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Precipitation gradient and crop management affect N_2O emissions: Simulation of mitigation strategies in rainfed Mediterranean conditions

Daniel Plaza-Bonilla[a,*], Joël Léonard[b], Céline Peyrard[b], Bruno Mary[b], Éric Justes[a]

[a] INRA, UMR-AGIR, 24 Chemin de Borde Rouge–Auzeville, CS 52627, 31326 Castanet-Tolosan cedex, France
[b] INRA, UR 1158 AgroImpact, Site de Laon, 02000 Barenton-Bugny, France

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ABSTRACT

In Mediterranean areas high precipitation variability and crop dependence on soil water availability make the interaction between climate and agricultural management a key issue for mitigating N_2O emissions. In this study we used the STICS model to capture the effect of a water deficit gradient and precipitation variability on N_2O emissions and mitigation strategies (i.e. N fertilizer type, grain legumes introduction in crop rotations and crop residues management) in a rainfed Mediterranean transect (HWD-Senés, MWD-Selvanera and LWD-Auzeville, i.e. high, medium and low water deficit, respectively). The model was first tested against a database of daily N_2O fluxes measured during twelve growing seasons of winter crops at the LWD site. Several scenarios were then run on each site, always over 9 successive growing seasons to take into account precipitation variability. STICS showed a good ability to simulate the driving variables of N_2O fluxes at the daily time scale. The mean observed and simulated cumulative emissions during the growing season were 0.71 and 0.82 kg N_2O–N ha^{-1}, respectively. The simulated N_2O emissions (mean of all scenarios) decreased with increasing water deficit being 2.51, 0.65 and 0.26 kg N_2O–N ha^{-1} yr^{-1} for LWD-Auzeville, MWD-Selvanera and HWD-Senés, respectively, which is consistent with published results. The lower N_2O emissions in the driest sites were not only related to lower fertilization rates but also to other factors associated with the Mediterranean characteristics, particularly, the drier water regime. Simulated N_2O emissions were highly sensitive to the interannual variability of the climatic conditions. According to the simulations, urea fertilizer would lead to slightly higher N_2O emissions (+6 and +8%) than ammonium- and calcium nitrate, respectively. The incorporation of winter pea in the traditional cereal-based Mediterranean rotations would reduce by ca. 22% the N_2O emissions in HWD-Senés without changing wheat yields. Differently, in MWD-Selvanera and LWD-Auzeville, N_2O emissions would remain unchanged since the emissions associated to the decomposition of low C:N ratio pea residues would counteract the lower application of N fertilizer. The systematic removal of crop residues at LWD-Auzeville would decrease the N_2O emissions by 20%. However, this practice seems not recommendable if tillage is practiced due to the concomitant decrease of soil organic matter, fact that would worsen the C footprint of the system and increase the susceptibility to soil erosion. Our work highlights the interest of combining experimental and modelling approaches to account for climatic variability and evaluate long-term effects of N_2O mitigation practices under Mediterranean conditions.

1. Introduction

The Mediterranean climate is defined by warm to hot, dry summers and mild to cool, wet winters. It is located between 30 and 45° north and south latitudes. Although it presents a large variability between regions, its common feature is the presence of a severe water deficit during the summer months, while in winter months rainfall usually exceeds evapotranspiration, leading to a soil water recharge (López-Bellido, 1992). Rainfall presents a high intra- and inter-annual variability, with an increasing trend of extreme events in spring and summer months (Ramos and Martínez-Casasnovas, 2006). Crops in the non-irrigated

* Corresponding author.
E-mail address: dplaza.bonilla@gmail.com (D. Plaza-Bonilla).

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Mediterranean areas strongly depend on the amount of water stored in soil during the recharge period (i.e. September to January) (Cantero-Martínez et al., 2007), and cropping systems are mainly based on winter cereals, given their cycle synchrony with water availability (López-Bellido, 1992; Álvaro-Fuentes et al., 2009). Crop dependence on soil water availability makes the interaction between climate and agricultural management a key issue both for crop production and N_2O emissions mitigation.

Nitrous oxide is a powerful greenhouse gas with a global warming potential (GWP) 265 times greater than carbon dioxide (IPCC, 2013). Besides its strong implication in radiative forcing, N_2O also influences the depletion of the ozone layer in the stratosphere (Crutzen, 1974). Soil N_2O emissions are the result of the nitrification-denitrification processes (Bremner, 1997). They are known to be highly dependent on mineral nitrogen availability and soil moisture. The continuous increase in fertilizer use since the invention of the Haber-Bosch process of industrial N_2 fixation has exacerbated N_2O emissions from soils (Gruver and Galloway, 2008). Nitrogen management has been traditionally oriented towards optimizing the use of N by the crop. In some areas, a significant fraction of N fertilizer is still applied before sowing, which, especially for winter crops, can enhance leaching losses in the rainiest locations and/or lead to an overuse of soil water due to the increase in plant transpiration during the vegetative stages. Because it remains difficult to optimize N fertilization strategies to crop needs under variable water stress conditions, the resulting periods of high mineral N availability can also induce N losses as N_2O. Different fertilization strategies have been tested as a means of mitigating N_2O emissions in the Mediterranean agroecosystems. Among them, (i) the adaptation of N fertilizer application to crop needs, (ii) the split of N fertilizer at key crop development stages, (iii) the use of organic and synthetic fertilizers, and (iv) the use of nitrification inhibitors (e.g. Aguilera et al., 2013; Meijide et al., 2007, 2009; Plaza-Bonilla et al., 2014a; Sanz-Cobena et al., 2012; Vallejo et al., 2001). Although there is a growing set of knowledge about the impact of fertilization management on N_2O emissions in the Mediterranean areas, the site and temporal specificity of the studies carried out limit our ability to establish general rules for optimized management practices at the regional level, according to climate idiosyncrasies. In particular it would be useful to better know, among fertilization management strategies, which ones are more strongly affected by a more or less pronounced aridity or precipitation variability. Process based models are complementary to site specific studies in that they have the potential to integrate a range of processes and to study the interactions between pedoclimatic conditions and agricultural management practices (De Antoni-Migliorati et al., 2015; Doltra et al., 2015).

The objectives of this study were to i) compile a dataset of N_2O emission obtained in Mediterranean conditions and evaluate the ability of a simulation soil-crop model (STICS) to predict the observed fluxes, ii) evaluate its ability to capture the effect of a gradient in mean precipitation and year to year irregularity on N_2O emissions in a Mediterranean transect and iii) to test the efficiency of several agricultural management strategies for mitigating N_2O emissions along such a climatic gradient.

2. Materials and methods

2.1. Selection of a representative precipitation transect under Mediterranean conditions

Three locations representative of the Mediterranean climate were chosen according to a rainfall gradient: Senés, Selvanera and Auzeville (Table 1). This choice was based on (i) the availability of soil N_2O emission data in (or close to) each location to validate the STICS model or check the range of simulated values (Plaza-Bonilla et al., 2014a; Peyrard et al., 2016) and (ii) the presence of cropping systems representative of dryland Mediterranean agriculture. Senés (NE Spain), representative of the Monegros county, was chosen as the lower yield potential threshold given its low annual precipitation (336 mm), large potential evapotranspiration (1250 mm) and long water deficit period (Fig. 1). The upper threshold of the transect was located in Auzeville (SW France) which represents one of the most northern latitude under

Table 1
Site and general soil characteristics in the 0–30 cm soil depth of the three experimental sites. HWD, MWD and LWD indicate high, medium and low water deficit, respectively. PET = potential evapotranspiration.

	Site		
	Senés (HWD)	Selvanera (MWD)	Auzeville (LWD)
Country/Region	Spain/Aragón	Spain/Catalonia	France/Midi-Pyrénées
Latitude	41°54′N	41°49′N	43°31′N
Longitude	0°30′W	1°17′E	1°30′E
Elevation (m)	395	470	150
Annual precipitation (mm)	327	450	685
Annual PET (mm)	1197	800	905
Annual water deficit (mm)[a]	870	350	220
Soil classification[b]	Typic Calcixerept	Fluventic Xerochrept	Typic Hapludalf
pH	8.0	8.3	7.0
Soil organic carbon ($g\,kg^{-1}$)	15.6	10.5	8.7
$EC_{1:5}$ ($dS\,m^{-1}$)	1.04	0.16	0.0
CaCO3 eq. (%)	29.5	35.0	0.3
Water retention (% vol.) at			
−33 kPa	26.8	27.3	30.7
−1500 kPa	13.9	12.1	12.8
Particle size distribution (%)			
Sand (2000–50 μm)	6.2	36.5	37.6
Silt (50–2 μm)	63.3	46.4	36.8
Clay (2 μm)	30.5	17.1	25.6
Rooting depth (m)	0.6–0.9	0.9–1.0	1.2

[a] Calculated as the difference between annual precipitation and annual evapotranspiration.
[b] According to the USDA classification (Soil Survey Staff, 2014).

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