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The use of biogeochemical models to evaluate mitigation of greenhouse gas emissions from managed grasslands

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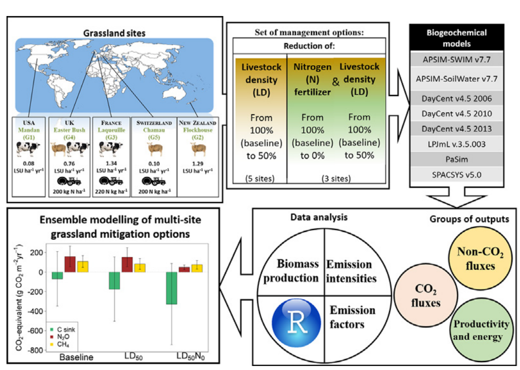
HIGHLIGHTS

- We perform multi-model simulations of C and N fluxes at five grassland sites.
- We assess modelled greenhouse gas emissions with alternative management practices.
- We use multi-model medians to reduce the uncertainty of the responses.
- We identify some shift towards a C sink with decreasing inputs.
- We show the considerable effect of N fertilizer reduction on C and N emissions.

GRAPHICAL ABSTRACT



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ABSTRACT

Simulation models quantify the impacts on carbon (C) and nitrogen (N) cycling in grassland systems caused by changes in management practices. To support agricultural policies, it is however important to contrast the responses of alternative models, which can differ greatly in their treatment of key processes and in their response

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to management. We applied eight biogeochemical models at five grassland sites (in France, New Zealand, Switzerland, United Kingdom and United States) to compare the sensitivity of modelled C and N fluxes to changes in the density of grazing animals (from 100% to 50% of the original livestock densities), also in combination with decreasing N fertilization levels (reduced to zero from the initial levels). Simulated multi-model median values indicated that input reduction would lead to an increase in the C sink strength (negative net ecosystem C exchange) in intensive grazing systems: -64 ± 74 g C m^{-2} yr^{-1} (animal density reduction) and -81 ± 74 g C m^{-2} yr^{-1} (N and animal density reduction), against the baseline of -30.5 ± 69.5 g C m^{-2} yr^{-1} (LSU [livestock units] ≥ 0.76 ha^{-1} yr^{-1}). Simulations also indicated a strong effect of N fertilizer reduction on N fluxes, e.g. N_2O-N emissions decreased from 0.34 ± 0.22 (baseline) to 0.1 ± 0.05 g N m^{-2} yr^{-1} (no N fertilization). Simulated decline in grazing intensity had only limited impact on the N balance. The simulated pattern of enteric methane emissions was dominated by high model-to-model variability. The reduction in simulated offtake (animal intake + cut biomass) led to a doubling in net primary production per animal (increased by 11.6 ± 8.1 t C LSU^{-1} yr^{-1} across sites). The highest N_2O-N intensities (N_2O-N/offtake) were simulated at mown and extensively grazed arid sites. We show the possibility of using grassland models to determine sound mitigation practices while quantifying the uncertainties associated with the simulated outputs.

1. Introduction

Finding solutions to emerging ecological and societal challenges (climate change, food security, ecosystem sustainability) requires improved knowledge of the underlying processes affecting carbon nitrogen (C-N) pools and fluxes in agricultural systems (West and Marland, 2002; Giardina et al., 2014; Campbell and Paustian, 2015). Grassland ecosystems have a potentially important role to play in meeting the challenge of climate change because they can act as a source or sink for atmospheric carbon dioxide (CO_2) (Smith et al., 2008; Oates and Jackson, 2014) and are a source of non-CO_2 greenhouse gases (GHG) such as nitrous oxide (N_2O) and methane (CH_4). Importantly, these GHG emissions can be manipulated by management such as the method of grazing and the fertilizer regime (Soussana et al., 2004; Herrero et al., 2016). Several grassland experiments have addressed the role of management on the short-term GHG balance and global warming potential (e.g. Allard et al., 2007; Soussana et al., 2007; Hörtnagl et al., 2018). However, direct measurement of C-N balances should be supplemented by the use of simulation models, to support the implementation of effective practices and policies in agriculture, e.g. to mitigate GHG emissions (Rosenzweig et al., 2014; Elliott et al., 2015; Folberth et al., 2016). Biogeochemical process models address many of the complex interactions of weather, soil, vegetation and management practices (Bondeau et al., 1999; Churkina et al., 1999; Huntzinger et al., 2012; Warszawski et al., 2014; Chang et al., 2015) and can do so over long time intervals that are not feasible with experimentation. Existing modelling studies have focused on the determination of the C source and sink activity of grasslands (Soussana et al., 2010). Grassland models have been shown to provide adequate accuracy in representing observed yield and GHG emissions across a wide range of environments and management intensities (e.g. White et al., 2008; Chang et al., 2013; Graux et al., 2013; Ben Touhami and Bellocchi, 2015; Ma et al., 2015; Senapati et al., 2016; Ehrhardt et al., 2018).

Models can thus be beneficial for decision makers and farmers because they can be used to explore the productivity and environmental performances of specific systems as a consequence of changed management. However, the effect of management on C and N fluxes in agriculturally managed permanent grasslands (not re-sown more frequently than every five years, which is the focus of this study) is often uncertain (Schulze et al., 2009; Ciais et al., 2010), and such uncertainties are reflected in the outputs of the models used to simulate responses to management (Sándor et al., 2017). Grasslands are highly complex ecosystems and their behaviour is affected by multifaceted interactions of management drivers with water and nutrient availability, soil physics, and vegetation dynamics (Rees et al., 2013; Soussana et al., 2013). The dynamic grassland simulation models developed since the 1990s (e.g. Challinor et al., 2013; Snow et al., 2014; Calanca et al., 2016; J.W. Jones et al., 2017) differ greatly in their treatment of key processes, and hence in their response to environmental and management conditions (Brilli et al., 2017). A thorough assessment of the variation in the response, or sensitivity, of different grassland models to management factors can be critical in determining to what extent simulated responses may vary depending on the model used. From a policy perspective, it is critically important to identify the extent to which management interventions influence C-N fluxes (including productivity) prior to promoting policies that alter farming practices. If the impact of a given practice is uncertain, a sensitivity analysis can give information on the reliability of the models when representing C-N fluxes-management relationships under a variety of conditions. It is thus important to examine model behaviour under changed management in order to characterise the types of responses estimated, contrast the responses of different models and consider the reasons for these differences. In particular, hypotheses about the contribution of grassland management to GHG emissions can be tested via simulation models, which allow understanding, diagnosing and forecasting complex interactions (Chen et al., 2008; Seijan et al., 2011; Graux et al., 2012; Sándor et al., 2017, 2018).

Consequently, using five case studies, we tested the sensitivity of eight grassland models to gradients of management intensity that were selected for their potential to mitigate GHG emissions (e.g. Soussana et al., 2014; Abdalla et al., 2017). With the aim of increasing the reliability and confidence in simulated results, a multi-model ensemble approach was adopted to explore patterns of simulated C and N responses against imposed gradients of N fertilization and animal stocking rate (to which grassland models are generally sensitive, after Brilli et al., 2017). For this study, we included a range of well-known grassland models, and used them to simulate biogeochemical and related outputs (productivity and energy measures). The wider ensemble analysis presented in Ehrhardt et al. (2018) forms the baseline for the work presented here, which analyses factors that may explain the major differences observed in model responses. We further explored to what extent multi-model ensembles can be used to help identify farming practices that reduce GHG emissions. While restricting the analysis to a limited set of management options, this study examines a wide range of output variables and thus provides a framework for assessing grassland performance where direct casual links with farming practices are not obvious, and changes in performance are difficult to measure. As a corollary outcome, viewing and interpreting a variety of model outputs lay ground for future model developments.

2. Materials and methods

We refer to a sub-set of the grassland models described in Ehrhardt et al. (2018), in which models were initialized and calibrated using vegetation and soil variables, and surface-to-atmosphere fluxes at four sites worldwide. We used an ensemble of grassland models (Table 1) and compared their sensitivity to changes in management by comparing