The Impact of Conservation Grazing on GHG emissions

Appendices

February 2024

Natural England Commissioned Report NECR489

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Catalogue code: NECR489

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Keywords

Conservation grazing, greenhouse gas emissions, carbon sequestration, livestock, habitats

Acknowledgements

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The Wildlife Trusts: Nigel Doar

Citation

Manning, F., Green, L., Webb E., and Wynn, S. 2023. The Impact of Conservation Grazing on GHG emissions. NECR489. Natural England.

Foreword

The climate and nature crisis are interlinked problems. Climate change accelerates biodiversity loss and erodes the ability of species to respond to future extreme weather events brought about by climate change. Greenhouse Gas (GHG) emissions reduction across all sectors is therefore essential. Natural England are driven to exploring long-term, nature-based solutions, which work to address both the restoration of habitats and the challenges of climate change. However, the solutions do not always solve both problems, with the solution to one problem potentially causing challenges for another.

Conservation grazing is an important tool for delivering high biodiversity outcomes through increasing the diversity and structure of vegetation swards. As an extensive system, conservation grazing only removes a proportion of the annual vegetation growth, leaving opportunities for other species to exploit for feeding and breeding requirements. Furthermore, livestock species preferentially eat different vegetation species, meaning that conservation goals can be designed with specific grazers in mind. This helps create variation in habitat structure which can help species adapt to changing climate conditions.

Livestock produce GHG emissions during grazing. These emissions are produced by enteric fermentation of the vegetation during digestion or following manure deposition. The magnitude of GHG emissions vary depending on the different species or the size of the animal. Different habitat vegetation will also influence the extent of GHG emissions due to how easy the vegetation is to digest.

Natural England commissioned this work as there is a need to understand the significance of GHG emissions within conservation grazing systems. To better support land managers' decision making on how to limit GHG emissions whilst also achieving conservation outcomes for biodiversity. Conservation grazing is widely used in many sites to benefit wildlife outcomes. We presently use it on many of our National Nature Reserves and within Agri-environment schemes we set up with land managers.

This project constructs a carbon calculator for conservation grazing which aims to give an indication of how changing breed size/ species choice as well as stocking rate for different habitats quantifiably affects GHG emissions while maintaining conservation outcomes. **However, the lack of robust data to populate key parts of the model used in the calculator means that any outputs are limited and cannot be used to justify one mode of land management over another.**

We hope it can be read and used for the purposes of stimulating thinking among land managers of extensive grazing systems and act as a guide in attempting to balance limiting GHG emissions in conservation grazing systems while achieving good conservation outcomes for biodiversity. This is seen as the start of building better understanding of this subject by highlighting the areas of uncertainty to inform future work.

Contents

Appendices

Grazing habitats influence emissions in different ways in IPCC Tier 2 calculations. Firstly, livestock emissions can vary depending upon the habitat they are grazing. In the model, this can happen in three ways:

- The amount of energy expenditure required to obtain sufficient food within the habitat (net energy for activity).
- How digestible the vegetation in the habitat is.
- The crude protein of the vegetation.

Secondly, habitats store carbon and can remove or release carbon dependent on habitat type, and management. There is potential for sequestration to offset the livestock emissions in certain instances.

The current limited availability and quality of relevant habitat data prevent the model from capturing the full variation in emissions expected between different habitats. This will be discussed in more detail in the following Appendices:

Appendix 1 considers how different habitats impact diet and what this means for livestock emissions.

Appendix 2 looks into habitat carbon stores and sequestration rates.

Appendix 3 presents a case study comparing carbon emissions from the same livestock type grazing the same habitat at different grazing densities.

Appendix 4 shows the calculations used in the model for the livestock emissions.

Appendix 1: Habitat impacts on livestock emissions

The emissions from livestock (enteric methane, and methane and nitrous oxide from excretion) are influenced by diet. However, in order to be able to calculate the differences in emissions due to diet, it is important to have sufficient data on the nutritional composition of the forage being consumed (crude protein and digestible energy in particular). Available data on the forages present in the habitats assessed, were insufficient and lacked the required consistency to enable us to discriminate between the habitats on the basis of forage quality. Therefore, the primary model does not currently differentiate between habitats when calculating the livestock enteric emissions.

The secondary model (i.e. the part that is restricted access only) provides data on the habitat carbon stocks and carbon sequestration – at present this is the main point where the grazers interact with the habitat. The only other area is where in the primary model there is an indication of indicative stocking densities for different grazing outcomes on the different habitats.

When calculating livestock emissions, there are three data inputs in the model that could produce different results by habitat, assuming there was sufficient data available to draw robust estimates from:

- Activity coefficient used to calculate net energy for animal activity
- Digestibility of feed
- Crude protein

Activity coefficient used to calculate net energy for animal activity

Activity coefficients are values that determine how much energy the animal needs in order to obtain its food, water and shelter. These coefficients could be altered depending on the habitat being grazed. For example, some environments, such as managed pasture are easy to graze (flat, abundant forage), and livestock do not need to expend large amounts of energy to obtain the food they require. Other environments are more challenging for livestock (rougher ground, steep land, poor quality, sparce forage) and require greater energy to be expended for the animal to gain food. It is assumed that in conservation grazing systems, where stocking densities are low, that the animals will travel extended distances (compared to those on enclosed rich grazing) to gather their food because the habitats are less nutritionally dense.

The IPCC specifies a range of different activity coefficients that can be used to estimate the net energy for animal activity, ranging from 0 to 0.36 (Gavrilova et al. 2019; Table 1; Table 2), where 0 would effectively be a housed animal with feed brought to it, whilst the higher values represent stock travelling large distances over sparce forage to access resources. A shift from housed cattle with little movement to cattle ranging extensively can increase total emissions of CO_2e by 33%. In sheep GHG emissions can increase by 15% when moving from relatively sedentary systems to ranging hills and uplands.

For cattle and buffalo, the following coefficients are available from IPCC:

- **Stall |** Animals are not expected to need much energy to obtain feed, due to being restricted to a small area.
- **Pasture |** Animals are likely to use modest energy to obtain feed, being confined in areas with sufficient forage.
- **Grazing large areas |** Animals are expected to need large amounts of energy to obtain feed as they graze hilly terrain and/or open rangelands.

Table 1 – Activity coefficients for cattle and buffalo in different feeding situations. Units are dimensionless. Data are from Gavrilova et al. (2019).

Situation	C_a
Stall	0
Pasture	0.17
Grazing large areas	0.36

For sheep and goats, the following coefficients are available:

- **Housed ewes |** Animals are not expected to use much energy to obtain feed, due to being limited to a small area, in particular when pregnant.
- **Grazing flat pasture |** Animals are likely to use modest energy to obtain feed, grazing in lowland pastures.
- **Grazing hilly pasture |** Animals are expected to need large amounts of energy to obtain feed as they graze hilly terrain.
- **Housed fattening lambs |** Animals are not expected to require much energy to obtain feed, due to being confined to a small area for fattening.
- **Lowland goats |** Animals are likely to use modest energy to obtain feed, grazing in lowland pastures.
- **Hill and mountain goats |** Animals are expected to need large amounts of energy to obtain feed as they graze hilly terrain.

Table 2 – Activity coefficients that correspond to the habitats that sheep and goats tend to feed in. Units are in MJ d^{-1} kg^{-1}. Data are from Gavrilova et al. (2019).

Situation	C_a
Housed ewes	0.0096
Grazing flat pasture	0.0107
Grazing hilly pasture	0.0240
Housed fattening lambs	0.0067
Lowland goats	0.0190
Hill and mountain goats	0.0240

The coefficients selected for the model were:

- **Cattle and buffalo -** Grazing large areas
- **Sheep -** Grazing hilly pasture

This may overestimate emissions for some of the habitats, such as salt marsh, where forage is more abundant, but conditions may remain challenging due to the ground conditions, therefore the activity coefficient for animals grazing flat pasture may underestimate emissions.

Digestibility of feed

Digestibility of feed is the percentage of gross energy in the feed that the animal can absorb and use, and that is not excreted by the animal (Gavrilova et al. 2019). Digestibility of feed impacts greenhouse gas (GHG) emissions by changing the rate of enteric methane (Hristov et al. 2013). This is because less digestible feeds release more hydrogen ions, which can be converted into methane in the rumen by bacteria (Wolin 1960 as in Hristov et al. 2013).

According to the IPCC, it has been suggested that feed digestibility ranges from 45 – 55% in rangelands, whilst managed pastures produce swards with feed digestibility values within the range of 55 – 80% (Gavrilova et al. 2019). Here, the IPCC define rangelands as land that is primarily grassland, shrubland, savanna or woodland, but not forest (Grice et al. 2008 as in Gavrilova et al. 2019). In the model, all eight habitats were assumed to have the same digestibility of feed value. This value was selected from Gavrilova et al. (2019) and assumed to correspond to the digestibility of low-quality feed (52%).

A sensitivity analysis shows that emissions in the model vary depending on the digestibility (Figure 1). In cattle, total emissions increased by 76% when digestibility was reduced from 50% to 40%. In contrast when digestibility was improved from 50% to 60% this resulted in a 37% decrease in total emissions from the cattle. The same level of change was observed whether cattle were grazed on large areas or pasture (i.e. different IPCC coefficients were used for net energy for animal activity). Sheep had a similar but less pronounced pattern. In sheep, total emissions increased by 52% when feed digestibility reduced from 50% to 40%. Total emissions decreased by 28% when feed digestibility improved from 50% to 60%.

This sensitivity analysis suggests that habitat specific digestibility factors could have a significant impact on the results from the tool, if it is found that there are large differences in digestibility. This would allow the tool to give more accurate estimates for how GHG emissions from conservation grazing vary between livestock type and habitat.

Horses have not been included in this sensitivity analysis; they are monogastrics and, as a result, the impact of forage quality on methane production is far less pronounced. For this reason the IPCC have not developed Tier 2 approaches for horses, and instead utilise a simpler Tier 1 emission factor (Gavrilova et al. 2019). In the Tier 1 methodology there is no response to nutritional quality. It is only in the more detailed Tier 2 approaches used for ruminants that nutritional quality has an impact.

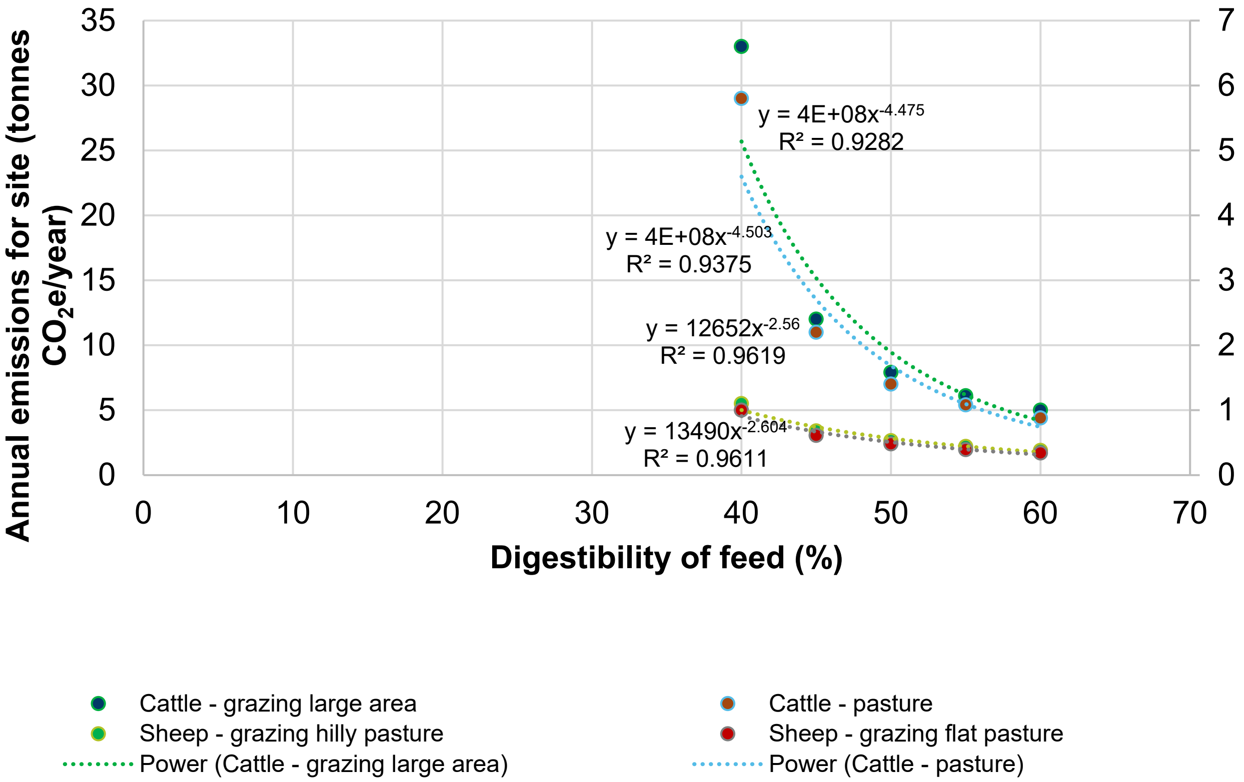

Figure 1 – Sensitivity analysis comparing annual emissions from cattle and sheep grazing fodder of different hypothetical feed digestibility.

Crude protein

Crude protein refers to the total proportion of protein present in animal diet (Gavrilova et al. 2019). Crude protein has been shown to link to the amount of nitrogen excreted by animals, with lower rates of excretion at lower crude proteins. The excreted nitrogen is converted to N_2O by soil bacteria following deposition (Montes et al. 2013). Therefore, in theory, the lower the crude protein in the diet, the lower the nitrogen excretion and the lower the nitrous oxide emissions from manure deposition. Crude protein is taken into account as part of the Tier 2 N_2O calculations, where the nitrogen excretion rate is calculated (Gavrilova et al. 2019).

The IPCC suggests crude protein content ranges from 9.5 – 17.1% in the diets of non-dairy cattle when considering different countries and diets (Gavrilova et al. 2019). In the model, a value of 15% was chosen for all animals and habitats; this is the value suggested for adults growing in Western Europe. It is likely that the habitats would vary in the crude protein available for grazing. Fraser et al. (2009) shows crude protein is different between different plants at two different heathland sites, and between the same plant at the two sites. For example, at one site *Erica spp.* had a crude protein content of 20%, whereas on a separate site, measured in the same months, it had a crude protein content of 14%. *Calluna vulgaris* had a crude protein content of 23% at the first site and 18% at the second site. These values represent single samples and not averages – but show the level of variability between species and sites.

A sensitivity analysis looking at hypothetical crude protein contents and annual emissions found an increase in GHG emissions as crude protein in the diet increased (Figure 2). The change in emissions in the model was linear and more apparent in cattle than sheep, with an approximately 5% decrease in GHG emissions when reducing from 15% to 5% crude protein and a 5% increase in total emissions when increasing crude protein from 15% to 25%.

The coefficients selected for the model were:

- **Cattle and buffalo -** Grazing large areas
- **Sheep -** Grazing hilly pasture

This may overestimate emissions for some of the habitats, such as salt marsh, where forage is more abundant, but conditions may remain challenging due to the ground conditions, therefore the activity coefficient for animals grazing flat pasture may underestimate emissions.

Digestibility of feed, horses have not been included in this sensitivity analysis. Here, the Tier 1 emissions factor for horses has been used, as recommended by the IPCC (Gavrilova et al. 2019). The emissions factor is therefore independent of diet information, unlike the Tier 2 nitrogen excretion factor calculated for cattle, bison, buffalo and sheep.

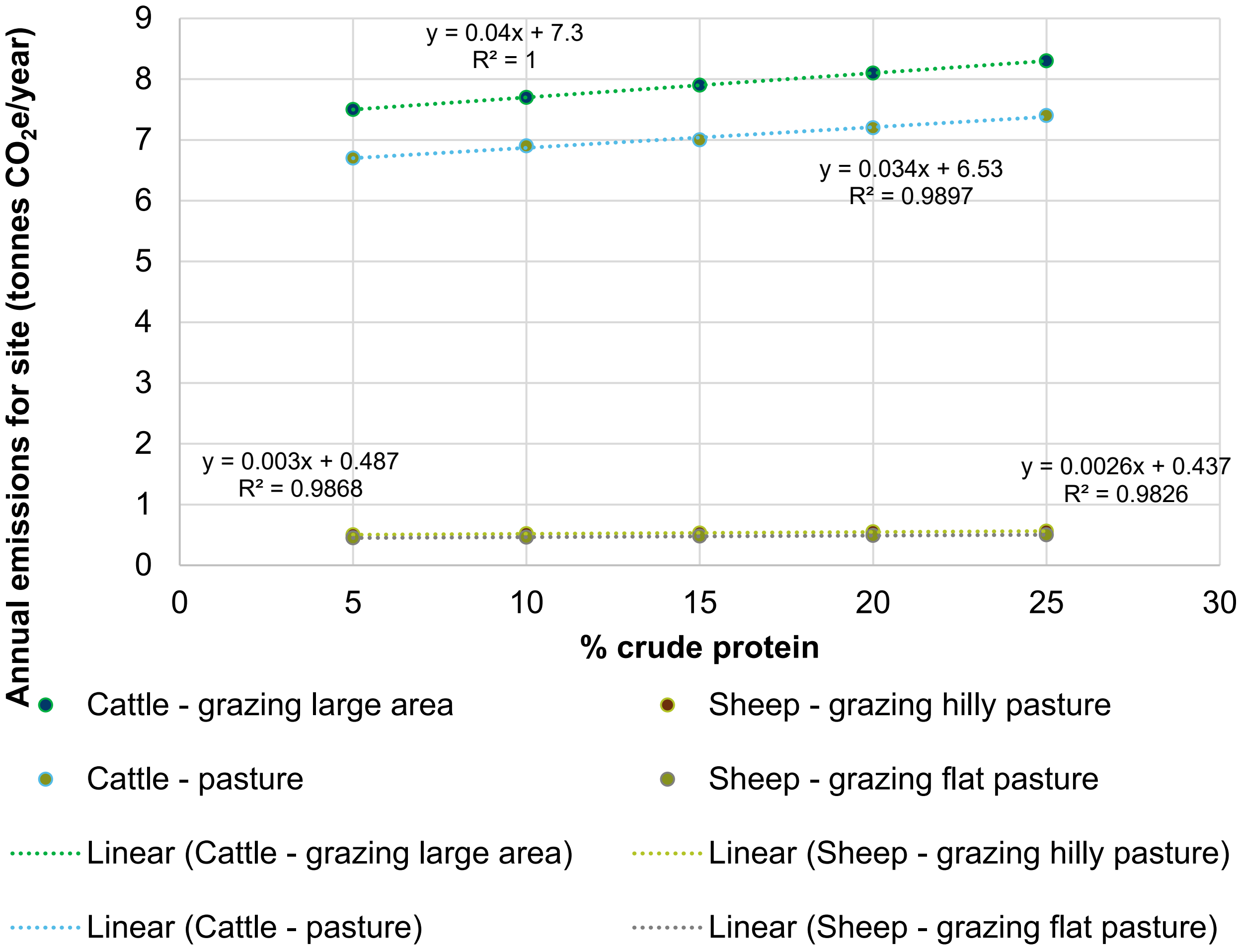

Figure 2: Sensitivity analysis comparing annual emissions from cattle and sheep grazing fodder of different hypothetical crude protein contents.

Appendix 2: Habitat carbon cycle and challenges in available data

Carbon cycles between different carbon sinks or stores, such as the land, atmosphere and oceans, through processes collectively known as fluxes (Gregg et al. 2021). When more carbon is taken up from the atmosphere into vegetation or the soil than is returned, this is called carbon sequestration. Carbon sequestration occurs where the rate of carbon accumulation via photosynthesis exceeds the rate of decomposition and respiration of that carbon back to the atmosphere. For a net increase in stored carbon to occur this sequestered carbon must either be stored in vegetation (e.g. trees) or in soils (e.g. peat or other organic matter). Alternatively, carbon can be released from the land into the atmosphere through respiration, oxidation, or other decomposition processes.

Carbon sequestration and storage will vary by habitat, although there can also be large variability within habitats (Gregg et al. 2021). The challenge is that there is only a relatively small set of data available for the different habitats, with some values based on single assessments at single sites, and therefore the evidence base is weak and patchy with regards to applying it to modelling scenarios. As a generalisation, woodland habitats typically have the highest carbon sequestration rates, and native broadleaved trees are reliable carbon sinks, especially for the first few decades of growth. While sequestration rates decline over time, older woodlands are important for carbon storage but may add little in the way of additional sequestration if most of the trees are mature (Gregg et al. 2021). Other habitats that are large carbon stores include salt marshes and peatland habitats, such as blanket bogs, and fen. Peatland habitats are able to sequester carbon indefinitely when in a healthy condition but damage to these habitats, particularly agricultural land use, results in the release of stored carbon, thereby becoming a source of GHG emissions (Gregg et al. 2021). Additionally, management practices that lead to erosion, draining of peatlands or burning of organic matter (such as heather burning) can lead to rapid losses of stored carbon. In situations where carbon sequestration exceeds carbon emissions, the habitat is a net sink habitat. Conversely, where carbon emissions exceed carbon sequestration, the habitat is a net emitter.

Habitat carbon stocks

Carbon stock data used in the model were selected from Gregg et al. (2021), who compiled data from a comprehensive literature review (Table 3). However, it is important to recognise that, although a comprehensive review was conducted, there were a number of habitats with very limited available data and therefore the robustness of some of the data remains uncertain.

Table 3 – Carbon stock data.

Habitat	Soil carbon stocks (t C ha^{-1})	Soil depth (m)	Vegetation carbon stocks (t C ha^{-1})	Reference
Calcareous grassland	69	0 – 0.15	No data	Gregg et al. (2021)
Salt marsh	59	0 – 0.3	0.6	Gregg et al. (2021)
Sand dunes	9.5	0 – 0.15	0.005	Gregg et al. (2021)
Heathlands	94	0 – 0.3	6	Gregg et al. (2021)
Wood pastures	No data	No data	No data	Gregg et al. (2021)
Rush pastures	No data	No data	No data	Gregg et al. (2021)
Blanket bog	799	0 – 2.0	No data	Gregg et al. (2021)
Fen	1,971	0 – 3.8	No data	Gregg et al. (2021)

Data limitations

One challenge with the available data is that the reported measurements for soil carbon have been made to different depths, meaning that it is not possible to compare stocks between habitats accurately (Table 3). Habitat soil carbon varies with depth, regardless of location (Jobbágny and Jackson 2000). Whilst the majority of the soil carbon will be found in the topsoil (Balesdent et al. 2018; Jobbágny and Jackson 2000), the studies have varied the depths of soil carbon measured from 15 cm to 200 cm (Gregg et al. 2021). Part of this is due to expected variation between habitats, for example peat soils are often deeper than other soils and store more carbon at greater depth. However, some of the variation in soil depths will be due to different sampling methodologies, making it harder to compare between the studies and habitats.

Habitat GHG fluxes

GHG flux data used in the model were selected from Gregg et al. (2021) and Thom and Doar (2021). Both reports used comprehensive literature reviews to compile the data (Table 4). Although again the caveat remains that these reviews were not always able to find multiple data points for each habitat and therefore robustness of some data points is limited.

Table 4 – Range of GHG fluxes on different habitats in t CO_2e ha^{-1} yr^{-1}. With low GHG flux representing the lowest value in the published data and high GHG flux the highest value in the published data. Negative numbers indicate sequestration, whilst positive numbers indicate emissions.

Habitat	Low GHG flux	High GHG flux*	Reference
Calcareous Grassland	0.00	4.96	Thom & Doar (2021)
Salt Marsh	-6.00	-2.35	Gregg et al. (2021)
Sand Dunes	-2.68	0.00	Gregg et al. (2021)
Heathlands	-5.60	0.20	Thom & Doar (2021)
Wood Pastures	No data	No data	Gregg et al. (2021); Thom & Doar (2021)
Rush Pastures	No data	No data	Gregg et al. (2021)
Blanket bog	-0.02	13.14	Gregg et al. (2021)
Fen	-0.93	32.89	Gregg et al. (2021)

*Some of the higher values presented in this data set are expected to include grazing emissions as it is difficult to assess habitat emissions in grazing systems without capturing emissions from the livestock as well.

Data limitations

The available carbon sequestration data were taken from a small number of sites for each habitat. Caution must therefore be taken when extrapolating these data to other sites, as there are many nuances between sites (geography, climate, precise habitat make-up, historical and current management practices) that will influence the actual rate of either sequestration or emissions. It is therefore not possible to get accurate estimates of carbon sequestration that represent the nuances at different sites.

For instance, micro-climates vary throughout the UK. This will have a large impact on fluxes – small changes in temperature can greatly change the rate of biogeochemical reactions and therefore the amount of carbon dioxide that can be produced or sequestered (Lloyd and Taylor 1994). This may change the emissions factor to be used in the model. Similarly, precipitation ranges vary throughout the UK. Hydrology can impact biogeochemical cycles, with many processes requiring either oxic or anoxic soil microclimates.

Land management practices vary between sites and can have impacts on carbon sequestration data (Figure 3; Gregg et al. 2021). For example, disturbance events often cause an increase in carbon emissions, due to the exposure of stored carbon to microbes that previously could not access it for decomposition.

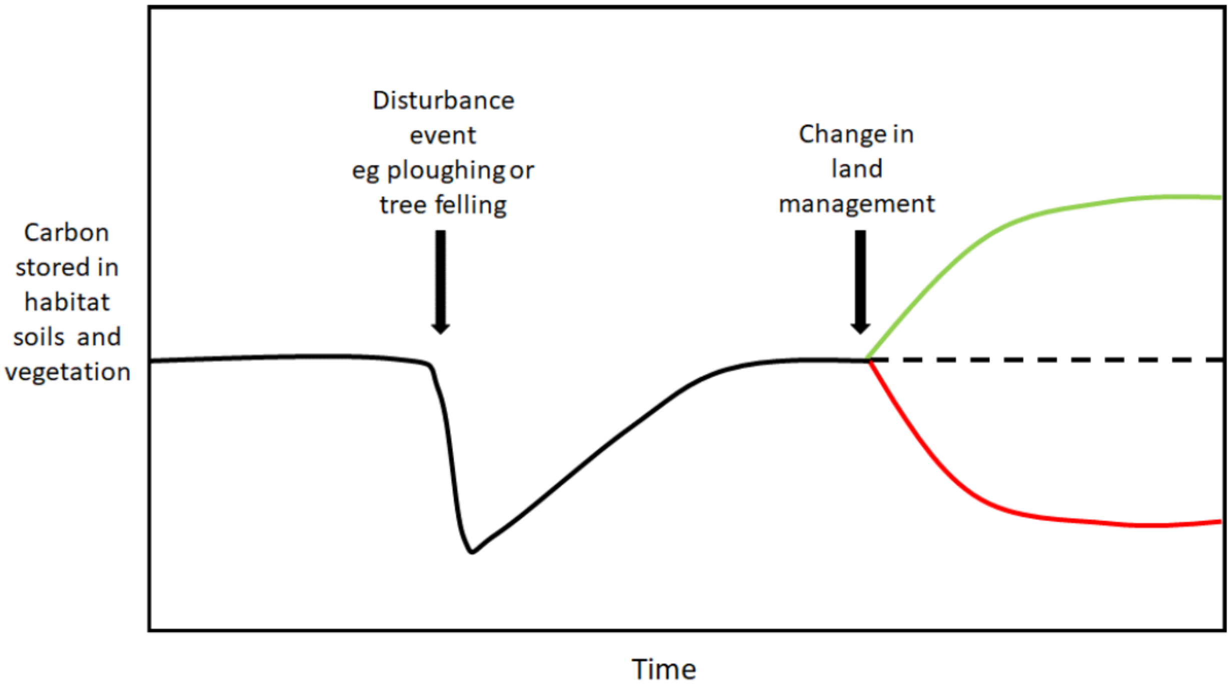

Figure 3 – Conceptual model of the impact of disturbance events and land use change on habitat carbon stocks over time (Gregg et al. 2021).

Habitats in equilibrium

Habitats that have been undisturbed for an extended period can be assumed to have reached a state of equilibrium, where the carbon emissions equal the rate of carbon sequestration (Gregg et al. 2021). For example, converting arable land or intensively managed grasslands to semi-natural grasslands, particularly extensive species-rich grasslands, can cause sequestration, but this only happens until the new habitat has reached an equilibrium state (Thom and Doar 2021). Established grasslands themselves have been shown not to act as carbon sinks (no net carbon sequestration) (Smith 2014; Sozanska-Stanton et al. 2016; Thom and Doar 2021), it is the process of change that causes sequestration, rather than the habitat having an infinite capacity for sequestration. Observed carbon sequestration comes from land use change, with semi-natural grassland having higher carbon stocks than more intensively managed lands. Carbon sequestration occurs whilst the carbon stocks build from the depleted levels in the intensively managed grassland to the more carbon rich semi-natural grassland.

It is not always possible to understand from the reviewed data whether assessments were taken from habitats in a state of change, or whether they were mature and likely to be in a state of equilibrium. This is likely to have further impact on the robustness of the habitat data. For example, data from Gregg et al. 2021, indicated that saltmarsh was constantly sequestering, however in the same report they indicate (Figure 4) that saltmarsh should reach a point of equilibrium. Habitats reaching a carbon equilibrium can be observed in woodlands and saltmarsh, as well as in grasslands (Figure 4). Intact peatlands are an exception, due to their ability to create peat overtime, resulting in a gradual increase in the depth of the peat laid down. However, where peatlands are disturbed (eroded, drained) they switch from carbon sequestration and peat formation to erosion of peat and loss of carbon.

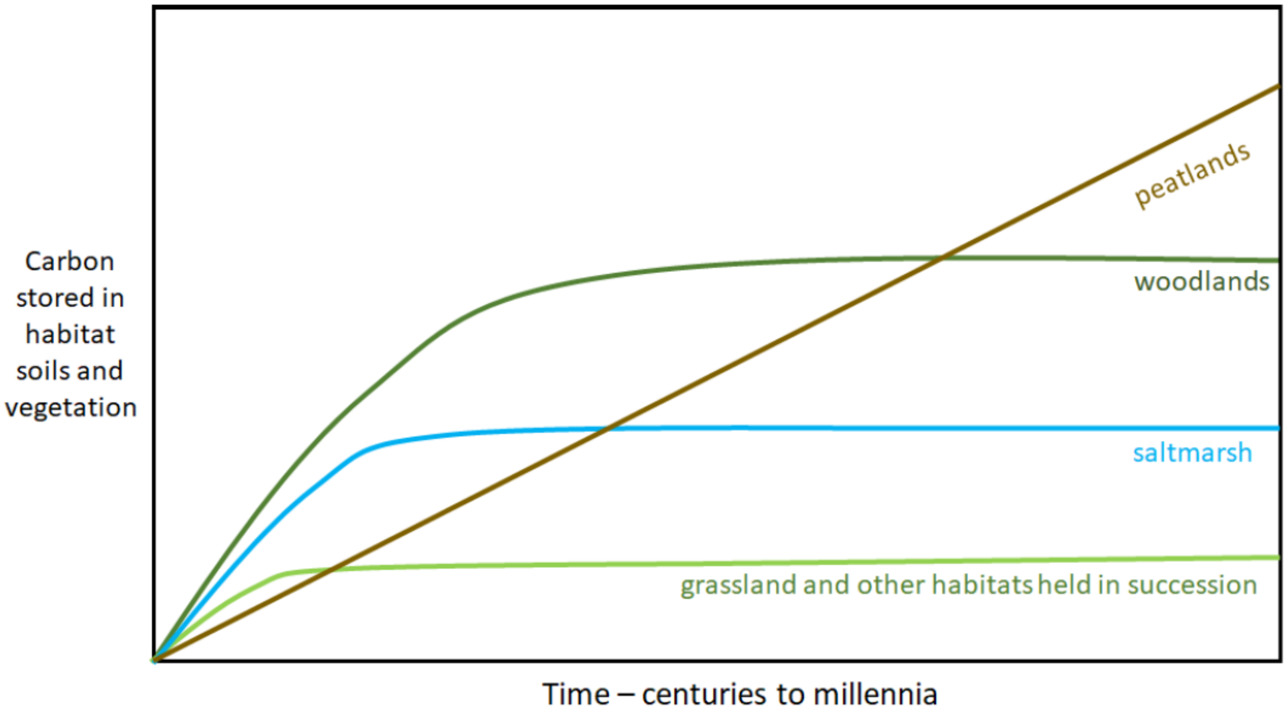

Figure 4 – Conceptual model of time to carbon stock equilibrium from (Gregg et al. 2021).

Missing GHG flux pathways – methanotrophs

The GHG flux pathways included in Gregg et al. (2021) and Thom and Doar (2021) considered pathways with available data that are commonly known. However, methanotrophs have not been included in either report. Methanotrophs are micro-organisms that oxidise methane in either oxic or anoxic conditions (Guerrero-Cruz et al. 2021). Methanotrophs have been found in estuary and coastal sediments, lakes, riverbeds, peatlands, swamps, paddy fields and canals (Guerrero-Cruz et al. 2021). Oremland and Culberton (1992) found that methanotrophs can consume more than 90% of potentially available methane. Limited data exist on the impact of methanotrophs from different habitats, meaning that clear emissions factors are not currently available.

Appendix 3: Case study 4 - Comparing carbon emissions from the same livestock type grazing the same habitat at different grazing densities

A fourth case study was undertaken (not presented in main report), which examined habitats where sequestration may occur and considered the stocking density they could potentially sustain while maintaining a neutral or positive carbon balance. Similar to the case studies in the report, the habitat inputs were kept consistent to facilitate the comparison, with 100 ha of each habitat entered into the model, which were all assumed to be grazed all year round by small sheep.

Concerning salt marsh – it needs to be recognised that there is a limited data set, which indicates that the habitats assessed were still in a process of sequestration, and had not reached equilibrium. Therefore, this is a case study for one example of a salt marsh and may not represent all salt marsh habitats. In this example the minimum sequestration was estimated to be 235 tCO_2e yr^{-1}; here it would be possible to increase the stocking density of sheep to 68 livestock units over 100 ha (0.68 LU ha^{-1} yr^{-1}; 884 individuals) and still achieve carbon neutrality. If carbon sequestration within the habitat was greater, with a maximum of 600 $tCOe_2$ yr^{-1}, it would be possible to graze up to 173.5 livestock units of sheep over 100 ha (1.73 LU ha^{-1} yr^{-1}; 2,256 individuals) and still achieve carbon neutrality. The indicative maximum recommended commercial stocking density for this habitat to limit overgrazing would be 50 livestock units over 100 ha (0.5 LU ha^{-1} yr^{-1}; 650 individuals).

Again, data for sand dunes are limited to a small number of sites, and therefore this should be treated as an example of selected sand dune habitats and may not reflect all sand dune habitats. The analysis by Gregg et al. (2021) found that at least some sand dunes have the potential to sequester carbon, but research studies are limited and based on a small number of sites with relatively few data points. This assessment assumes they can range from a point of equilibrium through to sequestration of up to 268 tCO_2e yr^{-1} across 100 ha. In these higher sequestering sand dunes, the model predicts that a maximum of 1,008 small sheep (77.5 livestock units across 100 ha; 0.76 LU ha^{-1} yr^{-1}) could be grazed and maintain the system at net neutral carbon flux. Due to the sparse nature of forage and sensitivity of these habitats this stocking density is unlikely to be applied to sand dune habitats as it is double recommended rates.

In blanket bog, the condition of the peat has a significant influence on GHG fluxes, with degraded peat potentially emitting 1,314 tCO_2e yr^{-1} across the 100 ha. However, a near natural habitat that is actively laying down new peat is able to sequester carbon. Although this is a slow process. Natural England data indicate that over a year the 100 ha would sequester a maximum of 2 tCO_2e (Gregg et al. 2021). This slow rate of sequestration and the sensitivity of these habitats to erosion and over-grazing, means that grazing may not be appropriate. However, where it is used, a near natural intact bog could remain carbon neutral if the stocking density of small sheep is kept below 0.58 livestock units across the 100 ha (0.0058 LU ha^{-1} yr^{-1}), equivalent to 7.5 individuals. It would be possible to maintain neutrality with up to 3.3 Exmoor ponies (3.3 livestock units across 100 ha, 0.033 LU ha^{-1} yr^{-1}), reflecting their lower overall emissions. Any degradation of the peat will cause emissions, and therefore grazing on degraded blanket bog will merely increase total emissions.

It is important to note that these are theoretical values, and do not take into account the level of damage that increased stocking densities might do to the habitat, which may result in a change from being a net sink to net source of carbon emissions. Therefore, these values should be taken in context of understanding the environmental impact of changing stocking density, to understand how far you can go in different habitats whilst maintaining a negative carbon balance (removing more carbon than emitted).

Appendix 4: Livestock assumptions

Enteric methane – Tier 1 methodology

The simplest method to estimate enteric fermentation is through using Tier 1 emissions factors. Functionality has been developed in the model to allow all species to be calculated using Tier 1, however as Tier 2 methods are available for the ruminant species the default is to use Tier 2, and Tier 1 is used only for ponies where no Tier 2 model is available. The model is built to calculate the Tier 1 enteric emissions from all animals but only the results from ponies are presented in the output. The equation for this method is presented in the following equation {Equation 1}. The emissions factors are presented in (Table 5). Tier 1 emissions factors vary by species. Tier 1 emissions factors are not scaled to weight, and they do not respond to nutritional quality of the diet.

$$Methane\ emissions = Emissions\ factor\ x\ Number\ of\ animals$$

{Equation 1}

Table 5 - Tier 1 emissions factors for enteric emissions (Gavrilova et al. 2019)

Species	Tier 1 emissions factor (kg CH_4 animal^{-1} yr^{-1})
Ponies	18
Cattle*	52
Sheep*	5
Water buffalo*	78

* These data are included in the model, but the presented results used Tier 2 methodology. Bison do not have a Tier 1 emissions factor.

Enteric methane – Tier 2 methodology

Tier 2 methodology first estimates the gross energy intake of the different livestock, before using this to determine the methane emissions. The Tier 2 methodology is used in the model to calculate enteric methane emissions from cattle, bison, buffalo and sheep. The IPCC sets out the following equation for estimating gross energy {Equation 2}:

$$Gross\ energy = \left[\frac{\left(\frac{NEm + NEa + NEl + NEwork + NEp}{REM}\right) + \left(\frac{NEg + NEwool}{REG}\right)}{Digestibility} \right]$$

{Equation 2}

Where:

NEm = net energy required by the animal for maintenance

NEa = net energy required by the animal for activity

NEl = net energy required by the animal for lactation

NEwork = net energy required by the animal for work

NEp = net energy required by the animal for pregnancy

NEg = net energy required by the animal for growth

NEwool = net energy required by the animal for wool

REM = ratio of net energy available in a diet for maintenance to digestible energy consumed

REG = ratio of net energy available in a diet for growth to digestible energy consumed

This equation has been simplified due to lack of data availability. The equation used in the model is {Equation 3}:

$$Gross\ energy = \left[\frac{\left(\frac{NEm + NEa}{REM}\right) + \left(\frac{NEg}{REG}\right)}{Digestibility}\right]$$

{Equation 3}

Here, gross energy is linked to weight. This can be seen in the calculations for net energy required by the animal for maintenance {Equation 4}, net energy required by the animal for activity {Equation 5} and {Equation 6} and net energy required by the animal for growth {Equation 7} and {Equation 8). Coefficients used in these equations can be found in Table 6, Table 7,Table 8, Table 9, Table 10 and Table 11.

$$Net\ energy\ for\ maintenance\ (all\ animals)\ = Coefficient\ x\ Livestock\ weight^{0.75}$$

{Equation 4}

Table 6 – Coefficients for calculating net energy for maintenance (Gavrilova et al. 2019)

Species	Coefficient for calculating net energy for maintenance ($MJ\ day^{-1}\ kg^{-1}$)
Cattle	0.32
Sheep	0.22
Water buffalo	0.32
Bison*	0.32

* Assumed to be the same as cattle and buffalo.

$$\begin{aligned} &Net\ energy\ for\ activity\ (cattle\ \ buffalo\ and\ bison) \\ &\quad = Coefficient\ x\ Net\ energy\ for\ maintenance \end{aligned}$$

{Equation 5}

Table 7 – Coefficients for calculating the net energy for activity in cattle, water buffalo and bison (Gavrilova et al. 2019)

Species	Situation	Coefficients for calculating net energy for activity (dimensionless)
Cattle	Inactive[a]	0.17
	Active[b]	0.36
Water buffalo	Inactive[a]	0.17
	Active[b]	0.36
Bison*	Inactive[a]	0.17
	Active[b]	0.36

* Assumed to be the same as cattle and buffalo.

[a] Animals use a small amount of energy to graze the food they need.

[b] Animals expend large amounts of energy to acquire their food.

$$Net\ energy\ for\ activity\ (sheep\ ) = Coefficient\ x\ Livestock\ weight$$

{Equation 6}

Table 8 – Coefficients for calculating the net energy for activity in sheep (Gavrilova et al. 2019)

Species	Situation	Coefficients for calculating net energy for activity (MJ day^{-1} kg^{-1})
Sheep	Inactive[a]	0.0107
	Active[b]	0.024

[a] Sheep use little energy to gain the food they need.

[b] Sheep use large amounts of energy to obtain their food.

$$Net\ energy\ for\ growth\ (cattle\ \ buffalo\ and\ bison) = 22.02\ x\ \left(\frac{Livestock\ weight}{Coefficient\ \ x\ Mature\ body\ weight}\right)^{0.75}\ x\ Average\ daily\ weight\ gain^{1.097}$$

{Equation 7}

Table 9 – Coefficients for calculating the net energy for growth in cattle, water buffalo and bison (Gavrilova et al. 2019)

Species	Coefficient for calculating net energy for growth (MJ day^{-1} kg^{-1})
Cattle	1[a]
Water buffalo	1[a]
Bison*	1[a]

* Assumed to be the same as cattle and buffalo.

[a] Using the average of females and males.

$$Net\ energy\ for\ growth\ (sheep) = \frac{Weight\ gain\ x\ (Coeffient\ a + Coefficient\ b\ x\ (Body\ weight\ at\ weaning + Body\ weight\ at\ slaughter\ or\ 1\ year)}{365}$$

{Equation 8}

Table 10 – Coefficients for calculating the net energy for growth in sheep (Gavrilova et al. 2019)

Species	Coefficient a for calculating net energy for activity (MJ kg^{-1})	Coefficient b for calculating net energy for activity (MJ kg^{-1})
Sheep	2.5	0.35

Finally, a methane conversion factor is used to convert the gross energy intake into methane emissions {Equation 9}:

$$Tier\ 2\ emissions\ factor = \frac{Gross\ energy\ intake\ x\ \left(\frac{Methane\ conversion\ factor}{100}\right)\ x\ 365}{Energy\ content\ of\ methane}$$

{Equation 9}

Where the energy content of methane is 55.65 MJ kg CH_4^{-1} and the methane conversion factors can be found in Table 11.

Table 11 – Methane conversion factors (Gavrilova et al. 2019)

Species	Methane conversion factor (%)
Cattle	7
Sheep	6.7
Water buffalo	7
Bison*	7

* Assumed to be the same as cattle and buffalo

Manure methane – Tier 1

Manure methane is calculated using the following equation, which has been slightly modified from the IPCC equation {Equation 10} and the coefficients in Table 12. The model is built to calculate the Tier 1 manure methane emissions from all animals but only the results from ponies are presented in the output.

$$\begin{aligned}&Manure\ methane = Number\ of\ livestock\\ &x\ Annual\ average\ volatile\ solid\ excretion\ per\ head\ x\ Emissions\ factor\end{aligned}$$

{Equation 10}

The IPCC provides a methodology to estimate the rate of average volatile solid excretion as well as different emissions factors depending on the manure management system. The Natural England model assumes all manure is deposited in the field. The equation has therefore been modified to remove the option for different manure management systems.

Table 12 – Volatile solid excretion rates and Tier 1 emissions factors for manure methane (Gavrilova et al. 2019)

Species	Volatile solid excretion rates (kg VS (1000 kg animal mass)$^{-1}$ day^{-1})	Tier 1 emissions factor for Pasture/Range/Paddock (g CH_4 kg VS^{-1})
Ponies	5.65	0.6
Cattle*	5.7	0.6
Sheep*	8.2	0.6
Water buffalo*	7.7	0.6

* These data are included in model, but the presented results used Tier 2 methodology. Bison do not have a Tier 1 emissions factor.

Manure methane – Tier 2

The Tier 2 method for estimating manure methane calculates the emissions factor using the following equation, which has been slightly modified from the IPCC equation {Equation 11}. The Tier 2 methodology is used in the model to calculate methane emissions from manure for cattle, sheep, bison and water buffalo.

$$Emissions\ factor = Volatile\ solids\ x\ 365\ x \left(Max\ methane\ producing\ capacity\ \ x\ 0.067\ x\ \frac{Methane\ conversion\ factor}{100}\right)$$

{Equation 11}

The IPCC provides methodology to estimate the rate of average volatile solid excretion {Equation 12} as well as factors for the maximum methane producing capacity, coefficients and the methane conversion factor. The value of 0.067 is the conversion factor for m^3 CH_4 to kg CH_4.The Natural England model assumes all manure is deposited during grazing. The equation has therefore been modified to remove the option for different manure management systems. This equation was multiplied by the number of animals to get the manure methane.

Table 13 – Maximum methane producing capacity and methane conversion factors for estimating manure methane emissions (Gavrilova et al. 2019)

Species	Maximum methane producing capacity (Tier 2)	Methane conversion factor for Pasture/Range/Paddock (%)
Cattle	0.18	0.47
Sheep	0.19	0.47
Water buffalo	0.1	0.47
Bison*	0.1	0.47

* Assumed to be the same as buffalo

The following equation is used for estimating Tier 2 volatile solid excretion rates {Equation 12}:

$$Volatile\ solid\ excretion\ rates = \left[Gross\ energy\ intake\ x\left(1 - \frac{Digestible\ energy}{100}\right) + (Urinary\ energy\ x\ Digestible\ energy)\right] x \left[\left(\frac{1 - Ash\ content\ of\ feed}{Conversion\ factor\ for\ dietary\ gross\ energy\ intake}\right)\right]$$

{Equation 12}

Here, gross energy intake values are the same as the values calculated for Tier 2 enteric emissions, and therefore link to animal weight. Digestible energy currently does not vary between habitat types, but functionality is included to allow values to be updated in the future. The IPCC provides coefficients for urinary energy (0.04), ash content (0.06) and the conversion factor for dietary gross energy intake (18.45 MJ kg^{-1}).

N_2O emissions from deposition

The model uses Tier 1 emissions factors for estimating rates of N_2O emissions from manure for ponies and Tier 2 emissions factors for cattle, sheep, water buffalo and bison. In both instances, the method for estimating direct N_2O emissions calculates the emissions factor using the following equation, which has been slightly modified from the IPCC equation {Equation 13}:

$$\begin{aligned}&Direct\ N_2O\\&= Number\ of\ animals\ x\ Annual\ average\ N\ excretion\ per\ head\ x\ Emissions\ factor\end{aligned}$$

{Equation 13}

The IPCC provides methodology to estimate the average annual N excretion per head as well as emissions factors for the production of N_2O. The equation used to determine N excretion varies depending on whether the Tier 1 or Tier 2 pathway is being assumed. The Natural England model assumes all manure is deposited whilst grazing. The equation has therefore been modified to remove the option for different manure management systems.

Table 14 – Emissions factors for direct N_2O emissions

Species	Emissions factor for direct N_2O emissions (kg N_2O-N)
Cattle	0.004
Sheep	0.003
Bison	0.004
Water buffalo	0.004
Ponies	0.003

Estimating N excretion rate – Tier 1

The nitrogen excretion rate is calculated using Tier 1 methodology for ponies (data for other species are available but not presented in the default output). The Tier 1 value is estimated using the following equation {Equation 14} and the values in Table 15. The results from this equation are then used in the previous equation {Equation 13} in order to get the N_2O emissions from grazing.

$$Annual\ average\ N\ excretion\ per\ head = N\ excretion\ rate\ x\ \frac{Animal\ weight}{1000}\ x\ 365$$

{Equation 14}

Table 15 – Nitrogen excretion rates for the Tier 1 calculations for N_2O emissions (Hergoualc'h et al. 2019)

Species	Nitrogen excretion rate (kg N (1000 kg animal mass)$^{-1}$ day^{-1})
Ponies	0.26
Cattle*	0.42
Sheep*	0.36
Water buffalo*	0.45
Bison*º	0.45

* These data are included in the model, but the presented results used Tier 2 methodology.

º Bison assumed to be the same as buffalo.

Estimating N excretion rate – Tier 2

Tier 2 methodology is used to estimate the nitrogen excretion rate for cattle, sheep, buffalo and bison. Here, the following equation {Equation 15} is used alongside values in Table 16.

$$Annual\ average\ N\ excretion\ per\ head = N\ intake\ x\ (1 - N\ retention\ fraction)\ x\ 365$$

{Equation 15}

Table 16 – Nitrogen retention fraction (Gavrilova et al. 2019)

Species	N retention fraction (dimensionless)
Cattle	0.04
Sheep	0.1
Water buffalo	0.06
Bison*	0.06

* Assumed to be the same as buffalo.

Nitrogen intake is estimated using the following equation {Equation 16}:

$$N\ intake = \frac{Gross\ energy\ intake}{Conversion\ factor\ for\ dietary\ gross\ energy\ intake\ per\ kg\ dry\ matter}\ x\ \frac{Crude\ protein}{Conversion\ factor\ to\ kg\ dietary\ N}$$

{Equation 16}

For this equation, the values used for gross energy intake are the values that were calculated for enteric methane emissions. The crude protein estimate currently does not vary between habitat types, but functionality is included to allow values to be updated in the future when more data are available. The conversion factor for dietary gross energy intake per kg dry matter is 18.45 MJ kg^{-1}. The conversion factor from dietary protein to dietary nitrogen is 6.25 kg feed protein kg N^{-1}.

Indirect N_2O emissions

The Tier 1 method for estimating volatilized N_2O emissions calculates the emissions factor using the following equation, which has been slightly modified from the IPCC equation {Equation 17}:

$$Volatilized\ N_2O = Number\ of\ animals\ x\ Annual\ average\ N\ excretion\ per\ head\ x\ Fraction\ of\ volatilized\ manure\ N\ x\ Emissions\ factor$$

{Equation 17}

The IPCC provides methodology to estimate the average annual N excretion per head as well as the fraction of volatilized manure N and the emissions factor for N volatilisation (Table 17). The Natural England model assumes all manure is deposited whilst grazing. The equation has therefore been modified to remove the option for different manure management systems.

Table 17 – Fraction of N volatilized during grazing and emissions factor for N leaching and runoff (Hergoualc'h et al., 2019)

Species	Fraction of N volatilised from dung and urine deposition during grazing	Emissions factor for N volatilisation and redeposition (kg N_2O-N)
All animals	0.21	0.01

The Tier 1 method for estimating N_2O emissions from leaching calculates the emissions factor using the following equation, which has been slightly modified from the IPCC equation {Equation 18}:

$$Leached\ N_2O = Number\ of\ animals\ x\ Annual\ average\ N\ excretion\ per\ head\ x\ Fraction\ of\ leached\ manure\ N\ x\ Emissions\ factor$$

{Equation 18}

The IPCC provides methodology to estimate the average annual N excretion per head as well as the fraction of leached manure N and the emissions factor for leaching (Table 18). The Natural England model assumes all manure is deposited in the field. The equation has therefore been modified to remove the option for different manure management systems.

Table 18 – Fraction of N leached during grazing and emissions factor for N leaching and runoff (Hergoualc'h et al., 2019)

Species	Fraction of N leached from dung and urine deposition during grazing	Emissions factor for N leaching and runoff (kg N_2O-N)
All animals	0.24	0.011

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