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Optimal grazing management to enhance soil biodiversity and soil carbon in upland grassland

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1. Abstract

Climate change, biodiversity loss and food security are key current global challenges. Grasslands and livestock production play critical roles in tackling all three of these challenges, but are under threat from increasing land use and economic pressures. Here we report on a project instigated by and co-designed with a group of livestock farmers in Wales who wanted to know more about the health and sustainability of their grassland soils.

The core aim of the project was to enhance the sustainability and resilience of livestock production relying on grassland whilst maintaining ecosystem services such as carbon sequestration and biodiversity provision. Soil carbon and nitrogen content and soil biodiversity measurements were obtained to determine whether these were being impacted by grazing management. The farmers were interviewed to determine the role of soil health in decision making as well as how best to communicate complex science evidence.

Soil carbon and nitrogen content varied from 3% to 5% for carbon and 0.3% to 0.5% for nitrogen across the farms, but the soil carbon to nitrogen ratio remained relatively constant between 9 and 10 for all farms. The impacts of land and grazing management on soil carbon and nitrogen was often inconsistent across farms meaning that confounding factors were at play. For soil biodiversity, no impact of land or grazing management could be detected, although there was a strong indication that biodiversity of both bacteria and fungi actually decreased with increased soil carbon and nitrogen.

The interview questions were co-created with the farmers to make sure that nothing was overlooked from a farming perspective. Similarly, co-designing the communication and outreach approach guaranteed maximum efficiency in both delivery and relevance. A series of short videos were created explaining farmer motivation for this project. The interviews showed that farmers wanted to do the best for their soils but that soil health was not always clearly defined and importantly there was a lack of evidence as to what the optimal practices are, especially for their specific locality.

A series of recommendations are made aimed at both farmers and policy makers:

- ***field level carbon assessment*** *of the true current baseline values*
- ***detailed long-term management history*** *to understand soil carbon stocks*
- ***effective monitoring*** *to ensure the intended outcomes are indeed occurring*
- ***regularly assessment of*** *the impact of hay and silage making on soil carbon content*
- ***targeted soil DNA profiling*** *of key beneficial or detrimental soil microbes*
- *sustainability policies* ***should cater for all segments*** *within the farming community*
- ***knowledge exchange*** *focused on soil health and how to improve it*
- ***assistance for evidence gathering*** *of the status of farmers' own fields and soil.*

2. Introduction

Achieving a secure food supply whilst tackling the climate change and biodiversity emergencies is the greatest challenge currently facing society. Extensive and intensive livestock production both contributes to, and is affected by, climate change (Rust 2018). Livestock production, often blamed for increasing the risk of climate change, relies on grassland productivity which provides the opportunity to act as a carbon store. Thus, grassland systems have a significant role to play with regard to securing sustainable long-term protein production as well as mitigating climate change by enhancing carbon uptake and restoring biodiversity for multiple ecosystem services (including water management).

Livestock production is central to Welsh farming, with 40% of the UK's sheep and cattle being farmed in Wales across only 10% of the agricultural land area for the UK (Armstrong 2016). Grazing has the biggest impact on these semi-natural and farm ecosystems, often in areas considered to be less favourable or marginal land. Much is known about grazing impacts on the productivity and sustainability of ecosystems. However, to date, research on the impact of grazing on productivity and sustainability of ecosystems has focused on comparing grazed with ungrazed (Faghihinia *et al*. 2020a), rather than aiming to identify an optimal grazing point allowing both livestock production and the maintenance of a healthy ecosystem (Faghihinia *et al*. 2020b). Surprisingly, soil, including soil biology, is still often neglected in research and even more so in policy (Staddon and Faghihinia 2021). One of the reasons for this is that soil is not easy to study – the opacity of the environment coupled with the complexity in terms of biodiversity (bacteria, fungi, protozoa, nematodes, mites, springtails, insects, earthworms, molluscs, etc.) and biological processes. A soil that is functioning well, in a sustainable manner, is termed a 'healthy soil'. However, defining what a healthy soil is in terms of measurable indicators, is complicated and often attempts to simplify it overlook some of the key processes that a soil delivers. Many of the key soil processes involved in nutrient and carbon cycling are controlled by soil microorganisms, especially bacteria and fungi (Naylor *et al*. 2020). This project aimed to address a key concern of our partner farmers in identifying the impacts of the various grazing management approaches they undertake on soil health (particularly soil biology).

Research on the impact of grazing on ecosystems has often focussed on simple comparisons between grazed and non-grazed land, thus missing significant nuances. This project evolved as a farmer-led research initiative to address local evidence gaps identified by farmer partners in Powys wanting to enhance the long-term viability and sustainability of their farms. We aimed to investigate how critical local knowledge of grazing type (species, regime) and intensity is in determining impacts on soil health and soil carbon stocks. The project aimed to identify optimal grazing management applicable to the local conditions and quantify the benefits to soil biodiversity, soil carbon content and grassland sustainability. Working with livestock farmers (beef and/or sheep) to co-design principles minimising livestock grazing impacts on ecosystems, could be taken as an exemplar of sustainable management of natural resources whilst maintaining food production and responding to the biodiversity loss and climate change emergencies. The project used the data obtained, and shared with the participants, to provide insights into the most appropriate way of communicating this complex topic to farmer partners and their networks to elicit a potential change in behaviour and the development and adoption of sustainable principles.

The project had the core aim of enhancing the sustainability and resilience of livestock production relying on grassland. The first aim of the project was to ***identify optimal grazing management that enhances soil health and carbon content***. This focussed on identifying the best current practices in the area in relation to soil health status including soil carbon content. The second aim of the project was to ***investigate how best to communicate these results to elicit behaviour change in farmers***. This part of the project took a co-design approach with direct involvement of farmer partners in the dissemination of our results to the wider farming community.

The specific objectives were as follows:

- What are the best current grazing regimes with regard to soil health (defined as containing the optimum biodiversity and soil carbon required for the soil processes underpinning soil ecosystem services) and carbon stocks?
- What role does soil health and carbon stocks play in farmers' decision making on their grazing regimes?
- Which communication approach works best (e.g. type of material, wording, peer, advisor, language)?
- What would facilitate change in farmers' grazing choices (e.g. information, evidence, incentives)?

3. Materials and methods

The farmer partners are all located within South Powys, Wales mainly within the lower Wye Valley. They include a mix of lowland and upland livestock farms, which vary in intensity of grazing practice. Eleven farms were partners in the project, although two of the farms work closely together and were merged for much of their data collection (Farm D includes Farm K).

3.1. Grazing regimes, soil health and carbon stocks

3.1.1. Grazing regimes and site history

The farmer partners were asked to identify areas/fields/plots on their farm which have been, or are being, treated either similarly or differently with regards to grazing. The farmers were asked to identify up to 4 fields under each type of management. This included the following:

- Seasonal differences in the way grazing is focused
- Differences in length of grazing
- Differences in number of animals / age of animals
- Number of grazing events in the season
- Type and quantity of nutrient input (manure / fertilisers / other)
- Other management that has occurred
- Slope of the site
- General wetness of the site
- Is forage harvested?
- Any other factors.

The farmers were asked to group all fields that were relatively similar in conditions and how they were treated/used, for example: 'standard farm livestock rotation'; 'standard farm livestock rotation with hay harvest'; 'standard farm livestock rotation with lime addition 2 years ago'. This data was collected using Table 1 (with example contents) as follows:

Table 1. Data collection table for field types.

Farm	Description of typical field grazing management and environmental conditions	Number of similar fields	Notes (anything else you think might be relevant)
Farm X	Standard farm livestock rotation	6	Family farm (last 50+ years)
Farm X	Standard farm livestock rotation with annual hay cut	6	
Farm Y	Standard farm livestock rotation with cereal grown every 5 years	10	Pasture-fed livestock only

The main purpose of this data collection was to then be able to select fields for sampling that maximised the different types of fields sampled, across a range of farms whilst keeping a target number of replicates per type of field management as 4 (where possible 4 replicate fields were obtained for each type of field management).

3.1.2. Soil sample collection

The soil sampling approach was discussed and agreed with the farmer partners. To overcome the issue of heterogeneity in the fields, the farmers suggested taking the classic W approach and to sample 5 times along the W. The samples were collected with 5 cm diameter and 15 cm deep spiral combination augers for grassland. The 5 samples taken along the W were mixed in a bucket and roughly 0.5 to 1.0 kg duplicate samples were then taken from the mixed soil in the bucket. Duplicate samples were therefore obtained for each field. This was to ensure plenty of soil sample available for testing, as well as leaving some stored for possible future linked analysis (e.g. chemical analysis of micronutrients or heavy metals). Only 1 sample from each set of duplicate samples was analysed. All samples were collected over a 2-day period in mid-December by the farmers themselves, collected by car and delivered to the Royal Agricultural University (RAU, Cirencester), where they were stored at -18°C within a walk-in freezer. This safely preserves soil DNA for future extraction and analysis (Iturbe-Espinoza *et al*. 2021). In total 142 fields were sampled with a maximum of four replicates of the same grazing management per farm; although some additional fields were also sampled above the advised four replicates. Accounting for the duplicates, there were 284 soil samples.

3.1.3. Soil carbon and nitrogen content

The preparation of the soil samples for analysis by an elemental C N analyser were as follows:

1. A subsample of 100g was extracted from each bagged frozen soil sample using a hammer/ trowel, taking care to label the extracted sample on a piece of paper in pencil to be placed under the sample in a foil tray.
2. The frozen/ wet sample was first weighed. The sample was placed in a foil tray with paper label under the soil and dried in the oven for 48hrs at 80 degrees C.
3. The samples were checked at 48hrs and re-weighed. They were returned to the oven for another 72hrs.
4. At 72hrs, samples were removed and weighed again. This was to ensure that all the moisture had been removed from the samples; in the event this was not the case the samples were dried for a further 24 hours and re-weighed.
5. Wearing PPE (face mask, goggles and ear muffs), each dried sample was first put through a coarse mill with dust extraction machine on.

6. The collected sample from the coarse mill, i.e. the finer soil that fell through the 1 mm sieve, was then put through a hammer mill resulting in a fine soil powder (similar to flour).
7. The samples were then weighed into tin capsules whilst wearing gloves and with the door to the lab shut to avoid contamination or loss of sample from air movement. The scales were first calibrated with the empty tin capsule to 0g with the door of the scales closed tight. The sample was then weighed into the tin capsule to a weight of close to 5mg of soil. The tin capsule was then closed using forceps/ tweezers with no contact with fingers. The tin capsule including sample was then weighed again and the weight recorded.
8. For each of the 142 field samples, 3 individual tin capsules with 5mg samples were obtained.
6. Samples were put into the 100 well box, taking care not to tip or flip it.
7. A template was used to record and match up the samples to the box well numbers.
8. The C:N analysis of the soil samples in the tin capsules was then performed on a CN elemental analyser.

3.1.4. Soil microbial biodiversity

83 samples were analysed by Nature Metrics for their soil DNA profile with a focus on fungi and bacteria. Subsamples were taken from the frozen samples using a hammer to break the frozen samples into small enough fragments to allow a representative mixed subsample to be taken. Nature Metrics were sent 10g frozen subsamples from 83 of the individual fields sampled (each sample represented a different field); these were kept on ice and delivered within the day via refrigerated courier. The 83 samples sent for DNA profiling were chosen to represent the full range of farms as well as a full range of selected field types with particular focus on livestock, grazing approach, and pasture permanency. Nature Metrics were provided with the farm codes, approximate location (GIS or postcode), livestock type, grazing type, fertiliser or lime additions, grassland type (permanency) and whether hay was taken. The details of the methods for DNA extraction and analysis are provided below.

Metabarcoding decontamination procedures. NatureMetrics have dedicated ultra-clean laboratories with a unidirectional workflow between multiple labs for different stages of the eDNA metabarcoding workflow, from DNA extraction to sequencing. Work was undertaken within dedicated laminar flow hoods, with ChemGene cleaning taking place after each use, and a regular weekly deep cleaning schedule. Equipment was cleaned using DNA decontamination wipes. Laminar flow hoods were UVC sterilised prior to setup and operated with air flow turned off to avoid contamination. All PCR (Polymerase Chain Reaction) preparation was conducted in a pre-PCR clean room within a PCR hood that is treated before and after any PCR set-up.

DNA extraction methods. DNA from soils was extracted using the DNeasy PowerSoil Pro Max Kit - Soil DNA extraction kit (QIAGEN) protocol. An extraction blank (contamination check) was also processed for each extraction batch. DNA was purified to remove PCR inhibitors using a DNeasy PowerClean Pro Cleanup Kit (QIAGEN). DNA was quantified using a broad range Qubit assay (Thermo-Fisher Scientific) after extraction.

PCR amplification. Aliquots of extracted DNA for each sample were then amplified for NatureMetrics Soil Bacteria (16S) and Soil Fungal (ITS) assays. PCR setup, primer information and cycling conditions are proprietary to NatureMetrics. Positive PCRs were purified and checked by gel electrophoresis and quantified using a Qubit broad range kit prior to being indexed, quantified, and pooled for sequencing. Positive amplification control and lab negative controls, and extraction blanks were run alongside each set of markers.

Sequencing. Samples were sequenced based on a two-step PCR protocol (Illumina 16S Metagenomic Sequencing Library Preparation protocol from Illumina Part # 15044223 Rev. B) and loaded on to an Illumina MiSeq platform (V3 600 cycle sequencing kit) following the manufacturers recommended specification.

Bioinformatic Processing. Bioinformatics processing was performed using a custom NatureMetrics bioinformatics taxonomy pipeline. Paired-end FASTQ files were merged to provide a single canonical sequence for each pair of sequencing reads for the Soil Bacterial Assay. The merged reads were then primer clipped to remove the first round PCR primer sequences. The forward reads only were used for the Soil Fungal Assay, after processing to retain only the variable region of the ITS gene. Reads were quality filtered, denoised and chimeric sequences flagged. Sequences were de-replicated and filtered to return sequences within the length distribution of each marker gene. The resulting zero-radius Operational Taxonomic Units OTU's (zOTU's) were assigned an initial taxonomic classification using megaBLAST against the National Centre for Biotechnology Information (NCBI) nt database to determine the presence of target, non-target and contaminant DNA from the environment in each sample. zOTU's were then clustered into OTU's and assigned a taxonomic label based on checks against custom reference databases. Thresholds were set on a per-marker basis to remove stochastic noise from the dataset as a percentage of reads observed.

Reference Libraries. The "nt" DNA nucleotide library provided by the NCBI, and custom, proprietary local databases were the primary source for taxonomy classification. SILVA v138.1 was used in addition for the Soil Bacteria Assay. UNITE v8.2 was used in addition for the Soil Fungal Assay. Where ambiguous species identifications were observed (such as two species being equally likely to be assigned to the same DNA sequence), these were elevated to the taxonomic level where there was consensus between the two potential taxonomic identities.

Quality Assurance process. All datasets were reviewed by either the Head of Bioinformatics at NatureMetrics, or the Lead Bioinformatics Developer at NatureMetrics to ensure consistency and accuracy of datasets. This included reviewing taxonomic identifications and ensuring appropriate analysis parameterisation.

3.2. Soil health in farmers' decision making on grazing regime

3.2.1. Approach to the design

Farmer partners were central to the design of this aspect of the project; the aim being to make sure that the questions asked and focus of the questioning were in line with what farmers would find useful and informative. The aim of this part of the project was to understand how soil health and soil C is or isn't considered in grazing decisions taken at the farm level.

It was initially thought that the farmers would interview each other, and to guide them in the sort of questions to ask and what they thought would be best to elicit useful responses, some starting points were suggested:

Possible questions on the content:

- What questions to ask?
- Do some terms / concept need clarifying?
- How should the idea be broken down?
- What broader details might be needed?
- Where information comes from (peers/ 'experts')?
- What are the constraints?
- What's the evidence?
- What leads to different field grazing choices?

Possible questions on the approach:

- How should the data be collected?
- Short interviews?
- Mini-survey?
- A workshop?

- Who will gather data?
- Pros and cons of different options?
- Issues of time.

Note that this data collection exercise was within group only, but would highlight any issues that would be important to address when considering the outreach and output dissemination planning.

The consensus was that interviews would be the best means of obtaining the data within this particular group of farmers, but that the interviews need not be face-to-face and could be online, which added flexibility. The questions decided upon are presented in the next section. It was also decided that interviews should be conducted by one or two people independent of the farmer group to ensure consistency.

3.2.2. Consent

Before the interview commenced, consent was specifically obtained for the interview. This was in addition to the general consent obtained for being part of the project. This was interesting as the farmer partners were on the one hand the drivers behind the project, but on the other hand also act as respondents.

The consent wording was as follows:
As a farmer partner in this AHDB-BBSRC project on grazing choices and grassland sustainability you have delivered soil samples for DNA profiling and soil carbon analysis. To aid in understanding why different fields have been managed different it is important to understand some of the decision making in relation to grazing choices and grassland sustainability. This interview aims to understand how soil or grassland health is taken into consideration when deciding on how a field is managed and what grazing approach is chosen. All data collected will be anonymised and no element will be used which could identify you or your farm.
You may stop the interview at any moment and you may request the data collected to be destroyed at any time after the interview. The data will be kept for 2 years after the end of the project for (anonymised) publishing purposes and further analysis.
The interview will be recorded to facilitate analysis.
Do you agree to be recorded? If yes, record now; if no do not record.
Do you agree to be interviewed? If yes, proceed; if no terminate.

3.2.3. Interview questions

The interview questions were co-created with the farmer partners as described above, with the final set of questions presented here and detailed in Appendix 1:

Q1. *Describe your livestock farming activity*.
Q2. *In terms of grassland status how sustainable do you view your livestock farming?*
Q3. *How do you assess the sustainability or health of the grassland?*
Q4. *What does soil health mean to you? How would you define it with your own words?*
Q5. *Do you consider soil health when making grazing management decisions?*
Q6. *Who/what is influencing your decision-making in relation to the soil health aspects mentioned above?*
Q7. *Are there constraints to managing the health of your grassland (soils)?*
Q8. *Any further comments on the health of your grassland?*

The interviews were conducted by two separate interviewers by video link at a mutually convenient time and then saved in a secured location on the University of Gloucestershire network. The prompts were useful both to guide the interviewers in capturing a similar level of detail but also for the interviewees in eliciting additional information. To assist in the process, the interviewees, who were involved in the development of the questions, had access to these questions and could prepare answers if they wished to.

3.2.4. Interview processing

The interview recordings were analysed by a third researcher who did not participate in the interviews themselves. This allowed all interviewee responses to be treated identically and impartially. The key points were extracted from each of the interviewee responses in line with the questions being asked; key quotes of particular interest were also highlighted during this process.

3.3. Communication approaches and delivery

3.3.1. Communication focus

A key element for achieving the translation of scientific evidence into practice lies in successful communication. Here, farmers co-designed and co-created the evidence base and the communication approach. Farmer-led soil science research and co-design of communication strategies for the dissemination of our findings ensures that outputs are directly applicable and relevant to local farming needs. Farmer involvement in how to effectively communicate best practice for maximum uptake firmly roots this research within the local farmer networks and the wider community. Furthermore, embedding the project within the NRW Mid Wales Area Statement (NRW 2022a) allows the project partners to engage with a wider network of stakeholders, and helps disseminate the project outcomes and encourage learning. The project, by being focussed on change in practice will help with AHDB's key aim of creating a world class food and farming industry that will be successful in a rapidly changing world.

3.3.2. Farmer-led research and industry engagement

In order to ensure that the research results reach relevant audiences, the farmer partners were asked to comment on the following questions, with a view to designing an outreach strategy:

- Where do you get farming advice? Who do you actually listen to / act upon their advice?
- Who should we tell about our project / results, specifically?
- How should we tell them? (If farmers, this will relate to question 1 - unless your sources are particularly unusual)
- What should we tell them, i.e., which bits of our project would suit which outreach methods?
- What are you able to contribute to this plan (be realistic)?

In particular, to stimulate engagement with the farming community we explored with farmer partners the possibility of creating a series of short YouTube style videos to enhance the farmer-led aspect of the communication and build on the importance of peer-to-peer learning and trust. The results of these comments are provided in Section 4.4.

3.3.3. Dissemination and impacts timeframe

Immediate benefits will be found within the local farming community. Wider dissemination of knowledge will take place at regional and national agricultural shows and conferences. Given the short duration of this project, much of the dissemination will take place after the end of this project. Specific arrangements are discussed in Section 4.4, but other likely outlets are a session with the Wales Land Management Forum (NRW 2022b) to present and discuss the project results with industry, regulatory and policy bodies. Similarly, we will work with the Farming and Wildlife Advisory Groups for the South West (FWAG 2022a) and Cymru (FWAG 2022b) to further disseminate our work on sustainable grazing for a healthy soil and resilient ecosystem. There are a number of events occurring in 2022 that will promote net zero within the consciousness of the general public and agricultural industry. Industry leaders will wish to be seen as proactive which provides opportunities for the dissemination of the impact of this project within the industry. There is now a realisation amongst the public that the greater the uptake of net zero initiatives, such as modifying grazing management to maximise soil organic matter, the sooner we will start to deliver real environmental and climate benefits.

4. Results

4.1. Soil carbon and nitrogen

4.1.1. Differences between farms

There were significant differences in average topsoil C content per farm, ranging from just over 2.5% to just under 5%. These results are presented as total carbon percentage; organic matter (OM) is calculated to contain 58% carbon, therefore to convert to OM these results are multiplied by a factor of 1.72. Thus, on average, farms within the project ranged from 4.3% OM to 8.6% OM. Average soil C per farm can be seen in Figure 1, where it becomes apparent that the farms could be grouped into types: those with a soil C content of around 4% to 5% and those with carbon contents between 2.5% and 3.5%. The underlying soils were freely draining, slightly acid loamy soils across all farms (Appendix 2).

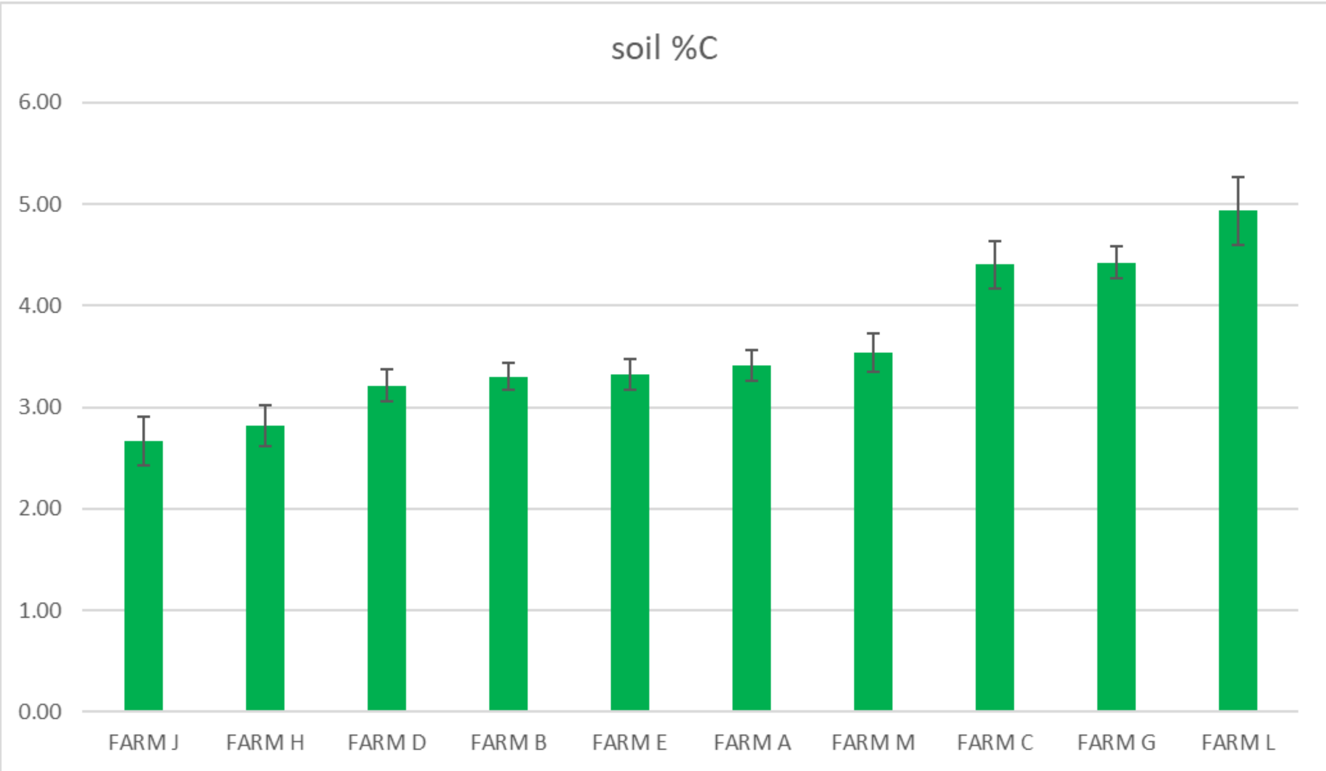

Figure 1. Soil carbon content average for selected farms. The average is for the range of fields selected for inclusion and representative of the farms. Results presented as mean ± standard error.

Similarly, there were significant differences in average soil N content per farm, ranging from just over 0.3% to just over 0.5%. This can be seen in Figure 2, where a range of soil N concentrations can be observed, with possibly two groups emerging but not as clear cut as for the carbon content results. Nonetheless, there are those with a soil N content of around 0.44%

to 0.51%, the same three that had higher soil carbon content, and those with N contents between 0.3% and 0.4%.

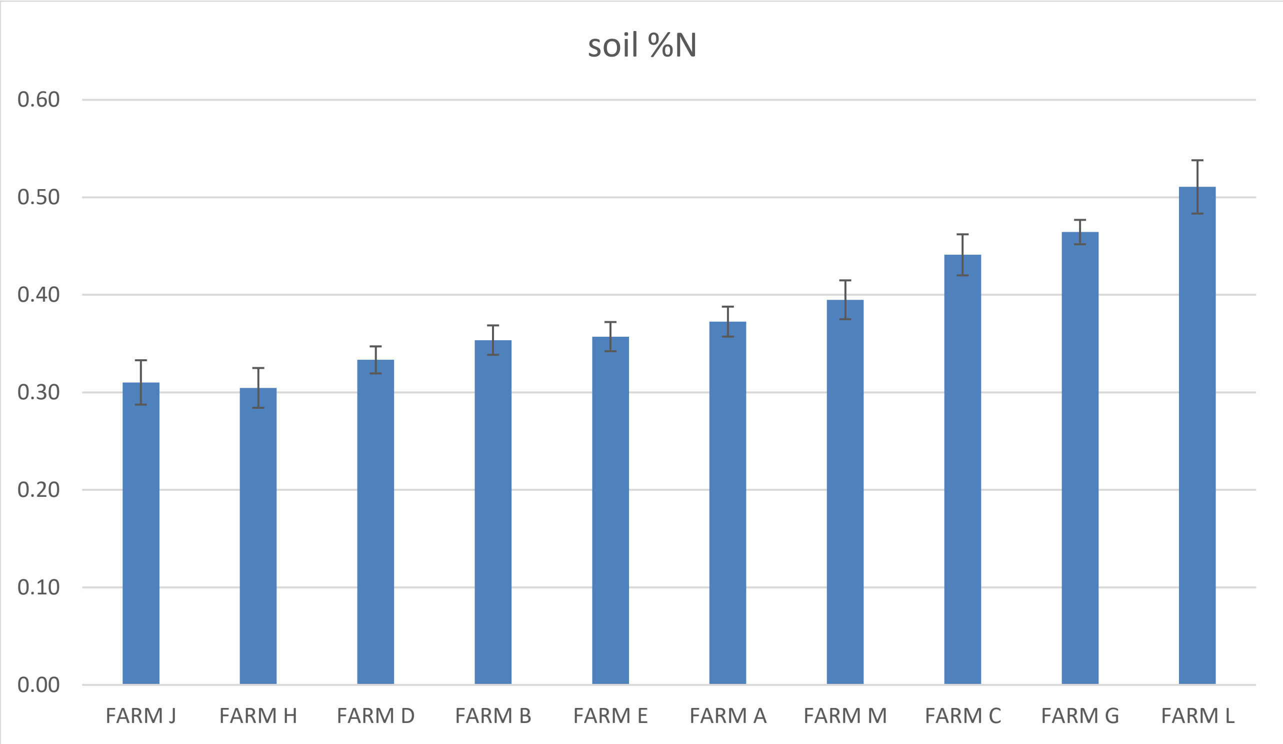

Figure 2. Soil nitrogen content average for selected farms. The average is for the range of fields selected for inclusion and representative of the farms. Results presented as mean ± standard error.

The carbon to nitrogen ratio was calculated from the averages for soil carbon and soil nitrogen content for each farm. These are provided in Figure 3 and in essence show a relatively stable C:N across farms, ranging from 8.8 to 9.9, which was to be expected as there was a clear correlation (not shown) between soil carbon content and soil nitrogen averaged at the farm level.

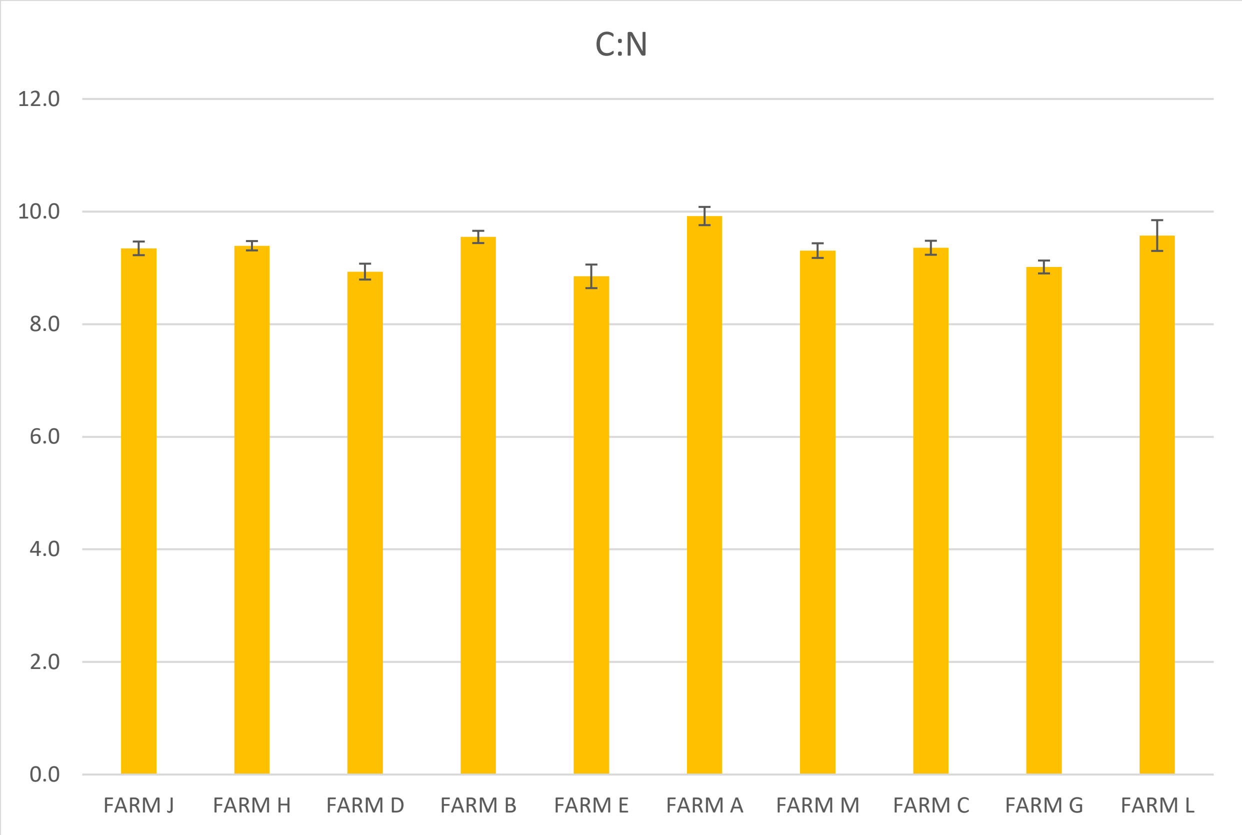

Figure 3. Soil carbon to nitrogen ratio average for selected farms. The average is for the range of fields selected for inclusion and representative of the farms. Results presented as mean ± standard error.

4.1.2. Farm level soil carbon

Interestingly, the range of soil carbon contents seen within a farm is as wide, or wider, than that seen between farms. Farm A shows this clearly, where soil carbon content is only 2.5% in the lowest sampled fields but over 4% in fields with the highest soil carbon (Figure 4). In this farm the highest values for soil carbon were found in fields continuously grazed by sheep or where sheep grazing occurred in an orchard (Figure 4). Fields with other types of grazing, such as cattle mob grazing or sheep rotational grazing lay in the middle range for soil carbon content, whereas fields noted for being wet, exhibited the lowest soil carbon content on this farm (Figure 4).

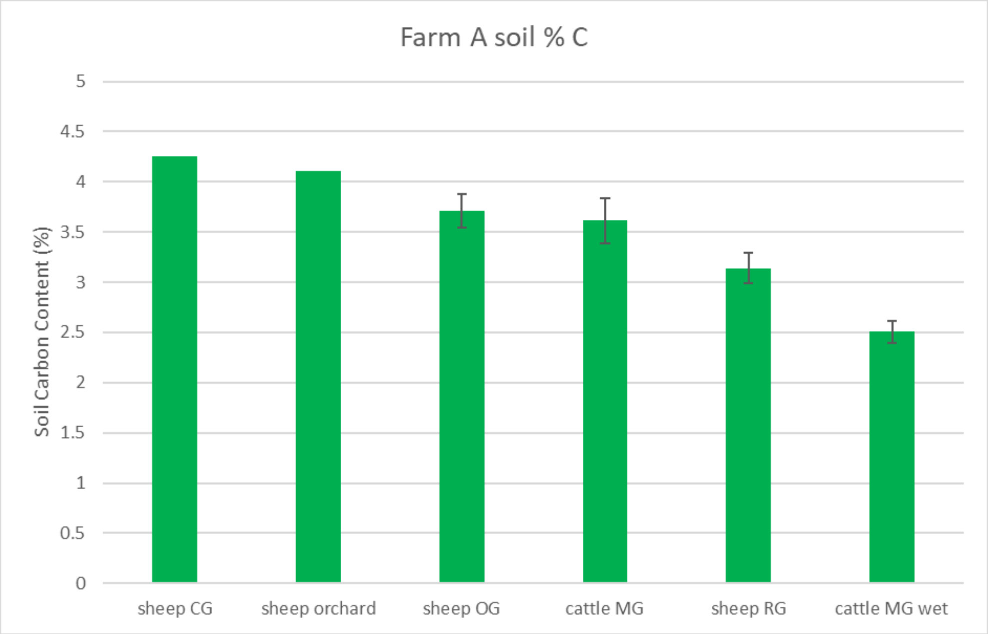

Figure 4. Soil carbon content for Farm A for fields under different grazing regimes and management. The average is provided along with a standard error where possible (absence of error bar indicates only two samples were available). CG: continuous grazing; OG: other grazing such as sporadic; MG: mob grazing; RG: rotational grazing.

For Farm B, limited differences were observed for the two main field types on the farm, namely short-term grazing by cattle compared to sheep and cattle rotational grazing; but there was possibly a trend for those fields with limited grazing to have slightly higher soil carbon content (Figure 5).

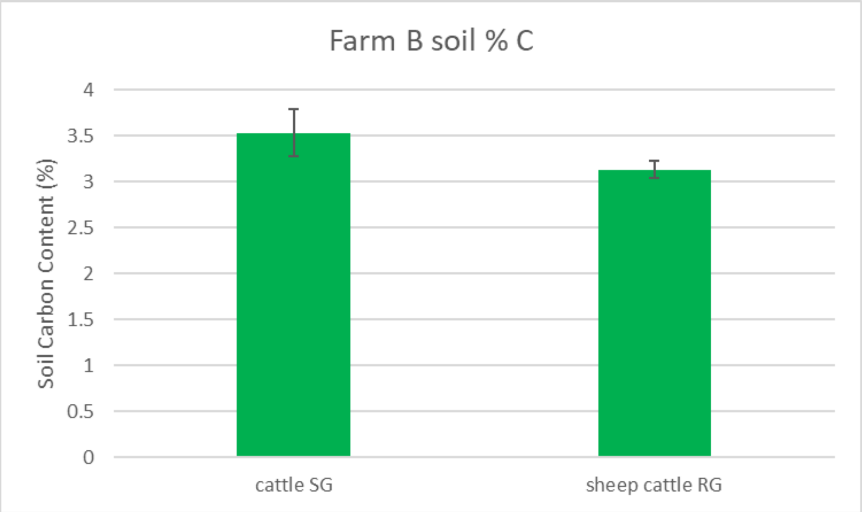

Figure 5. Soil carbon content for Farm B for fields under different grazing regimes and management. The average is provided along with a standard error where possible. SG: short-term grazing; RG: rotational grazing.

For Farm C, limited differences were observed for the two main field types on the farm, namely rotational grazing by cattle compared to fields used for arable or forage crops; but there was possibly a trend for those fields under cultivation to have slightly lower soil carbon content (Figure 6), but not as large a difference as one might have expected.

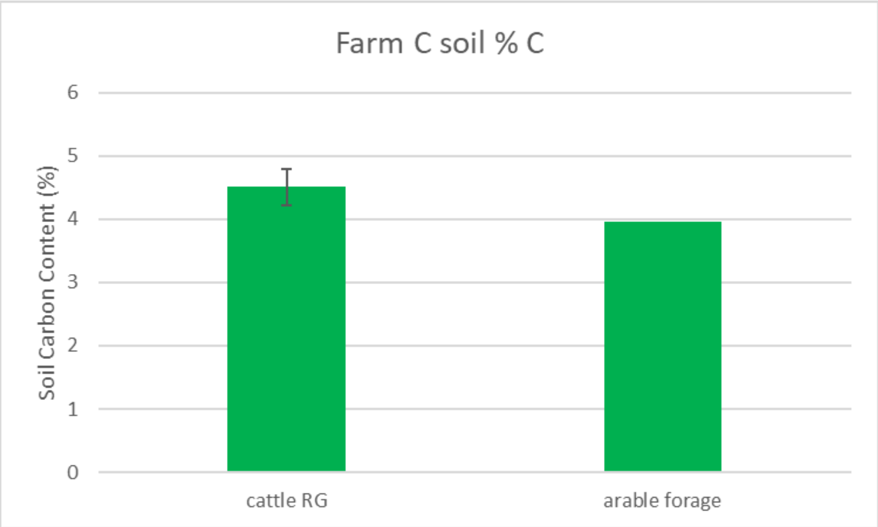

Figure 6. Soil carbon content for Farm C for fields under different land management regimes (grazing or cropping). The average is provided along with a standard error where possible (absence of error bar indicates only two samples were available). RG: rotational grazing.

Farm D had an interesting addition in terms of field types in that a few fields grazed with sheep also had chickens on them. This farm is one of the more mixed farms and also includes arable and herbal leys. There was broad range of soil carbon content values on this farm ranging from under 2% to nearly 4.5% (Figure 7). Of note is that contrary to Farm A, the grazed fields noted as wet did not have lower C content than those comparatively grazed fields. Also, the fields where chickens have been included appear to show the lowest soil carbon content (Figure 7), whereas, the two silvopasture fields grazed with sheep had the highest soil C content.

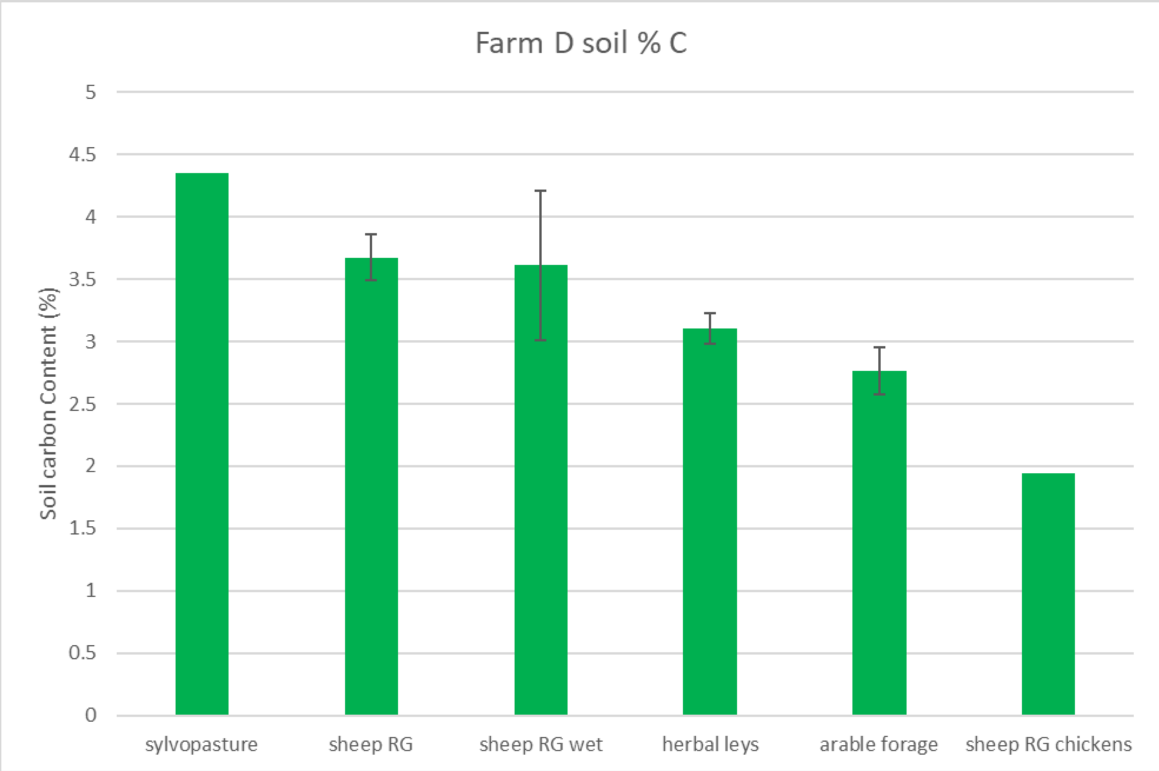

Figure 7. Soil carbon content for Farm D for fields under different grazing regimes and management. The average is provided along with a standard error where possible (absence of error bar indicates only two samples were available). RG: rotational grazing.

Farm G had relatively high soil carbon content in both field types with either short-term grazing by cattle, or sheep and cattle rotational grazed (Figure 8). For both types of fields, carbon content was above 4%.

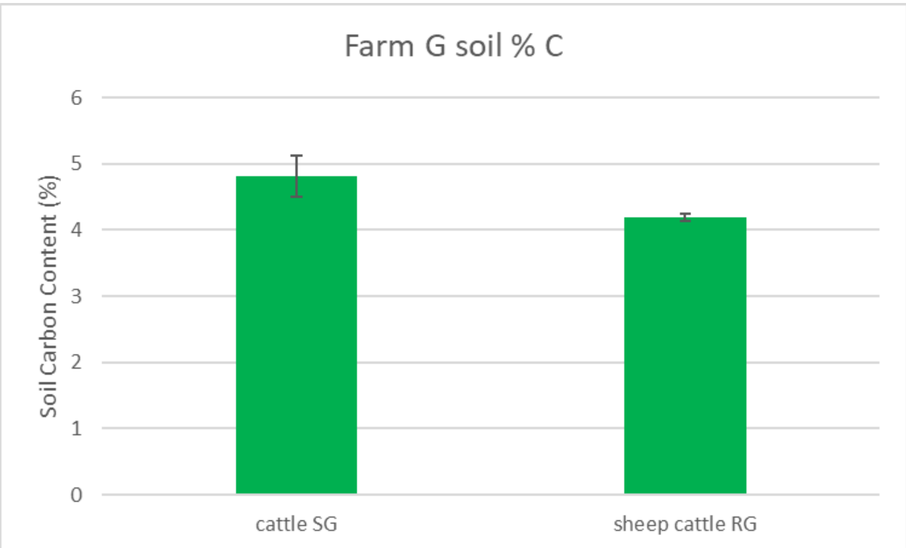

Figure 8. Soil carbon content for Farm G for fields under different grazing regimes and management. The average is provided along with a standard error. SG: short-term grazing; RG: rotational grazing.

Farm J has a relatively wide range of soil carbon contents between fields with herbal leys having under 2.5% and those fields with sheep and cattle rotational grazing above 3.5%, although these showed high variability (Figure 9). Interestingly, hay making on this farm might be impacting soil carbon content by decreasing the amount of grass litter being returned to the system (although this is not statistically significant).

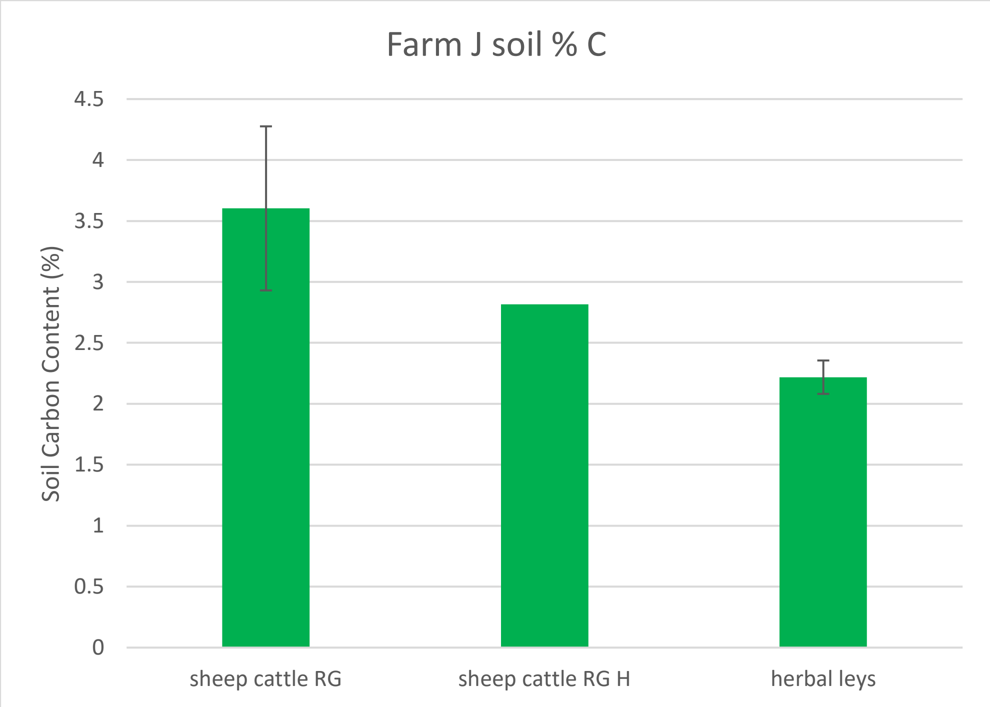

Figure 9. Soil carbon content for Farm J for fields under different grazing regimes and management. The average is provided along with a standard error (absence of error bar indicates only two samples were available). RG: rotational grazing; H: hay taken (main difference with the other sheep cattle rotational grazing fields).

Farm E has a relatively narrow range of soil carbon contents between fields ranging from just over 3% for silvopasture to just under 3.5% for standard sheep rotational grazing (Figure 10). Notably, and contrary to Farm D, the silvopasture fields on this farm appear to have lower carbon than the rest, which probably relates to the relatively short time since the trees were planted (a few years).

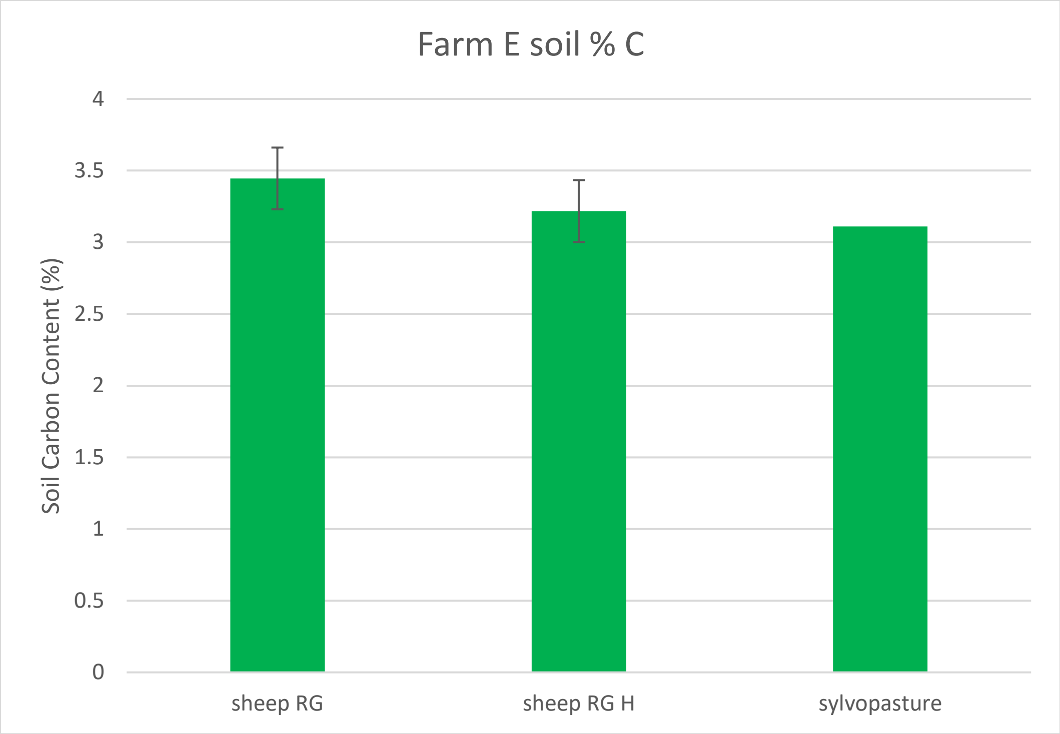

Figure 10. Soil carbon content for Farm E for fields under different grazing regimes and management. The average is provided along with a standard error (absence of error bar indicates only two samples were available). RG: rotational grazing; H: hay taken (main difference with the other sheep rotational grazing fields).

Farm M exhibits differences in soil carbon between fields that are used for grazing by sheep and cattle which have nearly 4% C and those used for forage or crop production where it drops to under 3.5% C (Figure 11).

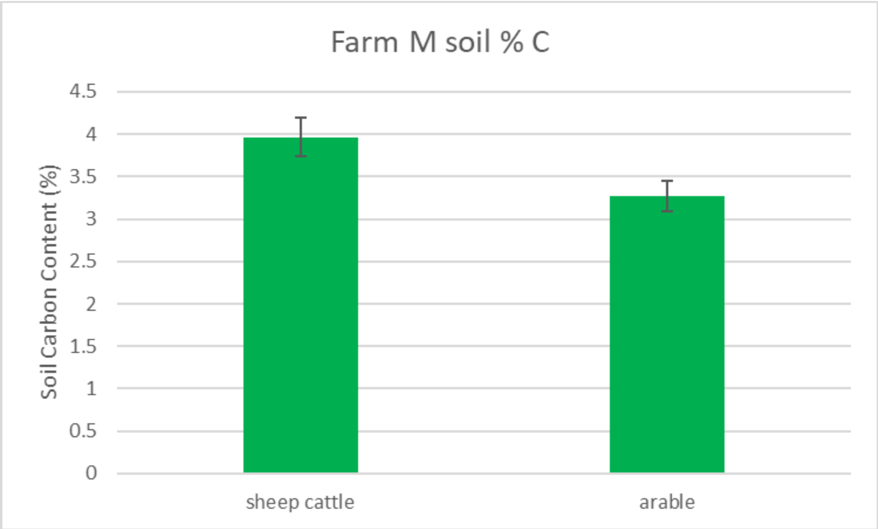

Figure 11. Soil carbon content for Farm M for fields under either sheep and cattle grazing or an arable focus. The average is provided along with a standard error.

Farm H has a very wide range of soil carbon content ranging from 4% C for those fields grazed with cattle and limited additional inputs to just over 1.5% C for grazed herbal leys (figure 12). There's the interesting point that here the ungrazed herbal leys have higher soil %C than the grazed herbal leys (Figure 12). The fields with addition of poultry manure (muck spreading) seem to show greater variation in %C than other fields, which could be as a result of when poultry manure was applied or the heterogeneity of application (Figure 12).

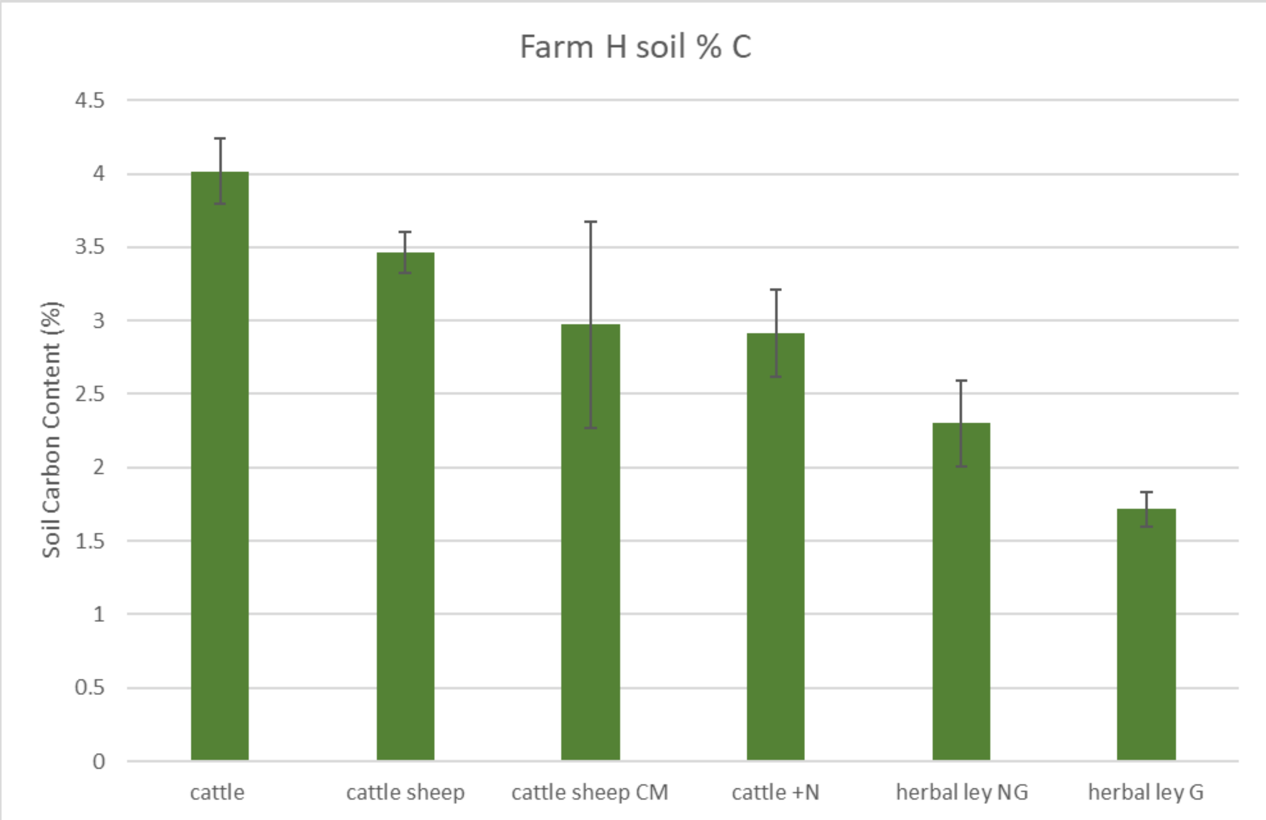

Figure 12. Soil carbon content for Farm H for fields under different grazing regimes and management. The average is provided along with a standard error. CM: chicken muck spreading; +N: additional inorganic fertiliser; NG: not grazed; G: grazed.

Farm L exhibits soil C content ranging from a very high value of just under 6% C for cattle only grazed fields to under 4% C for those under arable rotation (Figure 13). All fields under grazing by sheep and/or cattle have average soil C content just under 5% C to just under 6% C (Figure 13).

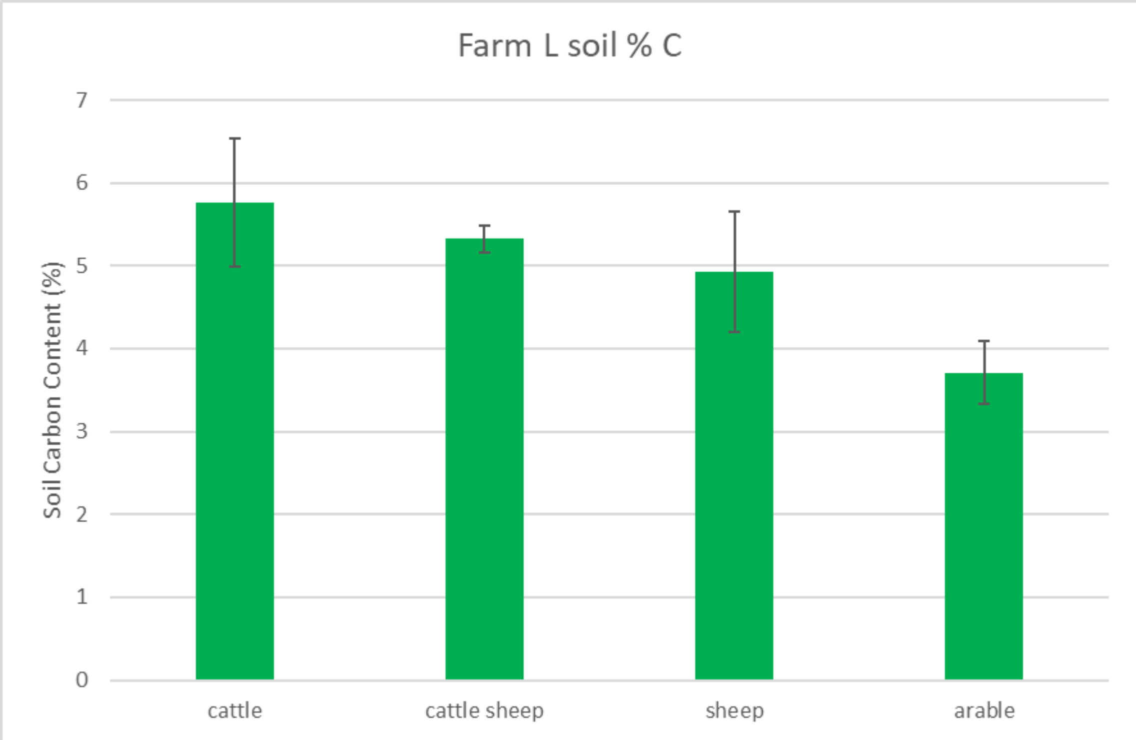

Figure 13. Soil carbon content for Farm L for fields under different grazing regimes and management. The average is provided along with a standard error.

4.1.3. Farm level soil nitrogen

The patterns seen for soil carbon content are very closely mirrored by soil nitrogen content. In particular the range seen within farms is just as broad as the range seen as averages between farms. Farm A exhibits a soil nitrogen content of 0.45% for fields continuously grazed by sheep and a low of under 0.3% for wet fields that are mob grazed by cattle (Figure 14). The rotationally grazed fields in Farm B have nitrogen content values of 0.33 and 0.38% for rotational grazing by sheep and cattle and short-term grazing by cattle respectively (Figure 15). Farm C has soil nitrogen content values of 0.4% for both cattle rotational grazed fields and those fields used for arable or forage crops (Figure 16). Farm D exhibits soil nitrogen contents ranging from over 0.4% under silviculture sheep grazing to under 0.2% for fields having chickens on them for part of the year (Figure 17). The low value of N in the fields with chickens is linked to the history of these fields which exhibit surface compaction and were previously used for forage crops with frequent slurry applications. Adding the chickens was an attempt at raising N levels. Farm G exhibits relatively high nitrogen values for both field types investigated (Figure 18). Farm J again shows a similar pattern for soil nitrogen content (Figure 19) as seen for soil carbon content, with herbal ley fields (0.28%) showing lower values than fields under sheep and cattle rotational grazing without any hay crop being taken (just under

0.4%). Farm E exhibits relatively even soil N content across all field types of around 0.35% (Figure 20). Farm M has an average of 0.44% N for grazed fields and 0.37% N for arable fields (Figure 21). Farm H, as for soil C, shows a wide range in values for soil N; these range from 0.4% N for fields under solely cattle grazing to under 0.2% N for grazed herbal leys, with interestingly ungrazed herbal leys showing a slightly higher N content at 0.25% N (Figure 22). Farm L has relatively high N content mirroring the findings for soil C; these averages range from 0.5 to 0.6% N in the grazed fields to 0.4% N in the arable setting (Figure 23).

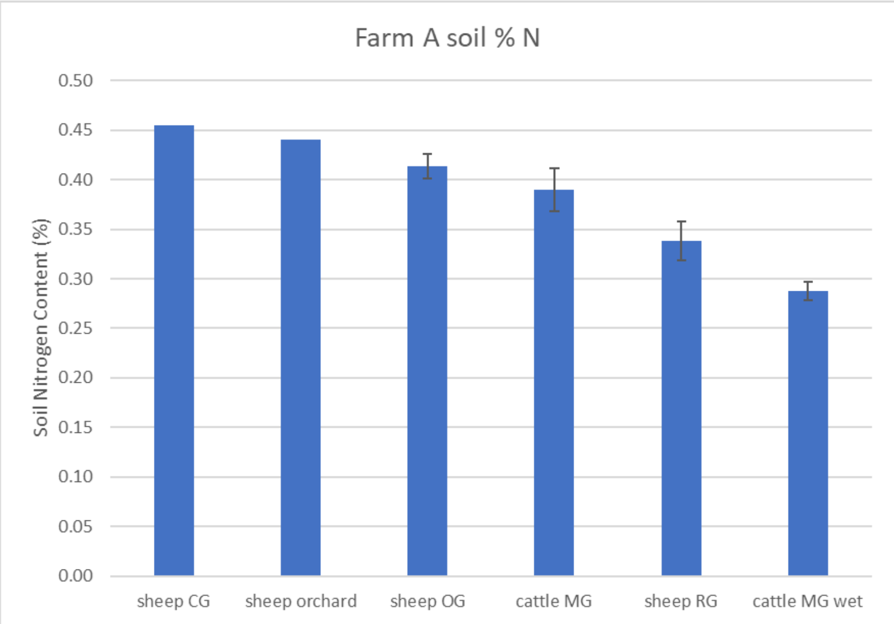

Figure 14. Soil nitrogen content for Farm A for fields under different grazing regimes and management. The average is provided along with a standard error where possible (absence of error bar indicates only two samples were available). CG: continuous grazing; OG: other grazing such as sporadic; MG: mob grazing; RG: rotational grazing.

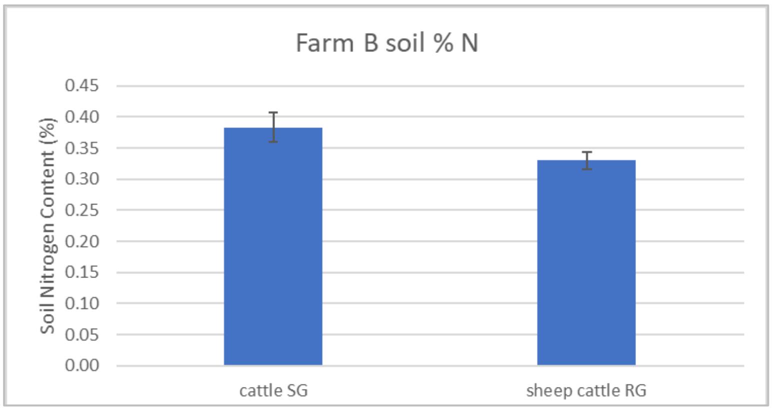

Figure 15. Soil nitrogen content for Farm B for fields under different grazing regimes and management. The average is provided along with a standard error where possible. SG: short-term grazing; RG: rotational grazing.

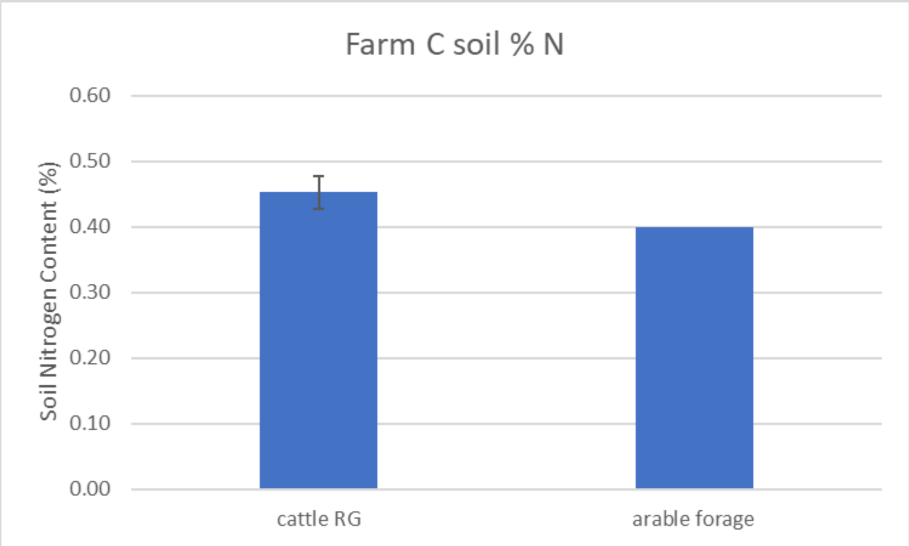

Figure 16. Soil nitrogen content for Farm C for fields under different land management regimes (grazing or cropping). The average is provided along with a standard error where possible (absence of error bar indicates only two samples were available). RG: rotational grazing.

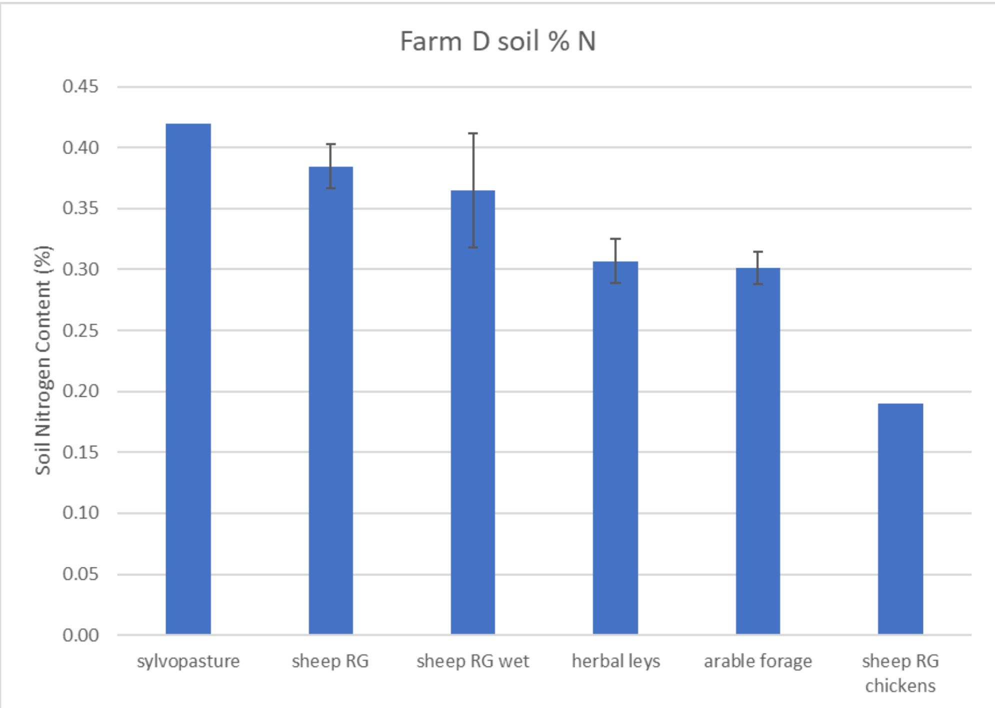

Figure 17. Soil nitrogen content for Farm D for fields under different grazing regimes and management. The average is provided along with a standard error where possible (absence of error bar indicates only two samples were available). RG: rotational grazing.

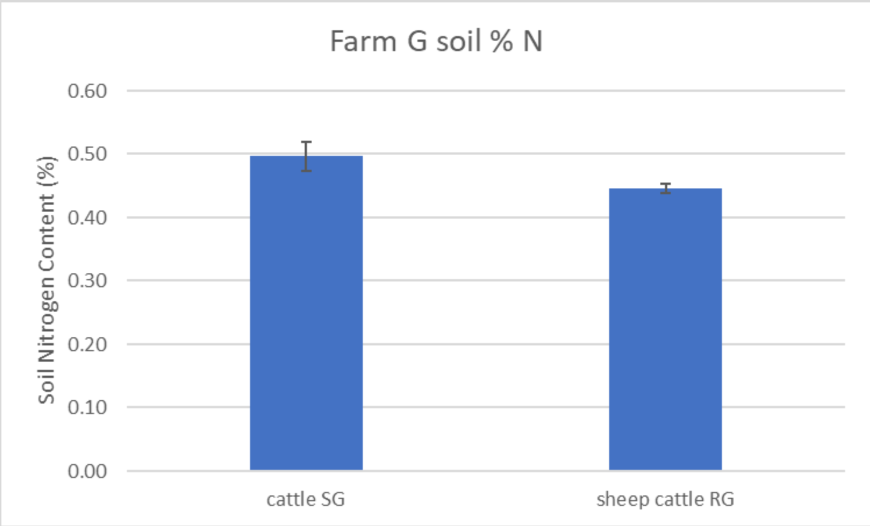

Figure 18. Soil nitrogen content for Farm G for fields under different grazing regimes and management. The average is provided along with a standard error. SG: short-term grazing; RG: rotational grazing.

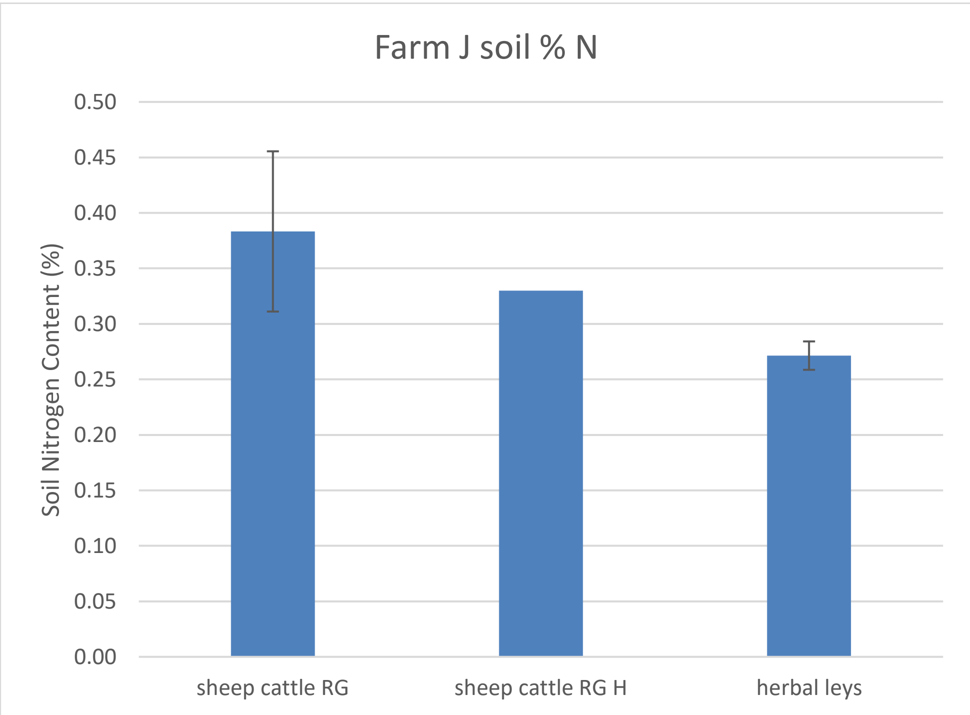

Figure 19. Soil nitrogen content for Farm J for fields under different grazing regimes and management. The average is provided along with a standard error (absence of error bar indicates only two samples were available). RG: rotational grazing; H: hay taken (main difference with the other sheep cattle rotational grazing fields).

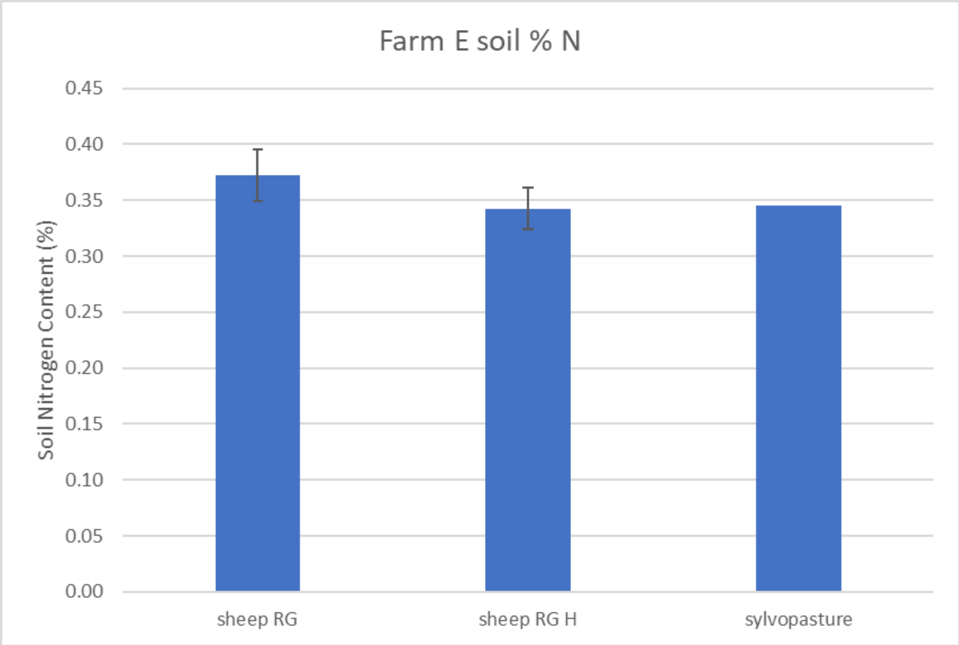

Figure 20. Soil nitrogen content for Farm E for fields under different grazing regimes and management. The average is provided along with a standard error (absence of error bar indicates only two samples were available). RG: rotational grazing; H: hay taken (main difference with the other sheep rotational grazing fields).

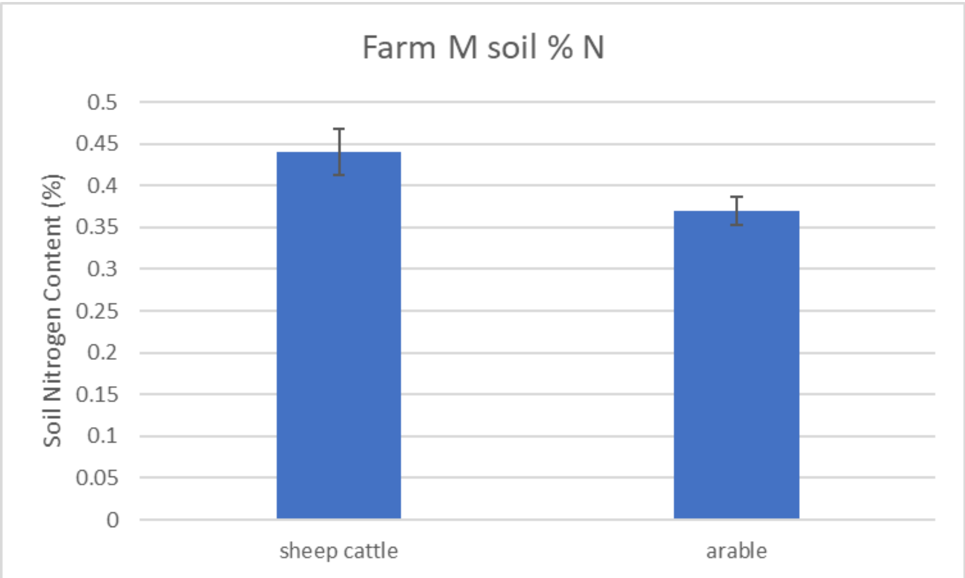

Figure 21. Soil nitrogen content for Farm M for fields under either grazing or arable land management. The average is provided along with a standard error.

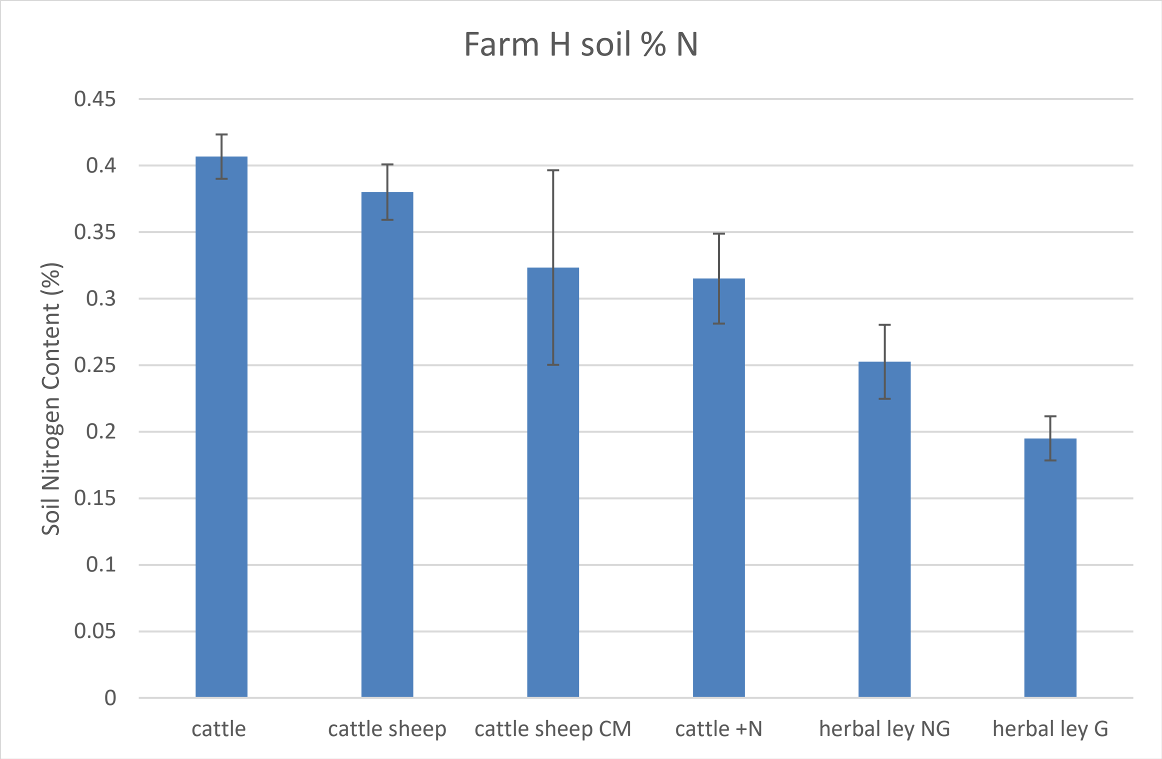

Figure 22. Soil nitrogen content for Farm H for fields under different grazing regimes and management. The average is provided along with a standard error. CM: chicken muck; +N: additional inorganic fertiliser; NG: not grazed; G: grazed.

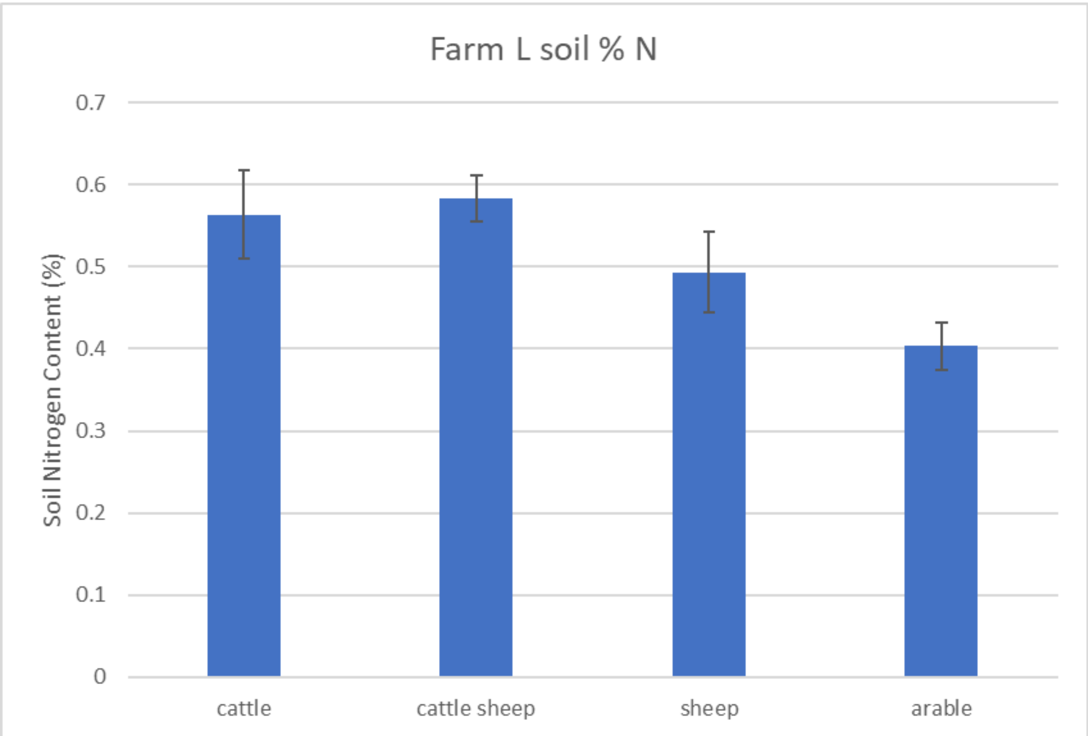

Figure 23. Soil nitrogen content for Farm M for fields under different grazing regimes and management. The average is provided along with a standard error.

4.2. Soil biodiversity

4.2.1. Biodiversity overview

A total of 2,221 targeted microbial taxa were detected across the 83 samples: 1,417 bacteria and 804 fungi OTUs (Table 2). No significant differences in community composition were detected amongst farms for bacteria or for fungi. There were also no differences in taxon richness amongst farms for bacteria or fungi. More fungal OTUs were identified at the species level compared to bacteria. This reflects differences in the availability of reference sequences for different organisms within the reference databases and a higher proportion of assignment conflicts (100% matches to multiple species) in bacteria.

Table 2. Summary of the number of OTUs detected and the percentage of OTUs successfully classified at each taxonomic level for each target

Target	Number of OTUs	Phylum	Class	Order	Family	Genus	Species
Bacteria	1417	73.3%	59.8%	43.7%	29.6%	13.4%	2.3%
Fungi	804	98%	86.3%	77.9%	61.6%	35.7%	14.7%

4.2.2. Bacterial community

In the bacterial dataset, OTUs were detected across 23 different phyla within the kingdom Bacteria. The average bacterial taxon richness per sample was 339 and ranged from 241 (Farm D silvopasture field) to 419 (Farm H arable rotation field). The overarching taxonomy of the detected OTUs is presented in Figure 24, which shows that the phylum with the highest richness of OTUs was Proteobacteria. The bacterial OTU with the most reads was from the class Verrucomicrobiae. This OTU was detected in all 83 samples. 36 bacterial OTUs were detected in every sample. There were 330 very rare (uncommon in this study) OTUs (23.3%) that were only detected in one sample each.

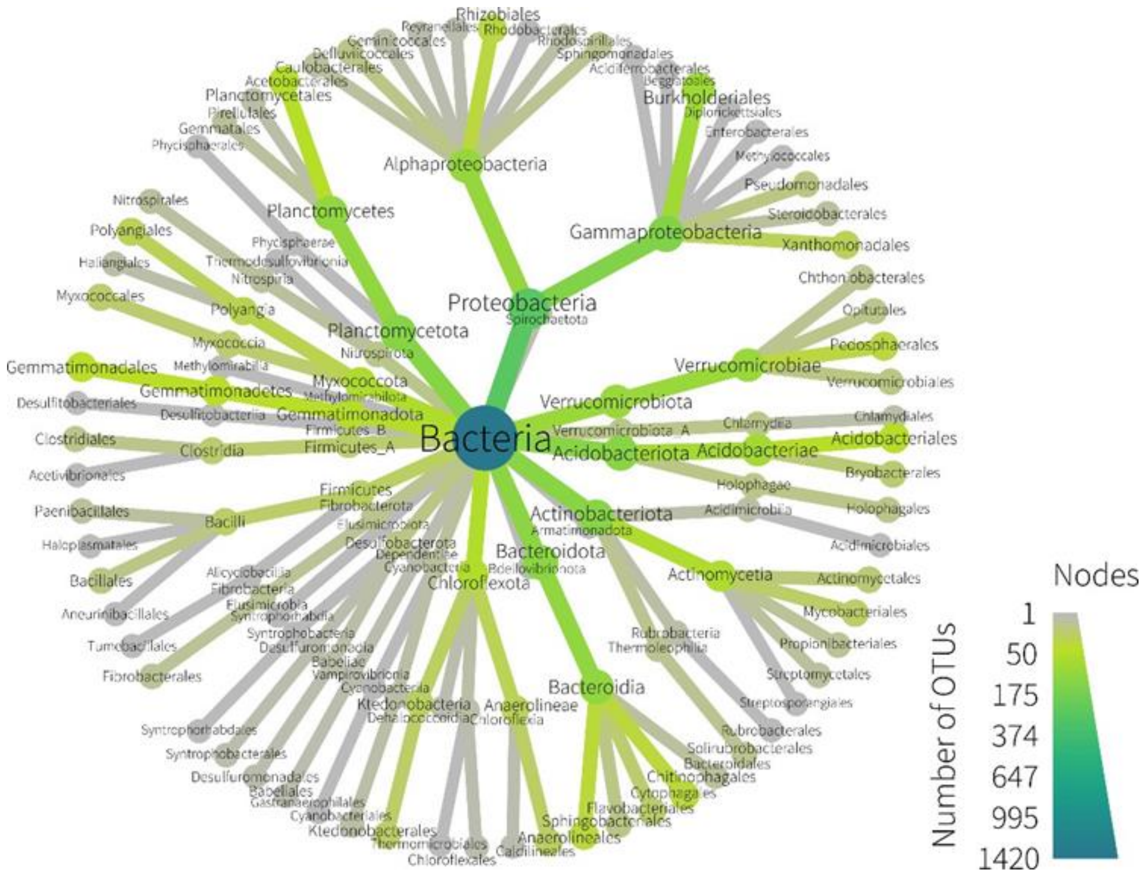

Figure 24. A taxonomic heat tree showing the number of OTUs across all samples for soil bacterial taxa down to the order rank. Each node (the circles) is a taxon and the edges (lines) show hierarchical relationships between taxa. The colour scale and the relative width of the node represent the number of taxa at each level.

There were no differences in soil bacterial community composition amongst the farms. This can be seen in Figure 25, where samples from each farm do not form distinct clusters. There was no significant difference in the community variability (group dispersion) amongst the farms (Permutation test $p > 0.05$). There were no significant differences in average sample-level bacterial taxon richness amongst the farms (ANOVA $p > 0.05$) (Figure 26).

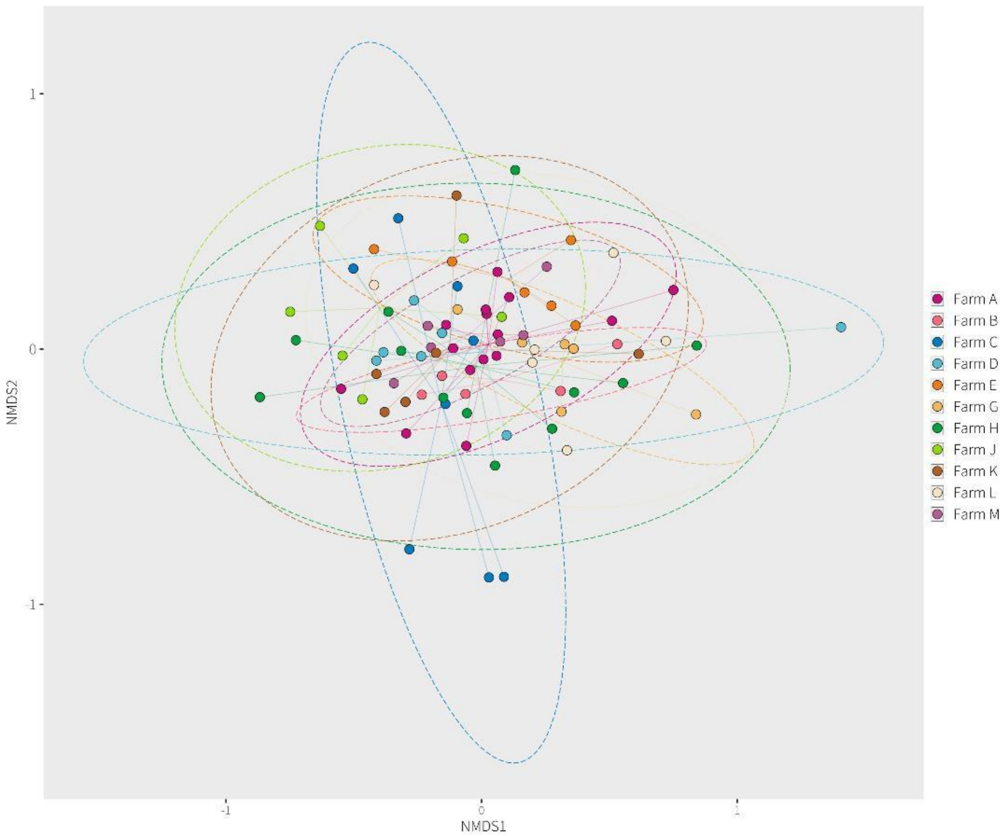

Figure 25. NMDS ordination plots based on Jaccard similarity index for soil bacterial communities. Points are coloured by farm, with 95% confidence intervals for each area indicated by dashed ellipses.

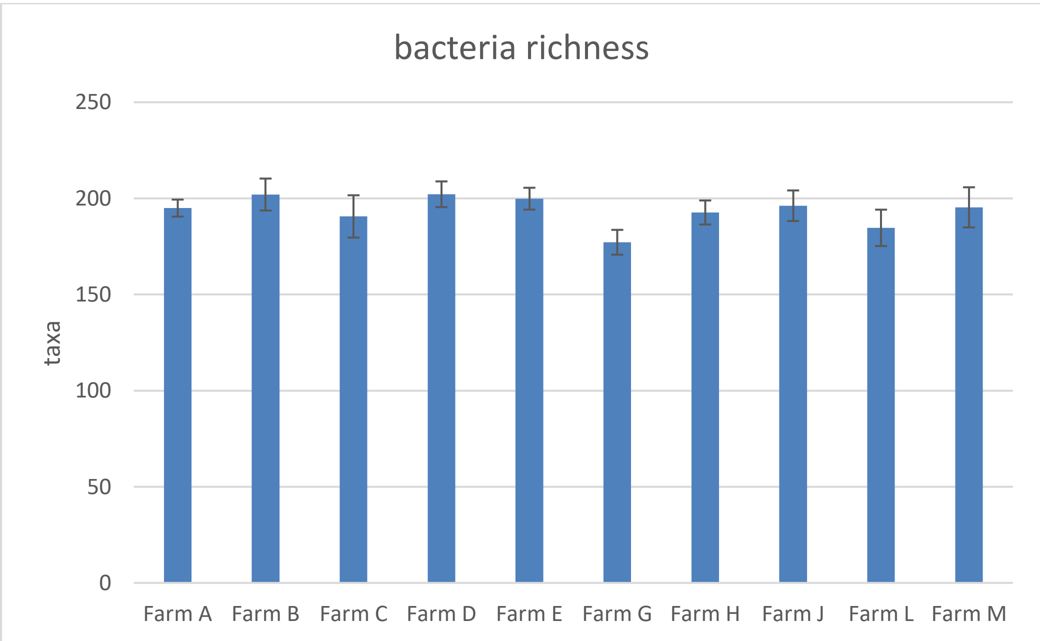

Figure 26. The average richness of bacteria per field for each farm. The average is provided along with a standard error.

4.2.3. Fungal community

In the fungal dataset, 804 OTUs were detected across 5 different phyla within the kingdom Fungi. The average fungal taxon richness per sample was 79.6 and ranged from 17 (Farm C wet permanent pasture) to 124 (Farm E silvopasture field and Farm J 5-year old ley). The overarching taxonomy of the detected OTUs is presented in Figure 27, which shows that the phylum with the highest richness of OTUs was Ascomycota. The fungal OTU with the most reads was the genus Mortierella. This OTU was detected in all 83 of the samples. 2 fungal OTUs were detected in every sample. There were 308 OTUs (38.3%) that were only detected in one sample each.

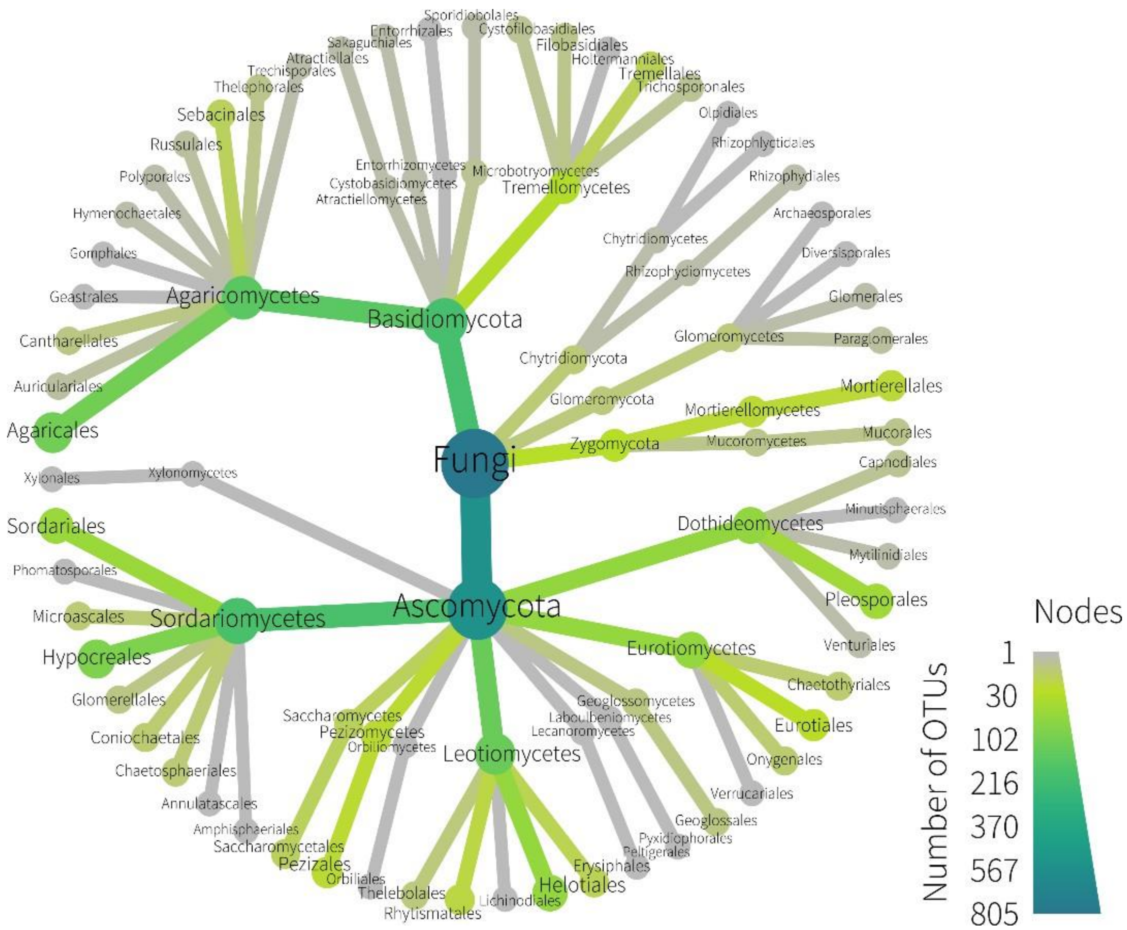

Figure 27. A taxonomic heat tree showing the number of OTUs across all samples for soil fungal taxa down to the order rank. Each node (the circles) is a taxon and the edges (lines) show hierarchical relationships between taxa. The colour scale and the relative width of the node represent the number of taxa at each level.

There were no differences in soil fungal community composition amongst the farms. This can be seen in Figure 28, where samples from each farm do not form distinct clusters. There was no significant difference in the community variability (group dispersion) amongst the farms (Permutation test p > 0.05). There was no significant difference in average fungal taxon richness amongst the areas (ANOVA p > 0.05) (Figure 29).

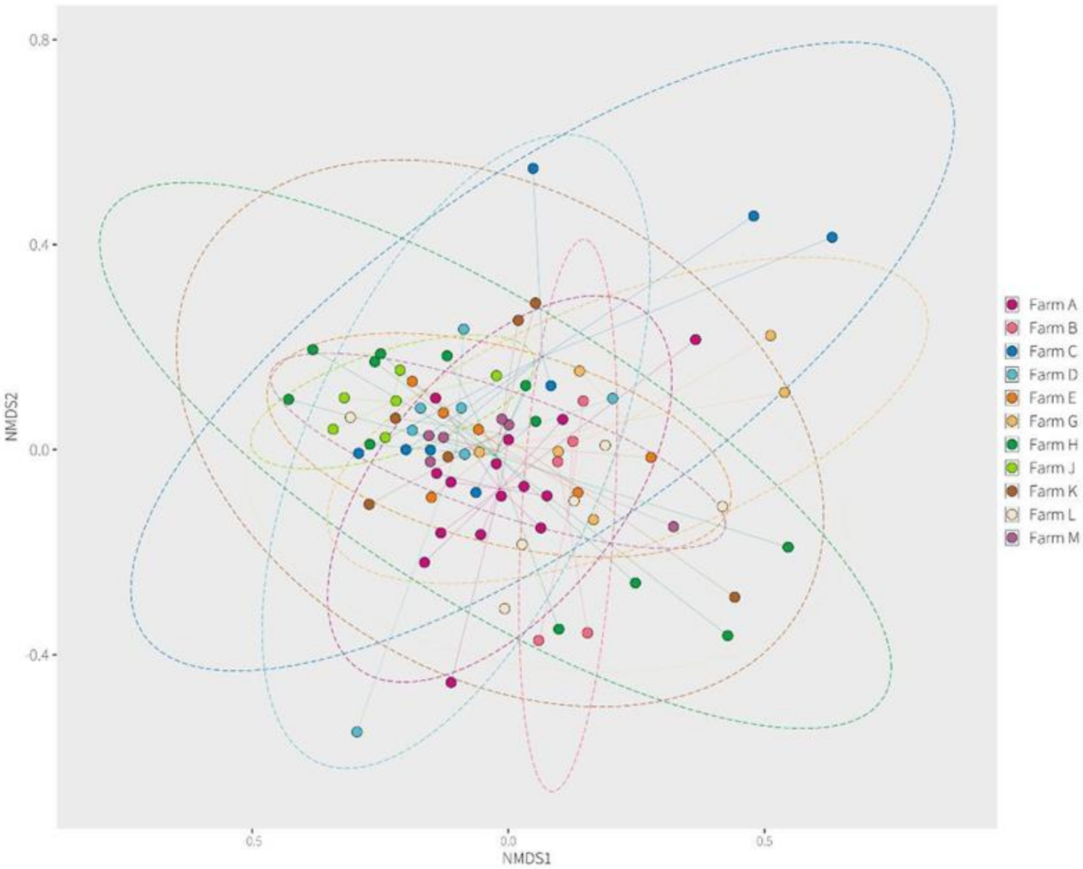

Figure 28. NMDS ordination plots based on Jaccard similarity index for soil fungal communities. Points are coloured by farm, with 95% confidence intervals for each area indicated by dashed ellipses.

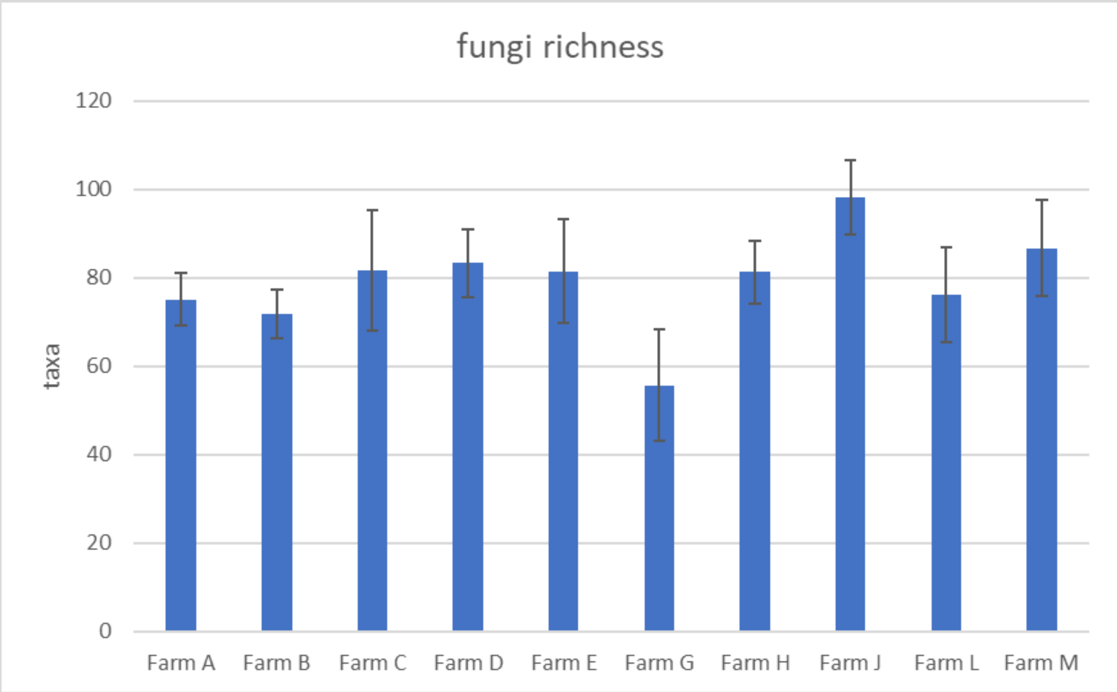

Figure 29. The average richness of fungi per field for each farm. The average is provided along with a standard error.

4.2.4. Relationship between microbial diversity and soil C and N

Across farms, there was a negative relationship, explaining around 15% of the variation, between the number of bacteria OTUs detected and soil C content (Figure 30).

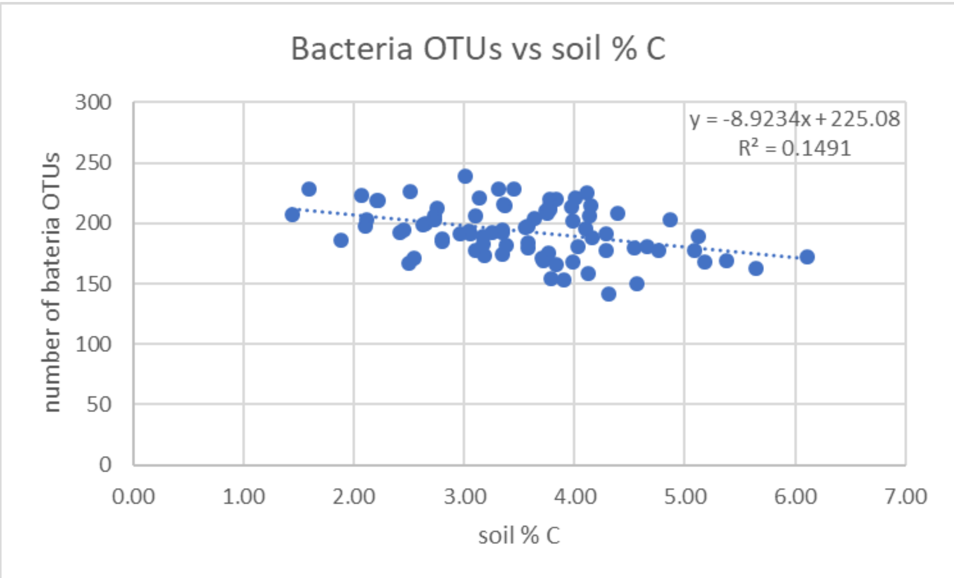

Figure 30. The number of bacteria OTUs detected across farms in relation to soil carbon content. Fitted linear regression is included.

A similar negative relationship was also seen between the number of fungi OTUs detected and soil C content, in this case explaining around 17% of the variation, but with a steeper slope (Figure 31). Note that the variation in OTU numbers was greater for fungi than for bacteria.

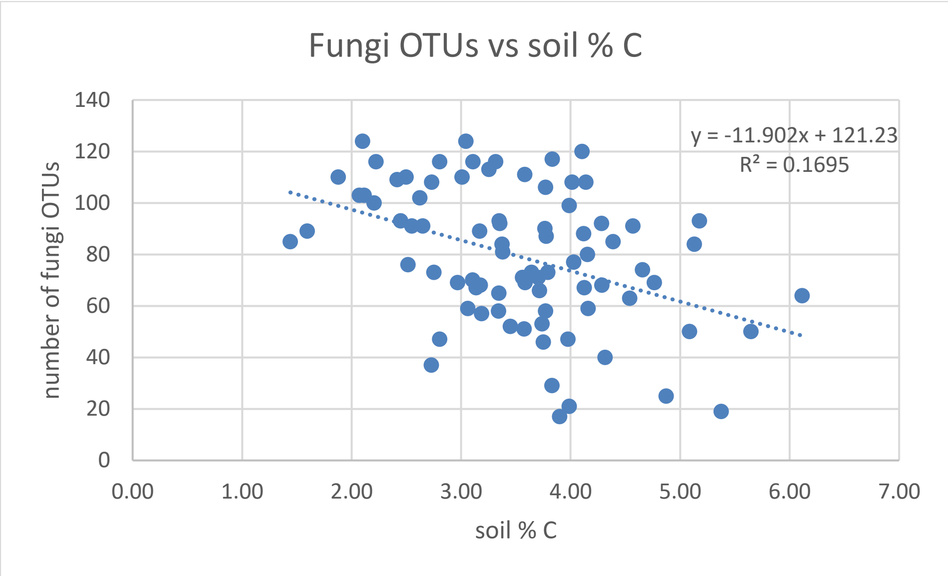

Figure 31. The number of fungi OTUs detected across farms in relation to soil carbon content. Fitted linear regression is included.

The Simpson D diversity index was calculated based on detected OTUs for both the bacterial and fungal communities. It was decided to do this separately as the relationship between the number of OTUs and biomass is quite different for fungi and bacteria (due to hyphal biomass in particular). Across farms, there was a negative relationship, explaining around 19% of the variation, between the diversity of the bacterial community and soil C content (Figure 32).

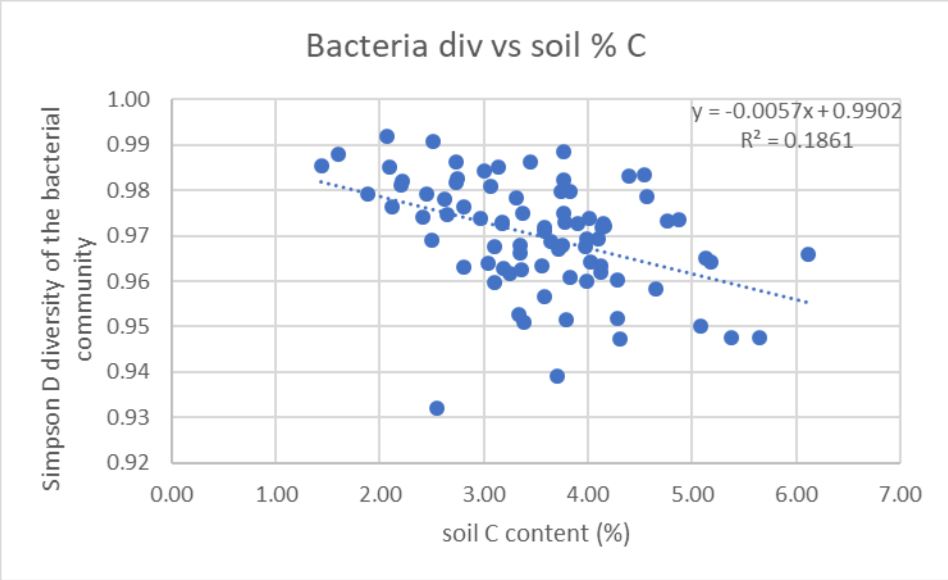

Figure 32. The diversity of the bacteria community based on OTUs detected across farms in relation to soil carbon content. Fitted linear regression is included.

Across farms, there was a negative relationship, explaining around 11% of the variation, between the diversity of the fungal community and soil C content (Figure 33).

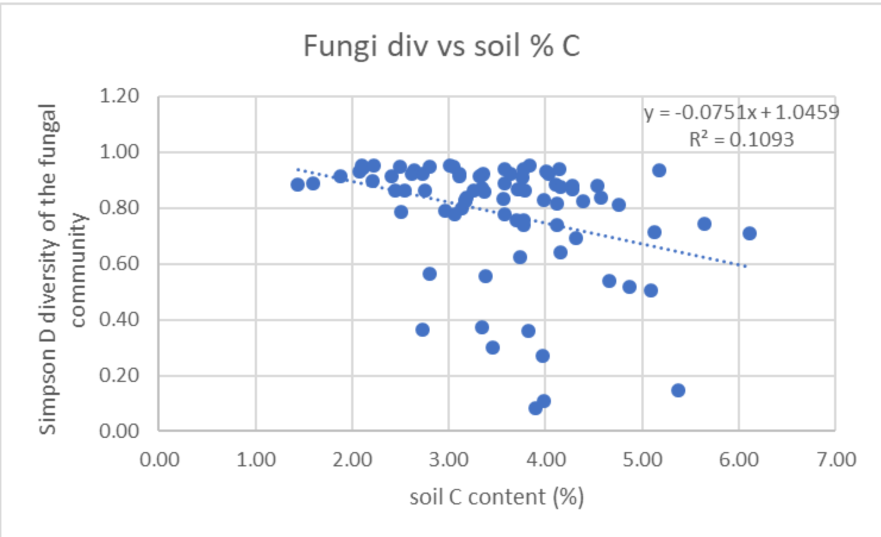

Figure 33. The diversity of the fungi community based on OTUs detected across farms in relation to soil carbon content. Fitted linear regression is included.

Similar patterns to those seen for soil C content were also seen for the relationship between bacteria and fungi OTUs and soil N content, in this case the fitted regression lines explained 15% and 17% of the variation in the data around the fitted lines for bacteria and fungi respectively (data not presented). Similarly, the relationship between bacteria and fungi diversity and soil N content mirrored that observed for soil C. This is not surprising as there is a very strong correlation (r = 0.973; i.e. 97%) between soil % C and soil % N (Figure 34).

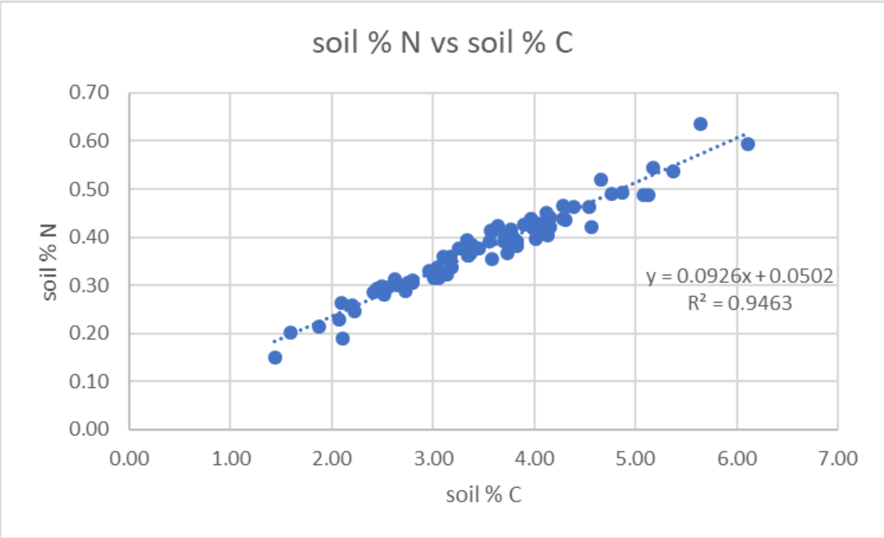

Figure 34. Soil carbon and nitrogen content are tightly correlated. Fitted linear regression is included.

The ratio of bacteria to fungi in terms of detected OTUs was assessed, but no clear relationship was found in relation to soil C or N content.

4.3. Interviews on soil health

4.3.1. Farm characteristics

'Larger scale' (whose sole income is their farm) and 'smaller scale' (whose income does not only rely on their farm business) farms had different priorities regarding their ability to make changes and the impacts of those changes on their short to medium term income from the farm business. The issue of farm tenancy was also mentioned and the fact that long term decisions can be difficult if land is tenanted. Many of the farms have some permanent pastures, but there are some reseeded fields along with herbal leys too.

There was a mix of farms in terms of livestock with three being predominantly sheep but also having chickens (which may be incorporated in the grazing regime), one solely sheep, two mixed cattle and sheep, two solely cattle. Farms practiced various grazing management approaches including rotational grazing by sheep (4), by sheep and cattle (2), by cattle (1), mob grazing by cattle (2). Some farmers are not using agrichemical inputs (5) or are making active choices to decrease or stop using them altogether (2). These may be replaced with manure application but not in all cases. There is some minor but irregular liming on several of the farms. Two of the farms are certified organic. One farmer mentioned that: "*I have never been happy using fertilizer or spraying. I just spray to kill some weeds [when needed]".* Several farmers mentioned the use of veterinary medicines and their choice to reduce their use because of the perceived (and real) threat to soil biodiversity; this is particularly interesting as it was not elicited via a prompt but raised independently.

Some smaller farms are driven by environmental awareness and biodiversity protection and have, for example, very high plant diversity including a high density of orchids. Some of the farms have also planted trees, mainly for the biodiversity benefits. Some of the farm businesses are focussed on the quality of the produce rather than quantity (3).

4.3.2. Information and knowledge

Farmers reported that they gained information via word of mouth, peer advice and farm visits more than any other source. A particularly useful way of obtaining information was targeted farm demonstrations or activities, e.g. on soil structure or soil biology. Family, neighbours and friends were also mentioned as key sources of information and advice. One farmer noted that a big decision on how his land was farmed was influenced by neighbouring farm businesses. They also cited the importance of farmer groups or networks. Some of the group looked at other resources, such as from farming organisations, books, scientific papers and grey literature. The internet and, in particular, YouTube were also mentioned as good sources of information. A few attended short courses to enhance their knowledge on particular subjects. It was interesting that several of the farmers mentioned academic papers as sources of information; this would appear to highlight a thirst for knowledge and specifically an understanding that this is a fast-progressing area of research. At the same time, it was also noted that experience and tradition are key and that farmers relied on their own instinct and observations of their livestock to make decisions on how to manage their grazing. As one farmer explained: "*the animals let you know when they're ready to move on..*.".

4.3.3. Soil health status

Some farmers had quite clear ideas about what soil health meant to them 'in their own words', but others did not express a distinct definition. One example was: "*Provision of a healthy ecosystem. For all different soil inhabitants like soil mycorrhiza, fungi, and bacteria. Provision of a balanced life for soil species."* A second farmer offered: "*Ability to be self-sustaining and self-supporting. To have its balance of microbes existing whilst we can feed and graze without degradation, including carbon content*". This particular definition indicates some very solid knowledge of ecology and how natural ecosystems function. Some farmers mentioned that there was more an 'overall feeling' of what a healthy soil is. Importantly, all the farmers interviewed had a solid understanding of the importance of soil health. One farmer noted that "*I think my soil is not in [best] condition and that is upsetting me*." Despite not always being confident in defining soil health, all farmers tried to do what was possible to ensure that their soils were healthy.

When asked how sustainable their grassland was, several answered by highlighting that no or very limited amounts of fertiliser and herbicide were used, and some also added that no concentrates are used. Other farmers have specifically chosen to take a minimal grazing approach to enhance the biodiversity of their grassland at the expense of higher livestock production. Some farmers acknowledged that there are differences within fields on their farm with regard to soil and grassland health and explained that there is a balance to be made with the requirements of the livestock and potential environmental impacts on grass growth. A typical description of what a healthy soil is was provided by a sheep farmer: "*a soil looks good when a hole is dug, [and it's] full of life, deep roots, friable, water penetrating all the way down and visibly above the surface there's a good biosphere and biodiversity*". Another farmer specifically noted that "*chemically, there should be a balance in properties; [but I am] leaning more now on biological properties of the soil*" as the key indicator of soil health. A further farmer stated that "*based on the information we have; we believe we are sustainable*" and have noticed improvements in grass sward growth and biodiversity since they took over the farm. Another interesting definition of soil health was presented in relation to farm outputs: "*soil health are defined by the output of the farm which in our case is our fruit trees and our grazing and sward health*". A similar definition was provided by a mixed sheep and cattle farmer: ***"**Making sure you see improvement yearly through grass growth and yield. Not seeing anything backward but improving. Making things better and you can continue to produce things better".* Another farmer noted that the application of manure in the hay meadows appears to have increased sward diversity. Keeping sheep at relatively low densities was also noted as being not only beneficial for the grassland biodiversity but also had the capacity to prevent worming issues. One farmer summarized soil health as "*where the whole farm starts and ends*".

4.3.4. Testing soil health

Farmers commonly mentioned testing for earthworms and visually assessing plant diversity (looking for a range of plant types), but several also carry out soil testing on a regular basis, looking at pH, NPK and micronutrient content. Depending on farm size, this soil testing may be carried out on a 2- to 5-year cycle. Several also mentioned tests on soil C content. The most common approach to assessing soil health was to do so indirectly by looking at grass growth and the health of the vegetation, plant diversity and earthworm casts. Several do soil tests using the visual assessment technique (VESS = visual evaluation of soil structure), where specifically they are also observing the roots and numbers of earthworms, giving an indication of how alive and healthy the soil is. One farmer noted that the major drawback with the VESS approach is that there is nothing to compare their samples to, meaning that VESS only works if you can make comparisons and by definition it is highly subjective. One sheep farmer stated "*We have done a few bits of digging holes and looking at earthworms, but I have to say we are probably not good at that but I'm part of a project where we measure grass for Welsh Government, so I just know what is going on in the rest of the ground*". Another farmer stated that "*I do not really do any formal monitoring, which is a reason why I [wanted] to be a part of this project*". Another farmer noted that "*soil health is in a good correlation with sward growth. [… and] having the right type of animal at the right density on the right field at the right time of the year*" is the key.

4.3.5. Soil health in decision making

The stocking density of livestock is a key element considered in the context of impacts on soil health and having the 'right' numbers of livestock on the pasture is noted as key; this was mentioned by several farmers. They understand and particularly highlighted the importance of not overstocking. One noted that there might have been a slight overstocking of cattle on their grassland but the density will be reduced to maintain grassland sustainability. Another noted that their focus is on grassland biodiversity, acknowledging the link between diverse vegetation and a healthy soil system. The type of grazing approach is also considered as having a bearing on soil health, and for many rotational grazing is the main choice, although some have tried mob grazing. Clearly there is also some overlap between the two grazing approaches and a middle ground likely exists. Several farmers noted the importance of a decent recovery period after grazing. One farmer (cattle and sheep) mentioned trying not to graze when the soil is dry and compacted. Similarly, a cattle farmer stated that "*I just try not to do anything to harm the soil and that is why we have to house the cows during winter.*"

Many farmers noted the importance of minimising chemical inputs in order to protect the sustainability of the soil and its health; there is a clear understanding that many of the standard agri-chemical inputs are detrimental to soil organisms. Several farmers noted the benefits of hay-making, leading to less reliance on external feedstuffs, which they propose could also be beneficial to the health of the grassland soil.

For some farmers, increasing rooting depth is considered a priority element in the quest for a healthier soil and more sustainable grassland. One farmer suggested that introducing cattle to his sheep farm might be beneficial for soil health and plant diversity. Another noted that the type of grazing could have particular value in terms of grassland health: "*if you can get maximum leaf coverage, you can mob graze, and then more carbon can be stored*". A farmer concentrating on sheep rearing stated: "*I think we are in a good place [and] can see that we're suddenly becoming more and more sustainable as we are moving away from higher inputs and grassland productivity is improving, and I feel we are moving to greater diversity and that's certainly an aim. Productivity is only improving.*" Another farmer stated that soil health is central to their decision making and comes with the aim of improving the farm's sustainability, without external inputs and as holistically as possible. One farmer explained that their view of soil health has altered during the course of this project and said, "*to be completely honest, to quantify an element of soil health, I have only been understanding [it] since I started chatting with Phil and I think to quantify that, it will be biodiversity and quality of the grass*."

4.3.6. Constraints

Nearly all the farmers noted that the major constraints to improving sustainability are time and money, but also knowledge. Time was mentioned as an issue linked to increasing the knowledge and understanding of best practice and discovering what new research shows. The financial aspects were particularly reported in relation to soil tests, which are expensive for soil carbon and even more so for any tests revealing the abundance or diversity of soil organisms such as bacteria and fungi. There are also business constraints in relation to, for example, less arable rotation or lower livestock density. Environmental constraints on the type of grassland obtainable and the type of grazing it can sustain were also noted with special reference to wet fields. Several of the farmers also raised the issue of policy and whether support is adequate or not.

4.3.7. General observations

Farmers want to improve the health of their soils and farmland in general, and are open to suggestions for improvements. One sheep farmer noted that they are open to experimentation, and are planning to add cattle to this currently sheep-only farm and determine what sort of grazing approach could lead to better grassland diversity and health. Another noted that a "*more scientific and improved way of assessing soil health*", maybe a standardised way of looking at soil biology, would greatly enhance the usefulness of the tests. One farmer mentioned the issue of fungal versus bacterial dominance in the soil and what that means in terms of soil health in grasslands. Nearly all farmers expressed their keenness to find out more about their soils as part of this AHDB-BBSRC project. The important thing is the need for evidence from their soils and how their management might be impacting the health of their soils. For example, one farmer said "*What I am looking forward to is for someone like Phil Staddon to have my samples and ask why there's no carbon and so many worms and ask what exactly I have been doing over the past years*". A mixed cattle and sheep farmer said "*in the future, we might have to have more of the native breeds to make better use of what grass we have got. We must be a bit more self-sufficient and rely a bit less on the importation of proteins. We need to learn a bit more about carbon and what to do to benefit from it*." With regards to the research project itself, a sheep farmer noted that "*it would be nice [if there was a] bit more of some of the stuff we are doing*" and also said "*I love this project because it brings [the possibility of] more protection for grassland*." Another farmer said: "*I will love for this project to have feedback into what we do, [and] for there to be more interconnectivity and sincerity between academic research and farming so that there is more trust in the system*."

4.4. Outputs and outreach

4.4.1. Non-technical information leaflet

A leaflet for lay readers is in the process of being produced. It describes in non-technical language the reason for the project, the tests undertaken, results and implications for livestock grazing management. When completed, it will be translated into Welsh. Physical copies will be distributed to all the partners for sharing among contacts and also at livestock markets and other events, such as the Royal Welsh Agricultural Society's events (see later). A digital copy will also be produced for partners to share online, as well as through existing networks, such as the regenerative farming group that many of the farmer partners belong to, the Nature Friendly Farming Network e-newsletter and the Wales Real Food and Farming Conference mailout.

4.4.2. Films

A series of three short films (5-10 mins each) has been shot and edited by project partner, Hal Drysdale. In these films, farmer partners explain their understanding of and feelings about soil health, its relevance to their farms and how the results of the project may affect their grassland management. The films will be hosted on YouTube (video link) and shared by the partners through their networks, as previously described.

4.4.3. Farm walk

As the participating farms are in a fairly small geographical area, a visit to two of the farms is being arranged for early July. This will take in two farms with different grazing regimes. As many of the participating farmers as possible will be present, in order to discuss their grazing management practices and the project's results, including the soil science and the sources of information that they commonly use when making decisions on grazing and soil health. The walk will be advertised locally using online networks and also the local newspaper.

4.4.4. Presentations at agricultural shows

A presentation at the Royal Welsh Agricultural Society's Smallholding & Countryside Festival took place on 21st May 2022 at Lantra's permanent building on the showground. An invitation list was drawn up of stakeholders who were likely to be interested, including farmers in groups mentioned above, the Nature Friendly Farming Network, RSPB Cymru and National Trust agricultural policy teams, Farming Connect, FWAG Cymru, farming union representatives, Natural Resources Wales staff, Welsh Government researchers and policymakers and others.

As more commercially minded farmers and organisations tend to visit the Royal Welsh Show, rather than the Smallholding & Countryside Festival, discussions are also being held with Farming Connect, who use the Lantra building during the Royal Welsh Show, for a similar event at the Show. This would be as part of their regular programme of presentations and activities. If Farming Connect are unable to host a presentation, Natural Resources Wales have also been approached, as they have a large stand at the Show.

4.4.5. Meeting with Welsh Government

In addition to the outputs initially proposed, a meeting with Welsh Government's Soil Policy group has been agreed (date to be finalised). This was facilitated by project team member, Natural Resources Wales' Thomas Vetter. The project was presented at the Wales Land Management Forum on 6th June 2022.

4.4.6. Other farming conferences

Calls for sessions for the next Wales Real Food and Farming Conference and Oxford Real Farming Conference will be made in the summer / autumn, and the project team will put forward offers to discuss the project and its implications.

4.4.7. Academic outputs

It is anticipated that at least two academic papers will be submitted to environmental or agricultural science journals. The project is also forming a base for further PhD and MSc research. Of particular note is the PhD research, which will begin in autumn 2022 and which will continue and widen the farmer partners' involvement with soil health and grazing, providing more data and outreach over the next few years.

5. Discussion

5.1. Soil carbon and nitrogen

The range of soil carbon content observed as averages for the farms varied from just under 3% to 5%, which is within the range commonly reported for livestock farms in the UK (Ward *et al*. 2016). Similarly, the range of soil nitrogen content across farms, from 0.3% to 0.5%, was consistent with commonly observed values (Watros *et al*. 2018). The C:N variation across farms was minimal with C:N showing remarkable stability, between 9 and 10 throughout; again this is within the expected range (Xu *et al*. 2019) and is unsurprising due to the tight coupling between the C and N cycles especially in systems, such those observed here, which had no or low inputs of inorganic nitrogen fertiliser.

Farm level data revealed differences between field types (defined by management regimes), but these were not always consistent between farms rendering generalisations difficult. For example, Farm A tended to exhibit greater soil C content for fields under sheep grazing compared to fields under cattle grazing, whereas an opposite trend appeared to emerge in Farm L.

However, more consistent observations were made for fields either grazed solely by cattle or where there was a mix of a cattle and sheep grazing. For example, fields grazed by only cattle in Farms B, G and H tended to have higher soil C content than the fields grazed by both cattle and sheep, although for Farm H, in fields with added N this pattern did not hold.

Grazing in silvopasture tended to result in fields with high or very high soil C content for some farms (Farm A and D) but not others (Farm E), but this could reflect the length of time since the establishment of the silvopasture.

Those fields that were arable or recently ploughed showed the lowest soil C content across the farms where these field types existed (Farms C, D, J, M, H, L). This was highly consistent but unsurprising as it is well established that perturbation of fields (e.g. ploughing, periods of bare soil) leads to loss of soil organic matter over time (Droste *et al*. 2020).

The impact of the wetness of the field (where noted) was inconsistent with Farm A showing lower soil C content in wetter fields mobbed grazed by cattle compared to similarly grazed but drier fields. However, this was not observed for Farm D, although here, both the wet and dry fields were grazed by sheep.

One farm (D) included chickens alongside sheep in two fields, which had the lowest carbon content on the farm; whether this could in part be as a result of the chickens is unclear, however the most likely explanation is previous intensive use of those fields for forage crops resulting in loss of SOM and soil compaction.

Within two of the farms (J and E) there were fields with similar grazing management with or without harvesting for hay or silage; in both cases those fields used for harvesting of biomass exhibited lower soil C content, although not significantly so. This would most likely be as a consequence of removing a proportion of the biomass which could otherwise have entered the soil carbon cycle.

A very similar set of observations, to those described above for soil C content, are also evident for soil N content. This is unsurprising due to the tight relationship observed between the soil C and N contents and the stable C:N ratio across farms and fields.

5.2. Soil biodiversity

As expected, the vast majority of soil microbial organisms are unknown and have not yet been assigned to genus level, let alone species level. This illustrates the ongoing lack of understanding about soil biodiversity and even more so about the gaps in knowledge around the function of many components of soil biodiversity. The link between biodiversity and ecosystem functioning (Bullock *et al*. 2021) is one of the great challenges in ecology, especially with regard to soil systems.

Across farms there are no discernible differences in the numbers and types of OTUs picked up for bacteria and fungi. It is also worth noting that the primers used to detect bacteria and fungi cannot be considered universal and it is likely that some bacteria, but especially some fungi, may not have been detected due to limitations in the primer chosen. This is especially true for mycorrhizal fungi, where it appears the detection was patchy. Indeed, it would be expected that arbuscular mycorrhizal fungi, a key component of the soil biota, would be present in all fields in the farms surveyed, as the vast majority of the plant species present would have been mycorrhizal. This will be verified in ongoing direct observation of mycorrhizal colonisation of plant roots in the fields surveyed (not within the scope of this project).

The bacteria community richness was relatively stable across farms with, in addition, limited variation between fields; on the other hand, the fungi community richness exhibited much greater variation both between and within farms, but no significant differences were observed at either the farm or field level. This markedly uniform distribution of soil microbial diversity across the farms is consistent with the observation that soil microbial diversity can be relatively homogenous over large areas and across regions.

The number and diversity (Simpson D) of bacteria and fungi OTUs tended to decrease with increasing soil C content (and correlated soil N content). It may be that a greater diversity of soil microbial biodiversity is able to utilise a greater number of organic compounds and thus degrade a greater proportion of soil organic matter. This would mean that greater soil biodiversity might not lead to higher soil organic matter content.

5.3. Soil health and farming practice

The farmers taking part in this project all have a strong interest in improving the sustainability of their operations. Farmers with a range of different sized farms were involved, and these tend to be linked to the business type, with the larger ones having farming as the main income. Tenancy of land for some could be an issue in deciding how the land will be managed over the medium to longer term; a common issue with tenancy (Hopkins *et al*. 2017). Many of the farmers have an active interest in improving biodiversity on their farms, including for example planting of trees or actions to benefit wildflower diversity.

A wide range of sources were cited as useful by many of the farmers, but one that stood out was the peer to peer exchange of information and the issue of trust whilst receiving knowledge. Again, these two elements have been widely observed as critical in achieving any change to farming practice (Staddon *et al*. 2021). The value of experience and tradition in making decisions was also evident, which could be argued as being strongly linked to the concept of self-identity of what being a farmer means (Staddon *et al*. 2021).

Although there was sometimes a lack of clarity in terms of what soil health means, all the farmers had a good feeling for either what it entails or what the consequences are. All aimed to manage their land in ways consistent with protecting their soils, even if it was not always clear which options might be best. This aim of protecting their soil resource is widely held amongst farmers generally (Ingram *et al*. 2010) even if not always evident in terms of soil outcomes. The need for easily measurable parameters to assess soil health was evident and has been reported previously (Doran and Zeiss 2000). It was clear that the farmers were well aware of the need to keep stocking densities at appropriate levels for their grasslands; this is something recently highlighted in work looking at the impacts of grazing intensity on grassland ecosystem functioning (Faghihinia *et al*. 2020c).

A range of approaches was taken to assess soil health, but the farmers noted that the cost or the consistency of the protocols used inhibited a more thorough assessment of soil health. It would seem that a clear set of robust methodological approaches for soil sampling, as well as analytical protocols, would be a great step forward in obtaining comparative soil health values that could inform changes in soil health. This request for a robust and simplified way of assessing soil health at the farm level is a goal many researchers are actively working towards (Farmers Weekly 2018).

Soil health appears to be central to many of the decisions taken with regard to grassland management, with farmers not wanting to do anything detrimental to the health of their soils. It was also noted that there are conflicting demands, and on occasions actions may need to be taken that are not beneficial for soil health (e.g. agri-chemical inputs). Several of the farmers use specific approaches to grazing, such as mob grazing, as there is a fairly widespread belief that this is beneficial to the grassland ecosystem and soil health as it more closely mimics the natural condition of grasslands; however, the science points to more nuanced impacts (Roberts and Johnson 2021).

Many of the constraints affecting decision-making are linked to time and money, with environmental limits also noted, e.g., wetness. The possibility of policy assisting with the financial constraints was raised – this targeted use of policy and financial tools can facilitate change, but is not always the case (Dandy 2012). A key element in decision-making is evidence, and specifically evidence for farmers' own farms and soils, which in large part was the motivation for the farmers developing a research proposal with academics. The need for farmers and scientists to work more closely together is becoming obvious (Krzywoszynska 2019).

5.4. Recommendations

This research has, as is often the case, raised more questions than answers. Nonetheless, there are some important points and recommendations to consider, both for farmers and for policy makers.

There is a marked range in soil C content which differs within farms and between farms leading to **recommendation 1**: ***field level carbon assessment*** *is required to get a clear picture of the true current baseline values*.

There were not always clear patterns in the relationship of current field management and soil carbon, most likely as a result of past management, leading to **recommendation 2**: ***detailed long-term management history*** *of individual fields needs to be incorporated where possible when developing plans to enhance soil carbon stocks*. This is particularly relevant to the development of policy tools. Note that accurate and regular measurement of soil carbon content down the whole soil profile is a prerequisite for robust estimation of total carbon stocks in t/ha.

The inconsistencies in some of the results, especially those that differ between farms raises questions around an optimal approach, leading to **recommendation 3**: *changes in grazing management with the aim of improving soil C content or soil health more generally need* ***effective monitoring*** *to ensure the intended outcomes are indeed occurring*.

There was a potential trend that fields used for hay or silage making exhibited lower soil carbon than otherwise similarly managed fields, leading to **recommendation 4**: *impact of biomass removal from grasslands on soil carbon content should be* ***regularly assessed***. If this is occurring a further **recommendation** (**5**) would be to return livestock waste (manure) as a priority to those fields used for biomass harvesting. Clearly there are other benefits to hay meadows, especially in terms of biodiversity and wildlife habitats, which would need to be taken into consideration before focusing on soil carbon or aspects of soil health in deciding any shift in management: indeed, in many cases biodiversity can be higher in nutrient and carbon poor grasslands.

The soil DNA profiling provided a general (but not necessarily comprehensive) picture of the diversity of the bacterial and fungal communities in the soil, but did not offer any obvious patterns with regard to field management regimes, leading to **recommendation 6**: ***targeted soil DNA profiling*** *of key beneficial (e.g. mycorrhizas) or detrimental (e.g. pathogens) micro-organisms should be preferentially used over general DNA profiling*. This is particularly so as interpreting the results and being in the position to use them in an informed way is lacking (the link between soil biodiversity and soil ecosystem functioning is a key ecological research challenge).

The farmer interviews highlighted (as expected) different farm business models and lifestyle choices leading to **recommendation 7**: *policies aimed at enhancing the sustainability of grasslands or specific ecosystem services (e.g. carbon sequestration)* ***should cater for all segments*** *within the farming community*.

There was sometimes a lack of clarity around soil health but a strong desire to learn more, leading to **recommendation 8**: *more effort at* ***knowledge exchange*** *focused on soil health, what it means and how to improve would be beneficial*.

There was a common feeling that the scientific evidence is not always clear and often lacking especially at the local level, leading the **recommendation 9**: *policy tools to facilitate the interaction between farmers and researchers, but also enhanced* ***assistance for evidence gathering*** *of the status of farmers' own fields and soil*. This is vital if increased monitoring of soil carbon and health is to be made possible.

5.5. Future research and development

The project was very successful in collecting a large amount of data, which was not always consistent between farms and therefore highlights many questions that need answering. The data will be further analysed after the end of this project in conjunction with additional data being collected by two MSc students. This new data targets some key elements of the soil biodiversity which were not focussed on in this project, namely arbuscular mycorrhizal fungi and soil microarthropods. Furthermore, a PhD student is building on this AHDB-BBSRC project by delving more deeply into aspects of grazing impacts on soil ecosystem functioning with the aim of identifying some of the advantages and disadvantages of different grazing management approaches.

From a scientific evidence and policy perspective, future research should aim to answer the following questions:

Question 1: *What are the confounding variables resulting in inconsistent outcomes of* ***different livestock types*** *(cattle; sheep; cattle & sheep) in terms of soil carbon content?*

Question 2: *What are the confounding variables resulting in inconsistent outcomes of* ***different grazing regimes*** *(rotation; continuous; mob grazing) in terms of soil carbon content?*

Question 3: *Why is the* ***soil carbon to nitrogen ratio*** *so uniform across this system of very different field management regimes?*

Question 4: *After what time period can **measurable differences in soil carbon sequestration** be expected to be observed in response to change of management approach (e.g. establishment of silvopasture system)?*
Question 5: *What is the impact of incorporating **poultry as livestock or poultry manure** on sheep or cattle grazed systems?*
Question 6: *How does the removal of **biomass for hay or silage** impact grassland soil carbon and biodiversity?*
Question 7: *Are there key **components of soil microbial ecology** that could be focussed on in order to capture impacts on critical aspects of soil health?*
Question 8: *Why did **soil microbial richness and diversity** appear to be negatively correlated with soil carbon and nitrogen content?*
Question 9: *Could maximising soil carbon content result in **decreased soil microbial biodiversity**, and therefore potentially decreased soil health?*
Question 10: *Why do apparently more stable systems (e.g. permanent grassland) **not show greater soil biodiversity** and yet are considered more resilient to environment perturbations (e.g. climate change)?*
Question 11: *What policy initiative would be most effective in **increasing the sustainability** of grassland management?*

Answering these 11 questions will greatly advance our understanding of how grazing management choices impact soil carbon content, soil health and grassland sustainability. Grazing is compatible with grassland sustainability, but it would be beneficial to know what the optimal grazing management is for a given locality. Grasslands, with their large capacity for carbon storage, could be a great asset in fighting climate change whilst being managed sustainably for livestock and food production.

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7. APPENDIX 1. Interview questions and prompts

Q1. ***Describe your livestock farming activity***.

Prompts: farm size; other farming activities (e.g. arable); livestock type and numbers; grazing management; grazing type (e.g. continuous; mob grazing); chemical inputs; type of pasture (permanent; plant diversity); major changes in the last 10 years or so (e.g. changes in mix of enterprises or shift in farming system; change in livestock breeds); reasons for any change and any advice received

For the following 2 questions, we use the term sustainable to mean continuing to carry out farming in such a way that the productivity of your grassland is being maintained without having to increase inputs and livestock production is similarly being maintained – in other words no deterioration in sward or livestock productivity is observed.

Q2. ***In terms of grassland status how sustainable do you view your livestock farming?***

Prompts: sward growth; livestock production; meat quality; diversity of grassland; any actions needed to maintain productivity (e.g. liming, FYM, etc); how long has current management being undertaken; history of management

Q3. ***How do you assess the sustainability or health of the grassland?***

Prompts: what are the tangible things you can assess? sward growth; grass nutrient content; biodiversity (vegetation; earthworms; etc); soil structure/health (VESS test - visual evaluation of soil structure); soil nutrient tests; livestock production; describe the process? what do you do when you assess it? which of your senses are involved; what tools and aids do you use the get an approximation of soil health? how often do you do these things? check whether grassland has any special conservation status

Q4. ***What does soil health mean to you? How would you define it with your own words?***

Prompts: understanding of what soil health means to them; how do they assess soil health?

Q5. ***Do you consider soil health when making grazing management decisions?***

Prompts: if yes - what aspects of soil health do you focus on (e.g. biodiversity, soil carbon)? what do you avoid or do to improve soil health (e.g. grazing approaches)?

if no – do you focus on grassland health rather than focussing on soil health (e.g. biodiversity, sward growth)? What do you avoid or do to improve grassland health (e.g. grazing approaches)?

Q6. ***Who/what is influencing your decision-making in relation to the soil health aspects mentioned above?***

Prompts: what advice and guidance they have received; have they been on a farm walk of event around soil health; have you tested your soils, regularly?

Q7. ***Are there constraints to managing the health of your grassland (soils)?***

Prompts: knowledge; data; evidence; cost; policy support; incentives; would you like greater soil testing?

Q8. ***Any further comments on the health of your grassland?***

Prompts: e.g. benefits of different grazing approaches, switching livestock type, switching breeds (e.g. away from continental ones), soil health, soil carbon, grassland diversity; are there known challenges or areas to work on (e.g. compaction or nutrient deficiencies)? what have they done about this? do they have any plans for the future relating to grassland management.

8. APPENDIX 2. Underlying soil data for the farms

Soil Data

Underlying soil data using farm postcodes from http://www.landis.org.uk/soilscapes/# showed that all farms lay within the 'Soilscape 6' area of freely draining slightly acid loamy soils. The map provided below shows the area within which all farms are located.