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Keywords: grassland, lime, N_2O, CO_2, CH_4, SOC, net greenhouse gas emissions.

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Abstract

Soil acidification has negative impacts on grass biomass production and the potential of grasslands to mitigate greenhouse gas (GHG) emissions. Through a global review of research on liming of grasslands, the objective of this paper was to assess the impacts of liming on soil pH, grass biomass production and total net GHG exchange (nitrous oxide (N_2O), methane (CH_4) and net carbon dioxide (CO_2)). We collected 57 studies carried out at 88 sites and covering different countries and climatic zones. All of the studies examined showed that liming either reduced or had no effects on the emissions of two potent greenhouse gases (N_2O and CH_4). Though liming of grasslands can increase net CO_2 emissions, the impact on total net GHG emission is minimal due to the higher global warming potential, over a 100-year period, of N_2O and CH_4 compared to that of CO_2. Liming grassland delivers many potential advantages, which justify its wider adoption. It significantly ameliorates soil acidity, increases grass productivity, reduces fertiliser requirement and increases species richness. To realise the maximum benefit of liming grassland, we suggest that acidic soils should be moderately limed within the context of specific climates, soils and management.

Keywords: grassland, lime, N_2O, CO_2, CH_4, SOC, net greenhouse gas emissions.

1. Introduction

Soil acidification (i.e. low soil pH) is a natural process that reduces grass productivity by reducing soil base status and nutrient availability, and increasing the solubility of metals such as aluminium (Al), iron (Fe) and manganese (Mn) that can be toxic to grass (Holland et al., 2018; Horan et al., 2018). It has been accelerated by higher nitrogen (N) and sulphur (S) deposition related to human activities (Kunhikrishnan et al., 2016). Soil acidification influences both top- and sub-soils, and decreased productivity is readily apparent where grass biomass is harvested (Goulding and Annis, 1998). Studies have shown that soil acidification negatively impacts the potential of grasslands to mitigate greenhouse gas emissions (GHG; N_2O, CH_4 and CO_2) from soils (Goulding, 2016). Soil pH is generally controlled by land use, geology and climate (Fabian et al., 2014), however, the main drivers of acidification are *via* precipitation (wet deposition) and deposition of acid gases and particles (e.g. nitric acid, ammonia and sulphur dioxide; dry deposition), especially in heavily industrialised regions such as western Europe, USA and Australia (Bouwman et al., 2002). For an alpine grassland, Wang et al. (2020) found that acidification changed plant composition, root morphology and litter decomposability and temporarily increased soil C stock. However, in the long-run acidification negatively impacts nutrient cycling and consequently, reduces grass productivity. The Park Grass experiment at Rothamsted in the United Kingdom, began in 1856, has shown that regular application of N fertiliser as ammonium sulphate progressively made the soil more acidic (Silvertown et al., 2006). However, regular application of lime is a common practice used to neutralise and control soil acidification. Previous studies on agriculture (croplands and grasslands) and forests reported that liming decreases Al toxicity, increases soil pH, increases soil phosphorus (P) and magnesium (Mg) availability, and improves soil physical condition (Tunney et al., 2010; Holland et al., 2018). Liming enhances soil nitrification (Meiwes, 1995) and thereby, increases soil nitrate concentration and N availability for grass uptake (Fuentes et al., 2006; Holland et al., 2018). It improves soil structure, mitigates soil degradation through its buffering capacity (Keiblinger and Kral, 2018), increases earthworm activities and makes grass more palatable to animals (DAERA, 2021). Additionally, the use of high Mg lime for soil treatment increases both soil pH and Mg contents in the soils and thereby, reduces the risks of livestock hypomagnesaemia (i.e. abnormally low magnesium levels in their blood) (Bide et al., 2021).

Research on liming found that application of lime optimised plant growth, by adjusting soil pH, and mitigating N_2O emissions, but the impact on soil organic carbon (SOC) was inconsistent in the literature (e.g. Goulding, 2016). Liming of grasslands can enhance SOM mineralisation and emission of CO_2 (Holland et al., 2018) but also increase SOM and create a net C sink due to high biomass production (Fornara et al., 2011). Barcelos et al. (2021) found the effects of lime on C cycling through microbial biomass, especially in the subsoil, were minimal. Eze et al. (2018) noted that the increase in global SOC due to liming (+5.8%) and fertilisation (+6.7%) was not large enough to replace that lost by heavy grazing (-15%), especially in the tropics. Though Johnson et al. (2005) reported that liming grasslands with or without N fertiliser decreased soil respiration by 37% and 70% respectively, the authors argued that these reductions in the CO_2 emissions by liming were either due to low concentrations of labile SOC, which decreased over time or by adaptation of the microbial community to acidic soil and low pH (Keller et al., 2005). In contrast, Hinsinger et al. (2003) reported that liming could increase CO_2 emissions by stimulating rhizosphere priming. Liming could change the structure of microbial community to one with a lower C use efficiency and higher respiration (Keiblinger et al., 2010). In acidic soils, high availability of Al^{3+} ions inhibits CH_4 oxidiser activity, whereas the addition of lime increases their activity thereby, reducing the total GHG emissions (Hilger et al., 2000; Kunhikrishnan et al., 2016). In a global review of agricultural lands, Holland et al. (2018) found that liming affected soil C storage variably due to differences in soil type, land use, climate and management. Furthermore, Rangel-Castro et al. (2005) found that the microbial communities in limed soils were more complex and active in utilising recently released C compounds than those of un-limed soils. However, regular application of lime to grasslands indirectly increased biomass production by increasing soil available nutrients (Holland et al., 2018), improved grass quality and hence livestock production.

Unlike cropland, where there is a general awareness of the importance of liming for crop production, liming of grassland is often neglected, especially when the overall profit of grassland is low. Due to scarcity of field data, it is still unknown how lime exactly influences grass productivity and nutrient use efficiency at different initial soil pH, number of grass species and agro-climatic zones. A meta-analysis where enough data are available, and a review of available studies where data are insufficient for a full analysis, could help to assess the present evidence on the importance of liming for grassland and fill this gap in knowledge. This meta-analysis and review aims to use the available literature globally to assess the impacts of liming grasslands on soil pH, biomass production and net GHG emissions. We first review the effects of liming on the soil pH and biomass production. We then review and assess the impacts of liming on GHG and net CO_2 emissions. Finally, we assess the impacts of liming on the total net GHG emissions and give some suggestions for future research to support the sustainability of grasslands. The specific hypotheses we critically evaluated were as follow: (a) liming grasslands ameliorates soil acidity; (b) liming grasslands increases grass productivity and species richness and; (c) liming grasslands increases SOC and has no effects on total net GHG emissions.

2. Materials and methods

2.1 Data collection

This review is part of a more extensive reviewing process for European permanent grasslands under a project called “Developing Sustainable Permanent Grassland Systems and Polices” (SUPER-*G*) (Schils et al., 2022). To review peer-reviewed publications on the impacts of liming on soil pH, grassland dry matter production and total net GHG emissions (i.e. nitrous oxide (N_2O), methane (CH_4) and net CO_2 emissions), we carried out a comprehensive search on the Web of Science database (accessed between September 2020 and November 2021). Due to the scarcity of published data on European grasslands alone, we collected all papers published globally between 1980 and 2021. We used the keywords: grassland, lime, N_2O, CO_2, CH_4, SOC and net greenhouse gas emissions. To comprehensively cover all available papers, we examined all references cited in the papers collected. Our search covered all types of managed grasslands, as shown in Tables 1 and 3. We excluded laboratory, greenhouse, pot and modelling papers and only included studies that were carried out in the field and had a control treatment. We defined the control treatment as a grassland on which no lime was applied. The total number of papers from the Web of Science search was 12,470 but the majority were excluded, in most cases, either because there was no control treatment or because the study did not meet the other criteria described above. Only 57 papers with studies carried out at 88 sites covering different countries and climatic zones were found suitable for this review (Table 1). From these papers, we found 33 papers on soil pH and grass production and 24 papers on SOC or GHG emissions. This shows that data on the impacts of liming grasslands on GHG emissions are very scarce in the literature. Therefore, our quantitative analysis was confined to data on soil pH and grass biomass production, while the papers on SOC (15 studies) and GHG emissions (N_2O (4 studies); CH_4 (2 studies) and CO_2 (5 studies)) were only reviewed and summarised. Most of the studies were short-term liming experiments of 2-4 years, though a few of them were long-term studies (>10 years). Where the original papers reported data from multiple years, we used the average of all years. 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 (Moore et al., 1987). Annual grass biomass production was measured in tonnes of dry matter ha^{-1}. The GHG emissions (N_2O, CH_4 and CO_2) data were reported from studies that measured the gas flux from grasslands and used a static / automated chamber gas measurement method or Eddy Covariance (EC). SOC (0 to 50 cm) was measured by direct sampling and laboratory analysis. We considered net CO_2 emissions as the balance between SOC stored in the soil and CO_2 emitted to the atmosphere and total net GHG emissions as the sum of net CO_2 emissions and N_2O and CH_4 emissions.

We used the global climate zones criteria proposed by Smith et al. (2008) to divide our dataset. The climatic zones were distinguished based on temperature and moisture regimes (cool, warm, dry and moist zones). The cool zone covers the temperate (oceanic, sub-continental and continental) and boreal (oceanic, sub-continental and continental) areas, whilst the warm zone covers the tropics (lowland and highland) and subtropics (summer rainfall, winter rainfall, and low rainfall). The dry zone includes the areas where the annual precipitation is ≤500 mm, whilst the moist zone includes areas where the annual precipitation is >500 mm. The four climate categories were moist cool (MC), moist warm (MW), dry cool (DC) and dry warm (DW). However, all datasets on liming grasslands were found under MC and MW climate zones only. The two other climatic zones have no available research / observations. We also divided the data into monoculture and multi-species grasses. Multispecies grass contains two or more species (not including perennial rye grass or white clover) (FAS, 2021). For the different studies, different methods were used to measure soil pH, for example using a pH probe or meter in deionised water or 0.01 M $CaCl_2$ in 1:1 and 1:2 or 1:5 v:v soil:solution ratios. We made no adjustment for analytical methods used for soil pH, and where a range of values was reported, we took the arithmetic mean. The mean annual air temperature (MAAT, in °C) and mean annual precipitation (MAP, in mm) values for each study were collected from the original published papers.

2.2 Data analyses

We explored, analysed, and visualised the data with R version 4.1.0 (R Core Team, 2021). The distributions of soil pH and grass dry matter production measurements were characterised using the “fitdistrplus” package version 1.1-5 (Delignette-Muller & Dutang, 2015). To investigate differences between the control and limed treatments on soil pH and grass dry matter production (t ha^{-1}) under the two climatic zones (MC and MW) and different number of grass species, we used the “glmer” method with random effect (different studies) and Gamma (link “log”) or gaussian (link “log”) distribution (“lme4” package version 1.1-27) (Bates et al., 2015), while p-values were calculated in order to confirm the significance of the relationships using the “lmerTest” package version 3.1-3 (Kuznetsova et al., 2017). In addition to linear mixed-effects modelling, we also used the response ratio (RR) (Hedges et al., 1999) of liming on the grass dry matter production between treatment and control, to confirm our results. We calculated the RR and performed analyses with it according to Li et al. (2019) using the "metafor" package version 3.0-2 (Viechtbauer, 2010). Based on recommendations (Wiebe et al., 2006; Kambach et al. 2020), we used multiple imputations of missing variance measures to overcome the problem of incompletely reported primary studies (standard deviations were missing in 28.6% of studies). The data imputation was made by "mice" package version 3.13.0 (van Buuren and Groothuis-Oudshoorn, 2011). We have not applied the RR method on soil pH due to unavailability of standard deviation values in the original papers.

Linear regression models were used to show relationships between the changes in soil pH and clay, silt and sand contents in the soil. In addition, linear regression models were also used to show relationships between the changes in grass dry matter production and soil pH due to liming, calcium carbonate equivalent lime, MAAT and MAP. For the relationship between calcium carbonate equivalent and applied N fertiliser and dry matter production in different climate zones and different grassland types, we created interpolated contour plots using the package "akima" version 0.6-2 (Akima et al., 2016). A contour plot is a graphical technique for representing a three-dimensional surface by plotting constant z slices on a two-dimensional format. That is, given a value for z, lines are drawn for connecting the (x, y) coordinates where that z value occurs. We performed linear regressions to show relationships between the calcium carbonate equivalent and applied N fertiliser variables against grass dry matter production. For exploring the fits of different models, inspection of residuals patterns for the entire model and posterior predictive simulation were used as diagnostic tools (Gelman and Hill, 2006; Bates et al., 2015; Harrison et al., 2018).

3. Results and Discussion

3.1. Impacts of liming on soil pH

In this global systematic analysis and review, we quantitatively analysed the data collected on the impacts of liming grasslands on soil pH and grass dry matter production (Table 1). A paired test with random effects showed that liming significantly increased the initial soil pH values ($p<0.001$; $n=85$) (Table 2). Similar impacts of liming on soil pH were reported in previous studies (e.g. Corbett et al., 2021; Zurovec et al., 2021). The optimum soil pH for the growth and development of grasslands is variable due to the tolerance of some grass-species to high soil acidity (Anderson et al., 2013). These grass species are less sensitive to soil acidity because they resist Al toxicity (Poozesh et al., 2010). For example, the grass species Browntop

(*Agrostis tenuis* Sibth) and Chewings fescue (*Festuca rubra* L. subsp. *commutata* Gaud) are not affected by Al^{3+} up to 30 and 12 μ*M*, respectively. However, Yorkshire fog (*Holcus lanatus* L.), Veld grass (*Ehrharta calycina* Smith) and Paspalum (*Paspalum dilatatum* Poir) are tolerant to Al with a 50% reduction in attainable yield, under optimal management and N input, due to Al^{3+} of 13, 10 and 7 μ*M*, respectively (Edmeades et al., 1991). Although liming is an important management to improve biodiversity, it could negatively influence species with different pH optima in the species pool (De Graaf et al., 1998). These significant increases in soil pH due to liming were also found when the data were segregated by climatic zones; MC ($p<0.001$; n=55) and MW ($p<0.001$; n=30) or by the number of grass species in the field: monoculture ($p<0.001$; n=48) and multi-species grasses ($p<0.001$; n=37) (Table 2). A previous synthesis on agricultural systems by Goulding (2016) also found significant increases in soil pH under variable numbers of grass species. Changes in soil pH due to liming have significantly positive correlations with amounts of clay ($t = 3.69$, $p<0.01$, $R^2 = 0.39$, $n = 23$) and silt ($t = 2.27$, $p<0.05$, $R^2 = 0.24$, $n = 18$) contents in soils but no correlation with the amounts of sand was observed ($p>0.05$) (Fig.1). Corbett et al. (2021) and He et al. (2021) reported significant correlations between soil pH and clay contents in soils. Thus, the initial soil pH and clay and silt soil particles should all be considered when deciding on the amounts of lime applied to soils. These soil parameters are related to the cation exchange capacity and base saturation percentage, which are in effect what determine the lime requirement.

3.2. Impacts of liming on grassland dry matter production

On one hand, a paired test with random effects for all available data showed that liming had statistically significant positive effects on the grass dry matter production compared to the control treatments ($p<0.001$; n=63) (Table 2). Soil acidity leads to low base status and high aluminium (Al) saturation (Horan et al., 2018) and therefore, reduces grass dry matter production (Mijangos et al., 2010) and abundance of desirable species (Olsson et al., 2009). Unlike N fertiliser, which aims to increase grass production by adding mineral N, liming aims to do so by optimising nutrient availability and plant growth conditions. Thus, correcting soil pH through liming provides the right environment for grassland to reach its growth potential. This reduces the need for animal supplementary feeding and improves the efficiency and sustainability of grazing livestock production. Significant increases in grass dry matter production due to liming were also found under the two climatic zones; MC ($p<0.01$; n=37) and MW ($p<0.001$; n=26) and under the different numbers of grass species: monoculture ($p<0.001$; n=34) and multi-species grasses ($p<0.01$; n=29) (Table 2).

On the other hand, as illustrated in Fig. 2a, a response ratio analysis (± 95% confidence intervals) showed that in the MC climate, the increase in grass dry matter production of 20.8% due to liming was significantly higher and the increase of 14.6% in the MW climate was higher but not significantly different from the control. Here, although temperature can increase grass productivity, it could also increase plant decomposition and microbial response to other perturbations (e.g. liming) (Ågren and Hyvonen, 2003; Wennman and Katterer, 2006; Jabro et al., 2008). The increase in grass dry matter production due to liming for both monoculture (17.4%) and multi-species (17.7%) grass were both significantly higher compared to the control ($p<0.05$) (Fig. 2b). The response ratio analysis showed that significantly higher biomass production of 34.4% could be achieved by liming grasslands grown on medium soil, and of 42.1% by applying an annual N fertiliser ranging from 100 to 200 kg N ha^{-1}. However, although the increases in grass dry matter production due to liming for other soil types / applied amounts of N fertiliser were higher, no significant differences were observed (Fig. 2c and d, respectively).

Contour plots (Fig. 3) show the relationship between the amounts of lime, applied N fertiliser and dry matter production for different climate zones (i.e. MW and MC) or different numbers of grass species. Here, the amounts of lime and applied N fertiliser explain 42.3% of overall dry matter variations ($n = 45$, $p<0.001$); dry matter correlated significantly with both calcium carbonate equivalent ($t = -2.2$; $p<0.05$) and applied N fertiliser ($t = 3.9$; $p<0.001$). Clear differences in vegetation and the number of species due to liming can be seen in the Park Grass Experiment in the UK (Fig. 4). In this experiment, combinations between N fertiliser and ground chalk lime resulted in a higher species richness compared to un-limed treatments. Many studies e.g. Jarvis (1984) and Poozesh et al. (2010) reported that liming also increased the total number of grass species, the proportion of di-cotyledons and the nodulation of white clover and thereby, increased N through symbiotic fixation. In contrast, Pavlu et al. (2021) reported no difference in species richness due to previously applied liming. Positive correlation between changes in soil pH and changes in grass dry matter production due to liming was found ($t = 1.62$, $p= 0.134$, $R^2 = 0.21$, $n = 12$) (Fig. 5a). However, although this correlation was not statistically significant, due to limited data and high variability, it shows a clear trend between them. In a 60-year experiment investigating impacts of N deposition on wild plant communities, Berendse et al. (2021) noted a faster recovery of species richness and plant diversity in limed plots than in the un-limed ones. Awad et al. (1976) and Poozesh et al. (2007) found inverse relationships between grass growth and Al concentration in soils. As shown in Fig. 5b, the changes in dry matter production due to liming was significantly negatively correlated with the applied amount of lime in the form of calcium carbonate equivalent ($t = -2.71$, $p<0.01$, $R^2 = 0.11$, $n = 62$). Thus, 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. Grassland productivity is also reduced if soil acidity is combined with a low soil phosphorus concentration (P) (Tanaka et al., 1984). The maximum recommended lime rate for grasslands in England and Wales is 7.5 t ha^{-1} for each application (AHDB, 2021). Excess liming can decrease grass productivity due to reduced nutrient availability (e.g. phosphorus and minor nutrients) in alkaline conditions (Higgins et al., 2012). It can also result in a lower grass root mass, higher root decomposition and higher N mineralisation (Heyburn et al., 2017). Moreover, the application of lime in silvo-pastoral systems can increase grass biomass production but, although not significant, it slows down tree growth due to competition between the grasses and trees (Mosquera-Losada et al., 2011). Li et al. (2019), found grasses and legumes in grazing systems have a highly variable response to liming because of variations in species richness and the number of grazing livestock, which make nutrient cycling processes very complex (Hooper et al., 2005). Liming improves feed quality and reduces the amount of N fertiliser required by the grass (Higgins et al., 2012; Mkhonza et al., 2020). In contrast, few studies reported that liming increased soil pH but had no significant gains (Toxopeus, 1989; Viadé et al., 2011), or even had negative effects (Cregan et al., 1989; Carran, 1991; Ryant et al., 2016), on grass biomass productivity. However, Ryant et al. (2016) noted that this low productivity due to liming was due to the suppression of some grass species that adapted to acidic soils. Biomass production under liming treatments was positively correlated with MAP ($t=2.3$, $r^2=0.08$, $p<0.05$, $n=63$) but the correlation with MAAT was not significant, as illustrated in Fig. 5c and d. Here, a wet climate plays an important role in enhancing soil acidity due to leaching and acid rain (Slessarev et al., 2016).

3.3. Impacts of liming on greenhouse gas emissions

3.3.1 Impacts on N_2O and CH_4 emissions

Data on the impacts of liming grasslands on N_2O and CH_4 emissions were scarce. Therefore, we analysed / summarized the collected studies qualitatively (Table 3). This represents a significant gap in knowledge which needs to be filled in order to better understand the benefits and impacts of liming practices. Available studies show that liming either decreased or had no significant effect on N_2O emissions. According to Bakken et al. (2012) and Liu et al. (2014), under acidic soil the N_2O reductase functioning in denitrifiers is weak. However, increasing soil pH by liming can improve the capacity of denitrifiers to reduce N_2O to N_2 and thereby, reduce N_2O emissions. Likewise, Jha et al. (2020) found that liming increases *nosZ* gene abundance in grazed grassland soils causing lower N_2O emissions and more complete bacterial denitrification. Wang et al. (2021) and Zurovec et al. (2021) found a decrease in both soil N_2O and yield-scaled N_2O emissions in limed grasslands compared to the un-limed grasslands and a negative linear relationship between soil pH and cumulative N_2O emissions. Moreover, Williams et al. (2021) reported that liming of fertilised grasslands was most effective in lowering the yield-scaled N_2O emissions compared to ploughing and reseeding of the grassland. In Norway, Byers et al. (2021) found that liming reduced N_2O emissions from the plots with grass only but not from grass-clover or pure clover treatments. They argued that the increased decomposition and nitrification of the N-rich clover biomass in winter led to higher soil NO_3^- and low O_2 and consequently, higher N_2O emissions from denitrification. However, Galbally et al. (2010) reported that liming had no significant impact on the overall average N_2O emissions (i.e. 0.96 ± 0.07 mg N m^{-2} d^{-1} for acid plots compared to 0.88 ± 0.04 mg N m^{-2} d^{-1} for limed plots) but decreased the yield-scaled N_2O emissions due to the significant increase in grass yield. The reduction in the amount of N fertiliser requirement (Higgins et al., 2012; Mkhonza et al., 2020) due to higher grass biomass production (Zurovec et al., 2021) and higher soil nitrate (i.e. higher soil nitrification) (Clough et al. 2004) under liming, significantly mitigate N_2O emissions from grasslands. Further, Cuhel et al. (2010) noted that soil pH is one of the main factors that determine end products of denitrification. They found N_2O/ (N_2O + N_2) ratio increased with decreasing soil pH due to changes in the total denitrification activity but had no change in N_2O production.

Available studies showed that liming either decreased or had no effect on CH_4 emissions from grassland soils. Although CH_4 emission from grasslands soils is less important compared to that release from ruminant livestock, anaerobic storage of manure (Corre, 2002) or N_2O emissions from soils, it still needs to be mitigated because it contributes to the climate change problem (Garnett et al., 2017). The CH_4 is produced in soils by methanogenic archaea (Watanabe et al., 2007) and consumed as C and energy sources by methanotrophic microorganisms (Smith et al., 2003). Usually, well-drained grassland soils consume CH_4, however there are important interactions with N fertilisation and soil pH that influence CH_4 consumption (Bodelier and Laanbroek, 2004). Specifically, in some cases, ammonium-N fertilisers reduce the soil oxidising capacity (Hütsch et al., 1994) by enhancing competing nitrifier communities that oxidise (i.e. consume) CH_4 at a slower rate than methanotrophs, or by increasing the threshold CH_4 concentration at which the methanotrophic activity starts (Mosier et al., 1998). The long-term Park Grass experiment (Hütsch et al., 1994; Stiehl-Braun et al., 2011) showed that the interaction of soil pH with N fertilisation was important. Here, liming for more than 100 years did not restore the CH_4 oxidising capacity of the soil that had received NH_4-N fertiliser, whereas it did in soils that received NO_3-N fertiliser (Hütsch et al., 1994; Silvertown et al., 2006). The authors argued that NH_4-N fertilisation had caused a shift in microbial population or had resulted in a very persistent NH_4^+ inhibition of CH_4 oxidation. Ammonium sulphate, which has an acidifying effect, seemed to cause an increase in CH_4 emissions at low soil pH when no lime was applied. In contrast, manure apparently had a buffering effect on CH_4 consumption, as CH_4 consumption was relatively stable at a varying soil pH (Stiehl-Braun et al., 2011). Soil pH strongly influences CH_4 consumption through several pathways, which are still not fully understood (Stiehl-Braun et al., 2011). Although soil acidity directly affects methanotrophs, availability of NH_4^+ as ammonia and toxic effects of Al^{3+} ions at low soil pH could be possible explanations (Hütsch et al., 1994; Powlson et al., 1997; Stiehl-Braun et al., 2011). Moreover, the accumulation of NO_2^- and NH_2-OH compounds at low pH, are also toxic to methanotrophs (Kunhikrishnan et al., 2016). Powlson et al. (1997), observed that low soil pH (below 5.1) significantly decreased the CH_4 consumption capacity of the soil. In contrast to the Park Grass experiment, a natural grassland experiment in Puerto Rico where lime was incorporated into the soil by tillage showed that liming did not completely restore CH_4 uptake. Here, the soil microflora were adapted to the acidic environment (Mosier et al., 1998). Incorporation of lime in soils has greater impacts on net CH_4 emission than surface application, as the soil layers that most contribute to CH_4 oxidation are the deeper ones that are scarcely influenced by a surface liming practice (Hütsch, 2001).

3.3.2 Net CO_2 emissions

The balance between SOC stored in the soil and CO_2 emitted to the atmosphere (net CO_2 emission) under liming was assessed. Although most studies collected and reviewed (Table 3) have shown lower SOC associated with liming, few reported contrasting results with either small increases (Fornara et al., 2011; Sochorová et al., 2016) or similar effects to un-limed treatments (Aye et al., 2016; Egan et al., 2018). Liming of grasslands can enhance SOM mineralisation and emission of CO_2 (Holland et al., 2018) but can also increase SOM and create a net C sink due to high biomass and root production (Fornara et al., 2011). The combination between liming and other sward management, such as frequent cutting and heavy grazing, reduced SOC (Forster et al., 2021). Moreover, Barcelos et al. (2021) found the effects of lime on C cycling through microbial biomass, especially in the subsoil, were minimal. The effect of liming grasslands on net CO_2 emission is the result of several processes that take place simultaneously. Firstly, there can be greater OM inputs due to increased biomass production. Secondly, the lime application can lead to increased OM mineralisation due to favourable soil pH, since soil biological activities that promote OM mineralisation and accelerate OM turnover rates are stimulated (Marcelo et al., 2012). If these higher microbial activities remain constant over time, they can result in higher CO_2 emissions and lower SOC stocks (Paradelo et al., 2015; Lochon et al., 2018). Thirdly, liming is a source of inorganic C and thereby, it enhances CO_2 efflux (Raza et al., 2021). Fourthly, high Ca^{2+} concentrations and ionic strength following lime application can also improve the aggregation of clay minerals and the formation of stable aggregates, thereby protecting SOC (Haynes and Naidu, 1998). According to Foereid et al. (2006), after a short-term isotope study, the control plots stored more C in the soil than the limed treatment. They found that although the limed treatment had a greater primary productivity, the throughput was slower in the control treatment. Therefore, the control treatment could accumulate more C in the soil in the longer-term (Foereid et al., 2006). Generally, liming grasslands resulted in higher net CO_2 emissions because of increased CO_2 emissions and decreased SOC. To reduce this net CO_2 emission, Snyder et al. (2009) suggested applying lime in the form of an oxide (e.g. quicklime or slaked lime) rather than as carbonate materials.

Liming has a direct chemical effect on inorganic C transformations, and an indirect biological effect on organic C transformations through diverse C flux pathways in the rhizosphere and mycorrhizosphere (Hinsinger et al., 2003; Ahmad et al., 2014). The results of these effects and the mechanisms behind them depend on the ecosystem, including many factors such as weather, soil type, soil OM content and liming practice (Soussana et al., 2014). In a long-term study by Kemmitt et al. (2006), enhanced CO_2 emissions continued for 16 years after the last liming event, as a consequence of direct pH effects on the functioning of the microbial community (e.g. nitrifiers), and on (decreasing) toxic Al concentrations, which in turn, indirectly increased substrate availability and biomass production. The long-term legacy effect of a single lime application in a subalpine ecosystem was confirmed by Schaffner et al. (2012). The authors found that the Ca^{2+} pool in soil was still significantly higher in limed than in the control treatments, but the soil C concentration was not affected. However, in a 30-month-experiment by Lochon et al. (2019), no longer-term effects of liming were found probably due to the relatively low amount applied. Moreover, decreased net CO_2 emissions were observed on peatlands after six years of annual liming and N and P fertilisation. In this case, liming increased available and total N and P at the surface peat, increased soil pH and shifted the dominant plant community but no impact on microbial C cycling was observed

(Keller et al., 2005). Other than the amount, type and quality of lime applied, the liming method may have an impact on the effectiveness of liming in increasing CO_2 emissions (Marcelo et al., 2012). In some studies, where the quantitative effect of lime on potentially mineralisable C was observed, the amount of respired C was proportional to liming rate (Kemmitt et al., 2006; Marcelo et al., 2012). However, liming increases grass productivity and SOC decomposition in organic and low productive soils (Alison et al., 2019). Furthermore, in an experiment in a silvo-pastoral system, Mosquera-Losada et al. (2011) showed that lime application in combination with sewage sludge fertilisation (200 kg total N ha^{-1}) reduced soil OM due to the increased mineralisation rate, which can reduce the soil capacity to store C. Further, Wang et al. (2016) noted that the total SOC (0-10 cm depth) decreased or remained constant after long-term liming, depending on the lime application rates, though the decrease in SOC occurred mainly in the labile C pools.

3.3.3 Total net GHG emissions

Liming grasslands showed neutral or even favourable effects on N_2O and CH_4 emissions. However, the main disadvantage of liming is the risk of high net CO_2 emissions, especially when over-applied (Aye et al., 2016). As the global warming potential of CO_2 is low compared to N_2O and CH_4 (the GWPs of N_2O and CH_4 are 273 and 27.2 to 29.8 times that of CO_2, respectively, over a 100-year period; IPCC, 2021), increased CO_2 efflux from liming of grassland could still have limited impact on total net GHG emissions. Here, the increase in net CO_2 emissions due to liming will be compensated by the saving in GHG emissions due to the reduction in N_2O and CH_4 emissions. In a meta-analysis, Wang et al. (2021) reported that liming global agricultural acid soils would have neutral impacts on total net GHG emissions with a significant increase in crop productivity. Thus, liming could help to fulfil the environmental targets proposed in the EU Green Deal and the Farm to Fork and Biodiversity strategies (EC, 2021). A new emerging technology to raise soil pH and potentially sequester CO_2 is the application of Mg or Ca silicates (mineral carbonation of e.g. wollastonite or olivine or other mafic rock powders) (O'Connor et al., 2001; ten Berge et al., 2012). However, to the best of our knowledge, no study has yet been carried out on grassland. Future research should focus on the development of methods to increase SOC with liming. This could be achieved by, for example, breeding of grass species with deeper or more extensive root systems e.g. *Festulolium* (ryegrass x fescue hybrid). These types of grass have a greater resource use efficiency (e.g. water), high biomass productivity, high contribution to SOC (Humphreys et al., 2003; Kell, 2011) and induce lower enteric CH_4 emissions when fed to ruminants if supplemented with feed diets (Celis-Alvarez et al., 2021). Moreover, practising of extensive grazing can also help to maintain soil C stocks due to regular organic matter input by livestock (Abdalla et al., 2018; Forster et al., 2021). However, for less profitable farms, acid-tolerant grass species can be grown. Long-term field experiments on grasslands should be conducted to investigate further the potential antagonistic or synergistic effects of lime on total net GHG emissions.

4. Conclusions

In this global systematic review and analysis, we found that liming grasslands significantly raised soil pH and enhanced grass biomass production in acidic soils. Liming either decreased or had no effects on N_2O and CH_4 emissions. There is a trade-off between the impacts of liming on grass biomass production and the soil net CO_2 emissions. However, as the global warming potential of CO_2 is low compared to N_2O and CH_4, the impacts on total net GHG emissions will be minimal. In conclusion, liming grassland increases the net CO_2 emissions, but it makes sense to lime acidic grasslands to increase nutrient use efficiency within livestock grazing systems. However, the application rate should be optimised according to soil type, climate and management.

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Table 1. Published studies on the impacts of liming on grass dry matter production

Coordinates (Country)	Grass type	MAAT* (°C)	MAP** (mm)	Climate zone	Soil texture	Average initial pH	Type/ rate of lime (t ha^{-1})	Calcium carbonate equivalent (t ha^{-1})	Duration (year)	Lime effects/ Δ dry matter (t ha^{-1})	Ref.
50.21°N, 06.85° E (DE)	Grassland	6.9	811	MC	N/A	5.3	Calcium oxide (1)	1.8	7	Increased	1
43.12° N, 2.85° W (SP)	Multi- species grassland	10.1	2000	MC	Clay loam	4.6	Calcium carbonate (2.4)	2.4	0.5	1.07	2
				MC	Sandy loam	4.2	Calcium carbonate (4.7)	4.7	0.5	-0.43	2
39.60° S, 176.58° E (NZ)	Ryegrass/clover	13.2	838	MW	Silt loam	5.4	Limestone (0.5)	(0.5)	3	0.23	3
						5.4	Limestone (1)	(1)	3	0.83	3
						5.4	Limestone (2)	(2)	3	0.69	3
						5.4	Limestone (4)	(4)	3	0.63	3
						5.4	Limestone (8)	(8)	3	0.84	3
43.23° N, 7.35° W (SP)	Silvopastoral▲	11.5	1083	MC	Sandy soil	5.2	Calcium carbonate (2.5)	3.4	6	0.24	4
						5.2	Calcium carbonate (2.5)	3.4	6	0.23	4
						5.2	Calcium carbonate (2.5)	3.4	6	0.15	4
49.50° N, 15.96° E (CZ)	Permanent grass	5.8	758	MC	Loamy soil	4.4	Dolomite limestone (1.8)	3.4	2	Decreased	5
27.48° N, 81.91° W (US)	Bahiagrass	17.2	1117	MW	N/A	4.3	Dolomite limestone (1)	1.09	5	No significant effects	6
38.33° S,175.16° E (NZ)	Multi-species grassland	13.8	1502	MW	Loam	5.6	Ground lime (2.5)	2.5	3	-0.49	7
						5.7		2.5	3	0.10	7
						6.2		2.5	3	0.38	7
43.50° N, 20.86° E (RS)	Natural grassland	9.1	1400	MC	N/A	4.1	Hydrated lime (1)	1.36	2	3.22	8
43.15° N, 07.48° W (SP)	Italian ryegrass/clover	19	1019	MC	Sandy loam	4.2	Magnesium limestone (3)	3.27	3	No significant effects	9

25.11º N, 103.48º E (CN)	Ryegrass/white clover	12	1008	MW	Fine loamy soil	4.5-5.4	Quick (or burnt) Limestone (0.5,1, 1.5)	(0.99, 1.79, 2.69)	3	No significant effects	10
55.72º N, 21.45º E (LT)	Cocksfoot/reed canary grass	6-7	518	MC	Loam	4.25-4.85	Calcium carbonate (6)	6	3	Increased	11
43.9º N, 20.31º E (RS)	Red clover/oat grass	12	680	MC	N/A	4.8	Calcium carbonate (3)	3	3	0.38	12
	Red clover/oat grass	12	680	MC	N/A	4.8	Calcium carbonate (6)	6	3	1.25	12
56.55º N, 23.73º E (LV)	Perennial grasses (red clover/ timothy)	5.6	670	MC	Loam	4.7-5.6	Dolomite limestone (2.58, 5.7, 11.4)	(2.81, 6.21, 12.43)	30	0.1	13
15.58º S, 47.70º W (BR)	Green panic grass	22	1230	MW	N/A	4.2	Dolomite limestone (1.6)	3.04	0.75	Increased	14
22.85º S, 48.38º W (BR)	Congo signal grass	26.1	1358	MW	Clayey	4.2	Lime stone (3.8)	3.8	2	1.03	15
36.12º N, 97.07º W (US)	Red clover	17.6	615	MW	Silt loam	4.1-4.7	Calcium carbonate (0.4, 0.7, 1.2, 2.0, 3.7)	(0.4, 0.7, 1.2, 2, 3.7)	3	Increased	16
93.25º N, 12.08º E (NO)	Grass leys	0.7-6.3	728-1708	MC	Multi-soils	5.2-5.54	Dolomite limestone (2.5, 5); Stone meal (2.5, 5)	(2.5, 5)	4	Increased	17
42.09º N, 01.32º W (FR)	Cocksfoot grass	12-13.4	751-1093	MC	Loam	3.9	(Calcium carbonate + Calcium sulphate) (2.37)	2.37	2	2.65	18
42.33º N, 07.86º W (SP)	Multi-species grassland	13	1400	MC	Loam	5.04	Limestone (1.8)	1.8	1	5.39	19
54.46º N, 06.08º W (UK)	Meadow/perennial ryegrass	8.6	1024	MC	Clay loam/silty clay loam	5.8	Ground limestone (0.10, 0.15, 0.23, 0.30)	(0.10; 0.15, 0.23, 0.30)	3	4.0	20
57.78º N, 06.49º W (UK)	Multi-species grassland	8.6	865	MC	Multi-soil types	4.7-5.6	Ground limestone (4,8)	(4, 8)	4	No significant effects	21
37.73º S, 142.01º E (NZ)	Multi-species pasture	14.9	1500	MW	Clay loam	4.6-5.4	Limestone (3)	3	1	2.5	22
								3	1	1.0	22
								3	1	6.2	22

17.45º S, 52.60º W (BR)	Urochloa pasture	28.9	1447	MW	Clay soil	4.7	Dolomite limestone (2)	2.18	2	No significant effects	23
35.38º S, 147.5º E (AU)	Perennial pasture (*Phalaris aquatica L.*)	15.8	500-800	MW	Sandy/clay loam	4-4.2	Limestone (3.3, 4.1)	(3.3, 4.1)	5	0.60	24
	Annual pasture	15.8	500-800	MW	Sandy/clay loam	4-4.2	Limestone (3.3, 4.1)	(3.3, 4.1)	5	0.46	24
35.90º S, 146.93º E (AU)	Perennial/ legume mixture	17.6	630	MW	N/A	4.3	Calcium carbonate (N/A)	N/A	2	Increased	25
29.01º S, 29.86º E (SA)	Italian ryegrass	16	1166	MW	Sandy clay loam	4.1	Dolomite limestone (4, 8, 12)	(7.6, 8.72, 13.1)	2	0.19	26
28.01º S, 50.42º W (BR)	Natural pasture	16.6	1441	MW	Clay	3.9-4.3	Limestone (7.2, 14.4)	7.2	4	0.30	27
								14.4	4	0.10	27
39.60º S, 176.58º E (NZ)	Ryegrass/clover (grazed)	14.3	838	MW	Silt loam	5.4	Limestone (2)	2	6	0.54	28
	Ryegrass/clover (grazed)						Limestone (7.5)	7.5	6	0.10	28
	Ryegrass/clover (cut)	14.3	838	MW	Silt loam	5.4	Limestone (2)	2	6	0.44	28
	Ryegrass/clover (cut)						Limestone (7.5)	7.5	6	0.03	28
39.33º S, 174.28º E (NZ)	Ryegrass/clover (grazed)	12	2000	MW	Sandy loam	5.3	Limestone (0.5)	0.5	4	0.74	29
55.59º N, 2.43º W (UK)	Upland grassland	8.4	716	MC	Loam	4.9	Calcium carbonate (6)	6	4	0.27	30
	Upland grassland	8.4	716	MC	Loam	4.9	Calcium carbonate (6)	6	4	1.23	30
	Upland grassland	8.4	716	MC	Loam	4.9	Calcium carbonate (6)	6	4	3.06	30
	Upland grassland	8.4	716	MC	Loam	4.9	Calcium carbonate (6)	6	4	3.01	30
59.65º N, 10.75º W (NO)	Grassland	5.7	795	MC	N/A	5.2	Dolomite limestone (23)	25.1	4	-0.03	31
	Timothy/Perennial ryegrass/meadow	5.7	795	MC	N/A	5.2	Dolomite limestone (23)	23	4	-0.12	31

	Clover	5.7	795	MC	N/A	5.2	Dolomite limestone (23)	23	4	0.39	31
07.42^{o} N, 38.66^{o} E (ET)	Grass/ herbaceous/ legume/ forb	20.5	825	MW	Clay loam	5.9	Dolomite limestone (7.5)	7.5	5	2.34	32
					Sandy loam	5.9	Dolomite limestone (7.5)	7.5	5	2.50	32
51.97^{o} N, 05.63^{o} W (NL)	Multi- species grassland			MC	Clay	4.9	Dolomite limestone (0.7)	0.7	2	0.94	33

*MAAT= mean annual air temperature. **MAP= mean annual precipitation. Ref. = reference. 1= Hejcman et al. (2010); 2=Mijangos et al. (2010); 3= Morton et al. (2005); 4= Mosquera-Losada et al. (2011); 5= Ryant et al. (2016); 6= Silveira et al. (2012); 7=Toxopeus (1989); 8=Zornic et al. (2019); 9= Viadé et al. (2011); 10= Junquan et al. (2007); 11= Šiaudinis et al. (2014); 12=Tomic et al. (2018); 13= Vigovskis et al. (2016); 14= Braga et al. (2013); 15=Castro and Crusciol (2013); 16= Caddel et al. (2004); 17=Fystro and Bakken (2005); 18=Poozesh et al. (2010); 19= Fernandez-Sanjurjo et al. (2010); 20=Higgins et al. (2012); 21=Adams (1984); 22= During et al. (1984); 23=Da Silva et al. (2018); 24=Li et al.(2006); 25= Hayes et al. (2008); 26= Manson (1995); 27= Prestes et al. (2016); 28= Morton et al. (1998); 29=Thomson (1982); 30=Rangel-Castro et al. (2004); 31=Byers et al. (2021); 32= Bedaso et al. (2021); 33=Berendse et al. (2021). NA= not available. ▲Three N fertilisation rates were applied (0, 200 and 400 kg N/ha).

AU= Australia; BR= Brazil; CH= Switzerland; CN= China; CZ= Czech Republic; DE= Germany; ET= Ethiopia; FR= France; LT= Lithuania; LV= Latvia; NO= Norway; NZ= New Zealand; RS= Serbia; SA= South Africa; SP= Spain; UK= United Kingdom and US= United States of America.

Table 2: Statistical analysis of the impacts of liming (t ha^{-1}) on soil pH and grass dry matter production (t ha^{-1}) under different climatic zones (MC = moist, cool; MW = moist, warm) and number of grass species. N is the number of observations.

	Soil pH	Control (Mean±SD)	Limed (Mean±SD)	N	t-value	p-value
Soil pH	All data	4.93±0.71	5.70±0.84	85	16.36	<0.001
	MC	4.87±0.74	5.56±0.96	55	10.94	<0.001
	MW	5.04±0.66	5.96±0.49	30	14.94	<0.001
	Monoculture grass	4.87±0.67	5.81±0.77	48	13.69	<0.001
	Multi-species grass	5.00±0.77	5.55±0.92	37	4.68	<0.001
Grass dry matter	All data	5.21±2.64	6.18±2.93	63	6.39	<0.001
	MC	4.66±2.12	5.70±2.69	37	3.89	<0.001
	MW	5.99±3.13	6.86±3.17	26	4.45	<0.001
	Monoculture grass	5.49±2.29	6.37±2.67	34	5.66	<0.001
	Multi-species grass	4.88±3.02	5.95±3.24	29	4.31	<0.001

Table 3. Published studies on the impacts of liming grasslands on greenhouse gas (GHG) emissions and soil organic carbon (SOC)

Coordinates (Country)	Grass type	Average N fertiliser (kg ha^{-1})	MAAT* (ºC)	MAP** (mm)	Soil texture	Initial pH	Type/rate of lime (t ha y^{-1})	Calcium carbonate equivalent (t ha^{-1})***	GHG / SOC measured	Duration (year)	Impact on GHG emissions	Mechanism(s) of response	Ref.
48.87°N, 14.22°E (CZ)	*Lolium perenne* and *Phleum pratense*	N/A	7	650	N/A	6.8	N/A	N/A	N_2O	0.8	No significant effects	Increased pH	1
35.38°S, 147.50°E (AU)	Rye grass/ clover	N/A	16.2	570	N/A	<6	N/A	N/A	N_2O	1	No significant effects	Increased pH	2
									N_2O	1	No significant effects	Increased pH	2
									N_2O	1	No significant effects	Increased pH	2
52.28°N, 147.50°W (AU)	Perennial Ryegrass	300	10.4	1037	Loam	5	Ground limestone (1.5)	1.5	N_2O	1	Decrease	Increased pH	3
		300	10.4				Ground limestone (5)	1.5	N_2O	1	Decrease	Increased pH	3
		300	10.4				Ground limestone (5)	1.5	N_2O	1	Decrease	Increased pH	3
59.65°N, 0.75°E (NO)	Perennial Ryegrass, Meadow Grass	140	5.7	795	Clay loam	8.2	Dolomite limestone (23)	25.1	N_2O	<1	Decrease	Increased pH	4
	Red clover/Perennial Ryegrass, Meadow Grass										No significant effects	Increased pH	4
	Red clover										No significant effects	Increased pH	4
51.81°N, 0.36°W (UK)	Mixed grass species.	65-240	9.1	700	Silty clay loam	5.7	Ground/slaked lime (N/A)	N/A	CH_4	>80	Decrease	Increased pH	5

18.48°N, 67.04°W (US)	Guinea grass (*Panicum maximum*)	75	24	1650	clay	4.5	Powder lime (10)	10	CH_4	1.8	No significant effects	Increased pH	6
47.01°N, 92.58°W (US)	Fen dominated by graminoids	N/A	3.2	497	Peaty soil	4.9	Calcium carbonate (N/A)	N/A	CO_2	6 (measurement 6 years after liming)	Decrease net CO_2 flux	Reduced available nutrients	7
51.83°N, 0.42°W (UK)	Grassland (*Festuca rubra L.*)	N/A	9.8	733	Silty clay loam	3.45	Calcium carbonate (15, 25, 53)	15, 25, 53	CO_2	37 (SR^{Δ} measurements 16 year after latest liming)	Increased longer-term CO_2	Increased pH; indirectly increased primary production substrate	8
51.98°N, 0.58°W (UK)	Grassland (*Lolium multiflorum L.*)	N/A	9.6	642	Sandy loam	3.7	Calcium carbonate (9, 25, 45)	9, 25, 45	CO_2	37 (in 4 steps; SR measurements 16 years after latest liming)	Increased longer-term CO_2	Increased pH; indirectly: increased primary production substrate	8
45.63°N, 2.73°E (FR)	Upland grassland	100	7.8	1094	Silty clay loam	5.2	Calcimer T400 (1.2)	1.2	CO_2	2.5 (twice, SR measurements 6 months after latest liming)	No significant effects	Increased soil pH.	9
37.72°S, 145.05°E (AU)	Unimproved pasture▲	0	14.8	666	Clay soil	4.8	Limestone (3 , 12.5 , 25)	3, 12.5, 25	CO_2	5 and 34 (SR measurements at 5 and 34 years	Increased basal CO_2	Increased pH; slow downward movement of alkalinity.	10

										after latest liming)			
37.71° S, 145.04° E (AU)	Unimproved pasture	N/A	14.8	666	Silty	4.8	Limestone (3, 12.5, 25)	3, 12.5, 25	SOC	1	No significant effects	Increased plant biomass & thereby, offset faster mineralization	11
55.47° N, 2.24° W (UK)	Acid upland grassland	N/A	7.5	995	Sandy silt loam	4.9	Calcium carbonate (6)	6	SOC	1	Decrease	Increased soil pH	12
55.47° N, 2.24° W (UK)	Acid upland grassland	N/A	7.5	995	Sandy silt loam	4.9	Calcium carbonate (6)	6	SOC	1	No significant effects	Increased soil pH; influenced microbial composition.	13
51.41° N, 0.64° W (UK)	Grassland	100	9.6	754	Sandy	4.8	Calcium carbonate (5 every 5 to 10 yr)	5	SOC	1	No significant effects	Increased soil pH.	14
55.47° N, 2.24° W (UK)	Acid upland grassland	N/A	7.5	995	Sandy silt loam	3.7	Calcium carbonate (6)	6	SOC	0.5	Decrease	Increased soil pH.	15
51.80° N, 0.37° W (UK)	Permanent pasture	N/A	10.4	733	Silty clay loam	3.6-6.1	Calcium carbonate (N/A)	N/A	SOC	129	Decrease	Increased soil pH	16
37.70° S, 142.11° E (AU)	Permanent pasture	N/A	13.4	684	Clay loam	4.56	Calcium carbonate (N/A)	N/A	SOC	1	Decrease	Increased soil pH	17
43.15°N, 7.33° W (SP)	Silvopastoral system	N/A	12	1222.3	Sandy loam	5.2	Calcium carbonate (2.5)	2.5	SOC	1	Decrease	Increased soil pH	18
37.70° S, 145.03° E (AU)	Unmanaged pasture	N/A	14.8	645	N/A	4.3-5	Calcium carbonate (12.5, 25)	12.5, 25	SOC	1	Decrease	Increased soil pH	19

50.22° S, 06.85° E (DE)	Permanent grassland	100	6.9	811	Pseudo gley	5.3	Calcium hydroxide (N/A)	N/A	SOC	70	Increase	Increased soil pH.	20
46.63° N, 07.85° E (CH)	Subalpine grassland	N/A	14.8	1338	N/A	4.5	Calcium carbonate (0.8)	0.8	SOC	4	Decrease	Increased microbial activities.	21
31.25° S, 146.92° E (AU)	Perennial pasture	N/A	12	645	N/A	N/A	Limestone (2.5)	2.5	SOC	10-35	Decrease	Increased microbial decomposition.	22
51.83° N, 0.42° W (UK)	Grassland (red fescue)	N/A	13.7	649	Silty clay loam	3.5-7	Calcium carbonate (15, 25, 53)	15, 25, 53	SOC	21	Decrease	Increased microbial decomposition.	23
52.00° N, 0.42° W (UK)	Grassland (Italian ryegrass)	N/A	10.3	696	Sandy loam	3.7-6.1	Calcium carbonate (9, 25, 45)	9, 25, 45	SOC	21	Decrease	Increased microbial decomposition.	23
552.29° N, 2.14° W (UK)	Upland grassland	N/A	8	964	Brown soil	3.3	Calcium carbonate (6)	6	SOC	6	No significant effects	Increased soil pH	24

*MAAT= mean annual air temperature. **MAP= mean annual precipitation. $^{\Delta}$Soil respiration. Ref. = reference. 1=Cuhel et al. (2010); 2=Galbally et al. (2010); 3=Zurovec et al. (2021); 4=Byers et al. (2021); 5= Stiehl-Braun et al. (2011); 6= Mosier et al. (1998); 7= Keller et al. (2005); 8= Kemmitt et al. (2006); 9= Lochon et al. (2019); 10= Aye et al. 2016; 11= Aye et al. (2016); 12=Rangel-Castro et al. (2004); 13=Rangel-Castro et al. (2005);14=Egan et al. (2018); 15= Foereid et al. (2006); 16=Fornara et al. (2011);17= Grover et al. (2017); 18=Mosquera-Losada et al. (2011); 19=Wang et al. (2016); 20= Sochorova et al. (2016); 21=Schaffner et al. (2012); 22=Orgill et al. (2015); 23=Kemmitt et al. (2006); 24= Grieve et al. (2005). NA = not available. ▲grassland have never been ploughed, reseeded or heavily fertilised.
AU= Australia; CH= Switzerland; CZ= Czech Republic; DE= Germany; FR= France; NO= Norway; SP= Spain; UK= United Kingdom and US= United States of America

Figures

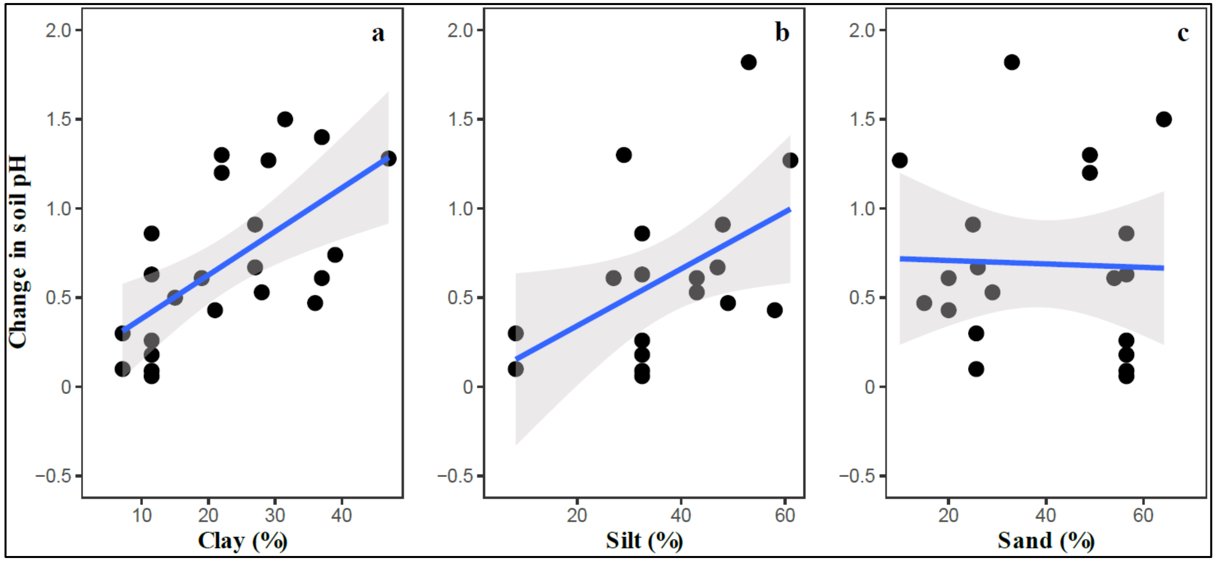

Fig. 1: Relationships between soil pH and clay (a) silt (b) and sand (c) contents. Clay was positively correlated with changes in pH ($t = 3.69$, $p<0.01$, $R^2 = 0.39$, $n = 23$). Silt was positively correlated with changes in pH ($t = 2.27$, $p<0.05$, $R^2 = 0.24$, $n = 18$). Sand was not significantly correlated with the changes in pH ($t = -0.14$, $p>0.05$, $R^2 = 0.001$, $n = 20$).

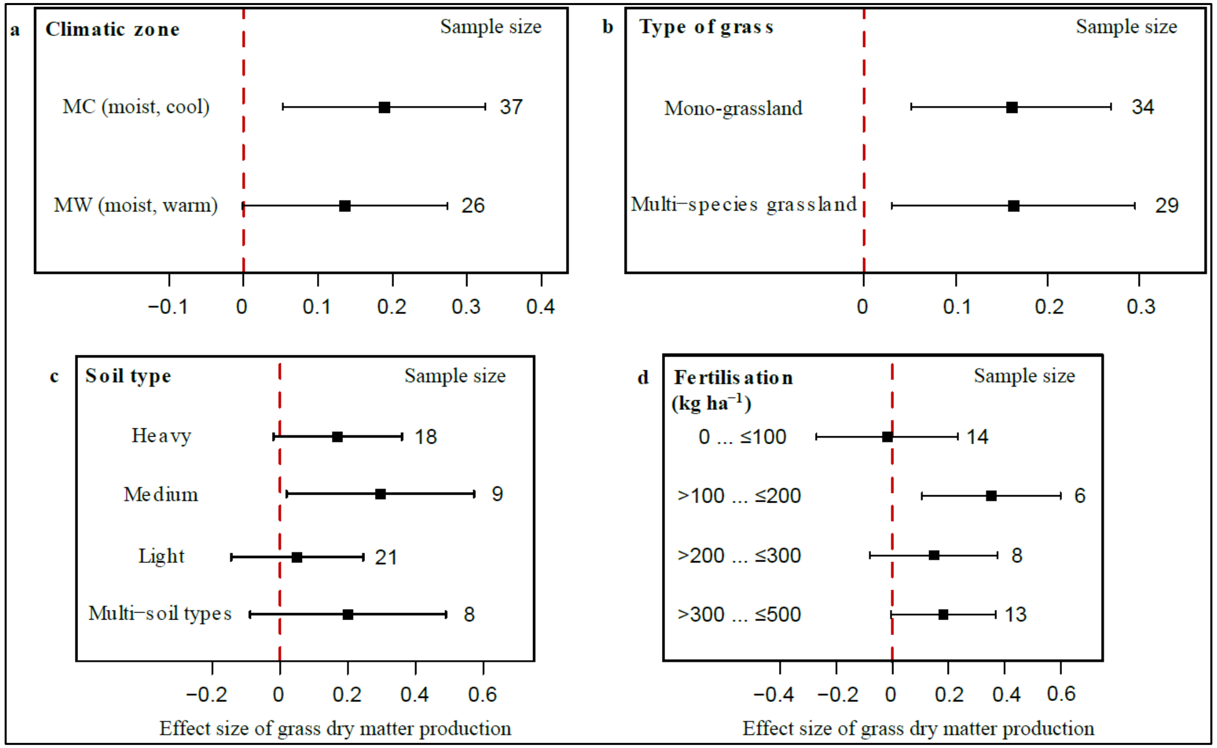

Fig. 2: Responses of grass dry matter production to liming in the different climatic zones (a), number of species (b), soil types (c) and amounts of fertilisation (d). Effect size stands for the response ratio between treatment and control. Bars represent the 95% confidence intervals. The number of observations of each variable is noted beside the bar. Response ratio ± 95% confidence intervals do not overlap 0 means $p<0.05$.

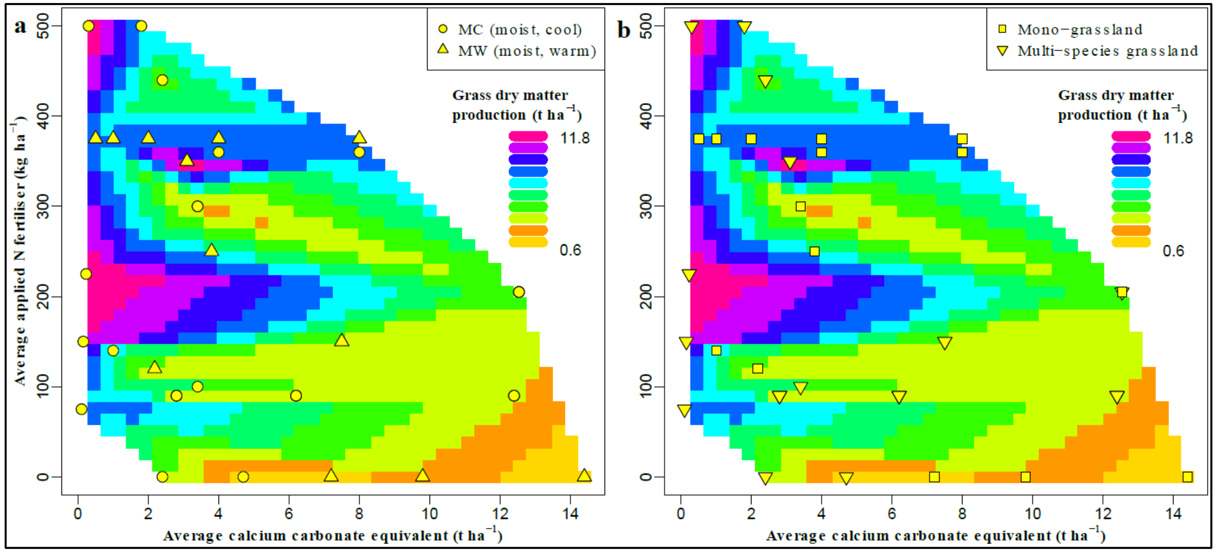

Fig. 3: Contour plots showing relationships between calcium carbonate equivalent, applied N fertiliser and grass dry matter production (a) in different climate zones and (b) different grassland types. Calcium carbonate equivalent and applied N fertiliser explain 42.3% of overall grass dry matter variations (n = 45, p<0.001); the grass dry matter correlated significantly with calcium carbonate equivalent (t = −2.2; p<0.05) and applied N fertiliser (t = 3.9; p<0.001).

Fig. 4: Aerial picture of the Park Grass Experiment in 2005 showing plot boundaries due to differences in fertiliser treatments producing different vegetation (top left); differences in the type and number of plant species (top right and bottom right) due to the different N fertiliser and lime combinations. Plots with lime show more plant species. The bottom left picture shows sub-plots a, b, c and d. Ground chalk has been applied as necessary to maintain soil pH (0-23cm) for sub-plots a (pH 7), b (pH 6) and c (pH 5), respectively. Sub-plot d received no chalk.

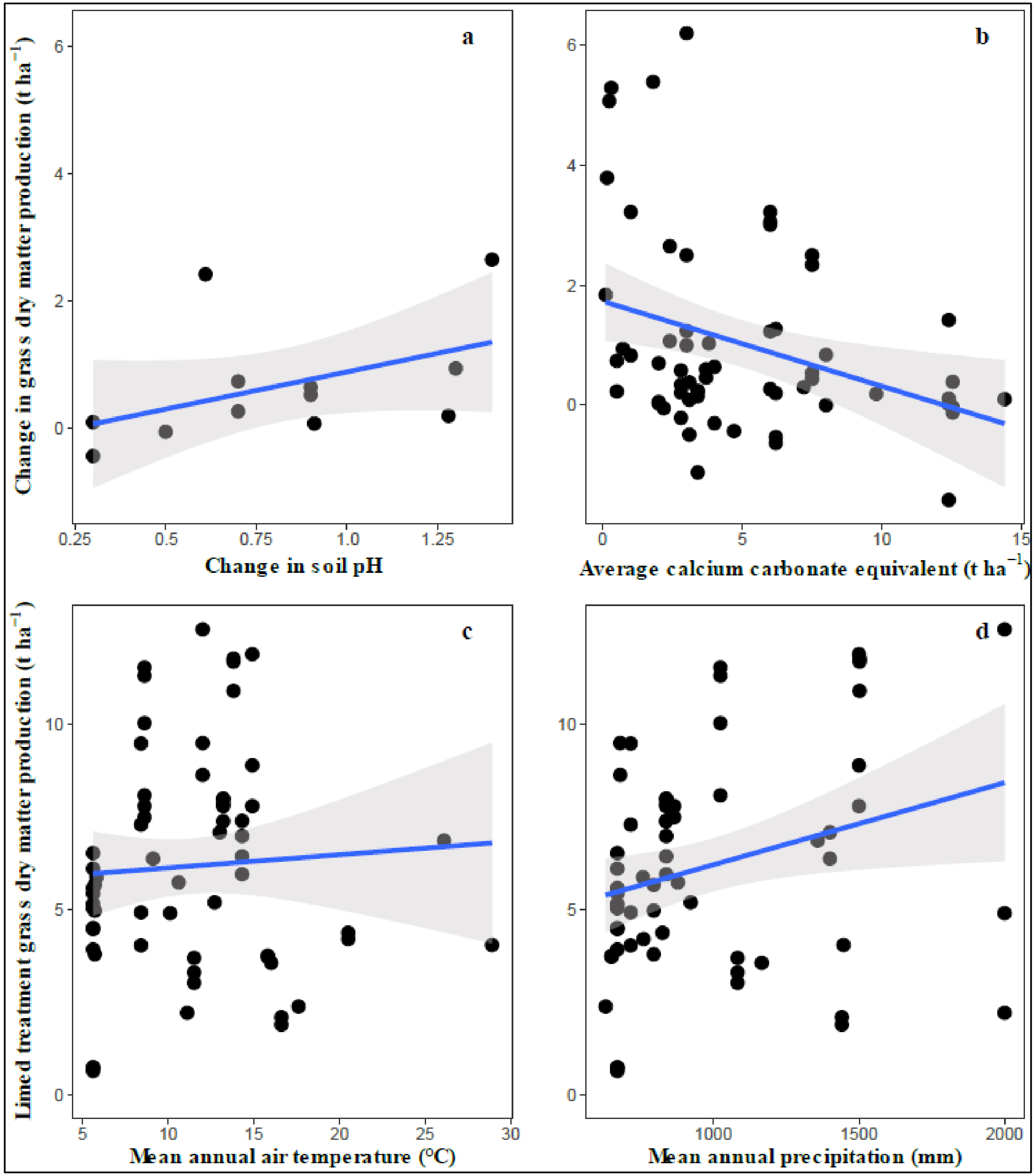
a
b
c
d
Change in grass dry matter production (t ha^{-1})
Limed treatment grass dry matter production (t ha^{-1})
6
4
2
0
10
5
0
0.25
0.5
0.75
1.0
1.25
Change in soil pH
0
5
10
15
Average calcium carbonate equivalent (t ha^{-1})
5
10
15
20
25
30
Mean annual air temperature (°C)
1000
1500
2000
Mean annual precipitation (mm)

Fig. 5: Relationships between grass dry matter production and change in soil pH (a); amounts of lime in calcium carbonate equivalent (b); mean annual air temperature (c); and mean annual precipitation (d). Change in soil pH was positively correlated with change in grass dry matter production ($t = 1.62$, $p = 0.134$, $R^2 = 0.21$, $n = 12$). Calcium carbonate equivalent was negatively correlated with change in grass dry matter production ($t = -2.71$, $p<0.01$, $R^2 = 0.11$, $n = 62$). Three outliers were removed in each case. Mean annual air temperature was not significantly correlated with the dry grass matter production ($p>0.05$, $n=63$). Mean annual precipitation was positively correlated with grass dry matter production ($t=2.3$, $R^2=0.08$, $p<0.05$, $n=63$).