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Deer in a changing climate – how do wild deer affect carbon sequestration in Scottish woodlands?

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Executive summary

The Scottish Government is investing significant resources into expanding Scotland's woodland cover to increase carbon sequestration and mitigate climate change. Wild animals are rarely considered in carbon storage policy. However, there is growing evidence that Scotland's wild deer population could hinder targets for woodland creation. High pressure from deer can also harm the health of pre-existing woodland and therefore reduce the ability of Scotland's woodlands to store carbon and off-set greenhouse gas (GHG) emissions.

The latest figures show Scotland's wild deer population to be approaching 1 million individual animals. The need to control wild deer has led deer management to become Scotland's largest terrestrial wildlife management challenge.

This short review explores the current state of knowledge on wild deer populations and how they effect carbon sequestration in Scottish woodlands. It gives an overview of the key factors and identifies areas where there is an absence of evidence.

1.1 Findings

- The impacts of deer fall into two categories:
    - Direct – such as removing vegetation, preventing natural regeneration, and increasing mortality of mature trees.
    - Indirect – promoting the dominance of less palatable species and reducing the quality of the plant litter that in turn can affect the nutrient balance.
- Analysis of the evidence indicates that the primary mechanisms by which deer interfere with carbon cycling in woodlands are largely identified. However, we found limited data that quantify the size of these effects. Therefore, more research is needed to establish the scale of the threat to carbon sequestration in woodlands.
- A larger body of evidence exists to demonstrate the effects deer have on above-ground carbon storage. Conversely, there were limited data on the less direct, but potentially significant, effect deer have on below-ground carbon stores.

- Although more data are needed to determine the significance of deer browsing in relation to meeting carbon sequestration goals in woodlands, reducing deer impact to a level where woodlands can naturally regenerate would likely increase woodland productivity and carbon storage.
- For Scotland's natural landscape and woodlands to recover, deer densities need to be reduced and maintained around a <5 deer/km^2 threshold. In some cases, deer fences may need to be erected temporarily to protect certain areas. Although, they are a costly solution.

1.2 Conclusions

This evidence review suggests that the mechanisms by which deer impact carbon cycling have been investigated and mostly identified. However, very limited evidence was identified that examined the size and significance of these effects. Without these quantitative data, it is difficult to create an informed mitigation strategy. Hence, further research is needed in Scotland to fully understand this complex relationship.

Given that the actions taken to mitigate the climate emergency are time sensitive, action may have to proceed using the limited data currently available. Scholars and practitioners largely agree that reducing deer numbers in woodlands to a threshold believed to allow natural regeneration of the full assemblage of woodland plant species would be beneficial for plant productivity and therefore carbon storage. Thus, reducing deer numbers to a sustainable threshold could counter many of the adverse effects presented in this report. In addition, reducing deer numbers will be essential in protecting the woodlands that will help Scotland reach its goals of net zero by 2045.

Contents

Glossary

Biomass – the total quantity or weight of individual or group of organisms.

Carbon sequestration – the process by which carbon dioxide is removed from the atmosphere and stored in solid or liquid form. In this report, carbon sequestration refers to the removal of atmospheric carbon dioxide and its storage in plant and soil biomass.

Enteric fermentation – fermentation that takes place inside the digestive system of an animal.

Fraying -the act of rubbing antlers to remove velvet or to mark territories. This is typically done on trees.

Herbivore – an animal that feeds on plants. In this report, the term herbivore relates to mammalian herbivores.

Ruminant – an even toed ungulate mammal that chews cud regurgitated from its rumen. The rumen is the first of the four stomachs possessed by ruminants. It acts as a fermentation chamber and digests feed-stuff with the aid of microorganisms.

Ungulate – a hoofed mammal.

Measurements

Kt – Kiloton. Equal to 1,000,000 kg.

kt/CO_2eq – Kiloton carbon dioxide equivalent. This is a measurement used to compare the global warming potential of greenhouse gas emission to carbon dioxide.

Tg y-1 –Annual emission of carbon in teragrams. 1 teragram is equal to 10,000,000,000 kg.

2 Background

Through the Climate Change (Emissions Reduction Targets) (Scotland) Act 2019, the Scottish Government has passed legislation which sets annual and interim emissions reduction targets for Scotland, on a trajectory to net zero emissions by 2045[1]. These targets include an interim goal of a 75% reduction in emissions by 2030 (relative to the 1990 baseline). The update to the 2018 Climate Change Plan [2], published in December 2020, sets out policies to achieve these targets and curb the impact of climate change due, overwhelmingly, to human-induced greenhouse gas (GHG) emissions. The Plan update includes an increased woodland creation target of 18,000 hectares per year by 2024/25.

Although the accumulation and storage of carbon in forests (carbon sequestration) does not stop emission of CO_2 from fossil fuel combustion entering the atmosphere, carbon fluxes into stable forest carbon pools have the potential to offset residual CO_2 emissions. In the UK, previous studies have shown trees to be capable of storing 40-80 tonnes of carbon per hectare[3]. The transfer and storage of atmospheric CO_2 into above and below-ground carbon pools in forests buys time for the development of low-carbon technologies and the decarbonisation of global economies, whilst providing benefits such as better flood protection and biodiversity[4]. Carbon sequestration in forests provides a low-cost opportunity in climate policy. But, for successful implementation, it needs efficient policy design, forest management and concise scientific knowledge[5].

Scotland has around 19% woodland cover, making it the most wooded of the UK countries. Despite this, it remains one of the most deforested countries in Europe, with much less woodland cover than the 37% European average[6]. Around a quarter of Scotland's woodlands are considered native, whilst the remaining three-quarters are commercial plantations which mainly consist of conifers[7]. Under the Scottish Government's Low Carbon Fund, Scottish Forestry will receive an additional £100m to fund tree planting efforts, while Forestry and Land Scotland is set to receive an additional £30m to expand Scotland's national forests[8]. These large investments are designed to increase woodland creation from the current 12,000 hectares per year, up to 18,000 hectares in 2024/25[8]. The increase in forest/woodland cover in Scotland, is not only promising for offsetting CO_2 emissions, but also for providing potential habitat restoration that can simultaneously tackle the global threat of biodiversity loss[9] and help society adapt to climate change. Although the new areas of tree-planting established is increasing, the importance of the condition, health and management of existing forests cannot be understated.

In its report to the Scottish Government, the Committee on Climate Change (2016) advised that creating 16,000 ha of woodland each year would sequester 1,560 kt of carbon dioxide (CO_2) emissions by 2030[10]. As increases in the atmospheric level of CO_2 are driving rapid climate change, sequestering carbon is crucial[11]. A critical step in expanding woodland cover is the establishment of strong young trees in a healthy ecosystem. However, this can be difficult as the young trees need to be protected from the grazing and browsing of wild deer. Scotland's wild deer population was estimated to be between 593,000 and 783,000 individual animals in 2013[12]. Eight years on, that figure could be well on its way towards 1 million individuals.

Wild animals are rarely considered in climate change policy and GHG emissions reduction targets, but there is growing evidence that Scotland's wild deer population could be altering both above and below-ground carbon stocks. Historically, a dominant factor in the increases in ranges and numbers of deer has been linked to expansions of tree cover, although the system is complex. The Scottish Government's plans for afforestation will provide further habitat for deer across a number of localities in Scotland, which will increase the need for deer management.

The primary influence deer have on carbon sequestration in woodlands is their consumption of vegetation which reduces the amount of plant biomass available for photosynthesis. The removal of plant biomass also alters vegetative community structures which can lead to poor quality leaf-litter and a depression of nutrient cycling and ecosystem productivity. Thus, consideration of how wild deer may affect the Scottish Government's targets for biodiversity and increased carbon sequestration in woodlands, is vital.

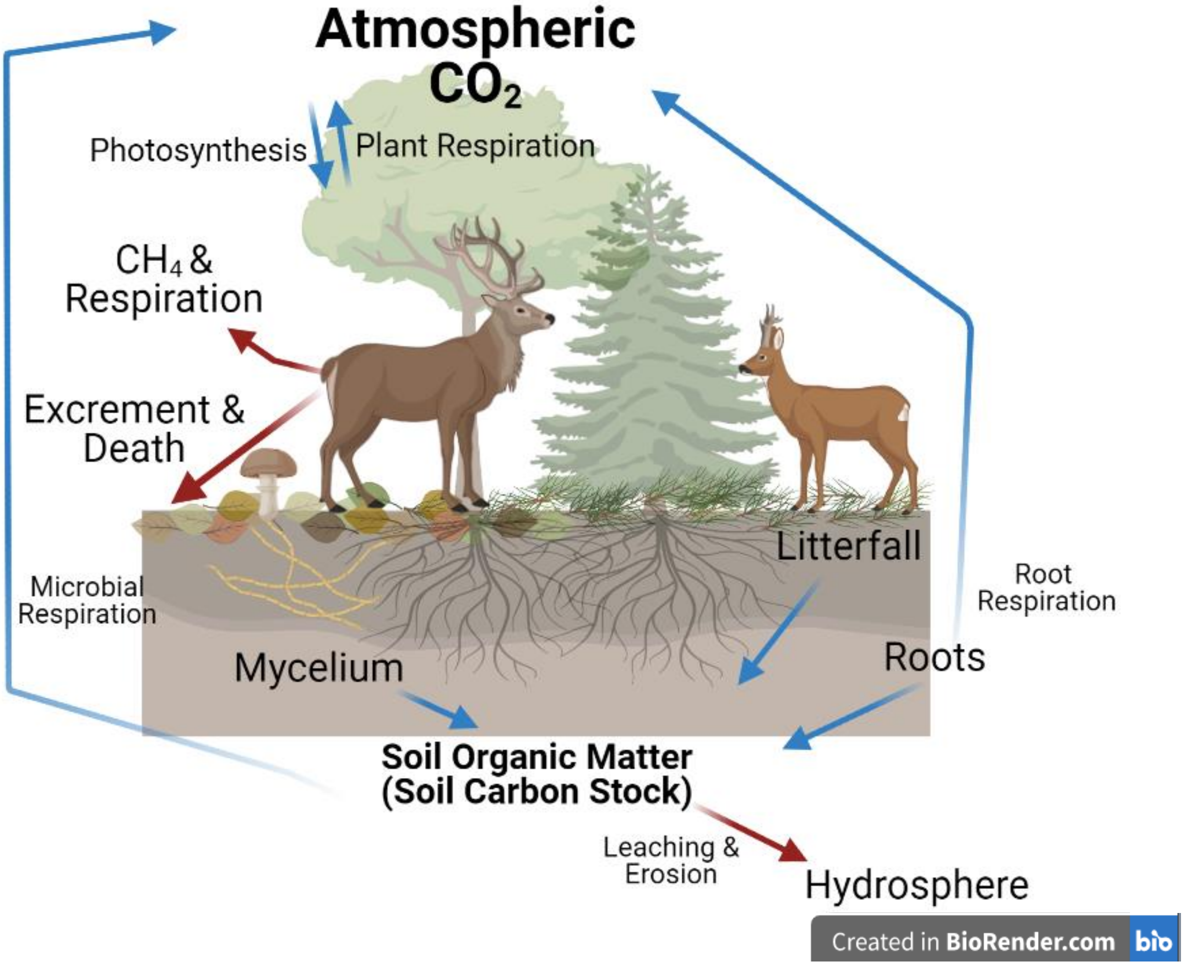
Forests are an enormous carbon sink[13] and increasing forest cover is a viable tool for sequestering carbon and reducing Scotland's net GHG emissions. Scotland has both temperate and boreal woodlands. Scotland's native broadleaved woodlands of oak, ash, elm, hazel, and alder form part of the temperate deciduous forest biome which extends through the British Isles, western Europe and parts of southern Scandinavia[14]. Temperate forests are adapted for seasonal climates and shed their leaves in autumn, growing a new set in spring. Scotland's native pinewoods and the closely associated birch, aspen and juniper woodlands form part of the boreal forest biome which stretches across parts of Scandinavia, Russia, Alaska, and Canada[14]. Dominant tree species are evergreen conifers, such as pines, which are adapted to deal with harsh winter conditions. These tree species keep their leaves (needles) throughout winter, although low temperatures and limited sunlight in boreal zones mean that winter growth is negligible. Carbon cycling in these ecosystems will operate slightly differently, but this report aims to draw broad conclusions that apply to both temperate and boreal biomes.

3 Impacts of deer on carbon sequestration

3.1 Introduction

Deer are often vital for the functioning of the ecosystems they inhabit, valued in both ecological and economical contexts[15,16]. However, in the UK, the absence of natural predators have left the deer population un-checked and allowed numbers to increase and fall out of balance with the environment. It is recognised that herbivores have a profound effect on their environment and in many cases this can cause conflict with human land-use objectives[17,18]. Deer directly impact their environment by grazing, browsing, bark stripping, trampling and fraying (a common behaviour of deer that involves rubbing their antlers against trees)[19]. These impacts are part of what make deer valuable to their environment. However, it is often considered "damage" when the impacts cause conflict with human interests and management objectives[16]. When deer populations reach a certain threshold, the pressure of browsing on palatable and/or vulnerable plant species can greatly impact understorey vegetative biomass, cover and species richness and inhibit forest regeneration[20,21].

Predicting – and evaluating – the effect herbivores have on carbon cycles means understanding the ecosystem processes that control carbon uptake and storage (Figure 1). Forest ecosystems cover large parts of the global land surface and are major components of the terrestrial carbon cycle. Trees and other vegetation absorb large amounts of atmospheric CO_2 via photosynthesis, and forests return an almost equal amount of CO_2 to the atmosphere from plant (autotrophic) and microbial (heterotrophic) respiration[4]. However, as carbon is the main building block of all plant material and vegetation, some carbon remains in forests, accumulating in the biomass of vegetation, detritus and soil[4]. A forest ecosystem includes all of its living components and both above and below-ground biomass[22], both of which are capable of natural carbon sequestration. Typically, in temperate and boreal forests, such as those present in Scotland, twice as much carbon, if not more, is stored in below-ground soil carbon pools than is stored in above-ground carbon pools[23]. Scottish soils contain an estimated 3,000 megatons of carbon, which is the majority of the UK's soil carbon stock[24]. Furthermore, the above and below-ground carbon pools are linked as carbon is exchanged between the two. Above-ground biomass stores carbon via photosynthetic uptake and eventually



loses this to the soil and thence to the atmosphere through decomposition. Whereas the loss from below-ground carbon pools occurs from the respiration of microbes and plants[25]. It is therefore important to consider the impact of deer on both above and below-ground carbon stores within Scotland's forests and woodlands.

Figure 1: Graphical depiction of the effect herbivores have on carbon cycling within forests. Arrows represent fluxes of carbon that are predicted to either increase (red lines) or decrease (blue lines) in response to herbivory. This diagram is based on Figure 1 from Tanentzap and Coomes (2012).

3.2 Overview of current knowledge

Despite a vast body of literature on the effects of deer within ecosystems, their impacts in the context of terrestrial carbon storage has received little attention[18]. From an initial literature search, it became clear that there are few studies directly investigating the effect deer have on carbon cycling within woodlands. Of the studies which did explore this relationship, many were from North America, modelling the impact of White-Tailed deer (*Odocoileus virginianus*) or Moose (*Alces alces*). Very few studies were conducted within Scotland and those that were only modelled the effect of red deer (*Cervus* *elaphus*) and roe deer (*Capreolus capreolus*)[26]. Given that deer are widespread in Scotland, and that as numbers and range increase, so too does their capacity to impact large areas of vegetation, it is important to understand the link between their role as herbivores and how this may impact the potential carbon sequestration of woodlands.

Studies directly investigating the link between deer and carbon stores commonly use matched plots of land where one is fenced off from deer, and the other allows deer to browse. There were no larger scale case studies that covered whole forest or estates returned in literature searches, although they may have been missed. Matched plot studies are often able to identify potential mechanisms at play, but it can be difficult to scale up the interpretation of any matched plot results to a whole ecosystem. This is mainly due to the limited size, and highly controlled nature of matched plot experiments. However, the primary and most direct influence these studies identified deer to have on terrestrial carbon cycling is their consumption and trampling of vegetation.

There is a vast body of literature on the effects of deer browsing and deer ecology within ecosystems which can be used to further support the limited studies with a direct carbon focus. This report will therefore present information from more general ecological studies of deer and their impact alongside more focused results from studies on carbon. In addition, data on the current state of forests and deer management in Scotland are used to draw conclusions on how deer may impact Scottish woodlands and forests' capacity to sequester carbon. See Appendix iv for a list of key references.

3.2.1 The impact of deer

As vegetation controls many biotic and abiotic processes within ecosystems, herbivores can directly and indirectly alter whole ecosystem function[27]. Therefore, as ecosystems respond to herbivores, other processes that are indirectly related to browsing and grazing will occur in parallel. This makes it difficult to distinguish the influences of herbivores on carbon cycling. For example, herbivores browsing at high pressure will reduce shoot density and height growth of browsed trees, this in turn increases the dominance of less preferred species and result in a more open canopy which can further influence changes in plant communities[28,29]. When browsing pressure is at a significant level, it can prevent tree and shrub regeneration and greatly reduce the diversity and abundance of plants species in the understorey. These effects have serious implications for biodiversity and the standing biomass available to sequester carbon[16,30].

An extensive review of hooved mammal (ungulate) management in Europe by Putman et al., (2011) summarised that ungulate impacts on plant communities can result in:

- A decrease in diversity and/or abundance of plant species
- An increase in diversity and/or abundance of plant species
- Changes in vegetation structure but without a change in diversity and/or abundance of plant species
- No observable influence

The same authors explain that the resultant change of an ecosystem to deer will depend on the type of disturbance (e.g., browsing, trampling or fraying), the intensity and the duration, as well as the reaction of the soil and plants present in the ecosystem. In Scotland, a 2019 survey found only 62.5% of Scotland's protected woodlands are deemed to be in a 'favourable' or 'recovering' condition; a decrease from 68.1% in 2017[31]. This suggests that Scotland's woodlands are vulnerable to the impact of deer and that the ability of Scottish woodlands to sequester carbon efficiently may depend on the management of deer.

3.3 Deer and above-ground carbon stores

3.3.1 Reducing biomass

The effect of deer on all levels of forest vegetation, from the forest floor and understorey to the canopy, becomes most obvious in studies comparing matched plots of land that have either allowed access to deer, or been fenced off to exclude them. A large number of studies have investigated the quantity of plant biomass that is removed by herbivores and the changes in plant species composition[6]. This body of knowledge can be used to infer the fate of carbon within ecosystems[18]. Tanentzap and Coomes (2012) produced a review of 108 matched plot studies in the context of estimating the effects herbivory had on carbon stocks. They concluded that herbivores annually remove 40,000 ± 60,000 tonnes of carbon from global temperate forests and a further 40,000 ± 40,000 tonnes of carbon from global boreal forests. By consuming plant biomass, herbivores are removing vegetation that would otherwise photosynthesise and store carbon. Instead, the plant biomass and its nutrients are assimilated by herbivores to build animal biomass which releases carbon to the soil via excrement and to the atmosphere via respiration[30,32,33].

Deer promote the relative abundance of unpalatable and browse-tolerant plants species by supressing palatable and/or vulnerable plant species through selective browsing. This means that deer alter plant community composition, plant and ecosystem productivity and shift the flow of nutrients within an ecosystem[16,19,34]. Browsing results in less plant biomass available for photosynthesis – especially when leaves are consumed. The change in plant diversity and the amount of foliage present can alter the potential for carbon capture and the density of carbon stored in standing biomass[33,35]. These changes engineered by deer browsing in turn affects litter production, litter decomposition and therefore the allocation of above and below-ground carbon[25]. Thus, there are two areas to consider. One is the impact deer have on above-ground carbon storage; the second is the less direct but potentially significant impact deer have on below-ground carbon stores.

3.3.2 Trees and the understorey

In forests, significantly more carbon is stored within adult trees that lie out of reach for deer. Much less carbon is stored within the seedlings, saplings, and understorey vegetation that deer can reach to feed on[36–38] (See Appendix i). This suggests that it is the effect of deer on tree survival and regeneration which may be the most important above-ground impact to manage. Surveys on the National Forest Estate in 2013 found 15-20% of young trees had been damaged by deer[39]. The damage is often thought to be dependent on the densities of deer present. For example, in an American study of white-tailed deer at densities of 33/ha (much higher densities than are typical in the UK), authors found 75% of the seedlings in the deer access plots damaged by trampling and herbivory[40]. Another study found wild, hooved mammals had significantly reduced shrub density and height in access plots when compared to plots from which they were excluded[30]. Similar findings from Ramirez (2020) showed sapling diversity and density to be reduced in plots with ungulate presence. In a healthy ecosystem, as older trees die back and collapse, smaller trees will naturally take their place, making use of the gap in the canopy to grow and eventually fill it. Where small trees are reduced by browsing, this succession will not occur, leaving generational gaps in the forest. As there are no younger trees to fill the gap in canopy cover created by dying adult trees, more light reaches the forest floor where understorey vegetation can become more dominant (often the species that are most resilient to the effects of deer), further reducing the success of any remaining young trees. However, in many parts of Scotland, the understorey is largely absent due to wild grazing pressure. Over decades or centuries of small tree reduction, forest size and structure will start to be affected, significantly altering above-ground carbon stocks[28,41,42].

It is not only young trees that deer can impact. Deer also strip the bark from mature trees with their antlers (fraying). The debarking that occurs can lead to mortalities of larger trees. Debarking of trees can lead to decay and mortality, or in commercial forests, can result in the presence of stains which reduce the timber value and often result in the logs being processed into pulp[43]. When logs are devalued in this manner, they are likely to be used in a way that reduces the longevity of the stored carbon. For example, damaged and stained logs are unsuitable for construction. Use in construction means the carbon stored in that timber is retained for long periods of time, compared to logs that are pulped for paper or used for biofuel. Welch and Scott (2008) estimated that bark damage in commercial timber in Scottish plantations could lead to financial losses of 3% of the crops value each rotation.

In the 1970s, the lack of natural regeneration of the surviving Caledonian pinewoods in the Cairngorms due to high numbers of deer became a prominent conservation issue[44]. Estates were bought by conversation charities such as the RSPB and the National Trust for Scotland; more recently, land-owning initiatives such as the Cairngorms Connect emerged to ensure that deer were reduced in large areas of native woodland. The Cairngorms National Park area has demonstrated that the regeneration of native woodland can be achieved by reducing densities of red and roe deer to within five or less deer per square kilometre. The <5 deer/km^2 is a common target for allowing regeneration of woodlands. However, achieving this density across Scotland is difficult. Nationally, high culling efforts are both expensive and time consuming and must be maintained for long periods of time as vegetation recovery from herbivory happens over the time scale of decades[21].Culling can also be insufficient when there is conflict between competing objectives or a lack of coordination over a local area[45]. This is often the case in much of Scotland.

The Cairngorms case study (see Deer Working Group 2020) suggests that unless deer are managed effectively, Scotland's existing forests risk becoming less productive and less secure reservoirs for carbon. The NWSS (2014) accessed 311,153 ha of native woodland, about 20% of Scotland's woodland area, and found that deer were a significant presence in 73% of this area. In addition, 33% of the woodland area had high or very high browsing impacts from deer that were considered too high for the woodlands to survive by natural regeneration[7]. These native species are particularly vulnerable to deer damage and new native woodlands, such as those proposed to mitigate climate change by sequestering carbon, generally need to be protected by deer fencing and/or heavy culling that provides low levels of herbivory. In Britain, woodlands (in just their living trees) store around 213 million tonnes of carbon. Ancient and long established woodlands hold 36% (77 million tonnes) of Britain's stored woodland carbon, despite the fact they only make up 25% of all woodland[46]. Although the afforestation of Scotland is a key part of reaching net zero, so too is our management and protection of existing woodlands and their natural expansion, especially the dwindling stands of ancient woodland.

3.4 Below-ground carbon stores

3.4.1 The impact on litter composition

Litter decomposition is a key process that recycles nutrients within forest ecosystems by providing nutrient rich organic matter for organisms in the soil to decompose[47]. By browsing and trampling plant species, the composition of leaf litter is also altered by deer.

Studies have demonstrated that herbivores indirectly control both the amount and the quality of litter produced[29,48,49], which could have consequences for the various below-ground processes necessary to store carbon. Animals, insects, and plants that feed on dead organic matter decompose the litter into small pieces that bacteria, fungi, and protists can decompose further. This group of organisms are referred to as decomposers and they convert organic matter, like leaf litter, into inorganic compounds like phosphate, ammonium, water, and CO_2[50]. This decomposition is influenced by litter chemistry, decomposer abundance and community composition as well as the climate of the ecosystem[51,52]. Below-ground carbon stores represent a significant proportion of the total forest carbon pool – up to 97% in some Scottish Forest Alliance Sites[53]. Any management practices that affect forest soil could significantly alter below-ground carbon. Hence, various studies have aimed to characterise the effect of deer and other herbivores on below-ground carbon stores. However, their role in litter decomposition remains a subject of debate.

Deer are attracted to plant species they find palatable. Part of what makes species palatable is their chemical composition, specifically, but not limited to, the levels of carbon, nitrogen and plant secondary metabolites[47,54] (fibres, sugars and crude proteins also drive palatability and food selection[55]). By selecting foliage that is rich in nitrogen and low in carbon, deer reduce the abundance of palatable plant species, promoting the dominance of less palatable plant species. As these unpalatable and browse-tolerant species become dominant, the proportion of litter they produce becomes greater. Because some of the chemical traits that make plant species palatable to deer also make them more decomposable, deer can promote poor quality litter that provides less nutrients to decomposers resulting in reduced nutrient cycling into the soil[48,56]. The change in litter quality and vegetation can also trigger changes in the community composition of decomposers, specifically species that are associated with localised litter decomposition[57]. Additionally, as a response to browsing by herbivores, plants produce defensive chemicals which make them less palatable and more toxic to herbivores[26]. This additional profile of defensive toxic chemicals can degrade leaf litter quality further as the chemicals may also be harmful to decomposers.

Communities of decomposers may also be directly affected by deer. Deer faeces and urine are a source of nitrogen from which decomposers may benefit[58], further affecting the structure and functioning of the decomposer communities. It is also suspected that the removal of canopy cover and the exposure of bare soil after ground vegetation is reduced, and the trampling and compacting of soil, can cause increases in soil temperature, salinity, water, and oxygen content[28,59]. These changes could affect soil chemistry and below-ground respiration rates of microorganisms, leading to a higher release of carbon from the soil[18,60].

3.4.2 The impact on litter decomposition

To explore these relationships, various studies have investigated whether herbivore presence slows down litter decomposition. One case study in Scotland by Harrison and Bardgett (2003) demonstrated that browsing from red deer significantly affected the rate of litter decomposition of silver birch (*Betula pubescens*) at Creag Meagaidh NNR. By comparing browsed, and un-browsed plots, the authors discovered that browsing generally reduced levels of nitrogen in foliage, increasing the carbon: nitrogen ratio which led to suppressed nutrient cycling. In combination with plant secondary metabolites produced as a result of browsing, the reduction in litter nitrogen produces a poorer quality litter that inhibits microbial activity, nutrient mineralisation and therefore reduces available nutrients for plant growth[26]. Similar findings have been reported in moose (*Alces alces*) from both North America and Europe[29,48], red deer and feral goat browsing in New Zealand[27], and Canadian Sitka black-tailed deer (*Odocoileus hemionus sitkensis*)[61].

If plant growth is suppressed, so is the potential to store carbon. However, the results of these studies across different habitats and continents are not consistent in the size of effects nor the principal mechanisms authors have described. One study with white-tailed deer in America showed that deer presence increased earthworm density which increased the rate of litter decomposition[47]. This suggests that there may be a strong effect of site, where factors such as climate, land use, herbivore density and species composition, and the species of plants and soil fauna and flora present may be important.

3.4.3 The implications of decreased litter quality and decomposition

Although the effects of deer and other herbivores are still being debated, it is likely that the changes in litter composition and decomposer activity that deer induce will slow down the release of nutrients stored in dead plant biomass into the soil. This is turn will slow down the uptake of nutrients from the soil. When into vegetation, ultimately slowing vegetative growth and therefore reducing the rate of carbon being sequestered in plant biomass. When the decomposition of organic matter is faster, the non-organic compounds produced by decomposers are more readily available to help plants meet their nutrient requirements and increase their productivity which can lead to greater sequestration of carbon. Thus, the concern is that deer can indirectly reduce the productivity of plant communities and their ability to store carbon.

As discussed in this section, the mechanisms by which deer exert their effect are largely identified. However, there is little to no data available to suggest whether the size of these effects is significant for plant productivity or for carbon sequestration on an ecosystem or even continental scale. The study of nutrient cycles in soils and their relevance to whole ecosystem function is still an emerging science and it may be a long time until there is enough data to quantify the knock-on effects of changes in litter composition and breakdown.

3.5 Mitigating the effect of deer on carbon stores

From the evidence presented in this section, it is clear that deer can impact woodland carbon stores in a variety of ways. However, there does appear to be commonality between all of the mechanisms presented in the literature. The direct and indirect influences of deer on above and below-ground carbon stem from browsing, fraying and trampling vegetation. These effects are valuable to ecosystems in moderation, but when deer populations and their pressure reach a threshold, these effects become negative. These very same effects underpin the basis of deer management, a practice which is well established in Scotland to control damage of commercial timber and agricultural crops and to protect Scotland’s natural landscape. However on the whole, deer numbers are still too high. By reducing the number of deer in Scottish woodlands to densities which allow natural regeneration of palatable and vulnerable plant species (both trees and the woodland understorey), the health, productivity and therefore the potential of carbon sequestration would be greater.

4 The role of deer management

4.1 Deer management

There are four species of wild deer currently found in Scotland: the native red (*Cervus elaphus*) and roe (*Capreolus capreolus*) deer, and the non-native fallow (*Dama dama*) and sika (*Cervus nippon*) deer. Red and roe deer are the most abundant and widely spread of the four species, present throughout much of the mainland, and several islands (See Appendix *ii* for deer distributions in Scotland). In the most recent population estimates, it was suggested that there were between 593,000 and 783,000 wild deer in

Scotland in 2013 (Scottish Natural Heritage, 2013). Eight years on, and that figure could be well on its way towards 1 million individuals at present. Deer management is the single largest terrestrial wildlife management operation carried out in the UK. It is expensive and time consuming yet vital to the protection and restoration of the Scottish landscape.

Scotland's wild deer are naturally woodland species. Although a large proportion of red deer have adapted to life on the open-hill, the majority of Scotland's deer live in and around woodlands [44]. The Scottish Government's plans for afforestation will provide further habitat for deer across a number of localities in Scotland, which will further increase the need for deer management. The principal influence deer have on carbon sequestration in woodlands is their consumption of palatable vegetation causing a reduction in plant biomass for photosynthesis, leading to poor quality litter and a depression of nutrient cycling. In order to mitigate these effects, deer need to be reduced to levels where natural regeneration can occur. This is typically around <5 deer/km^2 but can depend on the current state of a woodland, or the deer species present.

For Scotland's natural landscape and woodlands to recover, deer densities need to be reduced and maintained around this <5 deer/km^2 threshold. In some cases, deer fences may need to be erected to protect certain areas. Deer control through fencing and culling is a well-established methodology that has protected woodlands and reduced numbers of deer across Scotland. Although newly planted woodlands will be at a particularly high risk of damage, existing forests are still threatened through browsing impacts on the ecosystem. The need for deer control within existing woodlands to enable re-stocking and regeneration is vital to their health and productivity.

For the majority of the last 21 years, average annual culls of wild deer are estimated to be around 100,000 individuals [44]. An SNH information response figure[62] displayed in the Deer Working Group (2020) report shows that in 2015/16, 58% of the national deer cull took place within woodlands. Of these 61,881 deer culled in woodlands the species breakdown was as follows: 33,929 roe, 20,751 red, 5,397 sika and 1,804 fallow.

Whilst deer fencing will be crucial to the establishment of new woodlands to combat climate change, it is incredibly expensive to install, has a carbon footprint itself, is only a temporary solution which requires upkeep to prevent break-ins from deer, and deer still need to be managed when they get into fenced areas. From 2014 to 2019, Forestry & Land Scotland spent £1.3 million on deer fencing alone, whilst Scottish Forestry spent £13 million on grants for erecting and maintaining deer fences from 2015-19 (see Deer Working Group, 2020). Although this figure is high, for Forestry & Land Scotland this was only 3.4% of the £38.8 million total expenditure for deer management in that period (see Deer Working Group, 2020). The majority of the cost of deer management is the salaries, vehicles, machinery, equipment, and administration. Although in the case of Forestry & Land Scotland, venison sales do offset the total expenditure by 22.9%, this still leaves the net cost of deer management at £29.9 million between 2014-2019. These figures show the high cost of deer management in Scotland, a, cost that can be expected to rise as woodland areas increase, creating more habitat for wild deer.

5 Further research

5.1 Evidence gaps

From reviewing the literature, a few key themes emerge.

Although the general effects of herbivores, like deer, in the context of carbon storage are well described, the size of these effects is not. It is clear that deer have the potential to alter above and below-ground carbon stocks both directly and indirectly. However, without data describing the size of the effects, it is difficult to say how large an effect deer will have on the potential of afforestation to help reach Net Zero. This study found no reference to the use of modelling approaches for estimating the impact of deer at the landscape-scale.

Now that the scientific community has described the mechanisms by which deer alter carbon cycling, effort could be focused on understanding these processes in detail, although it may not significantly change the understanding of loss or gain of carbon stores. However, these studies are hard to design. Deer presence does not always correlate with the amount of browsing and grazing pressure and forest ecosystems differ in various geological, botanical, and climatic contexts that make comparisons between forests difficult.

Matched plots are one of the main experimental designs being used to define the impact of deer on vegetation communities, litter decomposition, nutrient cycling and carbon stores. Finding plots that can be matched and compared is difficult. In addition, these plots can take up large areas (sometimes reaching up to several hectares) and are studied on a time scale of several decades. Thus, there are logistical challenges when needing to control herbivore presence or absence. The results from these studies, also beg the question of whether such controlled and fragmented plots can be used to scale the insights across larger spatial extents or entire ecosystems. These studies are still valuable but can take a long time to draw conclusions.

5.1.1 Application of remote sensing

An emerging technology in the study of global carbon stores is remote sensing. Remote sensing involves equipment which interacts with landscapes by emitting energy towards a surface and measuring how much is reflected back to the sensor[63]. By combining types of remote sensing such as images from high-resolution satellites, radar and LiDAR (light detecting and ranging) with ground-based forest inventories, one can estimate carbon stocks over large spatial scales[64]. Additionally, a primary goal of this technology should be to identify small areas of forests with high densities of stored carbon and then use artificial intelligence and machine learning strategies to recognise patterns which could be extrapolated to inform management of larger areas[64].

With large areas of Scotland set for significant reductions in deer populations, incorporating remote sensing into the projects to quantify the changes in carbon stocks that occur over a gradient of deer reduction across multiple locations should be encouraged. This sort of initiative could provide valuable information on the size of the effect deer have on carbon stocks. Although these sorts of studies would still need careful experimental design, interpretation of results, and potentially only describe changes in above-ground carbon stores, their findings would likely be informative in a way that matched plots are not i.e. on landscape-scale impacts.

5.1.2 Understanding methane emissions

Another gap in our current understanding of deer in terrestrial carbon cycles is their role as methane emitters. Methane is a product of microbial fermentation of feed-stuffs in the rumen or gut of herbivores, especially ruminants [65]. It has been suggested that one third of global methane emissions result from ruminant enteric fermentation[66]. Despite a lack of data from wild deer (see Appendix *iii*), there are reports from farmed venison in Scotland. This is currently a small industry which slaughters 15,000 deer (mainly red deer) annually producing 100 of the 3,600 tonnes of total venison produced each year (the rest is from wild culls) [67]. A recent study found total methane of enteric fermentation from farmed deer to be 5.20 kt/CO_2eq [67]. These statistics from farmed deer are not applicable to wild deer. This is because methane emissions can increase when poorer quality feed or forage is consumed by ruminants[68].

Whilst there are estimates for the global methane production of wild ruminants, the data are limited by a lack of reliable population estimates[69]. Pérez-Barbería (2017) scaled methane emissions against body mass to review 503 experiments of ruminants fed natural feed to model methane emissions from wild ruminants. The review concluded that wild ruminants are responsible for 1.095-2.687 Tg y-1 of methane emissions, considerably less than had been presented in reports from the Intergovernmental Panel on Climate Change (15 Tg yr-1) [69]. For context, global methane emissions from enteric fermentation and manure management in 2010 were estimated to range between 99-115 Tg y-1 [70].

Red deer were found to produce similar methane emission to that of sheep [69]. Scotland's wild deer population could be around 1 million individuals, a large proportion of which would be red deer, but the remainder would be smaller bodied species such as fallow, sika and roe. Given the relationship between body mass and methane emissions discussed in Pérez-Barbería (2017), these smaller bodied deer species could produce less methane than sheep.

Although there is undoubtedly a contribution to methane emissions coming from Scotland's wild deer herd, it is likely far less than that contributed by the 6.73 million sheep and 1.8 million cattle currently present in Scotland[44]. Methane is a potent greenhouse gas, but unlike CO_2, is relatively short lived in the atmosphere. As a result, as deer management aimed at enhancing the role of Scottish landscapes proceed, Scotland's wild deer – along with their methane emissions – will decline.

6 Conclusion

This report presents information drawn from ecological studies of deer alongside more focused, but limited, studies on the relationship between deer and carbon. Additionally, data on the current state of forests and deer management in Scotland were used to draw conclusions on how deer may impact Scottish woodlands.

The primary influence deer have on carbon sequestration in woodlands is their consumption of vegetation which removes and reduces biomass that would otherwise sequester carbon through photosynthesis. This reduces above-ground carbon stores and alters plant communities leading to poor quality leaf-litter and a depression of nutrient and carbon cycling into the soil. The effects of deer can be categorised as direct and indirect:

Direct effects

- By consuming plant biomass, deer are removing vegetation that would otherwise photosynthesise and store carbon.
- Deer browse on young trees and saplings, causing generational gaps in forests by reducing natural regeneration of both trees and the understorey.
- By fraying mature trees, the debarking that occurs can lead to mortalities of large-sized trees.
- Trampling and compacting of soil, can cause increases in soil temperature, salinity, water, and oxygen content which has the potential to effect carbon cycling.
- Methane emissions into the atmosphere from enteric fermentation and excrement.

Indirect effects

- By selecting plant species to browse, deer reduce the abundance of palatable plant species, promoting the dominance of less palatable plant species.
- Deer faeces and urine are a source of nitrogen which some decomposers may benefit from, further affecting the structure and functioning of the decomposer communities and nutrient cycling.
- Through the selective removal of palatable species from woodland ecosystems, deer promote poor quality litter that provides less nutrients to decomposers resulting in reduced nutrient cycling into the soil. This can indirectly reduce the productivity of plant communities and their ability to store carbon.

Although a number of mechanisms of deer impact in regard to carbon sequestration in woodlands have been identified, the size of these effects has yet to be fully quantified. By integrating technologies like remote sensing into the management of landscapes in Scotland, the quantification of carbon cycling affected by deer may be more accurately measured. Understanding the size of the effect deer have on carbon cycling within woodlands would enable scientists, government and practitioners to understand the significance of Scotland's high deer density in relation to reaching net zero targets. By quantifying the effect of deer, data could be collected that would enable the measuring, modelling and predicting of the effect of deer have on carbon sequestration is. This would be an important step forward in Scotland's climate policy.

If deer do have a significant effect, controlling Scotland's deer density may need to take priority over other aspects of woodland creation and habitat restoration. This is especially important when considering the timescale it would take to reduce deer to sustainable numbers. It may take decades to get Scotland's wild deer population under control and as woodland cover increases, deer management will face new practical difficulties in reaching cull targets.

While there may be potential to add to the existing data sets, it is clear that reducing deer numbers in woodlands would be beneficial and counter many of the adverse effects presented in this report. In order to mitigate the effect of deer on carbon cycling and storage in forests, deer management must continue to be integrated into forest management. At a local level management groups could act together to fulfil the objectives of local and national policy. New woodland created to tackle climate change must be protected from the damaging impacts of deer. Existing forests must continue to be monitored, and deer management must deliver reductions in deer densities and herbivore impacts to a level where the forest habitat's annual biomass increment is not completely removed by herbivores.

For Scotland's natural landscape and woodlands to recover, deer densities need to be reduced and maintained at <5deer/km^2. In some cases, temporary deer fences may need to be erected to protect certain areas. However, deer are part of our environment and should be excluded only for limited amounts of time whilst vulnerable plant species recover and deer densities in adjacent areas are reduced.

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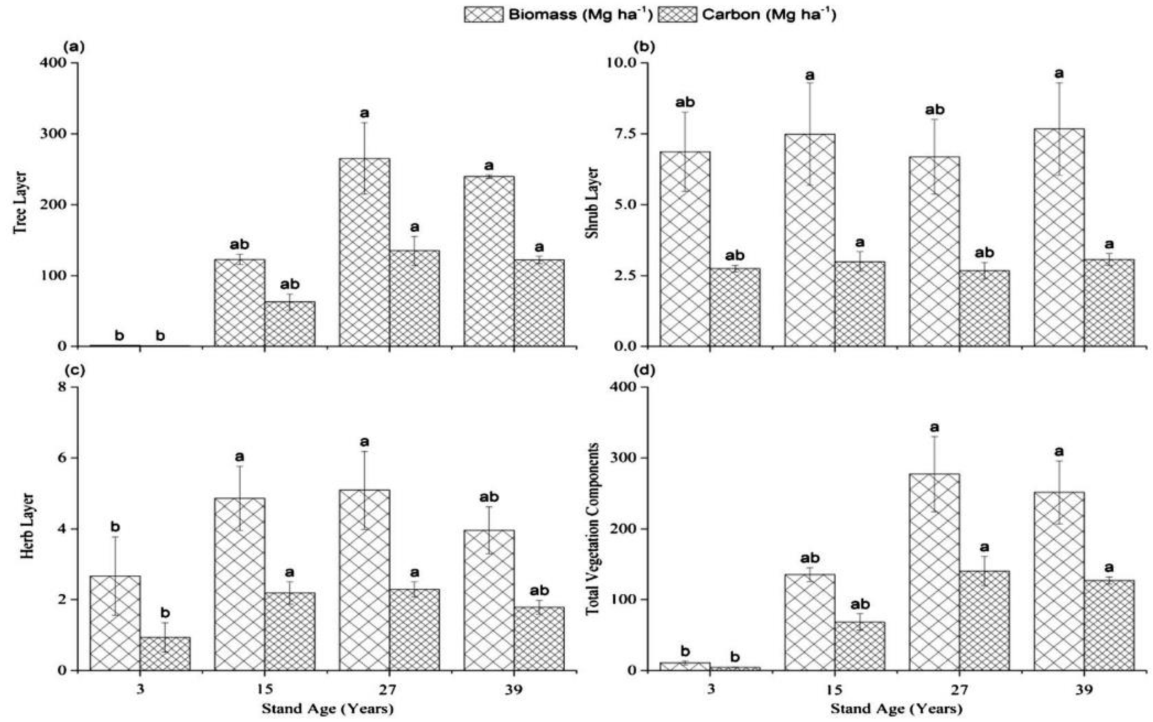
8 Appendix

i. Carbon stocks in pine plantation (Justine et al., 2017)



This figure (Figure 2. From Justine *et al*., 2017) visualises data of the biomass of carbon stored and allocated in sampled vegetation components such as (a) trees, (b) shrubs and (c) herbs as well as presenting (d) total vegetation biomass and carbon storage. Error bars show standard deviations and lowercase letters indicate significant ($p< 0.05$) differences between the same vegetation layer in the different stands. This figure suggests that trees are the main vegetation component carbon is stored in within the studied area.

ii. Distribution of Scotland’s wild deer

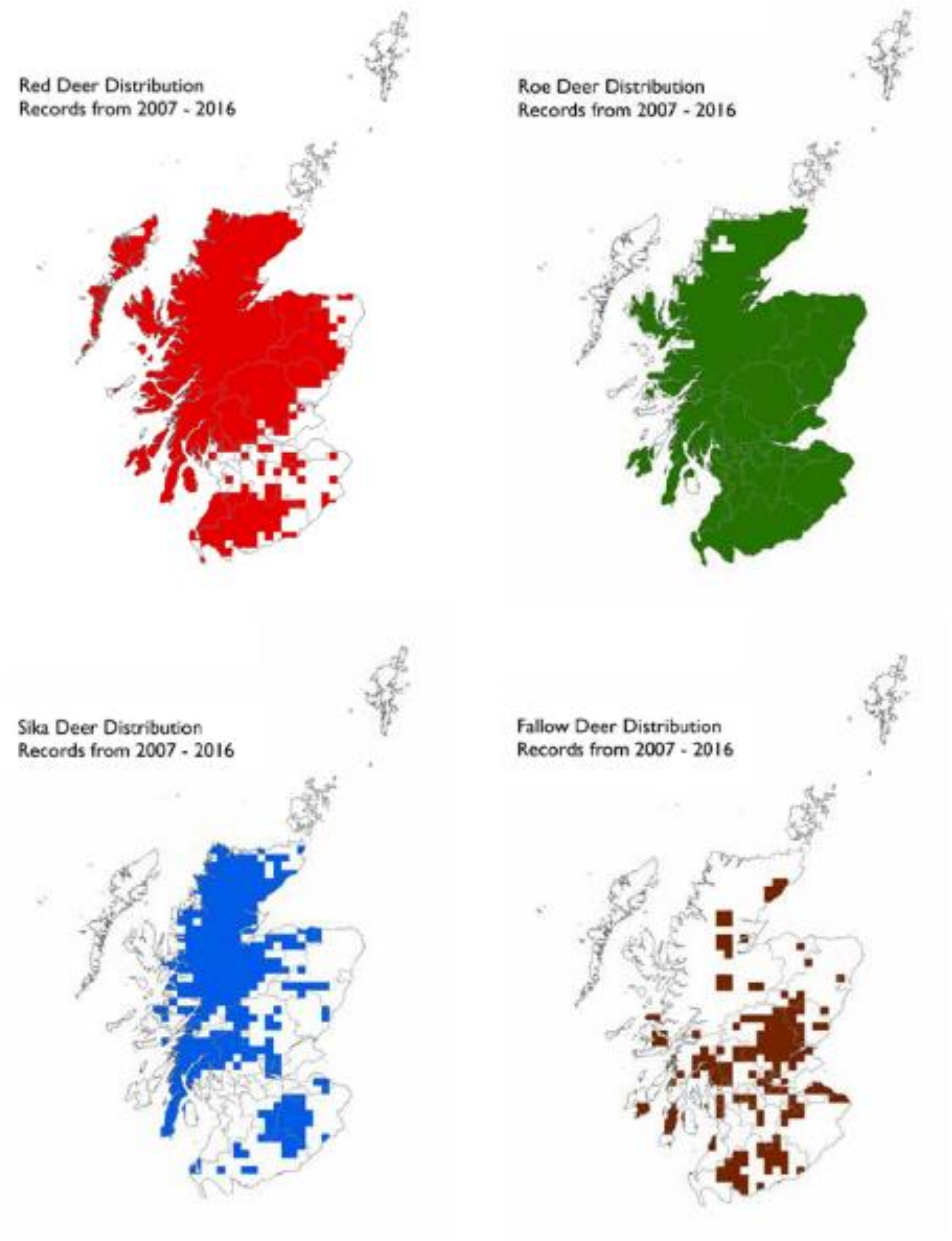


Figure 2: This figure was sourced from the Deer Working Group’s report “The Management of Wild Deer in Scotland”. The original data was sourced from the British Deer Society.

iii. Methane emissions of wild deer

A report by the Scottish Environment LINK reported that "As well as damaging emerging woodlands and peatlands, Scotland's red deer alone produce 5,500 tonnes of methane each year – the equivalent of 137,500 tonnes of CO_2. A 20 percent reduction in numbers would save the carbon equivalent of around 15 million car miles on Scotland's roads each year." This figure was then quoted in The Times and The Guardian. However, it is unclear what the source of this data is. See Scottish Environment LINK (2020). *Managing deer for climate, communities, and conservation Scottish Environment LINK*. 1–8.

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