REVIEW

Mitigating nitrous oxide emissions from agricultural soils by precision management

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Abstract Nitrous oxide (N_2O) emissions make up a significant part of agricultural greenhouse gas emissions. There is an urgent need to identify new approaches to the mitigation of these emissions with emerging technology. In this short review four approaches to precision managements of agricultural systems are described based on examples of work being undertaken in the UK and New Zealand. They offer the opportunity for N_2O mitigation without any reduction in productivity. These approaches depend upon new sensor technology, modeling and spatial information with which to make management decisions and interventions that can both improve agricultural productivity and environmental protection.

Keywords   decision support systems, mitigation, nitrous oxide, precision farming

1   Introduction

There is a growing acceptance that future agricultural production must be fully integrated with the protection of the environment. The requirement to feed humanity as its population rises toward 10 billion, at the same time as living within a safe operating space for a stable and resilient planet, remains a major challenge for society[1]. Agriculture is one of the biggest threats to the environment and the development of new approaches to environmental management within agricultural systems is therefore of utmost importance. Nitrous oxide (N_2O) is recognized as a powerful greenhouse gas and contributes to the destruction of stratospheric ozone[2]. Maintaining agricultural productivity while minimizing N_2O emissions is a critically

important consideration for the future development of agricultural systems.

Nitrous oxide is a long-lived greenhouse gas with a Global Warming Potential 265–298 times greater than that of carbon dioxide. Around 60% of anthropogenic sources of this gas are derived from nitrogen fertilizer and manure use in agriculture[3] and the urgent need to reduce greenhouse gas emissions in response to the current threats posed by climate change has highlighted the need to develop new approaches to mitigation. Global emissions are projected to rise by 28% during the remainder of this century if current trends in population growth and food production continue[4]. However, there is significant interest in developing new approaches to mitigation based on the application of new technologies and our increased understanding of source processes. Nitrous oxide is produced by microbial transformations of nitrogen in soils and water. Two main processes are recognized as contributing to emissions, these are nitrification and denitrification[5]. The nitrification process involves the oxidation of ammonium to nitrate, involving a group of chemoautotrophic microorganisms. This process occurs rapidly in fertile agricultural soils containing readily available supplies of ammonium nitrogen provided by inputs of fertilizers, manures and crop residues. A small proportion of the nitrogen which is converted from ammonium to nitrate is released as N_2O[5]. A second process contributing to emissions is denitrification which occurs when the nitrate ion is reduced during the process of microbial respiration. Such conditions commonly arise in wet soils containing a plentiful carbon and nitrogen supply[6]. In these conditions soil oxygen becomes depleted through respiration and microbes switch to nitrate as a terminal electron acceptor in order to maintain metabolic activity. Although much of the nitrate is reduced to N_2, N_2O is produced as an intermediate in these processes.

In many agricultural soils the processes of nitrification and denitrification occur simultaneously but are strongly influenced by environmental and management controls[6]. Soil nitrogen supply, moisture content and temperature are recognized as particularly important factors in influencing emissions[7]. However, changes in these factors are highly dynamic and interact strongly with management practices. Nitrogen supply is the most obvious factor controlled by agricultural management through the inputs of fertilizer and manure used to drive crop productivity. Dung and urine deposited by livestock grazing on pastures and forage crops are a further source of N input. Such inputs can be clearly seen to drive emissions of N_2O, which are often released in significant quantities shortly following fertilizer applications and urine deposition. However, the magnitude of these emissions can be modified by soil conditions and climate at the time of fertilizer application and grazing. Approaches to mitigating N_2O emissions from soils focus on three main strategies:

(1) Reducing nitrogen inputs or modifying the form in which nitrogen is supplied,

(2) using microbial inhibitors, and

(3) modifying soil conditions by management.

Extensive reviews of approaches to N_2O mitigation from agricultural systems have been published in recent years using individual approaches described above or a combination of these approaches[8–12]. Nitrous oxide emissions from soils are highly heterogeneous in time and space[13]. Current approaches to the management of farmland often ignore this heterogeneity, and instead apply uniform management decisions to land, taking no account of variations in the known drivers of emissions. The spatial heterogeneity of N_2O emissions is often a result of the coincidence of several key driving variables. This often leads to short periods of high N_2O emissions sometimes two or three orders of magnitude above baseline. However, detailed spatial information that can be collected precisely and temporally with the use of new measurements technology, often at high resolution, can help identify potential hotspots and provide opportunities for intervention to reduce emissions.

In this short review, we focus on the opportunities for precision farming technology to mitigate N_2O emissions through innovative approaches to soil and crop management. Precision farming uses information and technology to make better management decisions on farms. This technology provides an opportunity to manage heterogeneity in farmland in order to deliver improved productivity, profitability and better environmental outcomes. In recent years there have been very rapid developments in the technology used to deliver precision farming approaches. This includes improvements in sensor technology, satellite observation processing and management of big data and network and communication systems. The question therefore arises whether or not these technologies can be used to reduce greenhouse gas emissions from soils, and if so what evidence is there that this is happening. Here we describe examples of approaches in various stages of development in the UK and New Zealand that may offer opportunities for mitigation.

2   Precision management of soil pH

Soil pH is important in regulating and modifying N_2O emissions. In more acid soils, there is a higher emission of N_2O compared to N_2 because the N_2O reductase enzyme that converts N_2O to N_2 is inhibited[14,15]. Thus, in soils that have a tendency to produce N_2O by denitrification, more acid conditions are likely to lead to higher N_2O emission rates. Given that soil acidity can also reduce crop growth, maintaining soil pH at an appropriate level is considered important for both the optimization of crop production and efficient use of fertilizer inputs. Lower crop biomass and higher N_2O emissions in acid conditions can lead to a large increase in N_2O emission intensity (the quantity of N_2O produced per unit of crop). New precision approaches to lime application take account of the often large gradients in pH within fields (Fig. 1), applying lime with variable-rate applicators on a spatial basis according to the lime required to bring soil up to a target pH. Although this management approach is specifically designed to optimize crop growth through pH management, it is likely that there will be co-benefits in terms of N_2O mitigation given the sensitivity of emissions to pH. Preliminary measurements highlight the increased emissions of N_2O in the more acidic areas of grassland (Fig. 1). Work is currently underway at SRUC in the UK in partnership with other European countries and AgResearch in New Zealand to test this hypothesis using conventional and variable-rate lime applications on grassland soils, followed by subsequent measurements of N_2O emission during the growing season[16].

3   Managing organic nitrogen inputs

Organic matter is regularly added to agricultural soils in the form of slurry, manures and animal wastes. Grazing livestock deposit nitrogen rich dung and urine in grassland soils which are recognized as hotspots of greenhouse gas emissions and contribute significantly to the heterogeneity of emissions often observed in these environments[10,17,18]. Until recently it has been difficult to characterize the spatial and temporal distribution of these grazing inputs other than through manual observation. However, new remote sensing techniques using high resolution cameras linked to unmanned aerial vehicles (UAVs) is allowing improved understanding of the spatial and temporal patterns of deposition associated with such livestock management. A recent study used image analysis to quantify the appearance of urine patches in an intensively grazed grassland in
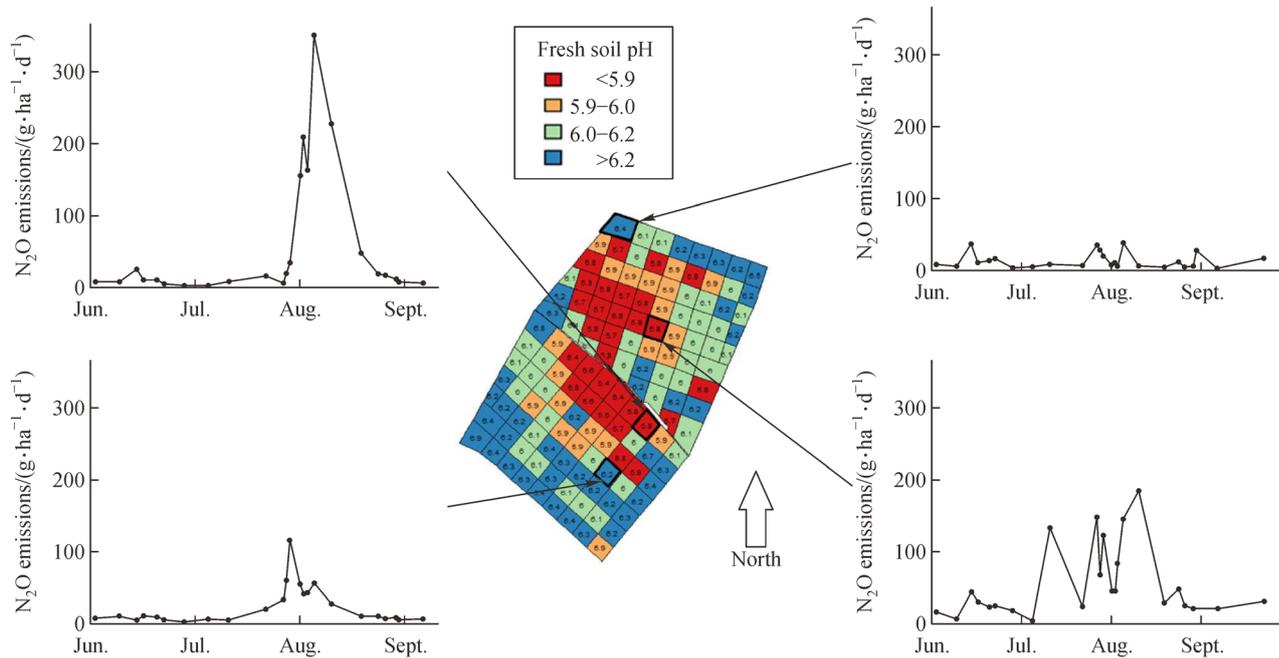
Fig. 1   Spatial heterogeneity of pH and associated N_2O emissions from a Scottish grassland soil to a depth of 20 cm measured on a 10 m × 10 m grid (each square on the map) at a field site in Easter Bush, Penicuik, Scotland. Measurements of pH performed by Soil Essentials (Angus, Scotland)

Scotland[19]. Previous studies have shown that such urine patches contribute to very high emissions of N_2O, which vary throughout the growing season in response to climatic conditions[20,21]. By linking the appearance of urine patches to site-specific emission factors it is possible to estimate field scale emissions of N_2O. The opportunity now arises from this work to develop innovative approaches to mitigation. This includes the potential to use UAV technology to deliver urease and nitrification inhibitors to newly formed urine and dung patches within the field. This could have the benefit of minimizing the quantity of inhibitors used, while achieving significant mitigation benefits, both in terms of reduced NH_3 and N_2O emissions. A potential difficulty with this approach is that urine patches only become visible from the second day and can take 5–8 d to appear. During this period significant emissions of N_2O can often occur. An alternative approach could therefore use animal based sensors to detect urination events allowing more rapid deployment of inhibitors to points of deposition[22]. Another option which has been tried in New Zealand is to monitor soil changes in soil electrical conductivity and use this as a proxy for the detection of urine patches[23]. Mapping urine patches in this way could allow early intervention and application of inhibitors in order to reduce N_2O emissions. Another potential benefit of this approach would be to use it in order to adjust mineral fertilizer applications, using spatial maps of urine deposition by livestock to adjust the inputs of mineral fertilizer through variable-rate fertilizer applications.

4   Decision support tools to reduce N_2O emissions in grazing systems

An alternative approach to N_2O mitigation in grazed grasslands is to remove livestock from grazing areas when environmental conditions exceed threshold values that are known to be associated with emission peaks. This approach has been used in a modeling study in New Zealand to assess potential reductions in N_2O emissions and wider environmental benefits of removing cattle from grazing areas during periods of excess wetness[24]. The approach involves monitoring when soil wetness exceeds a soil-specific threshold value above which large emissions of N_2O could be anticipated. Under these conditions, duration-controlled grazing is implemented where cattle are moved from the pasture to a holding yard, an area of land with a pine bark and sawdust base. A comparison of the whole system emissions (which assessed total N_2O and manure-derived CH_4 emissions) was made between current typical practice (100% in-paddock grazing, apart from milking time) and implementation of duration-controlled grazing. For the latter, grazing time was either 0 (i.e., complete removal), 13 or 17 h·d^{-1}. The analysis showed that in poorly drained soils removal of cattle from the grazing area could achieve up to 12% reduction in total N_2O and manure-derived CH_4 emissions, much of which was associated with reduced emissions from the N_2O released from urine and dung. There were ancillary benefits both in poor and imperfectly drained soils

associated with reduced nitrate leaching. A further advantage of management interventions of this type is associated with reductions in soil damage associated with compaction, which is particularly prevalent under wet conditions. Practical applications of this approach require further testing, but the results to date suggest a cost-effective and environmentally beneficial approach to greenhouse gas mitigation, particularly for farmers with poorly drained soils.

5   Variable-rate nitrogen fertilizer application in cropping systems

Improving the synchrony between fertilizer nitrogen applications and crop demand has long been recognized as a potential approach to reducing nitrogen losses from cropping systems[25]. In most current systems, crops obtain a significant proportion of their nitrogen supply from the mineralization of soil organic matter which is then supplemented by the addition of fertilizer nitrogen. However, the supply of nitrogen across a field from mineralization can be highly variable, and this is rarely considered when planning fertilizer application. Remote sensing techniques now offer the opportunity to monitor crop growth and development at increasingly high resolutions. Canopy reflectance can be used as a measure of the nitrogen concentrations in crop tissues and fertilizer recommendations can be adjusted to take into account of this variability in crop nitrogen content across a field[26]. Often this involves a system with sensors mounted on the front of a tractor which observe crop nitrogen reflectance and converts this into an index of crop nitrogen uptake and then adjusts the nitrogen fertilizer addition according to whether the uptake is above or below a threshold value. Advancements are being made in using satellite imagery to detect canopy reflectance[27,28]. Improvements in image resolution and visit intervals have the potential to increase the scale and temporal resolution of monitoring for targeted fertilizer applications, allowing targeted timing of interventions alongside altering fertilizer amounts on a spatial basis.

In some circumstances suboptimal nitrogen uptake is associated with poor soil conditions such as compaction, low soil organic matter concentrations or restricted soil depth. In these circumstances additional fertilizer nitrogen inputs may well exacerbate nitrogen losses rather than increase crop nitrogen recovery. A more sophisticated approach would look at variations in soil nitrogen supply across a field that could be directly linked to differences in mineralization of nitrogen, and then adjust nitrogen supply in accordance with this variation. Where soil conditions limit nitrogen recovery it would be more appropriate to either improve soil conditions, for example, through alleviating compaction, or in circumstances where this is not possible, to reduce fertilizer nitrogen applications. Any improvements in the recovery of crop N that can be achieved by precision management of this kind are likely to lead directly to a reduction in N_2O in emissions, given the strong link between nitrogen supply and emissions that has been characterized in many previous studies[7,29,30].

6   Conclusions

This short review has provided several examples of how precision management of agricultural systems can potentially be used to reduce N_2O emissions from soils. As we develop improved spatial and temporal knowledge of the farmed landscape, further opportunities will be developed that can support more efficient resource use with reduced environmental impacts. These approaches have yet to be widely adopted in agricultural systems and are still in the process of development, but they offer significant promise given their capacity to maintain or increase productivity while reducing environmental impacts. Solutions will involve the analysis of large data sets describing the farmed environment coupled with a modeling framework that encapsulates our understanding of the transformation of nitrogen in the environment, and linked eventually to decision support tools that will aid farmers and land users to make better decisions about crop management and environmental protection.

Compliance with ethics guidelines   Robert M. Rees, Juliette Maire, Anna Florence, Nicholas Cowan, Ute Skiba, Tony van der Weerden, and Xiaotang Ju declare that they have no conflicts of interest or financial conflicts to disclose.

This article does not contain any studies with human or animal subjects performed by any of the authors.

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