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Opportunities for mitigating nitrous oxide emissions in subtropical cereal and fiber cropping systems: A simulation study

Henrike Mielenz[a,*], Peter J. Thorburn[a], Clemens Scheer[b], Massimiliano De Antoni Migliorati[b], Peter R. Grace[b], Mike J. Bell[c]

[a] CSIRO Agriculture, 306 Carmody Road, St Lucia, QLD 4068, Australia
[b] Institute for Future Environments, Queensland University of Technology, Level 7, P Block, Gardens Point Campus, 2 George Street, Brisbane, QLD 4000, Australia
[c] Queensland Alliance for Agriculture and Food Innovation, University of Queensland, Gatton, QLD 4343, Australia

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ABSTRACT

23% of global agricultural land are situated in the subtropics. Nitrous oxide (N_2O) emissions were estimated to be higher under subtropical than under temperate climates. So mitigation of N_2O emissions from subtropical farming systems can make an important contribution to reducing global warming. Accordingly, in this study we explored long-term N_2O emissions and possible mitigation options for representative subtropical cropping systems (e.g., summer versus winter crops, inclusion of a legume in the rotation) and management practices (nitrogen fertilizer, irrigation) by calculating scenarios with the agricultural systems model APSIM. The model was tested against high temporal frequency data from experiments conducted on an oxisol and a vertisol in subtropical Australia, which comprised a number of fertilization and irrigation treatments. The threshold of water filled pore space above which denitrification starts was calibrated on a subset of the data while the rest of the large number of parameters controlling the carbon and nitrogen cycles were kept to default values. The validity of the model was confirmed with 11 validation data sets for yields of four different crops ($R^2 = 0.92$) and 16 validation data sets for seasonal N_2O emissions during crop and fallow periods ($R^2 = 0.77$). While these results show that the model performs well in sub-tropical environments, this modeling skill might not translate to other environments and the model would benefit from wider testing. In the scenario analyses, long-term average N_2O emissions from wheat, cotton, maize and sorghum were predicted to vary between 0.2 and 6.1 kg N ha^{-1} yr^{-1} and showed large interannual variability of N_2O emissions. This highlights the risk that results from short-term experiments may not be representative for the long-term behavior of these agro-ecosystems, and thus the value simulation studies add to experiments. The scenario analysis revealed that long-term average yields and N_2O emissions increased in response to the same management practices (e.g., increase in nitrogen rate), leading to a trade-off between maximizing yield and minimizing N_2O emissions. When crop yields were limited due to water stress either by low seasonal rainfall or by lack of irrigation, average N_2O emissions increased. Given the annual variability in climate and soil nitrogen stocks, mitigating N_2O emissions without compromizing in yield is not a simple task but requires an optimal nitrogen management considering other limiting factors such as water supply.

1. Introduction

Nitrous oxide (N_2O) concentration in the atmosphere has increased by 20% since 1750 (Ciais et al., 2013). Its global warming potential over a 100-year period is about 300 times greater than that of carbon dioxide (CO_2). Together with its contribution to stratospheric ozone destruction (Ravishankara et al., 2009), this makes N_2O very harmful to the environment. N_2O emissions from agricultural crop and livestock production have increased in recent years (Janssens-Maenhout et al., 2014; Saikawa et al., 2014) and contribute about 60% to anthropogenic N_2O emissions (Syakila and Kroeze, 2011). Mitigation of N_2O emissions from agro-ecosystems is therefore important. This requires a good understanding of N_2O emissions from the global range of agro-ecosystems.

* Corresponding author.
E-mail addresses: henrike.mielenz@csiro.au, h.mielenz@outlook.com (H. Mielenz).

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N_2O emissions from agro-ecosystems in temperate climates have been extensively studied (Stehfest and Bouwman, 2006). Yet, mechanisms and factors driving N_2O emissions from soils in the subtropics, which host another important agro-ecosystem, are not very well understood (Xu et al., 2013). Detailed studies on N_2O emissions from farming systems in the subtropics are still underrepresented in literature (Stehfest and Bouwman, 2006). Our current understanding (Bouwman et al., 2002a; Stehfest and Bouwman, 2006) is that N_2O emissions under subtropical climates (1.6–1.9 kg N ha^{-1} yr^{-1}) may be generally higher than those under temperate climates (0.8–0.9 kg N ha^{-1} yr^{-1}). In recent years, there has been a number of studies reporting N_2O emissions from cereal and fiber crops in the subtropics (Bayer et al., 2014; De Antoni Migliorati et al., 2014; Guo et al., 2009; Mahmood et al., 2008; Scheer et al., 2013; Wang et al., 2011). N_2O emissions observed in these studies showed high variability between years and among different management practices, with values mostly between 0.5 and 2.0 kg N ha^{-1} yr^{-1} and up to about 6 kg N ha^{-1} yr^{-1} during a rice cropping season. Most of the measured emissions were smaller than, or in the lower range of the values given by Bouwman et al. (2002a). The wide range of observed N_2O emissions and the fact that data from the subtropics continue to be scarce (Bouwman et al., 2002a; Stehfest and Bouwman, 2006; Xu et al., 2013) suggest that a clear knowledge of magnitudes of N_2O emissions in these regions is still lacking.

23% of global agricultural land (about 1130 M ha) is situated in the subtropics (Wood et al., 2000), of which a considerable part is devoted to rain fed and irrigated cereal production. Assuming that in the subtropics the same share of agricultural land is cropland as it is globally, i.e., about 28% (FAOSTAT, 2012), 320 M ha in this climate zone are used as cropland. Adopting the emission rates found by Bouwman et al. (2002a) implies that annual N_2O emissions from cropland in the subtropics total 0.5–0.6 Tg N_2O–N (or 240–290 Tg CO_2-eq), equivalent to 14–16% of global N_2O emissions from agricultural land (3.8 Tg N_2O–N yr^{-1}; Saikawa et al., 2014). Mitigating these high emissions clearly is important. Given the climatic differences of the subtropics from temperate zones, it cannot be assumed that mitigation strategies from temperate areas will be as successful in the subtropics. Therefore, effective mitigation opportunities for subtropical cropland need to be explored, for which a clear understanding of causes of N_2O emissions is required.

The biogeochemical processes involved in the production and emission of N_2O are regulated by the availability of mineral nitrogen (N) and organic carbon (C) and are driven by water content, soil temperature and pH (Hénault et al., 2012; Stehfest and Bouwman, 2006). In agricultural lands, most of these factors are determined by climate and management practices, such as fertilization, irrigation, residue management, and tillage practices. As a result of the complexity of environmental variables and management practices influencing the underlying biogeochemical processes, N_2O emissions are highly variable in space and time (Hénault et al., 2012). To capture this variability, observations of N_2O emissions with high temporal resolution are indispensable for characterizing N_2O emissions from managed ecosystems (Yao et al., 2009). Such data have only recently become available for some sites in subtropical regions (e.g., Wang et al., 2011; Rowlings et al., 2013; Scheer et al., 2013; De Antoni Migliorati et al., 2014). While these studies provide valuable information on the short-term variability in N_2O emissions at experimental sites, they cannot capture the range of existing environmental systems and management practices and, even less, climate variability. Process-based models provide a means of accounting for the effects of soil type, weather conditions and management interventions on N_2O emissions and, therefore, are important supplementary tools to gain information on N_2O emissions from managed ecosystems and to explore possible mitigation opportunities. A well established and calibrated model enables the extrapolation of site-specific and short-term experimental data to explore long-term effects at multiple sites encompassing varying soils, climates, cropping systems and management practices.

The utility and accuracy of process-based biogeochemical models depends on how well they are parameterized and calibrated. N_2O emissions are generally difficult to model due to the high temporal and spatial variability in measured emissions and the multitude of biogeochemical processes and influencing factors involved in the production and emission of N_2O. In most studies, many parameters controlling the C and N cycles as well as plant development parameters are calibrated to be able to reproduce measurements correctly (e.g., Li et al., 2012; Rafique et al., 2013). Obviously some model parameters such as soil hydraulic properties and C concentrations are site-specific and need to be determined (through some form of measurement or calibration against measured data) for an experimental site. However, the extent of the parameters calibrated in many modeling studies goes beyond these obviously site-specific parameters. In doing so the resultant model 'set ups' in these studies are site-specific, which raises the question of how far the insights gained from the simulation results can be extrapolated to other locations.

The aim of this study is to (1) analyze N_2O emissions from subtropical broad-acre cropping systems, (2) evaluate the trade-off between crop yields and N_2O emissions, and (3) identify strategies for mitigating these emissions. We employed a combined measurement–modeling approach. First, a widely used cropping systems model was calibrated and validated against data from three experiments in broad-acre crops conducted at two experimental sites in subtropical Australia. We focused on a thorough parameterization of soil hydraulic properties. This allowed us to refrain from calibrating a large number of parameters controlling the C and N cycles and plant development as is frequently done in other studies. The model was then used to simulate long-term scenarios comprising different crops and management strategies to determine their effect on N_2O emissions and yields. Through analysis of these scenarios potential mitigation strategies for typical broad-acre cropping systems in the humid subtropics were identified.

2. Material and methods

This study consisted of four parts: (1) soil hydraulic parameters within the Agricultural Production System sIMulator (APSIM) were calibrated against a subset of data from two field sites representing commonly occurring soil types used for cropping in the subtropics and common cropping practices. (2) The water content above which denitrification commences was calibrated against cumulative high-frequency measured N_2O emissions. (3) The calibrated APSIM model was validated with the remaining data sets. Thereby, all experiments were simulated with one set of soil and denitrification-process parameters rather than adjusting them for each site, season, crop or treatment. (4) Long-term (40 years) crop rotations representative for the humid subtropics were simulated with varying fertilization and irrigation strategies to assess possible N_2O mitigation strategies.

2.1. Field experiments

Data came from two field experiments conducted on an oxisol near Kingaroy (26°58′16.8″ S, 151°82′85.3″ E) and one on a vertisol near Kingsthorpe (27°30′44.5″ S, 151°46′54.5″ E) both situated in South Eastern Queensland, Australia. The experiments comprised five different broad-acre crops plus a fallow period, and a variety of