Research & Evidence

The Wildlife Trusts

Reducing Greenhouse Gas Emissions from Conservation Grazing: a literature review and exploration of options

Jennifer Ramsay, Helen Wheeler, Christopher J. Sandom

Reviewed by: Joseph W. Bull, Nigel Doar

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Summary

Large herbivores are generally considered to be 'ecosystem engineers', performing important ecological roles through their impacts on vegetation, nutrient cycling, and food webs *(Bakker et al., 2016; Danell et al., 2006; Frank et al., 2018)*. There are multiple processes through which large herbivores can enhance biodiversity and habitat heterogeneity (through grazing, browsing, trampling, seed dispersal, wallowing and defecation). In the UK, many habitats and scarce species are maintained through managed conservation grazing with large herbivores. However, habitats and biodiversity are also threatened by climate change. In recent years there has been increasing recognition that by modifying ecosystems, large herbivores may exert significant impacts on climate feedback and forcing effects *(Cromsigt et al., 2018; Sandom et al., 2020)*, as well as contributing to Greenhouse Gas (GHG) emissions through enteric methane emissions and excrement.

In the UK, conservation grazing with large herbivores is dominated by cattle and sheep. The Wildlife Trusts have more than 10,300 cows and around 20,000 sheep grazing their nature reserves, compared to just 870 horses, 110 goats and 30 pigs (*Nigel Doar, The Wildlife Trusts, personal communication*). The carbon footprint of these animals adds up to around 17,000 tonnes of CO_2 equivalent every year for The Wildlife Trusts alone (*The Wildlife Trusts, 2022*). Identifying and trialling appropriate mitigation strategies could help to reduce the carbon footprint of grazing whilst maintaining biodiversity benefits. Successful strategies could generate substantial reductions in GHG emissions from livestock, particularly if adopted widely across the conservation sector (within the UK and beyond) and in agricultural livestock grazing.

In this report, we examine the literature relating to GHG emissions and carbon dynamics in the context of livestock grazing. We review the evidence for a variety of possible measures to reduce GHG emissions from conservation grazing and compare them with the potential biodiversity and habitat impacts of these measures. As the evidence base is patchy, with many gaps in the research, we have focused our recommendations on measures with the most evidence. This report is a starting point for further research, discussion, and trials to allow recommendations to be refined and improved based on experience and field trials.

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KEY INFORMATION

This paper is the result of work carried out in 2022, by Jennifer Ramsay, Dr Helen Wheeler and Dr Chris Sandom, from the Wild Business consultancy, under contract to the Royal Society of Wildlife Trusts (RSWT).

It presents a systematic review of published evidence concerning the relationship between grazing animals, biodiversity and greenhouse gas emissions.

It has been published by The Wildlife Trusts as part of a strategic commitment to generate, share and use good evidence, and to be open about the data, evidence and reasoning that underpin the federation's decisions, policies and actions.

This paper has been published as part of a series launched in 2025, to fulfil a commitment made in The Wildlife Trusts' Collective Framework on Data, Research & Evidence, a copy of which can be obtained by e-mailing evidence@wildlifetrusts.org

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1. Foreword

It is widely acknowledged and arguably undeniable, that continuing climate change driven by human activity – especially the burning of fossil fuels – is a major contributor to ecological change and associated biodiversity loss around the globe. At the same time, the loss of and damage to wildlife-rich, ecologically functioning natural systems caused by human activity of all sorts often results in the release of additional carbon dioxide and other greenhouse gases, which contribute further to climate change. Or they undermine nature's ability to stabilise the climate for itself, by damaging and disrupting the natural processes that are normally responsible for transferring carbon from the air into living matter, soils, sediments and (given sufficient time) onward into rocks and other minerals. In short, the climate crisis and the nature crisis are inseparable; to solve one, we must solve both together. And it is vital that we do so, for nature and wildlife and also for human beings – for ourselves. Failing to address either will have very serious consequences across the board.

Consequently, it's perhaps not surprising that the protection, maintenance and restoration of functioning ecosystems are being widely recognised as essential components of future efforts both to reverse the decline in global biodiversity and to restrict global warming to below 1.5oC. Nature conservation action of this sort brings enormous value to the many species of wildlife that have been and are being driven towards extinction by other human activity and also to the wider ecological communities of which they are a part. But more than that, it is vitally important and incredibly valuable to human society and the economies on which its health, wealth and sustainable wellbeing depend.

This was recognised by The Wildlife Trusts as a central part of the federation's new collective strategy for 2022 to 2030. The strategy committed the 46 individual Wildlife Trusts and the federation's central charity (the Royal Society of Wildlife Trusts – RSWT) to achieving three goals:

- nature in recovery – including at least 30% of the UK's land and seas being actively managed for nature's recovery;
- meaningful action – including at least 1 in 4 people taking meaningful action for nature and climate; and
- nature-based solutions – including nature playing a central and valued role in helping to address local and global problems, such as supporting society's health and wellbeing, stabilising the climate, managing water resources sustainably and improving food security.

Unfortunately, right at the heart of this is a fundamental conflict between The Wildlife Trusts' work to protect, maintain and restore wildlife-rich natural systems, and the federation's intention to actively tackle climate change. In particular, the work of our staff, volunteers, contractors and partners in delivering nature conservation generates greenhouse gas emissions. And typically, the more nature conservation work we deliver (especially through land management), the more energy it requires and so the more emissions it generates… ironically leading to a need for more nature conservation work as global temperatures rise and biodiversity declines. The Wildlife Trusts have committed themselves to doing what they can to break this linkage – to delivering nature's recovery while also contributing to a more stable climate. In practice, this means being more explicit about the relationship between the work we do and the emissions generated, and proactively making decisions that lead to reduced greenhouse gas emissions and an increased amount of greenhouse gases being removed from the air and put into long-term natural storage, as well as delivering gains for wildlife and the natural world.

Individual Wildlife Trusts have variously kept an eye on their greenhouse gas emissions and tried to keep them down, for many years. A lot of climate-conscious pro-nature action has happened across the federation, but it has been ad-hoc, often opportunistic and inconsistent. Good practice (some of it ground-breaking) has happened in some places and not others. To meet the urgency of the climate crisis, the Wildlife Trusts are now taking a more pro-active, strategic approach to this aspect of our work and addressing it more effectively as a collective.

So: in 2020, The Wildlife Trusts carried out their first combined assessment of the federation's carbon emissions (for the previous year – 2019). This initial assessment estimated that during the 2019-20 financial year the Wildlife Trusts emitted greenhouse gases equivalent to nearly 26,000 tonnes of CO_2. Fully 68% of this (17,500 tonnes) came from the livestock used for conservation grazing… most of that from the thousands of cattle that graze on Wildlife Trust land each year. On the face of it, though these are small emissions compared to many other organizations and many other sectors, this poses a direct challenge to the way in which The Wildlife Trusts and many others deliver conservation land management.

The Wildlife Trusts are working to reduce emissions across the whole range of sources within our operations. But the challenge of delivering conservation land management across the 97,000 ha of land for which the federation has responsibility, in a way that makes the biggest possible contribution to both our biodiversity and climate ambitions, is very significant. As one of Europe's biggest nature conservation organisations and managers of one of the UK's biggest landholdings, The Wildlife Trusts collectively have a significant role in developing and demonstrating solutions to this challenge.

In many places, grazing animals are an integral part of the natural system that we are working to protect or restore. Livestock – often cattle and sheep – shape the ecosystem that they live within, by eating and trampling vegetation, moving nutrients around, creating seedbeds, transporting propagules, affecting soil structure and in numerous other ways. So they are a widely used and generally accepted part of conservation land management, that is highly valued and normally cost effective. After all, the use of domesticated cattle in maintaining traditional grazing marsh, meadow or heathland, or in maintaining the structural diversity of scrubland and woodland edge, in many ways substitutes for the impacts that would result from wild grazing animals (such as aurochs) if they hadn't long-since been driven to extinction. How should you approach something like this, to achieve what's right for the natural world and right for the climate, without tying yourself in knots? Particularly in the face of many practical challenges and technical uncertainties.

Beyond The Wildlife Trusts, many other land managers – either organisations and individuals – explicitly manage land for nature conservation. Land managers such as Natural England, RSPB or the National Trust, or those with a stronger emphasis on commercial livestock farming, who farm land of high conservation value, are facing the same issue. How can you reduce the greenhouse gas emissions generated by the grazing animals that are a central part of restoring or sustaining the wildlife-rich habitats that they graze? Is this possible without undermining the contribution grazing makes to our conservation land management efforts? Can it be done without displacing environmental impacts elsewhere or creating unforeseen harmful consequences? Can we achieve our conservation goals – can nature recover – in a way that generates substantially fewer greenhouse gas emissions, removes significantly more greenhouse gases from the air and also maintains and restores the UK's wildlife-rich natural ecosystems? If so, what role should wild and domestic grazing animals play in that?

When The Wildlife Trusts started to look for credible evidence to inform our decision-making, we found that it wasn't readily accessible, it was often complex, confusing and/or contradictory and so difficult to access, interpret and apply. More-so when a large part of the most readily available published material appeared to relate very strongly to the question "how can we produce as much edible animal protein as possible per kg of methane emitted in its production?", rather than "how can grazing animals contribute most effectively to the protection, maintenance and restoration of the UK's natural environment while minimising associated emissions of greenhouse gases?". Individual pieces of evidence could be identified and used to support different (often conflicting) views, but it was clearly not easy to arrive at well informed, soundly based practical approaches that drew consistently from a coherent body of supporting evidence of direct relevance to the UK.

A group of Wildlife Trusts, represented by a variety of individual staff and volunteers, came together in 2022 to start the process of unravelling this issue, with the support of staff from the Royal Society of Wildlife Trusts (RSWT). A number of expert land managers, conservation grazing specialists, ecologists and others with a direct interest in this commissioned a group of researchers from Anglia Ruskin University, the University of Sussex and the University of Oxford (working through the Wild Business consultancy) to map the available evidence, to review the literature and produce some initial materials that could be used to give us a better understanding of the interaction between grazing animals and the natural systems of which they're a part (including their contribution to global warming and climate change). It was intended to start our evidence-led journey towards more climate-friendly conservation land management.

This report is a composite output for this initial (fairly limited) project. As expected, it doesn't, in itself, propose any absolute sure-fire winners. It doesn't conclude that "if you do x, y and z, you'll immediately (and definitely) achieve double the conservation impact with half the greenhouse gas emissions". But it does bring together a broad, credible and relevant evidence-base in a way that is relatively easy to navigate and interrogate. It does identify some obvious practical steps and approaches to conservation grazing that would be worth putting in place or exploring further. It highlights the potential for mixed livestock herds including horses and pigs to achieve similar conservation outcomes with significantly fewer greenhouse gas emissions than using cattle or sheep alone. It does start to generate insights (some of them surprising) into where solutions might lie. It also unearths and clarifies a number of additional barriers, uncertainties and questions that may merit further exploration. And it starts the process of change.

A second stage of the project will take this initial output and develop more polished, more easily accessible materials from it, and will share them more widely. And a third phase is expected to take some of the proposals and emerging insights as the starting point for further exploration, including testing their application in practice and generation of further evidence. In the meantime, we're happy to share this initial project output as a contribution to the discussions and debates that many are having. We hope it will help everyone to get a little closer to achieving both nature's recovery and a stable climate.

Nigel Doar
Head of Science & Research
The Wildlife Trusts

2. Executive Summary

Conservation grazing has multiple potential benefits for biodiversity and habitat management. However, large herbivores used in conservation grazing are associated with high greenhouse gas (GHG) emissions, particularly methane and nitrous oxide. In an assessment of the total GHG emissions from all of their operations, The Wildlife Trusts found that around 68% of their emissions were estimated to come from conservation livestock (The Wildlife Trusts, 2022). As a first step towards reducing these emissions, this report aims to identify strategies with the potential to reduce GHG emissions of conservation livestock without detrimental impacts on achieving conservation grazing goals.

2.1. Report Format

The report is presented in three main sections with accompanying Annexes. Sections 1 and 2 are detailed reviews and Section 3 summarises the key findings and recommendations.

Section 1: Greenhouse gas emissions and conservation grazing
Section 1 is a systematic literature review that explores the scientific literature on large herbivores and greenhouse gas fluxes within the context of UK livestock grazing. It focuses on the influence of livestock species and breed on GHG emissions, and explores the potential impacts of using targeted grazing, methane-reducing supplements, reducing livestock numbers, or changing grazing season. This is an in-depth assessment.

Section 2: Conservation grazing and biodiversity outcomes
Section 2 provides an overview of the various purposes for which conservation grazing is used in the UK context. It summarises the conservation impacts of different livestock species and the primary goals of conservation grazing. This section is based on evidence from literature, conservation websites, and staff feedback from a workshop conducted with The Wildlife Trusts.

Section 3: Reducing GHG emissions while achieving conservation goals
Section 3 summarises the key recommendations and brings together sections 1 and 2 to identify management options that are most likely to reduce GHG emissions without negatively impacting biodiversity and habitat goals.

Annexes: The Annexes present detailed information from the literature review in visual formats, including Evidence Maps (displaying gaps and clusters in the evidence base) and Conceptual Diagrams of the key processes underlying herbivore impacts on GHG fluxes and carbon dynamics.

2.2. Recommendations:

Section 3 contains an outline of the key recommendations from this report. Based on current evidence, the management measures most likely to reduce GHG emissions whilst maintaining biodiversity and habitat benefits are:

- Change species composition to reduce cows and sheep and proportionally increase equines (horses, ponies and donkeys) and pigs.
- Use mixed herds where possible (incorporating equines and pigs as well as cattle, sheep or goats) to allow proportional reductions in cattle and sheep whilst maintaining similar grazing impact and enhancing habitat heterogeneity.
- Reduce livestock numbers and combine this with targeted grazing approaches to allow equivalent grazing impact from smaller herds.
- Where cattle and sheep are deemed essential for conservation goals, trial novel approaches to administer methane-reducing supplements (such as Bovaer® and UK seaweeds).

2.3. Research Gaps

There are other measures that could potentially reduce GHG emissions, but where the evidence base is insufficient to make recommendations. This includes the use of wild or novel species (such as bison, elk, and water buffalo) for which the evidence on GHG emissions is currently insufficient. The evidence on changing grazing season or using mowing and cutting to replace grazing was also insufficient to make recommendations. The existing evidence on these measures is discussed in Section 1, but we recommend further research before confident conclusions can be drawn.

There is also a paucity of evidence specific to GHG emissions from conservation grazing. Most evidence (including IPCC estimates) relates to agricultural grazing in lowland improved grassland. Further field studies would be required to assess the extent to which GHG emissions vary between habitats and to provide emissions estimates specific to conservation habitats.

Despite the gaps and caveats in the data, there are some areas for which the evidence is sufficiently robust and consistent to draw confident conclusions. In particular, there is good evidence that emissions from equines (horses, ponies and donkeys) are substantially lower than cattle, sheep and goats for similar levels of grazing (with the potential for 8-fold reductions in emissions).

2.4. Next Steps

The recommendations in this report are based on the evidence currently available. They have not yet been trialled in conservation grazing to assess the biodiversity impacts and GHG emissions of alternative options. There are likely to be considerable practical barriers to implementing these measures, which will vary from site to site. We therefore recommend the following steps to help implement and monitor these measures. Feedback and reporting from site managers will be fundamental to assessing the effectiveness of these measures and refining and targeting recommendations for different habitats and conservation goals.

Identifying Barriers and Solutions:

1. Conduct further research to identify barriers to implementing these measures (such as interviews and workshops with site managers representing a variety of habitats).
2. Identify Case Studies of sites where similar measures have already been implemented.
3. Conduct pilot studies at a number of sites representing different habitats. Use feedback and experience from the pilot sites to inform guidelines for other sites.
4. Create an ongoing feedback system to allow site managers to share their experiences of implementing these measures (challenges, solutions and impacts).

Monitoring Impacts:

5. Implement pilot studies at a number of sites to assess the GHG and biodiversity impacts.
6. Establish shared protocols for ongoing monitoring and reporting. Standardised monitoring systems would allow site data to inform academic research and strengthen the evidence.
7. Collaborate with academic researchers to address the research gaps on GHG emissions from conservation grazing. This may, for example, involve field studies to compare emissions from conservation grazing (in various habitats) with emissions from agricultural grazing.

3. Acknowledgements

Nigel Doar from The Wildlife Trusts provided detailed feedback and suggestions on an earlier draft of this document, for which we are very grateful. We are also grateful to site staff and managers at The Wildlife Trusts for providing us with data on their grazing operations and assisting with this report through workshop participation. We would like to thank Dr Thomas Ings for his contribution to the concepts and Protocol for the Systematic Map. We would also like to thank Russell Stevens, Edward Imber, Julian Flowers and David Hopkinson for their assistance with literature screening, coding and data visualisations.

4. Glossary and Abbreviations

Dry Matter Intake (DMI): DMI is the quantity of food intake excluding its water contents (usually measured as kg per day). This is often used in studies of enteric methane emissions to estimate emissions per DMI.

Enteric Methane Emissions: Methane that is produced during digestive processes by microbes in the gut. It is emitted when animals burp.

Global Warming Potential (GWP): GWP is used to compare the relative warming impacts of different greenhouse gases. It is based on the amount of energy absorbed by one tonne of the greenhouse gas compared to one tonne of carbon dioxide over a given time period. There are different versions of GWP (e.g. GWP20, GWP100 and GWP*) which account for longevity of gases in the atmosphere in different ways.

Greenhouse Gases (GHG): Gases that contribute to the greenhouse effect by absorbing infrared radiation. The main GHGs considered in this report are carbon dioxide, methane and nitrous oxide.

Livestock Units (LUs): A standard measure used to compare different livestock categories based on feed requirements. The standard measure is usually the equivalent of one adult cow. Other livestock categories are allocated units according to their feed intake in comparison to one adult cow.

5. Introduction

5.1. Large herbivore impacts on greenhouse gases

Large herbivores are generally considered to be 'ecosystem engineers', performing important ecological roles through their impacts on vegetation, nutrient cycling, and food webs (Bakker et al., 2016; Danell et al., 2006; Frank et al., 2018). There are multiple processes through which large herbivores can enhance biodiversity and habitat heterogeneity (through grazing, browsing, trampling, seed dispersal, wallowing and defecation). In the UK, many habitats and scarce species are maintained through managed conservation grazing with large herbivores. However, habitats and biodiversity are also threatened by climate change. In recent years there has been increasing recognition that by modifying ecosystems, large herbivores may exert significant impacts on climate feedback and forcing effects (Cromsigt et al., 2018; Sandom et al., 2020), as well as contributing to Greenhouse Gas (GHG) emissions through enteric methane emissions and excrement.

In the UK, conservation grazing with large herbivores is dominated by cattle and sheep. The Wildlife Trusts have more than 10,300 cows and around 20,000 sheep grazing their nature reserves, compared to just 870 horses, 110 goats and 30 pigs (Nigel Doar, The Wildlife Trusts, personal communication). The carbon footprint of these animals adds up to around 17,000 tonnes of CO_2 equivalent every year for The Wildlife Trusts alone (The Wildlife Trusts, 2022). Identifying and trialling appropriate mitigation strategies could help to reduce the carbon footprint of grazing whilst maintaining biodiversity benefits. Successful strategies could generate substantial reductions in GHG emissions from livestock, particularly if adopted widely across the conservation sector (within the UK and beyond) and in agricultural livestock grazing.

In this report, we examine the literature relating to GHG emissions and carbon dynamics in the context of livestock grazing. We review the evidence for a variety of possible measures to reduce GHG emissions from conservation grazing and compare them with the potential biodiversity and habitat impacts of these measures. As the evidence base is patchy, with many gaps in the research, we have focused our recommendations on measures with the most evidence. This report is a starting point for further research, discussion, and trials to allow recommendations to be refined and improved based on experience and field trials.

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Section 1: Greenhouse Gas Emissions and Conservation Grazing

Chapter Authors: *Jennifer Ramsay, Helen Wheeler, Christopher J. Sandom*
Chapter Reviewed by: *Joseph W. Bull and Nigel Doar*

6. Introduction

6.1. Conservation grazing and greenhouse gases

Conservation grazing has multiple potential benefits for biodiversity and habitat restoration (see **Section 2**). However, the impacts of conservation grazing on greenhouse gas (GHG) emissions and carbon stores are complex and under-researched. Large herbivores are associated with high GHG emissions, particularly methane and nitrous oxide. They can also influence carbon storage in soils and plant biomass. Multiple factors could influence the magnitude of GHG emissions from conservation livestock, including species and breed, habitat type, soil type and diet. Whilst these factors increase the complexity of estimating GHG emissions, they also provide potential mitigation opportunities in situations where these factors can be adjusted to reduce emissions. This requires sufficient understanding of the underlying processes that influence emissions and how adjustments to grazing management could alter these processes.

In an assessment of the total GHG emissions from all of their operations, The Wildlife Trusts found that around 68% of their emissions (17,000 tonnes CO_2 equivalent) were estimated to come from conservation livestock (The Wildlife Trusts, 2022). As a first step towards reducing these emissions, this report aims to identify strategies with the potential to reduce GHG emissions of conservation livestock without detrimental impacts on habitats and biodiversity. This section of the report focuses on GHG emissions from grazing livestock through an in-depth review of the scientific and grey literature. Details of the search strategy used to identify relevant literature is outlined in **Annex 1**, which also includes analysis of research gaps and clusters.

6.2. Measuring greenhouse gas emissions in conservation grazing

Throughout this report, we will refer to different ways of measuring GHG emissions from livestock. This reflects the diversity of the literature, with different studies reporting emissions relative to different measurement units. Here we provide a brief explanation of the different measurement units and why they are each important in different contexts.

Food Production: When livestock are primarily grazed for food production, emissions per unit of produce are highly relevant (e.g. g CH_4 per kg of meat or milk). Reducing total emissions requires mitigation measures that focus on reducing emissions for each unit of food produced. **Note**: There is also the wider context of consumption levels (sufficient overall GHG reductions will require substantially lower consumption of animal-based products). However, this report focuses on mitigation of livestock emissions in a grazing context and does not address the role of consumption patterns, which is reviewed in other publications (Benton et al. 2021; Garnett et al. 2017).

Conservation grazing: When the sole purpose of grazing is habitat and biodiversity conservation, emissions per head of livestock, per hectare of land, and per unit of grazing impact are more important. To quantify these, the most appropriate units are emissions per head of livestock (which can be totalled to estimate emissions per herd or land area) or emissions per Dry Matter Intake (DMI) (this is emissions per unit of food intake by each grazing animal). Assuming that equivalent grazing impact requires a similar level of DMI, this can be used to assess which livestock species are likely to release the lowest emissions for equivalent grazing impact (with the caveat that species also vary in food selectivity, so grazing impact will be similar in quantity for equivalent DMI, but not identical in vegetation impacts).

Conservation AND food production: In many cases, conservation livestock are supplied by local graziers and are used for both conservation and food production. This will require a case-by-case assessment as to whether emissions per head or per unit production are more appropriate for The Wildlife Trusts' carbon accounting. Where sufficient data is available, it would be worth estimating both.

This Review: For the purposes of this review, we focus on emissions per head and per unit DMI as these are most appropriate to the conservation grazing context. Where possible we have also included data on emissions per unit production for comparative purposes.

BOX 1: The Wildlife Trusts' Carbon Calculator

The Wildlife Trusts calculate GHG emissions from livestock using a bespoke methodology tailored to conservation grazing. Due to substantial differences between management of agricultural livestock and conservation livestock, agricultural calculators designed to estimate livestock emissions (such as the Farm Carbon Calculator) are only partially applicable to conservation grazing. For this reason, The Wildlife Trusts have developed their own calculator to provide conservative, evidence-based estimates for GHG emissions and carbon sequestration relevant to a variety of UK habitats (N. Doar, personal communication, Nov. 2022; and Thom and Doar, 2021). For livestock emissions, the calculation is based on the total number of each livestock category listed in the UK Greenhouse Gas Inventory (Brown et al. 2022) and the proportion of the year they spend on land managed by The Wildlife Trusts. Emission factors from the UK Greenhouse Gas Inventory are used to convert these figures into estimated enteric (digestive) methane emissions. Other livestock-related GHG emissions (e.g. from waste management and feed) are not included as they are less applicable in conservation grazing.

7. GHG sources, sinks and levers of change: an overview

7.1. Key sources and sinks

There are multiple sources and sinks for greenhouse gases (GHG) in the context of conservation grazing (**Table 1**). Each GHG can be influenced by a wide variety of habitat and management factors. **Annex 2** provides a detailed series of conceptual diagrams and summaries of key processes driving fluxes of the three main GHGs in livestock grazing (CO_2, CH_4, and N_2O).

Table 1: Key Sources and Sinks of Greenhouse Gases in UK conservation grazing.

Greenhouse Gases (Sources)		
Greenhouse Gas	Key Sources	Global Warming Potential (GWP)
CH_4 (methane)	Enteric methane; manure emissions; soil emissions	27.2 x CO_2e
CO_2 (carbon dioxide)	Respiration of organisms (above- and below-ground)	1 x CO_2e
N_2O (nitrous oxide)	Dung and urine emissions	273 x CO_2e
Carbon Stores (Sinks)		
Carbon Store	Key Stores	Global Warming Potential (GWP)
Soil carbon	Vegetation decomposition; manure; soil organisms	Negative GWP
Above-ground biomass	Vegetation (above ground); other organisms	Negative GWP
Below-ground biomass	Vegetation (roots); soil organisms	Negative GWP

7.2. Levers of change

Within these processes we have identified 'levers of change' that could reduce emissions by adjusting management practices. These levers can be categorised as changes in:

- Stock (livestock species, breed or age structure of herd)
- Timing (season and duration of grazing)
- Intensity (herd density or stocking rate, grazing frequency, and targeted grazing)
- Management (supplements, breeding, and other interventions)

Some factors that influence GHG emissions cannot be changed by land managers (such as rainfall, altitude, air temperature and soil type). There are also factors that could potentially be changed but may not be desirable changes due to habitat priorities (e.g. vegetation type and water levels). This report focuses on 'levers of change' that could be adjusted by land managers, whilst also acknowledging the high variability in site-specific conditions that can influence GHG fluxes.

7.3. Global Warming Potential (GWP)

In this report we have used IPCC (2021) figures for 100-year Global Warming Potential (GWP100) to compare the different types of GHGs and to estimate CO_2 equivalent (CO_2e) emissions for the different gases. More information on GWP values is provided in **Box 2**.

Box 2: Global Warming Potential (GWP)

When estimating emissions of different types of GHG, it is important to consider the differences in Global Warming Potential (GWP) of each gas. Methane has a higher warming impact than carbon dioxide but is short-lived in the atmosphere. Nitrous oxide has a much higher warming impact than methane and carbon dioxide - and is long-lived in the atmosphere – so even relatively small emissions can have large warming impacts. GWP is used to compare the potential warming impact of different GHGs, taking into account the strength of their warming effect (radiative forcing) as well as their longevity in the atmosphere (IPCC, 2021).

There are alternative versions of GWP available and debates around the merits of GWP20, GWP100 or GWP* in relation to estimating the actual warming impacts of different gases (Lynch et al. 2020). These debates are particularly pertinent to conservation grazing due the short-lived nature of methane in the atmosphere combined with the biogenic origin of livestock emissions (from living organisms), and the natural carbon cycles within ecosystems. This report does not address these issues in detail, but we acknowledge that the choice of GWP calculation method can generate different outcomes over different timescales.

For the purposes of this literature review we have used GWP100 as this is most commonly used in the literature to date (GWP* is a relatively new concept but is worth exploring in future research). In the IPCC's Sixth Assessment Report (2021) they provide a distinction between methane from fossil fuel sources and non-fossil origin (e.g. animals). We have used IPCC (2021) values for nitrous oxide (273) and non-fossil methane (27.2). However, it should be borne in mind that most of the literature reviewed uses CO_2 equivalent values for GWP100 from previous IPCC reports in 2014 or 2007 (**Table 2**).

Table 2: Global Warming Potential (GWP100) for different greenhouse gases (from the IPCC Assessment Reports for 2007, 2014 and 2021). Figures in bold are those used in the current literature review.

Greenhouse Gas	100 Year Impact (GWP100)			20 Year Impact (GWP20)		
	2007 Report	2014 Report	2021 Report	2007 Report	2014 Report	2021 Report
CO_2	1	1	1	1	1	1
CH_4 (fossil origin)	25	28	29.8	72	84	82.5
CH_4 (non-fossil)	25	28	27.2	72	84	80.8
N_2O	298	265	273	289	264	273

8. Impacts of species, breed and body mass

8.1. Summary

Enteric (digestive) methane emissions from livestock are one of the main sources of GHG emissions from the agricultural sector in the UK, constituting around 50% of CO_2 equivalent emissions (Brown et al. 2022). Methane is a potent greenhouse gas, and although short-lived in the atmosphere (around 10 years), it has around 27 times the warming impact of CO_2 over 100 years and 81 times the warming impact of CO_2 over 20 years. Conceptual Diagram A2 (**Annex 2**) indicates key levers for reducing enteric methane emissions per head of livestock (including stock changes (species and breed), supplements, diet and habitat, microbe manipulation and genetics). Conceptual Diagram A3 (**Annex 2**) shows potential levers to reduce emissions per land area (including herd density, herd structure, season and timing, and spatial targeting).

In this section, we review the literature relating to methane emissions from different species and breeds to assess which stock choices could reduce methane emissions for equivalent grazing impact. This requires assessing emissions per head of livestock, as well as emissions for equivalent grazing impact.

Within the UK conservation grazing sector, equivalent grazing impact can be roughly estimated through the use of equivalent Livestock Units

(LUs), which can be used to estimate the number of each livestock type that would have the equivalent feed intake as one adult cow (Chesterton, 2006). Whilst there are some problems with using LUs as units of equivalent grazing impact (see **Box 3**), LUs are widely used by conservation grazing managers so are appropriate for estimating reductions (or increases) in methane emissions when changes to livestock type are being considered.

Methane emissions for equivalent grazing impact can also be compared through studies of methane emissions per unit of Dry Matter Intake (DMI), where DMI is the weight of food consumed. This is a more direct way of comparing methane emissions from different livestock types but is not generally used by livestock managers. For this review, we will consider the evidence based on both DMI (from scientific studies) and based on the Livestock Units commonly used by land managers (**Box 3**).

There are four key characteristics that are postulated to influence enteric methane emissions from large herbivores: digestive type, body mass, species and breed. **Box 4** summarises the key points followed by a detailed review of the evidence.

Box 3: Livestock Units and DMI

When comparing different livestock for conservation grazing, the relative grazing impact of different species is important. Livestock Units (LU) are generally used to estimate the equivalent number of livestock required to consume similar grazing intake to one adult dairy cow. Estimated daily Dry Matter Intake (DMI) is another way of comparing grazing impacts of different livestock types.

Livestock Units

Table 3 below shows LUs commonly used for conservation grazing and recommended for UK Countryside Stewardship schemes. When considering enteric methane emissions for different species, LUs can be used to estimate how emissions per head will translate into emissions per land area for different species providing equivalent grazing impact. However, LUs do not account for differences between breeds of different sizes or dietary preferences, which may be additional considerations for livestock comparisons.

Table 3: Livestock Units (LUs) for different livestock types, and number of head per livestock type for equivalent grazing impact (LU data from Rural Payments Agency UK, 2021)

Livestock Type	Livestock Unit (LU)	Number of head for equivalent grazing impact
Cattle over 2 years	1.0	1.0
Cattle 6 months to 2 years	0.6	1.7
Lowland ewe and lamb / Ram	0.12	8.3
Store lamb, hill ewe and lamb /Hogg /Teg	0.08	12.5
Horse	1.0	1.0
Pony / Donkey	0.8	1.25
Goat	0.12	8.3

Dry Matter Intake (DMI)

Dry Matter Intake (DMI) is the amount of food consumed by livestock in a given timescale. This is usually measured in kg per head per day. Enteric methane emissions per unit of DMI can be measured for different livestock types to estimate the likely methane emissions for equivalent grazing impact. This is usually measured as g CH_4 per kg DMI. In theory, this should produce similar results to the Livestock Units as both are based on equivalent grazing consumption. However, in practice, variations in the conditions under which studies are conducted, food type, and variations between livestock individuals and breeds, can result in slightly different outcomes for DMI studies compared to LUs.

Box 4: Summary of characteristics affecting enteric methane emissions

Digestive Type

Domestic ruminants (such as cows, sheep and goats) emit more enteric methane than non-ruminants (e.g. horses and pigs). However, recent studies indicate that ruminant emissions are not always higher than non-ruminants when a wide range of global species are included. When considering wild species it cannot be assumed that ruminants will always have higher emissions.

Body Mass

Smaller breeds and individuals generally emit less methane per head (but not necessarily per DMI or unit of production). Several studies have indicated 'allometric scaling' of methane emissions to body mass. This would imply that several smaller animals have lower emissions than one large animal of equivalent body mass. However, recent research disputes the evidence for this.

Species Differences

There are substantial differences in methane emissions of different species. Horses, pigs, rabbits and kangaroos emit substantially less methane than other species relative to DMI. Amongst ruminants, cows (especially dairy cows) emit more than sheep, goats and red deer. There is some evidence that water buffalo and moose (Eurasian elk) may have relatively low emissions per DMI, whilst bison may have high emissions per DMI. However, further research is needed for these species.

Breed Differences

Evidence suggests that some breeds have slightly lower emissions than others, but that these differences may be habitat-dependent. Traditional breeds often have lower emissions (per head) compared to modern breeds (which may be due to smaller size), but there is often no difference per DMI or unit production. There are some instances of smaller breeds producing higher emissions than larger, which may indicate the role of gut microbes.

Key Points:

- **Species differences in enteric methane emissions per Dry Matter Intake (DMI) are generally more substantial than breed differences.**
- **There is some evidence of differences in methane emissions between breeds, but this can be habitat-dependent and requires further primary research on a wider variety of breeds.**
- **Horses (and other equines) and pigs have substantially lower emissions than other domestic livestock, even when body mass and DMI is accounted for.**
- **Using UK GHG Inventory estimates (Brown et al. 2022), cows and goats have higher emissions than sheep and red deer (per head and for equivalent LUs). However, some studies indicate goats to have lower emissions than sheep per DMI. This is an area for further research.**
- **Bison appear to have high emissions per DMI compared to water buffalo and moose (Eurasian elk), but more research is required for these species, particularly European bison.**
- **Smaller animals usually have lower emissions per head, but this does not always equate to lower emissions per DMI or unit food production (of meat or milk).**

8.2. Body mass and enteric methane

Key Points: Smaller animals (of lower body mass) tend to emit less methane per head (due to lower consumption levels). However, this does not always equate to lower emissions per DMI or unit production. Several studies suggest 'allometric scaling' of methane emissions with body mass, meaning that several smaller animals would produce less total methane than one larger animal of equivalent total body mass. However, recent studies have disputed the evidence for this allometric scaling relationship. Body mass is therefore unlikely to be an important consideration in reducing emissions from conservation grazing.

Evidence: Several studies have found methane emissions to increase with body mass to a greater extent than expected from metabolic rate alone (Franz et al. 2010; Franz et al. 2011; Smith et al. 2015a). This suggests that using a larger number of smaller animals could produce less emissions per hectare of grazing land than using a smaller number of large animals to graze the equivalent area.

"Because of the allometric scaling of methane output with body mass, national emissions could be reduced if countries favoured more, smaller livestock, over fewer, larger ones."
- (*Smith et al. 2015a*)

However, recent studies have disputed the evidence for this allometric scaling relationship (Müller et al. 2013; Clauss et al. 2020). A meta-analysis involving 37 herbivore species found no significant effect of body mass on digestive methane emissions per DMI or gross energy intake (Clauss et al., 2020):

"In contrast to previous claims, absolute CH4 emissions scaled linearly to DM intake, and CH4 yields (per DM or gross energy intake) did not vary significantly with body mass."
-(*Clauss et al. 2020*)

The charts below (**Figures 1 and 2**) are generated from datasets in two meta-analyses (Clauss et al. 2020 and Jorgensen et al. 2011). For these charts we have extracted data on species relevant to conservation grazing in the UK. There is a paucity of data on domestic pig (only one data point). **Figure 1** indicates a general trend for increasing methane emissions (per head) at larger body mass. However, when methane emissions per unit DMI are plotted against body mass (**Figure 2**) there is no trend for body mass.

Figure 1: Methane emissions compared to body mass for a range of herbivore species (based on data extracted from Clauss et al. 2020 and Jorgensen et al. 2011

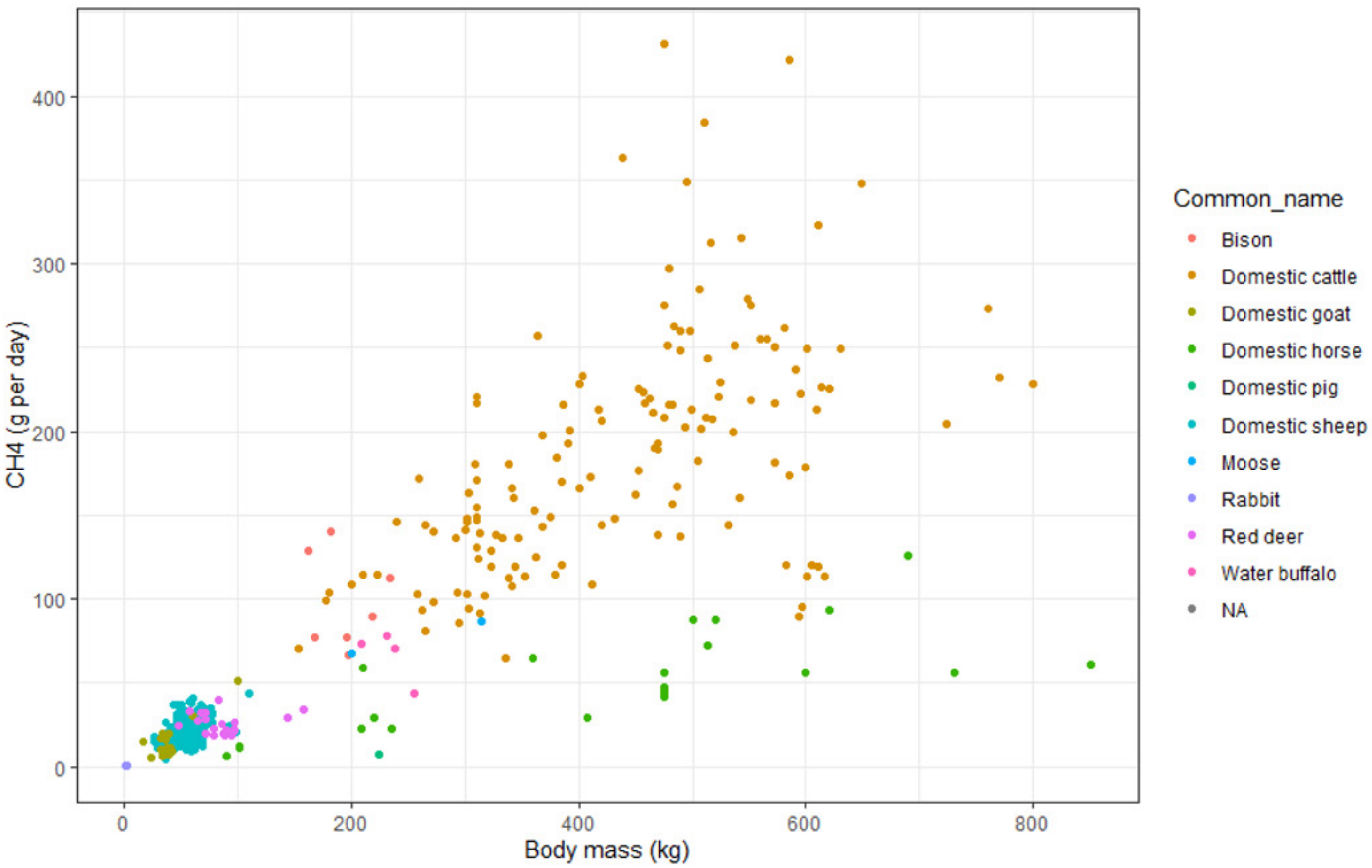
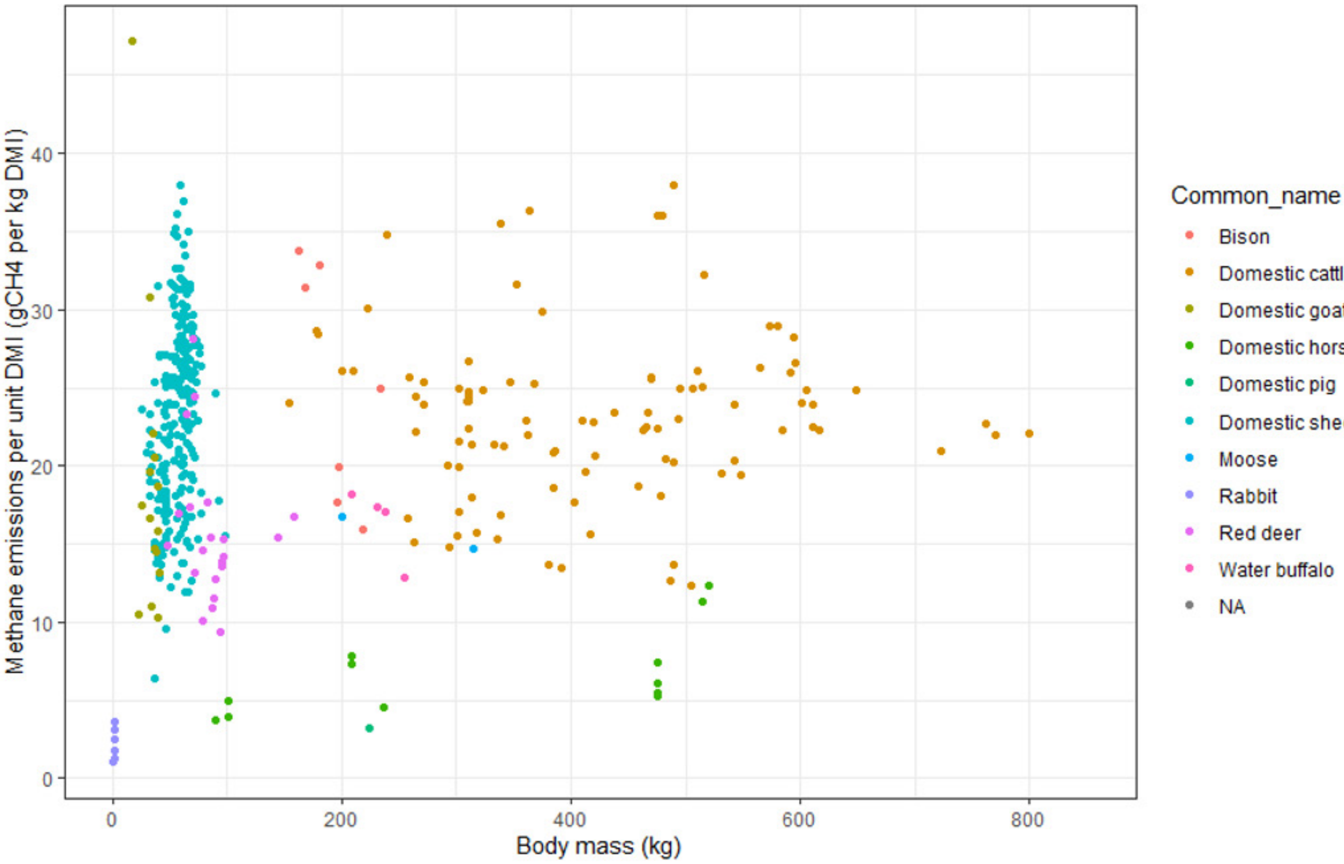


Figure 2: Methane emissions per unit DMI compared to body mass for a range of herbivore species (based on data extracted from Clauss et al. 2020 and Jorgensen et al. 2011).



In the context of conservation grazing, this evidence suggests that body mass is unlikely to be a key consideration for reducing GHG emissions. Whilst switching to individuals of lower body mass is likely to reduce emissions per head of livestock, this may require increasing the number of individuals to maintain equivalent grazing impact. However, in situations where stock density is fixed (such as agri-environment schemes) and some reduction in grazing impact would be acceptable, then using smaller individuals (e.g. younger age structure or smaller breed) could achieve some overall emission reductions compared to the same stock density of larger individuals.

Figure 2 also highlights the wide variability in emissions per unit DMI within species – particularly sheep – even at equivalent body mass. The reasons for this high variability are poorly understood and would require further primary research to investigate the extent to which within-species variability is related to breed differences, diet, or natural variability in gut biomes.

8.3. Digestive type

Key Points: Domestic ruminants generally produce higher methane emissions than non-ruminants. However, this is not always the case when a wide range of non-domestic species are considered. In the UK conservation grazing context, domestic ruminants (cows, sheep and goats) generally have higher emissions per DMI than domestic non-ruminants (horses, donkeys and pigs). However, when considering wild species, emissions should be assessed on a species-by-species basis rather than assuming ruminant emissions will be higher than non-ruminants.

Evidence: Several studies have found emissions from domestic ruminants to be higher than domestic non-ruminants (Crutzen et al. 1986; Franz et al. 2010; Franz et al. 2011). However, recent research incorporating a wider variety of non-domestic animals suggests that ruminant emissions are not always higher than non-ruminants. A meta-analysis by Clauss et al. (2020) found that some non-ruminants emit similar methane emissions as ruminants of equivalent body mass. They suggest that previous studies finding higher emissions for ruminants have focused on a limited range of domestic species. When a wider range of species are included, the distinction between ruminant and non-ruminant emissions is not so clear:

"The dataset does not support traditional dichotomies of CH4 emission intensity between ruminants and nonruminants, or between foregut and hindgut fermenters."
- Clauss et al. 2020

However, the number of studies involving methane emissions from non-domestic mammals is very small (most of these species have only been the subject of a single study). Further research would be beneficial to strengthen the evidence on different digestive types and a wide range of species.

"More detailed in vivo studies on a wide range of herbivore species are needed to identify differences between groups characterized by a specific taxonomy or digestive physiology."
- (Franz et al., 2011)

From a conservation management perspective, it is more helpful to consider variations in emissions for different livestock species and breeds than for classifications based on digestive types (particularly as general rules of thumb for digestive types cannot be relied upon for all species).

8.4. Species Differences

Key Points: Clear differences in methane emissions have been found between different species and taxonomic groups. Horses, pigs, kangaroos and rabbits have substantially lower emissions (per DMI) than cows, sheep, goats and deer. Amongst all domestic livestock, dairy cows have the highest emissions per DMI. Differences between sheep, goats and red deer are unclear as the evidence is mixed. There is a paucity of research on emissions from water buffalo, moose (Eurasian elk) and bison, however the evidence that does exist indicates relatively low emissions per DMI for water buffalo and moose. Overall, the existing evidence suggests three tiers of emissions levels (per DMI):

1. Highest emissions: cattle and bison (though data is only available for American bison, not European)
2. Medium-level emissions: sheep, goats, red deer, water buffalo, moose
3. Lowest emissions: horses (and other equines), pigs, rabbits

Emissions per head: In the UK context, methane emissions per head are based on estimates in the UK Greenhouse Gas (GHG) Inventory (Brown et al. 2022). These estimates are based on agricultural livestock and may not accurately reflect emissions from livestock in conservation grazing (due to differences in diet, breeds and habitats; see 'Habitat and Diet' section below). There is currently insufficient research to provide robust estimates tailored to different habitats in conservation grazing (this is an area for further primary research). For the purposes of this report, we therefore use the UK GHG Inventory estimates **(Table 4),** with the caveat that these may not provide accurate estimates of absolute emissions but are useful for assessing comparative emissions for different species.

Table 4: Estimated enteric methane (and manure) emissions (per head) for UK Livestock - from the UK Greenhouse Gas Inventory 1990-2020: Annex 3 (Brown et al. 2022)

Animal Type		Enteric Methane kg CH_4/head/year	Methane from manures kg CH_4/head/year
Cattle	Dairy cows	123.81	38.43
	Dairy heifers	54.90	6.9
	Dairy replacements >1 year	51.32	5.91
	Dairy calfs <1 year	43.50	3.89
	Beef cows	76.23	10.64
	Beef females for slaughter	49.18	5.92
	Bulls for breeding	57.39	7.96
	Cereal fed bull	49.88	9.20
	Heifers for breeding	48.67	6.37
	Steers	50.04	5.98
Pigs	------	1.50	4.06
Sheep	Ewes	7.11	0.19
	Rams	8.31	0.23
	Lambs	3.03	0.07
Other livestock	Goats	9.0	0.39
	Horses	18.0	0.41
	Deer	20.0	0.22
Poultry	Laying hens	NA	0.016
	Growing pullets	NA	0.007
	Broilers	NA	0.017
	Turkeys	NA	0.061
	Breeding flock	NA	0.007
	Ducks	NA	0.121
	Geese	NA	0.122
	All other poultry	NA	0.007

Estimated methane emissions (per head) in the UK GHG Inventory (**Table 4**) indicate that cows have the highest enteric emissions per head (with dairy cows higher than beef cows), followed by deer, horses, sheep, goats and pigs. Emissions from manure follow a slightly different order (dairy cows highest, followed by beef cows, pigs, horses, goats, deer and sheep), but cows have substantially higher emissions per head for both enteric and manure emissions. Manure emissions in an agriculture context are multiplied by conversion factors depending on the manure handling system, with considerably higher emissions for liquid and deep bedding systems (Brown et al. 2022). In conservation grazing, where manure is left on the field, no additional conversion factors are required. For this reason, this report does not provide detailed analysis of manure handling systems. However, it is worth noting that daily spreading of manure over the field can provide a ten-fold reduction in manure methane emissions (Brown et al. 2022) compared to leaving it in place (due to the reduction in anaerobic conditions).

Emissions per head are useful for calculating estimated emissions from a herd of known size and species composition. However, for assessing how livestock species composition could be adjusted to reduce emissions, we also need to incorporate Livestock Units (LUs) to compare herd sizes of equivalent grazing impact (see **Box 3**). When the LUs from **Box 3** are combined with emissions per head in **Table 4**, it is possible to compare methane emissions for equivalent livestock numbers (**Table 5**). The categories used in the LU recommendations are slightly different from the categories used in the methane emission estimates. Estimates for hill ewe and pony/donkey are likely to be over-estimates as they use methane estimates for lowland ewe and horse respectively. No LUs for pigs are provided in the UK context, so we have used EU recommended LUs for adult sows from Eurostat (2022).

Table 5: Annual methane emissions from different livestock types when using Livestock Unit (LU) equivalents and UK methane estimates (for enteric and manure emissions). Methane estimates do not distinguish the same categories as the LUs. Figures in square brackets [...] are therefore likely to be over-estimates. Figures are calculated from LUs provided by DEFRA (Rural Payment Agency UK, 2021) and methane estimates in the UK Greenhouse Gas Inventory (Brown et al., 2022). LUs for pigs are based on Eurostat (2022).

Livestock Type		Number of head for equivalent LUs	CH_4 emissions (kg per head)	CH_4 emissions (kg per eq. LUs)	Manure CH_4 (kg per head)	Manure CH_4 (kg per eq. LUs)	Total CH_4 (manure & enteric) kg per eq. LUs
Adult cattle	Dairy cows	1.0	123.8	123.8	38.4	38.4	162.2
	Beef cows	1.0	76.2	76.2	10.6	10.6	86.8
Lowland ewe		8.3	7.1	58.9	0.19	1.6	60.5
Hill ewe		12.5	[7.1]	[88.8]	[0.19]	[2.4]	[91.2]
Horse		1.0	18.0	18.0	0.41	0.41	18.4
Pony / Donkey		1.25	[18.0]	[22.5]	[0.41]	[0.51]	[23.0]
Goat		8.3	9.0	74.7	0.39	3.2	77.9
Pigs (sows over 50kg)		2.0	1.5	3.0	4.1	8.2	11.2
Red Deer		3.3	20.0	66.0	0.22	0.73	66.7

Table 5 indicates that if livestock species are switched according to recommended Livestock Units, and enteric methane emissions are then calculated according to the UK GHG Inventory estimates (Brown et al. 2022), the order of species from highest to lowest emissions would be:

- Dairy cows
- Beef cows
- Goats
- Red deer
- Sheep (lowland ewe)
- Horses
- Pigs

The order above is based on only one way of comparing emissions, based on combining LUs and UK GHG Inventory figures. It is also possible to compare methane emissions of different species by collating evidence from studies of emissions per Dry Matter Intake (DMI). The following section considers the literature on methane emissions per DMI and how this compares to the outcomes produced by combining LUs and UK GHG Inventory figures.

Methane emissions per DMI: Studies of methane emissions per DMI confirm the previous findings (in **Table 5)** that cows, sheep and goats produce substantially more methane than horses and pigs for equivalent grazing impact. However, studies of differences between cows, sheep, goats and red deer produce mixed findings. The evidence for other species (including moose (Eurasian elk), water buffalo and bison) is based on a very small number of studies and would benefit from further research.

Cows, sheep, goats, horses, pigs and red deer: There is one area of clear agreement in all of the studies reviewed for this report, which is the substantially lower emissions from horses and pigs compared to other livestock. Several studies have found horses to have substantially lower methane emissions (per DMI) than other domestic ungulates (Clauss et al. 2020; Crutzen et al. 1986; Franz et al. 2010). This is consistent with the emissions estimates in **Table 7** and indicates high confidence that horses (and other equines) emit substantially lower enteric methane emissions than other large grazers for similar grazing impact (though there are fewer studies of equines compared to cattle and sheep).

Franz et al. (2010) compared digestive methane emissions from sheep and ponies of similar body mass (around 90 to 100 kg). 'Mini' Shetland Ponies had considerably lower methane emissions than adult ewes of similar body mass (13 vs 30 litres CH_4 per day). Ponies had lower enteric methane emissions for all measurement units (e.g. litres per day per animal; litres per kg DMI; percentage of gross energy; and percentage of digestible energy). The ponies produced less methane than sheep but consumed more roughage, suggesting horses and ponies could graze equivalent biomass with substantially lower emissions than sheep.

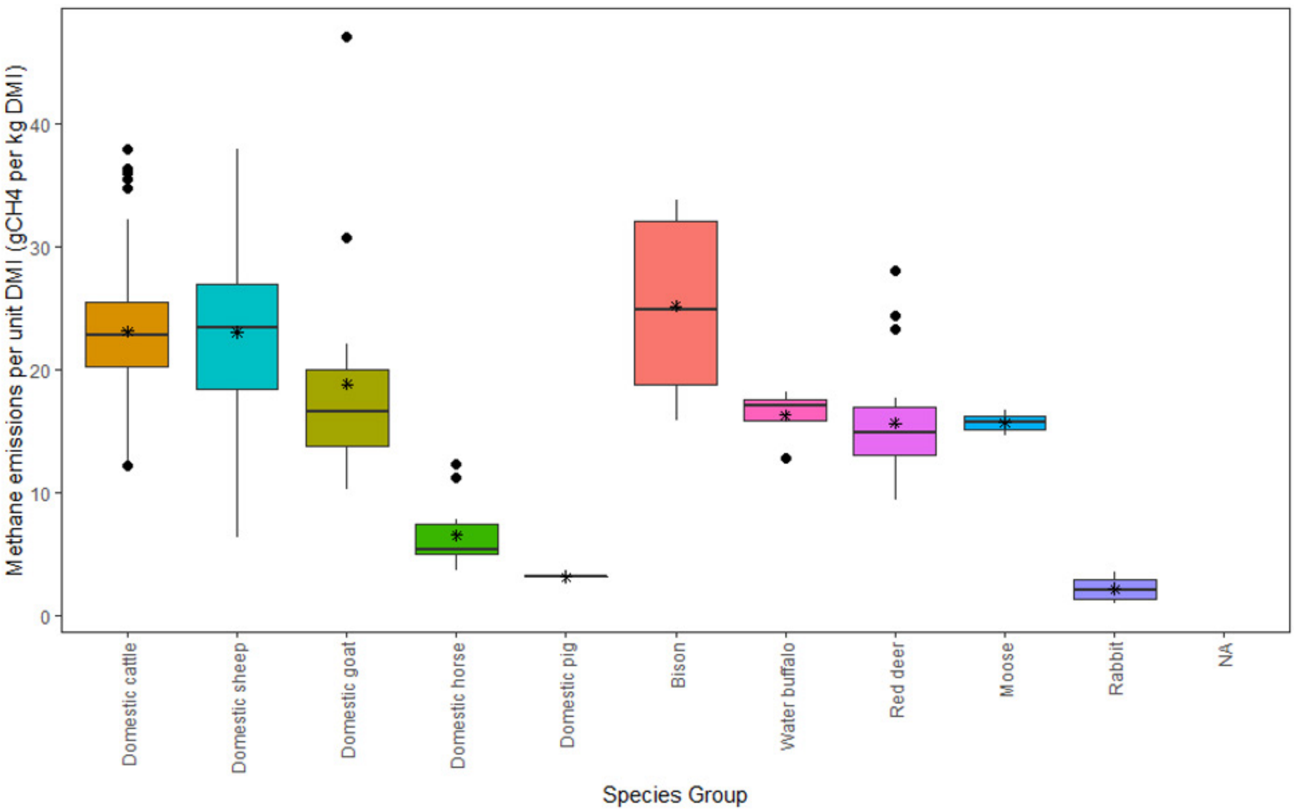
A meta-analysis and modelling study by Pérez-Barbería (2017) found that cows had significantly higher enteric methane emissions (per DMI) than sheep, red deer and goats. However, this study found goats to have significantly lower emissions (per DMI) than sheep and red deer (contrary to the **Table 7** estimates above). No significant difference was found between emissions from red deer and sheep. This suggests that more research on comparative emissions of sheep, goats and red deer would be beneficial.

A more recent meta-analysis by Clauss et al. (2020) included a wide range of domestic and wild species from multiple studies globally. By extracting data for species relevant to UK conservation grazing (and adding pig data from Jorgensen et al. 2011), we have generated a chart of methane emissions per DMI for the most relevant species (**Figure 3**). This data suggests a slightly different order for species emissions compared to the order in **Table 5**, with highest to lowest as follows:

- Cattle and sheep (and American bison)
- Goats, red deer (and water buffalo and moose)
- Horses, pigs (and rabbits)

This data should be approached with caution as it is from a global dataset (from multiple countries) and has not been statistically analysed. It also lacks the detailed livestock categories of the UK GHG Inventory data (which distinguishes between dairy and beef cows). It is therefore not possible to say whether this data set provides more accurate estimates for conservation grazing, but it does suggest that more research would be beneficial to clarify emissions comparisons for different species.

Figure 3: Enteric methane emissions per unit DMI (g CH_4 per kg DMI) for a range of grazing species (based on data extracted from Clauss et al. 2020 and Jorgensen et al. 2011). The horizontal lines across the boxes indicate the median value and * indicates the mean.



The species with the lowest emissions per DMI are the non-ruminants – horses, pigs and rabbits. In a conservation grazing context, this indicates that (for equivalent grazing impact) these three groups would have substantially lower emissions than ruminants. Franz et al. (2010) point out that emissions for pigs are even lower than horses, but have not been assessed on roughage diets that would be more appropriate to conservation grazing:

"With an even lower contribution of microbial fermentation to the overall energy gain from feed compared with the horses, pigs potentially have an even lower methane output at the same body mass and gut fill, but this remains to be investigated on roughage-only diets or diets resembling the natural diet of suids."
- Franz et al. 2010

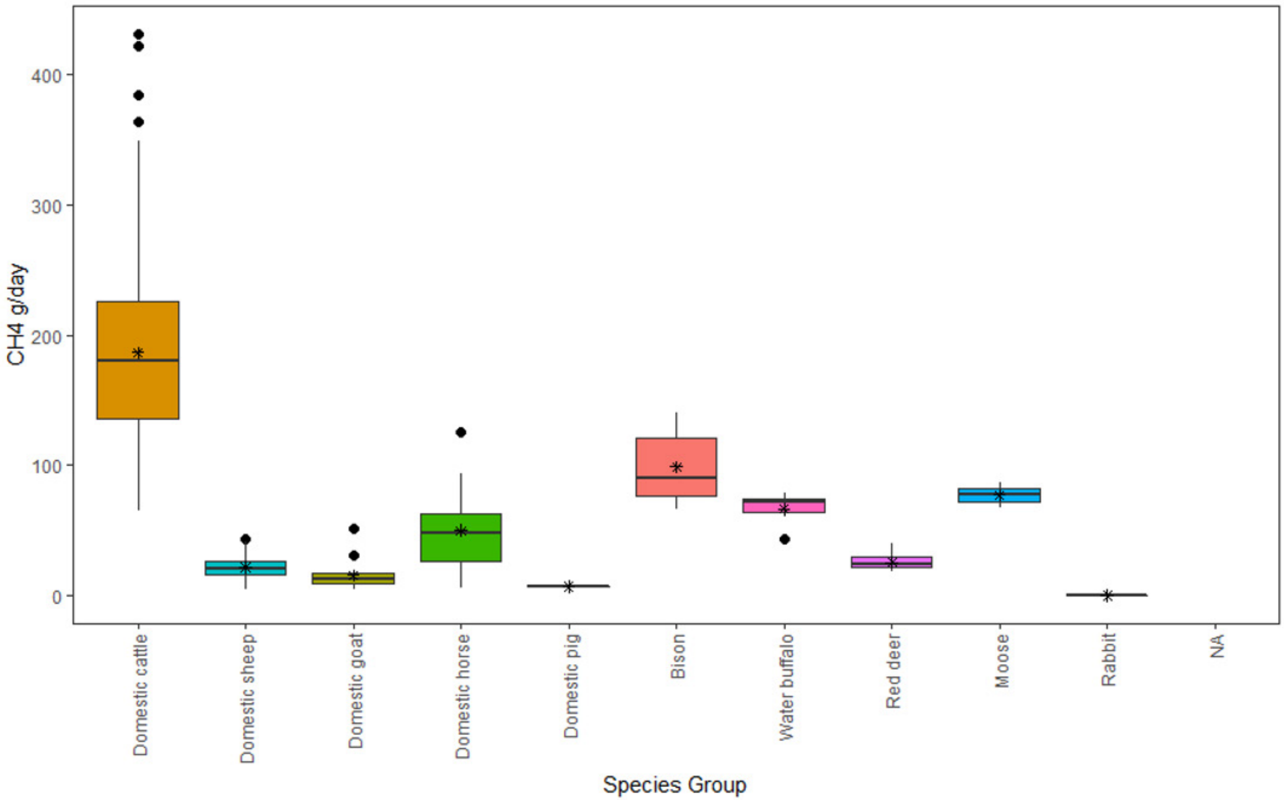
Horses (and other equines) could potentially fulfill similar ecological roles to large ruminant grazers whilst producing around one-third of the methane emissions. Pigs can also provide a range of ecological benefits (see **Section 2**) and are worth considering as components of a mixed herd that would allow a reduction in cattle or sheep numbers.

Other Species: water buffalo, bison, and moose (Eurasian elk)

When considering emissions per head generated by the same dataset (**Figure 4**) bison and water buffalo are particularly interesting as they have substantially lower emissions per head than domestic cattle. However, when DMI is taken into account, bison emissions are high per DMI (similar to domestic cattle), whilst water buffalo emissions are relatively low (**Figure 3**).

Research on methane emissions from bison is difficult due to their free-roaming nature. The few studies that have been conducted focus on American bison, which may differ in emissions and conservation impacts from European bison (as the latter browse more and graze less than the former). The dataset in Clauss et al (2020) shows emissions per head ranging from 67 to 140 g CH_4 per day. This data is taken from a single study in which captive bison were fed alfalfa pellets. A recent study by Stoy et al., (2021) found average emissions of 81 g CH_4 per head per day in a herd of outdoor grazing bison.

Figure 4: Enteric methane emissions (g CH_4 per day) for a range of grazing species (based on data extracted from Clauss et al. 2020 and Jorgensen et al. 2011). The horizontal lines across the boxes indicate the median value and * indicates the mean.



Even with the uncertainty, the figures for bison from both studies are substantially lower than emissions per head for domestic cattle. However, when measured per DMI (Galbraith et al. 1997), bison emissions were found to be similar to domestic cattle emissions (**Figure 3**). Stoy et al. (2021) point out that the captive diet of the bison in the Galbraith study could produce higher emissions per DMI than an outdoor grazing context, however this has not yet been studied in the field.

In contrast to bison, water buffalo appear to have low emissions per head and per DMI. This suggests that water buffalo could be particularly useful in a conservation grazing context as they can provide the ecosystem benefits of a large ruminant but with lower methane emissions for similar grazing impacts. These conclusions should, however, be treated with caution as there is a dearth of research on emissions from water buffalo. The dataset used for the charts includes only four data points for water buffalo and seven for American bison (compared to 149 data points for domestic cattle). Further research on these large ruminants would be beneficial to elucidate the differences between species and how emissions vary in different habitats and biomes.

The data on deer species - red deer and moose (also known as Eurasian elk, *Alces alces*) - suggest relatively low emissions for both species per DMI (**Figure 3**). However, this data should be treated with caution as only two data points were available for moose (compared to 22 for red deer). Further research on moose emissions would be beneficial to provide more robust evidence.

Data caveats: It should be noted that the global dataset used to generate these charts (**Figures 3-4)** includes studies from a wide variety of habitats and locations (including countries less relevant to the UK context). Whilst the charts are indicative of emissions differences between species, more primary research would be required to provide robust and reliable evidence specific to UK habitats.

Nitrous Oxide Emissions: Whilst research on enteric methane emissions clearly indicates horses (and other equines) to be very low emitters, the evidence on nitrous oxide emissions should also be taken into account. **Table 6** indicates estimated N_2O emissions from urine and dung of different livestock types (calculated from Brown et al (2022) and Chadwick et al. (2018)). It shows that dairy cows produce the highest N_2O emissions per head, followed by pigs, horses and non-dairy cattle. Goat, deer and sheep are comparatively low. However, when scaled up by equivalent Livstock Units (to achieve similar grazing impact), goats emit more N_2O than cattle for equivalent grazing levels.

Table 6: Estimated annual N_2O emissions (kg per head) for different livestock types in the UK (based on estimates in Brown et al (2022) and Chadwick et al. (2018)). Uncertainty: Due to lack of data, the EF for cattle is used for horses, goats, deer and pigs, however this may be inaccurate.

Livestock category	Nitrogen Excretion (kg N animal place -1 year-1)	N_2O Emissions Factor (% of total N)	Annual N_2O (kg per head)	Annual N_2O (kg) for equivalent LUs
Dairy cows	133	Urine: 0.629 Dung: 0.193 Combined: 0.49	0.55	0.55
Horses	50	Combined: 0.49	0.25	0.25
Non-dairy cattle	44	Urine: 0.629 Dung: 0.193 Combined: 0.49	0.22	0.22
Pigs (Sows)	18	Combined: 0.49	0.09	0.18
Goats	21	Combined: 0.49	0.10	0.83
Deer	13	Combined: 0.49	0.06	0.20
Sheep (Ewes)	9	Urine: 0.315	0.02	0.17 (lowland) [0.25 (upland)]

Nitrous oxide Emission Factors (EF) have not been well researched for livestock other than cattle and sheep. The figures reported here have therefore applied the cattle EF to horses, deer, goats and pigs. Further research on nitrous oxide EFs would be beneficial to allow more accurate comparisons of livestock species. However, inaccuracies in nitrous oxide EFs are unlikely to make a substantial difference in overall GHG emissions comparisons between livestock as they contribute only a small proportion of overall emissions (see **Table 7**).

Combined methane and nitrous oxide emissions: To assess the combined methane and nitrous oxide emissions for different livestock, we have converted the estimates into CO_2 equivalent (CO_2e) using IPCC values in **Table 2** (x 27.2 for CH_4 and x 273 for N_2O). **Table 7** indicates the high mitigation potential of horses and pigs compared to other livestock (for equivalent LUs). Estimates for sheep are differentiated due to the higher LUs for hill ewes compared to lowland ewes (though GHG emissions per head are not differentiated).

Table 7: Annual GHG emissions from combined enteric methane, manure methane, and urine and manure nitrous oxide emissions (in C02e) for different livestock types for equivalent Livestock Units (based on IPCC values for C02e). NOTE: These are not emissions per head (they have been multiplied by equivalent LUs).

Livestock category	Enteric and manure methane emissions (kg CO_2e per year)	Annual N_2O emissions (kg CO_2e per year)	Total CO_2e emissions from combined CH_4 and N_2O (kg CO_2e per year)
Dairy cows	4,412	150	4,562
Non-dairy cattle	2,361	60	2,421
Goats	2,119	227	2,346
Deer	1,814	55	1,869
Sheep (Ewes)	1,646 (lowland ewes) 2,481 (hill ewes)	46 / 68 (lowland /hill ewe)	1,692 (lowland ewe) 2,549 (hill ewe)
Horses	500	68	568
Pigs (Sows)	304	49	354

Table 7 indicates that substantial reductions in GHG emissions could be achieved by replacing high-emitting livestock (such as cows, goats and sheep) with horses and pigs of equivalent LUs. For example, the total GHG emissions from dairy cows are around eight times higher than emissions from horses at equivalent LUs and thirteen times higher than those of pigs at equivalent LUs.

Other Wild Species: There are few studies of the impacts of wild species on GHG fluxes. This is a substantial research gap requiring further primary research. Moose, red deer and bison are considered in the discussion above. For this report we also searched for studies relating to wild boar and beavers, as these are increasingly incorporated into conservation management and rewilding initiatives. Wild boar could potentially have an impact on soil processes through rooting and trampling, however there are few studies of their impacts. Mohr et al. (2005) found no significant impact on soil carbon from simulated wild boar rooting. Don et al. (2019) found that simulated rooting had no effect on total soil carbon but did transform a large proportion of labile soil carbon into more stable carbon stores.

Impacts from European beavers are likely to be substantial due to methane and nitrous oxide emissions from rewetted soils. Most beaver research involves North American beavers, with only a few focused on European beavers. Minke et al. (2020) examined the impacts of flooding by European beavers on GHG emissions (CO_2, N_2O and CH_4) at three different sites in an area of fen. Impacts varied depending on site conditions, with one site turning into a long-term GHG source:

"Water level fluctuations with prolonged drawdown during… summer, a large amount of decaying biomass and slow establishment of wetland vegetation turned the site into a large GHG source."
- Minke et al. (2020)

Cazzola et al. (2018) looked at differences between streams and ponds with European beaver dams and those without. Those with dams were found to be significantly higher in dissolved CH_4, but also had higher sediment carbon. The authors conclude that beaver impacts generate more CH_4 emissions but potentially store more carbon in the sediment.

In a review of beaver studies, Nummi et al. (2018) found high variation in net CO_2e emissions from beaver activity. In many sites, CH_4 and N_2O emissions from beaver activity are unlikely to be balanced by carbon storage, but further research would be beneficial to assess net CO_2e impacts of beavers in different habitats over varying timescales. Beavers can have multiple ecosystem benefits but won't always enhance climate mitigation due to GHG fluxes induced by water level fluctuations.

"This feature of simultaneously acting as both a source and a sink for C turns a landscape of beaver ponds into a very complicated system […]. The widely varying figures for beaver ponds show that, globally, the ponds range from a sink (−0.47 Tg year−1) to a source (0.82 Tg year−1) of C."
- Nummi et al. 2018

8.5. Breed Differences

Key Points: Due to the wide variety of breeds and limited research comparing their emissions, there is a substantial evidence gap on methane emissions from different breeds. The limited research that has been conducted (primarily on cows and sheep) suggests that smaller sized breeds generally (but not always) have lower emissions per head. However, emissions per unit production or DMI are often similar between different sized breeds (and can sometimes be higher for smaller breeds). Changing breed is likely to have a very small effect on GHG mitigation (if any) compared to the substantial impact of changing livestock species (e.g. from cows and sheep to horses and pigs).

Cattle Breeds: Fraser et al. (2014a) compared enteric methane emissions from mixed sheep/cattle herds with two different cow breeds (Belted Galloway versus Limousin X). When sheep were mixed with Belted Galloway total enteric methane emissions were lower per hectare of land compared to when the sheep were mixed with Limousin X (80 vs 91 kg CH4/ha for the summer grazing period). This was probably due to the smaller size and slower growth of the Belted Galloway. However, when measured per unit of live weight gain per hectare (relevant for food production) emissions were higher for the Belted Galloway (BG) mixed herd compared to the Limousin X mixed herd (443 vs 425 g CH_4 per kg lwt gain/ha).

"The lower daily rates of estimated methane emissions for the BG cattle were due to these animals having lower energy requirements, in keeping with the slow-growing nature of this breed. However, the same animals had the highest methane emissions intensities (i.e. g methane per kg calf growth) for the same reason, because a greater proportion of energy intake was used for cow and calf maintenance requirements rather than growth."
- Fraser et al. 2014a

The authors of this study also compared the impacts of the different mixed herds on species richness and abundance of butterflies and birds, but found no significant differences between breed systems:

"We found no evidence that the system using BG cattle was any better for bird and butterfly species than those based on conventional cattle at the same stocking density"
- Fraser et al. 2014a

In a different study, Fraser et al. (2014b) compared enteric methane emissions from traditional (Welsh Black) and modern (Limousin X) cattle breeds in both upland and lowland habitats. The Welsh Black (WB) had slightly lower emissions than Limousin X (LX) for both habitats when measured per head (g CH4 per day). The difference was greater in the upland habitat (173 vs 190 for WB vs LX in upland, and 216 vs 217 in lowland). Although this suggests lower emissions per head for the Welsh Black in the upland habitat, the difference was not statistically significant for breed type. Emissions per kg production were also lower for WB in the upland habitat, but not statistically significant. Habitat type (upland vs lowland) had a substantial and significant impact that outweighed breed differences (see 'Habitat and Diet' section below).

"…emissions per unit of live-weight gain are substantially higher for animals grazed extensively on semi-improved hill pasture than animals grazing lowland ryegrass swards. Breed had comparatively little impact on the results obtained, and any numerical differences observed are likely to be caused by differences in feed intake."
- Fraser et al. 2014b

In a study comparing three cow breeds (Aberdeen Angus X Limousin (AxL), Charolais (CHA), and Luing (LUI)) there was no significant difference in methane emissions between the breeds when measured per kg production (Ricci et al., 2014). However, there were some differences in emissions per head: the Aberdeen Angus X Limousin (AxL) had significantly higher emissions per adult cow than the other two breeds (524, 490 and 482 g CH_4 per day for AxL, CHA and LUI respectively). The difference between LUI (a hardy hill cow) and CHA (a large cow suited to intensive systems) was not statistically significant. However, emissions per calf were significantly lower for CHA compared to the other two breeds (150, 125 and 160 g CH_4 per day for AxL, CHA and LUI respectively). This highlights the potential impact of age structure within herds when comparing breeds.

The authors of this paper also highlight the potential importance of landscape topography (such as hill slopes) and diet selectivity in influencing methane emissions from different breeds:

"A gap in the knowledge of the relationship between energy expenditure of animals grazing across a range of slopes was identified, which could help to explain large differences observed in the literature. Methane estimations were highly sensitive to changes in quality of the diet, highlighting the importance of considering animal selectivity on heterogeneous grasslands in future carbon budgeting."
- Ricci et al. 2014

De Mulder et al. (2018) found significant differences in methane emissions between Holstein-Friesian (dairy) and Belgian Blue (beef) heifers when measured per head. Belgian Blue had lower emissions per animal when fed on the same diet at the same age (223 vs 264 g CH_4 per day). As the Holstein-Fresians were slightly smaller than the Belgian Blue (558 ± 39 kg vs 594 ± 42 kg respectively) the higher emissions from the Holstein-Friesians per head suggest that smaller animals are not always lower emitters. The authors attribute the higher emissions to the higher food intake and growth rate of the Holstein-Friesians compared to Belgian Blue. When measured per unit DMI, there was no significant difference between breeds.

The authors of this paper also compared rumen bacterial and methanogen communities of the two different breeds. Although bacterial communities differed between breeds, there was little difference in methanogen communities. The authors conclude that differences in methane emissions between the breeds are more influenced by feed intake than the composition of rumen methanogens:

"…the bacterial communities showed a breed specific composition… In contrast, the methanogen communities were consistent and stable between breeds and at different sampling times. Our results suggest that breed related factors (including early life events) influence the bacterial community composition, while the variation in methane emission levels can be attributed mainly to the feed intake of the animals."
-De Mulder et al. 2018

In a comparison of methane emissions from Jersey steers and Holstein steers fed the same diet (Islam et al., 2021), there was no significant difference in emissions per head per day (although Jersey emissions were generally slightly higher despite their smaller body mass). However, when measured per unit DMI per day Jersey steers had significantly higher emissions than Holstein steers (16.8 vs 11.5 g CH_4 per kg DMI) as well as higher emissions per body mass. This suggests that in a conservation grazing context, Holstein steers could produce significantly lower emissions than Jersey steers for equivalent grazing impact. However, this experiment was conducted under controlled conditions and diets that may differ significantly from conservation grazing. It was also conducted in Korea, so may differ from the UK context. However, it has been included here as there are few UK-specific studies of breed differences, and Holstein and Jersey are both UK-relevant breeds.

The authors of this paper also considered the influence of season on methanogens and methane emissions. They found that season and breed influenced methanogen composition, but only breed (not season) had a significant impact on methane emissions:

"Both season and breed affected the rumen microbiome and rumen fermentation, while only breed affected enteric CH4 emissions."
- Islam et al. 2021

Summary for cattle breeds: Due to variations in the age of cattle for the studies above it is not possible to create a comparative table of quantitative breed differences. However, in combination, these studies indicate differences in emissions between breeds, particularly in emissions per head (see **Table 8**). Large breeds (Limousin and Holstein-Friesian) generally have higher emissions per animal than small- and medium-sized breeds (Belted Galloway, Welsh Black and Luing). However, Charolais and Jersey diverge from this trend, with Charolais (a large breed) having comparatively low emissions (similar to Luing) and Jersey (a small breed) having high emissions. Further research with different cattle breeds (at similar ages with similar diets) would be beneficial to elucidate emissions differences for a wider range of breeds.

Table 8: Relative emissions (per animal) for different species pairings in studies by Fraser et al. (2014a and 2014b); Ricci et al. (2014); De Mulder et al. (2018); and Islam et al. (2021). Note: quantitative data is not detailed in this table due to the variation in ages of cattle for different studies, which makes inter-study breed comparisons invalid.

Enteric methane emissions per head (relative)	
Higher Emissions	Lower Emissions
Limousin X	Belted Galloway
Limousin X	Welsh Black
Aberdeen Angus x Limousin	Charolais
Aberdeen Angus x Limousin	Luing
Holstein-Friesian	Belgian Blue
Jersey	Holstein-Friesian

Although the evidence indicates there are slight differences in emissions for different cattle breeds, these differences are insubstantial compared to differences between species. For example, based on the studies above, switching from Holstein-Friesian to Belgian Blue, or from Aberdeen Angus to Luing, could save around 15 kg CH_4 per cow per year. This compares to savings of around 4,000 kg per year for each dairy cow that is switched to a horse.

Sheep Breeds: Fraser et al. (2015) compared methane emissions from lambs of two sheep breeds (Welsh Black and Welsh Mule X Texel). No difference was found between the breeds when measured per Metabolic Live Weight (MLW). This applied even under different diets (perennial ryegrass only or mixed grass and forbs). However, when fed on a forage of mixed grass and forbs the Welsh Black had slightly lower emissions than the Welsh Mule X Texel when measured per head (12 vs 14 g CH_4 per day) and per DMI (16.7 vs 18.8 g CH_4 per kg DMI) but the difference was not statistically significant. When fed on perennial ryegrass the Welsh Black had slightly lower emissions per head (15 vs 17 g CH_4 per day), but the difference was not statistically significant. Emissions per DMI were similar for both breeds (16.1 vs 16.7 g CH_4 per kg DMI).

"Overall the results indicate that forage type has a greater impact than breed type on CH_4 emissions from weaned lambs."
- Fraser et al. 2015

In a comparison of two breeds of lowland ewe lambs (Highlander and Texel) fed the same diet, Wang et al. (2019) found no significant difference in methane emissions between the two breeds when measured per head or per DMI. When measured per Body Weight (BW), emissions were significantly higher for the Highlander breed (0.55 vs 0.42 CH_4 g per kg). However, this study was conducted in confined conditions, so it should be borne in mind that results could differ in the context of conservation grazing. The study also looked at the impact of dietary concentrates on methane emissions and found no significant effect:

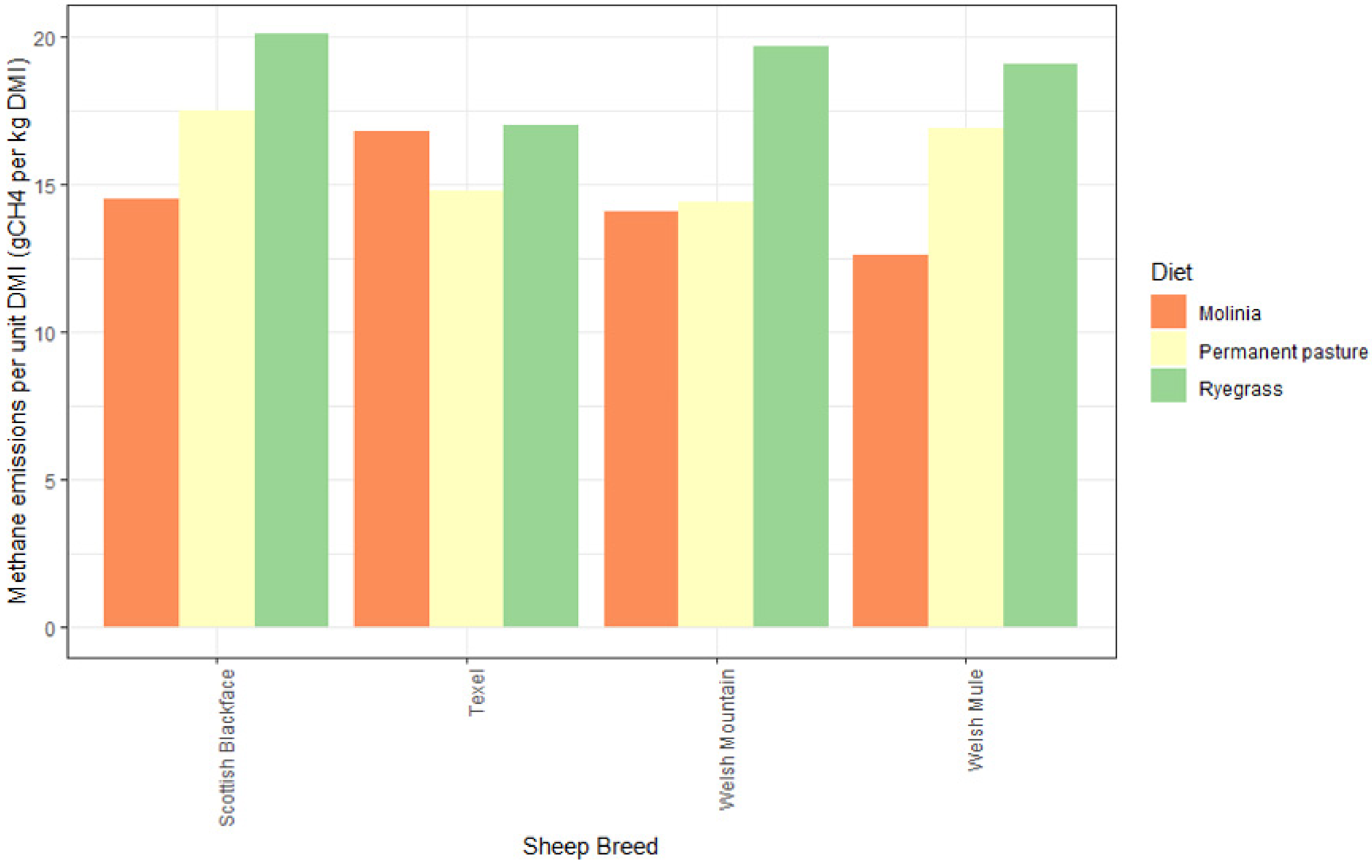
"…diets had no significant effects on nutrient digestibility, energy or N utilization, or CH_4 emission. Texel breed had a significantly lower DM intake and CH_4 emissions per kg live weight."
- Wang et al. 2019

Moorby et al. (2015) compared methane emissions from four different sheep breeds (Welsh Mountain, Scottish Blackface, Welsh Mule and Texel). They found that breed differences in methane emissions were dependent on forage quality (see **Figure 5**). When feeding on Molinia, methane emissions per head were significantly higher in Texel compared to Welsh Mountain (14.9 vs 8.9 g CH_4 per day respectively). However, methane emissions per DMI were not significantly different between any of the breeds, suggesting that the higher emissions per animal may reflect the larger body mass and DMI of the Texel. When feeding on permanent pasture, there was no significant difference in methane emissions per head, but emissions per DMI were significantly higher for Scottish Blackface compared to Welsh Mountain (17.5 vs 14.4 g CH_4 per kg DMI). All breeds except Texel had higher emissions per DMI when feeding on ryegrass and lowest when feeding on Molinia.

"There was no effect of breed type on the quantity of CH_4 emitted when the ewes were offered ryegrass, but a breed effect was seen on the amount of CH_4 emitted per kilo DMI when offered the permanent pasture. Only on Molinia was there a breed effect on grams of CH_4 emitted per head."
- Moorby et al. 2015

These results suggest that breed type can have a small impact on methane emissions in a conservation grazing context, however further primary research would be required to assess the extent of breed effects in different habitats with different forage types.

Figure 5: Average enteric methane emissions per unit of Dry Matter Intake (DMI) for four different sheep breeds on three different diets (Molinia, Permanent Pasture and Ryegrass). Adapted from Moorby et al. 2015.



The chart below (**Figure 6**) is generated from a meta-analysis dataset in Clauss et al (2020). We extracted emissions data for sheep where breed was specified and the research was conducted in a temperate European climate. The only breed not generally used in the UK context is the Blackbelly (a tropical breed). We have included it here as the original study (Archimède et al., 2018) compared emissions from the Blackbelly in the West Indies (tropics) to emissions in France (temperate). In **Figure 6** we have only included the data from France, so the data is relevant to a European temperate context. The authors of the Blackbelly study found that Blackbelly emissions were significantly higher than Texel in the temperate region, but lower than Texel in the tropical region. This suggests that enteric methane emissions can be substantially influenced by the origin of the species and its environment:

"In the tropical site, methane emission was lower for Blackbelly compared to Texel, whereas the opposite was observed in the temperate site. Differences in methane emissions between the temperate and tropical sites could only be the result of diet and breed interactions with the environment."

- Archimède et al. 2018

Summary for sheep breeds: Comparisons of emissions from different sheep breeds suggest there are some differences between breeds, however these differences vary depending on habitat and diet. Using breeds adapted to the UK climate is likely to produce lower emissions than using tropical breeds (though the latter are unlikely in conservation grazing anyway). Of the UK-relevant breeds, Welsh Mountain tends to have slightly lower emissions per animal and per DMI than other breeds (see **Table 9** and **Figure 6**), but this is not the case across all diets and habitats. Any emission reductions achieved from changing sheep breed is likely to be very small compared to the substantial reductions achievable by switching from sheep to horses or pigs.

Figure 6: Enteric methane emissions per unit of Dry Matter Intake (DMI) for five different sheep breeds (data extracted from dataset in Clauss et al. (2020)). The horizontal lines across the boxes indicate the median value and * indicates the mean.

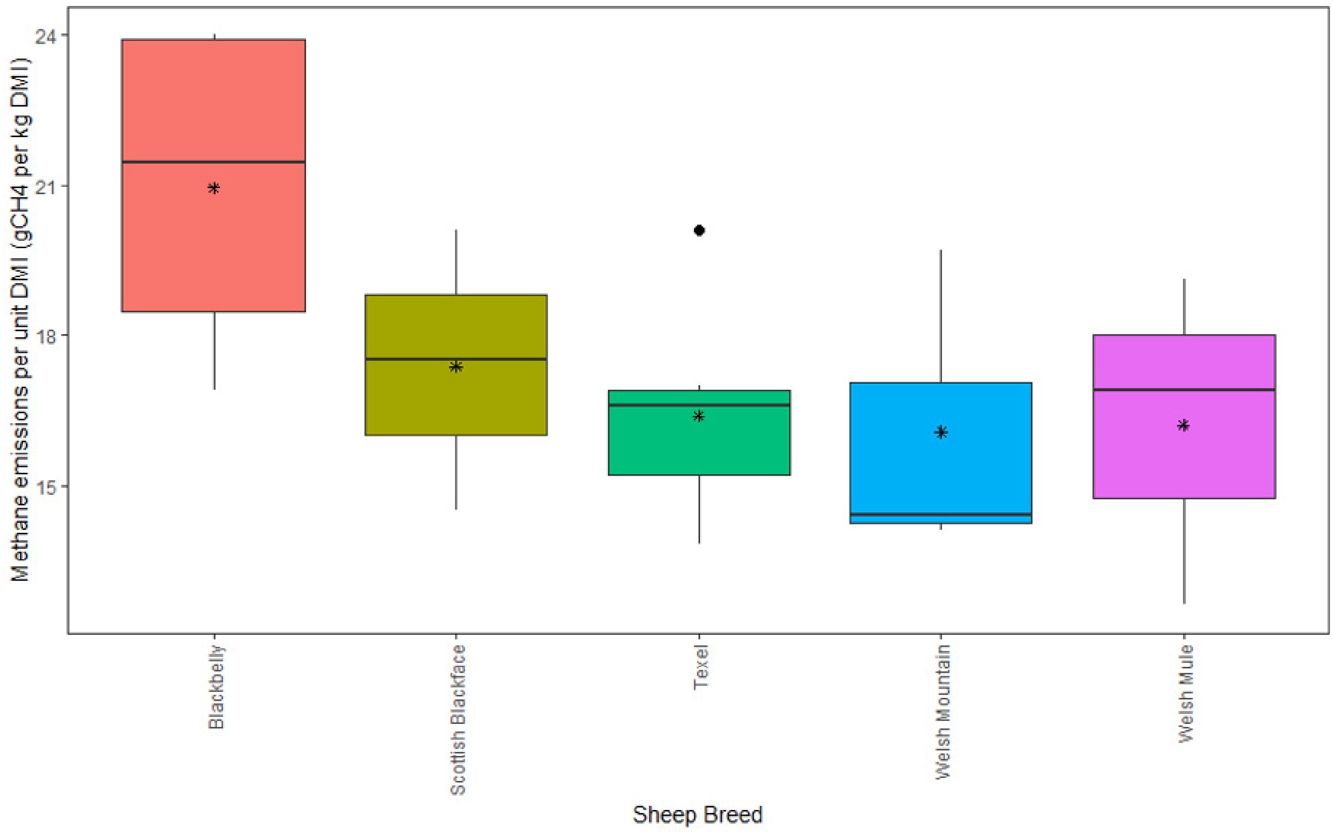


Table 9: Data for different sheep breeds (taken from studies by Moorby et al. 2015; Fraser et al. 2015; and Wang et al. 2019). NOTE: The data is not directly comparable as studies differ in age of animals, habitat and forage type.

Sheep Breed	Body Mass (kg)	CH_4 per animal (g per day)	DMI per animal (kg per day)	CH_4 per DMI (g per kg DMI)
Scottish Blackface	57.5	15.6	0.89	17.4
Texel	55.6	18.6	1.05	18.7
Welsh Mountain	42.4	13.6	0.83	16.1
Welsh Mule	67.9	17.0	1.06	16.2
Welsh Mule X Texel	NA	NA	NA	18.8
Welsh Black	NA	NA	NA	16.7
Highlander	NA	NA	NA	17.5

Horse, Goat and Pig Breeds: For this report, we were unable to identify research on emissions differences for breeds of pigs and goats. Research on equines (horses and relatives) is very limited. Crutzen et al. (1986) found lower emissions per head for mules and asses (10kg CH_4 per year) compared to horses (18kg CH_4 per year). It is likely that ponies and donkeys would have lower emissions per head than horses but primary research is required. This report highlights a significant research gap for breed comparisons within equines, goats and pigs.

Gut Diversity and Breeding: Figure 2 (above) reveals high within-species variability in methane emissions per DMI even at the same body mass. Moorby et al. (2015) point out that high individual variability is common even within the same breeds under the same conditions and diet. They suggest that this could reflect individual gut microbiota and genetics:

"Such variation between individual sheep not attributable to feed composition has been observed previously and contributes significantly to the uncertainty in the estimates of CH_4 emissions for national inventory reporting. However, such variability among individuals, which likely has a genetic basis, also indicates the potential for breeding livestock with reduced methane emissions."
- Moorby et al. 2015

It is possible that differences in the composition and diversity of gut microbiota may have significant impacts on methane emissions intensity for different individuals, species and breeds (Liu et al. 2012; Misiukiewicz et al. 2021; Martinez-Alvaro et al, 2020; De Mulder et al. 2018). Individual variations in emissions intensity, combined with advances in genome sequencing could allow selective breeding for low-emitting individuals (Hayes et al. 2013). Selective breeding could facilitate the use of low-emitting herds in conservation grazing but this is a strategy that requires further research and development.

9. Impacts of changing livestock numbers, timing and targeting

9.1. Summary

Reducing the total number of livestock (stocking rate) across a site is likely to substantially reduce GHG emissions and enhance the net carbon sink potential of the system. Small reductions in livestock numbers are unlikely to have substantial impacts on biodiversity. However, more research is required to assess if there are density thresholds below which significant shifts in community composition could occur (Li et al. 2016). The use of mixed herds and spatially targeted grazing could allow reductions in high-emitting livestock whilst maintaining similar grazing impacts and habitat outcomes. **Table 10** summarises the likely carbon outcomes and conservation impacts.

Table 10: Impacts of changing livestock numbers, timing and targeting on GHG emissions and conservation.

Lever of Change	GHG and carbon impacts	Conservation impacts
Reduce number of livestock	Reducing livestock numbers could substantially reduce GHG emissions whilst having little impact on carbon storage. Example: a 10% reduction in a herd of 20 dairy cows would lead to approximate savings of 9,000kg CO_2e per year.	A small reduction in livestock numbers is unlikely to have substantial impacts on habitats and biodiversity. However, there may be herd density thresholds below which significant biodiversity impacts could be incurred. Further research would be beneficial to identify thresholds in different habitats.
Mixed Herds	Mixed herds could achieve substantial GHG reductions with little impact on carbon storage. Mixing high-emitting livestock (cows and sheep) with low-emitting livestock (horses and pigs) would allow equivalent Livestock Units to maintain grazing impact, whilst allowing for a reduction in high-emitting species.	Mixed herds are likely to benefit biodiversity through facilitating a wider range of grazing modes. However, the particular livestock mix and proportions will need to be tailored to habitat and species goals, accounting for the specific impacts of different livestock on vegetation
Change grazing season	There is mixed evidence on the impacts of grazing season on GHG emissions. There is currently insufficient evidence for a recommendation.	Changing grazing season is likely to impact habitat goals depending on the extent of the seasonal change. This is due to seasonal differences in vegetation, which may require grazing in particular seasons to achieve habitat goals.
Stop grazing or use alternative	Stopping grazing altogether would generate the highest possible reduction in GHG emissions and is likely to have a low impact on carbon storage. Alternatives to grazing, such as mowing and cutting, may generate other emissions from machinery and staff/volunteer travel. These emissions would need to be quantified to allow comparisons with emissions from grazing livestock.	Stopping grazing is likely to have high habitat impacts in most situations and may not be an option for restoring and maintaining early successional habitats and species. Alternatives to grazing, such as mowing, may prevent succession, but with a loss of heterogeneity and microhabitats created by grazing.
Targeted grazing	Targeted grazing could potentially allow for herd size reductions whilst maintaining desired levels of grazing impact. Smaller herds could be moved around compartments to ensure adequate grazing of the whole compartment or to increase habitat heterogeneity through differential grazing impacts. An experimental approach would be beneficial and could involve 'virtual fences' and collars or placement of troughs or mineral licks. Targeted grazing could also allow wetter areas (where soil GHG emissions from grazing are highest) to be avoided.	Targeted grazing is likely to benefit biodiversity as it could be aimed at achieving similar conservation goals with fewer livestock. It would also allow grazing to be targeted (spatially and temporally) for specific biodiversity and habitat goals.

9.2. Changing livestock numbers

Methane emissions: Reducing stocking rate (see **Box 5** for definitions) would reduce overall enteric methane emissions (and manure methane) per hectare due to the lower number of animals. However, the impacts on habitat structure and biodiversity would need to be considered (see **Section 2**). The impact of lower stocking rates on individual emissions per head or per DMI is unclear due to a lack of studies. In a conservation grazing context it is unlikely to have a significant impact as diet quality and quantity per individual is unlikely to be affected by small changes in livestock numbers, particularly with free-roaming livestock over a large area. However, with targeted grazing (where higher densities of livestock may be concentrated in smaller spaces for short periods) it is possible that emissions per head or per DMI could be influenced by changes in feeding patterns and selectivity. This would require primary research to assess potential impacts.

BOX 5: Herd Density and Stocking Rate

A variety of terms are used in livestock management to refer to the number of livestock over a given area and timescale. For the purposes of this report we have used the following terminology:

Herd density (also known as stocking density): We use the term herd density to refer to the number of livestock in a particular portion of the grazing area for a particular amount of time. We have used herd density rather than stocking density to avoid confusion with stocking rate.

Stocking Rate: We use the term stocking rate to refer to the total number of livestock over the whole grazing area (usually per year or per grazing season).

What is the difference? Herd density refers to the number of animals on a particular portion of land for a particular time period. When livestock are free roaming over the whole site, then herd density and stocking rate are the same (and are often used interchangeably by authors). For targeted grazing, the herd may be moved around so that grazing is focused intensively on particular portions of land for short periods. Herd density may therefore be high in one portion of land for a fixed time and low in other portions. Stocking rate refers to the total number of animals over the whole site (usually annually). Stocking rate can therefore remain the same over the year for the whole site, while herd density changes in different portions of the site for different time periods.

Example: In a 50 ha site there are 20 horses over the year. The stocking rate is therefore 20/50 = 0.4 horses per ha (per year). If the horses roam freely across the whole site for the whole year, the herd density is the same as the stocking rate (0.4 horses per ha). However, if all of the horses are confined to a 10 ha portion of the site for 2 months, the herd density in this portion at this time is 20/10 = 2 horses per ha.

"Stocking rate is the basic relationship between livestock and the forage resource. Stock density [herd density] is essentially animal concentration."
– Gerrish, 2006

Chiavegato et al. (2015) compared low stocking rate, high density grazing (rotating between paddocks) with higher stocking rate and lower density grazing (less frequent rotation). No significant differences were found for enteric methane emissions per head. Further research would be beneficial to assess if there are density thresholds at which levels and patterns of vegetation consumption are affected by herd density, which may have knock-on effects on emissions per head.

Nitrous oxide and carbon dioxide emissions: A lower number of livestock would also reduce total N_2O emissions from urine and dung. Several studies have found reduced N_2O emissions from grasslands with lower stocking rates or grazing frequencies (Rafique et al. 2011; Wang et al. 2012). This reduction is likely to be partly due to a reduction in the total volume of urine with fewer livestock. N_2O emissions can be around 15 times higher on urine patches compared to control patches without urine (Cardenas et al. 2016). However, the extent of N_2O emissions from urine is likely to be influenced by habitat and soil (Marsden et al. 2019), therefore the magnitude of the reduction will vary between sites.

Urine patches also emit more CO_2 than control patches without urine, indicating that reducing stocking rates could slightly reduce CO_2 emissions. Boon et al. (2014) assessed CO_2 and N_2O emissions from urine patches in UK peat grassland. As well as substantially higher N_2O emissions, the urine patches caused large short-term spikes in CO_2 emissions (possible due to urea hydrolysis or stimulation of microbial respiration):

"The CO_2 fluxes peaked at 5262 mg CO_2 m−2 d−1 initially a few hours following urine application to the soil, exceeding baseline fluxes by approximately 4000 mg CO_2 m−2 d−1."
- Boon et al. 2014

Overall GHG emissions: Several studies have assessed how changes in herd density impact overall GHG emissions, finding lower emissions (or greater ecosystem net carbon absorption) with lower herd densities. Sandor et al. (2018) used eight different models combined with field data from different sites. Lower herd densities were found to produce lower overall GHG emissions, and the net carbon sink of the system was larger at lower densities. Worral and Clay (2012) conducted a modelling study of the impact of sheep grazing on total GHG flux in upland peat habitats. They modelled emissions for a range of sheep densities for five different vegetation scenarios. The model found GHG emissions to decrease with decreasing sheep density under all five vegetation scenarios.

In a field study in France, Allard et al. (2007) compared two paddocks at high (intensive) and low (extensive) density. Whilst both acted as net GHG sinks, the extensive paddock was a greater sink over the three years than the intensive. However, the sink activity increased over time in the intensive and decreased in the extensive. This study also differed in fertiliser application rates to the two paddocks, so results should be treated with caution (as fertiliser application can significantly influence GHG emissions and carbon sink potential).

"The average greenhouse gas (GHG) balance across the 3 years was -10 and -31 g CO2-C equivalents in the intensive and extensive treatments, respectively. However, the net biome productivity (NBP) and GHG sink activities increased over time in the intensive grazing treatment."
- Allard et al. 2007

Soil carbon: The evidence for impacts of herd density (including grazer exclusion) on soil organic carbon (SOC) is mixed. Whilst several studies indicate a reduction in SOC when grazers are excluded (Czobel et al. 2015; Elschot et al. 2015; Johnson et al. 2017; Zani 2021) others indicate no change in SOC (Acharya et al. 2012, Ford et al. 2012; Futa et al. 2021, Garnett et al. 2000; Medina-Roldan et al. 2012). The impacts of changes in herd density are unclear. Large herbivores are likely to increase SOC through incorporation of dung into soil, however physical trampling could relocate carbon to lower depths in the soil, reducing SOC measurements in topsoil. Studies that only include topsoil may exclude an important component of carbon storage. The movement of SOC through the soil can also be influenced by soil type and rainfall, creating high variation in study results.

Askari and Holden (2014) compared twenty grazed grassland sites in Ireland. No significant difference in SOC was found between high- and medium-density sites, but low-density sites were found to have significantly higher SOC than medium- and high-density sites. This suggests that grazing at higher densities can reduce SOC. However, only the topsoil SOC was measured, so the potential impact of trampling on SOC distribution to deeper soil levels was not considered. As the study compared multiple sites, there may also be site-specific conditions that could have influenced the results of this study. In a separate study of 22 saltmarsh sites in the UK, Harvey et al. (2019) compared SOC at different grazing densities and found that herd density had no significant impact on soil carbon. The authors conclude that other environmental factors have more impact than grazing density.

As well as changing livestock numbers, grazing impact can be altered by changing frequency and rotation of grazing patterns. There are few papers assessing the GHG impacts of changing frequency or rotation, but the research that has been conducted suggests that carbon sink potential can be enhanced by reducing grazing frequency. Diaz et al (2021) compared the impact of different sheep grazing systems on soil carbon (conventional rotational grazing vs regenerative rotational grazing). Both systems involved rotational grazing (periods of grazing interspersed with periods of no grazing), but the regenerative system involved grazing for fewer days with longer rest periods. This reduction in grazing frequency was found to result in slightly higher (3.6%) topsoil carbon (over a six year period) than the system with more frequent grazing.

Density thresholds: Whilst small changes in herd density or stocking rate are unlikely to have substantial impacts on biodiversity, there may be density thresholds at which significant shifts in community composition or species dominance could occur (Li et al. 2016). Further research would be beneficial to estimate minimum and maximum thresholds for different habitats to ensure that herd density changes do not come at a cost to biodiversity.

9.3. Mixed herds

There is very little research comparing the impacts of mixed herds versus single-species herds on greenhouse gas emissions or carbon storage. Fraser at al. (2014a) compared enteric methane emissions from a sheep only system and a mixed system with both sheep and cows (Beulah Speckled Face sheep and Limousin X cattle). Both systems were on upland permanent pasture dominated by perennial ryegrass and white clover with a mix of unsown grasses.

When measured by unit of live weight gained (relevant for food production), the mixed system was found to produce lower methane emissions (398 vs 438 g CH_4/kg-1 lwt gain ha-1). However, when measured per hectare of land (more relevant for conservation grazing), annual emissions were higher for the mixed system (78 vs 62 kg CH_4/ha-1). This is unsurprising as the comparison was made between a single-species herd of a lower-emitting species (sheep) with a mixed herd containing a higher-emitting species (cows). For mitigation scenarios, it would be useful to compare mixed herds including lower-emitting species (e.g. cow-only systems versus horse and cow systems). However, this is a significant research gap.

The authors also compared mixed herds with different ratios of sheep to cows (ratio 6:1 versus ratio 12:1 (sheep:cow)). The system with the highest proportion of cows had higher methane emissions per hectare (91 vs 79) and per live weight gain (425 vs 410). It is unsurprising that mixed systems with more cows have higher enteric methane emissions per hectare. Conversely, it would be expected that switching from single-species herds of high-emitting species (e.g. cows) to mixed herds including low-emitting species (e.g. horses) would reduce enteric methane emissions per hectare. However, changing herd composition could potentially impact biodiversity and habitat structure.

The authors of this study also assessed the impacts of herd composition changes on species richness and abundance of butterflies and birds. They found that sheep-only systems supported higher densities of birds, but lower densities of butterflies than mixed cow and sheep systems. However, species richness was higher on the mixed systems for both birds and butterflies.

"Areas grazed solely by sheep had consistently lower species density than mixed sheep and cattle systems for butterflies, but higher species density for birds."
- Fraser et al 2014a

Although the results of this study suggest some benefits of mixed herds for biodiversity, further research is required to assess the biodiversity impacts (across a range of taxa) of mixed herds incorporating low-emitting species such as horses, ponies, donkeys and pigs.

9.4. Targeted Grazing

Targeted grazing is an approach that allows specific habitat management and biodiversity goals to be met by focusing grazing efforts on particular areas for a period of time (Bailey et al. 2019). The spatial and temporal impacts of the livestock are managed to concentrate grazing where (and when) it is most needed. This can help to achieve specific conservation goals within a site and could also be used to reduce GHG emissions. Using targeted grazing could allow lower overall livestock numbers (lower stocking rate) across the whole site, but with targeted grazing in specific areas to achieve required herd density for biodiversity and habitat goals.

"Targeted grazing prescriptions optimize the timing, frequency, intensity, and selectivity of grazing (or browsing) in combinations that purposely exert grazing/browsing pressure on specific plant species or portions of the landscape."
- Bailey et al. 2019

Targeted grazing can be managed with fences, herding, or strategic placement of cattle licks and other attractors. Recently, electronic collars (such as 'NoFence' collars) have become a more popular method for managing targeted grazing through the creation of 'virtual fences' (Campbell et al. 2017). The collars allow livestock to be moved around virtual compartments within a site to achieve desired grazing impacts with fewer overall livestock. Trials of their use in reducing livestock numbers (and therefore GHG emissions) would be beneficial.

9.5. Changing grazing season

Summary: There is mixed evidence on the impacts of season and timing on GHG emissions from livestock, with some indicating higher emissions in spring/summer and others finding higher emissions in autumn/winter. This may be due to variability in site and weather conditions in different studies. No clear conclusions can be drawn on the impacts of grazing season due to wide variations in results from different studies.

Nitrous oxide emissions: A number of studies have compared nitrous oxide emissions from urine and dung in different grazing seasons. The results of these studies are mixed. Cardenas et al (2016) found that N_2O emissions were significantly and substantially higher from urine compared to the control (for all seasons) and were highest in spring (though emissions from dung were highest in summer):

"The resulting EF values were 2.96, 0.56 and 0.11% of applied N for urine for spring, summer and autumn applications, respectively. The N_2O EF values for dung were 0.14, 0.39 and 0.10% for spring, summer and autumn applications, respectively."
- Cardenas et al. 2016

Contrasting findings were reported by Bell et al. (2015) who found N_2O emissions from urine to be substantially higher in summer (more than double) compared to spring and autumn. No seasonal difference was found for dung emissions. They ascribe the high urine emissions in summer to temperature and soil moisture:

"Mean annual cumulative emissions from urine were the highest when applied in summer (5034gN$_2$O-Nha−1), with lower emissions from spring (1903gN$_2$O-Nha−1) and autumn (2014gN$_2$O-Nha−1) application, most likely due to higher temperatures and soil moisture."
- Bell et al. 2015

In contrast to both of the above studies, Allen et al. (1996) found emissions to be higher during autumn/winter grazing compared to spring/summer.

"N_2O emission rates were much higher during autumn winter than during spring summer, and in the case of well-drained soil were substantial for both excreta types (207 mg N_2O-N kg-1 of deposited dung and 197 mg N_2O-N kg- 1 of urine in autumn winter). The corresponding data for poorly-drained soil were 0.2 mg (dung) and 148 mg (urine)."
- Allen et al. 1996

Marsden et al. (2018) found both N_2O and CO_2 emissions from urine to be higher in spring than autumn, whilst CH_4 emissions were highest in autumn. As these differences also applied to non-urine controls as well as urine patches, it suggests seasonal differences in soil factors can drive seasonal differences in urine-related emissions. It also indicates that the combined impacts of seasonal effects on all GHGs should be considered, as opposite effects may occur for different GHGs.

These studies highlight the uncertainty of conclusions for seasonal impacts. It is likely that other factors (eg soil type, moisture, temperature) may be interacting in complex ways that preclude clear conclusions on seasonal differences. High interannual variations in N_2O emissions have been found ranging from 4.4 to 34.4 kg/ha on the same site (Burchill et al. 2014) as well as high spatial variability within sites, which may explain the inconsistent results of studies for seasonal variations.

"Interannual variation in N_2O emissions was attributed to differences in annual rainfall, monthly (December) soil temperatures and variation in N input. Such substantial interannual variation in N_2O emissions highlights the need for long-term studies of emissions from managed pastoral systems"
- Burchill et al. 2014

9.6. No grazing: impacts of ceasing grazing

Summary: Removing grazers is likely to provide substantial reductions in GHG emissions. There is uncertainty (and mixed evidence) on how grazer removal impacts carbon storage, with impacts likely to vary with habitat and soil conditions. The magnitude of GHG reductions from removing grazers suggests that under many conditions a net reduction in GHG emissions is expected, with any reduction in carbon storage likely to be outweighed by GHG reductions. However, the impact of ceasing grazing on biodiversity and habitats could be considerable.

There are multiple studies assessing the impacts of grazing versus no grazing through herbivore exclusion experiments. Whilst reducing or removing grazers would clearly reduce enteric methane emissions and dung and urine emissions, the impacts on ecosystem GHG fluxes and carbon cycles are less clear. Results for GHG fluxes and carbon storage are inconsistent between different studies and tend to show only small impacts. This suggests that the impacts of large herbivores on GHG fluxes and total carbon storage may be insubstantial compared to other environmental factors.

Ecosystem GHG fluxes: Studies of grazer exclusion have found mixed results for impacts on GHG fluxes from soils and vegetation. Clay et al. (2010) measured net GHG emissions (CO_2 equivalent) from grazed versus ungrazed plots and found the grazed plots to have significantly lower CO_2e emissions than ungrazed (350g CO_2e m/y in grazed sites vs 585 in ungrazed). However, Ford et al. (2012b) compared grazed and ungrazed saltmarsh and found no significant difference for N_2O or CH_4. CO_2 flux was lower on the grazed site, but other factors were found to have greater impacts on emissions:

"Seasonal variation in the key drivers of soil greenhouse gas efflux; soil temperature, moisture and water table, plus the presence or absence of aerenchymatous plants such as J. gerardii were more important to the magnitude of greenhouse gas emissions than grazing management per se."
- Ford et al. (2012b)

These studies do not include measures of enteric methane emissions, which if accounted for would increase the total GHG emissions from grazed systems.

Soil and Biomass Carbon: The impacts of grazing on soil carbon are also complex and influenced by multiple variables including soil type, moisture and atmospheric N deposition. Elschot et al. (2015) evaluated the impacts of small grazers (geese and hare) and large grazers (cattle) on soil carbon, and above- and below-ground biomass in a saltmarsh. Small grazers were found to have no significant impact on soil carbon, above- or below-ground biomass. In contrast, large grazers (compared to no grazers) were found to significantly increase soil carbon (roughly 0.45 vs 0.30 g/cm) and below-ground biomass (doubled), whilst reducing above-ground biomass (by around four fifths). The authors attribute the soil carbon changes (in part) to the impacts of trampling on the fine soils, which caused soil compaction and anoxic conditions that reduced the carbon mineralisation rate. Large herbivores could therefore have contrasting effects on SOC depending on soil structure (e.g. fine- or coarse-grained), wetness, and habitat differences:

"When the direct effects of biomass removal is the predominant grazing effect, increased grazing intensity in well-drained sandy grassland systems such as savannas could decrease carbon sequestration. However, trampling by large grazers will most likely increase local carbon sequestration, and this may be the predominant effect in wetland ecosystems such as marshes with fine-grained soils."
- Elschot et al. 2015

In contrast, Garnett et al. (2000) found no significant effect of low-density grazing (0.2 sheep/ha) on soil carbon in upland blanket bog. Medina-Roldán et al. (2012) examined the impact of grazing exclusion on soil carbon in an upland grassland and found no significant difference after seven years:

"Our observations suggest that grazing exclusion [...] results in a slowing down of rates of C and N cycling. However, as yet, this has had no detectable impact on total C and N stocks in surface soil."
- Medina-Roldán et al. 2012

Ford et al. (2012a) found no significant difference for total C stock in fully grazed (cattle and rabbits), partially grazed (rabbits only) and ungrazed sites. However, the allocation of carbon between roots and litter differed between sites:

"This study found that total C stock from four combined pools, soil, roots, litter and shoots, did not differ with grazing intensity but that root C was greatest in fully and rabbit grazed, while litter C was greatest in rabbit and un-grazed grassland."
- Ford et al. 2012a

Other studies have found similar impacts of grazing on root biomass. Olsen et al. (2011) found above-ground biomass to be lower in grazed areas of saltmarsh compared to ungrazed (0.3 vs 1.0 kg dry wt m2), but below-ground biomass was higher in grazed areas (3.4 vs 1.0 kg dry wt m^2). Plant species richness was also higher in grazed marsh: 6.6 vs 3.7 (species per $metre^2$).

Smith et al. (2015b) evaluated the impact of long-term herbivore exclosures on carbon storage (on multiple upland heathland sites). Grazing was found to reduce above-ground carbon (particularly for shrub-dominated habitats). The impact on SOC was less clear and was dependent on atmospheric N deposition. When N deposition was high (more than 11kg N ha-1 year-1) SOC decreased under herbivory (and increased in exclosures). At low levels of N deposition there was no significant difference for SOC between grazed and ungrazed.

The impacts of wild species on carbon storage have received little attention. Kumbasli et al. (2010) compared soil carbon in areas of red deer disturbance compared to areas without deer. They found substantially lower SOC in areas with deer disturbance (1.4 vs 7.7 %). In contrast, Mohr et al. (2005) found SOC to be higher in the presence of deer. The difference in these studies may be due to differences in deer density, soil conditions and habitat.

Overall, the highly variable results of different studies suggest that grazing impacts on soil carbon are highly complex and likely to be influenced by multiple environmental factors.

9.7. Cutting and mowing

Summary: there is little research on GHG emissions from mowing or cutting compared to grazing. Further studies are required to assess the full impacts of these alternative options on emissions.

Replacing grazing livestock with mechanical cutting and mowing would eliminate livestock-related GHG emissions, but could generate GHG emissions from machinery and staff or volunteer travel. Data on these alternative emissions would need to be quantified for comparison. Some of the biodiversity benefits of grazing could also be lost (see **Section 2**). There is also evidence that large grazing animals invoke different responses in root growth and nutrient cycles (compared to mowing), which could potentially impact ecosystem GHG fluxes and carbon storage.

Differences in carbon storage for grazed and mown systems have received little research. Acharya et al. (2012) found no difference in soil carbon between grazed and mown compartments, but root biomass was significantly higher in grazed areas, suggesting that grazing stimulates root growth more than mowing does. Plant composition was also found to differ between treatments. Futa et al. (2021) compared red deer grazing (in a managed deer farm) with mowing. Soil carbon was slightly higher under deer grazing but the difference was not significant.

Grazing has also been found to induce a different response in ecosystem CO_2 exchange compared to cutting. Peichl et al. (2012) found higher CO_2 emissions from cutting compared to grazing:

"…a comparably smaller reduction in GEP [Gross Ecosystem Production] caused NEE [Net Ecosystem Exchange] to remain negative during and after each grazing period suggesting a continuous net CO_2 uptake as opposed to a net CO_2 loss observed following harvest events. Secondly, in contrast to the decline in ER [Ecosystem Respiration] after harvest cuts, ER was not affected during or after the grazing periods."

- Peichl et al. (2012)

10. Methane-reducing supplements and other interventions

10.1. Summary

Several dietary supplements have been trialled to assess their potential for reducing enteric methane emissions. Of these, UK seaweeds and Bovaer® appear the most promising. Black et al (2021) conducted a review of supplements and their potential for methane reductions. Their findings are summarised in **Table 11**. Supplements require regular administration to maintain their effects, however rumen microbe manipulation (supplementing mothers and calves then isolating them from un-supplemented herds) has the potential to prolong the methane-reducing effects of supplements for many months or even years. Other interventions, such as vaccination, are being developed and trialled but current evidence is insufficient to recommend other interventions.

Table 11: Summary of research findings for supplements and vaccination to reduce enteric methane emissions (adapted from Black et al. 2021)

Supplement or Vaccine	Potential methane reduction	Comments and Caveats
Asparagopsis taxiformis (red seaweed)	90%	Despite the high methane-reducing potential of this supplement there may be environmental impacts from harvesting, transport, and high bromoform levels (damaging to the ozone layer). Native UK species are likely to be more sustainable (see **Table 13** below).
Crushed wheat	30-40%	Compared with pasture alone, adding 9kg of crushed wheat across two feeds daily reduced methane emissions by 30% to 40% per DMI. Due to the high daily amounts required, this may be less practical in a conservation grazing context than other supplements.
Nitrate supplements	6 - 50%	Due to the potential for nitrite poisoning, nitrate can only be supplemented at low levels, leading to small methane reductions (around 6%). As other supplements are more effective and less potential for toxicity, we do not recommend nitrate supplements.
Biochar	0 - 22%	Despite some studies indicating the potential for biochar to reduce emissions, other studies have not found significant results. The effect may depend on the composition of the biochar.
Grape marc	10-20%	Grape marc was found to reduce methane emissions but could negatively impact animal growth.
Bovaer® (3-NOP)	8-70%	Most studies show a reduction of 8–30% except for one study that found 70% reduction. Trials would be beneficial to assess the use of Bovaer® in conservation grazing. Only small quantities are required.
Vaccination	0 to 69%	"Attempts to reduce methane emissions through vaccination have returned varying results from 20% methane increase to 69% methane reduction with half the experiments being unsuccessful." – Black et al. 2021

10.2. Seaweeds

A review by Abbott et al (2020) compares the methane-reducing properties of a variety of seaweeds. The tropical red seaweed Asparagopsis taxiformis consistently achieves high reductions of over 90%. However, this species is high in bromoform (which impacts the ozone layer) and would currently require import from tropical countries. This option is therefore unlikely to provide a sustainable solution in the UK context.

"The bioactive bromoform found in the red seaweed Asparagopsis taxiformis has been identified as an agent that can reduce enteric CH_4 production from livestock significantly. However, sustainable supply of this seaweed is a problem and there are some concerns over its sustainable production and potential negative environmental impacts on the ozone layer and the health impacts of bromoform."
- Abbott et al. 2020

Brown and green seaweeds may offer a more sustainable source of seaweed in the UK context due to the potential for local supplies of native seaweeds and the lower levels of bromoform. **Table 12** summarises research findings for the methane-reducing potential of a range of UK seaweeds. Trials with native UK and Irish seaweeds have recently commenced, led by Queen's University, Belfast (a three year project that started in early 2022):

[2021 | Seaweed methane mitigation | News | Queen's University Belfast (qub.ac.uk)]

Table 12: Summary of research findings for methane-reducing potential of different species of UK seaweed (adapted from Abbott et al. 2020).

Seaweed Species	Study findings for methane reduction
Alaria esculenta	Linear I with increasing dose
Ascophyllum nodosum	I 15% at 24 h
Chaetomorpha linum	I 40%
Chondrus crispus	I 12%
Colpomenia sinuosa	I 49%
Ulva spp.	I 50%

Administering supplements in conservation grazing: In a review of methane mitigation strategies in a grazing context, Vargas et al. (2022) found several studies demonstrating methane-reducing impacts from lipid supplementation (e.g. sunflower, linseed and canola oil). Some of these studies involved spraying oil over sections of pasture or including crushed oil-rich seeds in trough feed. Methane reductions ranged from 0 – 40%.

There may be practical constraints around providing supplements in a conservation grazing context where herds are free ranging. Seaweed supplements have the advantage of only requiring small amounts to be effective so have the potential to be administered in the field via cattle licks. Bovaer® (the trademark name of DSM's supplement 3-nitrooxypropanol) is also administered in small doses (a quarter teaspoon per day) and has the advantage of being well-researched. Experimental approaches may be required - in association with lick block producers or supplement providers - to develop methods for easily administering methane-reducing supplements to free-ranging livestock.

"Research is also needed to show that the supplement can be fed to rangeland animals through lick-blocks or other methods to prove applicability for reducing methane emissions from rangeland and grazing breeding herds and flocks."
- Black et al. (2021)

Rumen microbe manipulation: Supplements could potentially be combined with rumen microbe manipulation to provide long-lasting effects (Meale et al. 2021). Rumen microbe manipulation involves isolating pregnant females from untreated members of the herd and giving a methane-reducing supplement to them and their newborn young. This alters the gut microbes and can keep methane emissions lower for several years after initial treatment. This has potential to alter the microbe populations of whole herds.

"The possibility generated from these experiments is for whole herds with desired rumen populations to be created and maintained through generations provided they are isolated from animals with different rumen populations."
- Black et al. 2021

11. Other factors influencing GHG emissions from grazing

11.1 Habitat and Diet

Habitat and diet have substantial impacts on GHG emissions and carbon storage in conservation grazing. As the objective of conservation grazing is to manage the vegetation for biodiversity and habitat goals, habitat is not an aspect that can be changed to alter emissions. Whilst it may not be possible to use habitat or vegetation differences as a 'lever of change' it is important to understand how management decisions may produce different outcomes in different habitats.

Studies comparing enteric methane emissions in different habitats have produced mixed results. Fraser et al. (2014a) found that including semi-natural grassland alongside improved grassland (compared to improved grassland only) resulted in higher methane emissions per hectare and per live weight gain (91 vs 78 kg CH_4 per ha and 425 vs 398 g CH_4 per kg LWG per ha). However, a comparison of grazing in upland semi-natural grassland versus lowland improved grassland (Fraser et al. 2014b) found higher emissions per head in the lowland habitat (216 vs 173 for Welsh Black and 217 vs 190 for Limousin X on lowland vs upland (g CH_4 per day)). As feed intake was higher in the lowland habitat methane emissions per DMI were slightly higher for the upland habitat (22.9 vs 21.0 for Welsh Black and 23.4 vs 18.7 for Limousin X). Emissions per Live Weight Gain were also higher on the upland habitat.

"While emissions per unit feed intake were similar for the lowland and upland systems, CH_4 emissions per unit of live-weight gain (LWG) were substantially higher when the steers grazed the poorer quality hill pasture (760 vs 214 g kg−1 LWG)"
- Fraser et al. 2014b

These results suggest that annual enteric methane emissions (per head) are likely to be lower on upland semi-natural habitats compared to lowland improved grassland, but emissions per kg food production are likely to be higher.

In a similar study, Fraser et al (2015) compared CH_4 emissions from lambs of two sheep breeds (Welsh Black and Welsh Mule X Texel) when fed different diets (perennial ryegrass vs mixed grass and forbs). For both breeds, grass and forbs produced slightly lower emissions than ryegrass when measured per head and per Metabolic Live Weight, but emissions per DMI were slightly higher.

Moorby et al. (2015) found similar results in a comparison of sheep fed diets of ryegrass, permanent pasture or Molinia, with ryegrass producing the highest emissions per head and per DMI:

"When CH_4 emissions from the pasture-fed animals were multiplied up to give annual values, as used in the Tier 1 IPCC inventory approach, the EFs recorded when the ewes were offered ryegrass were broadly in keeping with the value for sheep quoted by the IPCC, whereas those on the permanent pasture and Molinia were substantially lower."
- Moorby et al. 2015

This suggests that using IPCC values (based on ryegrass-dominated improved pasture) may over-estimate enteric methane emissions from livestock in a conservation grazing context.

Within the context of conservation grazing, there may also be substantial differences for different habitats, soil types and altitudes. Worrall and Clay (2012) conducted a modelling study that compared different grazing scenarios at increasing altitudes for upland peatlands. The models indicated significant effects of altitude on the total carbon balance, suggesting that grazing densities should be reduced at higher altitudes to avoid peatlands becoming net GHG sources. They suggest a GHG carrying capacity of 1.7 to 0.2 ewes/ha for altitudes of 350 – 900 metres above sea level.

"The study suggests that emission factors for upland sheep have been greatly underestimated and that in some cases the presently accepted grazing intensities would lead to peatland environments that are net sources of GHG."
- Worrall and Clay 2012

As well as differences in methane emissions for different habitats, there are likely to be differences in nitrous oxide emissions. A field study by Marsden et al. (2019) found that N_2O emissions from sheep urine on grazed upland heath were substantially lower than the UK GHG Inventory emissions factor for sheep excreta (based on lowland grassland):

"We calculated the potential impact of using hill-grazing specific urine N_2O EFs on the UK inventory of N_2O emissions from sheep excreta, and found a reduction of ca. 43% in comparison to the use of a country-specific excretal EF."
- Marsden et al. 2019

Soil type and vegetation type can have significant impacts on N_2O emissions. Chatskikh et al. (2005) conducted a modelling study based on field data from three sites in UK, Denmark and Finland. They found N_2O emissions to be lower for coarse sand soils compared to loamy sand soils and sandy loam soils. They concluded that simulated N_2O emissions increased with increasing clay content of soils. Charteris et al. (2021) compared GHG emissions from grass-dominated, bracken-dominated and marsh patches under extensive grazing. Grass-dominated and bracken-dominated patches both had higher N_2O and lower CH_4 emissions compared to marsh.

Further research would be required to determine the extent to which GHG emissions vary between different habitats and soil types. Given the wide range of environmental variables that can influence emissions it is currently difficult to identify clear relationships.

11.2. Water levels and GHG emissions

One of the main habitat variables that can substantially impact GHG emissions is water level. Soil wetness influences aerobic and anaerobic soil microorganisms that produce GHGs (see **Conceptual Diagrams A4, A5, A6** and **A8**). The combination of wet soil and grazing can lead to particularly high GHG emissions compared to wet soils without grazing. Renou-Wilson et al. (2016) compared simulated grazing and non-grazing at a drained peat grassland and a rewetted peat grassland. Under simulated grazing, the rewetted site had substantially higher GHG emissions (from soil) than the drained site (due primarily to high soil methane emissions). Under no-grazing, this reversed, and the rewetted site had substantially less GHG emissions than the drained site. The option with the lowest emissions was rewetted without grazing, whilst the option with the highest emissions was rewetted with grazing. This suggests that once a site has been rewetted, grazing should be avoided if possible.

Wen et al. (2021) examined the impact of different Water Table Depths (WTD) in relation to N_2O emissions from urine on peat soils. Emissions were significantly higher with higher WTD (EF 0.25% vs 0.20% at 30cm vs 50cm WTD). The authors conclude that efforts to reduce CO_2 emissions by raising WTD of drained peatlands should also take into account N_2O emissions, which can be higher under grazing at higher WTD.

"Strategies to raise water levels in drained peatlands…need to account for the potential impacts of N_2O emissions when seeking to minimise overall GHG emissions."
- Wen et al. 2021

Whilst rewetting is important for restoring peatland habitats, avoiding or reducing grazing on rewetted habitats (where possible) could help to reduce overall GHG sources.

12. Conclusions

12.1. Challenges and evidence gaps

Based on a thorough review of the literature, we have identified management options that would be likely to produce substantial reductions in GHG emissions. However, there are also many options for which the evidence base is patchy, sometimes contradictory, and in some cases entirely absent. More details on the distribution of evidence (including 'evidence gap maps') is available in **Annex 1**. In particular, there is a dearth of studies that consider the net carbon impacts (CO_2e) across the system (including fluxes of CO_2, CH_4 and N_2O), with most studies addressing just one of these GHGs in isolation. There are also research gaps for studies specific to conservation habitats across a range of species and breeds. Further primary research would be highly beneficial to provide comprehensive evidence for a range of species, breeds and habitats.

Estimating livestock emissions in conservation grazing is challenging for a number of reasons. Firstly, evidence for emissions from different types and breeds of livestock is limited, and standard estimates are therefore based on broad categories in the UK Greenhouse Gas Inventory (Brown et al. 2022). Standard estimates are also based on assumptions about feed type and livestock management practices that are more applicable to the diets and management systems of agricultural livestock. Net carbon balances in conservation contexts are also likely to be affected by habitat-based variables - including vegetation, altitude, slope and fluctuating water levels – making accurate assessments highly context-dependent and complex.

In the context of conservation grazing, the high variability of habitats and vegetation means that standard estimates may under- or over-estimate emissions (depending on the habitat and livestock species or breed in question). There is currently insufficient research to provide more accurate emissions estimates for different habitats. There are also additional questions around the selection of GWP values, which this report does not address in detail, but which could lead to different estimates of livestock impacts depending on the timescale and GWP values applied.

An additional challenge with conservation grazing is the fact that the livestock are not principally intended for meat or dairy consumption. Many studies of livestock emissions and mitigation strategies are interested in the most GHG-efficient means of producing a unit of edible protein in an agricultural context. Conservation grazing, on the other hand, is interested in the most GHG-efficient means of exerting appropriate grazing impact for specific habitat and biodiversity goals. More research with this specific focus would be beneficial.

12.2. Potential Levers of Change

Despite challenges with the evidence base, there is sufficient evidence in some areas to identify levers of change that are likely to produce substantial GHG reductions from conservation grazing livestock. Potential levers of change, and their likely carbon impacts are summarised in **Table 13**.

Table 13: Potential levers of change to reduce GHG emissions in conservation grazing, and their likely impacts on GHG emissions).

Lever of Change	GHG and carbon impacts
SPECIES: Change from high- to low-emitting livestock species	All of the species-related evidence reviewed has identified substantially lower methane emissions from horses and pigs compared to other livestock. Cows (particularly dairy cows) are identified as particularly high emitters. Replacing a proportion of cows and sheep with horses and pigs would bring very substantial GHG reductions with little impact on carbon storage. **Example**: replacing 10 dairy cows with 10 horses could generate reductions of around 40,000 kg CO_2e per year.
BREED: Change from larger to smaller breed	Breed changes are unlikely to generate substantial reductions in emissions compared to species changes. Switching from larger to smaller breeds is likely to generate some GHG reductions per head (but is unlikely to make much difference per DMI). GHG reductions would only be achieved if the same stocking rate was maintained. **Example**: replacing a herd of 40 Texel sheep with a herd of 40 Welsh Mountain sheep could generate savings of around 2,000 kg CO_2e per year.
AGE STRUCTURE: Change to younger individuals of smaller body mass	A younger age structure is likely to generate some GHG reductions per head (but not per DMI). Emissions reductions would only be achieved if the same stocking rate was maintained (which could result in lower grazing impact).
HERD DENSITY AND STOCKING RATE: Reduce overall livestock numbers	Reducing the livestock numbers for a site could substantially reduce GHG emissions whilst having little impact on carbon storage. **Example**: a 10% reduction in a herd of 20 dairy cows would lead to approximate savings of 9,000kg CO_2e per year.
GRAZING SEASON: Change season or timing of grazing	There is mixed evidence on the impacts of grazing season on GHG emissions. There is currently insufficient evidence for a recommendation.
MIXED HERDS: Replace a proportion of high-emitting livestock species with low-emitting species	Mixed herds could achieve substantial GHG reductions with little impact on carbon storage. Mixing high-emitting livestock (cows and sheep) with low-emitting livestock (horses and pigs) would allow equivalent Livestock Units to maintain grazing impact, whilst allowing for a reduction in high-emitting species.
TARGETED GRAZING: spatial and temporal targeting of grazing impacts (by moving livestock around the site)	Targeted grazing could allow livestock numbers to be reduced whilst maintaining grazing impacts. Smaller herds could be moved around compartments to ensure adequate grazing of the whole site or to increase habitat heterogeneity. An experimental approach would be beneficial and could involve 'virtual fences' with collars or placement of troughs or mineral licks. Targeted grazing could also allow waterlogged areas (where soil GHG emissions from grazing are highest) to be avoided.
NO GRAZING: Stop grazing or use alternative (such as mowing).	Stopping grazing altogether would generate the highest possible reduction in GHG emissions and is likely to have a low impact on carbon storage. Alternatives to grazing, such as mowing and cutting, may generate other emissions from machinery and staff/volunteer travel. Further data would be required to quantify these alternative emission scenarios.
SUPPLEMENTS: Administer methane-reducing supplements	Of the supplements reviewed, Bovaer® and UK seaweeds, appear to have the highest potential for use in conservation grazing and are likely to achieve methane reductions of around 20 to 30%. Administering these to free-roaming conservation livestock will be more challenging than agricultural contexts, but would be worth trialling in association with manufacturers.
MICROBE MANIPULATION: Prolonging the effects of supplements through herd isolation	Rumen microbe manipulation could be used in combination with supplements to prolong their effects for many months or years. This involves administering a methane-reducing supplement to newborn calves and their mothers and maintaining them as a separate herd in isolation from other cattle. This would avoid the need for regular feeding of methane-reducing supplements.
VACCINE: Vaccination to reduced enteric methane emissions	Trials of vaccinations to reduce methane emissions have found varying results. Although some trials have shown up to 69% methane reduction, many trials have been unsuccessful (showing no emissions reductions, or even increased emissions). Whilst trials continue this is not currently an available option.
SELECTIVE BREEDING: Breeding individual animals identified as genetically low-emitters	There is high variability in individual enteric methane emissions within species (including within breeds). This is thought to have a genetic component, which could allow selective breeding for low-emitting individuals. In theory, this could allow the creation of low-emitting livestock herds. This is an area of developing research, which could have potential for future use in conservation grazing.

12.3. Recommendations

Based on the strength of the evidence base for different levers of change, we recommend the following four practices as the most likely to achieve substantial emission reductions whilst maintaining sufficient grazing impacts for conservation:

1. **LIVESTOCK SPECIES:** Use fewer cows. Replace a proportion of cows with horses and pigs to form mixed herds. Where this isn't feasible or desirable, replace some cows with sheep and/or goats. Where cows are deemed essential, use beef cattle instead of dairy cows where possible.

2. **LIVESTOCK NUMBERS:** Use fewer livestock. Try to use the smallest number of grazing animals required to achieve specific conservation objectives.

3. **TARGETED GRAZING**: Move livestock around. Changes to livestock species and numbers can be achieved with minimal impacts on site biodiversity by using targeted approaches to grazing (which may involve 'virtual fences'). Where possible, target smaller herds in particular site locations (and times of year) to achieve specific habitat and biodiversity goals. Using targeted grazing to avoid very wet soils is also likely to reduce GHG emissions.

4. **METHANE-REDUCING SUPPLEMENTS**: Conduct trials of supplements. Where it not possible to replace cows and sheep with low-emitting horses and pigs, we recommend that methane-reducing supplements be trialled. This could involve collaborating with the manufacturers of Bovaer® to develop techniques for administering supplements in the field (such as cattle licks).

Trials and Monitoring: We recommend that all of the above approaches be implemented as trials, with ongoing monitoring to assess their impacts on net carbon balance as well as biodiversity and habitat impacts (see **Section 3** for more details on monitoring). In addition to the above recommendations, we recommend experimental approaches to assess the impacts of species reintroductions. In particular, the net carbon impacts of beavers, wild boar, European bison, water buffalo and moose (Eurasian elk) are poorly studied and worth further exploration given their potentially high biodiversity benefits. The impacts of wild herbivores, including red deer and rabbits, would also be worth further research as they are often present in high numbers and subject to management interventions.

Some of the levers of change listed in **Table 13** have the potential to achieve significant emissions reduction but are insufficiently researched or developed for recommendations to be made. These levers are worth further exploration through field studies, in collaboration with scientific institutions. Particular areas for further research could include: impacts of grazing season, changes to age structure of herds, differences in breed emissions for different habitats, the use of microbe manipulation in combination with supplements, and selective breeding for low-emitting herds.

Biodiversity and Habitat Impacts: This section of the report has addressed the evidence on GHG emissions from livestock. To determine appropriate mitigation strategies for conservation grazing, these findings need to be combined with evidence for grazing impacts on habitats and biodiversity (see **Section 2**). All of the potential levers to reduce GHG emissions from grazing will need to be weighed against the biodiversity and habitat impacts of any change to grazing regimes. There are also likely to be practical, legislative and cost barriers to some mitigation measures. Further research is required to identify specific barriers and solutions to allow effective implementation of mitigation measures.

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Section 2: Conservation Grazing and Biodiversity Outcomes

Chapter Authors: *Christopher J. Sandom, Jennifer Ramsay, Helen Wheeler*
Chapter Reviewed by: *Joseph W. Bull and Nigel Doar*

14. Introduction

Nature in the UK is severely depleted (Hayhow et al. 2019). A global assessment revealed that the UK has an average Biodiversity Intactness Index of just 53%, placing it in the bottom 10% of studied countries (Natural History Museum 2021). To prevent further deterioration and achieve Government targets to halt and reverse the decline in nature, considerable additional effort is needed to build on current conservation successes (Hayhow et al. 2019). While officially 28% of land in the UK falls under some form of legal protection, only 11.4% of land is primarily protected for nature (i.e. protected under IUCN categories I - IV) and half of this area may be failing to achieve this goal (Starnes et al. 2021). Many of these sites are small and require management to maintain high biodiversity value (Lawton 2010). A key management practice is the use of large herbivores to graze and browse sites to help maintain biodiversity (conservation grazing). However, large herbivores are also a notable source of greenhouse gas (GHG) emissions, and so contribute to climate change and therefore also threatens biodiversity indirectly (Díaz et al. 2019; Hayhow et al. 2019). Here we explore large herbivore biology and ecology to allow us to consider how changing conservation grazing to reduce GHG emissions could influence their contribution to achieving biodiversity conservation goals.

The reason conservation grazing is an important conservation management practice has deep ecological and evolutionary roots. Wild large mammalian herbivores have shaped ecosystems through most of the Cenozoic (the last 50 million years; Pärtel et al. 2005; Janis 2008; Smith et al. 2010). Their grazing and browsing, bark stripping and tree toppling, seed dispersing and nutrient cycling has helped create mixed mosaics of vegetation structure and increased habitat heterogeneity (Sandom et al. 2019). The loss and decline of the large mammals beginning with the late Pleistocene megafauna extinction (Sandom et al. 2014b) and continuing until today (Ripple et al. 2015), has changed the balance between bottom-up processes of succession and top-down disturbance regimes, and with it habitat availability and diversity in many parts of the world, including the UK (Gill et al. 2009; Rule et al. 2012; Sandom et al. 2014a; Johnson et al. 2016).

In Britain during the Last Interglacial, when the large herbivore community was diverse and abundant, the vegetation structure was a mixed mosaic of closed canopy woodland, semi-closed woodland, and open wood pasture (Sandom et al. 2014a). By the early Holocene the largest herbivores were gone, and the density of remaining herbivores was lower. This allowed wooded habitats to become more prevalent and changed the mix of the mosaic. The UK's vegetation structure didn't begin to resemble that of the Last Interglacial again until low intensity, subsistence agricultural societies started felling trees and raising livestock around 5000 years ago (Pärtel et al. 2005; Sandom et al. 2014a). Since then, intensification of agriculture has homogenised the landscape and caused considerable biodiversity loss (Tilman et al. 2001; Gonthier et al. 2014). The species in the UK today are largely the same as those living here in the Last Interglacial and early Holocene (Svenning 2002; Svenning et al. 2019). This means the species we are seeking to conserve today are ones that evolved when large wild herbivores were shaping ecosystems and creating mixed habitat mosaics.

This evolutionary and ecological context explains why conservation grazing is often an important management approach to biodiversity conservation today. Here we explore how large herbivores support biodiversity and compare how different large herbivore species and stocking practices drive a variety of processes that can be used to achieve specific conservation goals.

15. Goals of Conservation Grazing

Conservation goals associated with conservation grazing are diverse and context dependent. Key goals include the conservation of specific species and habitats of high conservation value, as well as maintaining biodiversity across the landscape (Rook & Tallowin 2003). One key difference between these respective goals is spatial scale, with species management typically requiring the finest scale management, followed by larger scale land management to conserve habitat, with the management of more general drivers of diversity (natural processes) applied at the largest spatial scale of the three. Accordingly, we structure the following section by these three broad goals, recognising that each relate and contribute to the others:

1. increase structural diversity of vegetation and create keystone features to increase habitat heterogeneity and biodiversity,
2. create and maintain specific high-value disturbance-dependent habitats, and
3. support high conservation value species and manage less desirable species.

15.1. Increasing habitat heterogeneity

Summary: Conservation grazing can make important contributions to increasing habitat heterogeneity, and so support higher biodiversity, by:

a. Increasing sward structural diversity
b. Increasing structural diversity of open and woody vegetation
c. Creating bare soil
d. Removing thatch (dead grass and leaves)
e. Seed dispersal
f. Nutrient cycling
g. Creating dung resources
h. Ephemeral pool creation

Theory and evidence suggest habitat heterogeneity is best achieved with diverse and varied stocking practices, which primarily result in 'intermediate' levels of disturbance intensity, frequency, duration, and extent. What constitutes intermediate disturbance levels will be site and taxon specific.

Environmental heterogeneity has been identified as a 'universal driver of species richness across taxa, biomes and spatial scales' (Stein et al. 2014). While relationships between different metrics of heterogeneity and different taxonomic groups vary with context, on average increased habitat heterogeneity is associated with increased species richness, with diverse vegetation being particularly important (Stein et al. 2014). Environmental heterogeneity is important across multiple spatial scales from creating microhabitat variation within the sward (van Klink et al. 2015) to the distribution of keystone structures and increasing landscape scale complexity (Tews et al. 2004; Estrada-Carmona et al. 2022). Grazing, browsing, rooting, fraying, trampling, wallowing, seed dispersal and nutrient cycling can increase vegetation (sward and woody) structural diversity, create bare soil patches and ephemeral pools, diversify the distribution of dead vegetation, increase the dispersal of seeds and animals, create dung and carrion resources, and vary the distribution of nutrient availability (Lundgren et al. 2021). However, the effects of these processes must be weighed against the consumption of biomass of vegetation and invertebrate fauna that can reduce species richness of some groups, such as arthropods (van Klink et al. 2015).

Whether large herbivores do actually increase habitat heterogeneity is linked to the species of large herbivore present, the density they occur at, their distribution in space and time, how the herbivores are managed (e.g. use of Ivermectin), as well as the habitat conditions. All of this serves to influence the quantity, quality, and the variety of resources available within the ecosystem, with the potential of increasing niche space and so biodiversity (Henning et al. 2017).

Conservation grazing alters an ecosystem disturbance regime. Disturbance is a multifaceted concept that can be thought of in terms of disturbance intensity, timing, duration, extent, and the disturbance interval (Miller et al. 2011). Natural disturbance is varied across these characteristics, and reflects the disturbance regimes of the evolutionary and ecological history of current biodiversity. Disturbance is a key driver of habitat heterogeneity, but the relationship is complex. A key hypothesis is that diversity will be greatest at 'intermediate' levels of disturbance. Where disturbance is too high or frequent, only a few resistant species will survive. Where disturbance intensity is too low or infrequent few highly competitive species will thrive and at expense of diversity (although the full ecological theory is more complex (Roxburgh 2004), and the empirical evidence is mixed (Mackey & Currie 2001)).

Van Klink et al. (2015) found that in 80% of 141 studies they reviewed increasing herbivore density, so increasing disturbance, was associated with a decrease in arthropod species richness while there was no difference in plant species richness. Other taxa, including Eurasian Skylarks (*Alauda arvensis*), northern Lapwing (*Vanellus vanellus*), Black Grouse (*Tetrao tetrix*) and geese populations have been reported to increase after grazing is reduced or ceased (Williams et al. 2020). However, some species (such as those requiring warmer soils for larval development or nesting), are likely to benefit from higher stocking densities of livestock such as horses, which can create areas of bare ground (van Klink et al. 2015). These mixed responses to changes in disturbance indicate a diverse disturbance regime is likely needed to support high biodiversity. Overall, van Klink et al. (2015) conclude grazing can increase diversity when "(i) grazing causes an increase in biotic and abiotic heterogeneity, (ii) this increase in heterogeneity occurs at such a spatial and temporal scale that it can be exploited by new species immigrating from the regional species pool and (iii) this positive effect of increased heterogeneity is large enough to compensate for the negative effects of direct mortality and resource competition between arthropods and large herbivores." Thus, determining whether changes to conservation grazing will increase habitat heterogeneity, and so biodiversity, is strongly related to site conditions.

15.2. Habitat specific goals

Summary: Many habitats - including grasslands, heathlands, wetlands, scrublands and wood-pasture, and coastal - are maintained through the effects of herbivory in halting or partially disrupting succession (Lake S., Liley D. 2020; Department for Environment Food & Rural Affairs 2022). The loss of grazing disturbance could cause the loss of these high conservation value habitats. However, determining the most appropriate level of disturbance is challenging, with different taxa favouring different conditions within habitats. Controlling the establishment of woody scrub is a common habitat specific goal of conservation grazing, but overly tight control can result in negative outcomes for some species and taxa. Habitat specific conservation goals include:

a. Halting vegetation succession (preserve a valued habitat type)
    i. Prevent woody plant (shrubs and trees) encroachment
b. Maintaining specific sward height
c. Managing fire to maintain habitat

Many habitats of high conservation value are early to mid-succession communities such as grasslands and heathlands. Without natural or human disturbance, these habitats will typically develop into closed canopy woodland if a suitable seed source is present and the environmental conditions are suitable (Broughton et al. 2021). While woodland is an important and under-represented habitat in the UK (Reid et al. 2021), if there is extensive reversion to closed-canopy woodland at conservation sites there would be an overall loss of biodiversity (Wallis De Vries et al. 2002) and a decrease in habitat heterogeneity (Estrada-Carmona et al. 2022).

The expansion of shrubs and other woody plants into open habitats is a commonly cited reason for practising conservation grazing. Woody plant expansion is a phenomenon that is prevalent across much of the world's more open habitats, including southern England (Eldridge et al. 2011; to Bühne et al. 2022). Woody expansion can be seen as a form of ecological degradation and associated with reductions in ecosystem processes and function, and reduced plant and animal species richness. Equally, scrub expansion can also be seen as an integral part of a diverse and functional ecosystem, and an important habitat. A global review of shrub encroachment effects recorded diverse outcomes (positive, negative and neutral) for different aspects of ecosystem structure and function that varied by context (Eldridge et al. 2011). For example, while in lower rainfall regions scrub encroachment is typically associated with increased vascular plant species richness and no change in vertebrate richness, a few studies show a reduction for both in higher rainfall regions such as the UK (Eldridge et al. 2011). However, even in wetter regions outcomes are diverse.

The contrasting outcomes for different taxonomic groups under different habitat management regimes is a challenge for conservation. For example, Wallis De Vries et al. (2002) highlight that managing chalk grassland for increased floral species richness doesn't necessarily support higher invertebrate species richness. Research exploring different grazing regimes to reduce scrub encroachment on chalk grassland showed no change in beetle richness, abundance, and evenness, but did record a change in species composition, with ungrazed sites supporting different species to grazed ones (Woodcock et al. 2005).

The application of conservation grazing for habitat management can have contrasting results for specific species as well. For example, the Duke of Burgundy butterfly has declined under increasing management of chalk grassland because of intensive scrub clearance removing the delicate mosaic of vegetation structure that this species requires (Turner et al. 2009). A sole focus on increasing plant species richness in open habitats, which often includes scrub removal, can result in negative conservation outcomes for some fauna that need a more mixed mosaic of vegetation. It is thought this is why the Duke of Burgundy and three other butterfly species were performing better in chalk grassland SSSIs that are considered to be in unfavourable rather than favourable condition (Davies et al. 2007).

Conservation grazing can also be applied to manage for a specific sward height to favour certain taxa. The SUSGRAZ project investigated the outcomes of severe, moderate, and lenient grazing regimes in unimproved lowland grassland in the UK (Tallowin et al. 2005). Grazing intensity was assessed by the sward height maintained under different intensities of year-round cattle grazing, with severe grazing 6-8cm, moderate 8-10cm, and lenient 10-12cm. Monitoring revealed all treatments allowed some expansion of Cirsium species. Under severe and moderate grazing intensities positive indicator species for high nature value National Vegetation Classification (NVC) MG5 and MG4 communities declined. Moderate and lenient grazing intensities supported higher abundance and diversity of bumble bees, while spider abundance was higher under lenient grazing. Overall, a lenient grazing intensities maintained highest biological diversity, although this study did not consider whether a diversity of grazing intensities supported highest diversity overall.

Climate change, with the increased likelihood of drought conditions with higher temperatures and lower humidity predicted, is increasing the threat of wild fires in the UK (Arnell et al. 2021). Adapting conservation practices to this increased threat could be challenging. In fire prone areas of North America fire exclusion strategies have resulted in increased fuel load so that a system that is adapted to frequent small fires is now prone to occasional large-scale and devasting fires (Hulme 2005). Grazing by the larger herbivores (bulk feeders like cattle) can be an effective strategy for reducing fuel load and so helping reduce the threat of fire (Rouet Leduc et al. 2021).

15.3. Species specific goals

Summary: Grazing is an important management strategy for suppressing dominant species such as tor-, tufted hair- and purple moor-grass as well as bracken (*Pteridium aquilinum*), and can be used to reduce species named in the Weeds Act (1959) such as ragwort, thistles, and docks. Grazing can also provide specific conditions and resources for certain species of conservation value to thrive. Species specific aims of conservation grazing include:

a. Supporting specific species or groups, such as butterflies on grazed chalk grassland
b. Reducing dominant plant competitors (particularly grasses and bracken)
c. Controlling undesirable species or species classified as 'injurious' weeds under the Weeds Act (1959).

Grazing, trampling and rooting can create bare ground that results in the warming of soil which is important for the larval development of a variety of thermophilus arthropods, including grasshoppers and butterflies, and bare soil is also needed for egg deposition of tiger beetles and solitary bees (van Klink et al. 2015).

Grazing is often used to reduce the competitiveness and dominance of common species, including grasses such as tor-, tufted hair- and purple moor-grass to allow a greater diversity of plants to thrive (**Section 18.1**). Grazing is particularly effective at reducing the cover of competitive and taller grasses and forbs that are less protected against herbivores.

Grazing can also be used to reduce species that can be considered undesirable. The UK Weeds Act (1959) and the UK Ragwort Control Act (2003) can require land owners to control the spread of common ragwort *Jacobaea vulgaris*, creeping thistle *Cirsium arvense*, spear thistle *C. vulgare*, curled dock *Rumex crispus* and broadleaved dock *R. obtusifolius* (Balfour & Ratnieks 2022). Although, the considerable value of these species to pollinators should also be noted (Balfour & Ratnieks 2022). Where control is required, sheep grazing can reduce ragwort abundance, while grazing by cattle can increase it. Research found that ragwort ground cover was 5-6% in ungrazed pasture, 1.7-2% in sheep-grazed pasture, and 7.8-13.2% in cattle-grazed pasture, while other studies did not record a difference between cattle and sheep (Leiss 2011). As discussed in the previous section cattle grazing was not found to halt the establishment of Cirsium species, although may slow it (Tallowin et al. 2005).

Bracken is a native species but a strong competitor and normally considered to be of low conservation value (Pakeman & Marrs 1992). However, a review does highlight that bracken can support some rare plants and provide cover to warblers, tree pipits (*Anthus trivialis*), nightjar (*Caprimulgus europaeus*), raptors, and medium-sized mammals such as badger (*Meles meles*) and deer in some circumstances (Pakeman & Marrs 1992). Trampling by cattle can be an effective strategy to reduce bracken cover, while rooting by wild boar (*Sus scrofa*) can convert bracken communities to grassland at the patch scale (Ridley et al. n.d.). Wild boar root up and eat the rhizomes of bracken in the autumn and winter, making it particularly effective at reducing bracken's competitiveness but there are potential health risks to the animals (Sandom et al. 2013a).

16. The traits of large herbivores

In this report we define large herbivores as species typically weighing 10kg or more as adults and whose diet is primarily (>50%) vegetation. We focus on the domestic large herbivores that are primarily used in conservation grazing in the UK: cattle, sheep, horses/ponies, goats and pigs. However, we also consider some wild large herbivores to a very limited extent, which include European bison (*Bison bonasus*), Eurasian elk (moose; *Alces alces*), red deer (*Cervus elaphus*), fallow deer (*Dama dama*), roe deer (*Capreolus capreolus*), wild boar, and Eurasian beaver (*Castor fiber*). We also recognise the role smaller animals, from rabbits to invertebrates, can have in grazing, but we are focusing on the larger animals that are typically managed for conservation grazing purposes.

Each large herbivore species has its own physical and behavioural traits that influence their interactions with other organisms and their environment. These varying traits mean the presence of different large herbivores can create different ecological outcomes. The ecological processes driven by large herbivores considered in this report are grazing, browsing, bark stripping, rooting, fraying, wallowing, trampling, defecation, urination and seed dispersal. All large herbivores trample, defecate, urinate and disperse seeds in one way or another, while some processes are restricted to only some species (such as rooting by pigs and wild boar).

16.1. The traits of large herbivores and the ecological processes they drive

We briefly consider how large herbivore body mass, diet, dental morphology, digestive physiology, limb morphology, and behaviour influence herbivory (grazing, browsing, bark stripping), disturbance (rooting, fraying, trampling, wallowing), nutrient cycling (defecation, urination), seed and animal dispersal (endozoochorous, exozoochorous), and conservation grazing outcomes.

Body mass/size: A species' body mass is a key trait that interacts with multiple other traits to determine how the species influences ecosystems (Lundgren et al. 2021). Body mass is strongly related to other life history attributes, including home range size, gut passage time, and metabolism. The greater distances large herbivores travel in combination with longer gut passage times can translate to longer seed dispersal distances in unfenced and large sites, influencing vegetation composition. Larger body size increases a species' maximum browse height. Taller maximum browse heights increase the height woody vegetation needs to reach to escape browsing pressure that would otherwise limit its height, with implications for succession and habitat heterogeneity (Churski et al. 2017).

The allometric scaling relationship between body mass and metabolism means that while larger animals need more energy than smaller animals, smaller animals need more relative to their body mass (Demment & Van Soest 1985). This means that two stocked animals half the weight of a larger one will require more energy than the single larger one. This can translate into the smaller animals eating more or eating higher quality vegetation compared to the larger one. However, the larger absolute energy requirements of larger herbivores typically necessitates the consumption of the more abundant lower quality forage, compared to higher quality protein rich foods (Clauss et al. 2013). Thus, larger herbivores will typically be more effective at clearing more highly abundant and fibrous vegetation, while smaller more selective herbivores can negatively affect valuable species or plant parts (such as buds and shoots) (Clauss et al. 2013), or reduce the cover of undesirable species other than those that are undesirable because they are highly abundant and fibrous.

Mouth morphology: Bite size partly regulates the rate at which large herbivores can consume vegetation, in combination with a species' energy requirements and food availability (Shipley 2007). Bite size can also influence competition and facilitation between large herbivore species, with consequences for vegetation structure. For example, on the Isle of Rhum the ability of smaller female red deer to achieve large intake rate against energy required on more nutritious short sward vegetation forces the larger males to graze taller sward vegetation (Shipley 2007). Larger grazers, like cattle, can also facilitate access to and stimulate the re-growth of more nutritious younger leaves that benefit some smaller herbivores (Bakker et al. 2009). Other small herbivores fare better without the competition from larger herbivores (Bakker et al. 2009). A more diverse assemblage of large herbivores could promote greater variation in grazing pressure, increasing habitat heterogeneity.

Dental morphology also influences the type of vegetation used by large herbivores. Cattle use their tongue to wrap around and tear taller vegetation leaving a taller sward (Tallowin et al. 2005). Horses and ponies have forward protruding teeth that increase their ability to graze a shorter sward and create lawns with specific characteristics. Cervids and sheep have smaller mouths allowing them to be more selective in choosing specific plant species and parts which can help suppress specific undesirable species or result in a loss of palatable rare species or the loss of flowering plants.

Digestive physiology: Digestive physiology has important implications for the quantity and quality of vegetation that large herbivores can consume. The herbivores under consideration are ruminants and hind gut fermenters (**Table 14**). The hind gut fermenters, such as horses/ponies, need to eat relatively more and are more dependent on drinking surface water compared to the relatively efficient ruminants (Esmaeili et al. 2021). As a result, for equivalent body mass horses are expected to consume more vegetation compared to similarly sized cattle.

Dung quality, in terms of C:N:P stoichiometry, varies between species with different diets, body mass and digestive physiology (Valdés-Correcher et al. 2019) with implications for nutrient cycling. The dung produced from digestion is also an important resource for a variety of species. For example, research in Italy sampled dung beetles' use of horse and cattle dung, with 50 and 55 species of dung beetle found in each type respectively (Tonelli et al. 2021). Two dung beetle species indicated a preference for horse dung, and six preferred cattle dung. There was also a difference in the functional diversity of dung use with larger, nesting species preferring cattle dung and smaller, non-nesting species preferring horse dung. These results suggest cattle and horses produce a valuable resource and a diversity of dung supports the greatest diversity of dung beetles.

Limb morphology: Limb morphology, in combination with body mass, is important in determining where is accessible to large herbivores and the degree to which vegetation and soil is trampled. All the large herbivores being considered are hoofed unguligrade species, a morphology that have stronger effects on soils compared to others (Lundgren et al. 2021). Smaller species and breeds, such as sheep and goats, are more suited to steep topography. Larger species typically have relatively shorter legs, shorter stride lengths, and so trample a greater area for the same distance travelled (Cumming & Cumming 2003) which can result in increased surface run off, decreased albedo and reduced vegetation biomass and cover (Lundgren et al. 2021). Thus, smaller species increase the places that can be grazed and reduce soil compaction. Trampling has been associated with reductions in arthropod abundance, even with light footfalls of large herbivores (van Klink et al. 2015).

Diet: Large herbivores can be primarily obligate grazers or browsers, or mixed feeders (**Table 14**). Species with more specialist diets (e.g. European elk, roe deer and horse) have correspondingly more specific habitat requirements, while mixed feeders are more suited to adapting to the resources available (Lundgren et al. 2021). Smaller large herbivores (e.g. sheep and smaller cervids), whether grazers, browsers, or mixed feeders, can be selective for high quality and favoured plant species and plant parts, while larger large herbivores (cattle and horses) are typically bulk feeders that consume a greater variety of species in large quantities (Clauss et al. 2013). As a result, diet is a key trait in determining which conservation goals each herbivore will contribute to.

Grazing large herbivores reduce sward biomass and height, which can increase sward heterogeneity when stocking densities are more lenient and spatial and temporally varied (Stein et al. 2014). Browsing large herbivores can prevent the establishment and development of shrubs and trees, up until these woody species shoots exceed the maximum height the largest herbivore can browse (Fuller & Gill 2001). Bulk feeders focus their foraging activity where there is sufficient biomass for them to harvest rapidly, helping to create sward structural diversity in taller and more mature vegetation. Smaller herbivores can be more selective feeders, seeking younger vegetation that contains higher protein to fibre ratios, and will also seek out more valuable plant parts such as fruits and flower heads (Clauss et al. 2013).

Bark stripping by large herbivores can increase tree and shrub mortality and so reduce woody vegetation establishment. The intensity of bark stripping is typically highly variable in space and time, with higher intensities directed towards certain tree species targeted (e.g. Poplar and Scots Pine), when the availability of alternative foods are limited, and during winter and spring (Verheyden et al. 2006).

Suidae have the most diverse diet, and although primarily herbivores are naturally more omnivorous and opportunist (Ballari & Barrios García 2014). By using rooting behaviour they can access resources unavailable to other herbivores (see 'Behaviour' section below). Their opportunistic omnivore diet means they can pose a threat to species with small populations through predation (Risch et al. 2021), although within their native range these negatives effects are related to the wider degradation of nature making these prey species vulnerable to natural predation.

Behaviour: Large herbivore behaviours such as rooting, wallowing, and fraying can also have impacts on vegetation structure and biodiversity. Rooting (animals using their nose to forage by sifting through ground vegetation and soil) creates bare ground that is important for a variety of invertebrates and creates germination niches for colonising plants (Sandom et al. 2013a, 2013b). Wild boar, pigs, and badgers can create a patch-scale disturbance regime, with individual wild boar known to create reasonably large areas (21 to 75 m2 but variable seasonally) of rooted ground per week in wetter conditions in the Scottish Highlands (Sandom et al. 2013b). In spring and summer, pigs and wild boar switch their foraging to grazing and browsing. Rooting can increase habitat heterogeneity by converting vegetation monocultures of species such as bracken into more mixed communities (Ridley et al. n.d.).

Wallowing (rolling on the ground in dust and mud for the purposes of grooming, repelling insects, socialising, and getting protection from the sun) focuses high levels of disturbance on a patch of ground (Nickell et al. 2018). Wallowing typically clears the vegetation and can result in the soil becoming compact. Where this occurs, the ground can become wet and create ephemeral pools. Wallows will eventually be abandoned, and the new conditions will encourage alternative plant species to establish. Research exploring arthropod diversity in active and abandoned wallows in North America revealed that both active and abandoned wallows support different arthropod diversity and abundance to each other and compared to the surrounding prairie (Nickell et al. 2018). All feeding groups except detritovores had lower species richness and abundance in active wallows compared to control sites on the prairie, but carnivore and detritovore groups have higher richness and diversity in abandoned wallows, while other groups are the same as on the prairie.

Fraying, thrashing, and rubbing are behaviours that involve a large herbivore rubbing against trees and shrubs (Gill 1992). These are common behaviours for territory marking and removing velvet from antlers. It can weaken trees and can disrupt scrub establishment. Fraying by roe deer increases with population density and is more prevalent when they are establishing territory in spring and the rut in July. Fraying in red and sika deer is reported to be associated with the autumn rut.

Table 14: Large herbivore characteristics and behaviours summary to provide a basic means of comparing the broad characteristics of different species. Values are species level averages that mask considerable within-species variation.

SPECIES	COMMON NAME	BODY MASS (KG)	HERBIVOROUS DIET (%)	GRAZER, BROWSER, MIXED	VEGETATION CONSUMED (kgC/DAY)	DIGESTIVE PHYSIOLOGY	LIMB MORPHOLOGY	BARK STRIPPING	ROOTING	WALLOWING	FRAYING
Alces alces	Moose	357.00	100	Browser	3.25	Foregut ruminant	Ungulligrade	1	0	1	1
Bison bonasus	European bison	500.00	100	Grazer	3.26	Foregut ruminant	Ungulligrade	1	0	1	0
Bos taurus	Cattle	440.00	100	Grazer	3.32	Foregut ruminant	Ungulligrade	0	0	0	0
Capra hircus	Goat	30.00	100	Mixed feeder	0.55	Foregut ruminant	Ungulligrade	1	0	0	0
Capreolus capreolus	European roe deer	22.50	100	Browser	0.56	Foregut ruminant	Ungulligrade	1	0	0	1
Cervus elaphus	Red deer	131.25	100	Mixed feeder	1.65	Foregut ruminant	Ungulligrade	1	0	1	1
Dama dama	Fallow deer	56.25	100	Mixed feeder	0.91	Foregut ruminant	Ungulligrade	1	0	1	1
Equus asinus	Donkey	180.00	100	Grazer	2.28	Hindgut colon	Ungulligrade	1	0	0	0
Equus caballus	Horse	300.00	100	Grazer	3.20	Hindgut colon	Ungulligrade	0	0	1	0
Ovis aries	Sheep	60.00	100	Mixed feeder	0.79	Foregut ruminant	Ungulligrade	1	0	0	0
Sus domesticus	Pig	95.50	94	Mixed feeder	1.48	Hindgut colon	Ungulligrade	0	1	1	0

17. Management options in conservation grazing

We are primarily concerned with the conservation implications of changing large herbivore management to reduce the GHG emissions associated with conservation grazing. In **Section 1** we identify a variety of 'levers of change' that could influence GHG emissions associated with conservation grazing. Here we consider how altering these same 'levers' influence biodiversity conservation outcomes. Firstly, it is important to note that through our research and discussions with The Wildlife Trusts it is clear that the 'levers' for altering GHG emissions and delivering biodiversity conservation goals are essentially the same. For example, when considering conservation grazing of lowland heath, Bullock and Pakeman (1997) report "possible management variables include: the animals and breeds used, stocking rates and herd size, grazing season, the proportion of a heathland grazed, the form of stock management (enclosures, shepherding or free-ranging animals), the use of rotational grazing, and integration with other methods (burning, mowing, turf-stripping, etc.)." At a workshop with The Wildlife Trusts these management variables were supported as important for conservation outcomes and map clearly onto the 'levers of change' for reducing GHG emissions presented in **Section 1**.

Consultation with The Wildlife Trusts through a workshop also revealed that a variety of management approaches can be used to achieve the same conservation goals. For example, three different calcareous grassland sites were reported as being managed to achieve the same goals of: 1) increasing sward structural diversity, 2) preventing scrub encroachment, 3) halting vegetation succession, and 4) reducing the dominance of some plant species. However, their management differed considerably: Site 1 was being grazed with cattle, at medium intensity, during the spring and early summer; Site 2 had sheep, at low intensity, in autumn and winter; and Site 3 had ponies, at medium intensity, in the spring and early summer. Assuming each of these management strategies is proving successful and that they are widely practicable and applicable, this variety of options could allow the lowest emission option to be selected.

While there is a variety of options for conservation grazing, the workshop with The Wildlife Trusts also revealed that there are barriers to implementation of some options in some places. For example, Trusts can only use species and breeds available to them, and they can only be stocked at densities and times at which they are available and can be moved. Some species of large herbivore cannot be stocked at sites with high human use or where dogs are prevalent. These and other barriers constrain Trusts' ability to simply select the conservation grazing option that is best for biodiversity and climate.

Here we will explore the potential and variety of biodiversity outcomes possible from changing conservation grazing in a parallel structure to **Section 1**. Our comparisons are necessarily reasonably general as the unique and specific conditions of any site will influence conservation grazing outcomes. Our generalities will only partially reflect reality and there will be plenty of exceptions. Site-specific knowledge and wider expertise are essential in considering trade-offs between climate change, nature conservation outcomes, and other considerations for all sites. However, this higher-level exploration of conservation grazing and conservation outcomes offers the opportunity to consider alternative conservation grazing strategies to achieve specific conservation goals at any specific site.

17.1. Impacts of species, breed, and body mass on achieving conservation goals

Goal	Species, breed, and body mass
1: Habitat heterogeneity	All large herbivores have the potential to increase habitat heterogeneity, but their relative effectiveness and the composition of the heterogeneity created will depend on the species present and their traits (**Table 14**; as well as stocking density, frequency, and season which are discussed in **Section 17.2**). For creating a more varied sward structure larger species, such as cattle and horses, are generally thought to be more effective, while sheep are more likely to create more homogenised sward with lower plant species richness (Stewart & Pullin 2006). Cattle and horses vary sward structural diversity and nutrient distribution by not grazing around their dung, creating patches of taller vegetation and increased nutrients. Browsers and larger animals have the greatest capacity to disrupt and diversify scrub development. Grazing strategies that include pigs have the potential to diversify sward height, control scrub, and create bare ground. Introducing species that wallow will also vary sward structure and introduce patches of bare and potentially wet ground. Habitat heterogeneity is likely to be maximised by a grazing regime that varies in space and time, with a variety of species with varying traits stocked in different combinations (Mountford & Peterken 2003; Loucougaray et al. 2004). Different breeds of species may have slightly different traits, but breed selection is likely to be based on their suitability for the site. The absence of grazing will allow greater vegetation biomass to establish, which could increase habitat heterogeneity with woody vegetation establishing, but the loss of grazing disturbance is likely to result in a more homogeneous structure and the loss of keystone features and resource diversity.
2: Specific habitat targets	A variety of species will help arrest succession from one vegetation community to another, and in particular help limit scrub expansion. Cattles' size and winter browsing make them effective at limiting scrub, while a combination of horses and deer are reported to have prevented scrub expansion for decades in the New Forest (Mountford & Peterken 2003). Goats can heavily browse scrub helping to limit its expansion, while cervids are also likely to help diversify the grassland scrubland mosaic through browsing and fraying. Stocking sheep in spring is also a strategy to limit scrub. Where restoration grazing is the target the larger body size of cattle is likely to help break up established scrub. Short grazing by horses and sheep (and rabbits) can be important for establishing species-rich 'lawns' in grassland. Rooting by wild boar and pigs can be particularly effective at reducing the cover of bracken.
3: Specific species targets	Smaller large herbivores tend to have more specialist diets, as their lower absolute energy demands and smaller mouth morphology allows them to seek out and select specific, more nutritious, plant species and parts. This can be beneficial where they select common and competitive species such as ragwort, dock, and nettle. However, when stocked in spring and summer it can result in the loss of flowering heads of plants, removing a useful resource for pollinators and granivores, as well as influencing seed dispersal potential.

17.2. Impacts of stocking density, frequency, and grazing season on conservation goals

Goal	Density, frequency, and season of grazing
1: Habitat heterogeneity	Stocking density, frequency and timing are key factors in managing conservation grazing as they will strongly influence the intensity, timing, duration, extent, and interval of the grazing disturbance. In the broadest sense, 'intermediate' stocking densities and frequencies should increase habitat heterogeneity and so support greatest biodiversity (Stewart & Pullin 2006). However, what constitutes as 'intermediate' will vary with environmental conditions. A review of 141 studies on the effects of increasing stocking density on semi-natural habitats that were already under conservation grazing found that in 80% of cases higher stocking density resulted in reduced arthropod species richness, suggesting lower stocking densities are important. Lower stocking densities may be sufficient to maintain a mixed mosaic of woody and open vegetation, while intermediate and even high stocking densities will be needed to restore open patches where scrub is beginning to dominate (and where too established, other methods will be needed). High stocking will promote the creation of bare ground, wallow, and dung resources, but at the expense of vegetation biomass and other types of resources, so lower and intermediate stocking densities will improve heterogeneity. To account for the diverse needs of nature, a diversity of stocking practices should support greater biodiversity overall. Periods of high stocking density and frequency will serve to disrupt dominant communities, disperse seed, diversify nutrient distribution and provide resources such as dung, and so increase heterogeneity. However, rest periods of low or no grazing will provide increased vegetation resources and provide stability for more complex interactions to develop within the ecosystem. Grazing in different seasons presents risks and opportunities that vary with species and stocking density. Grazing with larger herbivores at higher densities in autumn and winter risks removing vegetation cover and poaching and compacting the soil. Intense, infrequent grazing in autumn can help break up established vegetation and promote the establishment of new communities. Varying stocking practices between sites may also be effective in increasing diversity overall.
2: Specific habitat targets	High stocking densities of large and/or browsing herbivores can be important in restoration grazing, especially when seeking to reduce scrub cover. Stocking frequency needs to be sufficiently regular to prevent too much woody vegetation from escaping the browse trap. The frequency of grazing will need to be greater when stocking smaller species with lower body mass and lower maximum browse heights. Spring browsing can be important for encouraging browsing of new shoots. However, stocking in winter can drive more browsing behaviour with reduced foraging alternatives at this time of year. Wild boar only root when conditions are suitable, so if bare ground creation or bracken cover reduction is a target, stocking will typically need to be in autumn and winter to ensure the ground is wet enough.
3: Specific species targets	Grasslands are important for supporting dozens of birds of conservation concern in the UK, and the way grasslands are grazed is partly responsible for the success of these species (Wakeham-Dawson & Smith 2000). The intensity of grazing can strongly influence the abundance of invertebrates, which are important prey for the chicks of species such as cirl bunting (*Emberiza cirlus*), yellowhammer (*Emberiza citronella*) and skylark. Higher stocking densities that reduce the sward to a uniform level of below 10cm in height have been recorded as supporting half the abundance of invertebrates compared to sward between 15 and 25cm in height. Taller swards created by lower grazing intensities also support higher rodent abundance, which supports predatory birds such as kestrel (*Falco tinnunculus*), barn owl (*Tyto alba*), and short-eared owl (*Asio flammeus*). The conservation of seed-eating birds on dry grasslands is improved by having ungrazed or lightly grazed areas as they can support 15 times as many grass seed-heads. Common redshank (*Tringa tetanus*) have been recorded to thrive in lightly grazed (<1 cattle/ha) saltmarshes (Sharps et al. 2017). However, even at low stocking densities nest trampling can be a considerable problem if livestock distribution doesn't vary. Conversely, if a key target is to conserve soil invertebrate feeders such as redwings (*Turdus iliacus*), lapwings (*Vanellus vanellus*), and stone curlews (*Burhinus oedicnemus*) then more intensive grazing is needed to reduce the sward height considerably and expose bare ground. For example, in East Anglia when grazing by domestic livestock and rabbits was reduced in grass heathland, breeding stone curlews, woodlarks (*Lullula arborea*), and wheatears (*Oenanthe oenanthe*) all decreased in numbers. Large herbivores can also be used to reduce dominant or undesirable species. For example, sheep grazing in spring can help reduce ragwort abundance. Wild boar and pigs are most likely to root bracken rhizomes in autumn and winter, when the ground is wet, reducing bracken's dominance.

17.3. Impacts of methane-reducing supplements on achieving conservation goals

There is currently insufficient evidence to assess the potential impacts of providing livestock supplements to reduce methane emissions on conservation outcomes. Supplementary feeding can influence nutrient loading and distribution, as well as influencing the distribution of trampling which may apply if supplements to reduce methane emissions have to be coupled with supplementary feed. Further research would be required to determine whether methane-reducing supplements can influence livestock health, growth or vegetation consumption.

18. Large herbivore species profiles

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18.1. Cattle

Conservation goal category	Relevant quote
Promoting habitat heterogeneity	• *"They [cattle] are generally better than sheep at creating and maintaining structurally diverse grassland: 1) their large size and heavy weight breaks up the ground; 2) they avoid grazing around dung pats which creates patches of longer vegetation important for insect communities. These in turn are eaten by birds and bats; 3) cattle are particularly good at knocking down and creating gaps in tall, coarse vegetation such as bracken and scrub."* http://www.magnificentmeadows.org.uk/assets/pdfs/Types_of_Livestock.pdf • *"Cattle wrap their tongues around vegetation and pull it up in tufts, which creates an uneven sward in terms of length and a tussocky finish. They are good at pushing their way through scrub and creating open areas, in addition to eating longer and coarser grasses. They are considered preferable to sheep and horses when improving a habitat for invertebrates. However, their size means that their presence can lead to undesirable levels of trampling and poaching if not managed carefully."* https://insideecology.com/2017/11/09/conservation-grazing/ • *"The manure from grazing livestock, especially cows, is a great source of nutrients for plants and insects. More than 250 species of insects have been found on cattle dung in the UK. An added benefit of low intensity grazing is that the smaller numbers of animals are less likely to need treatment for internal parasites and so no chemicals go into the soil or food chain."* https://www.gwentwildlife.org/living-landscapes/conservation-grazing • *"Although predominantly grazers, the breed [Belted Galloway] eats a greater degree of scrub and browse than many other cattle types. They don't graze as selectively as sheep and ponies, helping to remove coarse grasses and create a greater variety of structure in habitats. Their bulk also enables them to create areas of bare ground and break up dense vegetation."* https://www.surreywildlifetrust.org/what-we-do/restoring-surreys-nature/conservation-grazing
Habitat specific goals	• *"Livestock exclusion can benefit the abundance and diversity of multiple trophic levels. However, abandoning grazing in certain environments may not result in an increase to biodiversity and in some instances can cause further loss. For instance, we observed grazing having a positive effect on plant diversity and four studies within our meta-analysis where animal diversity increased with livestock grazing, contradicting the general trend (Ranellucci et al. 2012; Schmidt et al. 2012; Verga et al. 2012; Tabeni et al. 2013). In all four studies, livestock grazing maintained grassland structure by suppressing woody encroachment, which supports specific animal species."* https://onlinelibrary.wiley.com/doi/epdf/10.1111/ele.13527
Species specific goals	• *"Cattle are particularly good at reducing some problem grassland plant species. For example, tor-grass occurs on calcareous grassland and is not particularly palatable for livestock. However, it is most palatable earlier in the year when the shoots appear and cattle can be used to spring-graze pastures where it occurs. Spring-grazing can also be used to reduce other grasses like tufted hair-grass and purple moor-grass."* http://www.magnificentmeadows.org.uk/assets/pdfs/Types_of_Livestock.pdf • *"Cattle are also potentially a useful tool for spring grazing if a grassland has an excess of fibrous, invasive less desirable grass species such as tor grass. The non-selective grazing nature of cattle, means they will not seek out the broad-leaved species as sheep will, but instead will munch away at the grass species."* https://www.lrwt.org.uk/blog/fran-payne/conservation-grazing-what-it-and-why-do-we-do-it • *"Highland cattle are helping to improve habitats for butterflies, including the rare chequered skipper and pearl-bordered fritillary. The cattle graze the hillside and trample the bracken, encouraging the food plants that butterflies and their larvae like to eat. Careful management of grazing is also benefiting black grouse. Not only are cattle (and, in places, sheep) creating areas of short grass – perfect for males to display in the breeding season – they are also encouraging a wider variety of vegetation for the grouse and their chicks to feed on."* https://forestryandland.gov.scot/what-we-do/biodiversity-and-conservation/habitat-conservation/open-habitats/conservation-grazing
Potential negative outcomes	• *"Across all animals, livestock exclusion increased abundance and diversity, but these effects were greatest for trophic levels directly dependent on plants, such as herbivores and pollinators. Detritivores were the only trophic level whose abundance decreased with livestock exclusion. We also found that the number of years since livestock was excluded influenced the community and that the effects of grazer exclusion on animal diversity were strongest in temperate climates."* https://onlinelibrary.wiley.com/doi/epdf/10.1111/ele.13527
Practical considerations	• *"Traditional breeds are more adapt at eating rough grassland, putting on weight and maintaining condition for production, compared with commercial breeds."* http://www.magnificentmeadows.org.uk/assets/pdfs/Types_of_Livestock.pdf • *"Cattle need more water than sheep, and access to troughs is required at all times. The location of water troughs and mineral licks can be used to influence where cattle graze."* http://www.magnificentmeadows.org.uk/assets/pdfs/Types_of_Livestock.pdf

18.2. Horses/Ponies

Conservation goal category	Relevant quote
Promoting habitat heterogeneity	• *"The benefits of grazing with horses and ponies are: 1) they preferentially select sweet grasses, but will also eat a variety of sedges and rushes particularly later in the summer; 2) they tend not to select flowers, as sheep do, and avoid buttercup, common knapweed and ragwort; 3) they regularly graze tufted grasses, including tor-grass; 4) these 'fussy' diets are ideal for maintaining the mosaic habitat needed by many insects."* http://www.magnificentmeadows.org.uk/assets/pdfs/Types_of_Livestock.pdf • *"Ponies and horses graze close to the ground, but will also create latrines (toilet sites!) that they will not graze creating structural diversity within a grassland and as they are not ruminants (like sheep and cattle) they are constantly grazing."* https://www.lrwt.org.uk/blog/fran-payne/conservation-grazing-what-it-and-why-do-we-do-it
Habitat specific goals	• *"Ponies are nutritionally adapted to graze on unimproved, species-rich grasslands, which is seen as their main advantage."* https://insideecology.com/2017/11/09/conservation-grazing/
Species specific goals	• *"In the autumn, some breeds such as New Forest ponies, will graze large quantities of bracken once the toxicity has reduced, making them ideal for restoration grazing."* http://www.magnificentmeadows.org.uk/assets/pdfs/Types_of_Livestock.pdf
Potential negative outcomes	• *"Problems can arise in specific locations as horses may create latrine areas, which lead to a tightly grazed vegetation and can cause localised high nutrient levels and encourage the spread of thistles, nettles and docks. Regular collection of dung will alleviate this problem and usually the more species-rich areas of a site are not used as a latrine as they are become preferred grazing locations."* http://www.magnificentmeadows.org.uk/assets/pdfs/Types_of_Livestock.pdf
Practical considerations	• *"Native breeds such as Exmoor, Dartmoor and New Forest ponies are regarded as more suitable for rough grasslands and are hardy, being able to cope in adverse weather as they are often reared outside without ever being brought into a stable."* http://www.magnificentmeadows.org.uk/assets/pdfs/Types_of_Livestock.pdf

18.3. Sheep

Conservation goal category	Relevant quote
Promoting habitat heterogeneity	• *"Although they have a reputation for grazing vegetation very close to the ground, in actual fact this is generally as a result of over-stocking: if the numbers of sheep are fairly low for the area, then they can produce a varied sward structure."* https://www.kentwildlifetrust.org.uk/sites/default/files/2018-06/KWT%20Land%20Mgt%20Advice_Sheet%205%20-%20Choosing%20livestock%20for%20conservation%20grazing.pdf
Habitat specific goals	• *"Sheep have thin, mobile lips and move slowly over the sward nibbling the grass. They eat selectively when circumstances allow, biting off single leaves or shoots down to a height of 3 cm."* http://www.magnificentmeadows.org.uk/assets/pdfs/Types_of_Livestock.pdf • *"We try to achieve 'wigeon lawns' for them to feed on during the winter months (from November through to March). The best tool to create these 'lawns' are sheep! So through the Autumn months and into the winter many of the Rutland Water flock of sheep are on grasslands to manage this important winter habitat."* https://www.lrwt.org.uk/blog/fran-payne/conservation-grazing-what-it-and-why-do-we-do-it • *"The Hebridean sheep are hardy but also very happy to browse on woody vegetation such as encroaching blackthorn, hawthorn and silver birch, all species that we want to prevent from creeping into wildflower meadows and other species rich grasslands."* https://www.lrwt.org.uk/blog/fran-payne/conservation-grazing-what-it-and-why-do-we-do-it
Species specific goals	• *"Sheep are less susceptible to the toxins in ragwort and so can be used to spring graze it in its rosette stage to prevent flowering and setting seed. However, they are not immune to its toxins so require plenty of other vegetation to eat along with it."* http://www.magnificentmeadows.org.uk/assets/pdfs/Types_of_Livestock.pdf • *"Sheep are very selective grazers. With their small, dexterous mouths they can select out any tasty broad leaved species, which can be a useful tool when targeting unwanted species in a grassland such as ragwort, dock or nettle."* https://www.lrwt.org.uk/blog/fran-payne/conservation-grazing-what-it-and-why-do-we-do-it
Potential negative outcomes	• *"Sheep are useful in areas that can't be accessed by larger animals. They do need to be used with some caution as they can select flower-heads to eat, which may not be advantageous for certain conservation schemes. Sheep tend to nibble shorter grasses, they are good for the control of scrub and are easy to handle."* https://insideecology.com/2017/11/09/conservation-grazing/
Practical considerations	• *"The benefits of grazing with sheep are: 1) they are light and more agile than cattle and are more suited to steeply sloping land; 2) although on heavy, wet soils sheep can cause trampling and poaching they do not have such an impact as heavier grazers; 3) their dung is deposited randomly and they will graze next to it, therefore grazing swards to a uniformly low height."* http://www.magnificentmeadows.org.uk/assets/pdfs/Types_of_Livestock.pdf • *"It is notable that sheep only develop a full set of adult teeth after 3-4 years and then steadily lose them as they age, therefore young and old sheep may not graze as effectively as middle-aged sheep."* http://www.magnificentmeadows.org.uk/assets/pdfs/Types_of_Livestock.pdf • *"Extensive bramble can cause difficulties for sheep as their fleece may get caught."* http://www.magnificentmeadows.org.uk/assets/pdfs/Types_of_Livestock.pdf

18.4. Goats

Conservation goal category	Relevant quote
Promoting habitat heterogeneity	• *NA*
Habitat specific goals	• *"Feral goats may be managed as a livestock herd. They are browsers, consuming woody vegetation 50-75% of their feeding time where this is available, and do best on land that has scrub and tufted grasses making them particularly suited to restoration grazing."* *http://www.magnificentmeadows.org.uk/assets/pdfs/Types_of_Livestock.pdf* • *"Usually they graze grasses down to a height of around 6 cm and can target grass seed heads eating them before starting to eat the leaves."* *http://www.magnificentmeadows.org.uk/assets/pdfs/Types_of_Livestock.pdf* • *"Goats will bark strip taking in order of preference, holly, ash, rowan and willow, oak, hazel, alder and birch in upland situations. In lowland situations they tend to eat elder first, followed by ash, blackthorn, sycamore and rose. They generally do not eat field maple or hawthorn."* *http://www.magnificentmeadows.org.uk/assets/pdfs/Types_of_Livestock.pdf* • *"Deer and goats have a greater propensity for browsing woody shrubs and trees than cattle or sheep and therefore in habitats with this type of vegetation such as heather moorland, woodland and scrub, their impacts can be greater than an equivalent stocking rate of other livestock."* *https://www.fas.scot/downloads/tn686-conservation-grazing-semi-natural-habitats/*
Species specific goals	• *NA*
Potential negative outcomes	• *NA*
Practical considerations	• *"The benefits of grazing with goats are: 1) they have a small muzzle and a flexible upper lip allowing them to be highly selective about what they eat. Goats prefer to eat the newer growth and leaves of scrub, bramble and tufted grasses rather than finer grasses; 2) they are less prone to foot rot than sheep making them suitable for wetter sites but they do need some dry sheltered ground within their home range; 3) they are agile and can tackle steep hills and rock edges, particularly suited to cliff edges that other livestock would have trouble accessing."* *http://www.magnificentmeadows.org.uk/assets/pdfs/Types_of_Livestock.pdf* • *"Feral goats may be managed as a livestock herd. They are browsers, consuming woody vegetation 50-75% of their feeding time where this is available, and do best on land that has scrub and tufted grasses making them particularly suited to restoration grazing."* *http://www.magnificentmeadows.org.uk/assets/pdfs/Types_of_Livestock.pdf* • *"Goats can be difficult to manage, and are often considered to be escape artists breaking out of enclosures. However, they can be very effective and different breeds can be used to address separate situations and issues."* *http://www.magnificentmeadows.org.uk/assets/pdfs/Types_of_Livestock.pdf*

18.5. Pigs

Conservation goal category	Relevant quote
Promoting habitat heterogeneity	• *"Contrary to popular belief, pigs do not uproot everything. They willingly graze, browse and consume berries and fungi, and have been known to take invertebrates which helps to create and maintain a mosaic of bare ground, herb rich pasture and shrub layer."* https://www.wcl.org.uk/using-pigs-in-conservation-grazing.asp • *"At low densities, pigs will dig some areas forsaking others."* https://www.wcl.org.uk/using-pigs-in-conservation-grazing.asp
Habitat specific goals	• *"The Tamworths [pigs] have quite a different effect to the Red Poll [cattle] and Exmoors [ponies] – they disturb the soil, almost ploughing the top layer as they rootle in search of food. This behaviour helps vegetation to regenerate, and we're particularly hoping will help restore our acid heathland, which is rank and overgrown."* https://wildkenhill.co.uk/introduction-of-grazing-animals • *"Their rooting behaviour can clear dense ground vegetation such as bracken, reducing the need for weed control and creating seed beds for natural regeneration."* https://www.wcl.org.uk/using-pigs-in-conservation-grazing.asp • *"Dense oak stands in the Wyre Forest were opened up to restore old coppice plots relying on natural regeneration. Growth of bracken and bramble was preventing the growth of new oaks in some areas so pigs were turned out in mid-summer to break up this growth, creating bare patches and allowing light to reach acorns from the remaining oaks which resulted in the growth of new oaks. Removing pigs from the site before acorns fall in the autumn ensures they aren't eaten."* https://www.wcl.org.uk/using-pigs-in-conservation-grazing.asp • *"In other parts of the forest, pigs have been used in areas cleared of western hemlock to intensively clear hemlock seedlings and saplings, and to break up the ground in preparation for planting or natural regeneration of native broadleaves. Pigs usually only disturb young trees, saplings and seedlings once all other food sources have been exhausted so with the correct stocking densities, they can be used effectively to reduce competition between trees and other vegetation in a regenerative area."* https://www.wcl.org.uk/using-pigs-in-conservation-grazing.asp • *"Pigs have also been used by the Dunlossit Estate for bracken control in variety of different habitats including moorland, coastal woodland, coppiced woodland and rape fields. It was noticed that given a varied environment they had selected bracken, ignoring everything else. The undergrowth was stripped to soil and showed reduced bracken growth in later years."* https://www.wcl.org.uk/using-pigs-in-conservation-grazing.asp
Species specific goals	• *"Pigs are also useful in the management of Rhododendron, supporting management by improving access to the woodland floor for silviculture to commence. They can also be used after removal to break up the leaf litter, allowing light to the woodland floor and natural regeneration to occur as well as suppressing any new growth of Rhododendron. Though pigs won't eradicate Rhododendron themselves, they are an excellent alternative to herbicides and machinery."* https://www.wcl.org.uk/using-pigs-in-conservation-grazing.asp
Potential negative outcomes	• *"In the New Forest between 200 and 600 pigs are used to carry out a practice known as Pannage each autumn. To stop pigs causing damage to the woodland floor through rooting, rings are often placed through their noses and removed once Pannage has been completed."* https://www.wcl.org.uk/using-pigs-in-conservation-grazing.asp
Practical considerations	• *"the pigs got out 3 times and it wasn't until the third time that RSPB staff worked out that they had learned to cross the cattle grids. Some rapid modifications by the warden team ensued. On Wednesday, a group of 5 got out over a cattle grid that hadn't yet been modified. On Thursday, 3 of them learned to get around the modification and so further modifications were made."* https://group.rspb.org.uk/southwiltshire/news-blogs/news/conservation-pigs-are-really-smart/ • *"Traditional British breeds such as Gloucester Old Spot, Oxford Sandy and Black, British Saddleback or Tamworth pigs tend to be hardier, more suitable for feeding on a variety of food foraged for themselves and some are less prone to sun burn."* https://www.wcl.org.uk/using-pigs-in-conservation-grazing.asp

19. Impacts of species, breed, and body mass on achieving conservation goals

The tables below provide quotes and their sources from reports, webpages, and research papers on how different management options for conservation grazing can deliver the different goals of conservation grazing, the problems they may cause, and some of the practical considerations in stocking them. These have been captured using the same approach as **Section 18**.

19.1. Stocking density

Conservation goal category	Relevant quote
Promoting habitat heterogeneity	• *"To maintain good site condition, a balance must be achieved between the annual production of dry matter in the vegetation and the utilisation of this production by grazing herbivores. If the utilisation is too low, there will be a build-up of taller plants and dead plant material, while if it is too high there will be a loss of structural diversity in the vegetation. Both situations usually result in a loss of biodiversity."* https://www.fas.scot/downloads/tn686-conservation-grazing-semi-natural-habitats/ • *"If the aim of management is to maintain the balance of habitats in the mosaic then the initial stocking rate should be determined by the proportion of the site occupied by each habitat multiplied by the guideline stocking rate for that habitat."* https://www.fas.scot/downloads/tn686-conservation-grazing-semi-natural-habitats/
Habitat specific goals	• *"Where a pulse of new regeneration is desired on a site where moss and other ground vegetation is thought to be preventing seeds from reaching the soil, it may be better to have higher stocking rates for a short period to disturb the ground and create a suitable seedbed, before removing or significantly reducing grazing pressure and allowing the regeneration to occur."* https://www.fas.scot/downloads/tn686-conservation-grazing-semi-natural-habitats/
Species specific goals	• *"They have also been used to reduce rush on wet grassland, with restoration achieved after 3-4 years by spring mob grazing with goats at a stocking density of more than 10 animals per hectare."* http://www.magnificentmeadows.org.uk/assets/pdfs/Types_of_Livestock.pdf
Potential negative outcomes	• *"This quantitative assessment showed no overall significant effect of increasing grazing intensity on plant diversity, while arthropod diversity was generally negatively affected. To understand these negative effects, we explored the mechanisms by which large herbivores affect arthropod communities: direct effects, changes in vegetation structure, changes in plant community composition, changes in soil conditions, and cascading effects within the arthropod interaction web. We identify three main factors determining the effects of large herbivores on arthropod diversity: (i) unintentional predation and increased disturbance, (ii) decreases in total resource abundance for arthropods (biomass) and (iii) changes in plant diversity, vegetation structure and abiotic conditions."* https://onlinelibrary.wiley.com/doi/full/10.1111/brv.12113 • *"Having very high levels of stocking for short periods runs the risk of damage to the sward and soil."* https://www.fas.scot/downloads/tn686-conservation-grazing-semi-natural-habitats/ • *"Appropriate stocking rates are very low and in areas with bog pools, eroding peat or a high proportion of sphagnum moss, grazing by livestock may not be appropriate at all."* https://www.fas.scot/downloads/tn686-conservation-grazing-semi-natural-habitats/
Practical considerations	• *NA*

19.2. Stocking timing

Conservation goal category	Relevant quote
Spring	• *"Cattle are also potentially a useful tool for spring grazing if a grassland has an excess of fibrous, invasive less desirable grass species such as tor grass. The non-selective grazing nature of cattle, means they will not seek out the broad-leaved species as sheep will, but instead will munch away at the grass species."* https://www.lrwt.org.uk/blog/fran-payne/conservation-grazing-what-it-and-why-do-we-do-it • *" Winter and spring grazing may also be desirable where grassland is threatened by scrub encroachment: browsing of shrubs such as gorse (particularly in the spring when fresh growth is most palatable) can reduce the rate of encroachment."* https://www.fas.scot/downloads/tn686-conservation-grazing-semi-natural-habitats/ • *"Cattle are particularly good at reducing some problem grassland plant species. For example, tor-grass occurs on calcareous grassland and is not particularly palatable for livestock. However, it is most palatable earlier in the year when the shoots appear and cattle can be used to spring-graze pastures where it occurs. Spring-grazing can also be used to reduce other grasses like tufted hair-grass and purple moor-grass."* http://www.magnificentmeadows.org.uk/assets/pdfs/Types_of_Livestock.pdf • *"Sheep are less susceptible to the toxins in ragwort and so can be used to spring graze it in its rosette stage to prevent flowering and setting seed. However, they are not immune to its toxins so require plenty of other vegetation to eat along with it."* http://www.magnificentmeadows.org.uk/assets/pdfs/Types_of_Livestock.pdf • *"Where wintering birds are present you should reduce stock levels in spring to avoid livestock trampling nests."* https://www.gov.uk/guidance/graze-with-livestock-to-maintain-and-improve-habitats
Summer	• *"Where wintering birds are present you should reduce stock levels in spring to avoid livestock trampling nests."* https://www.gov.uk/guidance/graze-with-livestock-to-maintain-and-improve-habitats • *"During the summer, you can graze larger areas at low stock densities. This can be useful in the uplands and on grasslands that are less species-rich."* https://www.gov.uk/guidance/graze-with-livestock-to-maintain-and-improve-habitats • *"Flower-rich habitats are vulnerable to grazing in the summer, particularly by sheep which can selectively remove flower- heads."* https://www.fas.scot/downloads/tn686-conservation-grazing-semi-natural-habitats/
Autumn	• *"Late summer and autumn grazing is usually best for species-rich habitats. This allows wildflowers to flower and set seed in the spring and summer. On drier grasslands, you may be able to use a high livestock level for short periods."* https://www.gov.uk/guidance/graze-with-livestock-to-maintain-and-improve-habitats
Winter	• *"You'll usually need to remove livestock over the winter to avoid overgrazing and the risk of poaching wetter areas."* https://www.gov.uk/guidance/graze-with-livestock-to-maintain-and-improve-habitats • *"Tree and shrub regeneration and heather are vulnerable to browsing damage in the winter when more palatable food is in short supply."* https://www.fas.scot/downloads/tn686-conservation-grazing-semi-natural-habitats/ • *"Grazing pressure should not be increased above the overall annual recommended stocking rate during the winter as that is when browsing on heather is most frequent and excessive browsing can result in heather loss."* https://www.fas.scot/downloads/tn686-conservation-grazing-semi-natural-habitats/

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Section 3: Reducing greenhouse gas emissions while achieving conservation goals

Chapter Authors: *Jennifer Ramsay, Helen Wheeler, Christopher J. Sandom*
Chapter Reviewed by: *Joseph W. Bull and Nigel Doar*

21. Summary

Through a comprehensive and systematic review of the evidence, we have identified a number of strategies to reduce greenhouse gas (GHG) emissions in conservation grazing. By considering the combined implications of **Section 2** (grazing impacts on conservation goals) and **Section 1** (grazing impacts on GHG emissions), we have identified measures that are likely to achieve emissions reductions whilst minimising the impacts on conservation goals. These strategies would require trials and monitoring to assess short- and long-term impacts on biodiversity, GHG emissions and carbon sequestration.

Key strategies:

- Change species composition to reduce cows and sheep and proportionally increase horses, ponies and pigs.
- Use mixed herds to allow proportional reductions in cattle and sheep whilst maintaining equivalent grazing impact and enhancing habitat heterogeneity.
- Reduce herd density and combine this with targeted grazing approaches to allow equivalent grazing impact at lower densities.
- Trial novel approaches to administer methane-reducing supplements (seaweeds and Bovaer®).

We recommend combining these strategies to provide the widest benefits for both conservation and GHG reduction. In particular, mixed herds (replacing a proportion of cows and sheep with horses and pigs) could achieve reductions in high-emitting livestock whilst maintaining adequate grazing impact and habitat heterogeneity.

The extent to which these strategies can be implemented in different contexts will vary greatly between different sites and habitats. In some cases, options may be limited by the specific requirements of the habitat or scarce species, or by practical considerations such as public safety, stock availability from local graziers, or time and cost constraints. However, using a combination of approaches allows flexibility for different habitat goals and site-specific requirements.

This review has also highlighted where there are significant gaps in the evidence and where further research is required. An experimental approach, combined with sharing of experiences and outcomes between different sites and Wildlife Trusts, will be vital to identifying the most effective approaches in different habitats. Sharing successful approaches with other conservation bodies, agencies and land managers across the UK (and more widely) could generate substantial annual GHG reductions whilst achieving conservation goals.

22. Climate change evidence summary

The evidence base for GHG emissions and carbon storage is explored in detail (with references) in **Section 1**. Here we present a brief summary of this evidence.

22.1. Impacts of species, breed, and body mass on GHG emissions

Table 15 summarises the key GHG impacts and conservation implications of changes to livestock species, breed and body mass. Changes to species composition could generate substantial reductions in GHG emissions from livestock. In particular, switching from cows and sheep to horses and pigs would bring very substantial reductions. For example, dairy cows have around eight times the total GHG emissions of horses per head and for equivalent Livestock Units (see **Figures 7** and **8**). To maintain the conservation benefits of cows and sheep, this could be achieved through mixed herds, with a proportion of cows and sheep replaced by horses and pigs, but some cows and sheep retained for their unique conservation benefits. A proportion of cows could also be replaced by goats to contribute to scrub control with lower emissions.

Table 15: Summary of the key greenhouse gas (GHG) and carbon impacts from changes to livestock species, breed and body mass, as well as conservation implications.

Change	GHG and carbon impacts	Conservation impacts
Change from high- to low-emitting livestock	Replacing a proportion of cows and sheep with horses and pigs would bring very substantial GHG reductions with little impact on carbon storage. Example: replacing half a herd of 20 dairy cows with horses (from 20 cows to 10 cows and 10 horses) would generate GHG reductions of around 40,000 kg CO_2e per year.	Conservation impacts will depend on habitat goals, but use of mixed herds (to retain some cows and sheep) would reduce potentially negative impacts on conservation goals and could enhance biodiversity by introducing a wider diversity of grazers.
Change from larger to smaller breed	Breed changes are unlikely to generate substantial reductions in emissions compared to species changes. Switching from larger to smaller breeds is likely to generate some GHG reductions per head (but is unlikely to make much difference per DMI or kg production).	In most circumstances, when keeping LU the same, changing breeds is unlikely to have substantial biodiversity impacts. Priority may be given to selecting breeds that are best suited to habitat conditions and specific conservation goals.
Change to individuals of smaller body mass	The use of smaller individuals (e.g. Younger age structure or smaller breed) is likely to generate some GHG reduction per head (but not per DMI or kg production).	Using smaller individuals and younger age structures is unlikely to impact biodiversity. However, more individuals may be required for equivalent grazing impact, which could negate any GHG reductions.

Figure 7: Total CO_2 equivalent emissions (from combined CH4 and N2O) from different livestock types for similar grazing impact (using equivalent Livestock Units and UK GHG Inventory estimates).

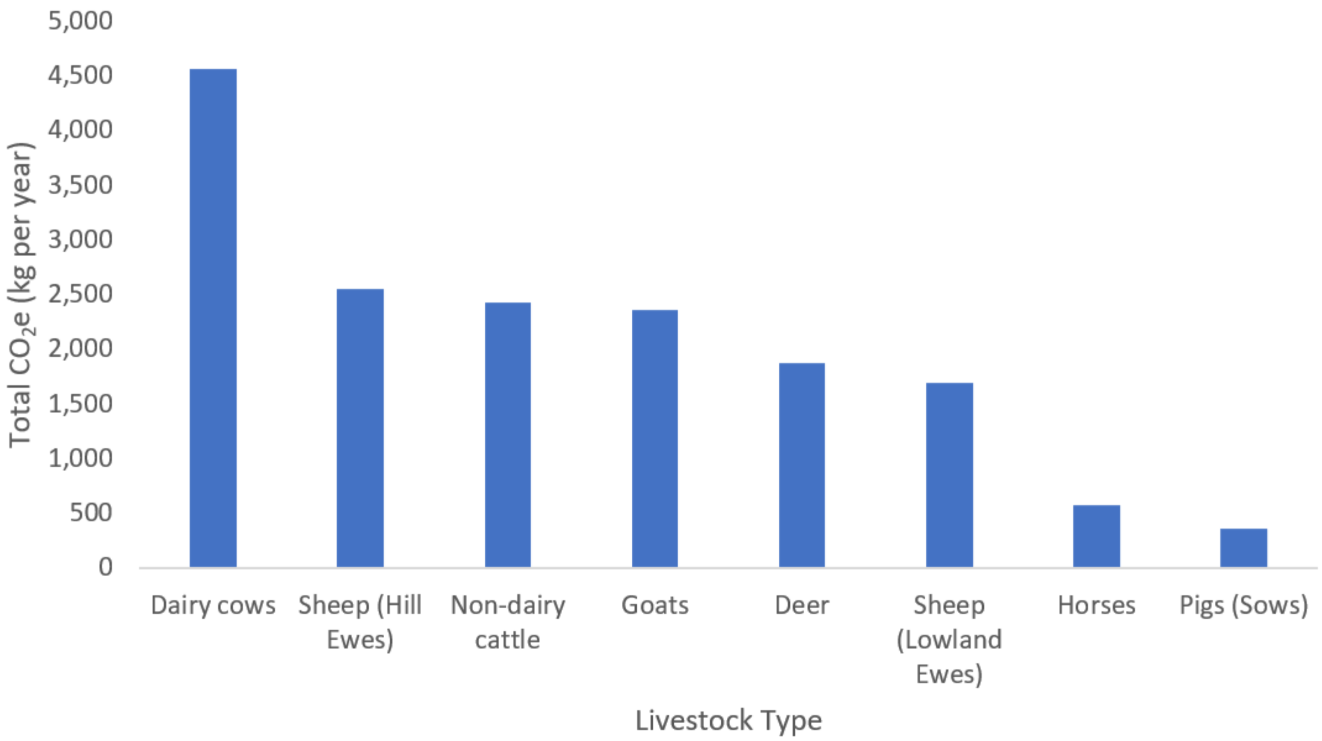


Figure 8: Enteric methane emissions from different livestock types for similar grazing impact (using methane emissions per DMI from the literature).

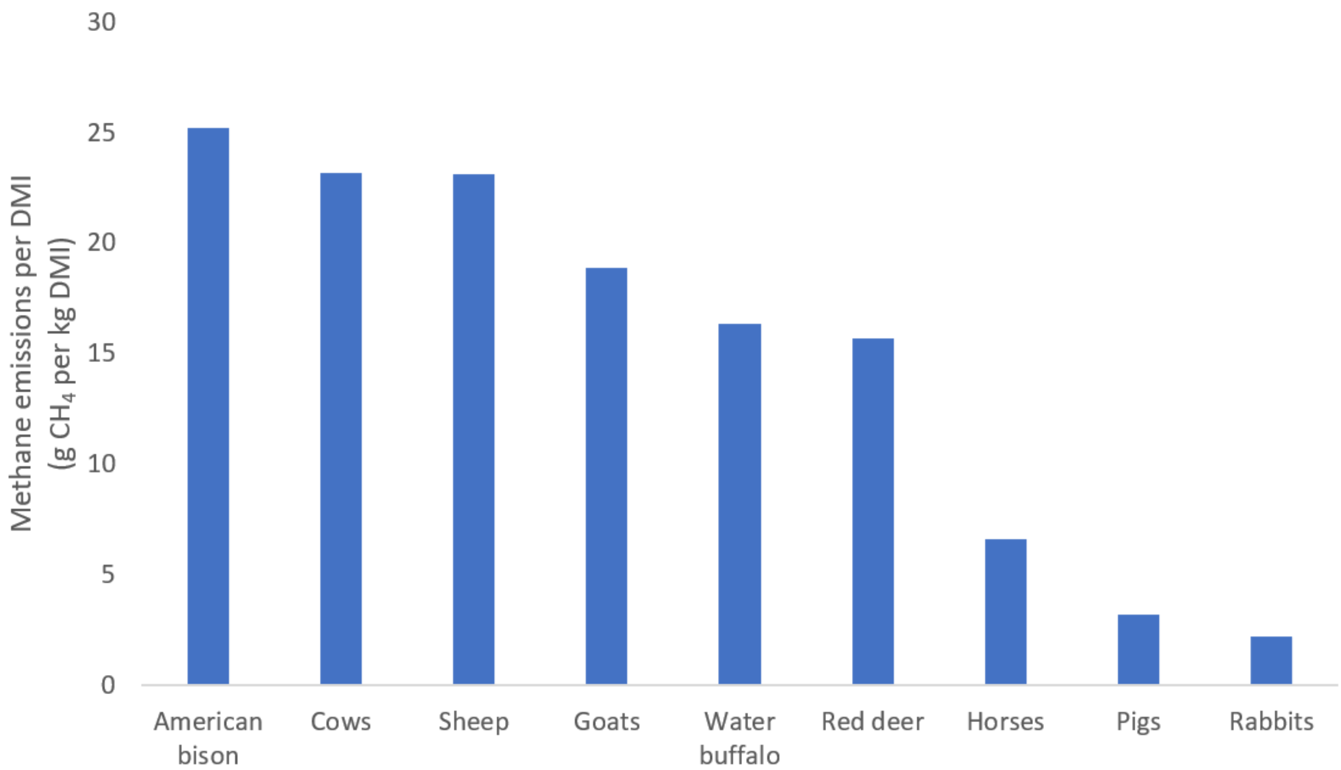


Table 16 and **Figure 7** indicate GHG emissions for different livestock categories, based on UK Livestock Units (LUs) and emissions estimates in the UK GHG Inventory. It indicates an order of emissions (for equivalent LUs) from highest to lowest of: dairy cows, hill sheep, beef cows, goats, lowland sheep, red deer, horses and pigs. The order of goats and sheep depends on whether LUs for lowland or hill sheep are used (goats are higher than sheep when lowland sheep LUs are used, but the order is reversed for hill sheep LUs).

When using DMI data from literature reviews (**Figure 8**), the order is slightly different for sheep, goats and red deer (with sheep significantly higher than goats and deer). The difference in order may be partly due to the different livestock categories used as well as differences in study conditions and diets. Despite these differences, horses and pigs remain substantially lower emitters than other domestic livestock for all data sources used. Other species are less well studied. Although bison appear to be comparatively high emitters (per DMI) compared to moose and water buffalo, this is based on a small data set and further research is required.

Using smaller breeds is likely to generate slightly lower emissions per head of livestock (as smaller individuals consume less DMI therefore have lower enteric methane emissions per head). For the same total number of livestock, smaller breeds could generate lower overall GHG emissions, but the savings are likely to be negligible compared to changing livestock species or reducing total livestock numbers. If the livestock are destined for the meat market, smaller breeds can potentially generate higher GHG emissions per kg of meat production. As smaller breeds are likely to consume less daily DMI, there may also be reductions in grazing impacts, which may need to be compensated by increasing herd size (negating any GHG reductions from using the smaller breed).

Table 16: Summary of species differences in GHG emissions per head and for equivalent Livestock Units. The final two columns indicate CO_2 equivalent emissions (by converting N_2O and CH_4 into CO_2e and adding them together).

Livestock Type		Enteric CH_4 emissions per head (kg/year)	Manure CH_4 per head (kg/year)	Total CH_4 per head (enteric and manure) kg/year	N_2O emissions per head (dung and urine) kg/year	Total CH_4 and N_2O per head (as CO_2e) kg/year	Total CH_4 and N_2O per LU equivalent (as CO_2e) kg/year
Adult Cow	Dairy	123.8	38.4	162.2	0.55	4562	4562
	Beef	76.2	10.6	86.8	0.22	2421	2421
Adult Sheep (ewe)		7.1	0.19	7.29	0.02	204	1693 (lowland) 2550 (hill ewe)
Horse		18.0	0.41	18.41	0.25	569	569
Goat		9.0	0.39	9.39	0.10	282	2346
Pig		1.5	4.1	5.6	0.09	177	354
Red deer		20.0	0.22	20.22	0.06	566	1868

22.2. Impacts of changes in herd density and timing on GHG emissions

The use of mixed herds and targeted grazing would allow reductions in high-emitting livestock whilst maintaining similar grazing impact and conservation outcomes. There is insufficient evidence to recommend changes to grazing season patterns. Whilst stopping grazing altogether would have the most substantial reductions for GHG emissions, the consequences for specific conservation goals would be significant for most sites. There is insufficient evidence for the GHG emissions from alternatives to grazing, such as mowing, which may generate emissions from fuel and travel. **Table 17** summarises the likely GHG outcomes and conservation impacts of herd density and timing changes.

Table 17: Summary of the key GHG and carbon impacts of changes to herd density, timing and targeting, as well as conservation implications

Change	GHG and carbon impacts	Conservation impacts
Reduce Herd Density	Replacing a proportion of cows and sheep with horses and pigs would bring very substantial GHG reductions with little impact on carbon storage. Example: replacing half a herd of 20 dairy cows with horses (from 20 cows to 10 cows and 10 horses) would generate GHG reductions of around 40,000 kg CO_2e per year.	A small reduction in herd density is unlikely to have substantial impacts on conservation goals. However, there may be thresholds of herd density below which significant conservation impacts could be incurred. Further research would be beneficial to identify thresholds in different habitats.
Mixed Herds	Mixed herds could achieve substantial GHG reductions with little impact on carbon storage. Mixing high-emitting livestock (cows and sheep) with low-emitting livestock (horses and pigs) would allow equivalent Livestock Units to maintain grazing impact, whilst allowing for a reduction in high-emitting species.	Mixed herds are likely to benefit biodiversity through facilitating a wider range of grazing modes. However, the particular livestock mix and proportions will need to be tailored to conservation goals, accounting for the specific impacts of different livestock on vegetation.
Change grazing season	There is mixed evidence on the impacts of grazing season on GHG emissions. There is currently insufficient evidence for a recommendation.	Changing grazing season is likely to impact conservation goals depending on the extent of the seasonal change. This is due to seasonal differences in vegetation, which may require grazing in particular seasons to achieve conservation goals.
Stop grazing or use alternative	Stopping grazing altogether would generate the highest possible reduction in GHG emissions and is likely to have a low impact on carbon storage. Alternatives to grazing, such as mowing and cutting, may generate other emissions from machinery and staff/volunteer travel. There is insufficient data to quantify this.	Stopping grazing is likely to have high conservation consequences in most situations and may not be an option for restoring and maintaining early successional habitats and species. Alternatives to grazing, such as mowing, may prevent succession, but with a loss of heterogeneity and microhabitats created by grazing.
Targeted grazing	Targeted grazing could potentially allow for herd reductions whilst maintaining grazing impact. Smaller herds could be moved around compartment sections to ensure adequate grazing of the whole compartment or to increase habitat heterogeneity through differential grazing impacts. An experimental approach would be beneficial and could involve electronic collars or placement of troughs or mineral licks.	Targeted grazing is likely to benefit biodiversity as it could be aimed at achieving similar conservation goals with lower herd density.

22.3 Impacts of supplements on GHG emissions

The use of methane-reducing supplements has the potential to achieve high reductions in GHG emissions (**Table 18**). The two most promising supplements (based on current evidence) are UK seaweeds and Bovaer. These are both effective at low doses and have the potential to be produced within the UK, avoiding emissions from imports. Combining supplements with rumen microbe manipulation could be a highly effective strategy for creating conservation grazing herds with low emissions. Trials would be necessary to assess the most effective way of administering supplements to free-roaming livestock (e.g. with cattle licks, troughs or other measures). Combining supplements with rumen microbe manipulation would reduce the need for on-going supplementation, as microbe manipulation generates long-lasting effects.

We have focused on the methane-reducing potential of supplements for this report. However, considerations would need to be given to potential health impacts on livestock (and consumers if used for food production) and whether supplements could influence consumption rates (and therefore grazing impact). This information should be available through trials conducted by supplement manufacturers and independent researchers. UK seaweeds are currently undergoing trials and DEFRA is conducting a Call for Evidence on methane-suppressing feeds (see **Section 1,** 'Methane-reducing Supplements').

Table 18: Summary of potential methane reductions from supplements and vaccines.

Supplement or Vaccine	Potential methane reduction	Comments and Caveats	Recommendation
Red seaweed (e.g. Asparagopsis) Or UK native brown and green seaweeds	90% (Asparagopsis) 12-50% (UK seaweeds)	Red seaweed (e.g. Asparagopsis) is unsustainable due to high bromoform content (which is damaging to the ozone layer and has negative health impacts). Native UK species have lower bromoform content and greater potential for sustainable harvest and local production. Trials would be required to assess options for administering supplements in conservation grazing.	Red seaweed – not recommended. UK native seaweeds – recommend trials.
Bovaer® (3-NOP)	8-70% (usually around 30%)	Most studies showed a reduction of 8–30% except for one study that found a 70% reduction. Small quantities are effective (half teaspoon) and it is commercially available. Trials are required to assess options for administering in conservation grazing.	Recommend trials.
Other Supplements: Crushed wheat; Biochar Grape marc	0 – 30%	Other supplements have mixed evidence or would require large daily additions to feed	Not recommended (unless further evidence emerges)
Rumen microbe manipulation	Variable at level attainable by supplement	Rumen microbe manipulation could be used in combination with supplements to maintain the effect of the supplement for many months or years. This involves administering the supplement to newborn calves and their mothers and maintaining them as a separate herd in isolation from other cattle.	Recommend trials.
Vaccination	0 to 69%	Trials of vaccinations to reduce methane emissions have found varying results. Although some trials have shown up to 69% methane reduction, many trials have been unsuccessful. Further research is required.	Not recommended until research and trials are further developed.

23. Comparison tables: Habitat Goals, Management Options and GHG Emissions

Combining the evidence on GHG emissions **(Section 1)** with specific conservation goals (**Section 2**), we have generated **Tables 19** to **21**. These allow approximate relative comparisons for both GHG emissions and specific conservation outcomes (see **Section 2** for details) of different livestock types and management practices. We have excluded wild large herbivores because of limited evidence available assessing their impacts on GHG emissions and conservation outcomes. The actual outcomes will vary between sites and habitats, but these tables are a guide to likely outcomes (based on current evidence). We recommend using these tables in combination with trials and monitoring to allow feedback and adjustments for different habitats.

Key: GHG emissions comparisons are relative to each other within each grazing management category (e.g. species, breed, body mass

(dark purple)	Much higher GHG emmissions
(light purple)	Higher GHG emissions
(pale lilac)	Mid-range GHG emissions
(green)	Lower GHG emissions
(grey)	Insufficient or mixed evidenceon GHG emissions

2	Assessed to be an effective strategy to achieve the conservation goal compared to other options in the category.
1	Assessed to make a contribution to achieving the conservation goal, but less effective compared to other options in the category.
0	Assessed to be an unsuitable strategy for achieving the conservation goal.
?	Unknown effectiveness

Table 19: Increasing habitat heterogeneity

Grazing management options		Increasing habitat heterogenety								
		Increase sward structural diversity	Increase structural diversity of open and woody vegetation	Create bare soil	Remove the thatch (dead grass and leaves)	Seed dispersal	Nutrient cycling	Dung resource creation	Wallow/ Ephemeral pool creation	**Total**
Species (per LU)	Dairy Cattle	2	2	1	2	2	2	2	1	**14**
	Beef Cattle	2	2	1	2	2	2	2	1	**14**
	Horse	2	1	1	2	2	2	2	1	**13**
	Sheep	1	1	0	1	2	1	1	0	**7**
	Goat	2	2	0	1	2	1	1	0	**9**
	Pigs	2	2	2	2	?	1	2	2	**13**
	Mixed herd	2	2	2	2	2	2	2	2	**16**
	No herbivores	0	1	0	0	0	0	0	0	**1**
Breeds (per head)	Traditional Breeds	?	?	?	?	?	?	?	?	**?**
	Commercial	?	?	?	?	?	?	?	?	**?**
(Number of individuals per area per year)	Intermediate grazing	2	2	2	1	?	?	2	2	**11**
	Heavy grazing	0	1	1	2	?	?	1	1	**6**
	Variable grazing	2	2	2	1	?	?	2	2	**11**
Stocking Frequency (per year)	Mob grazing	2	?	1	2	?	?	1	1	**7**
	Year-round grazing	1	?	1	1	2	2	2	2	**11**
Stocking season (per season)	Spring grazing	2	2	1	0	1	?	2	1	**9**
	Summer grazing	2	2	1	0	1	?	2	2	**10**
	Autumn grazing	1	2	2	2	2	?	2	1	**12**
	Winter grazing	1	2	2	2	1	?	2	1	**11**
Spatial targeting	Targeted grazing	2	2	2	1	1	?	1	1	**10**
	UK seaweeds	?	?	?	?	?	?	?	?	**?**
	Boaver®	?	?	?	?	?	?	?	?	**?**
	Others	?	?	?	?	?	?	?	?	**?**
Alternatives	Cutting and mowing	1	2	0	2	0	0	0	0	**5**

Table 20: Specific habitat goals

Grazing management options		Habitat creation and management					
		Halt vegetation succession (preserve a valued habitat type)	Prevent woody plant (shrubs and trees) encroachment	Create bare soil	Remove the thatch (dead grass and leaves)	Seed dispersal	**Total**
Species (per LU)	Dairy Cattle	?	2	2	1	2	**7**
	Beef Cattle	?	2	2	1	2	**7**
	Horse	?	1	1	2	2	**6**
	Sheep	?	1	1	2	2	**6**
	Goat	?	2	2	1	2	**7**
	Pigs	?	2	1	1	1	**5**
	Mixed herd	?	1	1	1	1	**4**
	No herbivores	0	0	0	0	0	**0**
Breeds (per head)	Traditional Breeds	?	?	?	?	?	**?**
	Commercial	?	?	?	?	?	**?**
Body mass (per head)	Smaller	?	?	?	?	1	**1**
	Larger	?	?	?	?	2	**2**
Stocking rate (number of individuals per area per year)	Light grazing	?	0	2	1	1	**4**
	Intermediate grazing	?	2	2	2	2	**8**
	Heavy grazing	?	1	1	2	2	**6**
	Varied grazing	?	?	2	1	2	**6**
Stocking Frequency (per year)	Mob grazing	?	?	?	?	?	**?**
	Year-round grazing	?	2	2	2	2	**8**
Stocking season (per season)	Spring grazing	?	1	2	2	2	**7**
	Summer grazing	?	1	2	2	2	**7**
	Autumn grazing	?	2	1	1	2	**6**
	Winter grazing	?	2	1	1	2	**6**
Spatial targeting	Targeted grazing	2	2	1	2	1	**8**
Supplements (per head)	UK seaweeds	?	?	?	?	?	**?**
	Boaver®	?	?	?	?	?	**?**
	Others	?	?	?	?	?	**?**
Alternatives	Cutting and mowing	?	2	2	2	2	**8**

Table 21: Specific species goals

Grazing management options		Promoting and surpressing specific species		
		Enhance specific species or groups, such as butterflies on chalk grassland	Reduce dominant plant competitors (particularly grasses and bracken)	Control undesirable or legislated species
Species (per LU)	Dairy Cattle	2	2	1
	Beef Cattle	2	2	1
	Horse	2	2	1
	Sheep	2	2	2
	Goat	2	2	1
	Pigs	2	2	2
	Mixed herd	2	2	2
	No herbivores	0	0	0
Breeds (per head)	Traditional Breeds	?	?	?
	Commercial	?	?	?
Body mass (per head)	Smaller	?	?	?
	Larger	?	?	?
Stocking rate (number of individuals per area per year)	Light grazing	2	1	1
	Intermediate grazing	2	2	2
	Heavy grazing	1	1	2
	Varied grazing	2	2	2
Stocking Frequency (per year)	Mob grazing	2	2	2
	Year-round grazing	1	1	1
Stocking season (per season)	Spring grazing	?	?	?
	Summer grazing	?	?	?
	Autumn grazing	?	?	?
	Winter grazing	?	?	?
Spatial targeting	Targeted grazing	2	2	2
Supplements (per head)	UK seaweeds	?	?	?
	Boaver®	?	?	?
	Others	?	?	?
Alternatives	Cutting and mowing	2	1	2

24. A case study: Old Sulehay

Beds, Cambs, and Northants Wildlife Trust provided us with a breakdown of grazing livestock numbers for their Northants sites. We have chosen Old Sulehay as a Case Study due to the high number of livestock compared to other sites. Old Sulehay consists of 85 hectares of woodland, grassland and scrub. Conservation grazing is applied to maintain varied habitat structure whilst also maintaining low soil fertility. The grazing practices are varied spatially and temporally within the site. Cattle and rare-breed sheep are currently used to achieve a variety of conservation goals including preventing scrub expansion and controlling particular species, such as ragwort.

For the Case Study we have selected several compartments where we present an alternative livestock assemblage. The stocking density at the site varies from month to month. Averaged over one year, the stocking rate is equivalent to 7 cattle and 113 sheep. This is similar to many other Wildlife Trusts where cattle and sheep are the predominant livestock. Following the evidence of this report we present a hypothetical alternative grazing strategy that is equivalent to 3 cattle, 64 sheep, 9 horses, and 5 pigs present year-round.

We have assumed all cattle to be non-dairy for the current and alternative scenarios. Targeted grazing would allow slightly lower LU equivalents than the current regime. The alternative scenario is likely to achieve similar grazing impact and habitat heterogeneity.

Table 22 indicates that considerable GHG emissions reductions could be achieved by altering the herd composition of one site (34% reduction). Scaling these savings across The Wildlife Trusts could achieve annual GHG reductions of approximately 5,780 tonnes CO_2 equivalent (based on current emissions of 17,000 t CO_2e).

Table 22: Estimated GHG emissions and vegetation consumption from current and alternative grazing strategies at Old Sulehay.

	Current grazing regime (cows and sheep)	Alternative grazing regime (cows, sheep, horses, pigs)
Total large herbivore biomass (Kg)	9860	8337.5
Total estimated vegetation consumed by the large herbivores (tonnes C/year)	40.9	35
Total GHG emissions from methane and nitrous oxide (CO_2e kg/year)	39,999	26,440

The alternative scenario comes with practical challenges. A greater diversity of large herbivore species would need to be sourced, transported and cared for. Horses and pigs could lead to more human-wildlife conflict on site and pigs are well suited to escaping fenced areas. Whether these and other challenges are surmountable is a site-specific challenge.

We have no familiarity with this specific site and have simply selected it based on the data available to us. Our alternative scenario is just one of many possible alternatives that has the potential to achieve similar outcomes with more appropriate tailoring to site conditions and goals. Every site will have their own unique suite of practical considerations, but this Case Study serves as an example of the scale of GHG reductions that could be achieved from moderate stock changes that aim to maintain conservation goals.

25. Recommendations

25.1. Levers of Change

A summary of the Levers of Change identified in this report is presented in **Table 24.** Based on the current evidence, we recommend that The Wildlife Trusts conduct trials of the approaches highlighted in green in **Diagram 1**. On the basis of the evidence reviewed, these approaches are likely to generate substantial GHG emissions reductions with low impacts on carbon storage and biodiversity. Given the high dominance of cattle and sheep within The Wildlife Trusts' current grazing operations (**Table 23**), very high emissions reductions could be achieved through the strategies identified in **Diagram 1.**

Table 23: Current livestock numbers across the whole of The Wildlife Trusts' conservation grazing operations (personal correspondence)

Livestock Type	Number
Cows	10394
Sheep	19556
Horses	872
Deer	160
Goats	112
Pigs	31

Diagram 1: Potential Levers of Change to reduce GHG emissions from UK conservation grazing. Levers in green represent the most promising approaches to reducing emissions whilst maintaining conservation benefits (see **Key** to the right).

Green	Potential for high GHG reductions at low boidiversity cost. Trials recommended.
Orange	Potential for low to medium GHG reductions at low biodiversity cost.
Blue	High GHG reductions but potentially high biodiversity costs. Not recommended.
Grey	Insufficient evidence on GHG impacts. Not recommended.

Table 24: Summary of Levers of Change that could reduce GHG emissions from conservation grazing, and their likely impacts.

Lever of change	GHG and carbon impacts
SPECIES: Change from high- to low-emitting livestock species	All of the species-related evidence reviewed has identified substantially lower methane emissions from horses and pigs compared to other livestock. Cows (particularly dairy cows) are identified as particularly high emitters, with emissions from dairy cows being 8 times higher than emissions from horses. Replacing a proportion of cows and sheep with horses and pigs would bring very substantial GHG reductions with little impact on carbon storage. Example: replacing 10 dairy cows with 10 horses could generate reductions of around 40,000 kg CO_2e per year.
BREED: Change from larger to smaller breed	Breed changes are unlikely to generate substantial reductions in emissions compared to species changes. Switching from larger to smaller breeds is likely to generate some GHG reductions per head (but is unlikely to make much difference per DMI). GHG reductions would only be achieved if the same stocking rate was maintained. Example: replacing a herd of 40 Texel sheep with a herd of 40 Welsh Mountain sheep could generate savings of around 2,000 kg CO_2e per year.
AGE STRUCTURE: Change to younger individuals of smaller body mass	A younger age structure is likely to generate some GHG reductions per head (but not per DMI). Emissions reductions would only be achieved if the same stocking rate was maintained (which could result in lower grazing impact).
HERD DENSITY AND STOCKING RATE: Reduce overall livestock numbers	Reducing the livestock numbers for a site could substantially reduce GHG emissions whilst having little impact on carbon storage. Example: a 10% reduction in a herd of 20 dairy cows would lead to approximate savings of 9,000kg CO_2e per year.
GRAZING SEASON: Change season or timing of grazing	There is mixed evidence on the impacts of grazing season on GHG emissions. There is currently insufficient evidence for a recommendation.
MIXED HERDS: Replace a proportion of high-emitting livestock species with low-emitting species	Mixed herds could achieve substantial GHG reductions with little impact on carbon storage. Mixing high-emitting livestock (cows and sheep) with low-emitting livestock (horses and pigs) would allow equivalent Livestock Units to maintain grazing impact, whilst allowing for a reduction in high-emitting species.
TARGETED GRAZING: spatial and temporal targeting of grazing impacts (by moving livestock around the site)	Targeted grazing could allow livestock numbers to be reduced whilst maintaining grazing impacts. Smaller herds could be moved around compartments to ensure adequate grazing of the whole site or to increase habitat heterogeneity. An experimental approach would be beneficial and could involve 'virtual fences' with collars or placement of troughs or mineral licks. Targeted grazing could also allow waterlogged areas (where soil GHG emissions from grazing are highest) to be avoided.
NO GRAZING: Stop grazing or use alternative (such as mowing).	Stopping grazing altogether would generate the highest possible reduction in GHG emissions and is likely to have a low impact on carbon storage. Alternatives to grazing, such as mowing and cutting, may generate other emissions from machinery and staff/volunteer travel. Further data would be required to quantify these alternative emission scenarios.
SUPPLEMENTS: Administer methane-reducing supplements	Of the supplements reviewed, Bovaer® and UK seaweeds, appear to have the highest potential for use in conservation grazing and are likely to achieve methane reductions of around 20 to 30%. Administering these to free-roaming conservation livestock will be more challenging than agricultural contexts but would be worth trialling in association with manufacturers.
MICROBE MANIPULATION: Prolonging the effects of supplements through herd isolation	Rumen microbe manipulation could be used in combination with supplements to prolong their effects for many months or years. This involves administering a methane-reducing supplement to newborn calves and their mothers and maintaining them as a separate herd in isolation from other cattle. This would avoid the need for regular feeding of methane-reducing supplements.
VACCINE: Vaccination to reduced enteric methane emissions	Trials of vaccinations to reduce methane emissions have found varying results. Although some trials have shown up to 69% methane reduction, many trials have been unsuccessful (showing no emissions reductions, or even increased emissions). Whilst trials continue this is not currently an available option.
SELECTIVE BREEDING: Breeding individual animals identified as genetically low emitters	There is high variability in individual enteric methane emissions within species (including within breeds). This is thought to have a genetic component, which could allow selective breeding for low-emitting individuals. In theory, this could allow the creation of low-emitting livestock herds. This is an area of developing research, which could have potential for future use in conservation grazing.

25.2. Further Research and Monitoring

The following areas for further research are recommended:

- Differences in GHG emissions from conservation habitats versus improved grassland.
- Conservation impacts of using mixed herds (with higher proportions of horses and pigs) in different habitats.
- Conservation impacts of reducing herd density and using targeted grazing approaches.
- Methods for administering methane-reducing supplements in a conservation grazing context.
- Impacts of methane-reducing supplements on livestock health and grazing consumption.
- Identification of practical, legislative and financial barriers to implementing strategies.

It will be highly beneficial to trial and monitor the recommended strategies. Where possible, the most effective approach would be a Before After Control Impact (BACI) design to monitor biodiversity and GHG emission outcomes. This requires baseline monitoring prior to any intervention and pairing of trial sites with similar sites where there is no intervention (to act as controls). Whilst there may logistical constraints that limit monitoring choices, the ideal approach would involve hypothesis-based monitoring, and would trial both singular and different combinations of interventions. Ideally any interventions would be trialled for a number of years before adaptive management is applied to allow sufficient time to assess inter-annual variation in outcomes.

26. Conclusions

A comprehensive review of the evidence has identified a range of strategies to reduce GHG emissions from conservation grazing operations. GHG emissions from cows are particularly high (especially dairy cows). Using a mixed grazing approach to reduce cow numbers would enable substantial reductions in GHG emissions, particularly by incorporating horses and pigs. Livestock numbers could also be reduced through targeted grazing approaches, allowing similar grazing impacts with fewer livestock. Where cattle and sheep are deemed necessary, methane-reducing supplements could be trialled to achieve substantial reductions in GHG emissions without compromising biodiversity (potentially alongside microbe manipulation strategies for long-term reductions). These approaches require experimental trials to assess feasibility and impacts.

We have also identified approaches that are unlikely to achieve significant reductions in GHG emissions or where there is insufficient evidence to draw conclusions. These include changes to breed composition, changes to grazing season, and replacing grazing with mowing or other alternatives. We have also identified that certain habitat qualities (such as soil wetness and soil type) can have substantial impacts on livestock emissions, which should be borne in mind when selecting grazing areas and timings.

The strategies identified in this report have the potential to enhance biodiversity (as well as lowering GHG emissions), by diversifying the range of livestock types and grazing strategies used in conservation grazing. However, a shift away from predominantly cattle and sheep will present substantial challenges. Following this review, we recommend further research to identify the practical and legislative barriers to implementing these measures. We suggest that a comprehensive review of barriers and solutions be conducted, followed by trials and long-term monitoring of recommended strategies.

Annex 1: Evidence Gaps and Clusters

27. Introduction

27.1. Systematic Map Overview

The scientific evidence for large herbivore impacts on greenhouse gas emissions and carbon stores has never been synthesised in a systematic way. Ramsay et al. (2022) are conducting a 'Systematic Map' research project, which aims to collate and synthesise all available evidence (globally) on the climate impacts of large herbivores (herbivores of 10kg adult weight or over). This will allow the identification of evidence clusters and gaps within the existing research base for this complex topic. For the purposes of this report for The Wildlife Trusts, we have extracted evidence from the Systematic Map that is relevant to the UK context. This evidence base will be used to inform the literature reviews in the accompanying sections of this report.

27.2. Systematic Map Methods

Full details of the methodology and search strategy are available in **Appendix A** below. A search of peer-reviewed and grey literature was conducted using a variety of bibliographic databases, search engines and websites (including Web of Science, Science Direct, Google Scholar, and others). Search results were screened for relevance according to specific eligibility criteria. Articles specific to the UK context were identified by searching the included literature for UK countries and specific habitats. All articles included as eligible were coded by multiple categories (listed in **Appendix B**) using EPPI-Reviewer (Thomas et al. 2020). The coding for these articles was uploaded to EPPI-Mapper (Digital Solutions Foundry and EPPI Centre, 2020) to generate visual representations of evidence clusters and gaps.

For the evidence on methane-reducing supplements, we used a separate search strategy of searching for recent reviews or meta-analyses that collated the evidence from multiple studies. This was due to time constraints, which did not allow us to code multiple original papers on this topic. Due to the lack of UK-based research on methane-reducing supplements, the evidence for supplements is not restricted to the UK context.

28. Systematic Map Outputs

28.1. Accessing and using the maps

Evidence maps can be accessed in the following files that accompany this review:

- *EPPI-Mapper A_ Interventions and Climate Processes*

  An overview of the literature relating to conservation grazing management interventions and a range of climate-related variables. Use this file to explore the evidence for how conservation grazing management interventions might influence GHG emissions and other climate-related variables.

- *EPPI-Mapper B_ Species and breeds comparisons*

  An overview of the literature involving comparisons of different livestock species and breeds. Use this file to explore gaps and clusters in the evidence comparing climate-related impacts of different species and breeds used in conservation grazing.

- *EPPI-Mapper C_ Species, Breeds and Climate Processes*

  An overview of the literature relating to the impacts of different species and breeds on a range of climate-related variables. Use this file to explore the evidence for how different species and breeds might influence GHG emissions and other climate-related variables.

- *EPPI-Mapper D_ Supplements for methane reduction*

  An overview of a range of evidence for the methane-reducing impacts of supplements, based on recent reviews and meta-analyses. Use this file to explore the evidence on the methane-reducing potential of different food additives and other methane-reducing interventions. **Note:** due to time constraints, the search method for evidence on supplements was based on recent review papers.

All four of these EPPI-Mapper files can be accessed and downloaded from the publications section of **The Wildlife Trusts' website**, at the following locations:

User Instructions: Instructions for using the evidence maps are provided in **Appendix C** below.

Important Note: Please read the 'About' section in each evidence map, which explains how to use the map and set filters.

Evidence Points: The maps are based on the number of Evidence Points (EPs) relating to each category. An EP is a specific point of evidence for a relationship between two variables. Some research papers contain multiple EPs where more than one relationship has been explored (e.g. multiple species compared in one study, or three levels of herd density explored in two different habitats). This means that the total number of EPs is larger than the total number of papers.

Reviews and meta-analyses: Evidence maps A, B and C include original studies and do not include reviews and meta-analyses. These are included in the accompanying literature review but could not be coded for inclusion in the evidence maps, due to the multiplicity of studies in each review paper. Evidence map D does include meta-analyses as the evidence on supplements required different coding categories and was conducted within a shorter timeframe (see **'EPPI-Mapper D'** above).

28.2. Clusters and Gaps

Greenhouse gases and carbon sinks: clusters and gaps
Across the whole of the UK-relevant literature included in the evidence maps, there are clusters of evidence relating to enteric methane emissions, nitrous oxide and soil carbon (**Table A1**). There is less evidence relating to methane emissions from dung and urine or total GHG emissions.

Table 24: Summary of Levers of Change that could reduce GHG emissions from conservation grazing, and their likely impacts.

Greenhouse gases and carbon sinks	Total Evidence Points
Enteric methane emissions (per animal)	39
Enteric methane emissions (per DMI)	24
Enteric methane emissions (Land Area)	11
Enteric methane emissions (Unit Production)	21
Dung or urine methane emissions	7
Methane flux	23
Nitrous oxide emissions	61
CO_2 flux	28
Total GHG Emissions (CO_2 equivalent)	13
Soil carbon	38

The interactive evidence map for species and climate impacts can be accessed in the accompanying file *"EPPI-Mapper C_ Species, Breeds and Climate Processes"*. It reveals evidence clusters relating to nitrous oxide emissions and cows, as well as methane emissions and sheep (**Figure A1**). There are substantial evidence gaps for all other species. Large dots indicate larger numbers of Evidence Points (EPs), small dots indicate a small number of EPs, and blanks indicate where no evidence was found.

Figure A1: Example clusters and gaps in the evidence for climate-related impacts of different species. The full range of species is not shown here due to the large size of the Evidence Map. The full interactive map is available in the accompanying file '*EPPI-Mapper C_Species, Breeds and Climate Processes*'.

Species and breed comparisons: clusters and gaps

Across the UK-relevant literature included in this review, there are large clusters of evidence relating to cows and sheep **(Table A2)**. Other species are poorly studied and represent substantial evidence gaps. The reason for this is the dominance of cows and sheep in UK agricultural systems. Reducing the climate impacts of both conservation grazing and food production will require a greater breadth and depth of research on other species that could potentially provide similar services for lower climate impacts.

Table A2: Number of Evidence Points in the coded UK-relevant literature relating to different species.

Species	Total Evidence Points
Cows (bovines)	122
Sheep (ovines)	98
Deer (cervines)	10
Goats (caprines)	7
Horses (equines)	4
Beavers	2
Pigs (suidae)	1
Geese	1
Hares and rabbits	1

The evidence map for research comparing different species and breeds is available in the accompanying file *'EPPI-Mapper B_Species and breeds comparisons'*. The map shows research clusters for cows and sheep and research gaps for all other species. Comparisons of different breeds within species reveal similar clusters, with breed comparisons only available for sheep and cows. This highlights the need for more research on a wider range of species. The low number of studies relating to pigs may be due to the search string terms. Pigs are classified as omnivores, not herbivores, so may not have been picked up in searches relating to herbivores and grazing. However, we have included them in this report due to their high levels of herbivory and grazing, which make them potentially important contributors to conservation grazing.

Within cows and sheep, the research on breed differences for climate impacts is limited to just a few studies (21 EPs for sheep; 10 EPs for cows). The higher number of EPs for sheep is largely due to one study involving comparisons of enteric methane emissions from various sheep breeds. Even within sheep breeds, there is a substantial number of gaps for breeds that have not been compared.

Levers of change and interventions: clusters and gaps
Interventions to reduce greenhouse gas emissions (or enhance carbon stores) can be assessed through studies that compare emissions from different scenarios. Aspects of conservation grazing that can be altered through management decisions are referred to here as 'levers of change'. The levers of change were not pre-identified by the authors, but were extracted from the evidence, based on which variables were addressed in the literature and can also be altered by land managers. For example, weather-related variables cannot be altered by land managers so are not considered levers of change. However, livestock species, breed, herd density and grazing frequency are all variables that can be adjusted by land managers and are therefore considered levers of change. Based on the evidence, we classified the levers of change into four main categories: **Stock** (e.g. species, breed or herd composition changes), **Timing** (e.g. changes in timing or season of grazing), **Intensity** (e.g. changes in herd density or grazing frequency) and **Habitat** (e.g. changes in habitat, habitat management or farming system).

The evidence map for levers of change can be accessed in the accompanying file "*EPPI-Mapper A_Interventions and Climate Processes*". The map shows the largest evidence clusters for impact of 'different species or breed' on methane emissions, and for impact of 'herbivory vs no herbivory' on soil carbon (see **Table A3**). There are comparatively few studies relating to changes in herd structure or density, which could be important levers of change in a conservation grazing context.

28.3. Other evidence maps

The evidence maps are interactive documents that can be generated from the file WT_Evidence_Maps_JSON by following the EPPI-Mapper instructions at: [EPPI-Mapper (ioe.ac.uk)]

The maps can be created for multiple combinations of coding categories. The JSON file is available for users to generate their own maps for different combinations of coding categories.

Table A3: Number of Evidence Points in the coded UK-relevant literature relating to different potential interventions or 'levers of change' to mitigate greenhouse gas emissions.

Lever of Change (Intervention)	Total Evidence Points
STOCK: Different Species or Breed	42
STOCK: Herd Structure Difference	1
TIMING: Seasonal Difference	12
INTENSITY: Herbivory vs No Herbivory or Alternative	24
INTENSITY: Herd Density Difference	9
INTENSITY: Urine or Dung Difference	12
HABITAT: Habitat Difference	10
HABITAT: Habitat Management Difference	7
HABITAT: Farm System Difference	1

29. Category Frequencies

Tables A4 to A6 show the number of Evidence Points for other coding categories. Evidence maps have not been generated for these but can be created from the JSON file.

Herd density, structure and grazing frequency
The vast majority of research has been conducted for single-species herds (183 EPs), with comparatively little research involving mixed herds (19 EPs). This highlights a substantial evidence gap for mixed herds requiring further primary research.

For studies that address herd density or grazing frequency there are relatively more involving herds of low and medium density compared to high density (**Table A4**). Grazing frequency is only mentioned in comparatively few studies (9 EPs), indicating a substantial evidence gap.

Table A4: Number of Evidence Points in the coded UK-relevant literature relating to grazing density or frequency in the context of climate-related impacts.

Density or Frequency	Total Evidence Points
High density	20
Medium density	37
Low density	39
High frequency grazing	1
Medium frequency	6
Low density	2

Habitat Types

The vast majority of research has been conducted in 'improved grassland' which is intensively managed and fertilised. There are fewer studies in habitats relevant to conservation grazing, but the largest clusters amongst these are semi-natural grassland, heath and saltmarsh (**Table A5**). This indicates the need for more field studies in conservation habitats, particularly where the impacts may be significantly different between habitats. The bulk of the research has been conducted in lowland habitats (82 EPs) with substantially fewer studies involving upland habitats (48 EPs). This demonstrates a requirement for further primary research in upland habitats.

Table A5: Number of Evidence Points in the coded UK-relevant literature relating to different habitat types.

Habitat type	Total Evidence Points
Improved grassland	109
Semi-natural grassland	41
Broadleaf and mixed woodland	8
Marsh	2
Fen	2
Blanket bog	6
Saltmarsh	10
Coastal sand dunes	2
Heath	12
Moorland	3
Bracken-dominated	2
Bracken-altered streams and ponds	2
Arable or Horticultural	4

Geographical distribution

As this review is focused on the UK context, the majority of studies included were conducted in the UK. Of these the largest cluster of Evidence Points are from England, followed by Wales, Ireland and Scotland. Some studies from other European countries were also included where relevant to UK habitats (**Table A6**). These studies were identified by searching for 'Europe' in the Title and Abstract of papers already screened for inclusion in the global Systematic Map and selecting those conducted in UK-relevant habitats (e.g. saltmarsh, heath etc). Some were also identified through additional searches for species missing from the UK literature (e.g. European beaver). There are likely to be additional UK-relevant studies from other European countries that were not identified through this search method (due to 'Europe' being missing from the Title and Abstract). These studies are likely to be picked up in the global Systematic Map and will be included in an updated JSON file for The Wildlife Trusts at the end of the global Systematic Map process.

Table A6: Number of Evidence Points from different countries where the research was conducted.

European country	Total Evidence Points
England	44
Wales	38
Ireland	31
Scotland	23
Denmark	12
France	10
Germany	9
Spain	8
Switzerland	7
Finland	7
The Netherlands	6
Hungary	4
Italy	3
Portugal	2
Austria	2
Belgium	2
Norway	2
Sweden	1
Poland	1
Slovakia	1
Belarus	1

30. Supplements for methane reduction

The potential for dietary supplements to reduce enteric methane emissions has been well researched in some non-European countries, particularly Australia. For evidence on supplements we have therefore used meta-analyses that include research from other countries. These papers have been coded separately as meta-analyses cannot be coded in the same way as primary studies.

The evidence map for supplements is available in the accompanying file *"EPPI-Mapper D_Supplements for methane reduction"*. It also includes other interventions such as vaccination and rumen microbe manipulation. The quantitative results of these studies are summarised in the accompanying literature review (**Section 1**).

31. Conclusions

All of the evidence identified in the Systematic Map as relevant to the UK context is discussed in the accompanying sections of this report (particularly **Section 1**). The overall purpose of the report is to collect, collate and review relevant evidence to inform future efforts by The Wildlife Trusts (and other land managers) looking to achieve their conservation goals with minimal negative impact on climate change. Identifying evidence clusters allows an assessment of which potential mitigation strategies have the most evidence to allow robust conclusions to be drawn (where the evidence is consistent). Identifying evidence gaps reveals areas of potential mitigation for which there is currently insufficient evidence to support their adoption. However, these gaps allow us to determine which areas require further research and field studies to assess their impacts. The evidence gap maps can be useful for prioritising future research and justifying research funding.

The evidence maps reveal evidence clusters around particular livestock species (cows and sheep) and particular types of greenhouse gas emissions (enteric methane emissions and nitrous oxide). There are also research clusters for improved grassland and lowland habitats. All of these research clusters reflect the predominance of research relating to livestock grazing for agricultural purposes. Substantial evidence gaps are revealed for many areas of research (**Table A7**) where further primary studies are required. In particular, there are substantial gaps in research specific to conservation habitats, livestock other than cattle and sheep, and total CO_2 equivalent emissions. These gaps are of particular pertinence to conservation grazing, so future research to elucidate these areas would be highly beneficial.

Table A7: Evidence gaps and clusters in the research base for climate impacts of large herbivores (in the UK context).

Evidence Gaps	• Other species (not cows & sheep) • Mixed herds • Upland habitats • Conservation habitats • Grazing frequency • Total GHG emissions (CO_2 eq.)
Evidence Clusters	• Cows and sheep • Enteric methane emissions • Nitrous oxide emissions • Improved grassland • Lowland habitats

32. Appendix A: Systematic Map Methods

Relevant literature for this report was identified through a Systematic Map already in progress (Ramsay et al. 2022). The Systematic Map has identified more than 800 studies relevant to climate impacts from large herbivores. Of these global studies, we selected those that are relevant to the UK context for inclusion in this report. The Systematic Map methods followed the Guidelines and Standards for Evidence Synthesis in Environmental Management (Collaboration for Environmental Evidence, 2018) and the ROSES reporting standards for Systematic Map Protocols (Haddaway et al., 2018).

Search strategy

Bibliographic databases: A search of five bibliographic databases was conducted (see list below). These databases were selected based on their relevance to the field of study and their comprehensiveness.

- Web of Science: Core Collection
- Scopus
- Science Direct
- GeoRef
- JSTOR

Search engines: One web-based search engine (Google Scholar) was searched to identify academic or grey literature not captured by the search of bibliographic databases.

Websites: Fifteen organisational and governmental websites were searched to identify relevant grey literature or other documents not identified through bibliographic databases.

Websites searched:

- Rewilding Europe
- Rewilding Britain
- Global Rewilding Alliance
- GrazeLIFE
- RSPB
- Wildlife Trusts
- Natural England
- NatureScot
- Natural Resources Wales
- United Nations Environment Programme
- European Commission Joint Research Centre
- European Environment Agency
- GRID Arendal
- International Union for Conservation of Nature
- United Nations Environment Programme

Search string scoping

Searching of bibliographicdatabases was conducted using a search string. The search string was tested and optimised by conducting a scoping exercise in Web of Science, following the CEE guidelines (Collaboration for Environmental Evidence, 2018). Narrower and wider search strings were trialled during scoping to ensure an appropriate balance of specificity (reducing the number of irrelevant studies) and sensitivity (maximising the number of relevant studies).

Nine different iterations of the search string were trialled. The specificity of each trial search string was assessed by modifying terms to see how many documents were returned by Web of Science in the 'Topic' field (which includes Title, Abstract and Keywords). The comprehensiveness of each search string was tested by listing 20 relevant articles already known to the authors, then checking if these articles were returned by the search string in Web of Science. These articles were chosen due to their relevance to the topic and the breadth of relevant research covered by these articles.

Of the search strings trialled, the search string below was found to be the optimum for specificity and sensitivity, returning all 20 of the test articles, and a total of 33,094 articles (*search date 17/11/2021*).

Search string (Web of Science Format):

(Herbiv* OR Graz* OR Brows* OR Rewild* OR Exclos*)
AND
(Climat* OR Albedo OR Fire OR Wildfire OR Carbon OR Methane OR Greenhouse OR Global OR 'Nutrient Cycl*')

The search string uses the Boolean operators OR and AND to identify literature that includes both herbivory-related terms and climate-related terms. Within each bibliographic database, the search string was adapted to the format required for that database but with the same terms and search fields (Title, Abstract and Keywords).

Website and search engine searches

Due to the limitations of using search engines for systematic reviews, we followed the recommendations of Haddaway et al. (2015), including searching by Title only and downloading only the first 300 search results (ordered by relevance) for inclusion in the screening process.

Websites: As most organisational websites don't provide for Boolean operators, each website was searched with the following key terms:

- Herbivores and climate
- Herbivores and wildfire
- Herbivores and albedo
- Herbivores and carbon
- Herbivores and nutrient cycles
- Herbivores and methane

The searches were then repeated replacing 'herbivores' with 'grazing' and then 'livestock'.

Only English language searches were conducted due to limited resources of the research team.

Article screening and study eligibility criteria

Screening strategy

Screening was conducted by Title and Abstract, where the relevance of each article was initially assessed based on the title and abstract. Articles that clearly met the exclusion criteria were excluded. Articles that met the eligibility criteria (or where there was uncertainty) were included for full text screening and coding. Articles included at the full text screening stage were then coded for the Systematic Map (see 'Data Coding Strategy' below). Screening was conducted using drop-down menus listing exclusion criteria. This allowed the reasons for exclusion to be recorded for each article. This process was conducted using specialist software for systematic mapping and reviews (EPPI-Reviewer Web (Thomas et al., 2020)). Within the bibliographic databases, search results were ordered by relevance (high relevance to low relevance). Due to trade-offs between time required for screening versus decreasing relevance of papers (diminishing returns for continuing effort), only the first 15,000 papers were screened. As the papers were ordered by relevance, this was considered sufficiently comprehensive for the time available.

Inter-reviewer reliability

A small team of researchers (reviewers) worked through the screening process. Inter-reviewer reliability was assessed by double-screening 500 articles to assess consistency of decisions between reviewers. A Cohen's kappa test (Cohen, 1960; McHugh, 2012) was conducted to assess the degree of agreement between pairs of reviewers (inter-rater reliability). A kappa result of over 0.6 was achieved, which is considered an acceptable level of agreement for inter-reviewer reliability. All disagreements were discussed and resolved. Where disagreements did occur, these were due to some papers having several possible reasons for exclusion (where different reviewers selected different reasons for exclusion, but both were valid reasons). These differences did not affect the final results for whether an article was excluded or included.

Eligibility criteria

All articles were included or excluded at screening according to the following PECO criteria:

1. **Population:** All terrestrial habitats.
   - All terrestrial habitats were included. Habitats that are exclusively aquatic were excluded. Terrestrial wetland habitats (such as marsh, bog and fen) were included.
   - To produce a broad and globally relevant systematic map, research conducted in all geographical locations was included. However, for the purposes of this report (The Wildlife Trusts), UK-relevant papers were identified and extracted (see 'Selecting UK-relevant studies' below)

2. **Exposure:** Introduction of large herbivores or change in density or species composition.
   - As the systematic map concerns the impacts of large herbivores, studies were excluded if they related only to herbivore species smaller than 10kg in adult weight. There are a variety of definitions of 'large herbivore' in the literature. Owen-Smith (2013) defines three broad categories of 'large herbivore': Megaherbivores (over 1000kg); Macroherbivores (100kg-1000kg); and Mesoherbivores (10kg-100kg). For the purposes of this study, we used the 10kg threshold as this allows the inclusion of goats and small deer (which may be of importance in management decisions), whilst excluding rodents, lagomorphs and other small vertebrates to ensure a manageable timeframe and focus for the systematic map.
   - All taxonomic groups were included.
   - As the systematic map relates to terrestrial herbivores, studies that involve exclusively aquatic herbivores were excluded. Semi-aquatic herbivores (such as beavers) were included.
   - Studies that involved simulation or modelling of impacts by large herbivores were included.
   - Studies that involved the introduction or reintroduction of large herbivores, or a change in species or density of large herbivores (including exclosures) were included.
   - Studies were included if they involved any type of impact by large herbivores (e.g. browsing, grazing, trampling, defecation etc.) and its effects on climate feedback or forcing effects.

3. **Comparator:** No large herbivores or difference in density or species composition of herbivores.
   - We included all studies where the comparator was a change in the presence/absence of large herbivores, or a change in density or species composition of large herbivores.
   - We also included studies where the comparator was a difference in management or habitat variables of large herbivores, or where herbivore impacts were compared to other interventions (e.g. mowing, burning).
   - Studies involving simulation or modelling of herbivory as the comparator were also included.

4. **Outcome**: Changes in climate feedback or forcing effects (e.g. albedo, carbon storage, carbon flux, wildfire regimes, methane or nitrous oxide emissions).
   - We included all studies that addressed the impacts of large herbivores on any aspect of climate feedback or forcing effects.
   - The search string returned numerous studies of the impacts of climate change on herbivores. As the systematic map concerns the impacts of large herbivores on climate (not vice-versa), studies were excluded if they related only to the impacts of climate change or climatic variables on herbivores.

Other eligibility criteria:

- Study type: All study types that include original data will be included (e.g. observational, remote sensing, experimental, modelling etc) to produce as broad a systematic map as possible.
- Theoretical papers: Papers that are purely theoretical will be excluded from the coding process but will be listed separately and referred to in the discussion.
- Review papers: Review papers will be excluded from the coding process, but individual studies referred to in the review will be identified and included or excluded separately in the screening process.
- We will exclude papers that report on data already reported elsewhere. This will be done by cross-checking references and citations.

Excluded articles

All articles excluded at full text are stored under their exclusion category. This will allow excluded articles to be retrieved at a future date if required. For example, articles excluded as 'aquatic' are stored separately from those excluded as 'climate impacts on herbivores'. However, due to time considerations, only one exclusion category was selected for each article, although some articles would fulfil multiple exclusion categories (for example a study of climate change impacts on aquatic herbivores may only be excluded as 'aquatic').

Study validity assessment As the systematic map is intended to provide a broad overview of research, the methodology of individual studies was not critically appraised but study design was coded. Where there are confounding variables likely to impact the study findings (such as differential fertiliser application as well as herbivore differences) the implications of confounding variables are discussed in the literature review.

Data coding strategy For each eligible study included at the screening stage, multiple aspects of the study were coded (see 'Coding Categories' list below). The herbivore-related coding terms were adapted from coding used by Soininen et al. (2018). Coding was conducted using EPPI-Reviewer Web software (Thomas et al., 2020) to facilitate coding with drop-down menus and to ensure consistency of coding between reviewers.

The coding strategy was piloted (and inter-coder reliability assessed) by four independent reviewers on a sub-set of between 5 to 10 full-text articles each. Detailed instructions were provided for each coder to ensure consistency. Any inconsistencies were discussed and instructions amended as necessary to clarify areas of uncertainty.

For articles that contained more than one original evidence point (for example multiple research questions within one study), each original evidence point was coded separately.

Selecting UK-relevant studies For the purposes of the Wildlife Trusts report, research relevant to the UK context and habitats was selected from the wider set of included studies. This was conducted by using the 'search' function within EPPI-Reviewer. Search terms used (for Title and Abstract) were: United Kingdom, UK, Britain, Scotland, England, Wales, Ireland. Attempts were made to include studies conducted in other temperate countries in UK-relevant wildlife habitats. However, identification of these papers was more difficult due to the large number of search terms that would be required to identify each relevant paper. This was simplified by searching for 'Europe' and 'European'. These initial searches returned a very high proportion of papers relating to cattle and sheep, with gaps for all other species. To address these gaps, studies relevant to particular species were also identified by searching for particular species names e.g. 'goat', 'deer', 'beaver', 'bison', 'elk', 'horse', 'pony', 'donkey'. These additional searches only found a small number of additional papers, confirming that there is a substantial research gap for other species.

Updating the Systematic Map Further coding of all included papers may uncover additional papers that are relevant to the UK context and habitats. When the full Systematic Map is completed, we will provide all additional relevant studies (and the completed Systematic Map) to The Wildlife Trusts.

33. Appendix B: Coding Categories

Table B1: Coding categories and descriptions used in the data extraction and coding process (adapted from the coding format in Soininen et al., 2018).

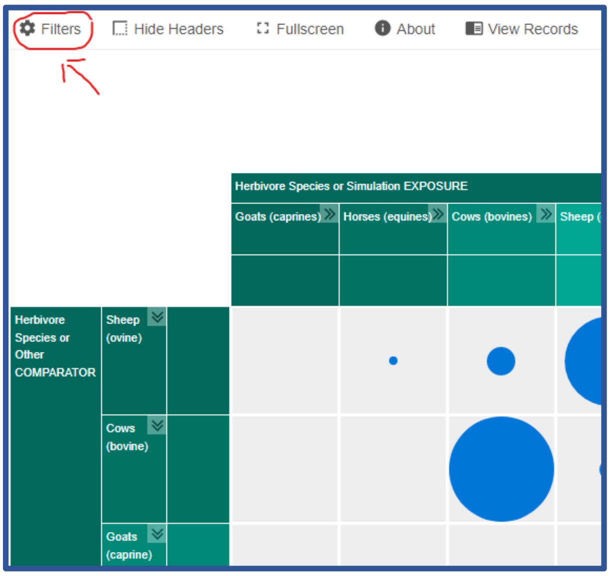
Topic	Coding variable	Variable description
Publication	Authors	List of authors
	Title	Title of article
	Journal	Journal or publishing house
	Year	Year of publication
	Language	Language
	Evidence Point (EP) number	An EP number was allocated for separate Evidence Points in the same paper.
Study location	Country	Country of study
	Continent	Continent of study
	Site name	Name of study site
	Latitude	Latitude of study location (or other geographical coordinates as published)
	Longitude	Longitude of study location (or other geographical coordinates as published)
	Elevation	Elevation or altitude as stated
Study details	Study type	Type of study e.g. experimental, observation, modelling etc.
	Study method	Study method e.g. remote sensing, field study etc.
	Spatial area	Size of study area
	Study length	Length of study
Population: habitat or land area (categorised separately for Exposure and Comparator)	Habitat type	Habitat type(s), Lowland or Upland, Habitat type as stated (e.g. heath, saltmarsh, fen etc.), Acidity
	Current land use	Current land use type(s)
	Biome	Biome type
	Soil type	Soil type
	Vegetation type	Dominant vegetation of study area as reported
	Conservation status	Conservation status of study location e.g. protected area
	Habitat management	Additional habitat management e.g. mowing, burning, scrub removal etc.
Exposure: herbivory	Herbivore species	Species of large herbivore involved in the study
	Herbivore breed	Breed of large herbivore
	Mixed or single	Mixed herd or single species
	Herbivory season	Season when herbivory occurs
	Effect on plants	Impact of herbivores on plants species e.g. removal of plant parts, trampling, seed dispersal
	Herbivore management	Management of herbivore e.g. culled, hunted, wild, captive, farmed
	Supplementary Feeding	If supplements are provided and of which type.
	Forage type	Type of forage when forage is provided
	Herbivore density frequency	Density and / or grazing frequency of each herbivore species (high, medium, low density; high, medium, low frequency)

Topic	Coding variable	Variable description
Comparator	Herbivore species comp	Comparator species of large herbivore involved in the study
	Herbivore breed comp	Comparator breed of large herbivore
	Mixed or single comp	Mixed herd or single species (comparator)
	Herbivory season comp	Season when herbivory occurs (comparator)
	Effect on plants comp	Impact of comparator herbivores on plants species e.g. removal of plant parts, trampling, seed dispersal
	Herbivore management comp	Management of comparator herbivore e.g. culled, hunted, wild, captive, farmed
	Supplementary Feeding comp	If supplements are provided and of which type (comparator).
	Forage type comp	Type of forage when forage is provided (comparator)
	Other comparator difference	Other difference between exposure and comparator e.g. different fertiliser regime, reseeding, plant composition etc.
	Density frequency comp	Density and / or grazing frequency of each herbivore species for comparator (high, medium, low density; high, medium, low frequency)
Outcome	Climate effect	Type of climate effect e.g. soil carbon, above- or below-ground carbon, nitrous oxide, enteric methane emissions etc.
	Direction of effect	No change, increase or decrease in climate effect (or uncertain)
	Heating cooling effect	Whether direction of change in effect is heating, cooling, no change or uncertain
Other variables	Air temperature	Temperature (degrees Celsius)
	Precipitation	Annual rainfall / precipitation (mm)
COMPARISON	COMPARISON	Variables being compared in the study e.g. breed X vs breed Y; high density vs low density; cows vs horses etc.

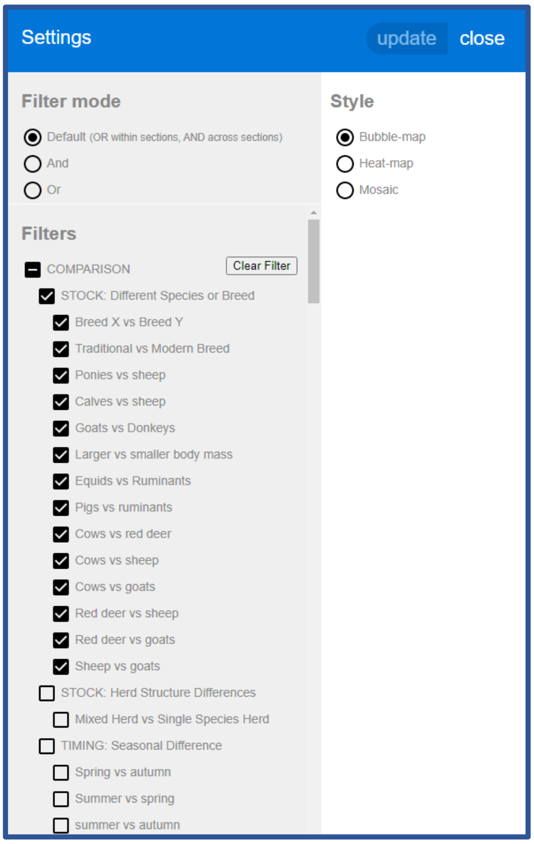
34. Appendix C: Evidence Gap Map – User Instructions

- When you open the file a grid with circles should appear. It will take a few moments to open.
- Not all browsers support the application. If it fails to open within one minute, try switching to Chrome.

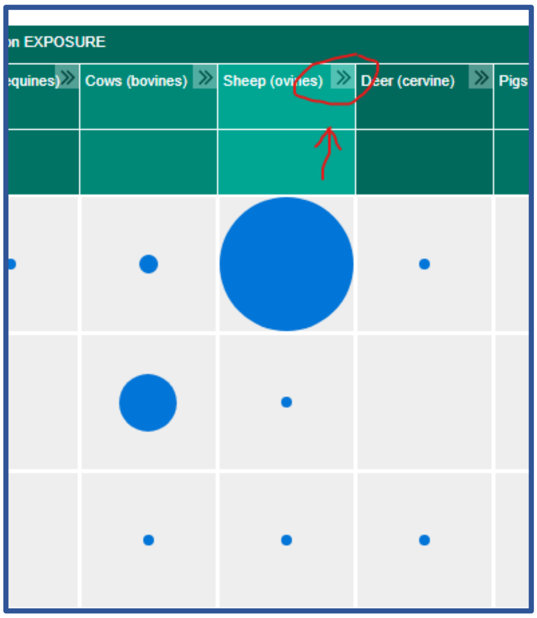
- Click the 'About' tab at the top of the page. This will provide instructions specific to that particular map, including which filter to set.



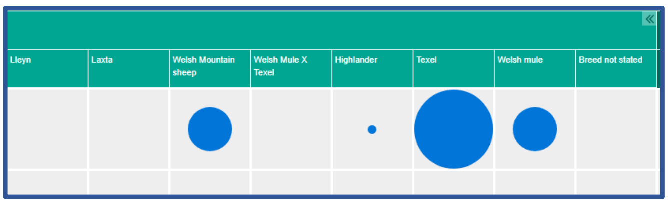
- Click 'Filters' at the top left of the page. Select the filter as described in the 'About' section.



- Click the relevant filters for that particular map. You can also use the filters to further refine your selection by other criteria in the filter list.
- Once you have selected the relevant filter click 'update'



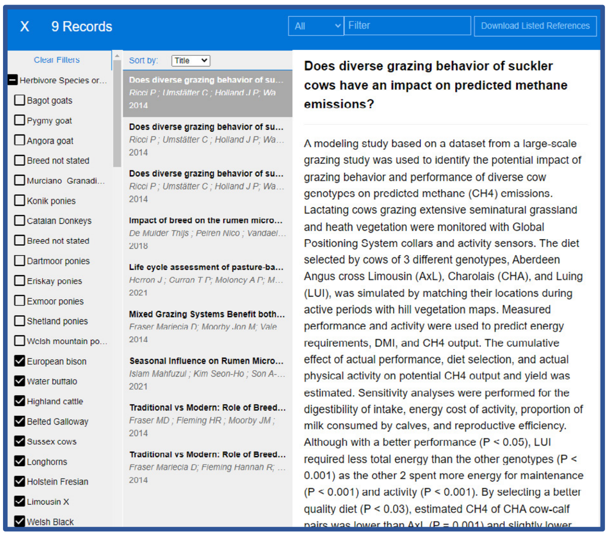
- For most maps there are sub-categories within categories, which can be viewed by clicking the double arrows on each category.



- After clicking the double arrows an expanded list of sub-categories is displayed. You can close this again by clicking the double arrows again

- Categories in the left column can also be expanded. The example shown here displays research clusters (large circles) for sheep breeds Texel compared to Welsh Mountain and Welsh Mule, and also for Welsh Mule compared to Welsh Mountain.

- Empty squares indicate research gaps. In this example it indicates which breeds have not been compared.



- Hovering over a circle displays the number of 'Evidence Points' relating to that circle.

- Clicking on a circle displays the abstracts of the relevant papers.

- **Note**: some papers contain multiple 'Evidence Points' where different comparisons are made (for example between several breed pairings). Some papers are therefore listed more than once.

- Underneath the abstract of each paper is a web link to the full text. If the full text is unavailable or subscription only, please refer to the accompanying literature review for access to full text pdfs

35. References (Annex 1)

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Annex 2: Key processes driving GHG emissions from grazing

36. Conceptual Diagrams of key GHG processes from grazing

These diagrams outline the key processes underlying climate impacts from conservation grazing in the UK context. These can be divided into sources of greenhouse gas emissions (CH_4, CO_2 and N_2O) and carbon stores (soil carbon, above-ground and below-ground carbon).

Influences and Levers: within these processes there are factors that influence stores and sources but cannot be changed in outdoor grazing (e.g. rainfall, altitude, air temperature). There are also factors that can be changed through management decisions – these are the levers that can potentially be adjusted to increase stores or reduce sources, or to change the rate of greenhouse gas emission and removal.

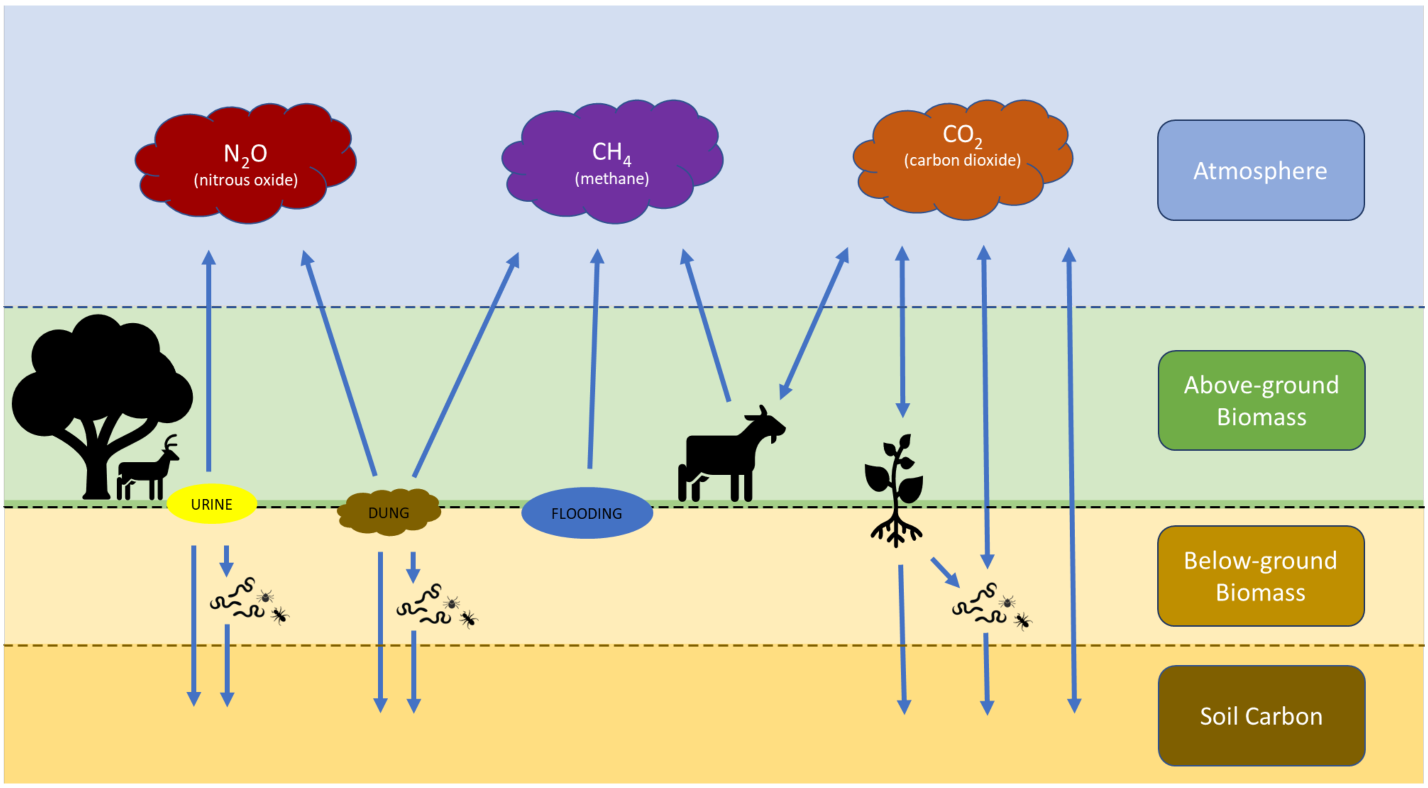
The levers are displayed in oval shapes: 

* indicates evidence gap (lack of research)

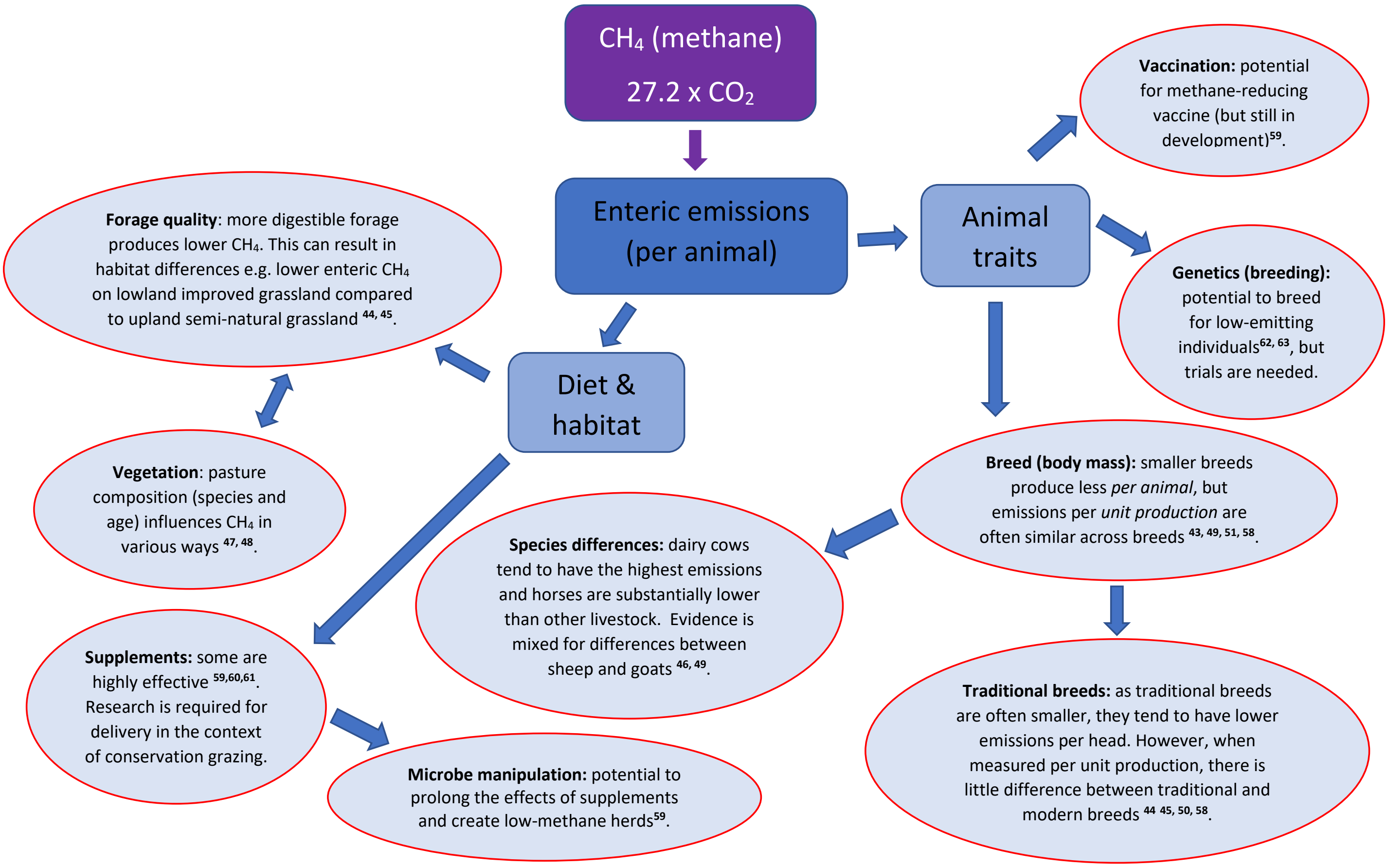
CO_2 equivalent values for CH_4 and N_2O are from IPCC values as described in Section 1 (27.2 x CO_2 for non-fossil fuel methane and 272 x CO_2 for nitrous oxide).

Note: Due to the high complexity of these processes (and in some cases mixed evidence) Conceptual Diagram A1 does not indicate all of the underlying processes mentioned in this report but indicates the key processes – those with significant impacts for which there is sufficient evidence.

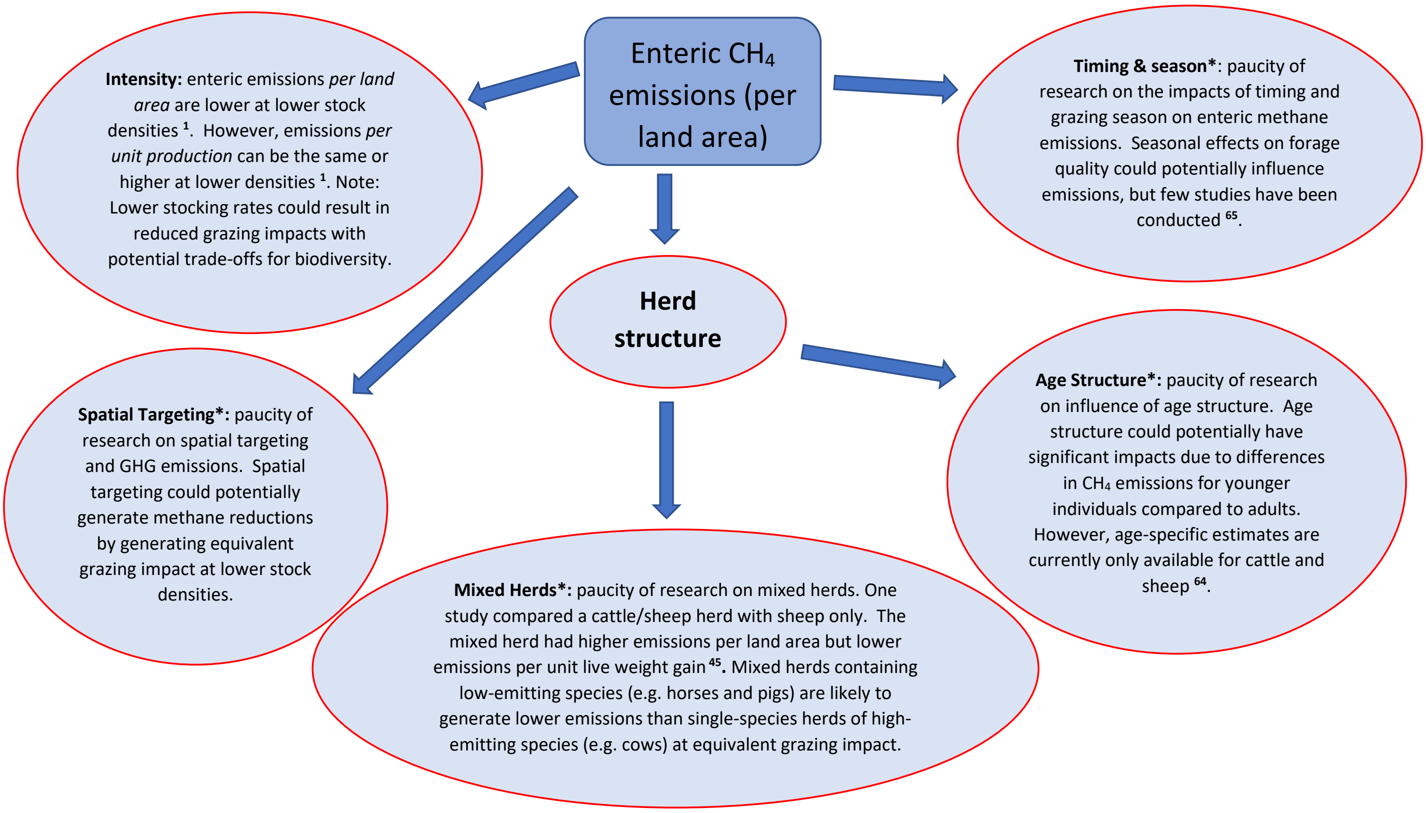
Conceptual Diagram A1: A simplified diagram of key sources and sinks of greenhouse gases in conservation grazing.



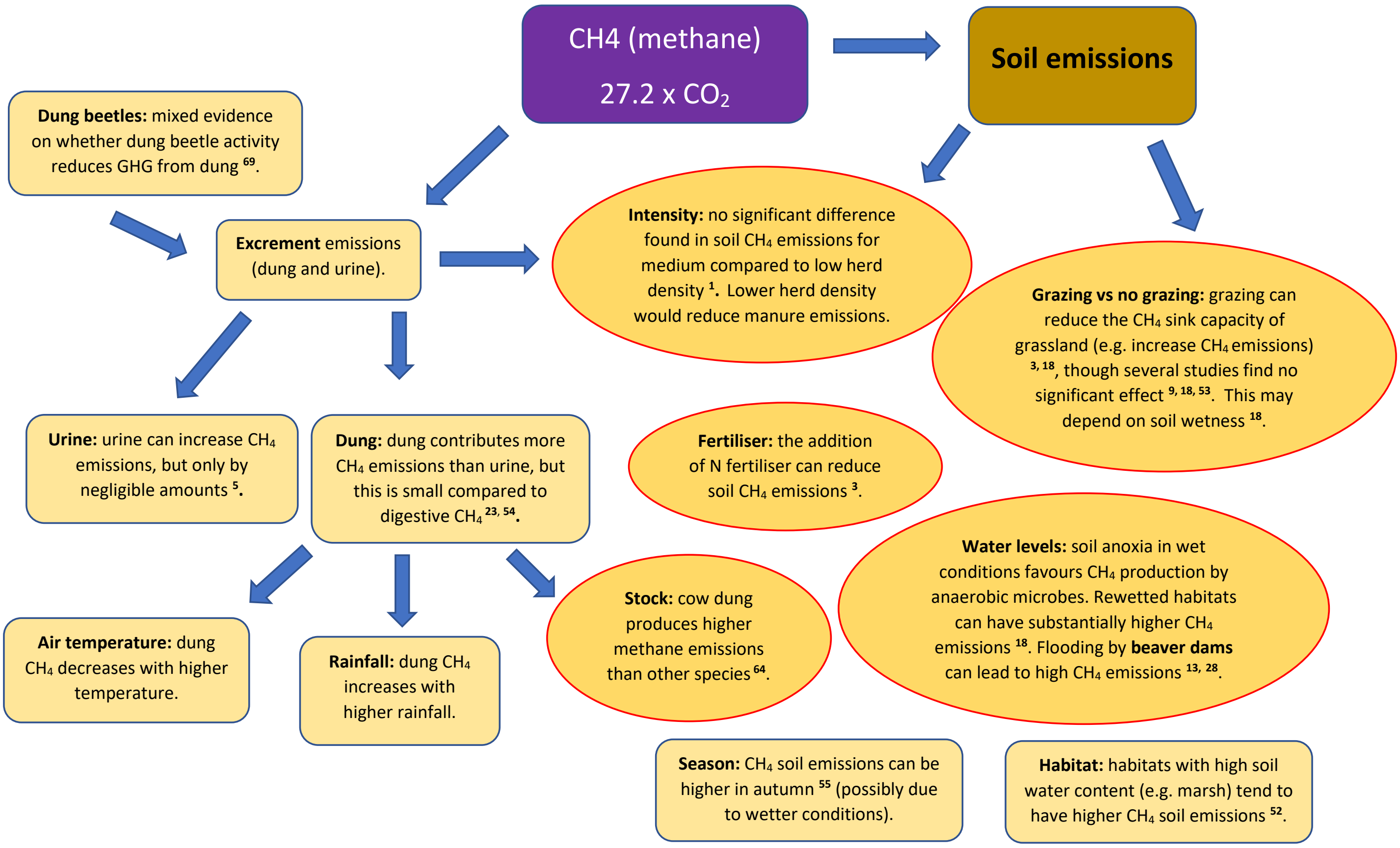
Conceptual Diagram A2: Factors influencing enteric (digestive) methane emissions from UK conservation grazing livestock.



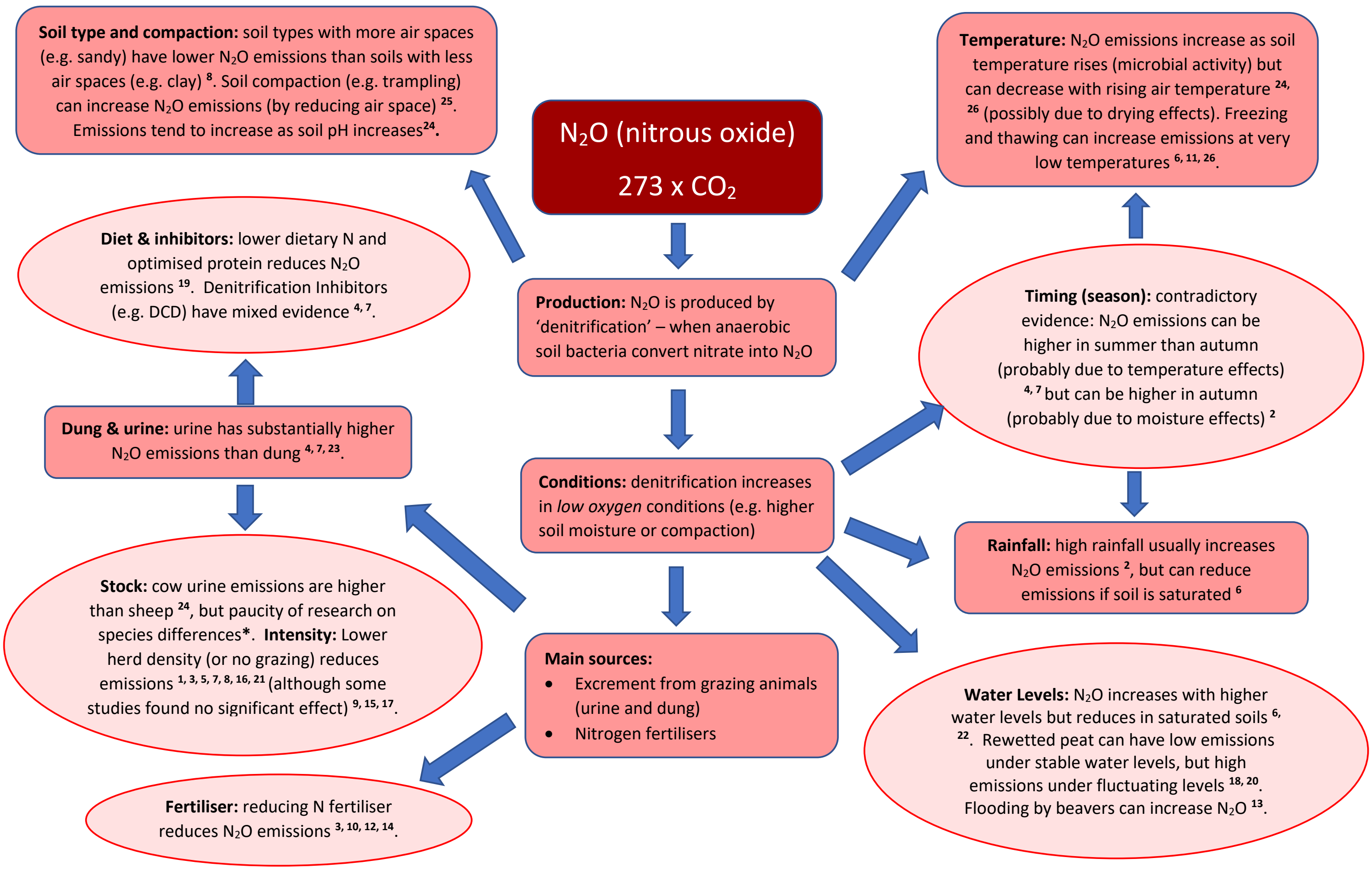
Conceptual Diagram A3: Factors influencing enteric methane emissions per land area within a conservation grazing context.



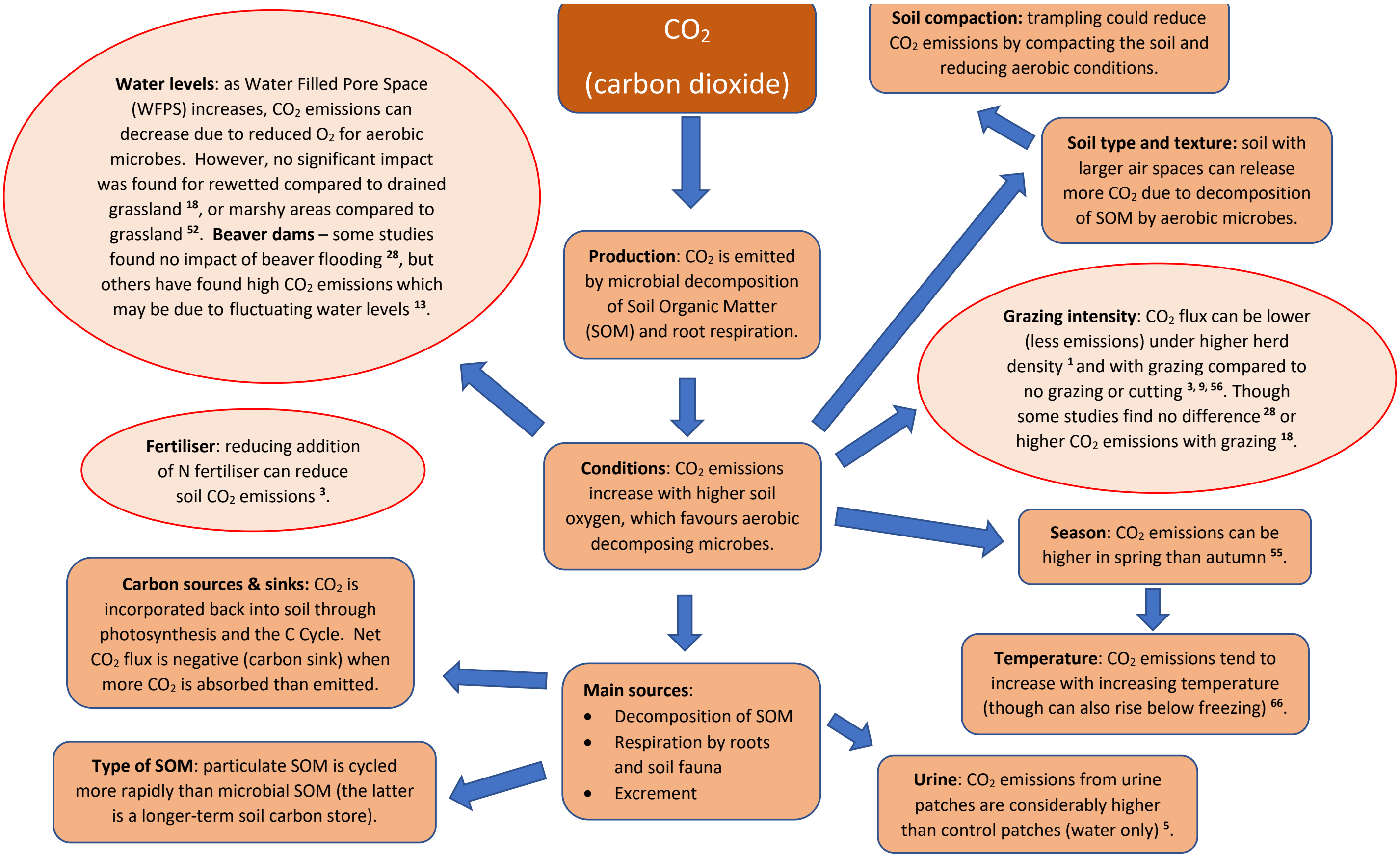
Conceptual Diagram A4: Factors influencing methane emissions from soils and excreta of grazing animals.



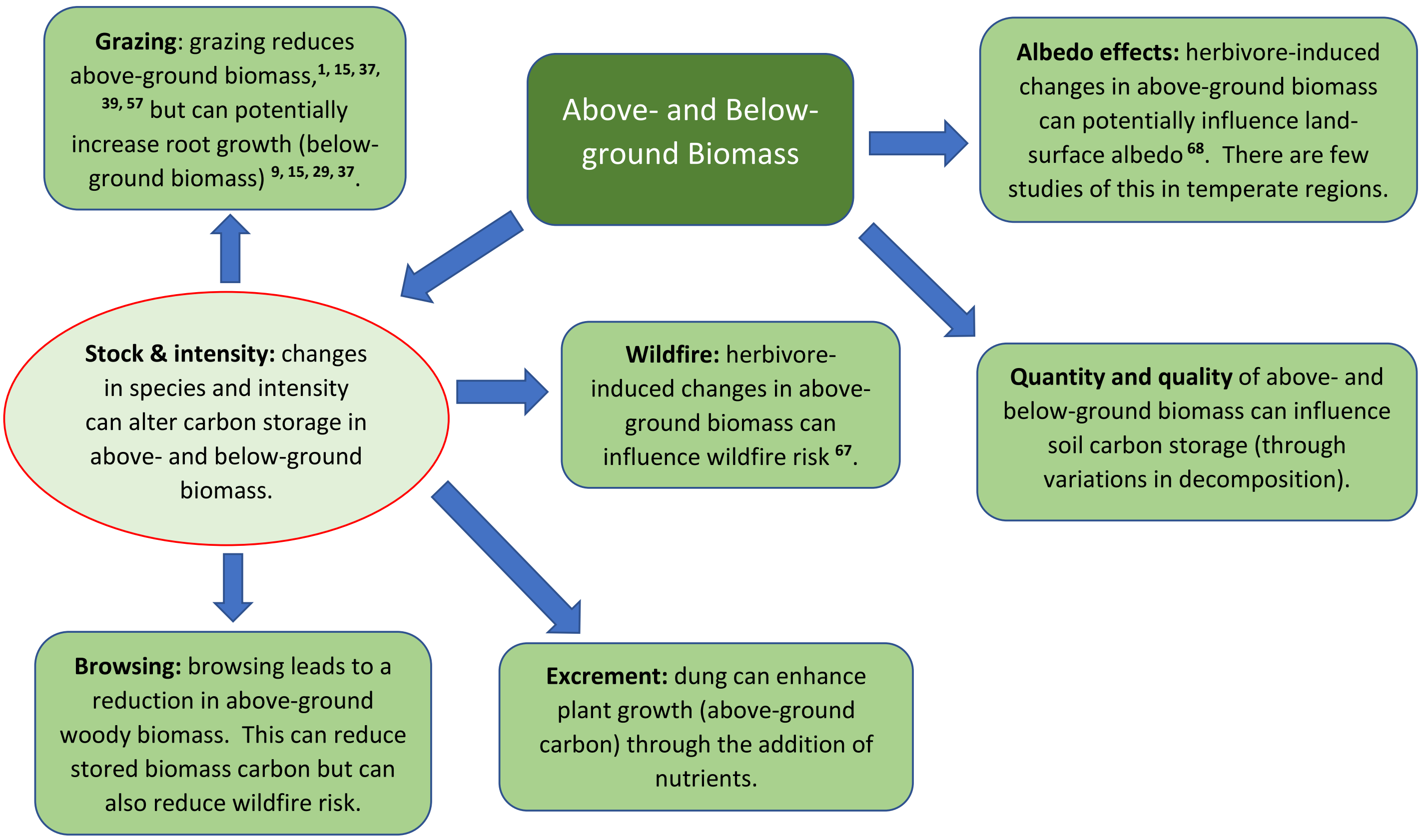
Conceptual Diagram A5: Factors influencing nitrous oxide emissions in conservation grazing.



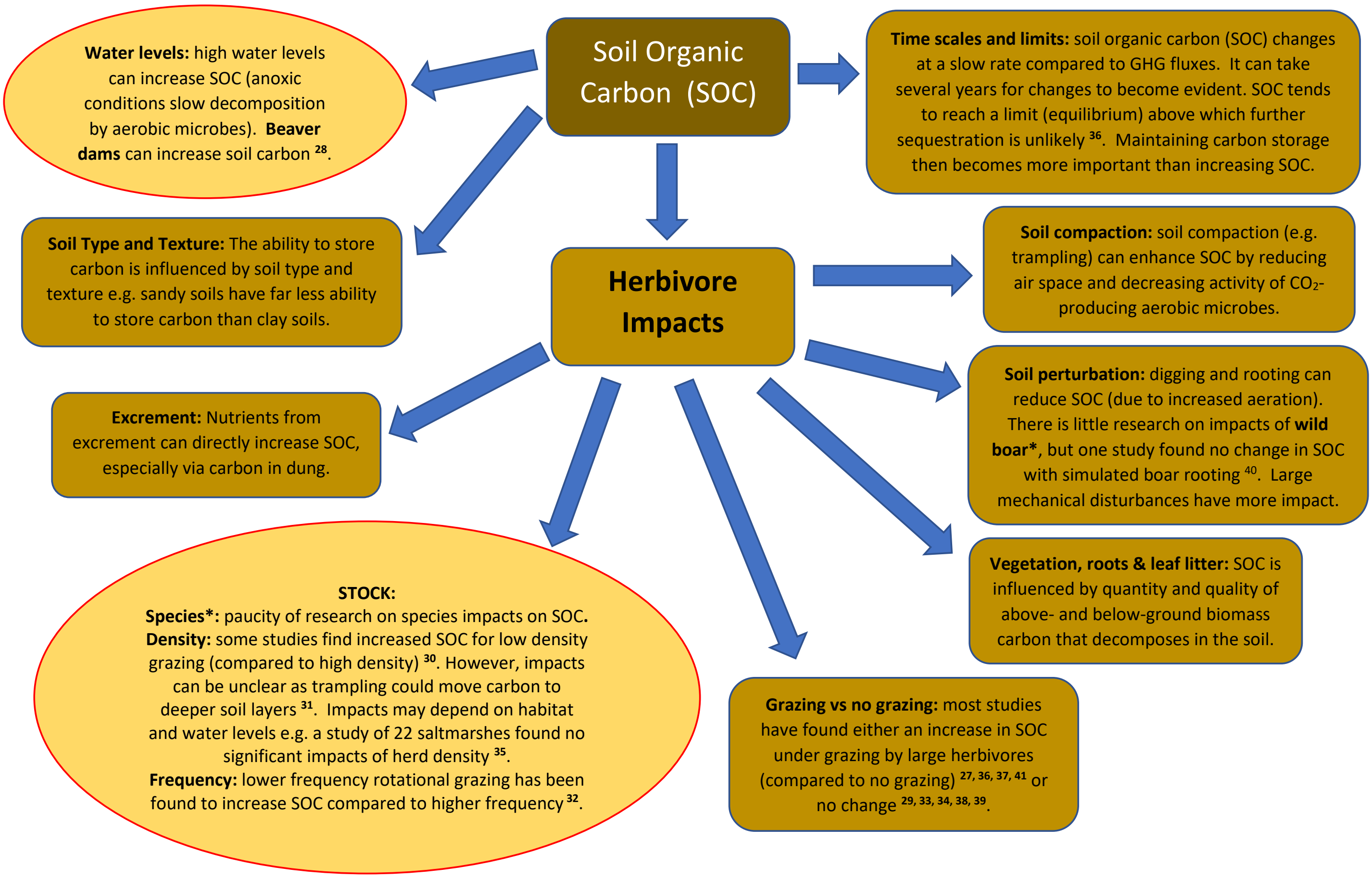
Conceptual Diagram A6: Factors influencing carbon dioxide emissions in a conservation grazing context.



Conceptual Diagram A7: Factors influencing climate effects through grazing-induced changes to above- and below-ground biomass.



Conceptual Diagram A8: Factors influencing climate effects through grazing-induced changes to soil carbon.



37. Summary descriptions of key processes

Enteric methane emissions (Conceptual Diagrams A2 and A3)

Methane is a potent greenhouse gas, and although short-lived in the atmosphere (around 10 years), it has around 27 times the warming impact of CO_2 over 100 years and 81 times the warming impact of CO_2 over 20 years (IPCC, 2021). Enteric (digestive) methane is the largest source of GHG emissions from livestock, so mitigation strategies targeted at enteric methane reduction are likely to have the most substantial impacts. **Conceptual Diagram A2** indicates the key levers for reducing enteric methane emissions, which include stock changes (species and breed), supplements, diet and habitat, microbe manipulation and genetics.

As well as considering emissions per head of livestock, it is important to consider emissions per area of land in a conservation context. **Conceptual Diagram A3** shows potential levers of change that could reduce emissions per land area (including herd density, herd structure, season and timing, and spatial targeting). However, it should be noted that these measures are unlikely to reduce emissions per unit of food production in contexts where the animals are destined for meat or milk production.

Methane: manure and soil emissions (Conceptual Diagram A4)

Methane emissions from manure and soil are important considerations for GHG emissions in livestock grazing (see **Section 1**). Manure and soil emissions can be influenced by weather conditions (e.g. soil moisture and rainfall, air and soil temperature (Oertel et al. 2016; Nazarie et al. 2013; Mazzetto et al., 2014). Land management to alter water levels (as well as flooding by beaver dams) can produce substantial methane emissions (Oertel et al., 2016; Minke et al., 2020). These emissions can be intensified by grazing of wet soils (Renou-Wilson et al. 2016). Methane emissions from manure could be reduced by changing livestock species or reducing livestock numbers, and potentially through spatial targeting (to avoid grazing on wetter soils).

Nitrous oxide (Conceptual Diagram A5)

Nitrous oxide is an even more potent GHG than methane. It is long-lived in the atmosphere (around 120 years) and has 273 times the warming impact of CO_2 (IPCC, 2021). The majority of the UK's nitrous oxide emissions (around 68%) are from the agricultural sector (DEFRA 2021). The main source of livestock-related N_2O emissions in a conservation grazing context is animal excrement, particularly urine. There is a paucity of studies on species and breed differences for N_2O emissions from excreta, but research indicates higher Emission Factors (EFs) for cows than sheep (IPCC, 2019 and Lopez-Aizpun et al. 2020):

"Our findings agree with the EFs suggested by the IPCC (2019) in that those for sheep urine were lower than those for cattle urine, highlighting that the animal has a significant influence on EFs. The IPCC attributes the lower EFs for the sheep, among others, to a wider urine distribution (smaller and more frequent urinations), and smaller effects on soil compaction during grazing (IPCC, 2006)."
- Lopez-Aizpun et al. 2020

Whilst data is available for cattle and sheep, there is a substantial research gap for other species. The UK GHG Inventory (Brown et al. 2022) uses the same EF for cows, horses, goats and red deer (though the evidence is based on cows). There are also considerable habitat differences in N_2O emissions. Emissions from wet soils are generally higher than emissions from dry soils (see 'Water Levels' in **Section 1**). Grazing and rewetting can have a synergistic effect on N_2O emissions leading to particularly high emissions when livestock are grazing wet habitats compared to grazing dry habitats or wet habitats without grazing (Wen et al. 2021). Reducing herd density can lower N_2O emissions directly through a reduction in total excreta and potentially indirectly through a reduction in soil compaction (Hernandez-Ramirez et al. 2021).

Changes in diet (reduced N content of food) can lead to lower N_2O emissions and dicyandiamide (DCD) can be applied to urine patches to reduce emissions. However, there is mixed evidence for the effectiveness of DCD (Bell et al. 2015; Cardenas et al. 2016) and these measures may have limited applicability in the context of conservation grazing (being more suited to confinement systems).

Carbon dioxide (Conceptual Diagram A6)

Carbon dioxide (CO_2) emissions from livestock grazing are not generally considered in emissions reporting for livestock. The CO_2 emissions from livestock respiration are considered to be balanced by the CO_2 uptake of the plants consumed, so net emissions from respiration are very low. CO_2 emissions from the soil can, however, be influenced by grazing. CO_2 flux is the difference between CO_2 emitted and CO_2 absorbed (e.g. through plant photosynthesis). When CO_2 flux is negative (more is absorbed than emitted) the system is a net carbon sink. Several factors can influence CO_2 flux in a conservation grazing context, including grazing intensity, soil type, temperature and water levels (see **Conceptual Diagram A6**).

Above- and below-ground carbon storage (Conceptual Diagram A7)

Vegetation provides temporary above- and below-ground carbon stores which can be influenced in various ways by grazing and browsing. Grazing generally reduces above-ground biomass due to consumption but can stimulate root growth, leading to higher below-ground biomass (Ford et al. 2012a; Olsen et al. 2011; Elschot et al. 2015). Dung can also stimulate vegetation growth through nutrient enhancement. By reducing woody plant growth, browsing can decrease above-ground carbon but may also reduce wildfire risk (Rouet-Leduc et al. 2021). The overall impacts of grazing depend on grazing intensity and species composition.

Soil carbon (Conceptual Diagram A8)

Soil organic carbon (SOC) can be influenced by livestock grazing through a variety of mechanisms. Whilst SOC can provide a long-term carbon store, there is a limit to carbon storage (equilibrium) when further sequestration is unlikely (Johnston et al., 2017). In systems already at high carbon storage capacity, maintaining carbon storage and reducing GHG emissions becomes more important than enhancing soil carbon. There is mixed evidence on the impacts of grazing on SOC, with some studies (Czobel et al. 2005; Elschot et al., 2015; Johnston et al., 2017; Mohr et al., 2005) finding a slight increase in soil carbon with grazing (compared to no grazing) and others finding no change in SOC (Acharya et al., 2012; Ford et al. 2012a; Futa et al., 2021; Garnett et al., 2000; Medina-Roldan et al., 2012). Changes in SOC can be difficult to detect due to long timescales, spatial variability in soils, and vertical movement of SOC to lower depths.

There is a paucity of research on the impacts of different livestock types or herd densities on SOC. Some researchers have found higher SOC at low densities compared to higher densities (Askari and Holden 2014) and some have found no difference in SOC at different herd densities (Harvey et al., 2019). However, impacts are likely to vary between habitats, soil types and water levels. Some changes in SOC may also be masked by trampling causing the movement of SOC to deeper soil levels (Cui et al., 2015).

38. References (Conceptual Diagrams)

Numbered references in Conceptual Diagrams (see below for full reference list):

1. (Allard et al., 2007)
2. (Allen et al., 1996)
3. (Barneze et al., 2022)
4. (Bell et al., 2015)
5. (Boon et al., 2014)
6. (Burchill et al., 2014)
7. (Cardenas et al., 2016)
8. (Chatskikh et al., 2005)
9. (Ford et al., 2012b)
10. (Hyde et al., 2006)
11. (Lampe et al., 2006)
12. (Maire et al., 2020)
13. (Minke et al., 2020)
14. (Murphy et al., 2022)
15. (Olsen et al., 2011)
16. (Rafique et al., 2011)
17. (Rafique et al., 2012)
18. (Renou-Wilson et al., 2016)
19. (Rivera and Chará, 2021)
20. (Tauchnitz et al., 2015)
21. (Wang et al., 2012)
22. (Wen et al., 2021)
23. (Yamulki et al., 1998)
24. (Lopez-Aizpun et al., 2020)
25. (Hernandez-Ramirez et al., 2021)
26. (Luo et al., 2013)
27. (Czóbel et al., 2005)
28. (Cazzolla Gatti et al., 2018)
29. (Acharya et al., 2012)
30. (Askari and Holden, 2014)
31. (Cui et al., 2015)
32. (Díaz de Otálora et al., 2021)
33. (Futa et al., 2021)
34. (Garnett et al., 2000)
35. (Harvey et al., 2019)
36. (Johnston et al., 2017)
37. (Elschot et al., 2015)
38. (Ford et al., 2012a)
39. (Medina-Roldan et al., 2012)
40. (Mohr et al., 2005)
41. (Zani et al., 2021)
42. (Chiavegato et al., 2015)
43. (Franz et al., 2010)
44. (Fraser et al., 2014a)
45. (Fraser et al., 2014b)
46. (Lockyer, 1997)
47. (McAuliffe et al., 2018)
48. (Murray et al., 2001)
49. (Pérez-Barbería, 2017)
50. (Ricci et al., 2014)
51. (F. Smith et al., 2015)
52. (Charteris et al., 2021)
53. (Clay et al., 2010)
54. (Jarvis et al., 1995)
55. (Marsden et al., 2018)
56. (Peichl et al., 2012)
57. (Smith et al., 2015)
58. (Fraser et al., 2015)
59. (Black et al., 2021)
60. (Vargas et al., 2022)
61. (Abbott et al., 2020)
62. (Moorby et al., 2015)
63. (Hayes et al., 2013)
64. (Brown et al. 2022)
65. (Islam et al., 2021)
66. (Byun et al., 2021)
67. (Rouet-Leduc et al., 2021)
68. (te Beest et al., 2016)
69. (Fowler et al., 2020)

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The Wildlife Trusts
The Kiln
Mather Road
Newark
Nottinghamshire
NG24 1WT

www.wildlifetrusts.org
evidence@wildlifetrusts.org
01636 677711