

# Does liming grasslands increase biomass production without causing negative impacts on net greenhouse gas emissions?

Abdalla A.<sup>1</sup>, Zavattaro L.<sup>2</sup>, Lellei-Kovacs E.<sup>3</sup>, Espenberg M.<sup>1,4</sup>, Mander U.<sup>4</sup>, Smith K.<sup>5</sup>, Thorman R.<sup>5</sup>, Dămățircă C.<sup>6</sup>, Schils R.<sup>7</sup>, Ten Berge H.<sup>7</sup>, Newell-Price P.<sup>5</sup> and Smith P.<sup>1</sup>

<sup>1</sup>*Institute of Biological and Environmental Sciences, University of Aberdeen, United Kingdom;*

<sup>2</sup>*Department of Veterinary Sciences, University of Torino, Italy;* <sup>3</sup>*Institute of Ecology and Botany, MTA Centre for Ecological Research, Hungary;* <sup>4</sup>*Institute of Ecology and Earth Sciences, University of Tartu, Tartu, Estonia;* <sup>5</sup>*ADAS, United Kingdom;* <sup>6</sup>*Department of Agricultural, Forest and Food Sciences, University of Torino, Italy;* <sup>7</sup>*Agrosystems Research, Wageningen Plant Research, Droevendaalsesteeg 1, 6708 PB Wageningen, the Netherlands*

## Abstract

This global review of grassland liming research assesses the impacts of liming on soil pH, biomass production and net greenhouse gas (GHG) exchanges (N<sub>2</sub>O, CH<sub>4</sub> and CO<sub>2</sub>). All studies showed that liming either reduced or had no effects on the emissions of N<sub>2</sub>O and CH<sub>4</sub>. Though the liming of grasslands can increase net CO<sub>2</sub> emissions, the impact on net GHG emissions is small due to the higher 100-year global warming potential (GWP) of N<sub>2</sub>O and CH<sub>4</sub> than CO<sub>2</sub>. Moderate liming of grassland significantly increases soil pH, grass productivity and species richness, and reduced fertilizer requirement, which justifies its wider adoption.

**Keywords:** grassland, lime, N<sub>2</sub>O, CO<sub>2</sub>, CH<sub>4</sub>, SOC

## Introduction

In grasslands, lime is applied to the soil surface and either left on the surface or incorporated into soil especially at sward renewal (Mosier *et al.*, 1998). Previous studies on agricultural (grasslands, croplands and forests) liming found that application of lime optimized plant growth by adjusting soil pH and mitigating N<sub>2</sub>O emissions, but the impact on soil organic carbon (SOC) was inconsistent (e.g. Goulding, 2016). Moreover, the addition of lime increased CH<sub>4</sub> oxidiser activity and, thereby, reduced the total greenhouse gas (GHG) emissions (Kunhikrishnan *et al.*, 2016). Unlike liming of cropland, liming of grassland is often neglected, especially when the overall profit of grassland is low (Goulding, 2016). Due to scarcity of field data, it is still unknown how lime exactly influences grass productivity and nutrient use efficiency in different soil pH, botanical and agro-climatic conditions. This review aims to use the available literature globally to assess the impacts of liming grasslands on soil pH, biomass production and net GHG emissions.

## Materials and methods

To cover all peer-reviewed publications (1980-2021) on the impacts of liming on soil pH, grassland biomass production and net GHG emissions (i.e. nitrous oxide (N<sub>2</sub>O), methane (CH<sub>4</sub>) and net CO<sub>2</sub> emissions), we carried out a comprehensive search on the Web of Science database. We used the keywords: grassland, lime, N<sub>2</sub>O, CO<sub>2</sub>, CH<sub>4</sub> and SOC. We only included studies carried out in the field and had a control treatment. From 12,468 papers, 55 papers (31 papers on soil pH and grass production and 24 papers on SOC and GHG emissions) with data from 72 sites were found suitable for this review. Our quantitative analysis was confined to data on soil pH and grass biomass production; papers on SOC (15 studies) and GHG emissions (N<sub>2</sub>O (4 studies); CH<sub>4</sub> (2 studies) and CO<sub>2</sub> (5 studies)) were reviewed and summarized. All types of lime materials were converted to calcium carbonate equivalent (CCE), which is the neutralizing value of a liming material compared to pure calcium carbonate. We considered net CO<sub>2</sub> emissions as changes in SOC stored in the soil and net GHG emissions as the sum of net CO<sub>2</sub> emissions

and GHG ( $N_2O$ ,  $CH_4$ ) emissions. Datasets referred to moist cool (MC) or moist warm (MW) climates (zonation by Smith *et al.* (2008)). We explored, analysed, and visualised the data with R version 4.0.3.

## Results and discussion

### *Impacts of liming on soil pH and biomass production*

A paired test with random effects showed that liming significantly increased soil pH ( $P < 0.001$ ;  $n = 49$ ). This effect held true also within climate zones MC ( $P < 0.001$ ;  $n = 36$ ) and MW ( $P < 0.001$ ;  $n = 13$ ), and within classes monoculture ( $P < 0.001$ ;  $n = 19$ ) and multi-species (excluding perennial ryegrass or white clover) grassland ( $P < 0.001$ ;  $n = 30$ ) (Table 1). Similar impacts of liming were reported in previous studies (e.g. Zurovec *et al.*, 2021).

A paired test with random effects showed that liming had a statistically significant positive effect on grass biomass production compared to the control treatments ( $P < 0.001$ ;  $n = 69$ ). This effect was also found within each climatic zone MC ( $P < 0.01$ ;  $n = 50$ ) and MW ( $P < 0.001$ ;  $n = 19$ ), and within monoculture ( $P < 0.001$ ;  $n = 34$ ) and multi-species grassland ( $P < 0.01$ ;  $n = 35$ ) (Table 1). Liming reduces the N fertilizer requirement to attain certain biomass production. Biomass increment due to liming was negatively correlated with initial soil pH ( $R^2 = 0.29$ ,  $P = 0.05$ ,  $n = 13$ ), and with lime dose ( $R^2 = 0.27$ ;  $P = 0.1$ ;  $n = 11$ ). Excess liming can decrease grass productivity due to reduced nutrient availability (e.g. phosphorus and minor nutrients) in alkaline conditions (Higgins *et al.*, 2012). Therefore, to get the maximum benefit of liming grassland, acid soils should be regularly limed but at a low rate depending on soil type and initial soil pH. The maximum recommended lime rate for grasslands in England and Wales is  $7.5 \text{ t ha}^{-1}$  for each application (AHDB, 2021).

### **Impacts of liming on net greenhouse gas emissions**

Due to the scarcity of published data on GHG emissions from liming grasslands, this part was only reviewed and summarized. Available studies show that liming either decreased or had no significant effect on  $N_2O$  and  $CH_4$  emissions. Increasing soil pH by liming can improve the capacity of denitrifiers to reduce  $N_2O$  to  $N_2$  and thereby reduce  $N_2O$  emissions. Zurovec *et al.* (2021) found a decrease in soil  $N_2O$  emissions and yield-scaled  $N_2O$  emissions due to liming. Moreover, reduced N fertilizer requirement for a given yield significantly mitigates  $N_2O$  emissions from fertilized grasslands.

The Park Grass experiment (Stiehl-Braun *et al.*, 2011) showed that the interaction of soil pH with N fertilization was important for  $CH_4$  consumption. Here, liming for more than 100 years did not restore the  $CH_4$  oxidising capacity of the soil that had received  $NH_4$ -N fertilizer, whereas in the soil that had received  $NO_3$ -N fertilizer it was restored (Silvertown *et al.*, 2006). The authors argued that  $NH_4$ -N

Table 1. Statistical analysis of the effects of liming ( $\text{t ha}^{-1}$ ) on soil pH and grass dry biomass production ( $\text{t ha}^{-1}$ ) under different climatic zones (MC = moist, cool; MW = moist, warm) and number of species.

	Soil pH	Avg applied N fertilizer ( $\text{kg ha}^{-1}$ )	Control (Mean $\pm$ SD)	Limed (Mean $\pm$ SD)	n	t-value	P-value
Soil pH	All data	189	4.56 $\pm$ 1.36	5.43 $\pm$ 0.52	49	4.69	<0.001
	MC	180	4.73 $\pm$ 1.20	5.38 $\pm$ 0.47	36	3.19	<0.01
	MW	231	4.09 $\pm$ 1.68	5.57 $\pm$ 0.62	13	4.01	<0.001
	Monoculture grass	258	3.72 $\pm$ 1.88	5.36 $\pm$ 0.66	19	4.24	<0.001
	Multi-species grass	134	5.09 $\pm$ 0.30	5.48 $\pm$ 0.40	30	11.27	<0.001
Dry biomass	All data	189	4.31 $\pm$ 2.82	4.74 $\pm$ 2.98	69	4.10	<0.001
	MC	180	3.91 $\pm$ 2.21	4.21 $\pm$ 2.17	50	11.52	<0.01
	MW	231	5.37 $\pm$ 3.89	6.12 $\pm$ 4.23	19	4.38	<0.001
	Monoculture grass	258	3.93 $\pm$ 2.49	4.54 $\pm$ 3.07	34	3.31	<0.001
	Multi-species grass	134	4.68 $\pm$ 3.10	4.93 $\pm$ 2.91	35	2.65	<0.01

<sup>1</sup> n = number of studies; SD = standard deviation; Avg = average.

fertilization had caused a shift in microbial population or resulted in persistent  $\text{NH}_4^+$  inhibition of  $\text{CH}_4$  oxidation to  $\text{CO}_2$ . Ammonium sulphate (an acidifier) seemed to cause an increase in  $\text{CH}_4$  emissions at low soil pH when no lime was applied. Soil pH strongly influences  $\text{CH}_4$  consumption through several pathways, which are still not fully understood (Stiehl-Braun *et al.*, 2011).

Our analysis showed that liming grasslands resulted in higher net  $\text{CO}_2$  emissions because of increased  $\text{CO}_2$  emissions and decreased SOC. This net effect can be due to: (1) greater organic matter (OM) inputs from increased growth; (2) increased OM mineralization due to more favourable soil pH for OM mineralization and OM turnover (Marcelo *et al.*, 2012); (3) direct  $\text{CO}_2$  emission from applied lime (Raza *et al.*, 2021); and (4) enhanced aggregation of clay minerals and aggregate stability due to  $\text{Ca}^{2+}$ , thereby protecting SOC (Haynes and Naidu, 1998). However, as the GWP of  $\text{CO}_2$  is low compared to that of  $\text{N}_2\text{O}$  and  $\text{CH}_4$  (c. 273 and c. 28 times that of  $\text{CO}_2$  over a 100-year period for  $\text{N}_2\text{O}$  and  $\text{CH}_4$  respectively; IPCC, 2021), increased  $\text{CO}_2$  efflux from liming of grassland will have negligible effect on the net GHG emissions. Overall, the increase in net  $\text{CO}_2$  emissions due to liming will be compensated by the saving in GHG emissions due to the reduction in  $\text{N}_2\text{O}$  and  $\text{CH}_4$  emissions.

## Conclusions

According to our review, liming grasslands raises soil pH and enhances grass biomass production in acidic soils. It decreases or has no effect on  $\text{N}_2\text{O}$  and  $\text{CH}_4$  emissions but increases net  $\text{CO}_2$  emissions. Given the higher GWP of  $\text{N}_2\text{O}$  and  $\text{CH}_4$ , the result of liming will be a negligible effect on net GHG emissions. Therefore, it makes sense to lime productive, acidic grasslands to increase nutrient-use efficiency within livestock grazing systems.

## Acknowledgements

This work contributes to the SUPER-G project (funded under EU Horizon 2020 programme), Estonian Research Council (PRG352) and the European Regional Development Fund.

## References

- Higgins S., Morrison S. and Watson C.J. (2012) Effect of annual applications of pelletized dolomitic lime on soil chemical properties and grass productivity. *Soil Use and Management* 28, 62-69.
- IPCC (2021) In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the IPCC [Masson-Delmotte V.P. Zhai *et al.* eds.]. Cambridge CUP.
- Kunhikrishnan A. and Thangarajan R. *et al.* (2016) Functional relationships of soil acidification liming and greenhouse gas flux. *Advances in Agronomy* 139, 1-71.
- Marcelo A.V., Corá J.E. and La Scala-Junior N. (2012) Influence of liming on residual soil respiration and chemical properties in a tropical no-tillage system. *Revista Brasileira de Ciência do Solo* 36 (1), 45-50.
- Mosier A.R., Delgado J.A. and Keller M. (1998) Methane and nitrous oxide fluxes in an acid oxisol in western Puerto Rico: effects of tillage liming and fertilization. *Soil Biology & Biochemistry* 30, 2087-2098.
- Raza S., Zamanian K., Ullah S., Kuzyakov Y., Virto I. and Zhou J. (2021) Inorganic carbon losses by soil acidification jeopardize global efforts on carbon sequestration and climate change mitigation *Journal of Cleaner Production* 315, 128036.
- Silvertown J., Poulton P., Johnston E. *et al.* (2006) The park grass experiment 1856-2006: its contribution to ecology. *Journal of Ecology* 94, 801-814.
- Smith P., Martino D. and Cai Z. (2008) Greenhouse gas mitigation in agriculture. *Philosophical Transaction of the Royal Society B: Biological Sciences* 363, 789-813.
- Stiehl-Braun P.A., Powlson D.S., Poulton P.R. and Niklaus P.A. (2011) Effects of N fertilizers and liming on the micro-scale distribution of soil methane assimilation in the long-term Park Grass experiment at Rothamsted. *Soil Biology and Biochemistry* 43 (5), 1034-1041.
- Zurovec O., Wall D.P. *et al.* (2021) Increasing soil pH reduces fertilizer derived  $\text{N}_2\text{O}$  emissions in intensively managed temperate grassland. *Agriculture Ecosystems and Environment* 311, 107319.