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Managing permanent grasslands for carbon sequestration in Scottish soils

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Executive summary

Soil can act as a carbon store or a carbon sink. The extent to which it does this will contribute to how Scotland can meet its emissions-reduction commitments.

Grasslands cover a large area of Scotland's land and their management can influence whether grassland soils release or store carbon and by how much. There are two ways to improve carbon sequestration in Scottish soils

1. through influencing the processing of carbon within soil and
2. altering the inputs of carbon to the soil.

Of these, the manipulation of inputs is better understood and easier to influence.

This project synthesises the best state of knowledge on the effect of management practices on soil carbon sequestration in permanent, managed Scottish grasslands and modelled potential application.

Key findings

- We found some good evidence for the effects of specific practices on carbon sequestration in managed grassland.
- However, we found little evidence on the interaction between factors and the efficacy of these measures under diverse environmental conditions.
- Our modelling simulations suggest increases of 1-2.5 tonnes of additional carbon stored per hectare where carbon inputs to soil can be increased by 10% for a 30-year period. If achievable, benefits would likely plateau as saturation in soil is reached. They also highlight the risk of negative effects of additional grazing.
- Factors affecting sequestration potential include grazing rates, grass species, application of fertiliser and tillage.
- Evidence supports the addition of non-synthetic substances (e.g., plant residue and manure) to soil and the selection of high yielding grass species mixes for increasing carbon sequestration where this is possible to apply. Some evidence exists for the use of synthetic fertiliser to increase soil carbon sequestration although the environmental costs of fertiliser production/ application make this less appealing.

- The application of biochar as a method for increasing soil carbon sequestration would require more research, especially on biomass for production and on its impact on yield and the environment. Evidence for the application of lime for increased productivity is inconclusive.
- The evidence for the effects of managing grassland for carbon sequestration in soil is mixed. We did find more conclusive evidence on the effects of altering inputs than on the effects of influencing carbon sequestration through the turnover (degradation) of existing soil carbon.
- Replacing synthetic fertiliser with carbon-containing fertiliser will lead to stronger increases in carbon sequestration when applied in the correct circumstances. However, this will not apply across the whole of Scotland due to limitations to supply. Sources of additional organic material hold the largest potential for increases as most manure produced on-site is currently also applied on-site.
    - While knowledge is imperfect, it is possible to make some decisions now on actions that might be taken.
- Next steps might include:
    - Further research on the management practices that impact on the turnover of soil organic carbon in Scottish grasslands.
    - More research on the practical application of specific management practices.
    - Integrating knowledge on soil carbon effects into a more holistic farm greenhouse gas budget to better understand the trade-offs of practices and avoid unintended consequences.
    - Quantification of the targeted implementation of specific management practices across Scotland.
    - Identifying sources of carbon-containing fertilisers and testing the impact of increased application under different conditions to highlight areas with large potential gains.

Table 1 below shows the qualitative effect of management practices on soil carbon sequestration in Scotland, the strength of the effect, the strength of evidence for this effect and the evidence for applicability at scale in Scotland.

- Qualitative impact is split into practices for which there is evidence for increases, evidence for decreases and either split evidence or evidence showing no overall effect. In cases where evidence is split it is still possible a practice may be an appropriate tool in the right circumstances.
- For the strength of impact column, the practices are split into significant impact, small impact, and no evidence of impact. Strength of evidence for impact indicates the evidence base. This is split into no good evidence of impact, some evidence for impacts in limited specific application and evidence for effect more generally.
- The final column shows evidence for applicability at scale in Scotland. This is split between
    - No evidence for commercial scale applicability in Scotland
    - Evidence for context specific applicability in Scotland and
    - General application already occurs in Scotland.

	Qualitative impact on SOC	Potential strength of impact	Strength of evidence for impact	Evidence for applicability at scale in Scotland
Grass species	↑	++	++	++
Grazing intensity	↓	++	+	+
Fertilisation	↑	++	++	++
Liming	↑	+	++	+
Earthworms	↑	+	+	
Tillage	↓	+	+	++
Biochar	↑	++	++	
Burning	→			+
Irrigation	→	+	+	+
Liming	→	+	+	+

Table 1. Summary of effect of management practices on soil carbon sequestration in Scottish grasslands. The table is specific for Scottish application and would look different for other contexts. Strength of evidence is split into three levels: strong evidence for the effect, contrasting/ weak evidence for the effect and no evidence for the effect. The applicability is split into three levels: widely applicable, context specific applicability and not yet applied at scale. Methodology for table can be seen in appendix 7.3

Contents

Glossary

Legumes	Family of plant species including peas and clover which fix nitrogen from the atmosphere through bacteria harboured in small growths on their roots called nodules.
Sequestration	The capture of a chemical in natural or artificial storage.
Land sparing	Reducing quantity of land required for agricultural production so that additional land can be used for non-farmland environmental use.
C3 and C4 grass species	Two categories of grass species which use different photosynthesis processes. C3 species are more prevalent and C4 species are generally found in warmer climates.
Non – synthetic fertilisers	These are fertilisers that are chemically organic. We use the term non-synthetic to avoid confusion with organic in its farm context meaning. These would include manure, slurry, and compost.
Carbon sequestration	The capture and storage atmospheric carbon dioxide.
Carbon Stock	The quantity of carbon contained in a system or reservoir. Stocks can increase to accumulate carbon or be depleted to release carbon.

1. Introduction

This project set out to explore the current state of the evidence on the choice of management practices and how they might influence carbon sequestration in the soils of managed Scottish grasslands and model the potential effect of their application.

1.1 Why the work is important

Scotland has committed to meeting a net- zero target for greenhouse gas emissions (GHG) by 2045 (and a 75% reduction by 2030). The targets are ambitious and to meet them every economic sector contributing to emissions, including agriculture and land use, will have a part to play. Agriculture is important as a significant component of overall emissions but also as a sector with the potential for negative emissions through soil carbon sequestration. Soil carbon makes up an estimated 80 percent of terrestrially stored carbon (Lal 2008) so protecting what is currently there and enhancing this pool will contribute significantly to meeting these targets. Scottish grassland soils contain 3000 Mt (Rees et al. 2018) of carbon and cover over 5 million hectares of land so these are a large component of agriculture and land cover (17%) in Scotland. There is evidence for grassland soils acting as either sources or sinks depending on environmental and management factors. A clear summary of the knowledge of how the management practices influence carbon sequestration in Scottish grasslands will enable management decisions to be made considering the effect on soil carbon in the context of food security and climate commitments. The wide spatial distribution of grassland in Scotland can be seen in figure 1a, highlighting its importance across a large area of Scotland. Figure 1b shows the intensity of grazing in each grid cell, which is a proxy for the grassland contribution to food production.

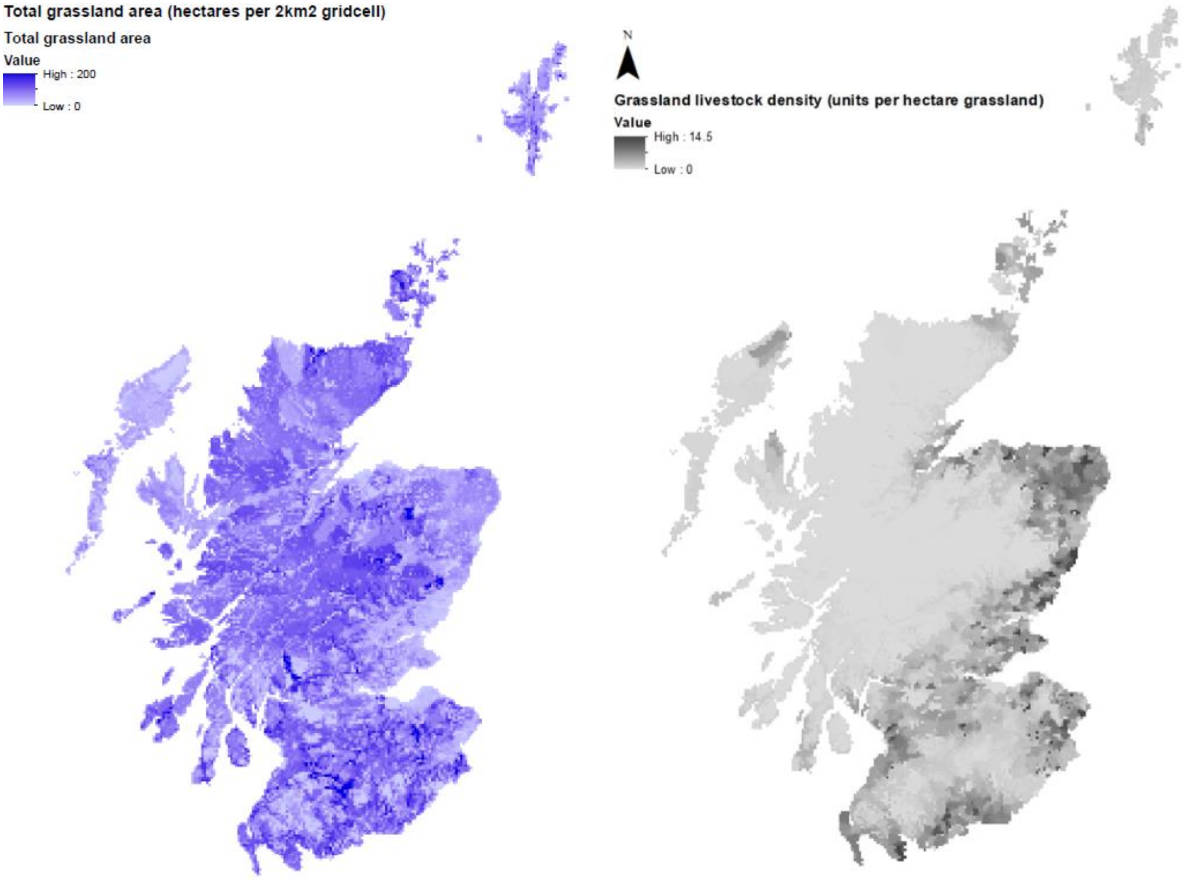

Figure 1a. Total grassland area on 2km^2 grid cell for Scotland. Figure 1b shows the distribution of livestock density across Scotland (in livestock units per hectare of grassland in each 2km^2 grid cell). Data for both obtained from Edina agCensus data (Need to check this is ok to be included as the user agreement has specific clauses for educational use)

1.2 What the report does not cover

This report focuses on the impact of management practices on soil carbon storage and sequestration in Scottish grasslands. Other aspects, which are related to livestock management and climate are outside the scope of this report and clearly stated below.

- While conversion from/ to grasslands is of great importance to the sequestration of carbon in Scottish grassland soils, it is outwith the scope of this report and is not addressed here.
- We have also excluded the practice of agroforestry to retain a tight focus.
- Direct emissions from livestock are a large component of the grassland carbon cycle and will often determine whether a system functions as a net source or sink of greenhouse gases. However, this report specifically focuses on soil carbon and as such, direct emissions from livestock are not accounted here.
- Non-soil GHG emissions and other sources of emissions, such as from machinery, are excluded from the analysis.
- GHG emissions from soil are not directly quantified but considered to the extent that they influence the soil carbon pools. Some management practices which increase soil carbon sequestration may also increase emissions from soil (e.g., fertiliser application).
- The impact of climate change on Scottish grassland carbon sequestration is also of great importance and beyond the scope of this report.
- Limitations to carbon stock increases occurring through saturation.
- The model used in the application is not designed for use in waterlogged soils, as such results do not cover peatland soil.

Our conclusions should be viewed in the context of larger land use management systems and with knowledge of these related factors. In the case of grasslands, emissions from grazers form a significant part of the picture and practices which can reduce these emissions should also be considered/investigated. Non-soil agricultural GHG emissions are frequently higher than soil emissions so these must be considered when considering the effects of practices for policy.

2. Carbon sequestration in Scottish grasslands

Carbon is accumulated in grassland soils from decaying plant and animal matter. Plant inputs come from above and below ground biomass, while animal inputs come from manure and decaying animal matter. Carbon in the soil is in turn ‘lost’ through microbial breakdown which is released as gases (carbon dioxide and methane) and hydrologically (including as dissolved organic and inorganic carbon).

The balance of soil carbon in grasslands depends largely on the balance between these processes. Higher inputs generally increase storage whilst faster microbial breakdown will reduce carbon stored in soils. The management of grasslands influences the ecosystem processes which control the carbon cycle in soil (see figure 2). These processes determine whether a soil will store more carbon or release some of the carbon currently stored in it. The rate at which carbon turns over in soil and the rate at which carbon is added to grassland soils have many contributing factors including environmental variables and management practices.

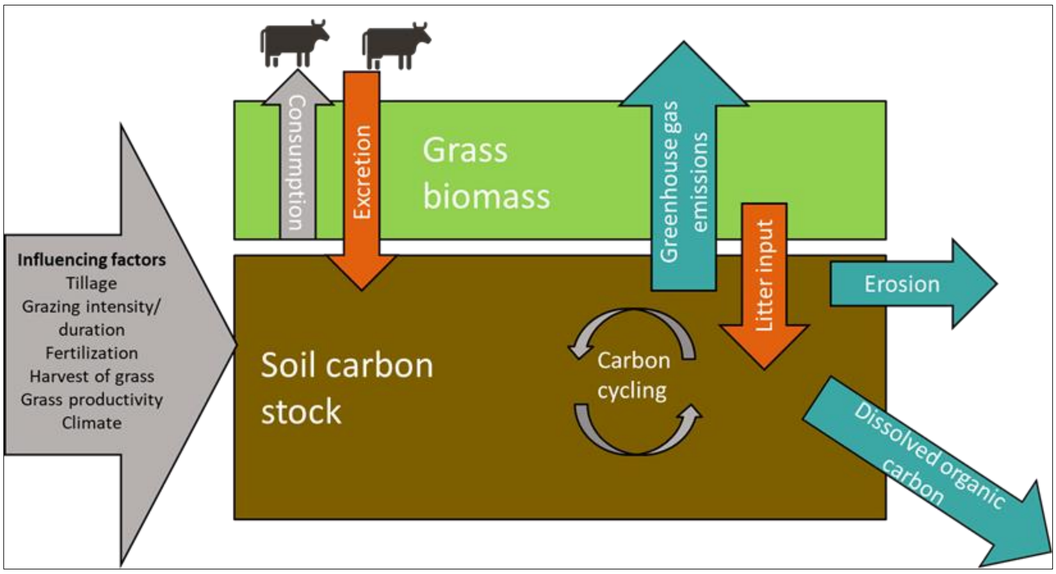

Figure 2: Grassland soil carbon cycling diagram with influencing factors

UK grassland soils sequester on average 242 (±199) kg C ha^{-1} yr^{-1}(Janssens et al. 2005). Scottish grassland soils contain 3000 Mt of carbon and cover over 5 million hectares of land (including rough grazing) (Rees et al. 2018), a slight decrease from 2009 estimates (Scottish agricultural census 2019). Scottish grassland is split between rough grazing and managed grassland with over 1.3 million hectares of managed grassland in Scotland in 2019 which is around 17% of Scotland's total land area.

The contribution of soils and land use to GHG emissions is set out in chapter 11 of the 2014 IPCC report (Agriculture, Forestry and Other Land Use) in which agriculture and land use is shown to contribute 10-12 $GtCO_2$ eq /yr of anthropogenic greenhouse gas emissions which equates to just under 25% of global anthropogenic emissions (Smith et al et al. 2014[b]). Emissions from soil are included in this total, which is important as soil also has the potential to sequester carbon from the atmosphere and act as a sink.

Some grassland soils have been observed acting as sinks (Soussana et al. 2007), whilst others have been measured as sources of carbon emissions (Bellamy et al. 2005). The ability of grasslands to act as perpetual carbon sinks has been questioned, with evidence suggesting that carbon is accumulated in grassland soils where carbon has previously been depleted. The evidence indicates that an equilibrium will be reached beyond which additional soil carbon gains will not be achievable (Smith 2014).

This emphasises the importance of protecting carbon already stored in grassland soil and the potential for additional storage means they are an important component of agricultural greenhouse gas budgets. Practices for improving soil carbon sequestration can be broadly grouped into three categories:

- those which increase inputs into soil,
- those which decrease outputs and
- those which influence both inputs and outputs.

The following section will set out the management factors which contribute to these processes, the impact they have, and the evidence base for each (summary given in table 1).

2.1 Grass species

The species composition of grassland is crucial for soil carbon storage as decaying grass material will form most of the carbon input into soil. Grass species are broadly split between cool season (C3) and warm season (C4) species. The split is based on the different methods of photosynthesis used and gives the plants different properties and requirements for growth. In Scotland the climate is not conducive to warm season species so the choice of cool season species mix is the key variable. Mixtures of grass species with faster biomass accumulation contribute to negative GHG emissions by sequestering carbon from the atmosphere, some of which is subsequently sequestered in soil (Lange et al. 2015). Recent research in the UK on cultivars bred for high forage yield indicate that high yielding varieties can contribute to increased soil carbon, particularly through root inputs (Gregory et al. 2021). The species composition influences yield and therefore carbon input to the soil, but also the availability of carbon in inputs to soil microbes which can determine the rate at which they are broken down (Dungait et al. 2012).

The choice of pasture composition is based on a larger number of factors. These include tolerance of growing conditions and palatability to grazers. The addition of legumes to grazing mixes is another method of reducing the environmental footprint of livestock production (Jarecki and Lal 2003). Legumes fix atmospheric nitrogen, providing the co-sown grass species with some of the nitrogen needed for growth. This will either improve growth rates of grass (potentially sparing additional land and improving the carbon stored as biomass and consequently soil) or replace some of the fertiliser which may be applied to improve grass yields. The replacement of chemical fertiliser is positive for the GHG balance as production is energy intensive (Snyder et al. 2009).

Diverse sowing mixes can improve soil biodiversity and increase soil carbon sequestration (Crotty et al. 2015) particularly for degraded and abandoned agricultural lands (Yang et al. 2019). These mixes should be comprised of plants with a combination of different traits to avoid inter species competition (Mason et al. 2016). Below ground this may influence the turnover of soil carbon but quantification on a large scale is not yet possible. The choice of species will be a determining factor in the rate at which biomass is broken down in soil, but this is an under-researched field (Hoffland et al. 2020). Species which are slower to decompose will store carbon for longer than those which are quickly broken down. The choice of grass species will also determine the resowing rate, more detail on the impact this has can be seen under soil disturbance.

2.2 Grazing intensity

As the number of grazing animals increases, so too does the quantity of emissions directly from them; reducing livestock numbers is an effective way to reduce agricultural emissions per area of land (Herrero et al. 2016). Reducing the number of grazers per hectare will lower the quantity of animal product produced and require larger areas to be in production for the same quantity of product. The distribution of a fixed number of animals, however, can also influence soil carbon sequestration. Increased numbers of grazers will consume larger amounts of grass biomass. They will excrete carbon and nutrients directly to the soil which will contribute to the quantity of soil carbon. The balance of biomass removed by grazers with the addition of manure inputs will influence the soil carbon balance. The chemical properties of biomass and manure mean their persistence in the soil will differ. More information on this can be seen in the fertilisation section.

For indirect emissions from soil use, there is some limited evidence that grazing can increase the sequestration of carbon in soil when compared to ungrazed grasslands. This is particularly true for degraded soils (Potter et al. 2001), northern latitudes (Bork et al. 2020) and in lower stocking densities (Hewins et al. 2018). Evidence suggests these increases are unlikely to be achievable long term and must be compared to direct emissions from livestock. As such this benefit could be best realised in a rotational system on degraded soils previously used for crops.

Mob grazing, (short duration high density grazing with a longer recovery period for grass) has been proposed as a potential stocking method for increasing soil carbon storage (Teague et al. 2011). In principle, the longer recovery period allows grass to grow at a faster rate thus increasing carbon capture; however, the evidence for this is still being gathered (Guretzky et al. 2020). A review from Smith (2014) suggests that the increases in carbon sequestration may be legacy effects from transitioning from previous land uses and the potential for these to be sustained perpetually is limited.

2.3 Disturbance

Reduced or zero tillage have often been suggested as management practices which can enhance carbon sequestration in soil. However, evidence for the effectiveness of reduced and no tillage for the sequestration of carbon in soil is limited and may be caused by sample bias (Baker et al. 2007, Luo et al. 2010). Where evidence does exist, the carbon sequestration increase is small and may be offset by increases in Nitrous Oxide (N_2O) emissions (Powlson et al. 2012). Although there are other reasons to practice reduced or zero tillage, including erosion reduction (Skaalsveen et al. 2019), the evidence suggests benefits to soil carbon storage are likely to be small in comparison. To reduce carbon loss when reseeding it is important to reduce the length of the fallow period (Ammann et al 2020) and sow in conditions that would enable the fast establishment of the newly sown pasture (Rutledge et al. 2017).

Grazers also disturb soil through trampling and compaction, with some evidence this can influence carbon turnover. Trampling has been put forward as a pathway to enhance the transfer of plant matter into soil matter (Wei et al. 2021), although evidence for this is inconclusive (Guretzky et al. 2020). Trample damage can also inhibit grass growth thus limit the yield and carbon sequestered (Tuñon et al. 2013) however there are temporal impacts of this effect. Soil with higher clay content was found to be more susceptible to tread damage (Phelan et al. 2012) and as such might be a good target for efforts to reduce this. Trampling is more likely to occur in the same field areas where nutrient addition through excretion is likely to occur and so the effect may be felt more strongly as these are areas where fertility should be higher. There is no linear correlation between the rate of disturbance and the grazing intensity, and impacts are only likely to be seen in susceptible conditions including specific pasture types (Menneer et al. 2005).

The evidence suggests that if decisions to reduce grazing intensity are taken (for soil carbon or other environmental reasons) then doing so in heavier soils will introduce a co-benefit of reducing soil disturbance which may increase biomass accumulation. This may add an additional soil carbon sequestration benefit to the original motivations of such a move. However, consideration needs to be given to the yield effects and subsequent environmental impact displacement.

2.4 Fertilisation

Applying fertiliser, in conditions where it can be utilized, to grassland can ensure grass has access to sufficient nutrients to grow. This has a positive impact on biomass production and in turn soil carbon accumulation (Eze et al. 2018). The biomass returns from fertilisation decrease with increasing rates of application and cease beyond a maximum rate of application where additional nutrients are unnecessary. Types and rates of fertiliser will vary depending on environmental factors and the grass mix in question. Ensuring application of fertiliser at times where it is less likely to be lost through leaching will ensure more of the added nutrients will be accessible to the grass, thus improving the potential positive soil carbon effect (and minimising other environmental impacts). The production of synthetic fertilisers is energy intensive and itself produces significant greenhouse gas emissions. Fertilisers can also be a significant source of nitrous oxide and ammonia emissions when applied to soil (Bouwman et al. 2002). The contribution of these gases should be evaluated against any potential benefit from additional soil carbon sequestration.

The appropriate application of manure to soil as a fertiliser has a positive impact on carbon sequestration in soil through both the carbon content of the manure itself and the improved nutrient availability increasing future yields and thus biomass input (Maillard and Angers 2014). The caveats about greenhouse gas emissions from synthetic fertiliser applications also apply here (with significant methane emissions also potentially occurring during manure storage and application). Whilst both synthetic and non-synthetic fertiliser application can aid the sequestration of carbon (until a new equilibrium is reached), the use of non-synthetic fertilisers will have a better result (Conant et al. 2017). The management of manure contributes to the determination of the fate of carbon and nitrogen excreted from livestock. This contributes significantly to agricultural emissions of both methane (CH_4) and nitrous oxide (N_2O) which are potent greenhouse gases. Pre-treating manure (for example with the addition of straw, addition of urease inhibitors or aeration), that a farmer sources from elsewhere before applying it to their field, can reduce the quantity of GHG emissions which occur before application to the field (Yamulki 2006). As it is common practice to apply on farm manure to soil it may be that little additional manure is available for application. The application of alternative non synthetic fertiliser (e.g., compost) could produce similar effects leading to to increased sequestration.

Fertilisation through manure and urine inputs from on field grazers have limitations. These may be unevenly distributed, with high concentrations around feeding and watering areas and other areas being depleted of nitrogen through grazer consumption without addition through excretion. Inputs from manure and urine may also be leached from the soil or converted into non-bio-available forms, preventing any benefit from increased fertility (Pavlů et al. 2019).

2.5 Liming

Soil acidity is a critical factor in determining what plants will grow, and how much carbon might be sequestered. This is measured on a pH scale, and plant species will sit within a range for which growth can be tolerated – and optimised. Above or below the optimum soil pH less grass will be produced annually. Less annual grass biomass production will reduce the quantity of plant inputs into the soil and lead to lower soil carbon sequestration. At lower pHs it is possible to select different grass species with lower pH ranges to improve productivity. It is also possible to apply lime to soil to increase the pH with the goal of achieving a pH within the optimal range for the selected grass species.

However, the disadvantage of adding lime is that it can increase the decomposition of soil organic matter, the rate at which this occurs will depend on the soil microbial community (Lochon et al. 2018). The trade-off can still be beneficial if the increase in biomass production is enough that the organic matter incorporated in soil carbon pools is larger than that which is lost. In a long-term UK experiment, Fornara et al. (2020)

assessed what level of? increased lime additions were needed to offset the decomposition losses; however, this will vary with microbial communities. More evidence on the cost- benefit of this trade-off is needed, particularly at sites with lower pHs for which lime is more likely to be applied.

The effect of liming on grassland soil carbon in Scotland is of interest as over 60 % of Scotland's soils have a pH of below 6.0 (Soil Survey of Scotland date?). As such the potential area of application would be large if the positive impact were to outweigh negatives (these include the production and application impacts/costs, the ecological impact of pH adjustment as well as the impact on SOC decomposition (Holland et al. 2018)). Recent research from Abdalla et al. (2022) suggests increases in carbon from productivity improvements through lime application are large enough that liming has a net positive effect on soil grassland GHG emissions. The report also suggests that the application of lime would reduce fertiliser requirements, potentially adding additional emissions benefits. Farmers do also have the option of selecting grass species with lower pH tolerances instead of liming which should provide higher yields and contribute to soil carbon sequestration. The wide prevalence of low pH soils in Scotland combined with the potential for higher yields means the analysis of soils pH and targeted application of lime are potentially beneficial however trade-offs with the environmental costs should be investigated before suggesting the application of lime be encouraged for carbon sequestration in Scotland.

2.6 Irrigation

Variable rainfall can drive a need for irrigation to provide water to grassland, increasing biomass production where water availability is a limiting factor (Low and Armitage 1959). This is rarely the case for Scottish grasslands so the necessity for irrigation for carbon sequestration is likely limited. It is possible under a changing climate that the need for irrigation will change however the impact of a changing climate is beyond the scope of the report. Some work suggests that irrigating pastures in temperate climates may reduce sequestered carbon in soil (Mudge et al. 2017) however this is unlikely to apply to periodic irrigation under drought conditions.

2.7 Removal of grass

Removing grass for use as animal feed will reduce the quantity of biomass input into soil. Where grazers feed directly on grass, in-field carbon will be returned to the soil as manure. Where grass is removed and stored for feeding, the carbon and nutritional content of the plant matter may not be returned to the field. Where manure from the fed animals is subsequently applied to the soil as fertiliser, differences in carbon content will depend on storage practices for the manure prior to application (Yamulki 2006) although some carbon lost during manure storage would have also been lost in field. In general, the removal of grass and failure to return subsequent manure to the field will reduce soil carbon sequestration.

2.8 Earthworm addition

Research has shown that soil aggregates formed by earthworms can protect carbon in soil from decomposition (Bossuyt et al. 2005) leading to longer residence times and theoretically improving soil carbon storage. Large scale commercial application or trials do not currently exist to support this as a management option, although it is worth noting as of interest for the future.

2.9 Fire

Burning as a management practice for grasslands exists as a method of vegetation and habitat control. The application of burning stubble and straw in Scotland is discouraged (Prevention of environmental pollution from agricultural activity: guidance[2]) while muirburn is permitted in line with the Muirburn code (NatureScot). The practice has been shown to influence carbon sequestration internationally (Pellegrini et al. 2017). Burning of biomass releases carbon dioxide and reduces the quantity of carbon available for accumulation in soil. Carbon left over may be more resistant to decomposition and have a longer lifespan and thus prove to be a longer-term addition to the soil carbon pool (a similar theory to biochar) but evidence that this would result in higher sequestration of carbon in Scottish grasslands does not exist. The burning of grassland can also accelerate succession and increase subsequent biomass accumulation however the evidence for this is based on succession to diverse plant species including warm season (C4) grasses which would not be suitable for managed Scottish grasslands. Overall, the evidence base does not suggest the application of burning, where compatible with permanent grassland, to be a proven method for increasing soil carbon sequestration in Scottish grassland soils.

2.10 Biochar

Biochar is charcoal produced from plant matter as a means of storing carbon removed from the atmosphere. It is produced through heating biomass without air to produce a stable, carbon rich product. Biochar amendments to soil for the purpose of increased soil carbon sequestration have been proposed as a potential negative emissions technology (Smith 2016). The application of biochar to grassland soils should increase the amount of carbon stored in those soils beyond that which would occur through conventional biomass addition (Woolf et al. 2010). Questions remain around the presence of contaminants, the sourcing of biomass and the impact on yield (Zhang et al. 2019). Biomass has been shown to provide additional benefits including yield increases and decreasing bioavailability of pollutants in some cases, although the evidence for these is mixed. A review of UK applications found overall there was no significant benefit or constraint to crop yield, but some benefits were present in individual trials (Hammond et al. 2014). This would suggest no yield penalty for using biochar for the purpose of carbon sequestration. In theory these could also prove pathways through which biochar could contribute to increasing soil carbon. Research suggests the prioritization of low fertility soils for maximum potential benefits of biochar application (Woolf et al. 2010). More research is needed on the effect of large-scale application in grassland and on the sourcing of biomass for this to be advisable. More research on the co-benefits to fertility could potentially provide incentives for application.

Overall, the evidence shows the potential for some practices to increase soil carbon sequestration in Scottish grassland soils. The evidence is stronger for practices which increase inputs into the soil either through increased biomass or through direct application. These pathways are simpler and easier to manipulate. Particularly strong evidence exists for the effect of grass type and non-synthetic fertiliser application on increased sequestration. These are already practiced to an extent but could be extended. For practices influencing the turnover of carbon already in soil (e.g., earthworm addition and reducing tillage) the evidence is less clear and more research to untangle complex interacting effects would be necessary.

2.11 What we do not know

The impact of mob grazing and other grazing rotation strategies on soil carbon storage is not fully understood. However, some theories suggest potentially effective carbon accumulation benefits. Untangling the multifactorial drivers of these impacts would be possible through well designed field/ lab trials, although quantification at scale would take time due to the speed of soil carbon accumulation. A better understanding of the effects of altering the duration and intensities of grazing on different sites could highlight techniques with the potential for carbon sequestration benefits.

It is still not possible to accurately quantify the impact of biodiversity on soil carbon sequestration in managed grasslands. While methods to enhance biodiversity are known, the impacts of improved biodiversity on carbon sequestration are multifactorial. Being able to calculate these impacts at scale might help highlight where these measures would be most effective and how they would contribute to increasing soil carbon storage.

The evidence for biochar application as a long-term scalable soil amendment for the increase of soil carbon in grasslands is incomplete. More information on the sourcing of biomass, economics of production and the effect on yield and contaminants would be beneficial.

We also found uncertainty on the impact of management practices on the hydrological export of carbon from soils (for example as dissolved organic carbon). This is of particular importance in upland soils and areas with high rainfall. A deeper understanding of the fate of this carbon would also be beneficial for determining the significance of hydrologically exported carbon to the GHG balance.

We found a lack of conclusive evidence for the following, and further research is required:

- the impact of compaction on grass yield and how this feeds into soil carbon accumulation.
- the interaction between practices and the spatial and temporal controls on individual practices
- The trade-off between non-soil greenhouse gas emissions caused by some of these practices and the potential benefit through soil carbon sequestration.

3. Model simulations

Our review of research highlights the benefit of increasing inputs into soil through changes to management practices. The application of soil models can give an idea of the impact this will have on total soil carbon storage in Scottish soils. For this project we simulated soil carbon sequestration in Scottish grassland soils using a carbon turnover model and data on Scottish soils to estimate how changes to quantities of biomass inputs might result in different quantities of carbon sequestered in soil. The simulations chosen to be run mimic the effects of certain management practices among the ones discussed in the first part of the report. We looked at changes in estimated soil carbon inputs as a proxy to investigate the effect of altering plant and manure inputs on soil carbon stocks and changes. We also investigate the impact of carbon removal as feed, and addition of carbon as manure on the soil carbon balance. This was done to consider effects of altering grazing intensity.

3.1 Background and approach

The following section will set out the results of the modelling work conducted to simulate the effect of management practices on the carbon content of Scottish soils. The section gives an indication of the impact of management changes on the sequestration of carbon in Scottish grassland soils. We use Scottish soil, management and climate data to simulate the turnover of carbon in Scottish soils using a well-tested carbon turnover model. The approach taken for the simulations is to simulate the effect of altering specific quantities of carbon input to the soil. The results of the simulations indicate the effects that changes in management practices could have on soil carbon storage across Scotland. We then link these back to the management practices discussed above. The goal is to help identify areas for future research and to guide policy and management of grasslands for increased carbon storage.

The modelling work uses the soil carbon model RothC (Coleman et al. 1996). RothC is a well-tested model designed for simulating the turnover of carbon in non-waterlogged soil. The model was run spatially for the soils of Scotland at a 2km^2 scale for 30 years. The model was set up using a consistent average climate to isolate the effect of management practices. Our approach was to highlight the impact of increasing inputs from plant matter and of altering the grazing intensity. This should give an indication of the benefits to soil carbon sequestration that can be achieved by changing certain management practices discussed in the first section of the report. It should be noted that these gains will not occur in perpetuity and will diminish as a saturation point is reached. The simulation results did not reach that point during the simulation period, but the same practices will produce smaller gains if applied over a longer period of time.

3.1.1 Basic model summary

The modelling work we completed was undertaken using the RothC model. The model has been widely used and validated including for simulating carbon turnover in UK grasslands (Jebari et al. 2021). The RothC model conceptualises carbon in soil as being comprised of different pools. These pools degrade at different rates producing carbon dioxide. The pools are representative and illustrate the variability of soil carbon residence time (Dungait et al. 2012). The rate of decomposition of each of these carbon pools is then further modified by environmental factors (temperature, vegetation cover and soil moisture). Litter inputs are added to the conceptual pools as the simulation continues, contributing to the overall soil carbon turnover. The model is driven by organic inputs to soil (e.g., grass litter), climate (temperature, precipitation and evapotranspiration) and soil properties (e.g., pH, texture, and soil carbon), and it simulates soil carbon content and greenhouse gas emissions over a prescribed period of time (from 1 year to centuries). Further details about the specific setup and function of the RothC model are found in the appendix 7.5.

3.1.2 Input data

Grazing intensity (Fig. 1) was calculated for the 2km^2 grid cells using the agCensus Digimap farm survey data (EDINA). For each grid cell, the grazing intensity was calculated by dividing the number of grazers (weighted for grazer size using the formula given in appendix 7.5) by the area of grassland in each grid cell. Plant input was derived from the net primary productivity (NPP), which, in turn, was calculated for Scottish grasslands using the Miami model (Lieth. 1975) by using long-term averaged climate data from CEH (Robinson et al. 2016 and Robinson et al. 2017). The estimated NPP was converted to plant residue by dividing it by two, to give surface dry matter. From this value, an amount was removed as consumed by grazers based on grazing intensity for grassland, and an amount returned as manure input. A full description of these calculations can be found in (appendix 7.5).

Soil input data was extracted from the Harmonised World Soil Database (Nachtergaele et al. 2010).

3.1.3 Simulations

Each simulation was conducted spatially on a 2km^2 resolution grid cell basis for Scotland for 30 years. A baseline simulation of Scottish soils was designed based on current stocking densities and soil data as described above. Carbon input to the soil was the dry matter input added to the manure input as calculated above. Carbon turnover was simulated under a long-term average climate condition for 30 years with consistent management.

Three scenarios were defined to simulate the effect of higher grazing density and grass productivity compared to current conditions. This has been achieved by changing the amount of plant (effect of grass productivity) and manure (effect of grazing density) inputs as shown in table2. The model was then run for 30 years for the baseline, as well as all scenarios; the change in SOC was calculated as the difference between the SOC at the end of the simulated scenarios minus the SOC estimated under the baseline conditions.

Scenario	**Plant matter produced**	**Grazer influence**
Baseline	100%	100%
Increase in grass productivity	110%	100%
Increase in grazing density	100%	110%
Increase in grass productivity and grazing density	110%	110%

Table 2. Changes made to simulation inputs from the baseline carbon input.

3.2 Simulation results and discussion

Figure 3 shows the modelled SOC changes after increasing grazing and/or grass productivity over a 30-year period. Increasing grassland productivity, compared to current conditions, leads to an average SOC increase of 1.8 t C ha^{-1} over a 30-year period (Fig, 3a), which, on an annual basis, is equivalent to 234.67 kg CO_2 eq ha^{-1} yr^{-1} (Table 3). SOC sequestration is higher where the climate conditions enable higher rates of photosynthesis; under these conditions, larger sequestration potential could be achieved under practices which will increase grassland productivity compared to baseline conditions. An example of this effect can be seen in the coastal regions (Figure 3A). On the other end, lower SOC sequestration rates are generally found in locations with higher elevation and in cooler areas, such as in the southern highlands and the western Cairngorms (Figure 3A).

In general, an increase in soil C was observed in areas with high NPP, such as in coastal areas, or in locations where average temperatures are mild. This is in part due to the method used, as a 10% increase was calculated from initial simulated grassland productivity. Therefore, a 10% increase in more productive areas would result in a larger overall increase than would occur in locations with smaller baseline NPP values. These relative changes feed back into the end results, although it is not certain whether potential gains through management practice changes would reflect this.

Increasing grazing whilst keeping grass productivity unaltered resulted in losses of carbon of -0.21 t C ha^{-1} on average (Figure 3B). On average, 25.67 kg CO_2 eq ha^{-1} yr^{-1} are lost when grassland productivity is increased compared to baseline conditions, which is equivalent to a 0.9% decrease in SOC (Table 3). The detrimental effect of grazing on SOC was higher in areas where grazing intensity was high. This can be found on the east of Scotland and the Borders (Figure 3B). The converse is also true, with lower values found on the west coast and highlands, where grazing intensities are generally lower. If the reduction in grazing intensity is enabled by converting more land to grazing elsewhere, the net effect will depend on the type of land-use that is being replaced by grasslands (Guo and Gifford, 2002). Our simulations suggest that soil carbon benefits are found in areas where the reduction in grazing intensity is the result of an increase in efficiency or a decrease in consumption. These findings are in agreement with previous studies (McSherry et al., 2013; Abdalla et al. 2018). In fact, Abdalla et al. (2018) also found that grazing at higher intensities was likely to result in higher losses of soil C; however, sites with warmer and drier climates were expected to show positive grazing impact on soil carbon sequestration.

Increasing both grazing and grass productivity leads to an SOC of 1.71 t C ha^{-1} on average (Figure 3C). However, the combination of these two practices has a mixed effect at spatial scale, with areas showing high potential for SOC sequestration, such as the north and the west coast, and others showing large carbon losses, such as the east coast and border regions. A key factor here was the initial grazing intensity, with SOC sequestration mainly being found in areas where increases in grazing intensity were taking place from a relatively low starting point. On an annual basis, the combination of improved grazing and grass productivity can sequester in the soil around 200 kg CO_2 eq^{-1} yr^{-1}, which is a 7.4 percent increase compared to current conditions (Table 3). The simulation results shows that in areas where grazing numbers were high, such as the east coast and borders (Figure 1B), an increase in grazing intensity would counteract the effect of an increase in grass productivity (Figure 3C). On the contrary, increasing productivity and grazing intensity in lower intensity areas resulted in the sequestration of additional carbon, which is mainly evident in the west coast and in the north of Scotland (Figure 3C). This finding highlights the importance of local interaction between grassland productivity and grazing intensity, and their effect on SOC sequestration. This supports the findings of Whithead (2020), which suggested that an increase in soil carbon may be attainable through improved management in grazed hill country grassland.

The results highlight the value of increasing carbon inputs to soil. Additional inputs lead to more carbon sequestered in the soil. This is beneficial as a climate change mitigation strategy, but also provides additional benefits, such as productivity increases for arable farmers, water storage enhancement (this can lead to reduced flood severity) and a reduction in soil loss through erosion (Blanco-Canqui et al. 2013). The review presented earlier in the report shows how productivity increases could be obtained through practices including the choice of grass species and application of fertiliser. The simulation setup ostensibly labelled these as productivity increases; however, these could be achieved through the incorporation of organic matter from external sources as well as through increases in productivity.

A variety of alternative sources of organic matter could be applied as input to the system, such as animal manure, crop residues, composted food waste, waste from paper mills/ timber yards, or biosolids like sewage sludge. The nutritional content of the added substances varies, as does the propensity for added carbon to remain stored in the soil (Marzi et al. 2020). Economic and ecological factors will also play a role in the choice of which substance to add, with the downstream impacts on water quality being particularly noteworthy. Judicious selection of the type and timing of organic amendments is critical and crucial to enable low impact application (Reetz et al. 2015).

A flat rate increase in productivity is representative rather than realistic, designed to show the impact of increases where they would occur rather than where increases are likely to occur. However, yield simulations for the UK from Qi et al. (2018) suggest that grass yield increases may be achievable through technology and management applications. The adoption of precision agriculture techniques may also provide new methods of enhancing grassland productivity across the UK (Higgins et al. 2019). The benefit of implementing these practices would have to be considered in the context of the environmental cost of application.

It is important to notice that the results presented here apply to soil carbon only. A full system balance was beyond the scope of this project but should be taken into consideration when assessing the environmental impacts of grassland management practices. For example, increasing grass productivity has a direct effect on livestock emissions which could be larger than the carbon stored in soil (Smith et al. 2016). Also, this report focused on mineral soils, as organic soils already have a high C content and should be preserved as a natural carbon resource. However, future work could include assessing restoration practices for damaged peatlands (Smith et al.2010) where potential for reducing soil emissions and/or increasing soil carbon sequestration is high (Nugent et al. 2018). Practices such as restoring water table depth and reducing extraction and burning have been shown to reduce emissions and/or increase carbon sequestration in peat soils (Marrs et al. 2019 and Evans et al. 2021). Given the potential benefit of carbon-rich amendments to soil, more work would be needed to understand the persistence of such organic materials in the soil and their different impacts on soil carbon and other soil properties. Interactions between the application of practices to increase soil inputs and other management practices applied to the site will play a role in the persistence of carbon added to the soil. Interactions between these would benefit from more research to highlight ways of improving the longevity of additional carbon sequestered in the soil.

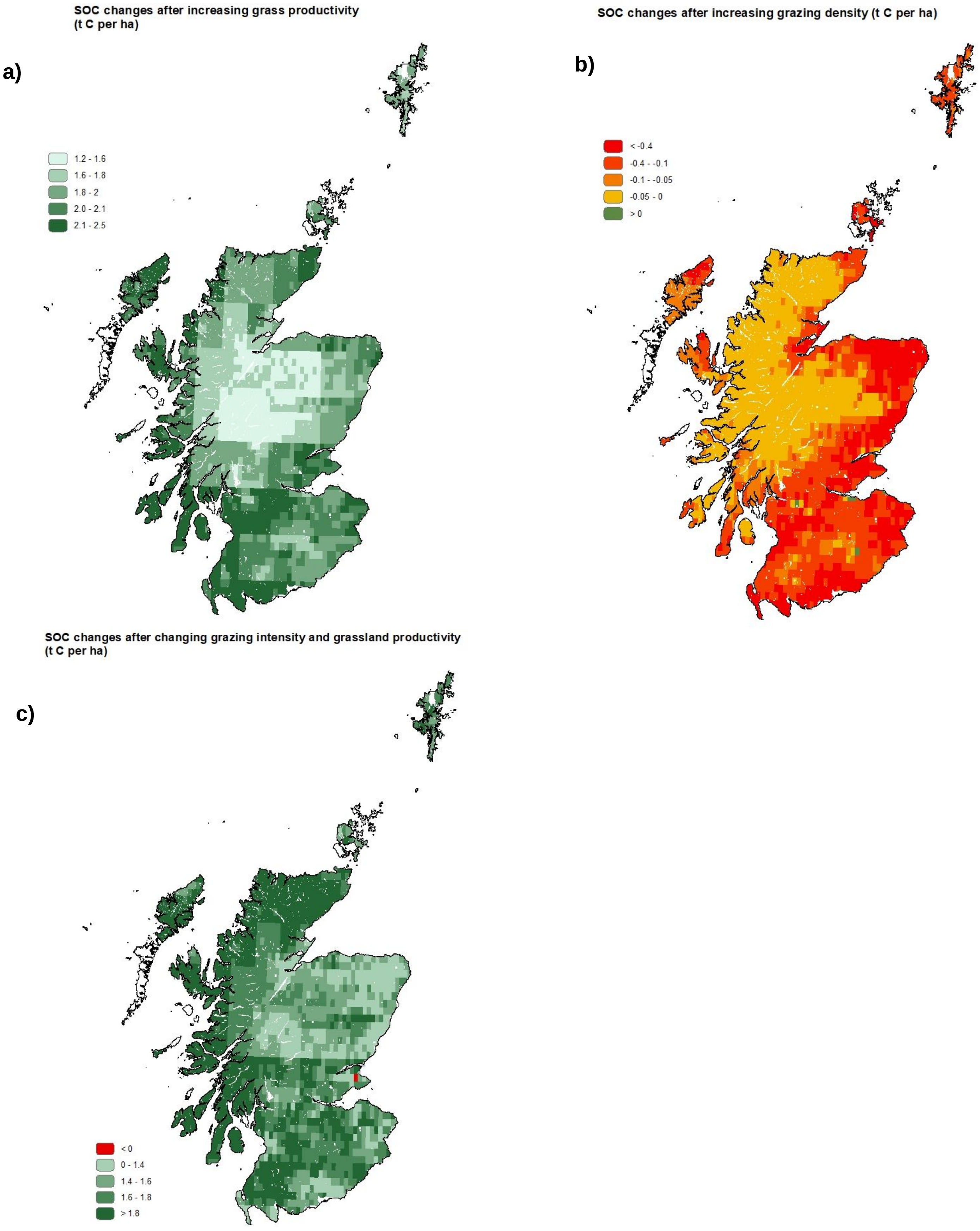

Figure 3: Modelled SOC changes (t C ha^{-1}) in mineral grassland soils to a soil depth of 30cm under different grassland managements. a) increase in productivity, b) increased grazing density), c) increased productivity and grazing density.

Scenario	SOC change over a 30 yr period ($t\ CO_2$)	Annual SOC change ($kg\ CO_2\ eq^{-1}\ yr^{-1}$)	Percentage SOC change
Increase in grass productivity	1.92	234.67	8.35
Increase in grazing density	-0.21	-25.67	-0.91
Increase in grass productivity and grazing density	1.71	209.00	7.43

Table 3. Mean SOC change for all management scenarios compared to baseline conditions.

4. Conclusions

The two pathways for improving carbon sequestration in Scottish soils are through influencing the processing of carbon within soil and altering the inputs of carbon to the soil. Of these, the manipulation of inputs is more straightforward and easier to influence.

The benefit of increased carbon sequestration in soil through grazing is most realizable when grazing occurs on soils previously depleted of carbon. These are likely to be soils previously used for arable agriculture for significant periods of time. Scotland has high quality soil carbon maps which would help identify areas with low levels that would benefit the most. Grazing of arable soils which have been depleted of carbon could play a role in recovering lost carbon, but more research is needed to quantify the effect of land-use changes to grasslands in Scotland.

Reducing stocking densities from high grazing intensity practices may lead to increases in soil carbon sequestration, but this will result in lower livestock production for the same unit area. Therefore, the economical trade-off between the potential production loss and the potential soil carbon sequestration should be taken into consideration when managing grazing intensities.

As soils may not act as perpetual carbon sink, but instead reach new higher equilibriums of carbon storage with selected management practices, it is important to focus on protecting carbon in highly organic soils.

Grassland that is poorly drained would be a good target for reduced grazing intensity measures, as these soils are likely to be less resistant to poaching damage caused by grazers' hooves which can lead to a reduction in biomass production.

Selection of methods (Table 2) to maximise grass yield will help increase soil carbon storage over the long term. This may include the selection of grass mixtures best suited to location (particularly mixtures including nitrogen fixers where commercially viable) and adequate fertiliser applications. In specific cases this may include liming or irrigation, but these are likely to be temporally and spatially limited. The applicability? of these practices will be determined by the costs of application and should also account for environmental costs of their pursuit.

Fertilising grass to provide adequate nutrient supply will lead to an increase in soil carbon sequestration. The application should be done in ways which minimize losses of fertiliser through leaching. The application of non-synthetic fertilisers is preferable as the carbon increase will be stronger. Decisions on using synthetic fertiliser specifically for the sequestration of carbon must consider the environmental cost of fertiliser production. This includes significant greenhouse gas emissions which may counteract any soil carbon benefit where fertiliser is inefficiently applied.

Replacing synthetic fertiliser with non-synthetic fertiliser will lead to stronger increases in carbon sequestration. However, this will not apply across the whole of Scotland due to supply limitations. Sources of additional organic material hold the largest potential for increases as most farm manure is already applied on-site. Care should be taken with the storage of manure prior to application to limit greenhouse gas emissions. Additional research on potential alternative sources of organic material would be beneficial. More research on the best use of organic residues would be also of benefit. This should consider sources of organic material and the benefit of uses as compost for soil amendment and as input for biochar production.

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Appendices

5.1 Review methods

Google scholar and web of science searches were performed using the following search terms:

- (grassland or grazing or pasture or prairie) and Carbon and Soil
- Sequestration and soil and (grassland or grazing or pasture or prairie)
- Greenhouse gas emissions or climate change and (grassland or grazing or pasture or prairie)

We took the first 100 results from each set of terms, discarded duplicate results and scanned titles and abstracts for relevance to the study. The articles provided the base knowledge for the review presented in section 1 of the report and guided further reading on the subject where information on subjects was insufficient.

5.2 Stakeholder engagement workshops

Our stakeholder engagement workshops were conducted online between Date and Date. The pool of attendees was drawn from participants of the ClimateXChange (Agriculture and climate change strategic stakeholder group) and were invited to take part in a series of workshops. The workshops took the form of a presentation followed by questions about Scottish grassland management. Participants were selected to cover farmers, farm advisors, government, and industry. The workshops provided valuable insight into the practical application of different grassland management practices on Scottish grassland, the scope of practices currently applied and the motivation behind selecting specific management practices.

5.3 Construction of table 2

Table 2 shows management practices and their impact on the sequestration of carbon in Scottish soils. The table also shows the applicability of these practices at scale and the strength of evidence for the impact on soil carbon sequestration. The table is specific for Scottish application and would look different for other contexts. Strength of evidence is split into three levels: strong evidence for the effect, contrasting/ weak evidence for the effect and no evidence for the effect. The applicability is split into three levels: widely applicable, context specific applicability and not yet applied at scale.

5.4 Model description

The RothC model is designed to model the turnover of organic carbon in non-waterlogged topsoils. It functions on a monthly timestep. RothC works by splitting soil organic carbon into five pools (four active and one inert). The turnover of carbon in each pool occurs at rates governed by the turnover rate constant of that pool modified by environmental factors. Carbon moves between these pools as products of decay. Active soil carbon pools also produce CO_2 at distinct rates as they decay. A detailed description of the RothC model can be found here: https://www.rothamsted.ac.uk/sites/default/files/RothC_guide_WIN.pdf

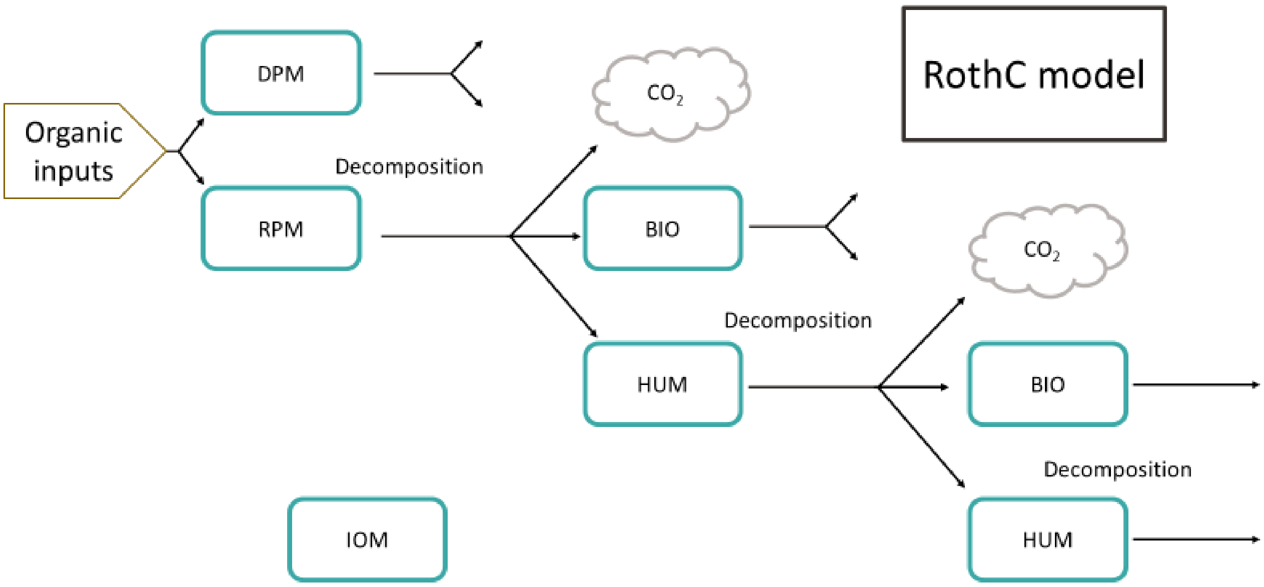

Figure 4 : Schematic showing the structure of the RothC model. Turquoise boxes represent carbon pools where BIO = Biomass, HUM = Humus DPM = decomposable plant material and RPM = resistant plant material. Arrows indicate the decay of organic material within the pools this moves carbon between soil pools producing CO_2.

5.5 Model setup

The Plant input for the model was simulated using weather data to simulate NPP using the NPP which was calculated spatially for grass in Scotland using the Miami model (Lieth. 1975) with long term average climate input data from the CEH (appendix 7.5). This value for NPP was converted to plant residue by dividing NPP by two to give surface dry matter. From this an amount was removed as consumed by grazers based on grazing intensity for grassland and an amount returned as manure input. NPP simulations were calculated using R version 4.1.0.

RothC was set to run for a 30 yr period for the top 30 cm of soil using a consistent climate dataset based on long term average data. Simulations were performed using the RothCModel function in the SoilR R package (Sierra et al 2012) using R version 4.1.0. The size of the inert organic matter pool was calculated using pedotransfer functions using methods from Falloon et al. (1998) and Weihermueller et al. (2013).

Grazing uptake was calculated assuming a consumption of 15kg dm per day per livestock unit (REF1). This was multiplied by 365 to get a yearly input value. The carbon contained in this was calculated by multiplying the yearly total by the fraction carbon of dry grass (0.43). This was multiplied by the number of livestock units per hectare for each gridcell.

$$Crem = G * Dg * Cgra$$

Where Crem is the yearly carbon consumed as grass grazed by the grazers (t) G is the yearly grazing uptake of grass per livestock unit (tonnes fresh weight), Dg is the dry matter fraction of grass and Cgra is the fraction of dry grass mater which is carbon.

This quantity was subtracted from the NPP in each gridcell. For manure input we assume 50kg of fresh manure per livestock unit per day and a 25% dry matter yield of that manure (Williams et al. 2016). We also assume a carbon content of the dry matter of 34.6%. To calculate input from manure the following equation was used

$$Cman = M * D * Cfrac$$

Where Cman is the yearly manure input per livestock unit, D is the dry matter fraction of the manure (0.25) and Cfrac is the carbon content of the manure (0.346). This was subsequently multiplied by the number of livestock units per hectare and adjusted for the grazing treatment for each simulation.

5.6 Data sources

Climate data was obtained from the Climate, Hydrological and Ecological research Support System meteorological dataset (Robinson et al. 2016 and Robinson et al. 2017) which is publicly available through CEH's Environmental Information Platform[*].

Data on grassland are and number of grazers were obtained from EDINA (2021)[**].

Soil input data for RothC was obtained from the Harmonised world soil database (Nachtergaele et al. 2010) and was accessed using the hwsdr package[**].

[*]https://eip.ceh.ac.uk/

**https://digimap.edina.ac.uk/agcensus

[***]https://cran.r-project.org/web/packages/hwsdr/hwsdr.pdf

climate X change

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