Simulating climate change and land use effects on soil nitrous oxide emissions in Mediterranean conditions using the Daycent model

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Abstract

In Mediterranean agroecosystems, limited information exists about possible impacts of climate change on soil N_2O emissions under different land uses. This paper presents a modelling study with a dual objective. Firstly, the biogeochemical model Daycent was evaluated to predict soil N_2O emissions in different land uses in a typical Mediterranean agroecosystem. Secondly, the study aimed to determine the impact of climate change on soil N_2O emissions in different Mediterranean land uses over a 85-year period. Soil N_2O emissions were measured in three land uses (cropland, abandoned land and afforested land) during 18 months (December 2011 to June 2013) in a characteristic Mediterranean site in Spain. For climate change simulations, Daycent was run with and without atmospheric CO_2 enrichment using climate data from the CGCM2-A2 model. The cumulative N_2O emissions predicted by the Daycent model agreed well with the observed values. The lack of fit (LOFIT) and the relative error (E) statistics determined that the model error was not greater than the error in the measurements and that the bias in the simulation values was lower than the 95% confidence interval of the measurements. For the different land uses and climate scenarios, annual cumulative N_2O emissions ranged from 126 to 642 g N_2O-N ha^{-1} yr^{-1}. Over the 85-year period simulated, climate change decreased soil N_2O emissions in all three land uses. At the same time, under climate change, water filled pore space (WFPS) values decreased between 4% and 15% depending on the land use and climate change scenario considered. This study demonstrated the ability of the Daycent model to simulate soil N_2O emissions in different land uses. According to model predictions, in Mediterranean conditions, climate change would lead to reduction in N_2O emissions in a range of land uses.

Keywords: Daycent model, Soil greenhouse gas emissions; Land use; Mediterranean agroecosystems

1. Introduction

In southern European drylands, agricultural landscapes are a mosaic of different land uses, mainly croplands, abandoned fields and afforested areas. The presence of different land uses responds to different causes such as limited plot access and workability, agricultural policies and subsidies. The co-existence of croplands and other land uses within the same area is recognized as an optimal strategy to enhance resources for agriculture and resilience during environmental change (Rey Benayas and Bullock, 2012). In this context, the new Common Agricultural Policy (CAP) reform encourages European farmers to maintain natural areas (the so-called "ecological focus areas") within their farms through the Greening payment scheme (European Commission, 2013). Under the new CAP, fallow land, afforested areas and field margins, are some of the land uses that shall be maintained in at least 5% of the total arable land in order to receive part of the total subsidy. Consequently, the reform could promote changes in the distribution of land dedicated to different uses in European agroecosystems.

Agricultural soils are the main contributor to global atmospheric nitrous oxide (N_2O) levels (Smith et al., 2007). Nitrous oxide is not only a powerful greenhouse gas but also an important stratospheric ozone-depleting substance (Ravishankara et al., 2009). Over the last 150 years, N_2O emissions from soils have increased from 11 to 18 Tg N yr^{-1} (Kroeze et al., 1999). Land use change has a significant impact on soil N_2O emissions (Mosier et al., 1997; Merino et al., 2004; Galbally et al., 2008). Variations in environmental and soil factors after a change from cropland to either forest or grassland can also have important impacts on soil N_2O emissions (Corre et al., 1996; Stehfest and

Bouwman, 2006). Thus, the adoption of certain on-farm decisions affecting the distribution of land uses throughout agricultural landscapes can have a noteworthy impact on the global atmospheric N_2O balance. At the same time, changes in climate can also impact the processes and factors controlling soil N_2O production and emission (Brevik, 2012). Thus, for instance, not only changes in soil water content and soil temperature but also changes in soil mineral nitrogen (N) and carbon (C) availability due to different climate conditions can have significant effects on N_2O emissions (Weier et al., 1993; Brevik, 2012; Luo et al., 2013). In this sense, biogeochemical models are interesting tools to evaluate the future impacts of climate on C and N dynamics and, in turn, on N_2O emissions. The link of climate outputs from atmosphere-ocean general circulation models (AOGCM) and biogeochemical models have been successfully used to predict climate change impacts on soil N_2O emissions (Kesik et al., 2006; Abdalla et al., 2010).

Mediterranean areas surround the homonymous sea and extend between latitudes 40 and 30° N over an area of some 4,300,000 km^2 (LeHouerou, 1992). In these areas, future climate scenarios predict an increase in warming and a decrease in precipitation (Gibelin and Dequé, 2003). These changes can have a significant impact on the processes controlling soil N_2O emissions in these areas, characterized by low annual precipitation and high evapotranspiration rates limiting net primary production. Up to date, the information about soil N_2O emissions in semiarid areas is limited (Galbally et al., 2008). At the same time, limited information exists about possible impacts of warming and CO_2 enrichment on soil N_2O emissions in Mediterranean agroecosystems. Accordingly, this paper presents a modelling study with a dual objective. Firstly, the biogeochemical model Daycent was evaluated to predict soil N_2O emissions in different land uses in a typical Mediterranean agroecosystem. Secondly, the study aimed to determine the impact of climate change and atmospheric CO_2 enrichment on soil N_2O emissions in different Mediterranean land uses. To accomplish both objectives soil N_2O emissions measurements were carried out in three land uses (cropland, abandoned land and afforested land) during 18 months in a typical Mediterranean site. Experimental data was used to evaluate the Daycent model, which was next used to simulate soil N_2O emissions under climate change conditions.

2. Methods

2.1. Experimental data

An experiment to evaluate the performance of the Daycent model in Mediterranean conditions was set up in Senés de Alcubierre, NE Spain (41º 54’ 12’’ N; 0º 30’ 15’’ W; 395 masl). The climate is continental Mediterranean with a mean annual precipitation and mean air temperature of 334 mm and 13.4 ºC, respectively. The most frequent soil type in the study area is *Typic Calcixerept* (Soil Survey Staff, 1994), whose main characteristics are presented in Table 1. The study area was selected as a representative Mediterranean dryland area with low annual precipitation (<350 mm) and high PET (1207 mm), showing the typical north-central Spain rainfall distribution with most precipitation occurring in spring and autumn (Austin et al., 1998) (Fig. 1). The agricultural landscape of the selected area represents the typical dryland Mediterranean agroecosystem with a mosaic of barley and wheat fields, almond and vineyard orchards, abandoned fields and pine plantations.

For model evaluation purposes, three adjacent fields were chosen with different land uses: cropland (CR), afforested land (FR) and abandoned land (AB). The CR field, with 2.3 ha, consisted of a barley (*Hordeum vulgare L.*) monoculture system under no-tillage for the last six years. Previously, the barley field had been tilled with a chisel plough every September during the last 30 years. Over this period, applications of mineral fertilizers were performed regularly at planting (September) and tillering (February) stages of the crop providing 30 to 40 kg N ha^{-1} per crop. During the two growing seasons in which soil N_2O measurement were performed (i.e., 2011-2012 and 2012-2013) the field was only fertilized during the first growing season at planting (September 2011) with 40 kg N ha^{-1} in the form of ammonium sulphate (21% N). The FR plantation, with a total surface of 0.9 ha and a tree density of 625 trees ha^{-1}, was established 50 years ago as part of an Aleppo pine (*Pinus halepensis L.*) afforestation plan in the area. In the pine plantation, which remained unmanaged since its establishment, the only exploitation has been the harvest of the pinecones once per year. Pine needles have accumulated on the forest floor to form a 7-8 cm thick layer. The AB field, with a total surface of 0.7 ha, was cultivated until 2003. From that year, no operations were performed and spontaneous vegetation growths with the predominance of the following grass species: Poaceae (*Bromus sp L.*; *Hordeum murinum L.*); Brasicaceae (*Lepidium draba L.*; *Sinapsis arvense L.*); Fabaceae (*Medicago orbicularis L.*; *Vicia sativa L.*); Asteraceae (*Silybum marianum L.*, *Anacyclus clavatus L.*); Papaveraceae (*Papaver rhoeas L.*); Malbaceae (*Malva silvestris L.*); and Tamaricaceae (*Tamarix gallica L.*).

In November 2011, a representative area of 400 m^2 was delimited in each land use and six (FR and CR) and five (AB) subsampling points were randomly selected. In each of these points, one polyvinyl chloride ring (31.5 cm internal diameter) was inserted into the soil to a depth of 5 cm. The rings were left in the soil for the entire study except in the CR land use in which they were removed during planting and reinserted in the same place afterwards. Vented chambers of the same material and 20-cm height were fitted into the rings when the measurements were performed. The chambers were covered with a reflective insulation layer to avoid internal increases of temperature during their deployment. Soil N_2O emissions were measured every two to three weeks throughout the entire study period (December 2011-June 2013). Gas samples of 17 mL were obtained with polypropylene syringes at 0, 30 and 60 minutes after closing the chamber. Measurements were carried out at the same time on each sampling date to avoid diurnal variation. Each sample was immediately injected into 12 mL Exetainer® borosilicate vials (model 038W, Labco, High Wycombe, UK). Gas samples were analysed with an Agilent 7890A gas chromatography system equipped with an electron-capture (ECD) detector. Emission rates were calculated taking into account the linear increase in gas concentration in the chamber over time and correcting for air temperature. At every sampling date, and near each gas sampling chamber (less than 1 m apart), soil temperature at 5 cm depth was measured with a soil temperature probe and a soil sample from the 0-5 cm soil depth was collected for soil water content determination by oven drying the soil samples at 105 ºC until constant weight and soil nitrate (NO_3^-) by extraction with KCl. The water filled pore space (WFPS) was calculated as the quotient between soil volumetric water content (VWC) and total porosity. Soil porosity was estimated as a function of soil bulk density assuming a soil particle density of 2.65 Mg m^{-3} (e.g. Plaza-Bonilla et al. 2014). Soil bulk density was determined by with the cylinder method (Grossman and Reinsch, 2002).

2.2. Daycent model description and evaluation

The Daycent model (Parton et al., 1998; Del Grosso et al., 2011) is the daily version of the biogeochemical model Century (Parton et al., 1987) created to simulate C, N, sulphur (S) and phosphorous (P) dynamics at a monthly step in different ecosystems. Daycent includes several submodels that simulate plant production, soil organic carbon

(SOC) decomposition, methane (CH_4) oxidation, nitrification, denitrification and soil temperature and water content from a multi-layered soil system (Parton et al., 1998). Primary model inputs are: daily maximum and minimum air temperature, daily precipitation, management data (e.g. fertilization, tillage, harvest), and soil texture by horizon (Del Grosso et al., 2011).

The N gas submodel simulates N_2O, NO_x from nitrification and denitrification, and N_2 from denitrification. In the model, different soil parameters control N fluxes from nitrification (i.e., water content, NH_4^+, temperature and texture) and from denitrification (i.e., NO_3^-, water content and labile C) (Parton et al., 2001). Furthermore, in Daycent denitrification increases exponentially between 50-60% and 70-80% WFPS and heterotrophic respiration is used as a proxy for labile C availability (del Grosso et al., 2011). A more detailed description of the Daycent model can be found in Del Grosso et al. (2011) and Parton et al. (2001).

The SOC submodel is composed of different pools with different turnover rates. Four of these C pools represent surface and soil litter (metabolic and structural) and the other three pools (i.e., active, low and passive) represent SOC. The initialization of C pools of the model was done similarly to previous studies performed with the Century model under similar conditions (Álvaro-Fuentes et al., 2009; 2012). Briefly, the model was run for 5000 years under a grazed grass system to initialize the most recalcitrant pool. For the last 200 years previous to the establishment of the experiment, past agricultural management in the area was obtained from the literature and directly from farmers (Álvaro-Fuentes et al., 2011). Historically, management in the study area consisted of cereal-fallow rotation, with use of intensive tillage and removal of most of the straw produced. For the last 30 years, tillage intensity was reduced (i.e., substitution of mouldboard ploughs by cultivators) and mineral fertilizers were applied. Table 2 presents the observed and simulated total SOC values at the beginning of the experiment once the initialization process was completed (December 2011).

Measured soil parameters at the beginning of the experiment (Table 1), climate data obtained from a weather station located 2-km apart (Fig. 2) and specific land use and management data for the three experimental fields were used to run the model. Crop and tree growth was parameterized differently for each land use. Barley crop and pine tree were modelled with similar crop.100 and tree.100 parameterization files used in previous studies under similar conditions (Álvaro-Fuentes et al., 2009; 2012). However, the grass growth in the AB field was modelled considering a default Daycent grass parameterization (i.e., GI4) consisting of a mix of grasses (25% warm and 75% cool).

Model evaluation was performed comparing simulated values with the daily observed data obtained in the land use experiment. Two statistical tests were chosen to evaluate the performance of the model in simulating N_2O emissions. The first one was the lack of fit (LOFIT), which has been proposed as a suitable test to determine degree of coincidence when replicated values are available (Smith et al., 1997).

The LOFIT was calculated, together with its associated *F* value in order to compare the variances of the model predictions with the error in the measurements, as follows:

$$\mathrm{LOFIT} = \sum_{i=1}^{n} m_i (O_i - P_i)^2$$

$$F = \frac{\sum_{i=1}^{n} (m_i - 1) \times \mathrm{LOFIT}}{n \sum_{i=1}^{n} \sum_{j=1}^{m_i} \left((O_{ij} - P_i) - (O_i - P_i) \right)^2}$$

where m_i is the number of replicates in each land use, O_i is the mean of the observed values in the ith sampling date, P_i is the simulated value in the ith sampling date, and n is the number of sampling dates.

The relative error (E) was also calculated to evaluate the bias in the difference between simulated and measured N_2O values:

$$E = \frac{100}{n} \frac{\sum_{i=1}^{n} (O_i - P_i)}{\bar{O}}$$

where $\bar{O}$ is the average of all the observed values.

The E statistics was evaluated against the E value assuming a deviation of the 95% confidence interval of the measurements (Smith and Smith, 2007).

$$E_{95\%} = \frac{100}{n} \frac{\sum_{i=1}^{n} (\mathrm{SE}_i - t_{m,95})}{\bar{O}}$$

where SE_i is the standard error of the observed values in the ith sampling date and $t_{m,95}$ is the Student's value for $n - 2$ and 95% probability (P value of 95%).

Calculations were made using the MODEVAL program (Smith et al., 1996). Likewise, regression analyses between observed and simulated soil surface temperature (5 cm depth) and VWC (0-5 cm depth) were also performed.

2.3. Simulation under climate change conditions

The Daycent model was used to simulate the impact of climate change on soil N_2O emissions under different land uses in Mediterranean conditions. The parameterization obtained for each land use was used to run the model for the 2015-2100 period, under three different future scenarios: (i) a baseline scenario with current mean weather conditions (baseline); (ii) a climate change scenario with weather data from the climate model CGCM2 forced by the A2 IPCC emission scenario previously used in Álvaro-Fuentes et al. (2012) (CC); and (iii) a climate change plus atmospheric CO_2 increase scenario (CC+CO_2). This last scenario was built with the weather outputs from the same CGCM2-A2 climate model and considering an atmospheric CO_2 concentration of 856 ppmv by the year 2100 (Nakicenovic et al., 2000). We assumed a linear CO_2 concentration increase over time. For the study area, the CGCM2-A2 model predicted a reduction in annual precipitation (from 345 mm yr^{-1} to 310 mm yr^{-1} in the baseline and climate change scenarios, respectively) and an increase in maximum and minimum air temperature (from 21.0 and 7.0 ºC to 21.5 and 9.6 ºC, in the baseline and climate change scenarios, respectively). Also, the climate model predicted a change in the monthly distribution of precipitation in which the autumn and spring rainfall peaks characteristics of some Mediterranean-climate areas would disappear and a steady monthly precipitation distribution would occur (Fig. 3). The climate change data were produced by the Meteorological State Agency (Spanish Ministry for Environment and Rural and Marine Affairs) using a regionalization technique explained in Brunet et al. (2008) to better adjust the climate change scenario to the conditions of the study area.

For the 2015-2100 period, the same three land uses were simulated under the three climate scenarios. The FR and AB land uses were modelled with the same parameterization and events as for the files used during the 2011-2013 model evaluation period. In the CR land use, however, the agricultural management simulated consisted of a barley no-tillage, medium-fertilized barley system, with annual mineral fertilizer rates of 60 kg N ha^{-1} split between sowing (50%) and top dressing (50%). This could be considered a typical cropping system in southern European dryland agroecosystems in which NT adoption is successfully spreading (Soane et al., 2012).

3. Results

3.1. Weather conditions

Monthly air temperature and precipitation over the study period is presented in Fig. 2. From December 2011 to June 2012 (first growing season) the precipitation registered was 172 mm. However, in the second growing season sampled (from December 2012 to June 2013) the precipitation raised to 270 mm (Fig. 2). Comparing these two values with the average seasonal precipitation for the site (204 mm; Fig. 1), the 2011-2012 and 2012-2013 growing seasons could be considered drier and wetter than the average, respectively. Air temperatures during the experimental period followed the same pattern as the average values with hot summers and cold winters typical of the Mediterranean region (Figs. 1 and 2).

3.2. Daycent model performance

Soil N_2O emissions were measured in three land uses from December 2011 till June 2013. Figure 4 shows the comparison between observed and simulated daily N_2O emissions for the three land uses. In the CR land use, the Daycent model tended to underestimate N_2O emissions in four out of ten sampling dates during the 2011-2012 growing season (December 2011 – June 2012). However, in the three sampling dates of April and May 2013 the model overestimated N_2O emissions (Fig. 4). In late August, the model predicted a sharp increase in the emissions, which lasted one day (achieving 37 g N_2O-N ha^{-1} day^{-1}). During the summer fallow season (July – October 2012), net N_2O uptake was observed in four out of five sampling dates, while for the same dates, the Daycent model estimated a net N_2O emission (Fig. 4). In the AB land use, during November and December of 2012, the model was able to predict the observed increase in N_2O emissions, but for a shorter period of increased N_2O emissions than the observed values (Fig. 4). From December 2012, the Daycent model predicted quite well the steady and near zero observed N_2O emissions. In the FR land use, the model tended to underestimate N_2O emissions during three out of the five sampling dates performed during the first four months (December 2011 – March 2012), when observed values showed the greatest deviation, but came close to the observed values throughout the remaining study period. The model predicted two sharp increases in June and September 2012. Similar to the observed in the CR field, these increases lasted for one day (Fig. 4).

The LOFIT and E tests were used to statistically analyse the performance of the model. In the three land uses, the *F* values associated to the LOFIT statistic were lower than the *F* critical 5% (Table 3). Consequently, the model error is not greater than the error in the measurements. In the three land uses, the calculated E statistic was lower than the 95% confidence interval of E (E_{95}) denoting that the bias in the simulation values was lower than the 95% confidence interval of the measurements (Table 3).

Observed and simulated cumulative N_2O emissions throughout the entire study are shown in Fig. 5. The cumulative N_2O emissions predicted by the Daycent model agreed well with the observed values. Simulated cumulative N_2O emissions were 868, 569 and 501 g N_2O-N ha^{-1} while observed values were 787, 618 and 442 g N_2O-N ha^{-1} for CR, AB and FR, respectively (Fig. 5). Consequently, in the three land uses, the difference between the observed and the simulated cumulative N_2O value ranged between 8% and 13%.

In general, the linear regressions between observed and simulated soil temperature and VWC values showed good agreement in the three land uses (Table 4). The only exception was the VWC for the AB and FR land uses where the slope somewhat differed from 1 (Table 4). However, the model was not able to simulate well the soil nitrate levels in the first 5 cm soil depth (Table 4).

3.3. Simulated N_2O emissions under climate change

Over the 85-year period simulated, climate change decreased soil N_2O emissions in all three land uses. For the different land uses and climate scenarios, annual cumulative N_2O emissions ranged from 126 to 642 g N_2O-N ha^{-1} yr^{-1} (Table 5). The reduction was different depending on the land use considered. In the CR land use, N_2O reductions in the CC+CO_2 and CC scenarios were about 11% and 17%, respectively, compared with the baseline scenario (Table 5). In the AB land use, the reduction in the N_2O emitted was about 4% and 20% for the CC and CC+CO_2 scenarios, respectively, and, finally, in the FR land use about 3% and 10%, respectively (Table 5).

For the 2015-2100 period, the Daycent model predicted higher cumulative N_2O emissions in the climate change scenarios (CC and CC+CO_2) than in the baseline scenario until the 2050-2060 decade (Fig. 6). However, after 2060, cumulative emissions in the baseline scenario tended to be slightly higher than in the other two CC scenarios until 2100.

All three land uses showed higher soil temperature to 20 cm depth (between 0.9 and 1.8 ºC) under climate change conditions. However, WFPS decreased in all three scenarios under climate change. The decrease in WFPS varied between 4% and 15% depending on the land use and climate change scenario considered (Table 5). In the case of the CR land use, the yearly evolution of the WFPS through the 2015-2100 period showed a sharply decrease after 2040 in both climate change scenarios while the values in the baseline scenario kept steady (Fig. 7).

4. Discussion

4.1. Evaluation of the Daycent model

The two statistics used demonstrated the ability of the Daycent model to simulate soil N_2O emissions in different land uses of the Mediterranean region. The Daycent model has been used to model soil N_2O emissions in different agroecosystems worldwide (e.g., Del Grosso et al., 2008; Fitton et al., 2014) but little work has been done previously in Mediterranean conditions. Recently, Lee et al. (2015) simulated the effects of switchgrass management on soil greenhouse gas emissions using the Daycent model in the Mediterranean climate conditions of California. In our representative conditions of the Mediterranean basin and for the three land uses, both the LOFIT and the E statistics indicated good performance of the model despite some exceptions occurred.

The N_2O emissions measured in our study were relatively low compared with the values observed in other agroecosystems located in more humid areas (Rees et al., 2013). In a meta-analysis published in this same issue, Cayuela et al. (201X) have analysed N_2O emissions from Mediterranean cropping systems. The observed values measured in the CR land use were even lower than the mean cumulative N_2O emission of 0.7 kg N_2O-N ha^{-1} estimated in the meta-analysis for rainfed systems (Cayuela et al., 201X). Although there are several factors that regulate the processes involved in the production of this gas, soil water content has been identified as a key factor (Linn and Doran, 1984; Butterbach-Bahl et al., 2013). The low N_2O fluxes observed are consistent with the low WFPS values measured, and less than critical values often cited for invoking denitrification (Barton et al., 1999, Sanz-Cobena et al., in press). Although nitrification and denitrification are two major processes contributing to N_2O formation in soils (Venterea et al., 2012), the limited soil water content observed in our study suggests that N_2O emissions would be mostly originated from nitrification as indicated by Plaza-Bonilla et al. (2014) working in similar conditions. Other processes could be also contributing to N_2O emissions. Processes such as nitrifier denitrification could have a significant effect in the production of soil N_2O under limited soil water availability (Kool et al., 2011; van Groenigen et al., 2015). However, the Daycent model simulates N_2O emissions derived only from nitrification and denitrification. Consequently, the model does not simulate soil N_2O emissions derived from other processes (e.g., nitrifier denitrification), which could result in the underestimation of N_2O emissions under low soil water conditions. This last could contribute to explain the behaviour of the model in certain sampling dates during the first growing season in which a slight tendency to underestimate N_2O emissions was observed. Furthermore, in the three land uses, negative N_2O fluxes were measured, especially during the fallow period (i.e., July-October 2012) in the CR field. Despite the processes involved are not entirely understood, N_2O sink records have been obtained under drought conditions in croplands (Meijide et al., 2009; Plaza-Bonilla et al., 2014) and forests (Goldberg and Gebauer, 2009). In our study, although the 85% of negative values were not statistically different from zero, these negative emissions could contribute to reduce the adjustment between observed and simulated values since the Daycent model does not simulate N_2O uptake.

4.2. Climate change simulations

In Mediterranean agroecosystems, limited information exists about the impacts of climate change on N_2O emissions. Soil N_2O emissions from manipulative experiments have not been previously reported for the Mediterranean basin (Dijkstra et al. 2012). At the same time, to our knowledge, simulation models have not been previously used to predict the impact of climate change on soil N_2O emissions in Mediterranean agroecosystems.

The Daycent model predicted a reduction in soil N_2O emissions under climate change conditions in all three land uses.. It is expected that the increase in soil temperature that the model predicted under climate change conditions in our Mediterranean conditions (1.5 ºC to 20 cm soil depth) could stimulate microbial activity and thus nitrification and denitrification processes (Smith, 1997). However, in our modelling experiment, the increase in soil temperature did not result in an increase in soil N_2O emissions. As commented previously, recent research suggest that in dryland conditions soil N_2O is produced mainly throughout nitrification (Galbally et al., 2008; Plaza-Bonilla et al., 2014) and the low soil moisture content typical of arid and semiarid areas is a main limiting factor for soil N_2O emissions (Martins et al., 2015). The Daycent model simulates an exponential increase in N_2O production by nitrification with temperature but this increase is limited by soil moisture stress (Parton et al., 2001; Del Grosso et al., 2011). Considering the three climate scenarios, the mean WFPS values predicted by the Daycent model were about 42%, 25% and 22% for the CR, AB and FR land uses, respectively. Particularly, for the AB and FR land uses, mean WFPS values are in the lowest limit at which N_2O from nitrification is produced (Linn and Doran, 1984; Davidson, 1991). For these two land uses, the Daycent model predicted about 20% reduction in the N_2O produced by nitrification under climate change conditions (data not shown). The mean WFPS did not vary substantially between the baseline and the climate change scenarios since the CGCM2-A2 climate model only predicted about 10% reduction in annual precipitation under climate change conditions. However, more important than the total reduction in precipitation would be the change in the typical annual precipitation distribution pattern that the climate change model predicts. The predicted increase in precipitation in summer under climate change could not greatly contribute to enhance WFPS since higher summer temperatures would increase soil water loss by evaporation.

The temporal evolution of the N_2O emissions during 2015-2100 was opposite to the evolution of the WFPS. This difference in the two trends revealed that as the future simulated period progressed, the more critical dry conditions in the climate change scenarios constrained WFPS and thus N_2O emissions. It is important, however, to remark that during the evaluation of the model, it was detected a slight underestimation of N_2O fluxes in certain dates when WFPS was low. Consequently, the accuracy of the predictions obtained in the climate change scenarios could be conditioned by the performance of the model found under drought conditions.

Atmospheric CO_2 enrichment showed a different effect on N_2O emissions depending on the land use analysed. CO_2 enrichment tends to stimulate crop growth and production, particularly in C3 plants such as the barley crop simulated in the present study (Lobell and Gourdji, 2012). The Daycent model predicted about 40% greater mean barley biomass production in the CC+CO_2 scenario compared with the CC scenario (data not shown). Furthermore, over the 85 years simulated and for CR, the CC+CO_2 scenario stored greater SOC when compared with the CC scenario (0.25 vs. 0.17 Mg C ha^{-1} yr^{-1} in CC+CO_2 and CC, respectively) but did not result in a marked effect on WFPS. After certain rainfall events, the greater organic C levels in the CC+CO_2 scenario could favour higher denitrification rates compared with the CC scenario as predicted by the Daycent model (Dijkstra et al., 2013). However, in the FR and AB land uses the opposite trend was observed, with lower N_2O emitted in the scenario with atmospheric

CO_2 enrichment. In these two land uses, the lack of N fertilization together with the increase in N demand for plant growth due to CO_2 enrichment could limit soil N availability for nitrification (Dijkstra et al., 2012).

The results observed in this work about the impacts of climate change on soil N_2O emissions should be taken with caution due to the large sources of uncertainty associated with this type of modelling studies, particularly that derived from input data and model formulation (Hastings et al., 2010; Ogle et al., 2010). Regarding the input data, the climate scenarios themselves can be a possible source of uncertainty (Álvaro-Fuentes and Paustian, 2011). Biases in the precipitation and temperature predictions in climate models can severely impact the N_2O emissions rates obtained due to the significant control of climate over N_2O production and emission. Another limitation of this study is the fixed agricultural management modelled in the CR land use over the 85 years. Regarding to this, it is expected that management practices will change over the next decades introducing new plant material and technology (e.g., crop varieties, machinery, fertilization) that may be designed in the future, especially if climate change predictions are achieved (Álvaro-Fuentes et al., 2012). The functioning of the Daycent model also presents some limitations that may contribute to the uncertainty of our results. For example, as commented in the previous section, the Daycent model is not able to simulate N_2O consumption values. Dijkstra et al. (2013) in a manipulative semiarid grassland experiment found that soil moved from a net sink to a net source of N_2O when climate change conditions were imposed. Consequently, in our experimental conditions, climate change conditions could also modify the soil’s ability to be a net or sink of N_2O.

5. Conclusions

We evaluated the Daycent model to simulate soil N_2O emissions under three different land uses (i.e., cropland, afforested land and abandoned land) in semiarid Mediterranean conditions. Despite the differences found between observed and simulated daily N_2O emissions values, the two statistics used (i.e., LOFIT and E) to evaluate model's performance demonstrated the ability of the Daycent model to simulate annual soil N_2O emissions from these land uses.

The Daycent model was also used to predict soil N_2O emissions from the same land uses under climate change conditions. For all three land uses, the model predicted a slight negative response of N_2O emissions to climate change. Significantly low soil moisture contents, typical in semiarid Mediterranean areas, could weaken the possible positive effect of warming on soil N_2O emissions. Since soils are the main contributors to global atmospheric N_2O levels, and taking into account the uncertainty associated with simulation studies, the results of the present work may contribute understanding the future role of Mediterranean soils as net sinks or sources of greenhouse gases under a changing climate as a function of land use.

Acknowledgments

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References

Abdalla, M., Jones, M., Yeluripati, J., Smith, P., Burke, J., Williams, M. 2010. Testing DayCent and DNDC model simulations of N2O fluxes and assessing the impacts of climate change on the gas flux and biomass production from a humid pasture. Atmospheric Environ. 44, 2961–2970.

Álvaro-Fuentes, J., Morell, F. J., Plaza-Bonilla, D., Arrúe, J. L., Cantero-Martínez, C. 2012. Modelling tillage and nitrogen fertilization effects on soil organic carbon dynamics. Soil Tillage Res. 120, 32–39.

Álvaro-Fuentes, J., López, M.V., Arrúe, J.L., Moret, D., Paustian, K. 2009. Tillage and cropping effects on soil organic carbon in Mediterranean semiarid agroecosystems: Testing the Century model. Agric., Ecosyst. Environ. 134, 211-217.

Álvaro-Fuentes, J., Easter, M., Cantero-Martínez, C., Paustian, K. 2011. Modelling soil organic carbon stocks and their changes in the northeast of Spain. Eur. J. Soil Sci. 62, 685–695.

Álvaro-Fuentes, J., Paustian, K. 2011. Potential soil carbon sequestration in a semiarid Mediterranean agroecosystem under climate change: Quantifying management and climate effects. Plant Soil 338, 261–272.

Austin, R.B., Cantero-Martínez, C., Arrúe, J.L., Playán, E., Cano-Marcellán, P. 1998. Yield-rainfall relationships in cereal cropping systems in the Ebro river valley of Spain. European Journal of Agronomy 8, 239-248.

Barton, L., McLay, C.D.A., Schipper, L.A., Smith, C.T. 1999. Annual denitrification rates in agricultural and forest soils: a review. Aust. J. Soil Res. 37, 1073-1093.

Brevik, E.C. 2012. Soils and climate change: gas fluxes and soil processes. Soil Horizons 53, 12-23.

Brunet, M., Casado, M.J., de Castro, M., Galán, P., López, J.A., Martín, J.M., Pastor, A., Petisco, E., Ramos, P., Ribalaygua, J., Rodríguez, E., Sanz, I., Torres, L. 2008. Generación de escenarios regionalizados de cambio climático para España. Agencia Estatal de Meteorología. Ministerio de Medio Ambiente, Medio Rural y Marino. Gobierno de España.

Butterbach-Bahl. K., Baggs, E.M., Dannenmann, M., Kiese, R., Zechmeister-Boltenstern S. 2013. Nitrous oxide emissions from soils: how well do we understand the processes and their controls? Phil. Trans. R. Soc. B. 368, 20130122.

Cayuela, M.L., Aguilera, E., Sanz-Cobena, A., Adams, D.C., Abalos, D., Barton, L., Ryals, R., Silver, W.L., Alfaro, M.A., Pappa, V.A., Smith, P., Garnier, J., Billen, G., Bouwman, L., Bondeau, A., Lassaleta, L. 201X. Direct nitrous oxide emissions in Mediterranean climate cropping systems: emission factors based on meta-analysis of available measurement data. Agric. Ecosys. Environ. XX (this issue).

Corre, M.D., van Kessel, C., Pennock, D.J. 1996. Landscape and seasonal patterns of nitrous oxide emissions in a semiarid region. Soil Sci. Soc. Am. J. 60, 1806–1815.

Davidson, E.A. 1991. Fluxes of nitrous oxide and nitric oxide from terrestrial ecosystems. In: Rogers, J.E., Whitman, W.B. (Eds.), Microbial production and consumption of greenhouse gasses: methane, nitrogen oxides and halomethanes. American Society for Microbiology; Washington, USA, pp. 219-235.

Del Grosso, S. J., Halvorson, A. D., Parton, W. J. 2008. Testing DAYCENT model simulations of corn yields and nitrous oxide emissions in irrigated tillage systems in Colorado. J. Environ. Qual. 37, 1383-1389.

Del Grosso, S. J., Parton, W. J., Keough, C. A., Reyes-Fox, M. 2011. Special features of the DayCent modeling package and Additional Procedures for Parameterization, Calibration, Validation, and applications. In: Ahuja, L., Ma, L. (Eds.), Methods of introducing system models into agricultural research. Advances in Agricultural Systems. Modeling Series 2; Madison, Wisconsin, USA, pp. 155–176.

Dijkstra, F.A., Prior, S.A., Runion, G.B., Torbert, H.A., Tian, H., Lu, C., Venterea, R.T. 2012. Effects of elevated carbon dioxide and increased temperature on methane and nitrous oxide fluxes: evidence from field experiments. Front. Ecol. Environ. 10, 520-527.

Dijkstra, F.A., Morgan, J.A., Follett, R.F., LeCain, D.R. 2013. Climate change reduces the net sink of CH_4 and N_2O in a semiarid grassland. Global Change Biol. 19, 1816-1826.

European Comission. 2013. CAP Reform – an explanation of the main elements. MEMO/13/621. Available at: http://europa.eu/rapid/press-release_MEMO-13-621_en.htm

Fitton, N., Datta, A., Smith, K., Williams, J.R., Hastings, A., Kuhnert, M., Topp, C.F.E., Smith, P. 2014. Assessing the sensitivity of modelled estimates of N_2O emissions and yield to input uncertainty at a UK cropland experimental site using the DailyDayCent model. Nut. Cycl. Agroecosyst. 99, 119–133.

Galbally, I.E., Kirstine, W.V., Meyer, C.P. M., Wang, Y.P. 2008. Soil-atmosphere trace gas exchange in semiarid and arid zones. J. Environ. Qual. 37, 599-607.

Gibelin, A.L., Déqué, M., 2003. Anthropogenic climate change over the Mediterranean region simulated by a global variable resolution model. Clim. Dyn. 20, 327–339.

Goldberg, S.D., Gebauer, G. 2009. Drought turns a Central European Norway spruce forest soil from an N_2O source to a transient N_2O sink. Global Change Biol. 15, 850–860.

Grossman, R.B.; Reinsch, T.G. (2002). Bulk density and linear extensibility. In: Dane, J.H.; Topp, G.C. (eds). Methods of soil analysis. Part 4. Physical methods. SSSA Book Ser. 5. SSSA, Madison, pp 201-228.

Hastings, A.F., Wattenbach, M., Eugster, W., Li, C., Buchmann, N., Smith, P. 2010. Uncertainty propagation in soil greenhouse gas emission models: An experiment using the DNDC model and at the Oensingen cropland site. Agric. Ecosys. Environ. 136, 97–110.

Kesik, M., Brüggeman, N., Forkel, R., Kiesse, R., Knoche, R., Li, C., Seufert, G., Simpson, D., Butterbach-Bahl, K. 2006. Future scenarios of N2O and NO emissions from European forest soils. Journal of Geophysical Research 111, G02018

Kool, D.M., Dolfing, J., Wrage, N., Van Groenigen, J.W. 2011. Nitrifier denitrification as a distinct and significant source of nitrous oxide from soil. Soil Biol. Biochem. 43, 174–178.

Kroeze, C., Mosier, A., Bouwman, L. 1999. Closing the global N_2O budget: A retrospective analysis 1500-1994. Global Biogeochemical Cycles 13, 1-8.

Lee, J., Pedroso, G., van Kessel, C., Six, J. 2015. Potential regional productivity and greenhouse gas emissions of fertilized and irrigated switchgrass in a Mediterranean climate. Agric. Ecosys. Environ. 212, 64-74.

LeHouerou, H.N. 1992. Vegetation and land use in the Mediterranean Basin in the year 2050: a prospective study. In: L. Jeftic, J.D. Milliman and G. Sestini (Eds.). Climatic change and the Mediterranean, Vol. 1, pp. 175-232.

Linn, D.M., Doran, J.W. 1984. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. Soil Sci. Soc. Am. J. 48, 1267–1272.

Lobell, D.B., Gourdji, S.M. 2012. The Influence of Climate Change on Global Crop productivity. Plant Physiol. 160, 1686–1697.

Luo, G.J., Kiese, R., Wolf, B., Butterbach-Bahl, K. 2013. Effects of soil temperature and moisture on methane uptake and nitrous oxide emissions across three different ecosystem types. Biogeosciences 10, 3205–3219.

Martins, C.S.C., Nazaries, L., Macdonald, C.A., Anderson, I.C., Singh, B.K. 2015. Water availability and abundance of microbial groups are key determinants of greenhouse gas fluxes in a dryland forest ecosystem. Soil Biol. Biochem. 86, 5-16.

Meijide, A., García-Torres, L., Arce, A., Vallejo, A. 2009. Nitrogen oxide emissions affected by organic fertilization in a non-irrigated Mediterranean barley field. Agric. Ecosys. Environ. 132, 106–115.

Merino, A., Pérez-Batallón, P., Macías, F. 2004. Responses of soil organic matter and greenhouse gas fluxes to soil management and land use changes in a humid temperate region of southern Europe. Soil Biol. Biochem. 36, 917–925.

Mosier, A.R., Parton, W.J., Valentine, D.W., Ojima, D.S., Schimel, D.S., Heinemeyer, O. 1997. CH_4 and N_2O fluxes in the Colorado shortgrass steppe: 2. Long-term impact of land use change. Global Biogeochem. Cycles 11, 29–42.

Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grubler, A., Jung, T.Y., Kram, T., La Rovere, E.L., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Riahi, K., Roehrl, A., Rogner, H-H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., van Rooijen, S., Victor, N., Dadi, Z., 2000. Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Ogle, S.M., Breidt, F.J., Easter, M., Williams, S., Killian, K., Paustian K. 2010. Scale and uncertainty in modeled soil organic carbon stock change sfor US croplands using a process-based model. Global Change Biol. 16, 810-822

Parton, W.J., Schimel, D.S., Cole, C.V., Ojima, D.S. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Sci. Soc. Am. J. 51, 1173–1179.

Parton, W.J., Hartman, M., Ojima, D., Schimel, D. 1998. DAYCENT and its land surface submodel: description and testing. Global Planet. Change 19, 35–48.

Parton, W.J., Holland, E.A., Del Grosso, S.J., Hartman, M.D., Martin, R.E., Mosier, A.R., Ojima, D.S., Schimel, D.S. 2001. Generalized model for NOx and N_2O emissions from soils. J. Geophys. Res. 106(D15), 17403–17419.

Plaza-Bonilla, D., Álvaro-Fuentes, J., Arrúe, J.L., Cantero-Martínez, C. 2014. Tillage and nitrogen fertilization effects on nitrous oxide yield-scaled emissions in a rainfed Mediterranean area. Agric. Ecosys. Environ. 189, 43–52.

Ravishankara, A.R., Daniel, J.S. Portmann, R.W. 2009. Nitrous oxide (N_2O): The dominant ozone-depleting substance emitted in the 21st Century. Science 326, 123-125.

Rees, R.M., Augustin, J., Alberti, G., Ball, B.C., Boeckx, P., Cantarel, A., Castaldi, S., Chirinda, N., Chojnicki, B., Giebels, M., Gordon, H., Grosz, B., Horvath, L., Juszczak, R., Klemedtsson, A.K., Klemedtsson, L., Medinets, S., Machon, A., Mapanda, F., Nyamangara, J., Olesen, J.E., Reay, D.S., Sánchez, L., Cobena, A.S., Smith, K.A., Sowerby, A., Sommer, M., Soussana, J.F., Stenberg, M., Topp, C.F.E., van Cleem- put, O., Vallejo, A., Watson, C.A., Wuta, M., 2013. Nitrous oxide emissions from European agriculture – an analysis of variability and drivers of emissions from field experiments. Biogeosciences 10, 2671–2682.

Rey Benayas, J.M., Bullock, J.M. 2012. Restoration of biodiversity and ecosystem services on agricultural land. Ecosystems 15, 883–899.

Sanz-Cobena, A., Abalos, D., Meijide, A., Sanchez-Martin, L., Vallejo, A. In press. Soil moisture determines the effectiveness of two urease inhibitors to decrease N2O emission. Mitig. Adapt. Strateg. Glob. Change. DOI: 10.1007/s11027-014-9548-5

Smith, K. 1997. The potential for feedback effects induced by global warming on emissions of nitrous oxide by soils. Global Change Biology. 3, 327-338.

Smith, J.U., Smith, P., 2007. Environmental Modelling. An Introduction. Oxford University Press, Oxford.

Smith, J.U., Smith, P., Addiscott, T., 1996. Quantitative methods to evaluate and compare soil organic matter (SOM) models. In: Powlson, D.S., Smith, P., Smith, J.U. (Eds.), Evaluation of Soil Organic Matter Models Using Existing Long-term Datasets. NATO ASI Series I, vol. 38. Springer-Verlag, Heidelberg, pp. 181–200.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S. 2007. Policy and technological constraints to implementation of greenhouse gas mitigation options in agriculture. Agric. Ecosys. Environ. 118, 6–28.

Smith, P., Smith, J.U., Powlson, D.S., McGill, W.B., Arah, J.R.M., Chertov, O.G., Coleman, K., Franko, U., Frolking, S., Jenkinson, D.S., Jensen, L.S., Kelly, R.H., Klein- Gunnewiek, H., Komarov, A.S., Li, C., Molina, J.A.E., Mueller, T., Parton, W.J., Thornley, J.H.M., Whitmore, A.P., 1997. A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. Geoderma 81, 153–225.

Snyder, C.S., Bruulsema, T.W., Jensen, T.L., Fixen, P.E. 2009. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agric. Ecosys. Environ. 133, 247–266.

Soane, B.D., Ball, B.C., Arvidsson, J., Basch, G., Moreno, F., Roger-Estrade, J. 2012. No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. Soil Till. Res. 118, 66–87.

Soil Survey Staff. 1994. Keys to soil taxonomy, 6th edn. United States Department of Agriculture, Soil Conservation Service, Washington, USA, pp. 306

Stehfest, E., Bouwman, L. 2006. N_2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modelling of global annual emissions. Nutr. Cycl. Agroecosys. 74, 207–228

Van Groenigen, J.W., Huygens, D., Boeckx, P., Kuyper, T. W., Lubbers, I. M., Rütting, T., Groffman, P.M. 2015. The soil N cycle: new insights and key challenges. Soil 1, 235–256

Venterea, R.T., Halvorson, A.D., Kitchen, N., Liebig, M.A., Cavigelli, M.A., Del Grosso, S.J., Motavalli, P.P., Nelson, K.A., Spokas, K.A., Singh, B.P., Stewart, C.E., Ranaivoson, A., Strock, J., Collins, H. 2012 Challenges and opportunities for mitigating nitrous oxide emissions from fertilized cropping systems. Front. Ecol. Environ. 10, 562-570.

Weier, K.L., Doran, J.W., Power, J.F., Walters, D.T. 1993. Denitrification and the dinitrogen/nitrous oxide ratio as affected by soil water, available carbon, and nitrate. Soil Sci. Soc. Am. J. 57, 66–72.

Figure captions

Fig. 1. Average precipitation, potential evapotranspiration (PET) and air temperature in the study area.

Fig. 2. Precipitation (bars) and air temperature (continuous line) recorded at a weather station in the vicinity of the field site during the study period (December 2011-June 2013).

Fig. 3. Monthly precipitation distribution in the study area under two climate scenarios: baseline and climate change. Values represent mean precipitation for the 85-year period simulated.

Fig. 4. Simulated and observed daily soil N_2O emissions from December 2011 to June 2013 under three different land uses (CR, cropland; AB, abandoned land; and FR, afforested land). Y-axis scale is different among graphs. Error bars represent standard errors of the observed values (n=6 for CR and FR and n=5 for AB).

Fig. 5. Simulated and observed cumulative soil N_2O emitted under three different land uses (CR, cropland; AB, abandoned land; and FR, afforested land) from December 2011 to June 2013. Error bars represent standard deviation of the observed values.

Fig. 6. Simulated cumulative N_2O emissions during the 2015-2100 period in three different land uses (CR, cropped; AB, abandoned; and FR, afforested) and for three

climate scenarios (baseline; CC, climate change; and, CC+CO_2, climate change and atmospheric CO_2 enrichment).

Fig. 7. Simulated mean yearly water filled pore space (WFPS) during the 2015-2100 period for cropland use under three climate scenarios (baseline; CC, climate change; and, CC+CO_2, climate change and atmospheric CO_2 enrichment).

TABLES

Table 1. Soil characteristics at the beginning of the study for different land uses.

Land use	Soil depth (cm)	pH (H_2O, 1:2.5)	$EC_{1,5}$ (dSm^{-1})	Organic C (g kg^{-1})	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})
Cropland	0-5	8.0	2.1	10.8	37	666	297
	5-10	8.1	1.9	7.7	35	666	299
	10-25	8.0	2.0	7.2	45	655	300
Abandoned land	0-5	7.8	1.2	16.8	131	631	238
	5-10	8.1	0.5	8.8	100	652	248
	10-25	8.0	0.7	7.4	86	677	237
Afforested land	0-5	8.1	2.4	34.6	327	460	213
	5-10	7.9	2.3	12.0	291	482	227
	10-25	8.0	2.3	6.3	298	464	238

Table 2. Observed and simulated soil organic carbon content (SOC) in the 0-20 cm soil depth at the beginning of the experiment for different land uses.

Land use	Observed SOC content (Mg C ha^{-1})	Simulated SOC content (Mg C ha^{-1})
Cropland	31.95 (1.97)[a]	34.78
Abandoned land	33.27 (2.72)	35.31
Afforested land	45.95 (6.17)	45.25

[a] In parenthesis the standard error of the mean

Table 3. Lack of fit (LOFIT) and relative error (*E*) statistics describing the performance of the Daycent model in simulating soil N_2O emissions for different land uses (CR, cropland; AB, abandoned land; FR, afforested land).

Statistics	Land use		
	Cropland	Abandoned land	Afforested land
LOFIT	1111	315	704
F	0.09	0.03	0.07
F critical[a]	1.44	1.44	1.44
E (%)	15	3	21
E_{95} (%)[b]	281	532	382

[a] *F* value at 5% probability

[b] 95% confidence interval of relative error

Table 4. Linear regressions between observed and simulated soil temperature (ST, 5 cm depth), soil volumetric water content (VWC, 0-5 cm depth) and soil nitrate content (SN, 0-5 cm depth) for different land uses.

Soil variable	Land use	Intercept	Slope	r^2
ST	Cropland	0.405	0.948	0.890^{***}
	Abandoned land	0.428	0.997	0.852^{***}
	Afforested land	0.433	0.997	0.832^{***}
VWC	Cropland	0.062	0.897	0.762^{***}
	Abandoned land	0.032	1.494	0.758^{***}
	Afforested land	0.076	1.647	0.754^{***}
SN	Cropland	1.586	1.146	0.051
	Abandoned land	2.980	-0.297	0.032
	Afforested land	2.546	-0.769	0.016

*** Significant at the 0.001 level

Table 5. Simulated mean annual cumulative soil N_2O emissions, water-filled pore space (WFPS, 0-20 cm soil depth) and soil temperature at 20 cm depth for different land uses and climate scenarios (baseline; CC, climate change; CC+CO_2, climate change plus atmospheric CO_2 increase).

Land use	Climate scenario	Cumulative N_2O (g N_2O-N ha^{-1} yr^{-1})	WFPS (%)	Soil temperature (ºC)
Cropland	Baseline	642	46	13.8
	CC	533	39	15.2
	CC+CO_2	572	40	14.7
Abandoned land	Baseline	158	27	13.8
	CC	151	24	15.6
	CC+CO_2	126	25	15.3
Afforested land	Baseline	303	23	13.0
	CC	295	21	14.5
	CC+CO_2	272	22	14.5

Figure 1

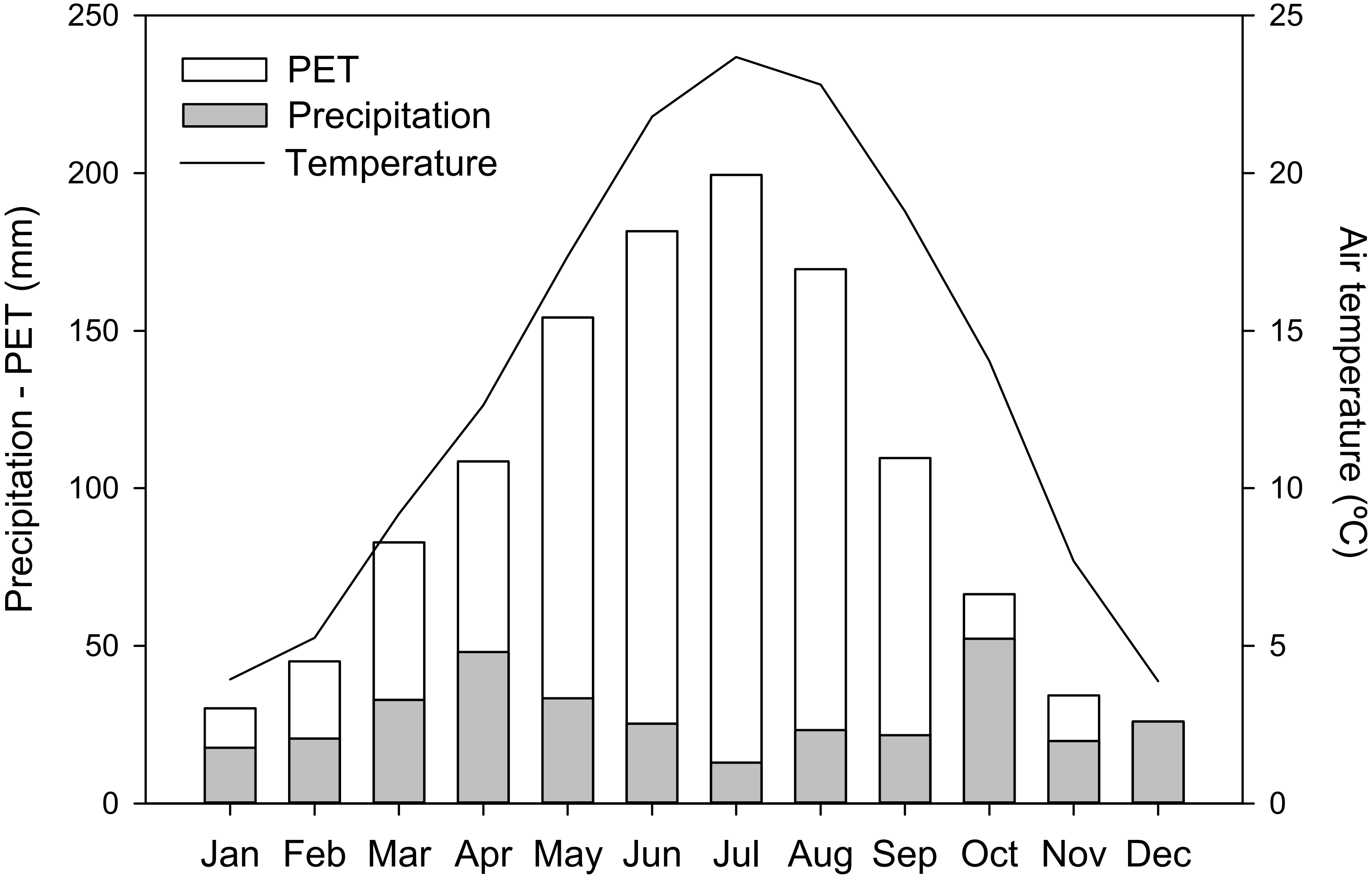
PET
Precipitation
Temperature
Precipitation - PET (mm)
Air temperature (°C)
250
200
150
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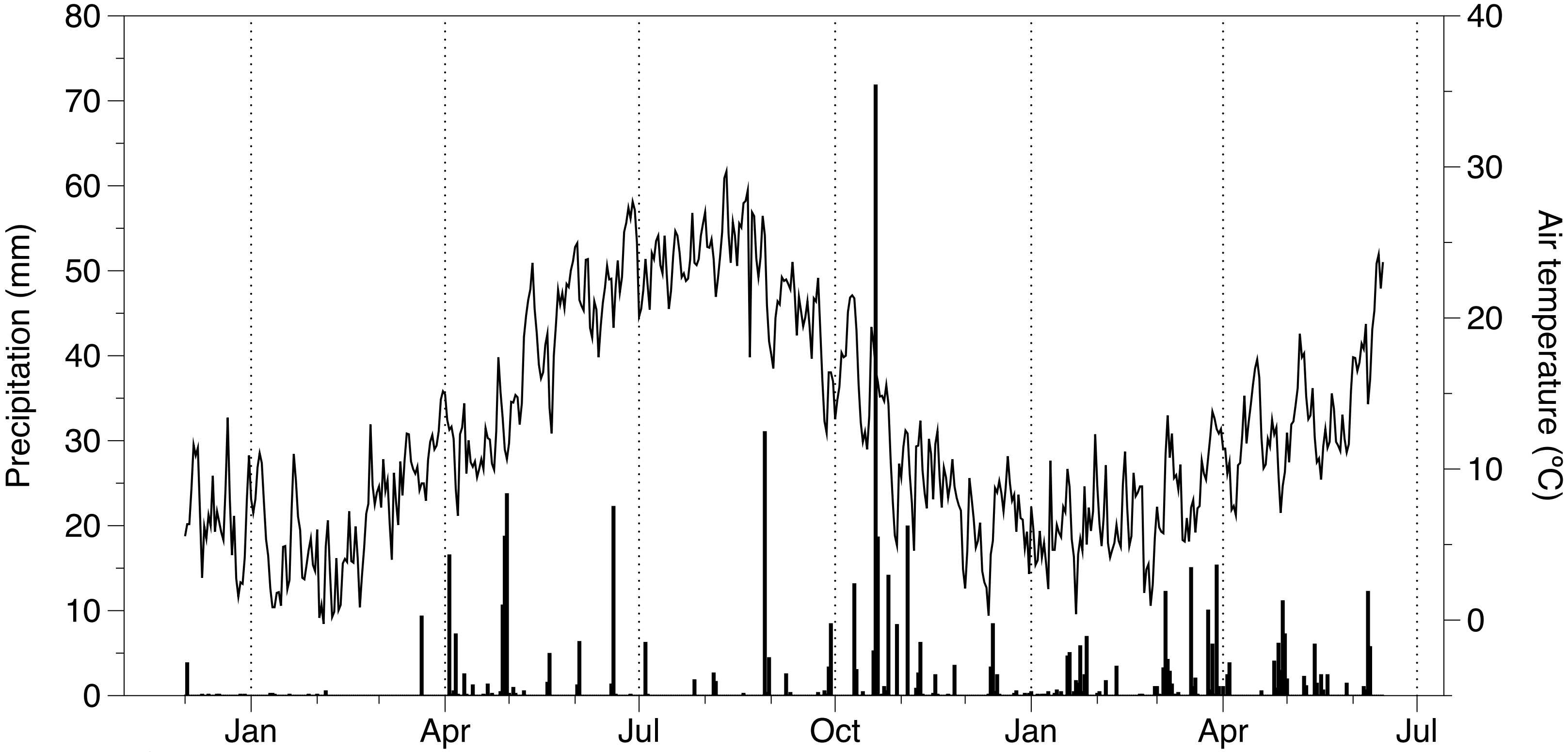
Figure 2


Precipitation (mm)
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10
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40
50
60
70
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Air temperature (°C)
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10
20
30
40
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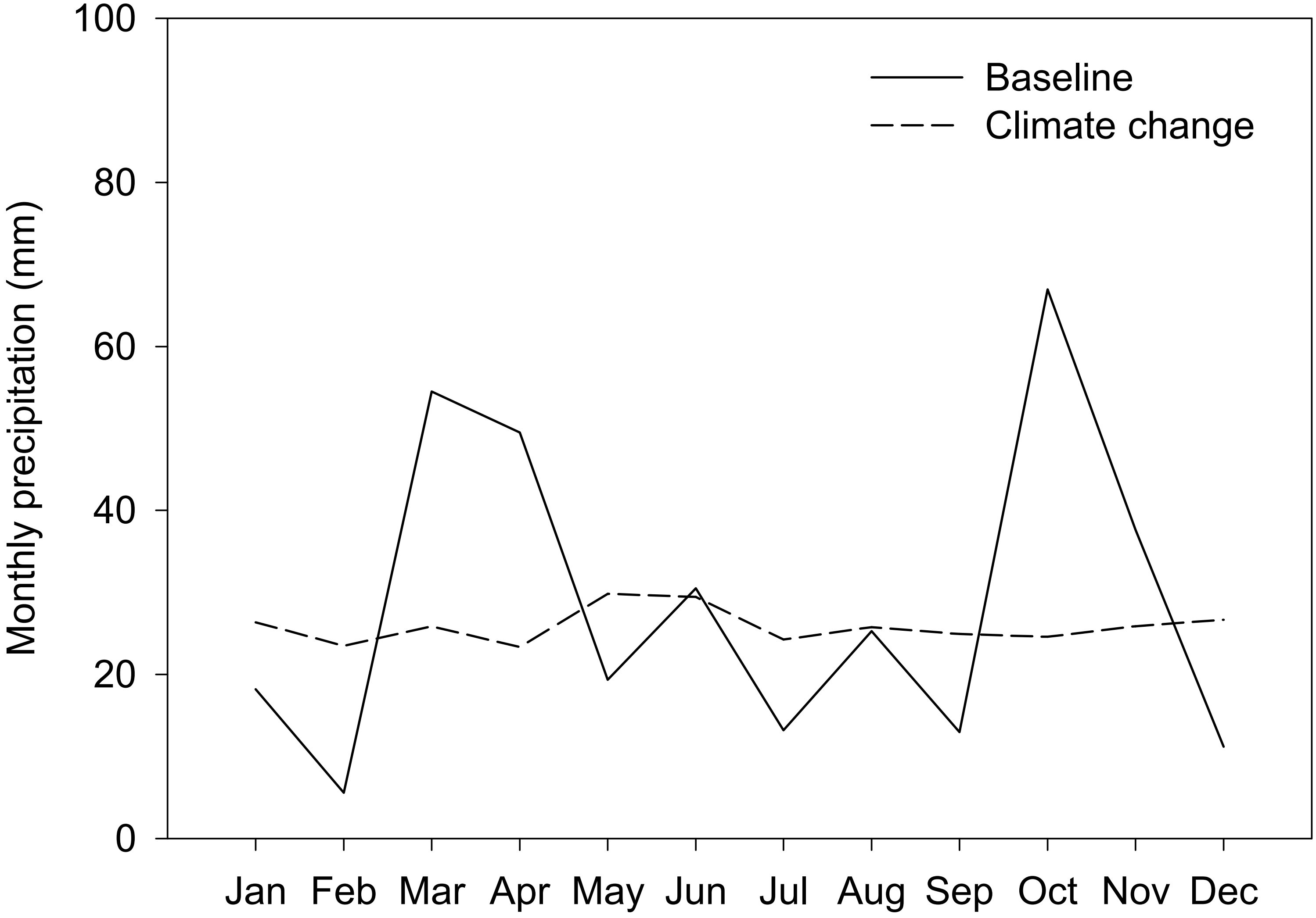
Monthly precipitation (mm)
0
20
40
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Baseline
Climate change

Figure 4

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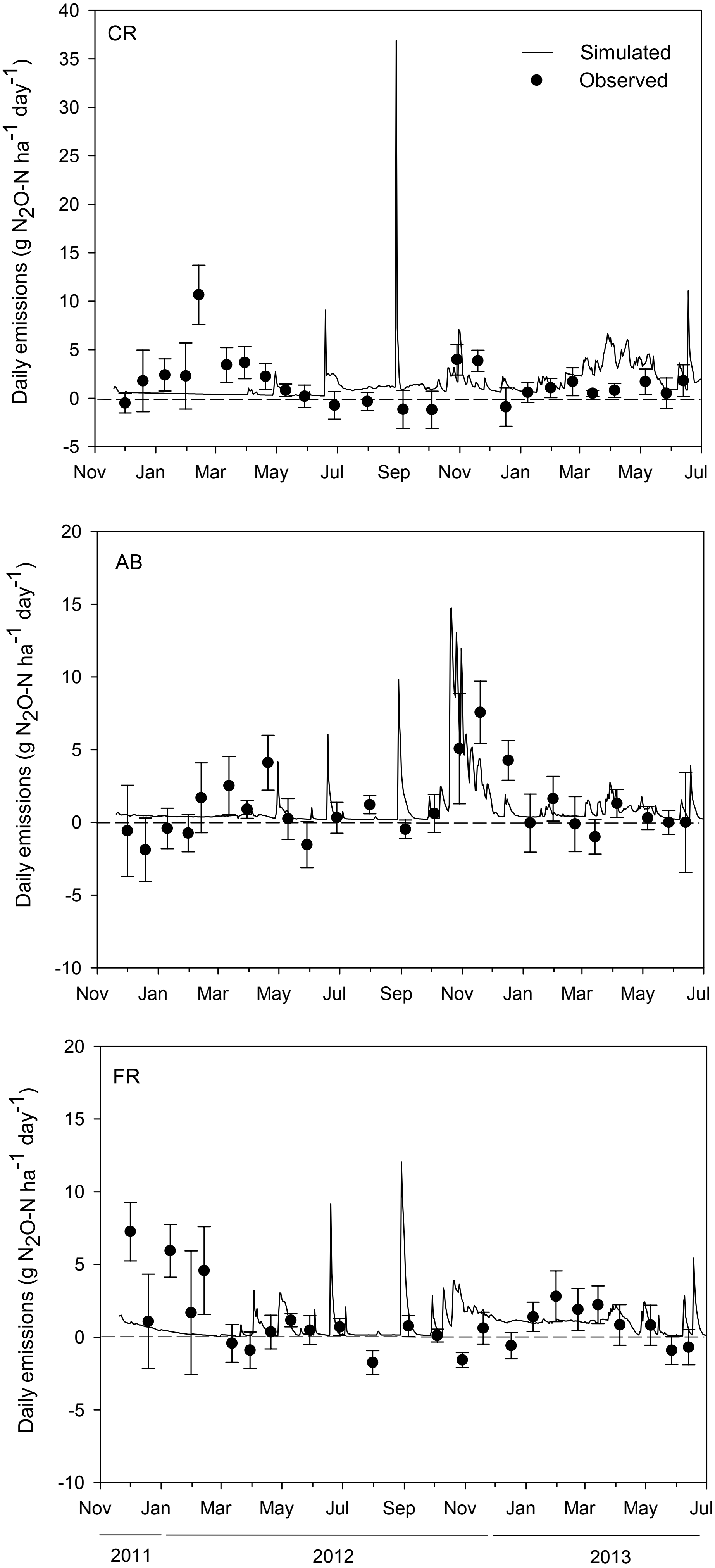

Figure 5

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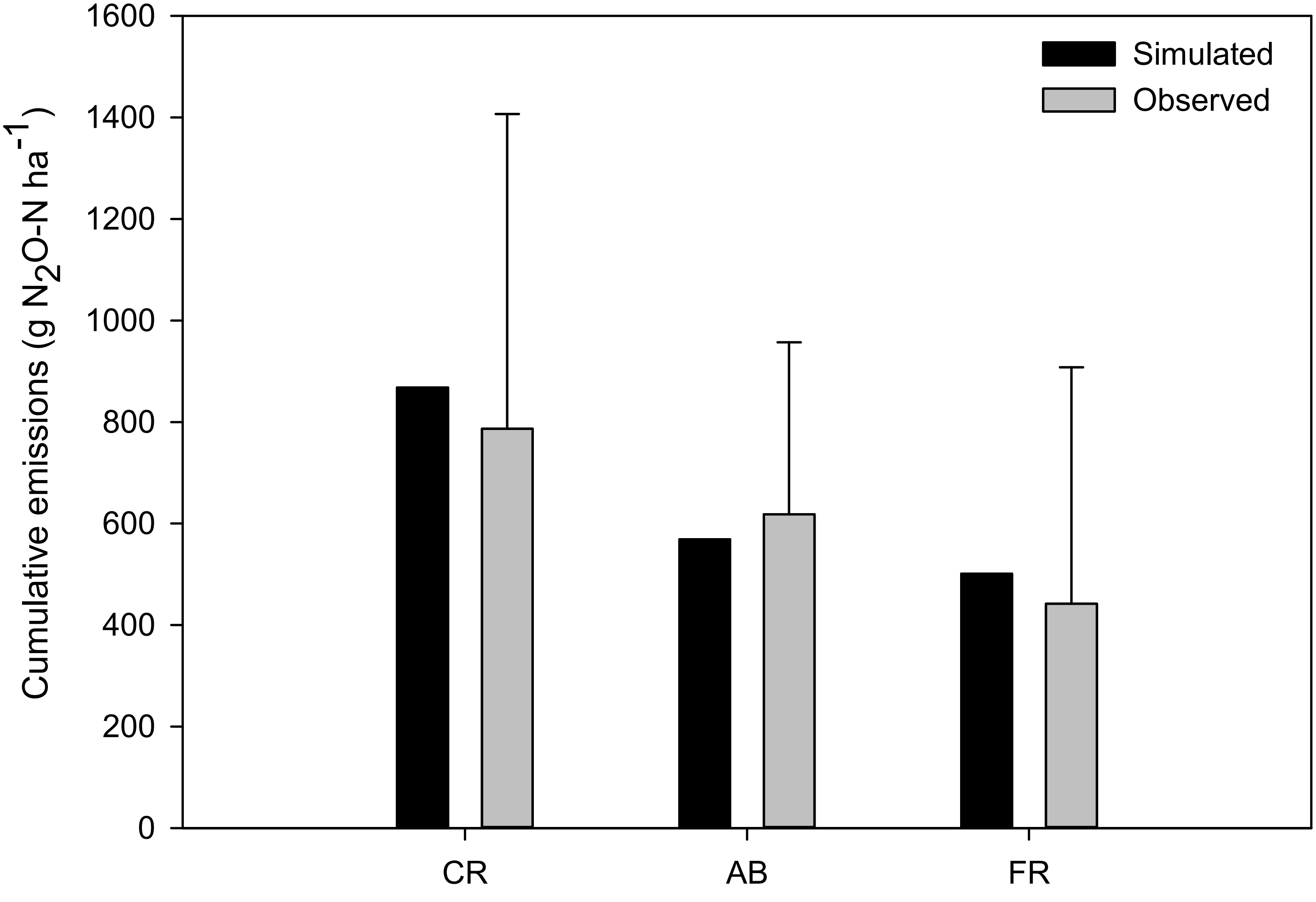

Figure 6

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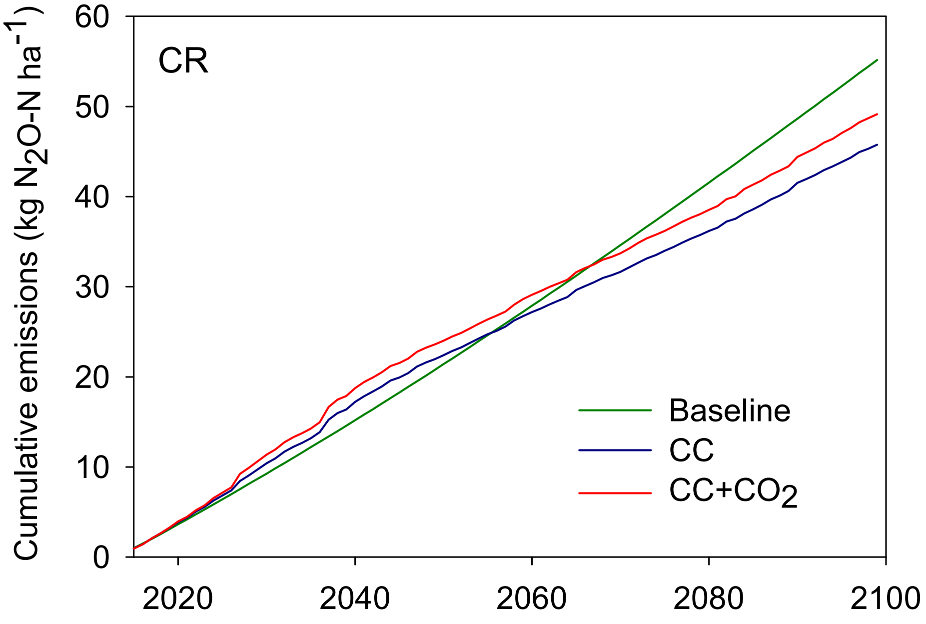

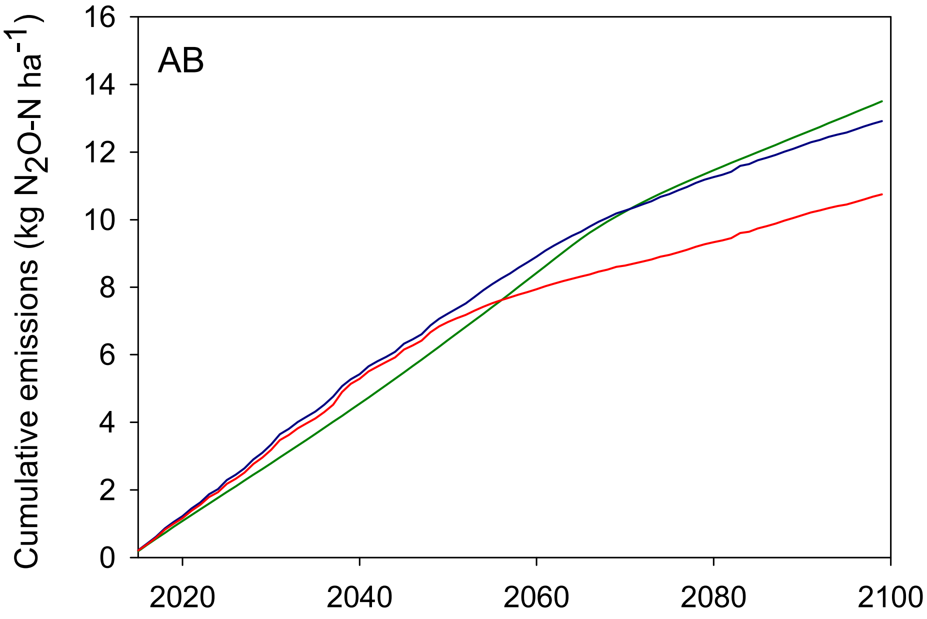

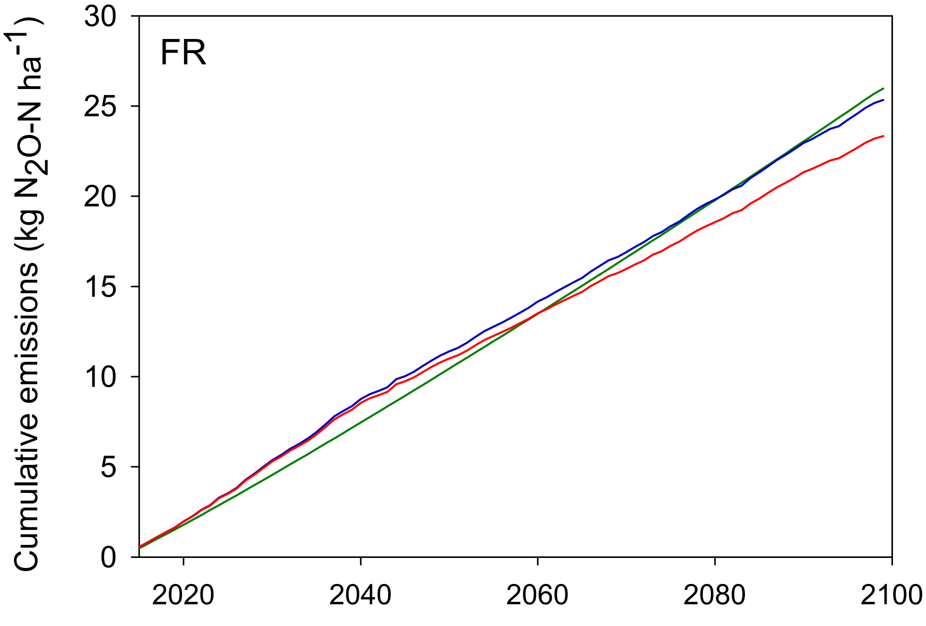

Figure 7

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