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RESEARCH ARTICLE

Climate change effects on northern Spanish grassland-based dairy livestock systems

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Abstract

Background Understanding the effects of climate change on agro-ecosystems is fundamental in order to select the optimum management practices to mitigate environmental pressures. There is a need to forecast greenhouse gas emissions (GHG) emissions of grassland systems under climate change scenarios whilst also accounting for SOC sequestration.

The objective of this study is to assess the net GHG emissions over > 405,000 hectares (ha) of moist temperate Northern Spanish grasslands utilised for dairy production, under climate change conditions (i.e., RCP 4.5, and RCP 8.5), compared to a reference baseline scenario. It is hypothesised that net GHG will increase under climate change conditions and that implementing specific manure management practices (namely the anaerobic digestion (AD)) may mitigate the global warming effect.

Methods We used an integrated modelling framework comprising: (i) geographic information systems (GIS); (ii) a modified RothC version to simulate SOC changes in managed grasslands under moist temperate conditions; and (iii) Tier 2 recent IPCC methods to estimate GHG emissions.

Results Average net GHG emissions contributed to global warming potential with average emissions of 5.8 and 6.2 Mg CO_2-e ha^{-1} $year^{-1}$, under RCP 4.5 and RCP 8.5, respectively. Anaerobic digestion allowed net GHG under both climate change scenarios to equal net GHG under the baseline reference scenario.

Conclusion Under climate change conditions, implementing specific manure management practices, namely AD, will likely reduce the net GHG emissions of the grassland systems associated with dairy production in Northern Spain.

Keywords Upscaling · Soil organic carbon · Net greenhouse gas emissions · Grassland-based dairy systems · Climate change · Manure management

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Introduction

Grassland-based dairy cattle farming is one of the dominant land uses in Northern moist temperate Spain (Galicia, Asturias, Cantabria, the Basque Country, and Navarra), which comprises about 1.2 million ha of permanent grasslands. Frequent rainfall and cool temperature conditions are key factors that promote plant growth and make grasslands within these regions very productive (Smit et al. 2008). Accordingly, these account for 60% of milk production in Spain, about 2.7% of the milk produced in the European Union (EU-28) (EUROSTAT 2019) and have an economic value of 1,300 million Euros, according to the Spanish Ministry of agriculture (MAPA 2016).

The grasslands in Northern Spain have a significant soil organic carbon (SOC) storage compared to other land uses (e.g., croplands) (Ganuza and Almendros 2003), reaching more than 100 Mg C ha^{-1} (Rodriguez-Martin et al. 2016). However, the carbon footprint of the grassland-based dairy production in Northern Spain under current climate conditions, which has been evaluated by several studies using mainly the Life Cycle Assessment (LCA) framework, has shown that milk production involves net Greenhouse Gas (GHG) emissions (Prado et al. 2013; Laca et al. 2020).

In general, dairy production systems are high producers of direct GHG from enteric fermentation (CH_4), manure storage and handling (CH_4 and N_2O), and feed crop and pastureland (mainly N_2O) (Gerber et al. 2013). In Northern Spain, a large proportion of total GHG emissions are associated with CH_4 output (27%–49%) from dairy farms, whilst a significant percentage comes from manure management, with enteric fermentation being the dominant source (Prado et al. 2013).

The interaction between ongoing climate change and demands for increasing livestock production make it challenging to increase production while lowering climate impacts and GHG emissions (Chang et al. 2021). By 2025, it is projected that dairy cows (including lactating dairy cows, dry dairy cows, heifers, and calves) will be producing around 30% of the total agricultural GHG emissions in the EU-28 (including the UK which is no longer an EU member state), according to projections using the CAPRI (Common Agricultural Policy Regionalised Impact) model (European Commission 2015). The intensification of dairy production systems has especially resulted in increased CH_4 and N_2O emissions originating from manure management (Rojas-Downing et al. 2017; Petersen 2018).Therefore, reducing GHG emissions sustainably requires an understanding of climate change effects on livestock production, as well as the effect mitigation actions (Chang et al. 2021). In this context, altered manure storage practices can reduce manure GHG emissions (Rojas-Downing et al. 2017). These include shortened storage duration, lowered storage temperature, solid–liquid separation, and anaerobic digestion (AD) (Montes et al 2013).

Climate models suggest that the global mean temperature will increase by between 1 and 5.7℃ by the year 2100, compared to the 1850–1990 period (i.e., 1.1 ℃) (IPCC 2021). Based on climate predictions, pluvial flooding will increase in Northern Europe, as will hydrological and agricultural/ecological droughts in the Mediterranean (IPCC 2021). Climate parameters (i.e., temperature and precipitation) have been proven to play a crucial role in the soil mechanisms controlling SOC decomposition (Paul 1984; Conant et al. 2008). The response of SOC content to climate change has been widely investigated at different scales, and both increases (e.g., Álvaro-Fuentes et al. 2012) and decreases (e.g., Smith et al. 2005) have been reported. These results depend mainly on the modelling approaches used, and the pedoclimatic conditions and management practices present in different study areas.

In temperate grasslands, climate change may significantly impact net GHG emissions (Eze et al. 2018). For instance, CH_4 emissions from manure management increase exponentially with increasing temperature (IPCC 2019). Consequently, greater effort should be focused on manure management to reduce potential climate change effects related to GHG emissions from dairy production systems. However, due to system interactions, mitigation practices that reduce emissions in one stage of the manure management process could increase emissions elsewhere (Montes et al. 2013). For example, AD, whilst initially reducing CH_4 emissions, may increase emissions after land application due to its higher total ammoniacal nitrogen (TAN) in resulting manures (Aguirre-Villegas et al. 2019).

There are fewer studies covering the contribution of grassland-based livestock systems to global warming under climate change conditions in moist temperate systems (e.g., Graux et al. (2012)). In Northern Spain, regional assessment of net GHG for grassland-based cattle production systems under moist temperate conditions was studied in Jebari et al. (2022) under current conditions. However, to our knowledge, there have been no regional assessments of net GHG, under climate change conditions, in Northern Spain. Our main objective was therefore to provide emission/sink estimates of the three major GHGs (CH_4; N_2O; and CO_2) for dairy production systems in Northern Spain, under different projected future climate and manure management scenarios, at different scales (including the grassland soil and barn levels). The SOC change rates were assessed in grassland soils, while the main GHG emissions, at the farm gate boundary, were assessed at the barn and grassland levels. We hypothesised that (i) climate change conditions would increase net GHG emissions, and (ii) alternative management practices could help to mitigate this global warming potential. The novelty of our study is that it uniquely combines GHG estimations with landscape-scale modelling, drawing upon various methods including spatial analysis, elements of LCA (i.e., Life Cycle Inventory Analysis), and temporal analysis, a combination rarely found within sustainability-based literature.

Materials and methods

Study area

The studied region comprises grasslands associated with dairy production in Northern Spain, with a total area of 405,000 ha (Fig. S1). The climate is mainly moist temperate, with annual mean rainfall ranging from 800 to 3,000 mm and an average annual air temperature of about 12–14 °C.

Grassland ecosystems used for dairy production in Northern Spain are commonly based on grasses (mainly ryegrass (*Lolium perenne)*) with around 5% white clover (*Trifolium repens* L.) swards. The most common cattle breed is Holstein–Friesian, with average body weight of 580 for dairy cows and 464 kg for heifers. Management typically consists of outdoor grazing heifers and dairy cows for most of the year (75%), while the lactating cows are confined to sheds for the majority of the time (77–90%) and are fed annual forage crops (often grass or maize silage, ~ 60–69%) and concentrates (~ 31–40%) (MAPA 2019). The urine and faeces of lactating dairy cows are generally excreted within the sheds and is subsequently stored as liquid (slurry) in tanks or lagoons. However, excreta from other dairy cows and heifers are generally mixed with straw and other bedding and handled as solid manure (farmyard manure; FYM). Full details on the study area and dairy system characterisation can be found in Jebari et al. (2022).

SOC change

The RothC model to estimate SOC change was modified to be appropriate for managed grasslands under moist temperate conditions according to the methods of Jebari et al. (2021). The RothC model description and the modifications made are outlined in the supplementary information and more in detail in Jebari et al. (2021). The municipalities with grasslands associated with dairy production are referred to as spatial units, according to the National Statistical Institute (INE 2009).

The edaphoclimatic layers and the spatial units, were overlayed through GIS, to assign the climatic data and the soil properties to the different spatial units.

For RothC initialisation, carbon pools were estimated according to Weihermüller et al. (2013), based on the clay content values from Rodríguez Martín et al. (2016), and SOC stocks for the year 2010 obtained from the simulation results from a previous paper by Jebari et al. (2022). The initial IOM pool was set to match the equation proposed by Falloon et al. (1998) (Eq. 1):

$$IOM = 0.049\ SOC^{1.139} \tag{1}$$

A Visual Basic for Applications (VBA)-based program was developed in Excel to simulate SOC stock changes simultaneously for the different spatial units (i.e., municipalities of the different regions of Galicia, Asturias, Cantabria, the Basque Country, and Navarra) for the period 2010 to 2100 due to the combination of a large number of runs (i.e., 689 approximately) for each spatial unit in the regional simulation.

Input datasets

The proposed regional analysis is based on a spatial division of the grassland systems for dairy production in Northern Spain into different spatial units (i.e., municipalities) assuming homogeneity for a set of specific parameters (e.g., soil properties).

Soil properties

Soil texture at 30 cm depth was provided spatially as a raster layer from Rodríguez Martín et al. (2016). The study area had a large variability in clay content (6 – 30%). The statistical mean clay content for each municipality was obtained using ArcMap 10. 2. Initial SOC stocks were extracted for each municipality from a previous work (Jebari et al. 2022) in which SOC stocks were simulated in the same study area for the period 1981–2010, using the aforementioned modified version of RothC (Jebari et al. 2021).

The soil water content at saturation and field capacity conditions were obtained from FAO estimations considering soil properties related to soil texture (Raes 2017). Soil textural classes, used to estimate soil moisture function under soil water saturation conditions, were derived from the European Soil Data Centre (Ballabio et al. 2016). These were extracted and ascribed to the different municipalities using ArcMap 10.2 overlays.

Carbon input derived from plant residues and animal manure

In agricultural soils, some previous studies have assumed carbon input increase under climate change (e.g., Smith et al. 2005; Graux et al 2012). According to Wiesmeier et al. (2016), this last assumption might be rather optimistic given rising evidence for negative effects of climate change on plant production. Therefore, the possibility of stagnation or even the reduction of carbon inputs should be considered in SOC projections (Wiesmeier et al. 2016). Given the negligeable effect of climate change on plant production in the Atlantic region of Europe, according to a meta-analysis by Dellar et al. (2018) constant plant production was assumed in this study.

It was also assumed that the grassland type was the same in the different scenarios, although the structure of the grassland community could be altered as a result of both grazing and climate change (Koerner and Collins 2014).

The same assumptions were used to estimate carbon input derived from plant residues and the same mass-balance approach (by subtracting gross carbon production from total carbon ingestion by livestock) to predict the carbon input derived from animal manure, as in our previous work (Jebari et al. 2022). Due to previously predicted negligible effects on GHG losses in the UK which has a similar climate (i.e., moist temperate), we did not consider inputs from feeding waste and bedding materials (McAuliffe et al. 2018), and, further, we did not consider any change in the amount of the manure.

Uncertainty analysis: Monte Carlo simulation

Monte Carlo simulation was used to assess the sensitivity of the SOC stock results to the model parameters and input variables considered to have potential uncertainties as carbon inputs (Jebari et al. 2022). The Monte Carlo simulation was performed iteratively (1000 times) to sample random values for carbon inputs derived from plant residues using normal distribution (Jebari et al. 2022). Plant dry matter production values were referred to as a proxy for plant residues; while selecting a range of maximum and minimum values based upon a sample of measured and reported dry matter data in the study area (Jebari et al. 2022). We assumed a normal distribution with a maximum- minimum range equal to the 95% confidence interval for both plant and animal residues (Table S5).

Since Monte Carlo simulations require many model runs and computational time we selected nine municipalities for the uncertainty analysis, which well represented the spatial distribution of our study area under the baseline scenario (Jebari et al. 2022).

Greenhouse gas emissions

We estimated both direct emissions (i.e., CH_4 and N_2O) and indirect emissions (i.e., precursors of N_2O: ammonia (NH_3) volatilisation and nitrate (NO_3) leaching from manure storage and grassland soils) for dairy production in Northern Spain (at the barn and grassland soil levels). Direct GHG emissions per ha were estimated using the recently refined IPCC Tier 2 method (IPCC 2019) and indirect emissions per ha were estimated according to the latest EMEP method (EMEP 2019). The data was collected for the different regions of the study area and assigned to the different corresponding spatial units (i.e., municipalities). The input data were obtained from several existing datasets and reports (MAPA 2019; Flores-Calvete et al. 2016), according to the typologies characterising the predominant practices in each region of the study area (regarding grazing practices, dietary information, and feed quality) (Tables S1, S2, S3 and S4). To predict the total emissions per spatial unit, we multiplied the different estimated emission factors by the corresponding number of dairy cows from each sub-category (i.e., lactating dairy cows, dry cows, and heifers) for each spatial unit in the study area (INE 2009).

To aggregate the different forms of GHG per ha, we used the global warming potential metric for a 100-year time horizon (GWP_{100}) based on the IPCC fifth assessment report (IPCC 2014). The net-CO_2-equivalent emissions (CO_2-e) were calculated for each spatial unit, as a balance between the overall GHG CO_2-e fluxes estimated at the field and barn scale (CH_4 and N_2O) and the estimated long-term soil carbon gains (i.e., SOC accumulation) expressed as CO_2-e (Eq. 2):

$$\begin{aligned} &Net\ GHG/yr(CO_2\_e) \\ &= CO_2\_eN_2O + CO_2\_eCH_4 - CO_2\_e_{CO_2}(SOC\ change) \end{aligned} \tag{2}$$

where CO_2-eN_2O are the total nitrous oxide emissions and CO_2-eCH_4 are the total methane emissions calculated according to IPCC (2019) in Mg CO_2-e ha^{-1} per year; eCO_2 is the multiplier between molar weights of CO_2, carbon (44/12); SOC change corresponds to the change in SOC stocks (Mg C ha^{-1} $year^{-1}$).

Methane emissions

CH_4 derived from enteric fermentation

The refined Tier 2 method was implemented to estimate enteric fermentation as in Eq. (3). The methane conversion factor (Y_m) was estimated according to the feeding typology reflected for each dairy cow sub-category depending on neutral detergent fibre (NDF) and the digestibility of the annual feed ration (specified for each animal category and region). The gross energy intake was calculated as outlined in the IPCC Tier 2 methods (IPCC 2019) according to the feeding typology of each dairy cow sub-category. Then, the emission factor was multiplied by the associated dairy cow sub-category number for each municipality in our study area.

$$EF = \frac{GE.\frac{Ym}{100}}{55.65} \tag{3}$$

where EF: the emission factor (kg CH_4 $head^{-1}$ $year^{-1}$); GE: gross energy intake (MJ $head^{-1}$ $year^{-1}$); Ym: methane conversion factor (MCF; % of GE in feed converted to methane); 55.65 MJ: energy content of methane.

CH_4 emissions derived from manure management

As manure is managed in multiple systems in the municipalities of the study area, the manure EFs were allocated to the dominant storage systems (i.e., the manure of lactating dairy cows is stored as slurry with a natural crust, while the manure of dry dairy cows and heifers is stored as solids). Emissions from manure management depend not only on the characteristics of the management system but also of the manure itself (i.e., volatile solids; VS), which were estimated based on feed intake and digestibility, and used to estimate enteric fermentation (EF) (Eq. 3). The MCF for slurry, was determined using the IPCC model (2019). The MCF model requires monthly air temperature profiles as well as the average number of manure stores and the frequency of their emptying. The VS and maximum methane-producing capacity for residues were based on the IPCC (2019) guidelines and the percentage of excreted VS handled as a liquid are additional input parameters. To ensure VS available is stabilised on an annual basis, the model calculations are run over a three-year period. The MCF model was run for the different municipalities of the study area, and the average value for each municipality was multiplied by the VS to obtain the CH_4 emissions from manure management (Eq. 4).

$$EF = VS.\left[0.24.\ 0.67.\left(\frac{MCF}{100}\right).\ ARMS\right] \tag{4}$$

where EF: the annual CH_4 emission factor for dairy cows (kg CH_4 dairy cow^{-1} $year^{-1}$); VS: volatile solid excreted for dairy cows (Kg dry matter dairy cow^{-1} $year^{-1}$); 0.24: maximum methane producing capacity for residues produced by lactating dairy cows — this is 0.18 for heifers and dry cows — (m^3 CH_4 kg^{-1} of VS excreted); 0.67: conversion factor of m^3 CH_4 to kg CH_4; MCF: methane conversion factor for each residue management system (%); ARMS: fraction of dairy cow residues handled using an animal excreta management system.

Nitrous oxide emissions

Tier 2 of the IPCC method (2019) was used to estimate N_2O emissions produced, directly and indirectly, during the storage and treatment of manure, as well as the direct and indirect soil N_2O emissions (derived from animal excreta, applied fertilisers, plant residues, and pasture renewal, and dung and urine from grazing dairy cows deposited onto the pastures). The N_2O emissions reported were generated using nitrogen excretion results and emission factors for N_2O emissions, as well as volatilisation and leaching factors; with total related N_2O emissions equalling the sum of the direct and indirect emissions.

Information on fertilisation management and nitrogen fertiliser quantities were obtained from expert knowledge of most common practices among local dairy farmers. Mineral fertilizer N application was low (<100 kg ha^{-1} $year^{-1}$) and almost negligible in some regions, while cow slurry was spread in most farms on their grassland fields (assuming a maximum of 500 kg N ha^{-1} yr^{-1} application).

Climate change scenarios

The SOC dynamics and GHG emissions of dairy grasslands in Northern Spain were simulated for the period 2010 to 2100 under two climate change scenarios (RCP 4.5 and RCP 8.5) and one baseline reference scenario. The RCP 4.5 scenario represents a medium–low emissions scenario with stabilisation of CO_2 emissions from 2050 onwards. The RCP 8.5 scenario represents a high emissions scenario with stabilising CO_2 emissions post-2100 (Meinshausen et al. 2011). These two scenarios have been widely used to evaluate the potential impact of climate change on the environment (e.g., Di Vittorio et al. 2014; Li et al. 2015). The baseline scenario consists of historical average monthly temperature and precipitation data from several decades. The climate data corresponds to 12.5 km grids and was produced by the Spanish Meteorological State Agency using a regional downscaling under the project CORDEX (AEMET 2017), together with climate data obtained from the global climate model HadGEM2, and the regional circulation model CCLM 4.8.17 (Kotlarski et al. 2014; Casanueva et al. 2016).

The climate data for each municipality was estimated using the intersection of the different municipalities with the climate grids. Then, the monthly average climate data of the different grids within the same municipality was calculated for each decade under the different climate scenarios. The potential evapotranspiration for each decade from 2010 to 2100 was estimated according to the Thornthwaite equations (Thornthwaite 1948), using average decadal climate data for all climate scenarios.

Compared with the baseline reference, the average annual temperature under RCP 4.5 and RCP 8.5 increased by 1.5 and 1.75 °C, respectively, until 2050 (Table 1). During the period 2050–2100, there was a further increase, by 2.8 and 4.2 °C, respectively (Table 1). However, by the end of the simulation period in 2100, average annual precipitation had decreased under both these climate change scenarios by 126 and 254 mm under RCP 4.5 and RCP 8.5, respectively.

Compared with the baseline reference, temperature showed the same decadal distribution of temperature and precipitation for both climate change scenarios with a significant increase in the final five decades, particularly for RCP 8.5 (with an increase of 35.4% compared to 23.6% under RCP 4.5) (*t*-test, $P<0.001$) (Fig. 1). However, the decadal changes in average monthly precipitation were often substantial

Table 1 Projected climate change (mean annual precipitation and air temperature) under the climate change scenarios (RCP 4.5 and RCP 8.5) by 2050 and 2100 compared with the corresponding values in the baseline data for the study area

Climate scenario	Time period	Mean annual precipitation (mm)	Mean annual temperature (°C)
Baseline	2010—2050	1161.81	11.94
	2050—2100	1161.81	11.94
RCP 4.5	2010—2050	1184.62	13.42
	2050—2100	1035.86	14.72
RCP 8.5	2010—2050	1142	13.69
	2050—2100	907.57	16.17

and showed considerable variation between all the climate scenarios. Moreover, both climate change scenarios presented lower precipitation levels at the end of the simulation period, by 18 and 34% under RCP 4.5 and RCP 8.5, respectively (*t*- test, $P < 0.001$) (Fig. 1 and Table 1).

Manure-related management scenarios

A total of four manure management scenarios were generated to assess their potential to mitigate climate change. A first, reference scenario was produced in which a natural crust for the slurry storage system was assumed. This management was modelled according to the IPCC refined equations, using the default emission factors for direct N_2O emissions of manure stored with a natural crust. This slurry is removed and applied to grasslands all year long, except in summer. The slurry removal was estimated using the MCF model (IPCC 2019). The reference scenario was compared to the following three GHG mitigation scenarios: (i) the presence of a cover on the slurry store (i.e., a rigid structure that covers the slurry, impermeable to water and gasses); (ii) the removal of the slurry during different seasons of the year; and (iii) AD.

Cover for slurry storage

Covers are a potential mitigation measure that could be added to liquid manure storage facilities. They are produced using materials that are natural (e.g.

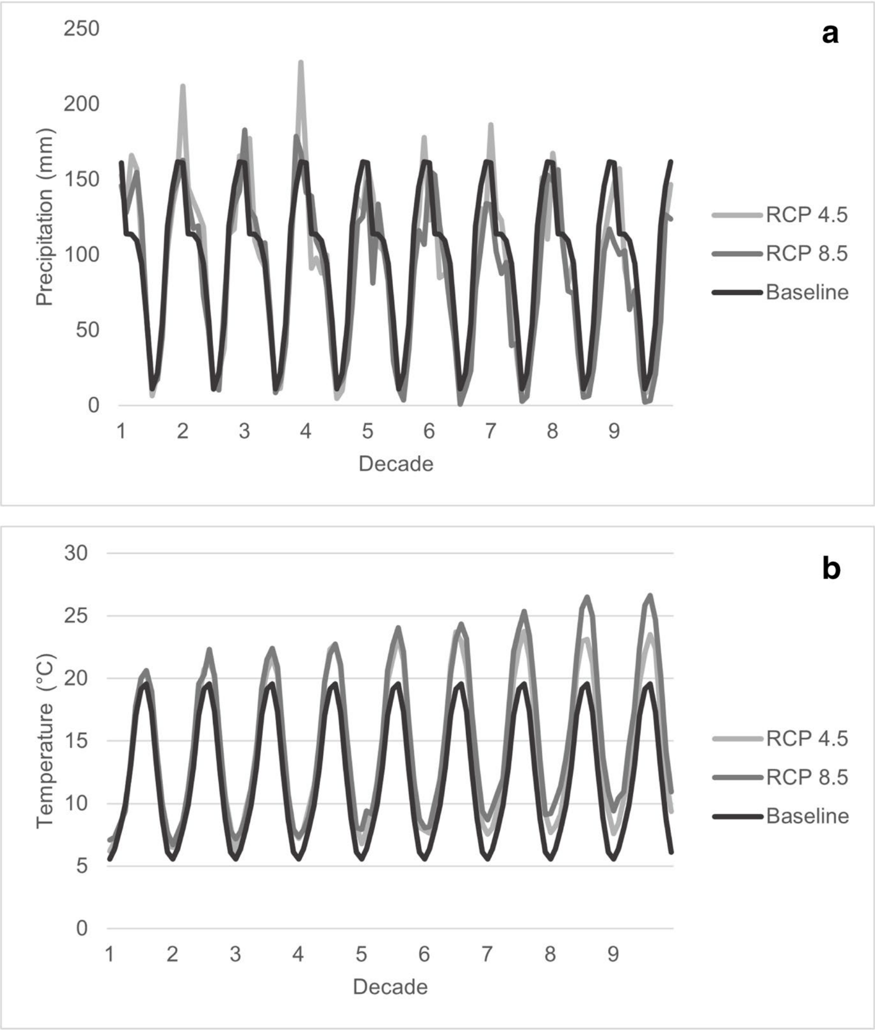


Fig. 1 Future projections of average 9 decadal temperature (on the left) and average decadal precipitation variation (on the right) for a moist temperate Spanish region under the climate change scenarios (RCP 4.5 and RCP 8.5) and the reference baseline scenario

clay aggregates), synthetic (e.g., plastic or rubber), and composite (VanderZaag et al. 2008). Compared to uncovered conditions, nearly all cover types have been shown to be capable of substantially reducing NH_3 emissions (Berg et al. 2006).

The scenario of a rigid cover for the slurry storage system was therefore implemented in the modelling framework to reduce total N_2O emissions derived from manure storage. In this context, the equations from IPCC (2019) and EMEP (2019) were for the covered manure management, where the equations were estimated as follows

$$N_2O = [N.\ Nex.\ AWMS.\ 0.005].\frac{44}{28} \tag{5}$$

where: N_2O: direct N_2O emissions from Manure Management in the country (kg N_2O year^{-1}); N: number of head of dairy cows category; Nex: annual average N excretion per dairy cows category (kg N dairy cow $^{-1}$ year^{-1}); AWMS: fraction of total annual nitrogen excretion for each category that is stored with cover (dimensionless); 0.005: emission factor for direct N_2O emissions from slurry storage with cover (kg N_2O-N per kg N); 44/28: conversion of N_2O-N emissions to N_2O emissions.

$$N_2O(V) = [N(v).\ 0.014].\frac{44}{28} \tag{6}$$

where: N_2O (V): indirect N_2O emissions due to volatilization of N from slurry storage (kg N_2O year^{-1}); 0.014: emission factor for N_2O emissions from atmospheric deposition of nitrogen on soils and water surfaces, kg N_2O-N (kg NH_3-N + NO_x-N volatilised)$^{-1}$ equal to 0.014 under wet climate.

$$N(v) = [N.\ Nex.\ AWMS.\ 0.1] \tag{7}$$

where: fraction of managed manure nitrogen that volatilises as NH_3 and NOx in the dairy slurry stored with cover.

Slurry removal

A direct way to avoid GHG emissions is to reduce the time manure is stored. Frequent manure applications to fields reduces GHG emissions from storage due to the shorter retention times and a reduced surface area (Aguirre-Villegas and Larson 2017). For this reason, the potential for CH_4 reduction through this method was explored while comparing the reference scenario with alternative slurry removing scenarios during different seasons of the year, and therefore different climate conditions.

Scenarios were considered that avoided manure application during times of high rainfall in the autumn or in winter, together with the reference scenario (i.e., avoiding manure removal in summer). However, avoiding manure application in spring is not feasible, as grasslands need to be fertilised in that season. Moreover, emptying a manure tank in the spring, before the temperatures increase, presents another opportunity to reduce GHG emissions in slurry storage systems (Novak and Fiorelli 2009).

The methane conversion factor model, using the refined IPCC method, was useful for evaluating the scenarios with different retention times over the year, while taking into account the monthly temperature under the baseline and climate change scenarios. The MCF model (described previously) was used by introducing the monthly air temperature profiles as well as the average number of manure stores and the frequency of their emptying for the different municipalities under the different climate scenarios.

Anaerobic digestion

Anaerobic digestion is a naturally occurring process in which microbial organisms break down organic materials (i.e., manure) in the absence of oxygen to produce biogas, which is primarily a mix of methane (CH_4) and carbon dioxide (CO_2). Biogas can be combusted to produce electricity or thermal energy for heating applications, upgraded for injection into a natural gas pipeline, or compressed to be used as transportation fuel. The fraction remaining after the digestion (known as digestate) can be used as a fertiliser as it retains the nutrient content of the initial feedstock. Manure processing via AD helps to mitigate GHG emissions from manure and energy (Aguirre-Villegas and Larson 2017). Emission reductions from energy come from the displaced emissions involved in biogas-based power replacing grid electricity (Ebner et al. 2015). Reductions from manure are mostly from the capture of CH_4 during digestion which is then converted to CO_2 during combustion, as well as the reduced carbon available to produce CH_4 in storage (Aguirre-Villegas and Larson 2017).

During the AD process, a carbon fraction is released to the atmosphere, instead of being applied to the soil (Pardo et al. 2017). In this context, distinguishing between emissions from manure in barns and outside storage facilities is important for assessing the effects of AD, where mainly posttreatment emissions are affected (Petersen 2018). The specific carbon and nitrogen cycling effects of the AD process was therefore included in the modelling framework using the method developed by Pardo et al. (2017), as these are usually neglected in other similar studies (Meier et al. 2015).

Results

SOC change

The trends in SOC over the simulation period are shown as the annual SOC change rate (Mg C ha^{-1} year^{-1}, 0–30 cm) per municipality spatial unit. On average, the model predicted that climate impacts (under climate warming conditions) on dairy grasslands soils will tend to decrease SOC stocks in Northern Spain. At the two time horizons (2050, 2100), the baseline reference scenario showed average SOC change rates of 0.49 and 0.28 Mg C ha^{-1} year^{-1} (Fig. 2). The two climate change scenarios, RCP 4.5 and RCP 8.5, showed similar median SOC change rates of 0.30 and 0.26 Mg C ha^{-1} year^{-1} until 2050 (t-test, $P < 0.001$), respectively (Fig. 2). However, the average SOC change rate was lower in 2100, reaching 0.038 Mg C ha^{-1} year^{-1} under RCP 4.5 and even a loss of -0.031 Mg C ha^{-1} year^{-1} under RCP 8.5 (t-test, $P < 0.001$) (Fig. 2). A paired samples t-test was used to compare the average SOC change rate of the different municipalities under the baseline and the different climate change scenarios. The P value was less than 0.001, showing a significant difference.

The SOC storage modelled using RCP 4.5 was substantially higher than the SOC stocks with RCP 8.5 (with up to a fourfold increase in SOC stocks; Fig. 2a). Under the baseline reference, average SOC stocks increased by 26.7% at the end of the simulation period. However, the average annual SOC change rate increased by 11.8% under RCP 4.5 (annual SOC change rate of 0.15 Mg C ha^{-1} year^{-1}) (t-test, $P <$ 0.001), and only 7.7% (annual SOC change rate of 0.10 Mg C ha^{-1} year^{-1}) under RCP 8.5 at the end of the simulation period (t-test, $P < 0.001$) (Fig. 2b).

The highest SOC change rates were found in the southern region (with values up to 1.57, and 1.32 Mg C ha^{-1} year^{-1} under RCP 4.5 and RCP 8.5, respectively), while the lowest SOC stocks were found in the Northern regions (with values up to -0.5, and 0.54 Mg C ha^{-1} year^{-1} under RCP 4.5 and RCP 8.5, respectively) (Fig. 3a, b, and c).

Under the RCP 4.5 scenario, with a 20% temperature increase, the annual SOC change rate decreased by 58% (Fig. 3a), whilst with a 35% temperature increase under RCP 8.5 the annual SOC change rate decreases by 73% (Fig. 3b) (both compared to the baseline reference).

Net GHG emissions

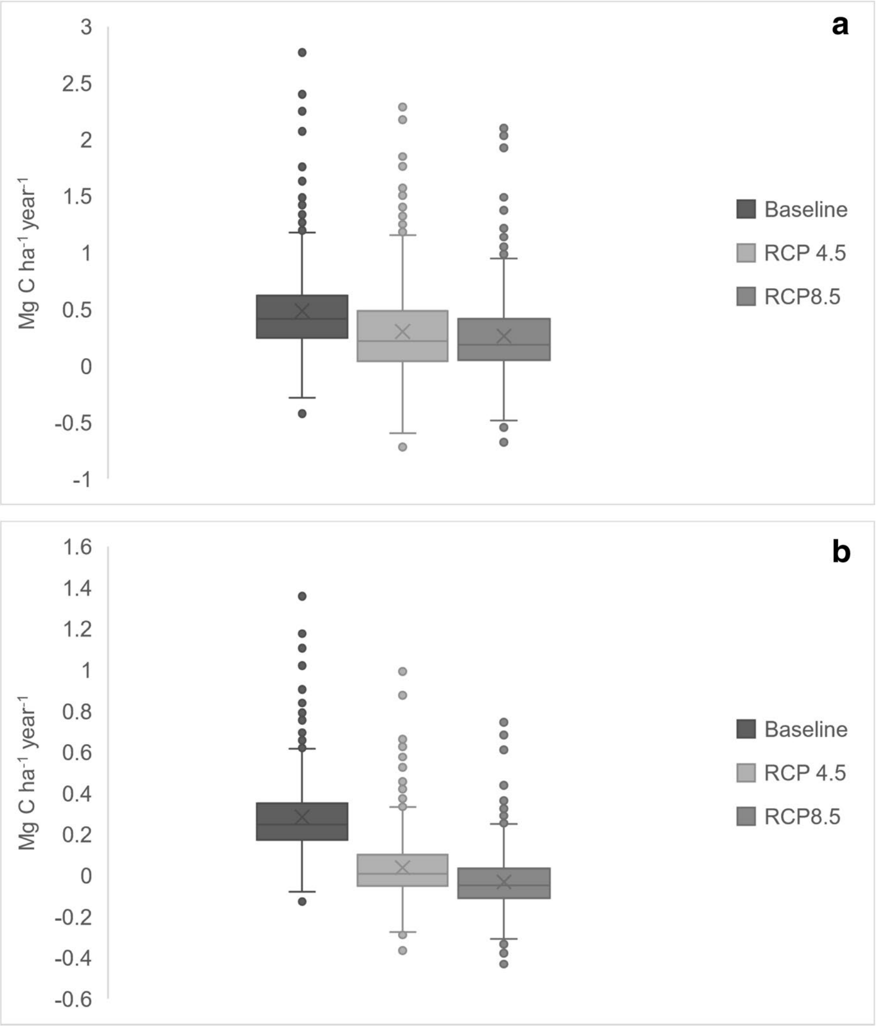
The average net GHG emissions associated with dairy farm systems (i.e., direct emissions from fields and barns) in Northern Spain were increased in the different municipalities, under the different climate scenarios, thus contributing to global warming: The estimated net GHG emissions for the dairy farming in the municipalities under RCP 4.5 ranged from -4 to 33 Mg CO_2-e ha^{-1} year^{-1} (with an average value of 5.8 Mg CO_2-e ha^{-1} year^{-1}) (t-test, $P < 0.001$) (Fig. 4a). Net GHG emissions under RCP 8.5 varied between -3 and 34 Mg CO_2-e ha^{-1} year^{-1} (with an average value of 6.2 Mg CO_2-e ha^{-1} year^{-1}) (t>-test, $P < 0.001$) (Fig. 4b). On the other hand, the net GHG under the baseline reference scenario presented an average value of 4.7 Mg CO_2-e ha^{-1} year^{-1} (Fig. 4c).

The spatial distribution of the net GHG emissions followed the same pattern in the different climate scenarios (Fig. 4a, b and c).

Climate warming conditions increase SOC losses and CH_4 emissions derived from manure management therefore explaining the higher net GHG emissions under both climate change scenarios compared to the baseline scenario (Fig. 5).

Higher temperatures also induced an increase in the MCF up to an average of 21.6 and 23.5% under the climate change scenarios RCP 4.5 and RCP 8.5, respectively, compared with only 16.2% with the baseline reference scenario. This increase in MCF resulted in greater CH_4 emissions from manure management (Table 2).

Fig. 2 Median and range (defined by the minimum, maximum and upper/lower quartiles) of the annual SOC change rate under the baseline and climate change scenarios (RCP 4.5 and RCP 8.5) for the time horizon 2010–2050 (**a**) and 2010–2100 (**b**) (*t*-test, $P < 0.001$)



Manure management scenarios for reducing GHG emissions

Rigid cover

An average 19% reduction in N_2O emissions by using a cover in the different climate scenarios was found (Table 3).

Slurry removal

The low-emissions scenario, consisting of removing slurry in all seasons except the winter resulted in up to 28% less CH_4 emissions from manure management (Table 3). Removing slurry throughout the year except in autumn presented the lowest reduction of the alternative practices, with more than 11%.

The GHG emissions from manure management can be further reduced by combining the use of a rigid cover and removing the manure throughout the year, except in the winter (Table 3).

Anaerobic digestion

Average SOC levels were reduced under an AD management scenario for both future climate change conditions (i.e., RCP 4.5 & RCP 8.5; Fig. 5). Moreover, emissions after land application increased ~ 17% under AD scenarios (Fig. 5). Anaerobic digestion did, however, avoid 95% of CH_4 emissions which would have been emitted from manure management (Fig. 5). Therefore, the

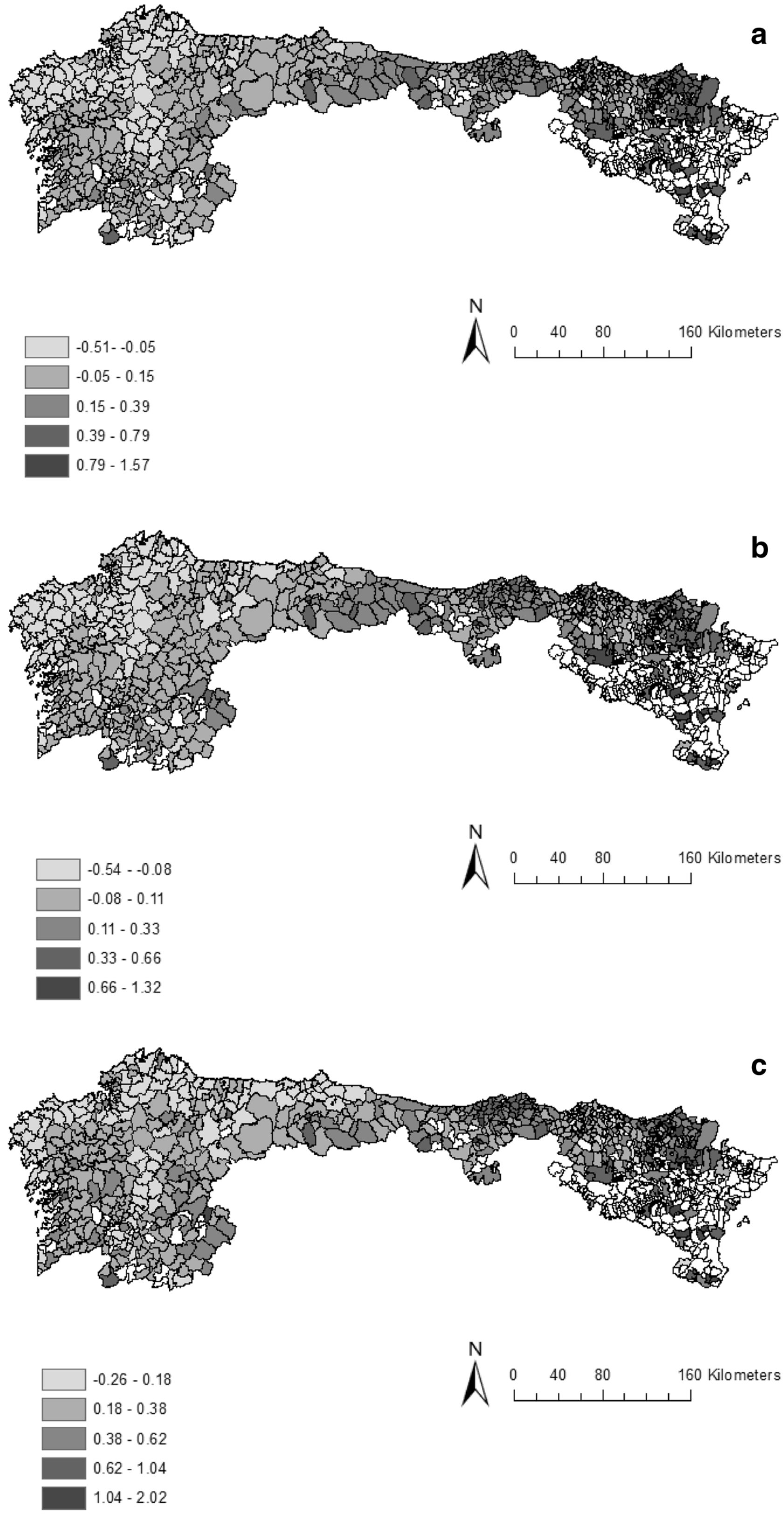
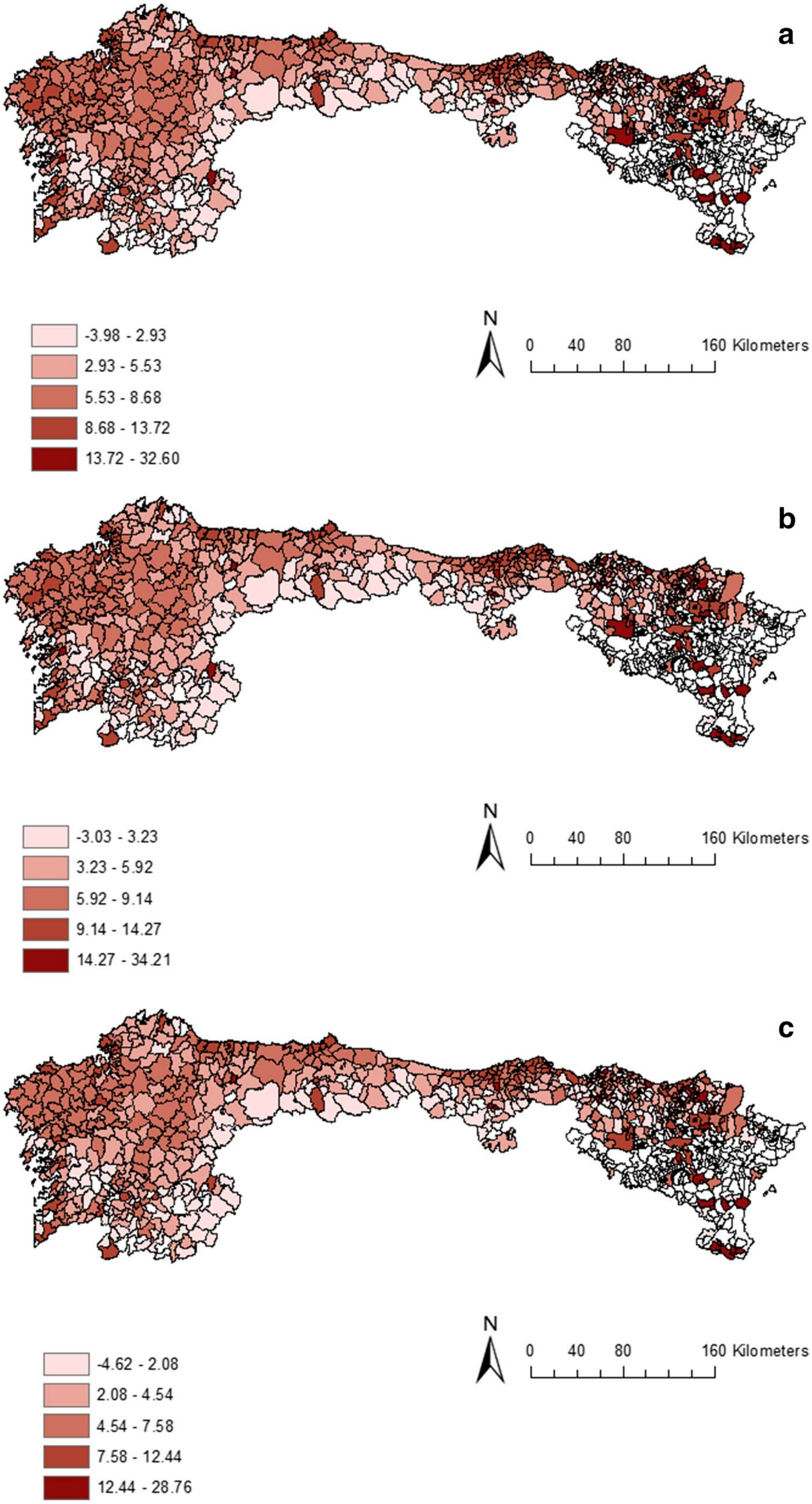


Fig. 3 Soil organic carbon stock change rates (Mg C ha^{-1} year.$^{-1}$) in dairy cow grasslands in municipalities of Northern Spain under the RCP 4.5 (**a**) and RCP 8.5 (**b**) climate change scenarios and the reference baseline scenario (**c**)

Fig. 4 Net GHG emissions per area in Mg CO_2-e ha^{-1} $year.^{-1}$ under RCP 4.5 (**a**), RCP 8.5 (**b**) and the baseline reference (**c**)



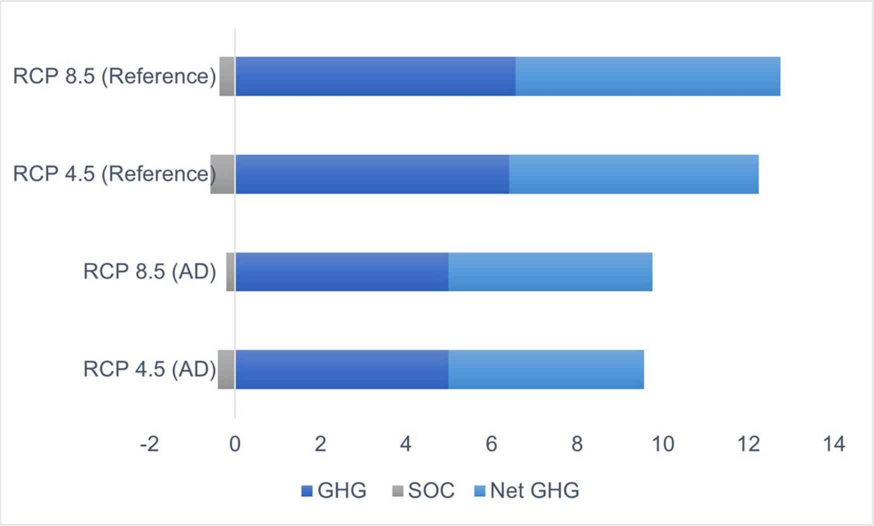


Fig. 5 Net balance of the reference scenario and alternative manure management scenarios (AD) under both RCP 4.5 and RCP 8.5 climate change scenarios during the period 2010–2100

Table 2 Average CH_4 and N_2O emissions, total greenhouse gas emissions, SOC storage and Net GHG expressed in Mg CO_2-e ha^{-1} $year^{-1}$ for the grasslands associated with dairy production in Northern Spain

Climate scenario	CH_4 from enteric fermentation	CH_4 from manure management	CH_4 from grassland soil	N_2O from manure management	N_2O from grassland soil	GHG emissions	SOC accumulation	Net GHG
Baseline	3.88	1.09	0.01	0.24	0.85	6.07	1.37	4.70
RCP 4.5	3.88	1.41	0.01	0.24	0.85	6.40	0.57	5.82
RCP 8.5	3.88	1.57	0.01	0.24	0.85	6.55	0.37	6.18

Table 3 Net GHG (Mg CO_2-e ha^{-1} $year^{-1}$) for a combination of climate scenarios (Baseline, RCP 4.5 and RCP 8.5) and manure management practices (M0, M1, M2 and M3) and their effect on N_2O and CH_4 emissions from manure management (%)

Scenario	Range of Net GHG	CH_4 reduction from manure management (%)	N_2O reduction from manure management (%)
Baseline—M0	-4.62 – 28.76	-	-
Baseline—M1	-4.63 – 28.50	-	19
Baseline—M2	-4.7 – 26.28	28.45	-
Baseline—M3	-4.65 – 27.55	11.75	-
RCP 4.5—M0	-3.98 – 32.60	-	-
RCP 4.5—M1	-4.00 – 32.34	-	19
RCP 4.5—M2	-4.08 – 29.33	27.8	-
RCP 4.5—M3	-4.02 – 30.86	11.22	-
RCP 8.5—M0	-3.03 – 34.20	-	-
RCP 8.5—M1	-3.04 – 33.95	-	19
RCP 8.5—M2	-3.14 – 30.69	27.2	-
RCP 8.5—M3	-3.08 – 32.26	11.35	-

M0, reference manure management scenario (slurry removed all year long except in summer, where the slurry storage system has a natural crust); M1, slurry storage system with a rigid cover; M2, slurry removed all year long except in winter; M3, slurry removed all year long except in autumn net reduction in GHG emissions of the AD manure management scenario under both RCP 8.5 and RCP 4.5 was 22.8% and 21.5% respectively (Fig. 5).

Discussion

SOC change

The findings related to changes in SOC were in agreement with Smith et al. (2005), who found that SOC decomposition is faster in regions where temperature increases, and soil moisture remains high enough to allow decomposition (Fig. 1). Opposite to these findings, Lugato et al. (2014) predicted an overall increase of SOC stocks according to different climate-emission scenarios up to 2100 for European agricultural soils. However, the declining SOC stocks under certain future climate change scenarios is in line with some other SOC projections for agricultural soils (Senapati et al. 2013; Wiesmeier et al. 2016). For instance Xu et al. (2011) modelled SOC changes using the RothC model in eight Irish grassland soils from 2021 to 2060 assuming constant carbon inputs and two different initialisation methods. They estimated a decrease of SOC stocks of between 2 and 6% for different climate change scenarios.

The reduction in SOC storage under the climate change scenarios was found to be greater here when compared to the work of Zhang et al. (2017) who simulated SOC stock changes for grasslands under the same climate change scenarios using the DNDC model. The reduction of SOC stocks (compared to the baseline) was estimated of 4.14% and 4.25%, compared with 15% and 19% in this study, under RCP4.5 and RCP8.5, respectively. This difference is partly explained by the different assumptions and pedoclimatic conditions. An alternate study by Smith et al. (2005) predicted a slight decrease of 1%, or even a slight increase of 1.6%, in SOC levels for European grasslands between 1990 and 2080 under climate change conditions, which are much smaller changes than our results indicate. This might also be attributed to differences in the soil and climate conditions in the regions studied by Smith et al. (2005) compared to those in Northern Spain.

Dairy grasslands in Northern Spain could potentially act as carbon source or sink depending on the interaction of carbon input and climate effects together with soil properties (Fig. 3): These findings are in line with a previous study assessing SOC changes in this region, under current conditions by Jebari et al. (2022). Under all three climate scenarios, declines in the SOC change rate were more evident in regions with a high initial SOC content (Fig. S2 and Fig. 3) and lower carbon inputs (Fig. S3 and Fig. 3), as in Doblas-Rodrigo et al. (2022). However, the regions with low initial SOC stocks and high carbon inputs from dairy manure, showed important increased rates of SOC accumulation (Figs. S2, Fig. S3 and Fig. 3). The grasslands located in the Southern area have a marked Mediterranean influence and are characterised by more intensive management together with increased C additions. Under climate warming conditions, the SOC stock for the grasslands in the Mediterranean region increased at a faster rate (i.e., 1 Mg C ha^{-1} $year^{-1}$) than other similar studies simulating grasslands under the same climatic conditions (Francaviglia et al. 2012). Applying manure is therefore likely to increase the SOC stocks (Whitehead et al. 2018; Kühnel et al. 2019).

In contrast to our findings, Kerr and Ochsner (2020) hypothesised that future soil moisture conditions, rather than precipitation or air temperature, may be the key determinant of climate change–SOC feedback effects in temperate grassland sites. The rate of modification by temperature is identical for each soil organic matter (SOM) pool in the RothC model, despite the varying temperature sensitivity of labile and stable SOM pools (Wiesmeier et al. 2016). According to the results from laboratory incubations and long-term experiments, more stable SOM pools are indeed more sensitive to temperature changes (Leifeld and Fuhrer 2005). Therefore, the decline in SOC stocks found herein could be much higher when considering that stable SOM pools are more sensitive to warming than labile SOM pools.

Net GHG emissions

Climate change associated changes in temperature and precipitation induce an increase in net GHG emissions, caused by SOC storage loss and CH_4 manure emissions increase (Table 2). This result is similar to Carozzi et al. (2022) for European grasslands under similar climate change scenarios. Carozzi et al. (2022) showed that on-CO_2 GHG emissions were triggered by rising air temperatures and increased exponentially over the century while exceeding the CO_2 accumulation. Graux et al. (2012), evaluating French grassland-based dairy systems under the IPCC special report emissions scenario (SRES) A2 forcing conditions, showed an increase in net GHG emissions in extensively managed grassland systems and a reduction in net GHG in intensively managed grassland systems (where SOM decomposition acceleration is compensated for by enhanced net primary production).

Manure management scenarios for reducing GHG emissions

Rigid cover

The reduction in total N_2O emissions under the rigid cover is explained by the reduced indirect emissions (e.g., NH_3 volatilisation by 56%; Chadwick et al. 2011) (Table S6). The findings of this study are in the range of more than 50% established by a meta-analysis conducted by Hou et al. (2015), and close to the measured 53% reduction in NH_3 emissions by Finzi et al (2019). The emission factors for production systems used herein, together with average annual temperatures were estimated based upon IPCC (2019) and EMEP (2019). However, this approach may present a certain degree of uncertainty since, during storage, microbial activities in the manure might be affected by local climate conditions (Petersen et al. 2013).

Slurry removal

Removing slurry in all seasons except the winter season presented the lowest emission scenario, as the temperature conditions in the storage system are lower than in autumn or summer seasons (Table S7). Shortening the time in house manure storage for only the winter season reduced GHG emissions by 5% in the range of 0–40% (Sommer et al. 2009). However, complete tank emptying can reduce overall GHG by 49% (Wood et al. 2014).

Although beyond the scope of this study, avoiding manure application in the winter would also help to avoid potential eutrophication since frequent application during precipitation events or snowmelt could lead to runoff, leaching and loss of nutrients (Aguirre-Villegas and Larson 2017). However, atmospheric emissions could increase during application as more ammoniacal nitrogen and VS are available to promote N_2O, CH_4, and NH_3 losses (Chadwick et al. 2011; Warncke et al. 2004).

The MCF model approach used (IPCC 2019) accounted for the timing, length of storage, manure composition, and monthly temperature variations, as well as retention time in the barn. In this context, Peterson et al. (2018) stressed that time is a key variable, as management decisions influence storage conditions on a daily basis, including storage time before or after manure treatment (Peterson et al. 2018).

Anaerobic digestion

The reduction in SOC level under AD scenarios is the result of lower carbon input from excreta, as part of these by-products were converted to CH_4 and CO_2 in the storage system (Petersen et al. 2013). Moreover, the increase in emissions after land application increased is due to the higher total ammoniacal nitrogen (TAN) in manure (Aguirre-Villegas et al. 2019) (Fig. 5).

However, according to our findings, emissions from manure management in dairy systems were reduced by more than 40%, which is in line with Aguirre-Villegas et al. (2015).

It is interesting to note that the net GHG emissions corresponding to the AD management scenario were equivalent to the net GHG under the baseline reference scenario. The total mitigation potential achieved with AD manure management in this study (i.e., 21 -23%) is included in the range, established by Scott and Blanchard. (2021) (i.e., 16.6 – 23%) for dairy farms in UK. The mitigation potential is also similar to Bacenetti et al. (2016) and Battini et al. (2014), who found a reduction of 22% and 23.7%, respectively, in environmental impacts of milk production. Anaerobic digestion has many other benefits that are not analysed in this study, such as the production of renewable energy, and the reduction/avoidance of on-farm fossil-based energy, which promotes the sustainability and profitability of dairy farms (Aguirre-Villegas et al. 2019). Moreover, injecting digestate during land application is an effective management practice for reducing NH_3 emissions, while at the same time increasing nitrogen availability and reducing GHG emissions (Aguirre-Villegas et al. 2019). Although the benefits of AD are numerous, it is a capital-intensive technology that might be justified at large farms (Aguirre-Villegas et al. 2019), or shared by smaller farms (Macmillan and Cusworth 2019).

We did not consider mitigation scenarios to avoid soil N_2O emissions derived from manure application in our study, as the IPCC method refers to emission factors rather than detailed climate-based equations for N_2O soil emissions. Referring to the scientific literature, there are several measures for reducing soil N_2O emissions. For instance, N_2O emissions are considerably reduced if the amount of nitrogen applied with the manure corresponds to the amount necessary for optimal pasture growth. In this context, optimised fertiliser rates and novel technologies such as ZELP (https://www.zelp.co/) could be an option. Moreover, nitrification inhibitors have the potential to reduce both N_2O emissions and nitrogen leaching from manure or fertilisers, and this reduction may be as high as 40 to 50% according to some meta-analyses (e.g., Qiao et al. (2015)).

Limitations

The originality of this research rests on our assessment of the net GHG emissions of grassland-based dairy systems at the regional level under climate change and alternative manure management mitigation scenarios. However, the study involved certain limitations that should be highlighted. In terms of the SOC dynamics estimation, uncertainty related to this work may be ascribed to the model applied, as well as the unavailability of some data at the temporal or spatial levels (Jebari et al. 2022). Changes in soil management and carbon input values throughout the study period were not considered and these may need to be refined. In this context, many studies (e.g., Dondini et al. 2018; Hewins et al. 2018) stressed climate impacts on plant productivity and the amount of carbon input. In particular, plant growth is vulnerable to shifts in temperature and precipitation (Emadodin et al. 2021). However, the mean value of possible SOC stocks (derived from the Monte Carlo simulation) was close to the predicted SOC stocks (Table S8). The findings on SOC storage could therefore be interpreted as a good indicator of potential SOC storage in the study area. Furthermore, in this study the RCP scenarios were used to simulate possible climate change, but as a long-term climate projection, the uncertainty in the projected climate increases as the time span increases (Moss et al. 2010). In particular, projected rainfall is the factor involving the greatest variability between the climate scenarios and the primary source of uncertainty in the SOC response (Meyer et al. 2018). The assumption in the simulation that the grassland community structure remains stable could induce uncertainty, and further research is required to clarify the specific responses of plant communities to climate change (Ghahramani et al. 2019).

Regarding GHG estimation under climate change projections, apart from the uncertainties induced from our main assumptions (Jebari et al. 2022), there others that could be related to the IPCC Tier 2 method (Clark 2017). For instance, N_2O emission factor calculations based on IPCC Tier 2 did not account for refined environmental regulators, e.g., on a daily or monthly basis, which may modify emissions from applied nitrogen. Moreover, the potential impact of climate change on N_2O mitigation strategies remains speculative and requires further research (Griffis et al. 2017). In this context, a multi-model ensemble could improve the predictions (e.g., NGAUGE Brown et al. 2005; Del Prado et al. 2006) and DNDC (Li et al. 1992; Giltrap et al. 2010)).

Finally, the net GHG emissions assessment is limited to grassland-based systems and does not account for mixed forage systems including maize silage, for example. The analysis described in this paper cannot be considered a full life-cycle assessment as our estimation for the net GHG of dairy grassland systems excludes pre-farm phases (e.g., feeds) and energy use on the farms.

Conclusions

Our study illustrates the fact that climate change will impact net GHG emissions from grassland-based dairy livestock systems in Northern Spain. Based on the findings, combining alternative dairy manure management practices (slurry storage systems with rigid covers; and year-round slurry removal, except in winter) would help to mitigate the effects of climate change and reduce net GHG emissions from the grassland-based dairy livestock systems in Northern Spain. Anaerobic digestion is the most effective strategy for mitigating GHG emissions from manure, as it allows net GHG under both climate change scenarios to equal net GHG under the baseline reference scenario.

Furthermore, our study emphasises the importance of improving our modelling capabilities, with consideration of off-farm emissions, to provide a clearer picture of the full implication of management practices in terms of mitigating the effects of climate change.

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Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Asma Jebari. The first draft of the manuscript was written by Asma Jebari and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

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