2009).

The fertiliser replacement experiment has illustrated that breeding is influential in determining the yield response to the introduction of plant protection chemicals. There is a greater divergence in yields between the control treatment and the fertiliser treatments for spring barley than spring oats (Fig. 4). As there has been a greater focus on breeding for barley than oats, and as plant breeders tend to focus on breeding crops for intensive systems, the yield increase of the barley has been greater, primarily as the improvements in weed, disease and pest control over time have enabled these varieties to move closer towards their potential yield (Fischer, 2015).

3.3.2. pH Experiment

Soil acidification (where soil pH drops below 5.5) is a major cause of soil degradation and poor crop productivity, thought to affect approximately 40% of arable land globally (Ferguson et al., 2013). Lime application in the UK has declined dramatically in recent years (Goulding, 2016). From 126,000 soils sampled in the UK in 2019/20, 37% of arable soils had a pH below 6.5% and 50% of grassland soils below 6.0 (Professional Agricultural Analysis Group, 2020), indicating that pH maintenance is still an important agronomic issue.

Soil pH is known to have large, direct impacts on soil microbial metabolism (Malik et al., 2018), soil aggregate stability (Jakšík et al., 2015; Rivera and Bonilla, 2020), as well as GHG emissions (Hénault et al., 2019; Wang et al., 2018). Using lime to stabilise or increase soil pH is a cost-effective solution for farmers which has been in common use for decades, with applications peaking between 1959 and 1963 (BACMI, 1983) around the time the SRUC pH experiment was established. However, the impacts of lime on greenhouse gas release are complex. The dissolution of the lime generally causes increases in soil respiration and CO_2 emissions but can also result in decreases in nitrous oxides (Hénault et al., 2019; Šimek and Cooper, (2002), and methane emissions (though much of the work on CH_4^+ has come from forest soils) (Weslien et al., 2009; Zhang et al., 2022b). Impacts of soil pH on C and N cycling are well recognised, but there is significantly less understanding of how pH influences soil biology in relation to soil function, particularly the relationships between soil biology, soil health and crop production. The long-term effects of liming on SOM have rarely been studied on their

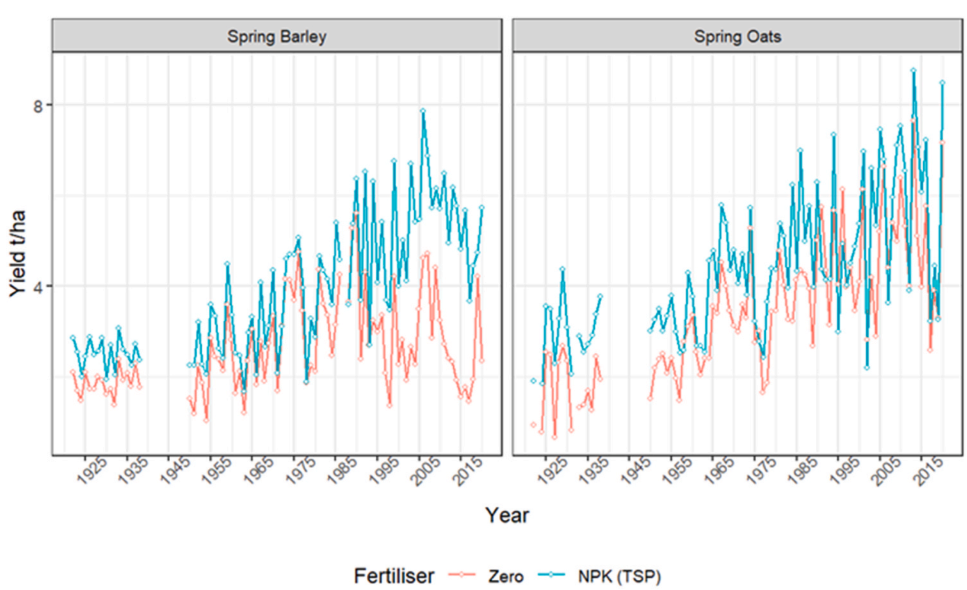

Fig. 4. The spring barley and spring oat yields for the control (Zero) treatments and the NPK (TSP).

own (Paradelo et al., 2015). Those results that do exist focus on rates of SOM mineralisation and are often contradictory due to the complication of co-factors such as tillage, climate and fertilisation regime (e.g. Garbuio et al., 2011; Hontoria et al., 2018; Kowalenko and Ihnat, 2013; Manna et al., 2007).

Long-term (50 + years) data from the pH experiment illustrates the variability between species, with regards to tolerance to high and low pH. Spring oats (Fig. 5) are more tolerant than winter wheat (Fig. 6) or spring barley (not shown) to low pH values. However, the low yields of spring oats at high pH values in this experiment reflects manganese deficiency common in these soils (Mitchell, 1974). In practice on farms, pH is usually managed at the rotational scale, so the target pH needs to be suitable for all crops to grow well, with a greater focus on the higher value crops, or those that are delivering greater public goods, e.g. forage legumes helping to reduce the N fertiliser requirements later in the rotation. There will also be a cost-benefit threshold at which the cost of liming beyond a certain pH will provide no benefit to yield and can reduce yield, e.g. above pH 6 in oats (Fig. 5) and wheat (Fig. 6). In addition, if the pH is not optimised for yield across the rotation, other agrochemical inputs are likely to be used less efficiently and uneconomically.

While the main use of the pH Experiment has in the past been linked either to agronomic yields or to microbial functions particularly allocating functional activity to archea or bacteria in the context of N-cycling (See step 4 bibliometric analysis), there are many other agronomic and environmental areas to explore. A controlled gradient of soils of different pHs offer a significant resource to address the links between GHG emissions, C storage, soil microbiomes and agricultural management. Soil pH affects plant (Schuster and Diekmann, 2003) and microbial communities (Fierer and Jackson, 2006) having implications for the control of weeds, pests and diseases which influence yield. As the legal framework surrounding the use of agrochemical inputs in agriculture becomes more restrictive to protect environmental and human health, there is an interest in both weed and disease suppressive soil where pH is known to be a factor (Latz et al., 2016). In terms of weed ecology, soil pH through direct and indirect impact via soil microbial communities is also a factor of interest affecting not only germination (Travlos et al., 2020) but also weed seed persistence in soils (Basto et al., 2015). These experimental soils provide an opportunity to investigate new understanding, leading to potential new management practices with reduced reliance on synthetic agrochemicals. They may also provide conditions where new or rare pathogens or weed species can grow. The links between pH and nutrient deficiency also mean that data and samples from this experiment could help in the development of digital tools for non-invasive diagnosis of crop nutrient deficiencies such as those described by Yi et al. (2020).

There are also direct questions that can be addressed about resilience and adaptation to environmental constraints imposed by the treatments.

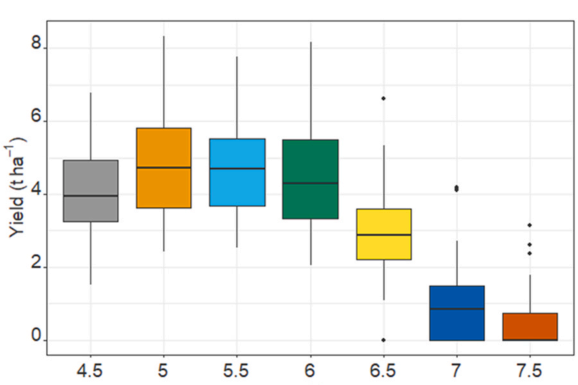

Fig. 5. Boxplot of the spring oat yields (1969–2021). Box and whisker plots show median, min, max and interquartile range.

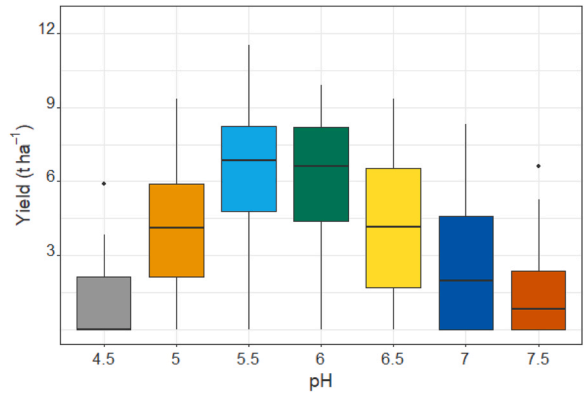

Fig. 6. Boxplot of the winter wheat yields (1969–2021) Box and whisker plots show median, min, max and interquartile range.

The treatments here also provide underexplored environments (same soil texture and climate but held long-term at different pHs) which can facilitate research and innovation, whether in new product discovery like antibiotics (Hutchings et al., 2019), or synthetic community construction (Saad et al., 2020) or mitigating against human disease (Brennan et al., 2022).

At Step 3 the evidence would suggest that either experiment could be relocated.

3.4. Step 4: Is there evidence of science and/or practice and/or policy reach nationally or internationally?

The Long-term Fertiliser Experiment has provided generations of farmers and students with information on the impact of different nutrient additions on crop yield (e.g. FAS, 2022). However, relatively little has been published in the scientific literature. Publications do include an early analysis of the impact of fertilisers and rainfall and crop yield (Cowie, 1945) and has also been used more recently to address disease suppressiveness in soils (Döring et al., 2020) and in studies on N cycling (Kuntz et al., 2016). The latter was part of a PhD thesis, alongside many other BSc, MSc and PhD theses from this experiment.

The pH Experiment at Craibstone has provided land-users and biological/environmental scientists, both in Scotland and worldwide, with a uniquely powerful resource to understand this pivotal role of soil pH in regulating agricultural productivity and environmental pollution. This is illustrated by a bibliometric analysis which showed between 1945 & 2023 that 67 papers have used either soil samples or data related to the soils from the pH Experiment. As of the 30 December 2023, these papers have been cited by 4767 papers in Scopus. Twelve of these papers have been cited over 200 times, and the most cited paper that assessed the influence of soil pH on ammonia oxidizing archaea and bacteria has over 1000 citations (Nicol et al., 2008). Additionally, data from the experiment has been used to inform Technical notes used by SAC Consulting and others to provide liming advice to Scottish farm businesses (FAS, 2019; MISR/SAC, 1985; SRUC, 2014). Both the long-term experiments speak to Scottish, UK and European policies including Climate Change (Emissions Reduction Targets) (Scotland) Act 2019 (Scottish Government, 2019) and Farm to Fork (European Union, 2020).

The significant publication record evidenced use of these publications, and continued use by the scientific community makes the soils from the pH Experiment a candidate for moving at Step 4. The lack of publications and use of the experiment by the wider scientific community effectively ends the journey of the Long-term Fertiliser Experiment through the decision framework at Step 4. At this stage it was decided this was not a candidate for moving. However, large quantities of soil from each treatment of the Long-term Fertiliser Experiment have been stored to allow their future use for laboratory or glasshouse experiments with soils of different, know fertiliser and management history.

Duplicate topsoil and subsoil samples were collected from all treatments prior to closing the Long-term Fertiliser Experiment and they were located in 2 places: the SRUC soil store directly related to the experiment and in the National Soil Archive at the James Hutton Institute. Replicate samples were stored air dry and at −80°C. In addition, soil from the 6 fertiliser treatments were used to create new demonstration plots (4×5m) at a new site to retain the knowledge exchange value of the Long-term Fertiliser Experiment. Soils were relocated next to the new pHoenix experiment in exactly the same way as described for the soils from the original pH experiment in Section 5 below.

3.5. *Step 5: Is there a suitable new location?*

Aside from the practicalities of moving soils from the Woodlands Field platform, there was a need to ensure it was moved to a location with similar soils, drainage, parent material, climate and environment. This led to a new partnership with the University of Aberdeen (known as the Aberdeen Cropping Experimental (ACE) Platform) who owns land adjacent to the SRUC Craibstone Estate. This location was ideal due to proximity and the same soil association (Countesswells Association (Glentworth et al., 1962)). It is approximately 900 m South of the original location at 57.18 N and 2.23 W. The partnership between SRUC and the University of Aberdeen enhanced our long-term research collaboration, building a critical mass of agronomic, crop and soil researchers in the region. It was therefore strongly supported by both sides. One current limitation of both the old and the new site is proximity to an international airport restricting the use of drone or other aerial technology.

In order to safeguard the experiment for the future, legal aspects of land ownership and regulations related to moving soil were carefully checked. In this case, the soil was moved from land owned by one organisation to land owned by a different organisation, requiring agreement from both parties. No details are given of the legal aspects as these related to regional legislation and will be different outside Scotland. While it cannot be guaranteed that the land where the new experiment is situated will not be repurposed at some future time, it is not anticipated this will happen in the foreseeable future. Part of the agreement between SRUC and the developer was that the site where topsoil was stripped from the pH experimental plots was returned to a good condition by replacing topsoil.

Ensuring funding to maintain any relocated experiment going forward is clearly a major challenge. Many long-term experiments are supported by core funding from their institution (for example, SLU has long-term experiments funded through faculty support for maintenance, data and sample archiving (https://www.slu.se/en/faculties/nj/this-is-the-nj-faculty/collaborative-centres-and-major-research-platforms/long-term-field-experiments-/) while in other cases charitable trusts have been set up, such as the Lawes Agricultural Trust at Rothamsted. In most cases, local committees are set up to manage and protect the integrity of the experiment while allowing access to scientists from their own and partner institutions. The management committees also have responsibility for making changes to the experiments as needed and ensuring that good records are kept assisting future generations in utilising the historic data and samples. The provision of suitable facilities to archive historical samples and data for collaborative purposes going forward is also a key consideration. Progressive institutions may even have the foresight to make sure there are legal restrictions placed on the land which restrict its future use, also reducing the risk of development or other similarly disruptive influences forcing premature termination of the experiments.

Having reached Step 5 of the decision-making process it became clear that relocating the soil from the pH experiment should be considered as long as the move could be resourced. The next section of the paper describes the statistical and agronomic redesign and practical details.

4. The redesign – statistical robustness and cropping plans

Features of successful long-term monitoring were set out by Lindenmayer and Likens (2009) and arguably many/all of them apply equally well to agricultural long-term experiments. They highlight the need to set manageable questions which can be adapted as the research develops alongside a robust experimental design with associated data and sample collection, collation and storage. They go on to discuss the importance of management, continued availability of resources (financial and personnel), and the need for collaboration and leadership. In our specific case, redesigning the pH experiment allowed us to correct the deficiencies of the pH experimental plots as originally established (1961–2021). This involved creating a robust experimental design, ensuring robust data and sample collection and storage procedures, developing new collaborative partnerships and aiming to ensure ongoing funding. In addition to allowing the flexibility to answer new questions, it is important to recognise that the design needs to be flexible enough to allow the cropping system to be optimised in the future. Implicit in this approach is the opportunity to adapt cropping systems over time to further optimize systems against the defined constraints and goals (Colnenne-David and Doré, 2015), without compromising the integrity of long-term data sets. The background constraint of utilising the soils from the former experiment inevitably constrained both the design (in terms of amounts of soil available) and the goals of the experiment, necessitating a more restricted approach than the broad one proposed by Li et al. (2023) to create a platform of emergent cropping systems for the UK. Ensuring a future for the pH experiment included considering how any new resources could increase the value of the experiment and how to make the overall design more robust going forward. Fig. 7 summarises considerations under four headings discussed below.

4.1. *Additional resources*

Thus, in the redesign extra “partner” plots were added next to each plot of relocated soil. The aim being to amend the “partner” plots to the same pHs over time and allow changes in soil organic matter, nutrient availability and the microbiome to be studied in real time. The original Woodlands Field contained a UK Met Office weather station which also had to be moved as a result of the urban development. The Met Office, in consultation with SRUC, chose to relocate the weather recording station next to the SRUC Tulloch Organic Rotations experiment (Willoughby et al., 2022), approximately 2 km West of the relocated experiment, known as the pHoenix. Each cropping strip is separated by a wide pathway (4 m) to allow access to soil sampling machinery, power cables and future instrumentation. The site is located in an area with 5 G allowing the possibility for networks of sensors to be added in the future.

It is increasingly important to quantify the impacts of management strategies not only upon crop production, but also upon multiple environmental and ecosystem functions, including soil health and above and

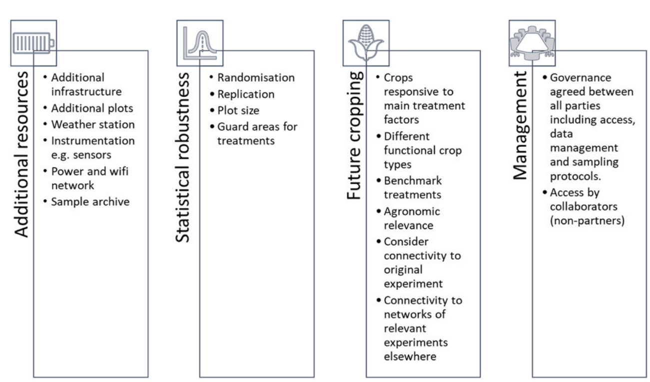

Fig. 7. Considerations for the redesign process.

belowground biodiversity. There are a myriad of sensors available to researchers, and it is an ever-expanding market. Data that was once collected manually can now be collected in real time directly to a digital device, including metrics such as soil moisture, temperature, salinity and electrical conductivity. There are also ever more reliable autonomous samplers for insects, pollen and spores, audio recorders for vocalizing animals, sensors for volatile organic compounds emitted by plants (pVOCs) and camera traps for mammals and small invertebrates (Wagele et al., 2022).

4.2. Statistical robustness

Whilst the re-design of the pHoenix experiment did not allow the incorporation of any "true" replication of treatment combinations within seasons (years), the re-design did provide opportunities to incorporate elements of randomisation. This was achieved both in separate randomisation of the pH treatments within each of the strips of plots for each of the different cropping treatments (incorporating both the two different lengths of rotations and the two different permanent crops), and in the randomised allocation of the rotation treatments (and phases) and the two different permanent crops to strips of plots. Further, the allocation of the old (re-located) and new soils to sub-plots within each of the pH plots was randomised separately for each plot. Hence the new experiment was arranged as an un-replicated randomised split-split-plot design, with crop (rotation/phase) randomly allocated to main-plots, pH randomly allocated to plots within each main-plot, and soil (type) randomly allocated to sub-plots within each plot. The continuing lack of "true" replication, essentially as a consequence of the lack of such "true" replication in the original design, so that soil was only available for 8 separate "cropping" strips, means that treatment comparison still need to be made across multiple years of the experiment, the inclusion of the two different rotation treatments also meaning that a fully-phased design is not possible, so that aggregation of responses for each plot or sub-plot over years is the natural way to provide this replication, rather than aggregating responses across multiple plots or sub-plots within each year.

4.3. Future cropping

In making decisions on the crop treatments for the new pHoenix experiment, the immediate limitation was plot size and the amount of soil of each pH available. The decision was reached to stay with the original layout of 8 beds, each including every pH level. The choice of crops followed a number of guiding principles: 1) crops chosen should have different sensitivities to pH, 2) include a diverse range of functional crop types likely to be important in the future including intercrops/multi-species sward as there is limited information available about pH response (plant/soil/microbe interactions) of such crop associations (Darch et al., 2022), 3) include benchmark treatments i.e. grassland, 4) include an all-arable rotation and a ley/arable rotation, due to current interest in both systems in Europe and to retain connectivity with the original experiment, 5) where possible include crops and sequences related to the nearby SRUC Tulloch organic rotations experiment and to the new Rothamsted long-term rotations experiment (Li et al., 2023), to allow facilitate comparisons between long-term experiments at different sites, 6) remain agronomically relevant to the pedoclimatic conditions. While many long-term experiments focus on all arable rotation, fewer focus on ley/arable systems. In the GLTEN database 58 out of 342 refer to leys (https://glten.org/). There is currently a growing interest in reintroducing leys into arable systems for the ecosystem services they deliver, including to help combat the loss of organic matter from arable rotations (Berdeni et al., 2021). While some published studies focused on understanding soil microbial community and function in ley/arable systems e.g. Lori et al. (2023), the authors are unaware of others with a focus on pH in these systems. Ley/arable systems are often prevalent in land areas marginal for agricultural crop production (Reumaux et al., 2023) where pH is often a constraining factor.

The rotations and functional crops are illustrated in Table 1 and Fig. 8. Crops included in the rotation are winter wheat, spring barley, spring field beans [*Vicia faba* L.], kale [*Brassica oleracea* L.], a Tricrop consisting of spring barley, spring peas [*Pisum sativum* L.] and buckwheat [*Fagopyrum esculentum* L.]. A ryegrass sward [*Lolium perenne* L.] was included as one of the permanent plot treatments and a multi-functional mixture was the second permanent treatment. This included Cocksfoot [*Dactylis glomerata* L.], Ryegrass, Timothy [*Phleum pratense* L.], Meadow Fescue [Festuca pratensis L.], White Clover [*Trifolium repens* L.], Red Clover [*Trifolium pratense* L.], Alsike Clover [*Trifolium hybridum* L.], Chicory [*Cichorium intybus* L.] and Ribwort Plantain [*Plantago lanceolata* L.]. Within the 7-year rotation the same multi-functional ley mixture was used. The spring barley was under sown with the multi-functional ley mixture. The crops are given in functional groups (Fig. 8) to allow future substitution of crops in the event of crop failure or in response to climatic or policy changes.

Ground was prepared by ploughing to approximately 20 cm depth several weeks prior to crop establishment, with secondary cultivation taking place before sowing, followed by rolling. Herbicide, fungicide and pesticides were applied as appropriate, after consultation with a BASIS qualified agronomist (https://basis-reg.co.uk/), based on typical regional practice for each crop. The fertiliser treatments for the first year of the experiment are shown in Table S5.

The constraint of having only 8 cropping strips available within which to incorporate comparisons between the two permanent crops (grass (PRG), multi-functional -grassland mixture (MFM)) and the different phases of the two different lengths of rotation (5-year, 7-year) required some careful planning of the starting phases to be included for each of the rotations. With three cropping strips allocated to each of the different rotation cycles, clearly only three of the phases of each rotation cycle can be observed in any year. A further constraint is that each of the strips for each rotation cycle must follow the same sequence across years, though from a different starting phase for each strip. The three phases to be included in each year can be identified from a partially balanced (for the 5-year rotation) or balanced (for the 7-year rotation) incomplete block design – in the latter, each phase of the rotation occurs together in a year with each of the other phases exactly once in any 7-year cycle, whilst in the former each phase of the rotation occurs together with two of the other phases in each of two years and the other two phases in one year each in any 5-year cycle. Statistical robustness and the ability to compare functional crops between rotations was essential. The choice of the starting phases was further constrained by the need to establish the 3-year multi-species ley in the 7-phase rotation (i.e. not allowing any cropping strip to start in the middle of this 3-year period), and a desire to maximise the frequencies of comparisons between the same crops in the different lengths of rotation cycles (and hence enable regular direct comparisons of the impact of the different rotation treatments on the responses of the common crops), Table 1. Whilst these choices did not allow a random allocation of the starting phases, the fact that both rotation cycles have a prime number of phases means that all 35 combinations of phases of the two cycles will appear together in three different years of a 35-year period of the experiment, and each of the subsets of three phases from each cycle will occur together exactly once in this period.

4.4. Management

A local management committee including academic staff from both SRUC and the University of Aberdeen, field and farm technicians and campus and estates staff has been set up to manage the site going forward. Written procedures have been put in place to allow both internal and external staff and PhD students to apply to sample the pHoenix experiment or to access stored samples or data. The committee will also ensure continued collection and cataloguing of topsoil, subsoil and crop samples in a safe location. Soil bulk density will also be monitored on an

Table 1
Bed layout, cropping in the first 7 years of the 5 and 7 course rotations, and the permanent crops (S=spring sown; W = winter sown; MFL 1,2,3 indicate age (years) of multi-functional ley (MFL); multifunction mixture permanent (MFM)). Species included in MFL, MFM and Tri-crop are detailed in the text.

Bed	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
5 course rotation							
1	Kale	S oats	Tri-crop	S barley	S beans	Kale	S oats
4	S beans	Kale	S oats	Tri-crop	S barley	S beans	Kale
8	Tri-crop	S barley	S beans	Kale	S oats	Tri-crop	S barley
7 course rotation							
2	W wheat*	Kale	S beans	S barley	MFL 1	MFL 2	MFL 3
5	Kale	S beans	S barley	MFL 1	MFL 2	MFL 3	W wheat
7	S barley	MFL 1	MFL 2	MFL 3	W wheat	Kale	S beans
Permanent crops							
3	PRG	PRG	PRG	PRG	PRG	PRG	PRG
6	MFM	MFM	MFM	MFM	MFM	MFM	MFM

*In 2023 this was spring wheat. In future it will be winter wheat but the new experimental design was implemented in spring 2023 necessitating the use of spring wheat.

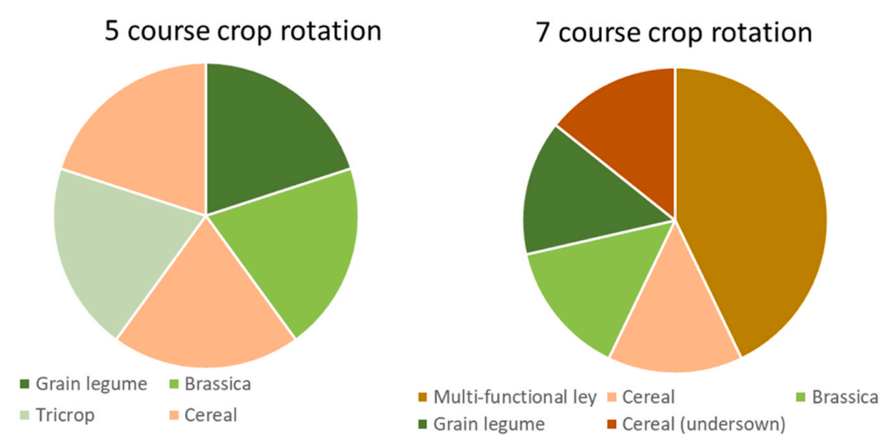

Fig. 8. Functional crops in the 5 and 7 course rotation of the pHoenix experiment.

ongoing basis to allow a) calculation of carbon and nutrient stocks and b) impacts of the movement and settling of soil to be assessed.

5. Moving the experiment – approach and logistics

Detailed discussions were undertaken several months prior to the movement of soils between SRUC scientific staff, technicians and the contractors employed to do the soil relocation. The contractor carried out test digs of the correct size and depth to get a better understanding of the logistics, soil volume, vehicle and manpower requirements, as well as a likely time estimate for the relocation process. This gave time for refining the protocols prior to a final approach methodology being agreed. Communication channels were maintained during the operations between all parties at both the original long-term experiment donor site and the new pHoenix site between SRUC staff and contractors moving the soil. Excavation of the new pHoenix sites was undertaken by skilled contractors using medium sized excavators and the soil was moved using large (12 tonne) trailers with low pressure tyres. At the new site, pits for only two of the target soil pH treatments were excavated at any one time in order to reduce the risk of soils being deposited in the wrong location, and the holes for the new pH 4.5 and the pH 5.0 plots were the initial starting point for this. These pre-prepared holes were 4 m wide by 5.5 m long and excavated to a depth of 20 cm, with this soil being removed from the new site to the edge of Woodlands field and eventually used to replace the excavated soil from the original pH long-term experiment. The soil at both the old and new sites had a natural indurated layer, so the excavation depth was easier to control. There was a 1 m ridge of uncultivated ground left between plot ends at the new site to reduce the risk of collapse and mixing of soils with different pH's when excavation and soil deposition were made. A 4 m wide paths between paired beds was also included in the design to reduce the need to drive over any of the newly formed plots and provide access for future activities. When the first two sets of holes (pH 4.5 and pH 5.0) had been prepared at the new site, soils from the original Woodland's Field pH long-term experiment were removed to a depth of 20 cm starting with those from the pH 4.5 treatments. The soils from all the pH 4.5 beds were mixed in the trailers prior to relocation into the pre-prepared holes at the new pHoenix site which had large marker posts indicating the soil pH destined for that plot. Soils were only ever out of the ground for between 30 and 90 minutes. Once the pH 4.5 soils had been relocated to their new "home", the pH 5.5 plots were marked out ready for excavation, and the pH 5.0 plots were relocated to their pre-excavated positions. This process continued until soil from all seven pH treatments (pH 4.5 through to pH 7.5) had been excavated and moved to the correct holes at the new location. The pHoenix long-term experiment was sown out to ryegrass immediately after the move to allow the plots to settle, and pH modifications were started once the first routine soil pH analysis was made on each plot. This has been done twice per year; the new rotations and management on the pHoenix long-term experiment commenced in spring 2023. Some 900 tonnes of topsoil were moved during the process, with approximately 450 tonnes moved from the original experiment to the new location, and the soil this was replacing at the new site (approximately 450 tonnes) returned to the original site as part of the legal agreement with the new owners of the original site. The soils travelled approximately 1.5 km by road between the old and new sites. Prior to moving the soil, duplicate topsoil and subsoil samples were collected in June 2021. Bulk density samples were also collected to allow comparisons of nutrient stocks to be made at a later date. Both air dry and frozen (-80°C) have been stored at SRUC and in the National Soil Archive at the James Hutton Institute.

6. Soil pH data before and after the soil was moved

Soils from Woodlands field have been pH amended since the late 1950's and while many annual reports of the experiments at Craibstone exist (from as far back as 1962) the cropping results are reported at the target pH rather than the actual measured pH. As such there is little information on how long it took for the amended plots to reach their intended pH value and how stable these were through time. On establishment of the new pHoenix experiment pH adjustments started on the twinned plots of undisturbed soil (referred to as Short-term amended soil (ST)). The first set of pH amendments were top dressed in early 2022 and cultivation did not occur until late March 2023 after the pH values shown here were measured (Fig. 9). The first 3 years of data (Fig. 9) show that over time (from 2022 to 2024) the soil pH in the newly amended soils is conitnuing to approach taget pH valuesafter even at the extremes of the gradient. Fig. 9 also shows that the pH gradient is well preserved in the long-term amended soils (LT) from Woodlands Field despite the physical disturbance of the move. As further data is accumulated, we expect to see more rapid change in the ST plots due to the incorporation of amendments into the soil through cultivation.

7. Conclusions

There is great value to long-term experiments and without them it is not possible to understand or predict the benefits of different crop and soil management practices that can take decades to materialise. As a result, long-term experiments have been integral to pivotal shifts in our understanding of agricultural systems, providing long-term data that underpin carbon and nutrient cycling models. However, due to the expensive nature of long-term experiments, and their somewhat restrictive nature in terms of experimental design, their future will continue to be questioned. Urban development, climate change and increasing land prices will continue to threaten existing long-term experiments. The decision scheme outlined here provides a framework to assist those faced with such challenges to formulate their thinking. In the case study provided here, moving the experiment has added strength to the statistical design through randomisation. Adding additional plots has provided the opportunity to study real time changes in soil pH and associated soil physical, chemical and biological properties as they might take place on farm. It is already clear that acclimation of microbial communities and their effects on plant growth and soil function is a long-term process.

So, what does the future hold for the pHoenix and similar long-term experiments s? Long-term experiments will become increasingly crucial for delivering reliable experimental data in an ever-changing world. Whether that be from environmental and climatic changes, land use and population pressures, or policymaking. The pHoenix experiment will continue to play a crucial role providing experimental data to underpin key advances in agronomy, agroecology, soil science, crop science and statistics, thus supporting future nutritious diets while safeguarding the environment. It will provide ongoing data on crop yield from 1960 for

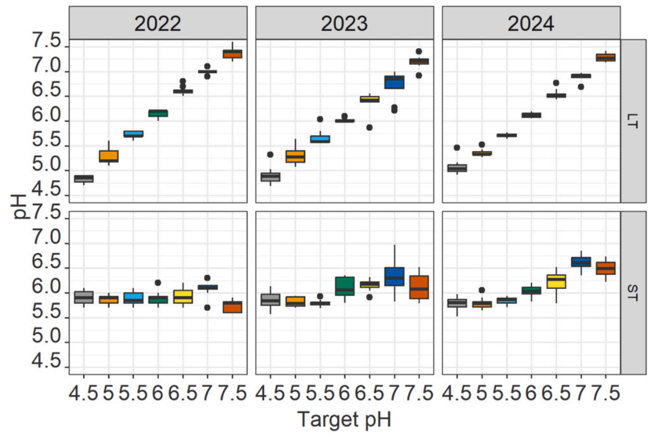

Fig. 9. Boxplots of the topsoil pH measurements against the target pH for the plots of the Woodlands Field soil (LT) moved to the new location, and the new paired pH plots (ST) in 2022, 2023 and 2024.

key crops including winter wheat and spring barley, allowing exploration of the effects of variations in weather and longer-term climatic changes on yield and quality. Rising from its ashes, the redesign of the pHoenix using long-established soils has given statistical robustness to explore contemporary cropping practices to improve food and environmental sustainability. pH is a key driver of microbiota community structure and function, and thus the ability to directly compare communities under the same treatment regime, in the same setting is unique. As our knowledge about the role and function of microbial communities continues to increase, so to do the opportunities. With increasing global connectivity, the importance of geographically separate, but networked, long-term experiments are key to providing reliable evidence for contemporary and future global agronomic practices. This vision extends into ensuring that experimental long-term experiments are at the heart of evidence-based global policymaking, food security and sustainable land use.

CRediT authorship contribution statement

Andrew Mead: Writing – original draft, Methodology, Conceptualization. **Fiona Fraser**: Writing – review & editing, Investigation. **Matias Fernández-Huarte**: Writing – review & editing, Investigation. **Jack Horne**: Writing – review & editing, Investigation. **Robert I Graeme**: Writing – review & editing, Conceptualization. **Robin L Walker**: Writing – original draft, Methodology, Conceptualization. **Christine A Watson**: Writing – original draft, Project administration, Investigation, Funding acquisition, Conceptualization. **Cairistiona F E Topp**: Writing – original draft, Formal analysis, Data curation, Conceptualization. **Paul D Hallett**: Writing – review & editing, Conceptualization. **Gareth Norton**: Writing – review & editing, Conceptualization. **Graeme I Paton**: Writing – review & editing, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declared that they have no conflicts of interest in this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2024.127214.

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