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– effect on N_2O emissions in a life cycle perspective

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Climate impact of liming arable soil – effect on N2O emissions in a life cycle perspective
Klimatpåverkan från kalkning av jordbruksmark – effekt på N2O-utsläpp i ett livscykelperspektiv

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The overarching vision of the programme Mistra Food Futures is to create a science-based platform to enable transformation of the Swedish food system into one that is sustainable (in all three dimensions: environmental, economic and social), resilient and delivers healthy diets. By taking a holistic perspective and addressing issues related to agriculture and food production, as well as processing, consumption and retail, Mistra Food Futures aims to play a key role in initiating an evidence based sustainability (including environmental, economic and social dimensions) and resilience transformation of the Swedish food system. This report is a part of Mistra Food Future's work to identify agricultural systems with potential to make agriculture net-zero, one of the central issues within Mistra Food Futures.

Mistra Food Futures is a transdisciplinary consortium where key scientific perspectives are combined and integrated, and where the scientific process is developed in close collaboration with non-academic partners from all parts of the food system. Core consortium partners are Swedish University of Agricultural Sciences (SLU), Stockholm Resilience Centre at Stockholm University and RISE Research Institutes of Sweden.

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Abstract

Agricultural soils are limed primarily to maintain high yields. Limed soils, with higher pH, often have lower emissions of the strong greenhouse gas nitrous oxide (N_2O), but also increased emissions of soil CO_2.

In this study, data from the long-term Ultuna outdoor frame trials were used to estimate the impact of increasing pH on agricultural soils, by comparing treatments with higher soil pH (7.2, representing liming) and lower pH (6.6). Climate impact was calculated in a life cycle perspective up to farm gate, meaning that impacts from producing inputs and field emissions were included. Measured field data were used to estimate effects on soil N_2O emissions. In addition, three existing empirical models for estimating soil N_2O emissions were applied.

Field data from the Ultuna trials showed that soil N_2O emissions from the treatment with higher soil pH were 71% lower than those from the treatment with lower soil pH. Assessed in a life cycle perspective, the results indicated that liming to increase soil pH can decrease the overall climate impact from crop production, by around 28% in this case. The reduction was mainly due to lower soil N_2O, but also increased soil organic carbon content. The climate impact from production and application of additional lime needed to maintain the higher soil pH was around 10% of the total climate impact assessed on a per-hectare basis.

Different models for estimating soil N_2O gave very different results, illustrating the uncertainty in estimates, which is crucial to consider in interpretation of results. The contribution of soil N_2O emissions to the overall climate impact varied between 18% and 43%, depending on the model used to estimate N_2O emissions. Model development is needed to enable more accurate estimation of N_2O emissions and more accurate prediction of the effects of management changes on soil N_2O.

Keywords: Soil pH, life cycle assessment, empirical models for soil N_2O.

Table of contents

1. Introduction

Agriculture accounts for 70% of anthropogenic nitrous oxide (N_2O) emissions, and increasing usage of nitrogen fertilizers and manure is a major source of increasing emissions of N_2O to the atmosphere (Tian *et al.*, 2020). Mineral nitrogen fertilizers are a critical input in arable farming, as they enhance crop growth and increase crop yield. On the other hand, applying nitrogen fertilizers can have an acidifying effect on the soil, with ammonium-based fertilizers, urea, and elemental sulfur fertilizer being the most important causes of acidification in agricultural soils (Goulding, 2016). Soil acidification has various adverse effects on soil microorganisms and plant growth, including loss of base cations such as calcium, magnesium, and potassium, leading to nutrient deficiencies, increased aluminium saturation, manganese and iron toxicity, lower bioavailability of plant nutrients, and reduced crop yield (Kunhikrishnan *et al.*, 2016).

Adding lime materials to agricultural soils is the most widely used and effective practice to neutralize soil pH and counteract the problems associated with soil acidification (Paradelo *et al.*, 2015). The benefits of liming include improved soil aggregate stability, reduced loss of plant nutrients, and enhanced immobilization of toxic heavy metals (Blomquist *et al.*, 2018; Kunhikrishnan *et al.*, 2016). Moreover, because liming affects soil carbon and nitrogen cycles, net greenhouse gas (GHG) emissions from soil are also changed. In efforts in recent decades to mitigate climate change from the agricultural sector, reducing N_2O emissions via liming has attracted much research interest (Wang *et al.*, 2018). Despite some inconsistent results, many field-based studies indicate that liming can reduce N_2O emissions from acidic soils. For example, managing soil pH has been found to have potential to decrease total N_2O emissions by 15.7% in France (Hénault *et al.*, 2019). Globally, a meta-analysis has shown that liming can reduce soil N_2O emissions by 21.5%, in addition to significantly increasing crop yield by 36.3% and soil organic carbon stocks by 4.5% annually, but while also increasing soil carbon dioxide (CO_2) emissions by 7.6% (Wang *et al.*, 2021b). Increased crop yield through soil liming has also been reported in another meta-analysis, where the increment in crop yield ranged from 13.2% to 66.5% depending on the lime material used (Li *et al.*, 2019). Despite these benefits, liming of acidic soils has not been scaled up due to economic and other constraints.

Many experiments have been conducted to evaluate how liming affects the microbial processes contributing to N_2O production in soil. N_2O is primarily produced within microbe-mediated nitrification and denitrification processes (Hénault *et al.*, 2019). Ammonia (NH_3) or ammonium (NH_4^+) is oxidized to nitrite (NO_2^-), and then to nitrate (NO_3^-), under aerobic conditions in the nitrification process, where N_2O is produced as a by-product. In contrast, denitrification, which reduces nitrate sequentially to nitrite, nitric oxide (NO), nitrous oxide (N_2O), and eventually to dinitrogen (N_2), mainly occurs under anaerobic conditions (Butterbach-Bahl & Dannenmann, 2011). Secondary N_2O emissions derive from nitrate leaching and ammonia volatilization (Hergoualc'h *et al.*, 2019). These processes are affected by various biotic and abiotic factors, with soil pH being one of main factors exerting a strong influence on nitrifier and denitrifier populations (responsible for nitrification and denitrification, respectively) and net N_2O emissions from soils (Baggs *et al.*, 2010). Specifically, liming of acidic soils can shift the dominant microbial N_2O source from nitrification to denitrification in short term, with unchanged magnitude of total N_2O emissions (Baggs *et al.*, 2010). On the other hand, N_2O emissions can be lowered in the long term because high pH favors synthesis and activation of N_2O reductase, which catalyses the reduction from N_2O to inert N_2 in denitrification (Abalos *et al.*, 2020; Nadeem *et al.*, 2020).

Various methods have been developed to estimate N_2O emissions from crop production systems in different climate zones, under different soil conditions, and from different soil management activities. Simple approaches, such as the emissions factors used in IPCC Tier 1 and Tier 2 methods, are often applied in estimating N_2O emissions over large areas. In addition, empirical relationships between N_2O emissions and nitrogen inputs have been established for different soil types and climate conditions, allowing emissions to be estimated based on minimal input data (Rochette *et al.*, 2018; Shcherbak *et al.*, 2014; Sozanska *et al.*, 2002). Process-based models (such as the DNDC model) can simulate complex soil processes with environmental data and management activities, but the many input parameters required limit the usage of processed-based models when scaling up over larger geographical areas (Goglio *et al.*, 2018; Chen *et al.*, 2008). Considering that N_2O emissions are highly variable both spatially and temporally (Hénault *et al.*, 2012), it is still unclear whether the emissions factor-based approach and empirical regressions can accurately predict the effect of liming on N_2O emissions from acidic soils.

Despite accumulating evidence of liming reducing N_2O emissions, few previous assessments on the net balance of GHG have considered crop yield, changes in soil carbon stock, stimulated CO_2 emissions, enhanced CH_4 sink, lime production, and other farm inputs (Wang *et al.*, 2021a). Rather than simply assessing the effect of liming on N_2O emissions from acidic soils, holistic approaches such as life cycle assessment (LCA) are needed to evaluate the total carbon footprint of liming in crop production systems (Paradelo *et al.*, 2015).

Many Swedish soils have suboptimal pH values for plant production, and liming is a common practice to rectify this (Kirchmann *et al.*, 2020). Therefore the effectiveness of liming in reducing the climate impact of crop production in a Swedish climate and for Swedish soils needs to be assessed.

In this study, we used data from a long-term experiment (the Ultuna outdoor frame trials, see Figure 1) (Kätterer *et al.*, 2011) as a case to evaluate the accuracy of different methods for calculating the total carbon footprint of corn silage production. Because of long-term treatment with different types of fertilizers and organic amendments since 1956, gradients of pH and soil organic carbon have been created in the frame trials. In 2019, the trial was equipped with state-of-the-art automatic devices (automatic gas exchange chambers, Picarro instruments for measuring CO_2, methane (CH_4), and N_2O gases, and sensors for soil temperature and moisture) for measuring N_2O fluxes continuously at high time resolution in frame plots with different pH values. Combined with measured data on corn yield, this dataset provides opportunities to assess the climate impact of raising soil pH by liming.

2. Aim

The aim of the study was to estimate the climate impact in a life cycle perspective of increasing pH in arable soils, as achieved by liming. The specific objective was to estimate effects on N_2O emissions and crop yield and on field operations and input demand. An additional objective was to compare three existing empirical models for estimating N_2O emissions from arable soil when assessing the impact of altering soil pH.

3. Method

3.1. System description

The climate impact in a life cycle perspective of two different treatments in corn cultivation was studied. These treatments were:

1. 'High pH', representing a case where the soil pH is kept high by liming.
2. 'Low pH', representing a case where no liming is done.

Data on soil N_2O emissions, corn yield, pH, and total soil carbon were obtained from the Ultuna long-term frame trials, where corn (*Zea mays*) has been cultivated continuously since the year 2000 (Figure 1). The trials and data used are described in section 3.2 of this report. In addition to field data on measured N_2O emissions, N_2O emissions were estimated using three existing empirical models for calculating soil N_2O emissions based on mineral fertilizer use in arable cropping. These methods are further explained in section 3.3.

The following processes were included in the life cycle climate impact assessment: Production of nitrogen (N), phosphorus (P), and potassium (K) fertilizers, production of lime, diesel use, and machinery use in field operations. Soil organic carbon (SOC) effects were also included, as were emissions of CO_2 and N_2O from soil. The corn was harvested as whole-crop silage. The flowing functional units used were 1 ha and 1 kg dry matter (DM) harvested.

Figure 1. Corn growing in the Ultuna frame trials (photo: Thomas Kätterer, September 2010).

3.2. Inventory analysis

3.2.1. Use of field trial data

Crop yield (whole crop), N_2O emissions, nitrogen fertilization rate (80 kg N/ha) and pH values were based on values measured in different treatments in the Ultuna frame trials, where forage corn has been cultivated since the year 2000 (Table 1). Treatments involving different types of mineral nitrogen fertilizers have resulted in differences in soil pH in different frame plots over time (Kätterer *et al.*, 2011). In this study, data from plots in a treatment fertilized with calcium cyanamide (soil pH around 7.2, denoted 'high pH') were used to replicate a situation where lime is applied to increase pH. Calcium cyanamide ($CaCN_2$) is commercially known as nitrolime, since it reacts with soil CO_2 during hydrolysis to form cyanamide (CN_2H_2) and bicarbonate (HCO_3^-). Calcium cyanamide was not considered in the climate impact calculations, and instead lime ($CaCO_3$) was assumed to be applied to maintain high soil pH. A treatment fertilized with calcium nitrate $Ca(NO_3)_2$, (soil pH around 6.6, denoted 'low pH') was used to represent a situation with unlimed soil at the same site (Table 1).

To estimate annual N_2O emissions, the difference between the two treatments was used. This is because many low fluxes were filtered out in determining the fluxes from the regression between N_2O concentration and chamber closure time, and aggregating the fluxes with high values resulted in overestimation of the annual emissions. Annual N_2O emissions in the low pH (no liming) treatment were calculated using the IPCC methodology (wet climate) for estimating soil N_2O emissions. Annual emissions in the high pH (liming) treatment were assumed to be 71% lower than in the low pH treatment, based on the relative difference in measured values.

The N_2O emissions in the low pH (calcium nitrate-fertilized) treatment showed clear seasonality, while those in the high pH (calcium cyanamide-fertilized) treatment were low throughout the growing season. High emissions after fertilization were not observed in these two treatments, due to dry soil conditions at the time of fertilizer application. For the low pH treatment, N_2O emissions became high in late summer and autumn, especially after heavy rain events, suggesting denitrification as the main source of emitted N_2O.

Table 1. Data from the Ultuna frame trial (year 2020 values) used in the present study (source: Lang *et al.*, 2022)

Treatment	Fertilizer[a]	N_2O flux (nmol m^{-2} s^{-1})	Corn biomass (kg DM ha^{-1})	pH	Total C (%)
Liming: High pH	$CaCN_2$	28.5±10.1	4029±339	7.2±0.1	1.37±0.04
No liming: Low pH	$Ca(NO_3)_2$	99.6±23.5	3694±934	6.6±0.1	1.9±0.02

[a]Fertilizer used in the frame trial. In climate impact assessments, it was assumed that both treatments were fertilized with calcium nitrate ($Ca(NO_3)_2$).

The difference in SOC content between the treatments was included by accounting for the higher SOC in the high pH treatment as SOC sequestration over 53 years (difference in SOC from 1956 to 2009 was 1.1 ton/ha) (Kätterer *et al.*, 2011).

3.2.2. Climate impact of inputs

The emissions inventory for nitrogen (calcium nitrate), phosphorus (triple superphosphate, $Ca(H_2PO_4)_2$), and potassium (potassium chloride, KCl) fertilizer production was taken from Biograce (2015). The field operations included in the analysis were: ploughing, harrowing, sowing, fertilizer application, pesticide application, chopping the fresh corn biomass, and loading onto a self-loading trailer. Data on fuel use for ploughing, harrowing, sowing, fertilizer application, and pesticide application were taken from Lindgren *et al.* (2002) and data on emissions from fuel production and combustion from Gode *et al.* (2011). Data on emissions from chopping the corn and loading onto the self-loading trailer, and on lime production, were taken from the ecoinvent database version 3.9 (Wernet *et al.*, 2016). For the high pH (liming) treatment, an additional field operation for lime application was added, and the emissions were assumed to be the same as for fertilizer application.

Nitrogen fertilizer rates were based on the actual application rates in the Uppsala frame trials (Lang *et al.*, 2022), while phosphorus and potassium fertilization rates were estimated as the amount removed with the harvest. Data on phosphorus and potassium content in whole-crop corn biomass were taken from Feedipedia (2016) (Table 2).

Quantities of lime needed to increase pH, and to maintain pH

It was estimated that 3.5 tonnes of quicklime (CaO) per hectare were needed to increase the soil pH by 0.5 units (Jordbruksverket, 2021). The difference in pH between the high and low pH treatments was 0.6 units, meaning that 4.2 tons of CaO (corresponding to 8.4 tonnes of lime) per hectare would be needed in a single liming event to increase soil pH to the level in the high pH treatment. The climate impact from lime production and application in this single event was distributed over 100 years (84 kg per year). For maintaining the higher soil pH (0.6 pH units higher), it was assumed that annual addition of 128 kg of lime per hectare was needed (Table 2). This was calculated as the difference between the liming effect of the two fertilizers used in the frame trials, i.e., cyanamide with a liming effect of 1.5 kg CaO/kg N (Nilsson, 2014) and calcium nitrate with a liming effect of 0.7 kg CaO/kg N (Jordbruksverket, 2022). The yearly lime dose was therefore assumed to be 128 kg per hectare, and can be seen as the difference in amount of lime needed to maintain the higher pH when using these two fertilizer types. If the plots were fertilised with e.g., the commonly used ammonium nitrate (NH_4NO_3), more lime would have to be added to increase and maintain pH in both treatments.

Table 2. Inputs of fertilizers and lime in the high pH and low pH treatments

	N (kg/ha)	P (kg/ha)	K (kg/ha)	Lime (kg/ha)
High pH (liming)	80	8.5	64	128+84
Low pH (no liming)	80	7.8	58	

CO_2 emissions from lime application

The CO_2 emissions from lime application was calculated using the IPCC Tier 1 method, with the emissions factor for limestone ($CaCO_3$) (0.12) (IPCC, 2006).

3.2.3. Methods for estimating soil N_2O emissions

As explained above, soil N_2O emissions were estimated using the IPCC method (emissions factor for wet climates) (Hergoualc'h *et al.*, 2019) for the low pH treatment, while N_2O emissions from the high pH treatment was estimated as the relative difference between the treatments measured in the Uppsala frame trials (Lang *et al.*, 2022). For comparison, the IPCC generic emissions factors and the emissions factor for wet climates were also applied without adjustments according to the frame trials.

In addition, three existing empirical methods for estimating soil N_2O emissions were applied:

i) A non-linear model of N_2O emissions in response to nitrogen fertilizer application based on a global dataset (Shcherbak *et al.*, 2014). Annual N_2O emissions were estimated using the equation for all crops (excluding nitrogen-fixing crops) as:

$$Emis = (6.58 + 0.0181N)N$$

where Emis is emissions in grams N_2O-N per hectare, and N is nitrogen inputs in kg per hectare (Shcherbak *et al.*, 2014).

ii) A method presented in Rochette *et al.* (2018) based on Canadian data. The equation for cumulative N_2O emissions and for mineral nitrogen fertilizer application (equation 1 in Rochette *et al.* (2018)) was applied:

$$N_2OCUMmin = e^{3.91+0.002P+0.0069MinN-0.0032SAND-0.747pH+0.097T_{air}}$$

where $N_2OCUMmin$ is cumulative N_2O emissions from synthetic nitrogen use, P is precipitation during the growing season (May to October) in mm, MinN is the amount of synthetic nitrogen applied in kg N per hectare, SAND is soil sand content in grams per kilogram, pH is soil pH, and T_{air} is mean annual air temperature in ºC (Rochette *et al.*, 2018). The values used for pH and synthetic mineral fertilizer rate can be found in Table 1. For precipitation and temperature, data from 2019 were used, where precipitation during the growing season was 445 mm and mean annual temperature was 7.44 ºC. The sand content at the frame trial site is 225 grams per kilogram (Kätterer *et al.*, 2011).

iii) A method developed by Eagle *et al.* (2020) where soil N_2O emissions are determined as a function of a simple nitrogen balance (i.e., nitrogen in fertilizer minus nitrogen in yield), called the partial nitrogen balance (PNB) (equation 2 in Eagle *et al.* (2020)):

$$N_2O = e^{0.339+0.0047PNB}$$

where N_2O is cumulative N_2O emissions in kg N_2O per hectare and PNB is the annual partial nitrogen balance in kg N per hectare. The empirical data used in the study by Eagle *et al.* (2020) were for annual field crops grown in the temperate region, and originated from field studies mainly in northern USA and northern Europe.

In addition to applying the PNB equation, we also adjusted N_2O by 3% for every 0.1% increment in soil C content between the treatments (Eagle *et al.*, 2020). The soil C content was 1.37% in the high pH treatment and 1.29% in the low pH trial (Lang *et al.*, 2022). The model developed by Eagle *et al.* (2020) also includes adjustment factors for number of samplings and number of precipitation events. However, precipitation was assumed to be the same for the two treatments, as they are located at the same site.

3.2.4. Indirect N_2O emissions

In all climate impact calculations, indirect N_2O emissions were included based on the IPCC method (Hergoualc'h *et al.*, 2019). Nitrogen leaching was estimated to be 24% of nitrogen added, while volatilization was assumed to be 5% of nitrogen added (Hergoualc'h *et al.*, 2019). Emissions factors (EFs) used were: 1% (wet climate) and 1.6% (general EF) (Hergoualc'h *et al.*, 2019).

4. Results

4.1. N_2O emissions from soil

Soil N_2O emissions per hectare and per kg DM estimated with the different methods are shown in Figure 2 and 3, respectively. When adjusted for the difference in N_2O emissions found in field measurements (Lang *et al.*, 2022), there was a large difference between the treatments (Figure 2). Per-hectare N_2O emissions (Figure 2), estimated with the commonly used IPCC method, were estimated to be slightly higher for the high pH (liming) treatment, which was due to the higher yield in that treatment (see Table 1) leading to more crop residues.

Among the different methods applied for estimating soil N_2O emissions, only the method of Rochette *et al.* (2018) includes the effects of pH. In the present analysis, that method estimated 36% lower N_2O emissions for the high pH (liming) treatment. Applying the method of Eagle *et al.* (2020) resulted in somewhat lower N_2O emissions for the high pH treatment, due to the higher yield giving a lower nitrogen balance (less nitrogen left in the field). However, when adjusted for soil carbon, using the method of Eagle *et al.* (2020) gave approximately 22% higher estimated N_2O emissions from soil in the high pH treatment, due to the higher SOC content in that treatment.

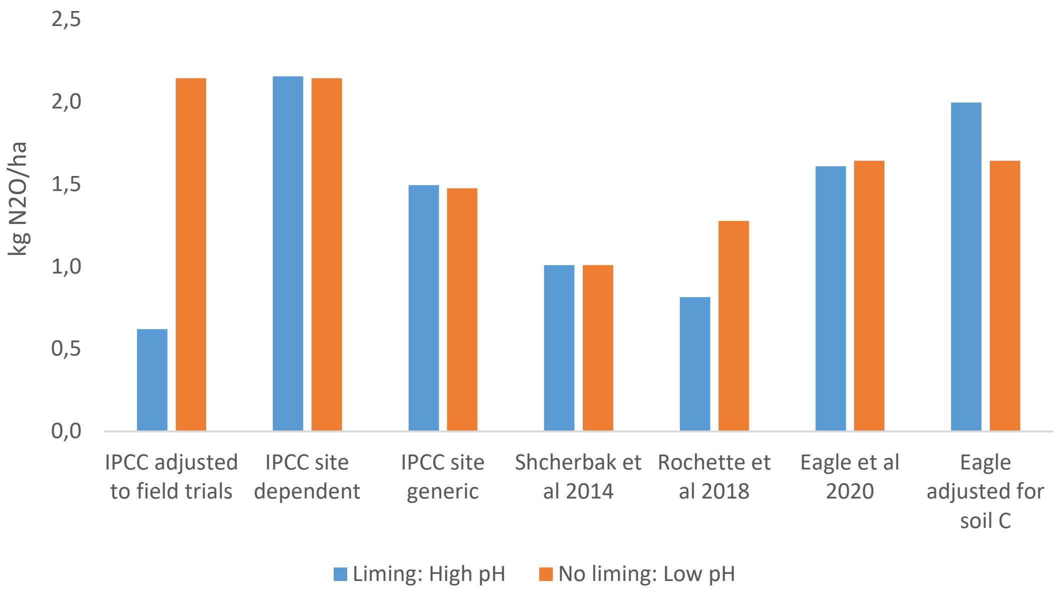

Figure 2. Nitrous oxide (N_2O) emissions from soil in the high pH (liming) and low pH (no liming) treatments, estimated using different methods.

The higher yield in the high pH treatment generally resulted in a larger difference in soil N_2O emissions between the treatments when calculated per kg DM (Figure 3). For the IPCC method, the higher yield resulted in the high pH treatment having lower N_2O emissions than the low pH treatment, i.e., the reverse of the per-hectare results. The reason is that the high pH treatment had higher yield.

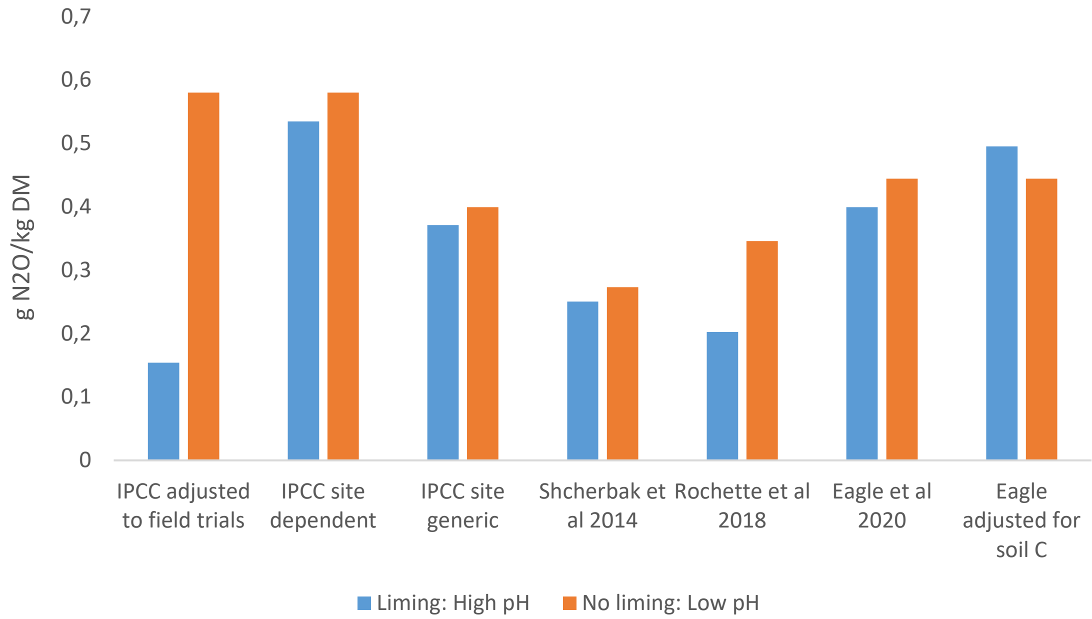

Figure 3. Soil nitrous oxide (N_2O) emissions per kg dry matter (DM) in the high pH (liming) and low pH (no liming) treatments, estimated using different methods.

4.2. Climate impact

Overall climate impact per hectare and per kg DM for the two treatments according to the different methods to estimate N_2O emissions are shown in Figures 4 and 5, respectively. Impacts from mineral fertilizers were the same for the two treatments, but impacts from field operations varied slightly due to the higher yield in the high pH (liming) treatment (which required more fuel during harvesting).

The effects of liming on the climate impact of corn cultivation primarily comprised soil CO_2 emissions from lime application, which were estimated to be around 93 kg per hectare (approximately 10% of the total per-hectare climate impact) (Figure 4). The climate impact from lime production was only about 5 kg CO_2e per hectare and year, which represented around 1% of the impact from all inputs into corn cultivation, including field operations. The reduction in N_2O emissions in the high pH treatment exceeded the increase in emissions of CO_2 from soil and emissions from lime production. The reduction in N_2O emissions, combined with the increase in SOC, resulted in the overall climate impact of the high pH (liming) treatment being around 28% lower than that in the low pH treatment

(Figure 4). Combined with the somewhat higher yield in the treatment with higher pH, the per-kg DM results showed a slightly greater difference between the treatments (Figure 5).

In general, direct N_2O emissions from soil were an important contributor to the overall climate impact, representing 18-43% of the overall impact. The range of climate impact values obtained clearly demonstrates that using different methods to estimate N_2O emissions from soil can give very different results for total climate impact. Since N_2O emissions generally dominate in overall climate impact assessments, differences in estimated values will be decisive for the outcome in such assessments.

Indirect N_2O emissions were estimated to be 114 kg CO_2e per hectare using the IPCC EF for wet climates, and 107 kg CO_2e per hectare using the generic IPCC factors. These values represented 9-13% of the total climate impact per hectare.

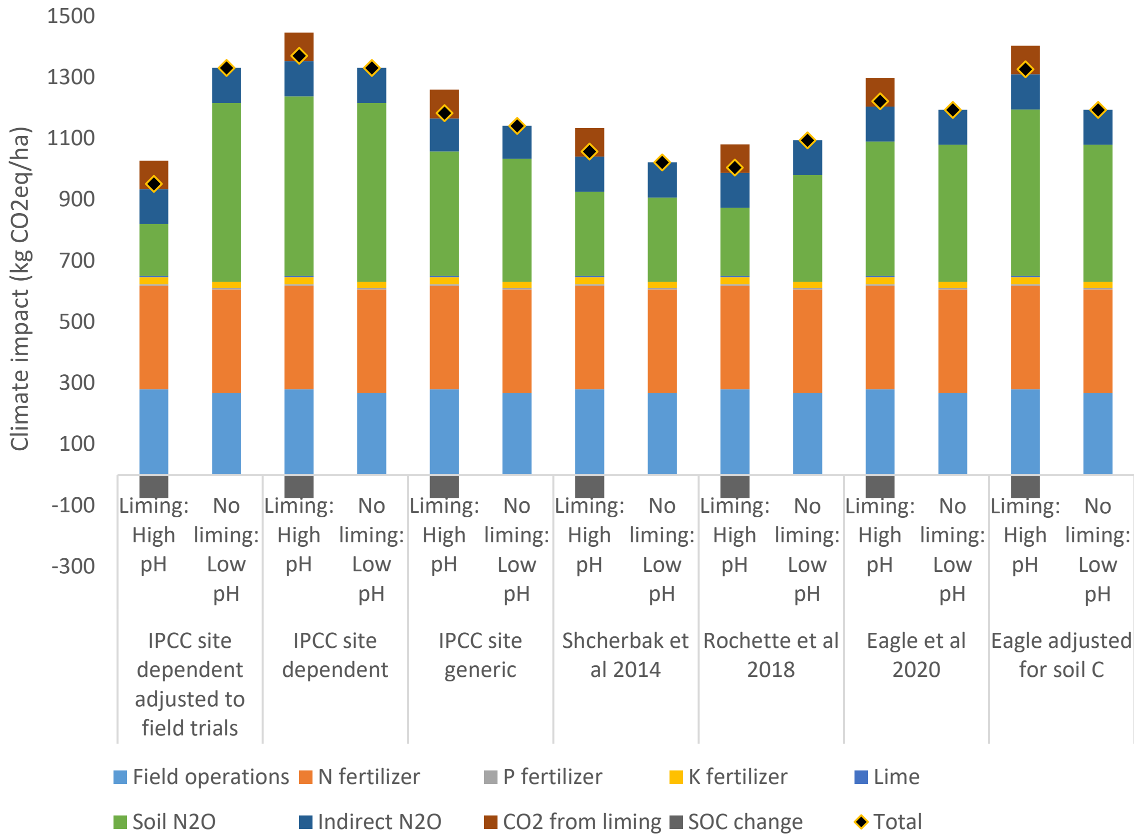

Figure 4. Climate impact (kg CO_2e) per hectare in the high pH (liming) and low pH (no liming) treatments according to the different methods used to estimate soil nitrous oxide (N_2O) emissions.

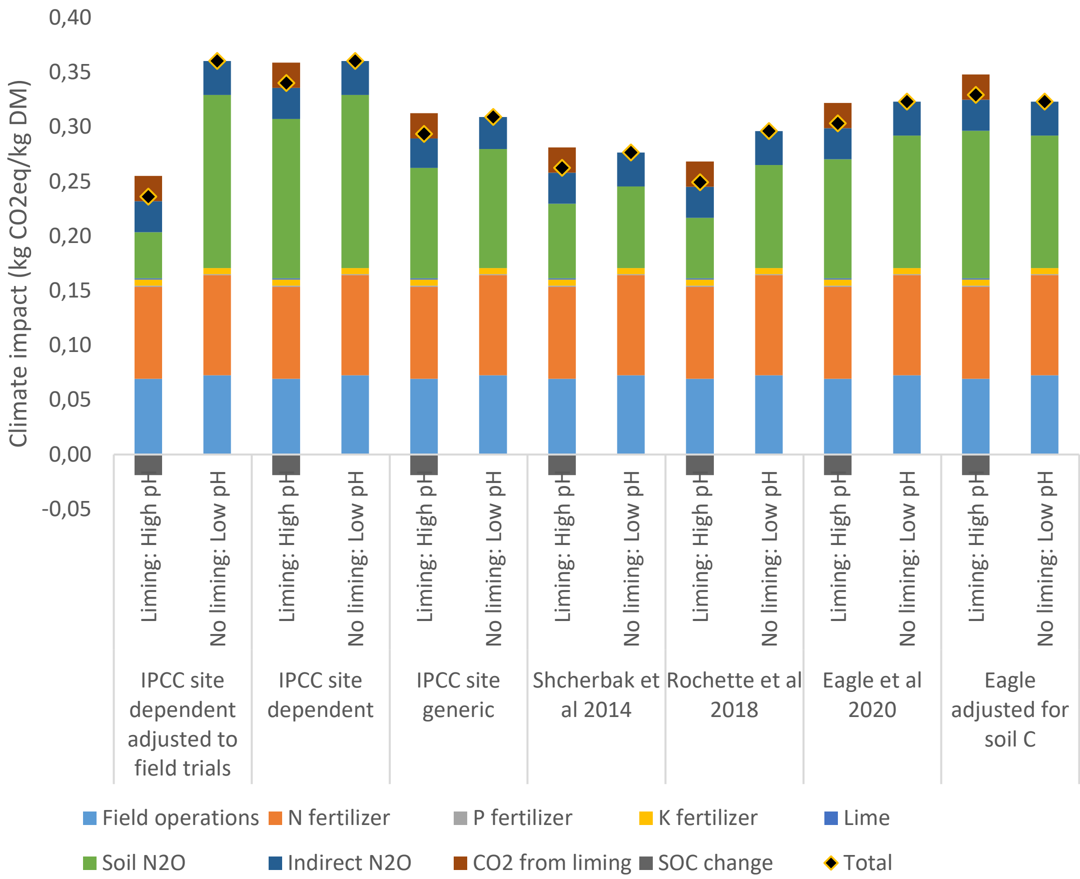

Figure 5. Climate impact (kg CO_2e) per kg dry matter (DM) in the high pH (liming) and low pH (no liming) treatments according to the different methods used to estimate soil nitrous oxide (N_2O) emissions.

5. Discussion

5.1. General discussion of the results

In field measurements, total N_2O emissions in the treatment with high pH (representing liming) were found to be 71% lower than those in the treatment with low pH (Lang *et al.,* 2022). This was a greater reduction due increased pH than found previously in global estimations (16-22%) (Hénault *et al.,* 2019; Wang *et al.,* 2021b). The reason for this greater emissions reduction could be that raising the soil pH can increase the proportion of N_2O reduced to N_2. The compound dicyandiamide ($C_2H_4N_4$) formed during decomposition of cyanamide may also contribute to lower N_2O emissions from soils.

Liming to increase soil pH from 6.6 to 7.2, as in this study, is probably not realistic for many crops, since more lime would be required to keep the pH at a higher steady state due to increased leaching. In many cases liming would also not be economically viable, since yield increases may be moderate within the higher range of soil pH values. For example, in the Ultuna frame trials, mean annual corn yields were 3.7% higher in the high pH (liming) treatment than in the low pH (no liming) treatment across the years 2000-2019. Thus the unique dataset from the Ultuna frame trials illustrates the effects of pH changes that most likely also apply for soils with lower numerical pH values.

5.2. Impact of geographical location and implementation potential

Around 80% of Swedish arable soils are naturally acidic, and regular liming is needed to maintain high productivity in cropping. Around 50% of Swedish soils have pH values below those currently recommended by the Swedish Board of Agriculture (Eriksson, 2021). The current liming rate is on average 50 kg CaO per hectare, but should be 150 kg CaO per hectare to achieve 70% base saturation, which corresponds to soil pH of 6.0-6.5 (Haak & Simán, 1992).

The current recommendations for liming will probably be reconsidered in the near future. It is likely that target pH values in the recommendations will be increased for certain crops, since increased productivity during recent decades has altered the cost:benefit ratio for lime application. Evidence for this is provided by two recent studies examining the effect of pH on soil fertility in Swedish soils (Börjesson & Kirchmann, 2022; Kirchmann *et al.*, 2020).

Liming of acidic soils is beneficial for soil fertility and crop yield, but the potential for implementation for field liming is constrained by the uncertain economic returns. Economic analysis of liming in long-term experiments has revealed large differences in gross margin between crops in both arable crop rotations and annual pasture-crop rotations (Holland & Behrendt, 2021; Li *et al*., 2009). For example, in the study by Li *et al*. (2009), wheat showed stronger responses to liming and higher gross margin than oats, while lupin yield increased only slightly after liming because of this crop's high innate tolerance to acidity. Although liming can improve economic returns for most arable crops, the economic performance is site-dependent, due to differences in soil texture and organic matter content, and is also dependent on the sequence of crops within a given rotation (Holland & Behrendt, 2021). Therefore, to achieve higher economic efficiency in liming, site condition, soil nutrient status, crop type, properties of the lime material, and economic cost need to be considered in practice.

5.3. Time perspective of the measure

Because a number of different processes contribute to soil acidification, acidic soils should be limed regularly to keep agricultural systems productive. However, it can take time to achieve pH changes in soil and associated crop yield responses, especially if coarse-grained lime is used, which can result in a long payback period. One previous study found that, depending on the choice of crops used in the crop rotation, cash flow became positive from year 5 in an annual pasture-crop rotation system, and from year 9 in a perennial pasture-crop rotation (Li *et al*., 2009). Distinct differences in economic benefits from liming take about 20 years to achieve according a study in England (Holland & Behrendt, 2021). Opting for high-value crops when soil pH becomes optimal can be a way to shorten the payback period.

Technologies for precision liming are available and their use will probably increase in future (SBA, 2022; Bönecke *et al.*, 2021). When using these technologies, lime application rate is calculated based on maps of soil pH, soil texture, and soil concentrations of calcium, magnesium, and organic matter, with the data combined to give a target pH value.

Whole-farm demand with regard to crops and crop sequence can also be considered when liming, so that lime is applied where this is most economically beneficial for the farm as a whole (Jordbruksverket, 2022). Liming is primarily carried out to maintain soil health, and thereby crop productivity, and thus it is important for the long-term economic sustainability of crop production.

Higher crop yield is generally associated with higher crop residue production. Returning a greater volume of root biomass and larger quantities of straw to the soil can increase SOC content, with multiple benefits for soil health (Lal, 2014). Increasing SOC stocks have also been suggested as a climate mitigation strategy, as storing more carbon in soil can decrease the amount of CO_2 in the atmosphere (Shukla *et al.*, 2019; Kätterer and Bolinder, 2022). Effects of liming on soil health were not included in the present analysis, but impacts on SOC observed in the Ultuna frame trials, with SOC sequestration corresponding to around 76 kg CO_2eq per hectare and year, were included.

Liming can increase fertilizer use efficiency and thus reduce consumption of nitrogen fertilizer, by 20% on average (Kreišmane *et al.*, 2016; van Roestel, 2014). Reduced nitrogen application rates and elevated pH in turn probably result in decreased N_2O emissions. However, the effects of reduced consumption of nitrogen fertilizer were not included in the present analysis, as the same nitrogen fertilization rate was assumed for both the high and low pH treatments (representing liming and no liming, respectively).

Lime is produced from limestone ($CaCO_3$) or dolomite ($CaMg(CO_3)_2$). Mining is known to be associated with several environmental impacts, such as negative effects on local wildlife and vegetation, loss of habitats, effects on water availability and quality, altered land use pattern, etc. (Ganapathi & Phukan, 2020). Lime is used in several industrial applications, including cement production, steel manufacturing, and wastewater treatment. Use in agriculture as a soil amendment accounts for approximately 3.3% of the global market for lime (FortuneBusinessInsights, 2022). The environmental impact from mining the lime was not included in this study, and only emissions of GHG in the production process (including mining) were accounted for.

5.4. Predicting soil N_2O emissions in climate impact assessments of crop production

Estimation of soil N_2O emissions from cropping is frequently performed for climate impact assessment purposes at different levels of detail and geographical resolution. The results can be used in national reporting, in farm climate budgets, or as general estimates of the climate impact of producing various crops. The climate impact of all significant inputs to the cropping system is accounted for. Notably, even in comparison with other life cycle steps, the climate impact deriving from soil N_2O emissions is generally estimated to be a large part of the overall climate impact of cropping. In the present study, soil N_2O emissions accounted for 18-43% of the cradle-to-farm gate emissions from corn cultivation.

Since the climate impact of N_2O emissions from soil is often high, any management practice that has the potential to decrease N_2O emissions can significantly reduce the climate impact of cropping. However, estimation of soil N_2O emissions is challenging because of the complexity of soil processes, high variability in soil N_2O emissions and in their response to different management practices, and other conditions, such as climate and soil properties. The commonly used IPCC method (Tier 1 and Tier 2) is quite a simple model based on nitrogen fertilization rates, and therefore it cannot predict changes in N_2O emissions due to management changes (other than changes in nitrogen fertilization rate).

In this study, we tested three alternative empirical models (developed by Eagle *et al.*, 2020; Rochette *et al.*, 2018; Shcherbak *et al.*, 2014), where only the model of Rochette *et al.* (2018) included the effect of soil pH on N_2O emissions. A number of process-based models, such as DNDC (Li *et al.*, 1992) and DayCent (Parton *et al.*, 1998), are also available. Such models often require more input data, but also provide estimates of e.g., soil carbon and nitrogen leaching. The most suitable model may differ depending on the purpose of the study and data availability.

In order to improve knowledge about climate mitigation options in agriculture, new models that can estimate the effect of soil management practices on soil N_2O emissions, and ideally have the capacity to handle regional differences (Xia *et al*., 2022), need to be developed.

6. Conclusions

Using empirical data from the Ultuna outdoor frame trials, this study showed that soil N_2O emissions from a treatment with high soil pH (7.2), representing liming, were 71% lower than those from a treatment with low soil pH (6.6), representing no liming of the same soil. Assessed in a life cycle perspective, these findings indicate that liming to increase soil pH could decrease the overall climate impact from crop production by around 28%, mainly due to the reduction in soil N_2O but also due to increases in SOC content. The climate impact from production and application of additional lime needed to maintain the higher pH was around 10% of the total climate impact, assessed on a per-hectare basis.

In most climate impact assessments of agricultural systems, soil N_2O emissions have to be modelled, since field measurements are expensive and data are often not available. Comparison of three different methods for estimating soil N_2O emissions showed that they gave very different results, and only one (developed by Rochette *et al.*, 2018) included pH as a variable that affected the final emissions estimate. According to the different methods, the contribution from soil N_2O emissions to overall climate impact varied between 18% and 43%. These results illustrate the uncertainty associated with estimates of soil N_2O emissions in climate impact assessments of crop production. In line with previous findings, the present study clearly identified a need for more reliable methods for estimating soil N_2O emissions, including the capacity to predict effects of different management options in different regions, which is essential when designing climate policies for agriculture.

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MISTRA

FOOD FUTURES