BEYOND UPLAND EXCLOSURES: WHAT IS THE EFFECT OF LOW-INTENSITY GRAZING ON CARBON STORAGE?

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SUMMARY

Land management is a key control of terrestrial carbon (C) storage and can be used to mitigate rising CO₂ emissions. The UK uplands hold approximately one-third of national terrestrial C in their soils. The dominant land-use is extensive livestock grazing management. However, our understanding of the impact of grazing on upland C storage is limited to studies comparing the presence versus the absence of herbivores. Utilising a grazing density manipulation we show no sheep and low-intensity sheep grazing provide similar benefits, in that they enhance plant and soil C accumulation. In contrast, under high-intensity sheep grazing there is a net loss in predicted soil C accumulation. We propose that low-intensity sheep grazing is optimal to sustain the diversity of key upland species, compared to high-intensity grazing and no sheep. We provide evidence that low-intensity sheep grazing can be used to minimise trade-offs between multiple upland land-use objectives, namely C storage and species conservation.

INTRODUCTION

Appropriate land management can be used to prevent the release of terrestrially stored carbon (C) to the atmosphere. Almost one-third of soil C in the UK is found in semi-natural upland habitats, due to their organic and peaty soils. The land-use of these habitats is primarily extensive grazing management; mainly sheep, cattle and red deer (Carey et al., 2008; Emmett et al., 2010). Upland livestock numbers have fluctuated through time because of multiple factors (i.e. market prices, climate conditions and policies). Recently there have been large declines in sheep numbers in the uplands, particularly in Scotland, with only 2.6 million breeding ewes in 2011; this number is the lowest recorded in over a century (Thomson et al., 2011). Currently there is insufficient evidence to predict the impact of declining sheep intensities on upland C storage, because the majority of studies have compared the presence of sheep grazing versus the absence, using small-scale exclosures. These studies suggest that removing sheep can increase vegetation and plant litter C storage. However current understanding is that removing herbivores has little impact on C storage in organic soils (Garnett et al., 2000; Ward et al., 2007; Medina-Roldán et al., 2012). Destocking has clear benefits for plant C storage, yet the majority of upland habitats are still being grazed, albeit at lower stocking densities. To improve our understanding of the impact of sheep grazing on C storage requires studies that use gradients of grazing intensities within a single landscape.

Historically upland landscapes have been managed for multiple purposes, yet only recently have ecologists suggested that upland management decisions should incorporate C storage (Van der Wal et al., 2011), and even more topical is the use of grazing management to store C
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The relative importance of managing uplands for cultural heritage, rural employment and the goods and services they provide in the context of storing C is the focus of much debate in the National Ecosystem Assessment (Van der Wal et al., 2011). In the context of grazing management, debates are limited by a lack of empirical evidence, particularly across a range of grazing intensities. For example, the merits of large herbivore grazing for biodiversity and C storage remain poorly studied. Minimising trade-offs between C storage and species conservation is increasingly being discussed for the UK uplands (see Van der Wal et al., 2011; Bateman et al., 2013). Therefore it is important to evaluate C storage under different sheep grazing intensities in the context of upland species abundance and diversity.

In this paper, we provide evidence from research conducted at a long-term, landscape-scale (each plot is 3.3 ha) grazing density manipulation in central Scotland. We address the following aims: (i) establish the impact of a gradient in sheep grazing intensities on plant and soil C storage for a *Molinia caerulea* (purple moor grass) dominated upland grassland; (ii) compare the trade-offs between storing C and the abundance and diversity of key upland species (e.g. plants, bird, mammal and invertebrates) across different sheep grazing intensities; (iii) highlight areas of future research that are needed to better inform predictive modelling, policy and practice intending to maintain or enhance upland C using sheep grazing management.

**A LANDSCAPE-SCALE GRAZING DENSITY MANIPULATION**

To investigate the impacts of gradients of sheep stocking densities on C storage and upland species diversity and abundance, we highlight work undertaken at a grazing experiment established in January 2003 at the Glen Finglas estate (4,039 ha) an upland area (200-500 m a.s.l.) in central Scotland (56° 16'N, 4° 24'W). The experiment location has organic soils including blanket peats, peaty gleys and humus iron podzols. The vegetation is dominated by *Molinia caerulea* (British National Vegetation Classification; M25; Rodwell, 1991) (see Smith et al., 2013). The experiment consists of three sites, each containing two replicate blocks; each block comprising 3.3 ha (c. 180 m × 180 m) plots. Treatments are randomly allocated within blocks, including: (a) ‘Commercial’ stocking, nine black-faced sheep per plot giving a typical commercial stocking rate of 2.7 ewes ha⁻¹ for nutrient-poor rough upland grassland; (b) ‘Low’ stocking, three black-faced sheep per plot or 0.9 ewes ha⁻¹ which is one-third the commercial rate and is similar to the stocking rate of the area before the experiment started and; (c) no livestock. Sheep remain in the plots throughout the year and are only removed for normal farm operations and during periods of severe weather.

**CARBON STORAGE UNDER LOW-INTENSITY SHEEP GRAZING**

Approximately 10% of the UK uplands are covered by *M. caerulea* (purple moor grass) dominated vegetation (Bunce and Barr, 1988). Given the large national extent of *M. caerulea* (~0.6 million ha) it is important for this species to be included in upland C budgets. *M. caerulea* is a deciduous grass that forms dense tussocks consisting of compact aggregations of shoot-bases. These tussocks represent particularly dense C stores (i.e. high C mass per unit area). An intensive study at Glen Finglas measuring 2009 *M. caerulea*-dominated tussocks, found that increasing sheep grazing intensities reduced the abundance of tussocks and thus C stored in grass swards after 7 years of treatments (Table 1; see Smith et al. 2013). However, change in
soil C storage occurs over a decadal timescale and grazing treatments at Glen Finglas were too short in duration to detect changes in soil C. This problem of limited duration was solved by using a predictive soil organic matter model, RothC. Measured *M. caerulea* tussock C from the three grazing treatments were used as annual C inputs into RothC to predict soil C accumulation for 100 years. RothC predicted soil C storage to decline under high-intensity sheep grazing and increase under low-intensity sheep grazing and no grazing (Table 1). Overall high-intensity sheep grazing negatively affected *M. caerulea* plant and soil C storage (Table 1). In contrast, low-intensity sheep grazing and livestock removal treatments accrued plant C. Subsequently, predicted rates of soil C accumulation were similar between low-intensity sheep grazing and no livestock for several decades. It is clear from these results that grazing intensity is a key control of upland C storage.

Table 1: Plant and predicted soil C storage under different sheep stocking densities on upland *M. caerulea*-dominated grassland. Average soil C storage at Glen Finglas at time zero for the predictive model was 114.3 t C ha\(^{-1}\). Sheep stocking densities are as follows; low-intensity sheep grazing 0.9 ewes ha\(^{-1}\) and high-intensity sheep grazing 2.7 ewes ha\(^{-1}\) (Smith *et al.*, 2013)

<table>
<thead>
<tr>
<th>Plant C storage after 7 years (t ha(^{-1}))</th>
<th>% difference against ungrazed</th>
<th>Predicted soil C accumulation after 100 years (t ha(^{-1}))</th>
<th>% difference against ungrazed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ungrazed</td>
<td>6.85</td>
<td>-</td>
<td>14.36</td>
</tr>
<tr>
<td>Low-intensity sheep grazing</td>
<td>5.01</td>
<td>-27 %</td>
<td>13.62</td>
</tr>
<tr>
<td>High-intensity sheep grazing</td>
<td>3.83</td>
<td>-44 %</td>
<td>-23.11</td>
</tr>
</tbody>
</table>

**TRADE-OFFS WITH UPLAND SPECIES DIVERSITY AND ABUNDANCE**

Using evidence from the Glen Finglas grazing experiment, C storage can be weighed against the diversity and abundance of upland species. In addition to its importance for C storage, structural heterogeneity of *M. caerulea* tussocks determines access to food and habitat quality for upland bird, mammal and invertebrate species. Tall, rank ungrazed *M. caerulea* swards are poor foraging habitats for the meadow pipit (*Anthus pratensis*), a common upland bird species (Vandenberghe *et al.*, 2009). In contrast, breeding and foraging success of meadow pipits is greatest under low-intensity sheep grazing compared to either high-intensity or no sheep grazing (Evans *et al.*, 2005; Prior *et al.*, 2011). Field vole (*Microtus agrestis*) densities and the frequency of population cycles (Evans *et al.*, 2006) and activities of their generalist predator red fox (*Vulpes vulpes*) are either reduced or disrupted by increasing sheep grazing intensities (Villar *et al.*, 2013a; 2013b). Likewise, nocturnal moth and other arthropod diversity are negatively affected by increasing sheep grazing intensities (Dennis *et al.*, 2008; Littlewood, 2008). Finally, although plant species diversity within *M. caerulea* communities has remained unchanged among grazing treatments after a decade, the abundance of key upland grass species showed marked changes within these communities; *Agrostis capillaris* increased in high-intensity sheep grazing treatments, while *Festuca ovina* declined in ungrazed treatments (unpublished data). Overall, these studies suggest that to minimise trade-offs between C storage
and species diversity and abundance in *M. caerulea*-dominated grasslands, low-intensity sheep grazing intensities are a more appropriate management practice, as opposed to high-intensity grazing intensities or removing sheep altogether.

**PRIORITIES FOR FUTURE RESEARCH**

- Detect the point at which upland habitats no-longer store C in the soil under different intensities of sheep grazing. Importantly, we have identified that reducing sheep grazing intensities can enhance C storage and sustain biodiversity. However, we need to identify grazing intensities that 'tip' upland habitats from C stores to sinks and how these grazing intensities influence biodiversity.

- Investigate the relationship between C storage and livestock production to provide evidence for implementing a C trading scheme that could enhance upland C storage. To include grazing management in a C trading scheme requires knowledge of soil C accumulation under a wider range sheep grazing intensities than the three intensities discussed in this paper. The approach taken here, coupling measured plant C stocks and predicting soil C accumulation via an organic turnover model can be used for a wider range of stocking densities. This evidence base can then be evaluated in an economic context.

- Evaluate the relationship between C storage and biodiversity across a range of grazing intensities for other habitat types and herbivores. The impacts of grazing are vegetation type and herbivore specific, and we particularly need evidence for other dominant habitats such as *Calluna vulgaris*-dominated heathland that covers ~1.2 million ha of the UK (Emmett et al., 2010). In addition, cattle and deer grazing are filling the void of declining sheep numbers (Thomson et al., 2011) and it is important to determine effects of gradients of cattle/deer intensities and mixed grazing practices that are becoming more common.

**CONCLUSION**

Our findings suggest that to maintain upland C and sustain biodiversity in *M. caerulea*-dominated upland grasslands, low-intensity sheep grazing is a better management practice than high-intensity and/or a cessation of sheep grazing altogether. Recent declines in the number of sheep in the UK uplands are expected to have enhanced upland C storage. Furthermore, we suggest that low-intensity grazing management can be used to minimise trade-offs between C storage and the diversity and abundance of upland bird, mammal and plant species.

**ACKNOWLEDGEMENT**

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For further information on the Glen Finglas project:
http://www.hutton.ac.uk/research/groups/ecological-sciences/community-ecology/glen-finglas-grazing

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