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Influence of liming and sward management on soil carbon storage by semi-improved upland grasslands

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Abstract

Soils in less favoured areas, (LFA's) defined as areas where unfavourable environmental conditions allow only extensive farming systems such as livestock rearing, are relatively stable, being rarely ploughed or disturbed, and cover extensive upland regions of the UK and Europe. Under low intensity management these soils have the potential to act as long-term carbon stores, mitigating the effects of climate change and potentially acting as a source of income for rural economies. However, upland grasslands are sensitive to management decisions, and careful planning is needed to ensure that they continue to provide a range of ecosystem services. Using the long-term grassland experimental plots at Brignant, Wales, management and liming effects on soil organic carbon and related soil parameters under long-term permanent pastures were explored. Results showed that interactions between management and liming could significantly influence carbon storage potential, making a difference of up to0.45 kg C m^{-2} in Hay-cut swards. The greatest reductions were found under pastures that had been cut (rather than grazed) and limed, probably due to a combination of enhanced soil microbial activity, increased root production and a lack of fresh biomass. These results indicate that while the potential to further increase soil organic carbon may be limited, grazing for all or part of the year can reduce losses by providing regular organic matter inputs.

Keywords: Soil Organic Carbon, Upland Grassland, Extensification, Ecosystem Services, Environmental Policy.

1 Introduction

Soils are the largest terrestrial sink of atmospheric carbon (C) (Guo and Gifford 2002) with ~20% estimated to be under grasslands (Conant, 2010). In the UK and Europe, total soil organic carbon (SOC) stores under pastures are estimated to be around 6.71 Pg (Yigini and Panagos, 2016). Due to low disturbance rates these C stores are expected to have longer residence times than those of arable soils (Gregory et al. 2009), making them a key component of a broader strategy to tackle climate change. In the UK, upland grasslands are largely utilised for livestock production, but such systems have been reliant on EU Common Agricultural Policy (CAP) support payments (Hanley et al., 2012) to counter the physical and social challenges associated with farming in less favourable areas by providing tiered payments for support and rural development (European Commission, 1975). Imminent changes to UK and CAP policies and payments are expected to further incentivise ecosystem service provision, including C storage, and there is a recognised need for scientific evidence to support such policies (Committee on Climate Change, 2020, 2019).

Extensification is the practice of reducing fertiliser inputs, stocking rates and/or management intensity, and has been a key part of a push toward sustainability in rural policies

(Marriott et al., 2004). At the same time, the value of grasslands as C stores may be promoted by livestock, which deposit up to 50% of the biomass they consume onto the ground surface as faecal matter (McSherry and Ritchie, 2013). In comparison, mechanically cutting pasture for hay can improve botanical diversity compared to sheep grazing (Tälle et al., 2016), and can improve root biomass (Weisser et al., 2017), an important route for organic matter (OM) into the soil (Lukac, 2012). Hay-cutting with aftermath grazing is further option, and has been shown to be the most effective management for increasing floristic (Pavlů et al. 2014) and invertebrate (García and Fraser 2019) diversity in upland grasslands.

Lime is commonly applied to upland grasslands to counteract the acidity of the underlying soils and improve the persistency and yields of more productive grass species such as perennial ryegrass (*Lolium perenne*) introduced as part of reseeding programmes. Liming has a positive impact on soil chemistry, improving plant growth (Mijangos et al. 2010), but its influence on SOC is highly soil type specific, and the net effects remain poorly understood. On acid soils the neutralising effects of lime may enhance mineralisation and release CO_2, (Holland et al., 2018), but in other instances higher biomass production can increase SOM accumulation and create a net carbon sink (Fornara et al., 2011).

Working with a unique set of long-term plots on previously improved upland permanent pasture in the UK, this study explored the impacts of different grassland management practices and liming regimes on SOC and related parameters. It specifically tested the extent to which soil C stores are influenced by type and timing of defoliation (grazing versus cutting versus a combination of the two), the application of lime on upland soils, and the interactions between liming and management.

2 Materials and method

2.1 *Site and management*

This study used a sub-set of the Brignant long-term experimental plots, established in 1994 at the Pwllpeiran Upland Research Centre, Wales, UK (52°21'55"N, 3°49'49"W). The experimental site is located at an average altitude of 310 m a.s.l., on free draining chromic mollic endoskeletic umbrisol l (WRB, 2014). Soil particle distribution is 20% sand, 58% silt and 21% clay (*R. Sándor, unpublished data*). The region has a maritime climate with a mean annual temperature of around 9.5 ± 0.7 ˚C and an annual rainfall of around 1750 mm. The pasture was last reseeded in 1973, and prior to the experimental regimes being imposed, had received regular inputs of fertilizer and lime.

The management treatments imposed are i) grazed (Gr), continual grazing by sheep from May to August, ii) hay cut (Hay), where animals are excluded and a single cut at 15-20 cm takes place in August, and iii) hay cut with aftermath grazing (Hay/Gr), in which animals are excluded until after a single hay cut in August and then allowed to graze freely until November. Each management option consists of limed (+) and non-limed (-) pairs. On the limed plots the application of ground magnesium limestone was carried out as required to maintain a target pH of approximately 6.0. Gr and Hay/Gr plots are 0.15 ha^{-1} in size, while hay-cut plots are 0.08 ha^{-1}. Each pair is replicated three times to give a 3 × 2 factorial design with n = 3 plots per treatment in randomised blocks.

2.2 *Measurements*

Ten soil cores per plot (n = 180) were collected according to a random grid sampling procedure in August 2016. Samples were taken using a 300 × 48 mm Split Tube sampler (Van

Walt Ltd, Haslemere, UK) and divided in the field into 0-7.5 and 7.5-15 cm sections with the top 1 cm litter layer removed, before being processed using the methodology of Keith *et al.*, (2015). For C and N analyses, subsamples were dried at 105 ˚C for 12 h in a muffle oven and ground to a fine powder in a ball mill, before concentrations were determined using an elemental analyser (Leco Truspec, Milan, Italy). The resulting data was then analysed for equivalent soil mass according to Gifford and Roderick, (2003). A further 10 g sub-sample was taken from each sample to determine soil pH.

The rate and degree of SOM degradation over a 3-month period was measured using a teabag-based method to simulate plant material decomposition in the soil. Teabag index (TBI) data were collected using methods developed by Keuskamp *et al.*, (2013). Lipton green tea (EAN: 87 22700 05552 5) and Lipton rooibos & hibiscus tea (EAN: 87 22700 18843 8) were used. Teabags were oven dried at 60 ºC, weighted to 4 d.p., and between May 1st and 30th July 2018 six pairs of tea bags were buried in each plot (n = 108), at a depth of 8 cm below the soil surface. Teabags were recovered after 90 d before once again being air-dried at 60 °C and re-weighed.

Root biomass was extracted in 6 cores per plot (n = 108) in 0-7.5 and 7.5-15 cm increments using a 42 mm gouge corer (Van Walt Ltd) in August 2017. The top 1 cm litter layer was removed and roots were separated from the soil by washing with water through a 250 µm sieve before being air-dried to constant weight at 60 ºC (Frasier et al., 2016). Bulk density (BD) values were obtained during soil processing.

2.3 *Data analysis*

A two-way ANOVA with a randomised block-design, using two factors: management (Gr, Hay, Hay/) and liming regime (Limed/Not-Limed), and *post hoc* Students Newman-Keuls test was carried out using Genstat (19th edition; VSN International Ltd, Hemel Hempstead, UK). For non-normal data bootstrapped (n = 1000) confidence intervals were generated, and N (0-7.5cm) was log transformed (Log10). The 'estimate missing values' function was used on the TBI data to account for samples not recovered from the field or else disturbed *in-situ* by foraging livestock or other animals (n = 25/108 samples). Where significant interactions were detected, simple effects analyses were carried out.

3 Results

3.1 C and N measurements

There were small but significant interaction effects on SOC between sward management and liming, but no significant main effects (Table 1). Liming within management reduced SOC within Hay treatments by 0.4 kg m^{-2} (P <.05). Management within liming showed SOC was higher in Gr+ (0.49 kg m^{-2}) and Hay/Gr+ (0.44 kg m^{-2}) compared to Hay+ (P <.05).

There was a strong interaction effect on soil N in the 0-7.5 cm layer, and a significant effect of liming (Table 1). Simple effects showed that liming within the Gr treatment was associated with a 0.08 kg m^{-2} increase in N compared to other treatments (P <.001). Management within limed treatments, showed higher N in Gr+ (0.05 kg m^{-2}) and Hay/Gr+ (0.02 kg m^{-2}) compared to Hay+ (P <.05). Management within not-limed treatments showed increased N in Hay- (0.02 kg m^{-2}) and Hay/Gr- (0.03 kg m^{-2}) compared to Gr- (P <.001). In the 7.5-15 cm layer there were no interactions and no significant main effects (Table 1).

There was an interaction effect on C:N ratio in the 0-7.5cm depth layer (Table 1). Simple effects for management within limed showed that C:N was lower in Gr+ than in Hay+ (1.15) or Hay/Gr+ (1.1) ($P < .001$). For liming within management, liming was associated with a 1.16 increase within Gr ($P < .001$). There were no significant main effects of either treatment at this depth (Table 1), but there was a highly significant simple effect of liming within Gr management ($P < .001$), where C:N was 1.16 lower. There were no interaction effects or main effects of liming in the 7.5-15 cm layer, but C:N in grazed plots was 1.6 and 1.8 higher than in Hay/Gr plots, and Hay plots respectively (Table 1).

3.2 Soil pH and bulk density

At the 0-7.5 cm depth there were no interaction effects of sward management and liming on pH or BD. Liming was associated with an increase in pH of 0.69 across all managements and the pH of the Hay/Gr plots was lower than that of Gr or Hay only. Liming was also associated with reduced BD (Table 1). At the 7.5-15 cm depth there were again no interaction effects on pH or BD. There were effects on pH for both sward management and liming, but only liming influenced BD. Soils under Hay/Gr again had a significantly lower pH than those under Gr or Hay, and the soil pH of limed plots was 0.43 higher than non-limed plots (Table 1).

3.3 SOM degradation parameters (TBI) and root biomass

There was no interaction effect on soil decomposition or stabilisation, but liming was associated with higher rates of stabilisation and mineralisation across all managements (Table 1). Stabilisation (S) rates did vary between managements (Table 1), being higher for Gr than Hay/Gr with rates for Hay being intermediary between the two, and not significantly different to either. There was no management effect on decomposition (k) but there was a small but positive effect of liming (Table 1).

There were no significant interaction effects or effects of management on root biomass in the 0-7.5 cm depth (Table 1) but liming increased root biomass by 0.18 g m^{-2}. At 7.5-15 cm there were again no interaction effects. Sward management influenced root biomass, with 0.04 g m^{-2} less recorded for Gr plots compared to the other two treatments, and in limed plots root biomass at this depth was 0.04 g m^{-2} higher than under non-limed plots (Table 1).

4 Discussion

This study showed that overall, neither sward management nor liming alone influenced SOC stocks under long-term upland permanent pastures. However, significant interactions between sward management and liming in hay-cut swards resulted in reduced SOC. Soil C stocks take decades and even centuries to accumulate, but can be lost in the space of a few years as the result of land-use change (Ostle et al., 2009). Long-term experiments at field relevant scales allow the evaluation of real-world management options relating to soil C stocking along timescales that reflect the duration and impact of management decisions.

While sward management did not affect SOC stocks directly, it did have an impact on the stabilisation (S) of OM, soil pH, C:N ratio, and root biomass. Mechanisms affecting OM stabilisation in the soil are mainly relevant in the initial stages of decomposition (Lützow et al., 2006) when freshly deposited, labile C is susceptible to management effects (Belay-Tedla et al., 2009). Grazing also results in the localised redistribution of OM (in dung) and N (in urine), potentially raising biological activity and increasing the species complexity of microbial communities (Millard and Singh, 2010). While soil N did not vary between sward managements, the C:N ratio at the 7.5-15 cm depth was lower under both Hay and Hay/Gr than under grazing alone. This is possibly due to increased root biomass, which has been linked to a priming effect of root exudates on decomposition processes (Bengtson et al. 2012). Additional organic N released into the soil can make OM less recalcitrant and more accessible to root systems and soil microbes which are the main drivers of decomposition (Lützow et al., 2006).

Soil pH is closely linked to microbial activity, fungal/bacterial ratio and enzyme activity, all of which can influence the stabilisation of OM (Weil and Brady, 2017). In the current study, a lower pH was found to be associated with reduced stabilisation, contrasting with the findings of workers such as Hopkins et al. (1990), who indicated that stabilisation should be higher in low pH soils due to reduced microbial activity. The effects of liming on microbial biomass and activity are mixed, (Aye et al., 2016; Badalucco et al., 1992; Pawlett et al., 2009), but is generally thought to increase microbial biomass and respiration (Neale et al. 1997) and consequentially N assimilation. This can potentially result in a loss of C into the atmosphere (Rangel-Castro et al., 2004), so we would expect to see reduced stabilisation under liming, suggesting other factors were at play. Liming was also associated with increased root production at both depths, agreeing with previous research in this area (Fornara et al. 2011), as well as reduced bulk density, which may have improved soil root penetration (Holland et al., 2018). This increase may be associated with higher decomposition rates due to increased plant/soil contact and the presence of root exudates (Bengtson et al., 2012; Lützow et al., 2006), possibly explaining higher soil N in the surface 0-7.5 cm layer under liming.

This study found a difference of ~0.45 kg C m^{-2} between resulting from interactions between management and liming, thought to be related to the lack of faecal matter from livestock. It seems that rather than a single factor being responsible for changes in C, three factors, namely i) animal presence/absence, ii) root biomass related to plant diversity, and iii) the presence/absence of liming, all have a part to play. In grazed only plots animal inputs are sufficient to support SOC irrespective of liming or root biomass mediated effects. In Hay/Gr treatments, improved TBI index, root biomass production, and faecal matter were sufficient to maintain C stocks regardless of liming. However, in hay-cut only plots, the result of liming was to reduce SOC.

5 Conclusions

This study showed that interactions between liming and sward management are key drivers of total C change in upland permanent improved pastures. Liming was found to enhance conditions contributing to OM decomposition but did not negatively affect C when used in conjunction with either grazing or hay-cutting and grazing. However, in the absence of grazers, liming resulted in a loss of C.

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Table 1: Summary of ANOVA results for SOC (ESM (Equivalent soil matter)), and for soil parameters in the 0-7.5 and 7.5-15cm layers. Letters in superscript in rows show the results of a Student-Newman-Keuls test between treatment plots (differences are significant to at least p <.05). For tea-bag index (TBI): (*S*) is the rate of stabilisation of C, and (k) is the rate of mineralization. Treatments are grazed only (Gr), hay-cut only (Hay) and hay-cut with aftermath grazing (Hay/Gr). In the *P* columns, 'ns' is not-significant.

		Management				Liming				
Sample depth	Soil Parameter	Gr	Hay	Gr/Hay	*P*	Not limed	Limed	*P*	s.e.d.	Interaction *P*
na	SOC (ESM) kg m^{-2}	4.53^{a}	4.34^{a}	4.55^{a}	ns	4.49	4.45	ns	0.179	**<.05**
na	TBI (S)	0.3059^{b}	0.2904^{ab}	0.2796^{a}	**<.05**	0.2674	0.3165	**<.001**	0.01419	ns
	TBI (*k*)	0.01994^{a}	0.02313^{a}	0.02265^{a}	ns	0.02055	0.02327	**<.05**	0.002316	ns
0-7.5cm	N kg m^{-2}	0.18^{a}	0.17^{a}	0.18^{a}	ns	0.16	0.19	**<.001**	0.014	**<.001**
	C:N ratio	11.99^{a}	12.29^{a}	12.19^{a}	ns	12.16	12.16	ns	0.390	**<.01**
	pH	5.39^{b}	5.43^{b}	5.03^{a}	**<.001**	4.94	5.63	**<.001**	0.104	ns
	Bulk Density g cm^{-3}	0.52^{a}	0.51^{a}	0.51^{a}	ns	0.54	0.48	**<.001**	0.022	ns
	Root biomass g m^{-2}	0.67^{a}	0.67^{a}	0.80^{a}	ns	0.62	0.80	**<.01**	0.112	ns
7.5-15cm	N kg m^{-2}	0.06^{a}	0.07^{a}	0.07^{a}	ns	0.07	0.07	ns	0.007	ns
	C:N ratio	12.52^{b}	10.72^{a}	10.88^{a}	**<.001**	11.07	11.68	ns	0.581	ns
	pH	5.32^{b}	5.35^{b}	4.89^{a}	**<.001**	4.97	5.40	**<.001**	0.115	ns
	Bulk Density g cm^{-3}	0.77^{a}	0.74^{a}	0.72^{a}	ns	0.77	0.72	**<.05**	0.041	ns
	Root biomass g m^{-2}	0.11^{a}	0.15^{b}	0.16^{b}	**<.001**	0.12	0.16	**<.001**	0.020	ns

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