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ORIGINAL ARTICLE

Effect of dairy cattle production systems on sustaining soil organic carbon storage in grasslands of northern Spain

Asma Jebari[1] · **Jorge Álvaro-Fuentes**[2] · **Guillermo Pardo**[1] · **Inmaculada Batalla**[1] · **José Antonio Rodríguez Martín**[3] · **Agustin Del Prado**[1,4]

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Abstract

Predicting the regional net greenhouse gas emissions (Net GHG) of grasslands is increasingly important, as these are one of the most globally widespread vegetation types, providing several ecosystem services. In this study, we assessed the regional soil organic carbon (SOC) change over a 30-year period (1981–2010), and the annual GHG balance for 405,000 ha of moist temperate Spanish grassland associated with dairy cow production. To do this we used the following: (i) an integrated modelling framework comprising geographic information systems (GIS); (ii) the RothC model to simulate SOC changes in managed grasslands under moist temperate conditions; and (iii) Tier 2 recent IPCC methods to estimate emissions. The results showed an average regional SOC change rate of 0.16 Mg C ha^{-1} $year^{-1}$, associated with the initial SOC and livestock density. The annual GHG balance was positive, contributing to global warming by 5.6 Mg CO_2-e ha^{-1} $year^{-1}$. Livestock density was the main factor affecting net GHG emissions in the grasslands associated with dairy production in northern Spain. We determined a livestock density threshold of 0.95 LU ha^{-1}, below which there is no SOC accumulation, and a threshold of approximately 0.4 LU ha^{-1}, above which net GHG per livestock unit (LU) are reduced. In conclusion, our study confirms the importance of dairy cow grazing systems in preserving and/or enhancing SOC stocks in the grasslands of northern Spain. It is therefore crucial to optimise the livestock density considering large variety of feed intake and alternative manure management mitigation options to reduce the net GHG emissions.

Keywords Upscaling · Soil organic carbon · Net greenhouse gas emissions · Grassland-based dairy systems

Introduction

Grasslands are often devoted to the production of forage to be grazed, cut, or both (Peeters et al. 2014). They are one of the most widespread vegetation types worldwide, occupying 70% of the world's agricultural land (Whitehead et al. 2018), and represent an important ecosystem that provides key services (Eze et al. 2018; Ma et al. 2015), including food production and soil organic carbon (SOC) sequestration (Klumpp and Fornara 2018).

Grasslands can act as a carbon sink, with a SOC sequestration of approximately 1 Mg C ha^{-1} $year^{-1}$ (Janssens et al.

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✉ Asma Jebari
asma.jebari@bc3research.org

Jorge Álvaro-Fuentes
jorgeaf@eead.csic.es

Guillermo Pardo
guillermo.pardo@bc3research.org

Inmaculada Batalla
inmaculada.batalla@bc3research.org

José Antonio Rodríguez Martín
rmartin@inia.es

Agustin Del Prado
agustin.delprado@bc3research.org

[1] Basque Centre for Climate Change (BC3), Edificio Sede no. 1, Planta 1, Parque Científico de UPV/EHU, Barrio Sarriena S/N, 48940 Leioa, Bizkaia, Spain

[2] Estación Experimental de Aula Dei (EEAD), Spanish National Research Council (CSIC), Av. Montañana, 1005, 50059 Zaragoza, Spain

[3] Department of Environment, Instituto Nacional de Investigación Y Tecnología Agraria Y Alimentaria (I.N.I.A), Ctra. La Coruña 7.5, 28040 Madrid, Spain

[4] Basque Foundation for Science (Ikerbasque), Bilbao, Spain

2005). However, the livestock sector, which ties in with grasslands, accounts for 12% of all human-induced GHG emissions, with the ruminant sector being responsible for 80% of these (Havlík et al. 2014). Indeed, the GHG balance of grasslands presents decadal fluctuations, with values ranging from a net GHG source of 0.6 ± 1.3 Gt CO_2-e year^{-1} in the 1970s to 1.8 ± 0.7 Gt CO_2-e year^{-1} in the 2000s (Chang et al. 2021). Specifically, the cattle dairy sector is a major contributor to total GHG emissions (responsible for about 3.2% of global anthropogenic GHG emissions) (Gerber et al. 2013). In particular, European dairy production continues to intensify, and the zone is expected to become the world's largest milk exporter (Styles et al. 2018). Important sources of direct GHG emissions from dairy farms include CH_4 from enteric fermentation, as well as CH_4 and N_2O from either manure storage and handling or soil grasslands. However, as grassland soils act as carbon sinks, grassland-based livestock systems can partly offset the climate impact of cattle production. For example, in Canadian beef cattle systems, two thirds of direct CH_4 and N_2O emissions are offset by SOC accrual (Liang et al. 2020). Quantifying the net balance between SOC stocks in grasslands and GHG emissions is therefore important to assess the climate impact of grassland-based livestock systems (Conant et al. 2017).

Spain is one of the seven major producers of cow's milk in the EU (Eurostat 2019). Of the 156 million tonnes that the EU is estimated to produce per year, Spain accounts for 5.1%, having provided 7.2 million tonnes in 2019. The dairy farming activity is mainly located in Spain's Northern Atlantic zone, where grasslands are very productive as a consequence of the prevailing frequent rainfall and cool temperatures (Smit et al. 2008). Dairy production grassland ecosystems in northern Spain are commonly based on a grass-white clover mix or forage rotations (e.g. maize silage (*Zea mays* L.) and Italian rye-grass (*Lolium multiflorum* L.). The dairy farming activity is characterised by a gradient of productive intensification according to farm size, explained by an increase in the per animal and per hectare productivity (Flores-Calvete et al. 2016). Whereas the number of milking cows in Spain has dropped substantially, by over 20% in the last years, the level of milk production has increased due to improvements in productive and reproductive management (MAPA 2019). Moreover, these improvements have resulted in a reduction in the national inventory of GHG in direct CH_4 emissions for dairy cattle of 25%, in addition to 36% for enteric fermentation and manure management (Cortés et al. 2021; UNFCCC 2021).

Alongside the national GHG inventory, there have been studies involving a life cycle assessment (LCA) framework and varied methods (e.g. farm modelling) to estimate the carbon footprint of dairy farms in northern Spain. Del Prado et al. (2013) assessed the carbon footprint of milk and the farm carbon balance on 17 confined commercial dairy farms in the Basque Country (northern Spain) using a combination of models (e.g. grassland model NGAUGE: Brown et al. 2005). Recently, Laca et al. (2020) analysed the carbon footprint of two different dairy systems (semi-confined and pasture-based) in Asturias (northern Spain) using the Greenhouse Gas Protocol (IDF 2015). Ibidhi and Calsamiglia (2020) estimated the carbon footprint, excluding emissions from transport and purchased feed, of twelve Spanish dairy farms selected from three regions in Spain, using the Integrated Farm System Model (IFSM) (Chianese et al. 2009). However, to our knowledge, in northern Spain there have been no regional assessments of net GHG at spatial scales larger than farm or field level. In general, globally, few studies have estimated the net GHG of grassland-based cattle production systems at larger spatial scales (i.e. regional scale) under moist temperate conditions. In this study, we aimed to: (i) describe an integrated modelling approach to estimate net GHG emissions and SOC storage in dairy cattle production systems in northern Spain (at the grassland soil and barn levels) under moist temperate conditions at a regional scale; (ii) present a spatially explicit map of net GHG emissions and SOC storage in our study area; (iii) assess the main factors influencing net GHG emissions and SOC storage; and (vi) evaluate the potential limitations and improvements of the modelling approach. In order to assess the regional net direct GHG emissions of managed grassland-based dairy cattle systems in northern Spain (at the grassland soil and barn levels), we used an integrated modelling framework comprising geographic information systems (GIS), the RothC model (Coleman and Jenkinson 1996) to simulate SOC changes, and Tier 2 IPCC methods to estimate the CH_4 and N_2O emissions from enteric fermentation, manure storage and handling, and grassland soils (IPCC 2019). We hypothesised that in northern Spain, grassland-based dairy cattle systems act as a GHG source and SOC storage may only partly offset the emissions.

Method

Study area and dairy system characterisation

The simulated area consists of 405,000 ha of grassland in northern Spain associated with dairy cow production. It includes all the provinces in the Spanish Autonomous Communities of Galicia, Asturias, Cantabria, the Basque Country, and Navarre (Fig. S1). The climate is mainly European Atlantic with an annual mean rainfall above 1000 mm and average annual air temperatures of about 12–14 °C.

In the study area, the land surfaces covered by permanent grasslands and forage crops are 1,388,007 ha (Fig. S2) and 265,217 ha, respectively (ESYRCE 2019). These two land uses correspond to 63% and 12% of the utilised agriculture area, respectively (ESYRCE 2019).

Dairy cattle production in northern Spain accounts for 60% of Spain's milk production (MAPA 2016). The most typical cattle breed is Holstein–Friesian. To best characterise the diversity of farm management in this area, we identified different typologies of dairy cattle farming based on two recent reports (Flores-Calvete et al. 2016, and MAPA 2019) and gathered input data to define each typology. These were classified according to the different regions in our study area, as illustrated in Table S1 and Table S2. The composition of the annual diets and management of the lactating dairy cows in the different regions of our study area are described in the "Cow diet" sub-section. The average annual dairy production per farm in the study region is about 233 tonnes of milk (Table S1), although this varies across the different northern Spanish regions as shown in Table S1 (Flores-Calvete et al. 2016). The common management strategy involves year-round grazing for heifers and dry cows (except in winter), while the lactating cows are confined for most of the year, being fed both annual forage crops (often maize silage) and concentrates (MAPA 2019) (see "Cow diet" sub-section).

Change in soil organic carbon stocks

We used a modified version of the RothC model (Jebari et al. 2021) to simulate SOC changes in managed grasslands under moist temperate climate conditions. The RothC model (Coleman and Jenkinson 1996) divides the SOC into five fractions, four of which are active and one of which is inert (i.e. inert organic matter, IOM). The four active pools are as follows: decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO), and humified organic matter (HUM). The decomposition of each active pool is governed by first-order kinetics, characterised by its own turnover rate constant and modified by environmental factors related to air temperature, soil moisture and vegetation cover, which are the main input parameters for the model. Incoming plant carbon is split between DPM and RPM, depending on the DPM:RPM ratio of the particular incoming plant material or organic residue. Both decompose to produce BIO, HUM, and evolved CO_2. The proportion that is converted to CO_2 and BIO + HUM is determined by the clay content of the soil, which is another model input. The model uses a monthly time step to calculate total SOC and its different pools change on a year to century time scale.

The modifications of the model version we used consisted of the following: (i) considering plant residue components and their quality variability throughout the year; (ii) established entry pools that account for the ruminant excreta as a specified type of exogenous organic matter; and (iii) water content up to saturation in the soil water function (Jebari et al. 2021).

The initialisation of the RothC model was based on the clay and SOC content obtained from Rodríguez Martín et al. (2016). We used the pedotransfer functions established by Weihermüller et al. (2013) to estimate all active carbon pools. The initial IOM pool was set to match the equation proposed by Falloon et al. (1998):

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

The assessment of SOC stock changes in dairy cow grasslands from 1981 to 2010 was based on spatial units (i.e. municipalities), using GIS (i.e. ArcMap 10.2). We developed a Visual Basic for Applications (VBA)-based programme in Excel to simulate simultaneous changes in SOC stocks for the period 1981–2010 at municipality level. We used this approach since the regional simulation is computationally intensive and time consuming due to the combination of a large number of runs.

Input data

Climate data The monthly average temperature and precipitation figures for the different municipalities in northern Spain were extracted from Spanish State Meteorological Agency data (AEMET 2012) for the range 1981–2010. Monthly potential evapotranspiration was estimated using Thornthwaite equations (Thornthwaite 1948).

Soil properties Soil property data was obtained from a previous national assessment (Rodríguez Martín et al. 2016). In this assessment, soil texture and SOC in the top 0–30 cm of soil were analysed and spatially represented for all of Spain (Rodríguez Martín et al. 2016). It is worth noting the large variability in SOC stocks (32–241 Mg ha^{-1}) and clay content (6–30%) across the study area (Fig. S3).

The soil water contents at saturation and field capacity conditions were deduced from FAO estimations considering soil properties related to texture (Raes 2017). Soil textural classes, used to estimate soil moisture function under water saturation conditions, were derived from the European Soil Data Centre (Ballabio et al. 2016).

Plant residues Grasslands associated with dairy cow production in northern Spain are commonly grass-white clover swards; mainly ryegrass with about 5–10% of white clover (*Trifolium repens. L.*). For our simulated swards, we assumed 5% of white clover.

Using the available records of estimated grass dry matter production (kg ha^{-1}) from 36 municipalities in our study area, gathered in a survey, we generated a simple linear regression model using climate data (i.e. temperature and precipitation) as explanatory variables since climate is considered the most important driver for grass production. The results of estimated dry matter production from the linear regression varied between 6308 and 11,363 kg ha^{-1} year^{-1} and were within the range of studies carried out in our study area (e.g. Doltra et al. 2019; Baizán et al. 2021; Batalla et al. 2015), as well as within the range of the regional Spanish Ministry of Agriculture Statistics (ESYRCE).

Given the lack of detailed carbon input data at refined spatial levels, we referred to the literature in order to estimate plant residue components, while also considering the rhizodeposition component, which is in general missing in SOC modelling studies (Balesdent et al. 2011). In order to estimate below-ground biomass from above-ground biomass values, we used a root to shoot (R:S) value of 4, typical for temperate grasslands (Mokany et al. 2006). In terms of plant residues, it was assumed that 65% of the above-ground biomass is harvested or consumed by dairy cows (Soussana and Lemaire 2014; and Poeplau 2016) and only 50% of the remaining fraction (i.e. of 35%) is turned over annually, becoming available for soil organic matter formation as above-ground residue (Schneider et al. 2006). Similarly, 50% of below-ground biomass was assumed to be below-ground residue as the annual root turnover is about 50% in the temperate zone (Gill and Jackson 2000). To estimate rhizodeposition, we referred to a ratio, typical of grassland species, between net rhizodeposition and below-ground biomass of 0.5, as in Pausch and Kuzyakov (2018). Finally, we assumed a carbon concentration of 45% of the plant biomass (Kätterer et al. 2012).

Cow diet Given the lack of information on the different feeding systems at a more refined spatial scale, we referred to the main diet typologies in the region according to Flores-Calvete et al. (2016), using the sub-category lactating dairy cows (Table S2), and MAPA (2019) for the remaining dairy cow sub-categories (i.e. heifers and dry dairy cows) (Table S3 and Table S4). The common management strategy involves heifers and dry cows grazing for most of the year (75%) while lactating cows are housed for most of the year (77–90%). The feeding regime of lactating dairy cows consists mainly of annual forage crops (e.g. maize silage) and concentrates (31–40%) (MAPA 2019) (Table S2). The different nutritional values were identified taking into account the ingredients offered in the different typologies. Crude protein varies from 17–19% for lactating cows while the average digestibility is 71%.

In our study area, the typical feeding regime of dry dairy cows and heifers in our simulation period consisted of a lower percentage of concentrates (25%), as illustrated in Table S3 and Table S4. The crude protein was only 13.5% for both dry dairy cows and heifers, while the digestibility was 65% and 66% for dry dairy cows and heifers, respectively.

The dry matter (DM) intake varied between 15 and 17 kg DM animal^{-1} day^{-1} for lactating dairy cows of the different typologies and was estimated at 7 and 8.6 kg DM animal^{-1} day^{-1} for dry cows and heifers, respectively.

Estimation of carbon inputs to the soil via carbon balance Soil carbon inputs from manure included the excretion of grazing animals and the application of managed manure. The carbon flows from manure can be estimated, using a mass-balance approach, subtracting the non-digested fraction which is egested as faecal material combined with urinary excretion from the fraction of the DM intake (C ingested$_{\text{animals})}$.

Carbon inputs $_{\text{from animal manure}}$ = C ingested$_{\text{animals}}$ − C in milk$_{\text{animals}}$ − C in body weight change$_{\text{animals}}$ − C in CO_2 resp$_{\text{animals}}$ − C in CH_4 enteric$_{\text{animals}}$ − C in CH_4 $_{\text{manure management}}$ − C in CO_2 $_{\text{manure management}}$.

C ingested$_{\text{animals}}$: equals the fraction of the diet consumed, referring to the carbon contained in the dry matter intake estimated according to the IPCC (2019) method.

C in milk $_{\text{animals}}$, C in body weight change $_{\text{animals}}$, and C in CO_2 resp$_{\text{animals}}$: equals the fraction of the digested fraction retained, which is used for milk production, for growth and animal respiration, respectively. The parameters were estimated as in the IPCC (2019) method.

C in CH_4 enteric $_{\text{animals}}$: equals the fraction emitted from animal enteric fermentation, as indicated in Supplementary Information B (IPCC 2019).

C in CH_4 $_{\text{manure management}}$: CH_4 emissions from management and grazing dairy cows were calculated annually as detailed in Supplementary Information B according to the IPCC (2019).

C in CO_2 $_{\text{manure management}}$: CO_2 emissions from manure management, derived from the ratio used by Pardo et al. (2017) from CH_4 manure emissions.

Manure carbon input per livestock unit (LU) was then multiplied by LUs for each category per municipality and divided by the average dairy cow holding area according to the Agricultural Census (INE 2009) to get tonnes of carbon excreted ha^{-1} year^{-1}.

We assumed a maximum quantity of dairy manure of 500 kg ha^{-1} year^{-1} per municipality. The excess was assumed to be exported 30 km away from the area to the nearest neighbouring municipality (Fealy and Schröder 2008). Any surplus dairy manure was assumed to be applied to arable lands.

Spatial layer linkages

According to the National Statistical Institute (INE 2009), we referred to the municipalities with grasslands associated with dairy production as spatial units. Monthly average climate data was assigned to the different spatial units using GIS (ArcMap 10.2), according to their proximity to the meteorological stations. For soil properties, we obtained the statistical mean of SOC stocks and clay content for each municipality (Rodríguez Martín et al. 2016) through ArcMap, in order to generate precise values of all pixels contained within them. Soil textural classes were also extracted and ascribed to the different municipalities using ArcMap.

Uncertainty analysis: Monte Carlo simulation

A Monte Carlo simulation was used to assess the sensitivity of the SOC stock results to uncertainties in certain parameters. This was done by constructing probability density functions (PDF) for the most relevant model parameters and input variables considered to be uncertain. As we aimed to explore the potential of management practices for increasing SOC stocks, specific attention was paid to evaluating the influence of carbon input as the main driver of SOC accumulation (see Results section). The Monte Carlo simulation was performed iteratively (1000 times) to sample random values for carbon inputs using normal distribution, with the aim of exploring the potential deviation of the SOC stocks when combining plant residues and animal excreta. To define the uncertainty, we referred to plant dry matter production values as a proxy for plant residues; we selected a range of maximum and minimum values based on a sample of measured and reported dry matter data related to the study area; and we assumed a normal distribution with a maximum-minimum range equal to the 95% confidence interval (Table S5). A similar approach was applied to estimate the PDF of the carbon inputs from animal excreta (Table S5).

On a large geographical scale, Monte Carlo simulations require many model runs and a great deal of computational time. For this reason, we selected nine municipalities for the uncertainty analysis, which well represented the spatial distribution of our study area. The municipalities considered were close to meteorological stations to minimise uncertainties deriving from climate data.

Greenhouse gas emissions

We used the recently refined IPCC Tier 2 method to estimate direct GHG (i.e. CH_4 and N_2O) emissions (IPCC 2019), and the latest European Monitoring and Evaluation Programme (EMEP) method to estimate ammonia (NH_3) volatilisation and nitrate (NO_3) leaching from manure storage into grassland soils at the municipality level (EMEP 2019). Ammonia and NO_3 leaching are not GHG, but they were considered to be N_2O precursors (indirect N_2O). To estimate emissions, the method relies on the enhanced characterisation of the animal population, assumed diet characteristics, and manure management. We multiplied the different emission factors by the corresponding number for each sub-category of dairy cows (i.e. lactating dairy cows, dry cows, and heifers) in the different municipalities in our study area. The typologies characterising the predominant practices in each region within our study area (details on grazing practices, dietary information, and feed quality) according to animal type, physiological status, age, growth rate, activity level, and production, were drawn from MAPA (2019) and Flores-Calvete et al. (2016). The explanation of the method used to estimate the CH_4 and N_2O emission factors is included in Supplementary Information B.

In order to aggregate the effect on climate of the different forms of GHG, we used the global warming potential metric for a 100-year time horizon (GWP100) based on the latest values from the IPCC (2014). For each spatial unit in our study area, we tried to consider the effect of SOC storage on the main GHG emissions. The net emissions equivalent to CO_2 (CO_2-e) for dairy cow production in northern Spain (at the grassland soil and barn level) was calculated as a balance between the overall annual GHG CO_2-e fluxes calculated at the field and barn scale (CH_4 and N_2O) and the estimated long-term soil carbon gains (i.e. average annual SOC accumulation over 30 years) for each spatial unit, expressed as CO_2-e (Eq. 2):

$$\mathrm{GHG/yr}\ (\mathrm{CO_2\_e}) = \mathrm{CO_2\_eN_2O} + \mathrm{CO_2\_eCH_4} - \mathrm{CO_2\_e_{CO_2}}\,(\mathrm{SOC\ change}) \tag{2}$$

where CO_2-eN_2O is nitrous oxide emission and CO_2-eCH_4 is methane emission, calculated according to the IPCC (2019) in Mg CO_2-e ha^{-1} $year^{-1}$; e_{CO2} 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} $year^{-1}$).

Results and discussion

Regional changes in soil organic carbon stocks

SOC change rate

The annual SOC change rate modelled for grasslands in the dairy cattle systems in municipalities in northern Spain presented an average of 0.16 Mg C ha^{-1} $year^{-1}$ at a depth of 30 cm, between 1981 and 2010 (Fig. S4), which is within the range of SOC change rates found in other studies of moist temperate European grasslands (Ma et al. 2015). For example, in Belgian grasslands, an average SOC change rate of 0.45 Mg C ha^{-1} $year^{-1}$ was described for the period 1955–2005 (Goidts and van Wesemael 2007). The difference in the values in our study and the work by Goidts and van Wesemael (2007) may be explained by greater manure application on Belgian grasslands (mainly during the first decades of the study period before this was regulated) compared with northern Spain.

The SOC change rates found (from – 0.95 to 3.24 Mg C ha^{-1} $year^{-1}$) are within the range of values reported in previous studies of the study area, both at regional and plot level (Table S6). Most municipalities (about 82%) showed SOC change rates of between – 0.5 and 0.66 Mg C ha^{-1} $year^{-1}$ (Fig. S4), and less than 6% of municipalities presented SOC change rates higher than 1 Mg C ha^{-1} $year^{-1}$ (Fig. S4). The small change in SOC in the majority of the spatial units could be explained by the fact that grasslands were generally undisturbed and that SOC accumulation is dependent on carbon input (Horwath and Kuzyakov 2018).

The highest rates of SOC change were observed in the grasslands located in the southeastern part of the study area (Fig. 1). This region is markedly influenced by the Mediterranean climate, with a mean annual precipitation of 731 mm, resulting in lower initial SOC stocks (49 Mg C ha^{-1}). Furthermore, the production systems are characterised by intensive dairy farming with large carbon inputs from dairy cow excreta (up to 500 kg N ha^{-1} $year^{-1}$). These factors resulted in high SOC change rates (Fig. 1). In contrast, the lowest SOC change rates were observed in areas with a high mean annual precipitation (> 1500 mm), high initial SOC stocks (171–223 Mg C ha^{-1}), and low animal density with low animal excreta input (< 30 kg N ha^{-1} $year^{-1}$). At the same time, the model predicted SOC losses in certain grassland areas with an initial SOC content above 91 Mg C ha^{-1} $year^{-1}$ and low livestock densities (Fig. 1).

Relationship between soil organic carbon change rate and various factors

The relationship between the SOC change rate and different carbon inputs, climate and soil variables, as well as the interrelation between all these variables, was analysed using stepwise linear regressions (Table 1) and correlation analyses (Table S7). The five variables analysed (carbon inputs, initial SOC, soil texture, mean annual temperature, and mean annual precipitation) were significantly related to the SOC change rate. We did not split the carbon input into its two components (i.e. plant residues and dairy manure), given the multicollinearity between plant residues and climate variables (Table S8 and Table S9). Two variables showed the closest relationship with the SOC change rate and explained the majority of the variance (about 81%): carbon inputs (positively correlated) and the initial SOC content (negatively correlated) (Table 1). This is, in fact, in line with the findings of previous studies on the long-term evolution of SOC stocks at a regional scale in similar European grasslands (e.g. Bellamy et al. 2005; Saby et al. 2008; Goidts and van Wesemael 2007). The relationship between the SOC change rate and the initial SOC content might illustrate the fact that soil organic matter dynamics tend to reach equilibrium (Goidts and van Wesemael 2007), since the SOC accumulation capacity is limited. The clay content presented a significant positive but weak correlation with the SOC change rate, as in the study by Goidts and van Wesemael (2007) (Table S7). This could be explained by the structure of the RothC

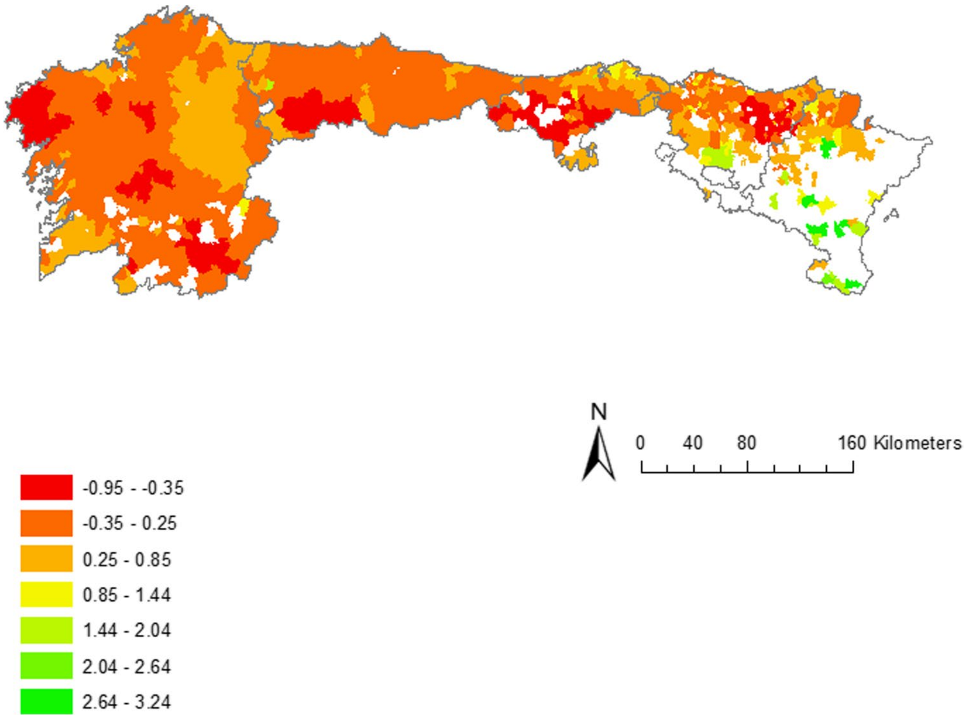

Fig. 1 Soil Organic Carbon (SOC) stock change rates (Mg C ha^{-1} $year^{-1}$) in dairy cow grasslands in municipalities in northern Spain

Table 1 Stepwise linear regression between annual soil organic carbon (SOC) change rate (Mg C ha^{-1} year^{-1}) and the different model input variables

	(1) SOC$_r$ Coefficient	(2) SOC$_r$ Coefficient	(3) SOC$_r$ Coefficient	(4) SOC$_r$ Coefficient	(5) SOC$_r$ Coefficient
C input	0.3990^{***}	0.3506^{***}	0.3567^{***}	0.3722^{***}	0.3924^{***}
SOCi		-0.0094^{***}	-0.0099^{***}	-0.0104^{***}	-0.0088^{***}
Clay			-0.0084^{***}	-0.0114^{***}	-0.0108^{***}
MAT				-0.1735^{***}	-0.1696^{***}
MAP					-0.0031^{***}
Constant	-1.7624^{***}	-0.3657^{***}	-0.1693^{*}	2.2728^{***}	2.2673^{***}
No. of Observations	690	690	690	690	690
R-Squared	0.580	0.808	0.818	0.913	0.935
F Statistic	949.437	1442.748	1031.095	1794.303	1954.323

$^{***}p<0.01$, $^{**}p<0.05$, $^{*}p<0.1$

model, which takes into account the clay component, as this affects soil organic matter decay rates. The temperature and precipitation presented weak negative correlations with the SOC change rate in our study area. However, in our work we found that mean annual precipitation correlated positively with initial SOC content, similarly to other studies performed in northern Spain (Calvo De Anta et al. 2015). Furthermore, sites with a high mean annual precipitation and high initial SOC tended to present lower SOC rates than sites with lower mean annual precipitation and low initial SOC levels (Meyer et al. 2016).

SOC$_r$ is the annual SOC change rate (Mg C ha^{-1} year^{-1}); SOC$_i$ is the initial SOC content (Mg C ha^{-1} year^{-1}); Clay is the soil clay percentage (%); C input is the carbon input derived from vegetation and animal excreta (tC ha^{-1} year^{-1}); MAT is mean annual temperature (℃); and MAP is mean annual precipitation (cm).

Overall, carbon input was the main controlling factor of SOC changes in the grasslands associated with dairy production in northern Spain. In particular, carbon inputs derived from dairy excreta presented a higher variability (0.16 and 6.96 Mg C ha^{-1} year^{-1}) and proportionality in terms of SOC change rate, compared with plant residues (ranging between 2.4 and 4.3 Mg C ha^{-1} year^{-1}) (Fig. 2a). Our findings could be partly explained by the different levels of uncertainty in the plant residue and excreta estimation. In particular, plant residues were derived from a regression as a function of climate variables. Our results are in line with those of Fornara et al. (2016), who identified the importance of manure application in increasing SOC stocks in grassland systems over longer time scales. In our study, the SOC change rate increased when carbon inputs derived from dairy manure exceeded approximately 0.88 Mg C ha^{-1} year^{-1} (Fig. 2a). In particular, according to our simulation, the average SOC change rate decreased to – 0.3 Mg C ha^{-1} in the absence of carbon inputs from dairy cows (Fig. S5).

Manure application rates were related to livestock density, as we assumed that it is not economically viable to export manure more than 30 km from the municipality (Fealy and Schröder 2008) (Fig. 2b). Consequently, variations in livestock density directly affected manure rates and SOC stock changes, as has been shown in studies involving grazing animals at different intensities (e.g. McSherry and Ritchie 2013). We determined a livestock density threshold of 0.95 LU ha^{-1} (Fig. 2b) (corresponding to a dairy manure quantity of 0.88 Mg C ha^{-1} year^{-1}), from where SOC changes were always positive (Fig. 2a). Other studies have shown that this relationship is not linear and tends to reach a plateau or even produce an inverted u- shape trend (Ward et al. 2016). This behaviour could be explained by overgrazing which increases soil disturbance and biomass removal, therefore reducing SOC (McSherry and Ritchie 2013). Plant residues are indirectly related to grazing (Scholefield et al. 1991), in particular, high densities of animals lead to declines in 8 (e.g. Biondini et al. 1998). Apart from overgrazing, manure application from housed livestock may enhance soil N$_2$O emissions and offset SOC sequestration as the changes in SOC turnover feed back into the N cycle (Lugato et al. 2018). In this sense, several studies (e.g. Eze et al. 2018) have stressed the key role of low to moderate grazing intensities as a sound management practice to enhance SOC storage. However, our study did not reflect this livestock density or excess manure input limitation, as we did not consider the overgrazing effect in the RothC model, or the interaction between the carbon and nitrogen cycles.

Net greenhouse gas emissions expressed as CO$_2$-e

We found that the average net GHG emissions in the study area associated with the cattle dairy system (including grassland and barn level but excluding pre-farm phases (e.g. feeds) and farm energy use) were positive. The estimated net GHG emission rates ranged

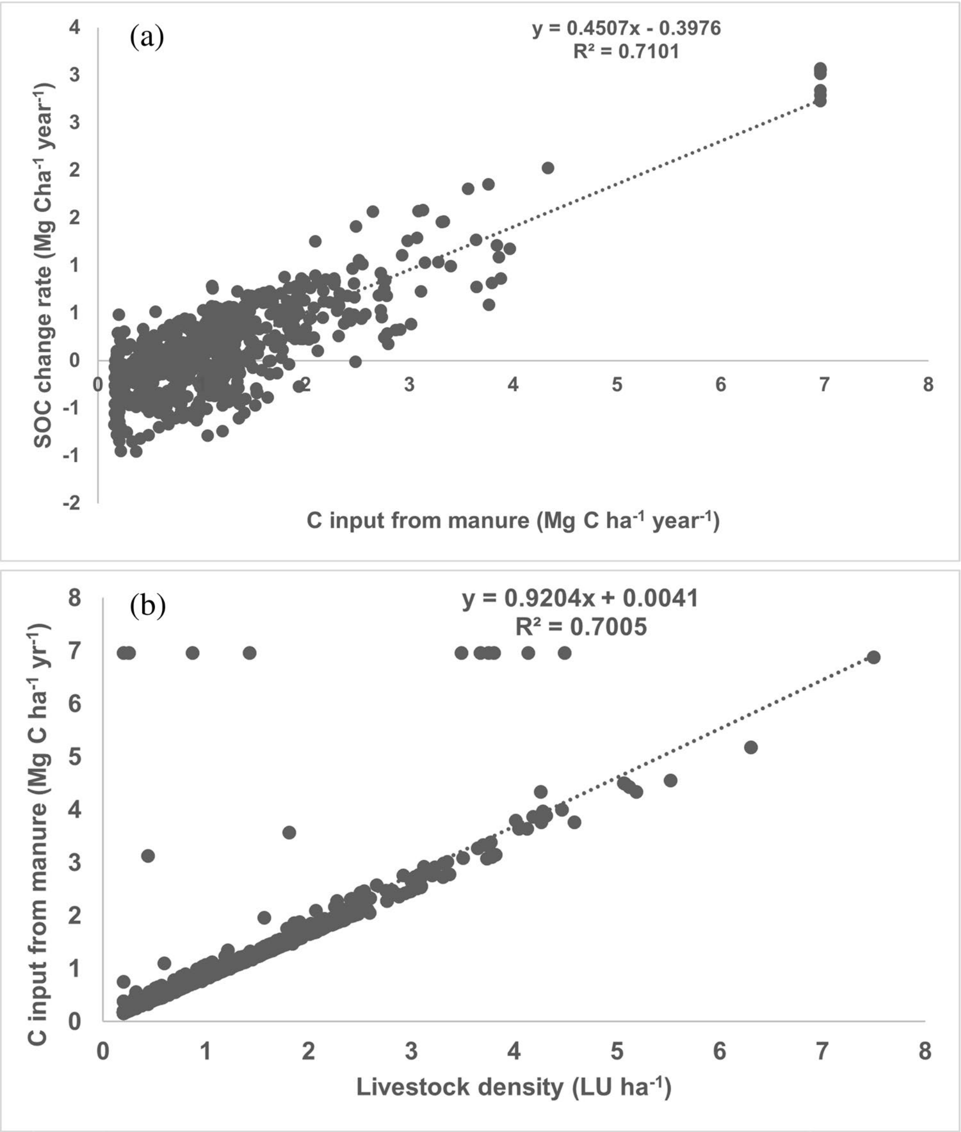

Fig. 2 **a** Soil organic carbon (SOC) change rate in relation to carbon inputs derived from dairy manure on grasslands associated with dairy production in northern Spain; **b** Carbon inputs derived from dairy manure in relation to livestock density on grasslands associated with dairy production in northern Spain

from − 9.8 to 22.4 Mg CO_2-e ha^{-1} $year^{-1}$ (average of 5.6 Mg CO_2-e ha^{-1} $year^{-1}$) (Fig. 3).

Our average estimation of net GHG emissions per ha is within the range of some of the values reported for dairy grasslands under a comparable temperate climate. However, studies of net GHG in these conditions are very diverse. For example, in Ireland, Fornara et al. (2016) estimated net GHG emissions per ha for dairy farming that were close to our findings (between 4.8 to 6.8 Mg CO_2-e ha^{-1} $year^{-1}$), using previous IPCC reports. Similarly, for central-eastern Europe, Koncz et al. (2017) used the chamber gas flux measurements technique and IPCC guidelines to estimate net GHG emissions per ha of 4.75 ± 1.44 Mg CO_2-e ha^{-1} $year^{-1}$, which is in line with our results. However, Del Prado et al. (2013) and Pirlo and Lolli (2019) estimated higher values of 7.8 and more than 8 Mg CO_2-e ha^{-1} $year^{-1}$, in northern Spain and Italy, respectively, using different modelling approaches. Conversely, our results were higher than those of Graux et al. (2012) who found a net GHG of 2.7–2.8 Mg CO_2-e ha^{-1} $year^{-1}$ for French grassland-based dairy cattle systems, under both intensive and extensive management, using the PaSim model and the 2006 IPCC guidelines. Chang et al. (2015) estimated the GHG balance for European grasslands using the process-based biogeochemical model ORCHIDEE-GM and found a net GHG sink. This latter study included both extensively and intensively managed grasslands, involving mowing and grazing regimes, and did not account for carbon export through milk products and live weight gain, which may partly explain the difference. The large differences between the various studies may be partly explained by the variety of production systems employed, as well as the different methods used to estimate net GHG.

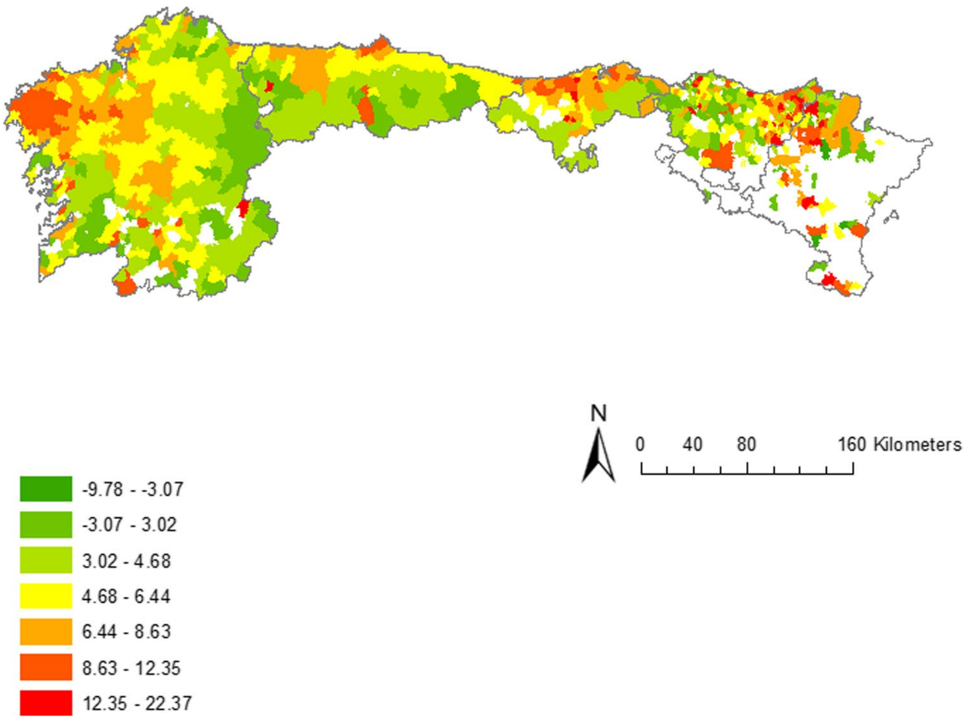

Fig. 3 Net greenhouse gas (GHG) emissions per area in Mg CO_2-e ha^{-1} $year^{-1}$ for municipalities in northern Spain

We estimated that, on average, SOC storage contributes to offsetting 9% of the overall GHG emissions, which is in the lowest range established by Fornara et al. (2016). However, this result should be taken with caution, as part of the emissions derived from feed (i.e. concentrates and silage) was not considered in our assessment. Feed produced elsewhere may have originated in cropping systems that may emit significant non-CO_2 GHG emissions, and which may also have involved some SOC release, which may compensate for this sink activity (Powlson et al. 2011).

In order to calculate the impact avoided (in terms of avoided CO_2 loss) caused by the storage of carbon in the soil over a 30-year time horizon, we took into account the impact of yearly carbon inputs on GHG emissions. The average CO_2 loss avoided in the 30-year perspective through carbon inputs derived from dairy manure was 1.72 Mg CO_2-e ha^{-1} $year^{-1}$ (estimated weighted average for the various spatial units according to the different surfaces) (Fig. S6). Considering an average total GHG emissions value of 6.4 Mg CO_2-e ha^{-1} $year^{-1}$ (estimated as weighted average for the different spatial units according to the different surfaces), carbon inputs derived from dairy manure generated an important decrease (i.e. 26.8%) in extra emissions load. Total GHG emissions varied between 1.1 and 34.3 Mg CO_2-e ha^{-1} $year^{-1}$ (Fig. S7). As expected, the largest share of emissions from the grassland-based dairy systems in northern Spain were derived from enteric fermentation (an average of almost 60%). The second largest source of GHG emissions was CH_4 from manure management (average of 18.6%), followed by N_2O soil emissions (average of 17.5%). Our findings were in line with the range of dairy farm emissions typical of temperate regions, as reported by Gerber et al. (2013).

The resulting methane conversion factor (MCF) values (CH_4 emitted per kg of volatile solid) for the different spatial units in our study were lower than that for locations in warm conditions (from 15 to 22%) as specified in the IPCC (2019).

The mean of our N_2O soil emissions estimates in the different municipalities was an average of 2.04 kg N_2O-N ha^{-1} $year^{-1}$ (corresponding to an average N input of 207 kg ha^{-1}).

Average estimated NH_3 volatilisation and NO_3 leaching, which are precursors of N_2O, were 19.3 kg N ha^{-1} $year^{-1}$ (corresponding to 8 Mg CO_2-e ha^{-1} $year^{-1}$) and 34.2 kg N kg ha^{-1} $year^{-1}$ (corresponding to 14.2 Mg CO_2-e ha^{-1} $year^{-1}$), respectively. According to our findings, NH_3 emissions, derived from manure applied to the grasslands, presented 61% of total ammoniacal nitrogen (TAN), which is within the range of the review findings of Sommer et al. (2019). The annual nitrogen leaching was also within the range of the values reported in the review by Lüscher et al. (2014) on European livestock-based grasslands with white clover (losses of 28–140 kg N ha^{-1}).

Relationships between GHG and different farm parameters

The relationships between GHG emissions and various farm parameters, related to management, productivity, and diet typology, were assessed at the province level and as a function of ha (Fig. S8).

Total GHG emissions per ha were lower in extensive production systems, according to the correlation results with feed quality (i.e. the level of concentrate in the diet) and livestock density (Fig. S8). Indeed, higher livestock density levels were linked to greater estimated GHG emissions per ha ($R^2 = 0.88$; $p = 0.009$) (Fig. S8). Livestock density is therefore the major factor controlling GHG emissions per ha in moist temperate grasslands. In particular, when animal diets are fairly similar, enteric fermentation emissions per ha, which account for the major proportion of GHG, are predominantly influenced by livestock density (Meyer et al. 2016). However, under tropical conditions, Ruggieri et al. (2020) found that GHG emissions are controlled by climatic variables and, to a lesser extent, livestock density. In general, GHG emissions and the SOC change rate in the simulated spatial units were conditioned by livestock density (Fig. 4a). The distribution of net GHG emissions per ha was almost proportional to the distribution of the SOC change rate (Figs. 1 and 3). Only a few municipalities presented the opposing net GHG trend (i.e. negative values), with a high SOC change rate. These municipalities have low livestock densities and consequently lower CH_4 enteric emissions, this being primarily influenced by livestock density (Liebig et al. 2010; Schönbach et al. 2012), although they do receive greater carbon input from dairy manure from their neighbouring municipalities. Therefore, using increased livestock densities, and thus carbon input, as a management choice to improve carbon accumulation may increase GHG emissions (Fig. 4a) (Soussana et al. 2010). In this sense, practices intended to offset GHG emissions using carbon sequestration must therefore consider the impact of other GHGs such as N_2O and CH_4 (Graux et al. 2012). For instance, the effect of different livestock densities can be explored over a wide variety of cattle feed intakes and for alternative manure management options (Graux et al. 2012).

Our analysed data enables us to establish a potential livestock density (approximately > 0.4 LU ha^{-1}), at which the net GHG emissions (expressed as CO_2-e per LU) would be the least (Fig. 4b). This result contrasts with some studies, e.g. grasslands under semiarid continental climate conditions, where moderate livestock densities (i.e. 0.39 animal ha^{-1}), lead to the smallest GHG emissions levels (Liebig et al. 2010).

It is important to point out that, in the case of more intensive livestock densities, imported feed may lead to even further carbon emissions and offset the carbon sink activity of the grassland soils (Powlson et al. 2011). The energy use on the farm and the build-up of SOC due to external C inputs via feed that has contributed to SOC depletion elsewhere were not included in the study.

Our results show the importance that livestock density as a management tool can have on the environmental sustainability of grasslands through its impact on net GHG emissions, in line with McGinn et al. (2014). It is also crucial to point out the importance of concentrate reduction in terms of diet quality. Dietary concentrate levels related to intensified dairy production could lead to significant carbon leakage not reflected in our estimation (e.g. land use change), which would correspond to greater emissions (Styles et al. 2018).

Sources of uncertainty

To evaluate our SOC modelling, we referred back to SOC stocks at the end of the simulation period, as no studies have measured the variation in the SOC rate in our study area. Calvo de Anta et al. (2020) observed that the values for the SOC stocks ranged between 103 and 146 Mg C ha^{-1} $year^{-1}$. Our average simulated SOC stock at the end of the simulation period, for our study area, was 147.5 Mg C ha^{-1}. This value is close to the top of the range in the cited study. Although SOC values are subject to uncertainty, we understand that this upper value in terms of our estimated level is reasonable considering that we are simulating managed grasslands associated with intensive dairy cow production that receive large manure inputs from the herds and, thus, high levels of carbon input.

In our study, carbon inputs derived from animal excreta and plant residues were identified as the main driver for SOC change. In order to quantify the uncertainty in carbon inputs, a Monte Carlo simulation was run to estimate the SOC change (over 30 years) for the selected municipalities. Our simulated values were close to the mean of possible SOC stocks, depending on the uncertainty (and variations) of the carbon inputs (Table S10). Our findings on SOC accumulation could therefore be interpreted as a good indicator of possible SOC storage in our study area.

GHG emissions from calves were not estimated as their contribution is the lowest (Mc Geough et al. 2012). Moreover, our study did not account for energy requirements or extra-costs in terms of the GHG emissions of future products. Furthermore, N_2O emissions factor calculations were based on simplified IPCC Tier 2 equations, although the component processes of nitrification and denitrification are highly complex and depend on several soil and environmental factors (Farquharson and Baldock 2008).

We employed a simple approach to estimate net GHG emissions for each spatial unit, as we tried to consider the effect of SOC storage on the main GHG emissions (at the grassland and farm level). Despite the uncertainty involved in only considering the main GHG emissions, our findings are a valuable indicator of net GHG emissions from grasslands associated with dairy production in our study area.

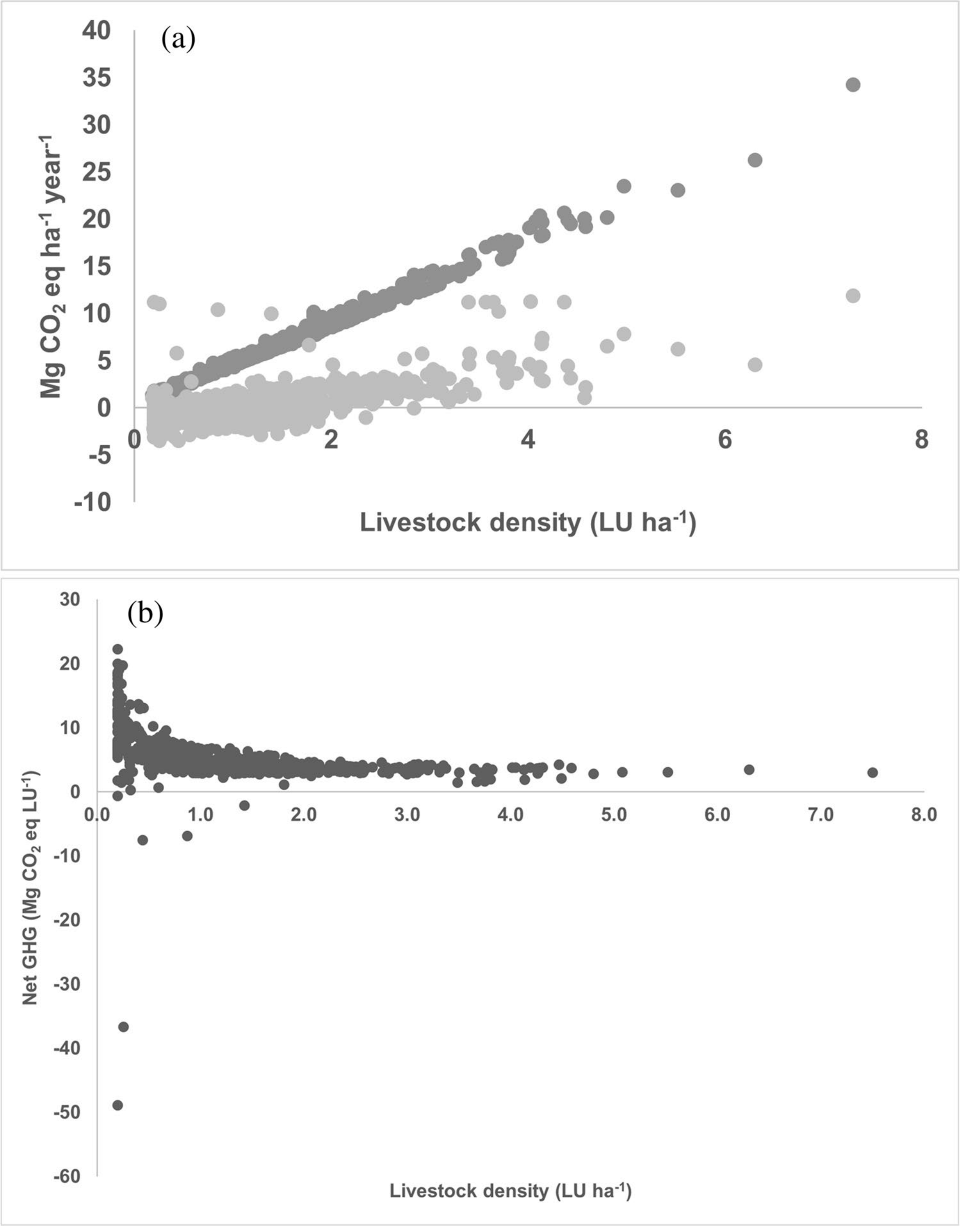

Fig. 4 **a** Relationship of livestock density with soil organic carbon (SOC) change rate (light grey) and total greenhouse gas (GHG) emissions (dark grey); **b** Net greenhouse gas emissions (GHG) per livestock unit (LU) in relation to livestock density

Conclusions

This work is the first modelling study of net regional GHG emissions from grasslands associated with dairy production in moist temperate Spain. The main factors influencing the changes in soil organic carbon (SOC) were the initial SOC content and carbon inputs. In particular, carbon inputs derived from dairy manure, and thus livestock density management, were a key factor in sustaining SOC storage.

Soil organic carbon is able to offset 9% of GHG emissions. Furthermore, the impact avoided by carbon sequestration in the soil (in terms of CO$_2$ not lost) via dairy manure, over a 30-year time horizon, was 26.8%. The livestock density threshold established in our study illustrates the importance of considering the effect of overgrazing on SOC storage and its interaction with the nitrogen cycle.

We found that these grassland systems make a positive contribution to global warming. The GHG emissions per ha were lower in extensive systems in terms of livestock density and feed quality.

Livestock density is the main factor affecting net GHG emissions associated with grassland sites under dairy production in northern Spain. The livestock density threshold for reducing net GHG emissions per livestock unit could be improved considering the entirety of the GHG emissions.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10113-022-01927-x.

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