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How does soil carbon sequestration affect greenhouse gas emissions from a sheep farming system? Results of an life cycle assessment case study

Pasquale Arca,[1] Enrico Vagnoni,[1] Pierpaolo Duce,[1] Antonello Franca[2]

[1]CNR-IBE, Institute of BioEconomy; and [2]CNR-ISPAAM, Institute for Animal Production System in Mediterranean Environment, National Research Council of Italy, Sassari, Italy

Correspondence: Enrico Vagnoni, CNR-IBE, Institute of BioEconomy, National Research Council of Italy, Trav. La Crucca 3, 07100 Sassari, Italy. E-mail: enrico.vagnoni@ibe.cnr.it

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Highlights

- Extensification of dairy sheep systems provides an environmental benefit when soil C sequestration is considered.
- Extensification of dairy sheep systems determines lower environmental impact per hectare of utilized agricultural area.
- Enteric methane emissions are the main source of GHG emissions of the sheep milk life cycle.
- Carbon sequestration in permanent grasslands can considerably contribute to climate change mitigation.

Abstract

A life cycle assessment (LCA) study of a transition from semi-intensive to semi-extensive Mediterranean dairy sheep farm suggests that the latter has a strong potential for offsetting greenhouse gas (GHG) emissions through the soil C sequestration (C_{seq}) in permanent grasslands. The extensification process shows clear environmental advantage when emission intensity is referred to the area-based functional unit (FU). Several LCA studies reported that extensive livestock systems have greater GHG emissions per mass of product than intensive one, due to their lower productivity. However, these studies did not account for soil C_{seq} of temporary and permanent grasslands, that have a strong potential to partly mitigate the GHG balance of ruminant production systems. Our LCA study was carried out considering the transition from a semi-intensive (SI) towards a semi-extensive (SE) production system, adopted in a dairy sheep farm located in North-Western Sardinia (Italy). Impact scope included enteric methane emissions, feed production, on-farm energy use and transportation, infrastructures as well as the potential C sink arising from soil C_{seq} with respect to the emission intensity. In order to provide a more comprehensive analysis, we used the following FUs: 1 kg of fat and protein corrected milk (FPCM) and 1 ha of utilised agricultural area (UAA). We observed that the extensification of production system determined contrasting environmental effects when using different FUs accounting for soil C_{seq}. When soil C_{seq} in emission intensity estimate was included, we

observed slightly lower values of GHG emissions per kg of FPCM in the SI production system (from 3.37 to 3.12 kg CO_2 equivalents – CO_2-eq), whereas a greater variation we observed in the SE one (from 3.54 to 2.90 kg CO_2-eq). Considering 1 ha of UAA as FU and including the soil C_{seq}, the emission intensity in SI moved from 6,257 to 5,793 kg CO_2-eq, whereas values varied from 4,020 to 3,299 kg CO_2-eq in SE. These results indicated that the —— emission intensity from semi-extensive Mediterranean dairy sheep farms can be considerably reduced through the soil C_{seq}, although its measurement is influenced by the models used in the estimation.

Introduction

Sheep and goats represent about 60% of the total world ruminant population (FAO, 2019) and milk production is expected to increase globally in the next years (Pulina et al., 2018). Sheep milk produced in Europe represents approximately 29% of global sheep milk production, with dairy sheep farms mainly concentrated in Mediterranean and Black Sea Regions (Pulina et al., 2018). One of the largest producers in these areas is Sardinia (Italy), with more than 250,000 Mg year^{-1}, which represents about 25% of total EU-27 sheep milk production (Rural Development Programme of Sardinia 2014–2020). The main sheep breed raised in Sardinia is by far the autochthonous Sarda breed (Gutiérres-Pena et al., 2018), a dual-purpose breed (milk and meat) that can be considered one of the most important dairy sheep breeds in the world (Macciotta et al., 1999) with more than 4.7 million heads reared in several Mediterranean areas. As well as in other Southern Europe areas, the Sardinian milk sheep sector is characterized by semi-extensive farms where grazing on temporary and permanent grasslands is the main feeding source (Pulina et al., 2018), with a wide range of natural resources and input utilization levels (Porqueddu et al., 2017).

Sustainable intensification of production systems is clearly identified by scientists as key action for climate change mitigation strategy in agri-food sector (Gislon et al., 2020). From this point of view, Sardinian sheep sector represents an interesting case study for testing strategies aimed to achieve a sustainable livestock supply chain and to better understand how to conciliate food provision with reduced environmental impacts. Several authors (Batalla et al., 2015; Escribano et al., 2020) showed how and to what extent the intensification level of Mediterranean dairy sheep farms affects the environmental performance of production systems, but the scientific evidences are not unambiguous and well defined. Usually, in life cycle assessment (LCA) studies, the intensification of agricultural and livestock systems improves the environmental performance per functional unit (FU) of product when the marginal yield increase is higher than the marginal input utilization (FAO, 2010; Notarnicola et al., 2017), although the ecological optimum (eco-efficiency) depends on the specific situation (Hayashi et al., 2006). On the other hand, in LCA studies on Mediterranean sheep and goat systems with different intensification level, contrasting results are showed when soil C sequestration (soil C_{seq}) is included in the emission intensity estimate per kg of normalized milk. Gutiérrez-Pena et al. (2019) and Batalla et al. (2015) showed that the emission intensity is not different in semi-intensive and semi-extensive systems when soil C_{seq} is included, whereas Escribano et al. (2020) observed higher environmental impact in semi-extensive ones, with or without soil C_{seq} inclusion. However, there is little agreement about the inclusion of the soil C_{seq} in LCA system boundaries. The methodological principle that excludes soil C_{seq} from LCA estimation is that C temporarily sequestered in the soil will be re-emitted in the future (Nayak et al., 2019). In the recent Product Environmental Footprint Category Rules for dairy products (EDA, 2018), change in soil C level is considered as change in C stock and, consequently, excluded from the impact category "Climate Change". Nevertheless, some researchers have highlighted the importance of accounting for the soil C change in LCA studies, because C removed from the atmosphere and stored in the soil temporarily reduces the cumulative radioactive forcing over that time frame, reducing the climate impact (Levasseur et al., 2013). Regarding these contrasting issues, Nayak et al. (2019) highlighted the availability of some estimation methods to be adapted to the context, but also confirmed what other authors pointed out about the unavailability of a common standard procedure for soil C_{seq} accounting in agricultural LCA (Brandão and i Canals, 2013; Petersen et al., 2013; Arzoumanidis et al., 2014).

Another scientific controversy within the agri-food LCA community concerns the criteria to be used to identify the most appropriate FU to express the environmental impacts of livestock systems. Salou et al. (2017) highlighted that the effects of intensification on emission intensity differ significantly depending on the FU adopted; indeed, the authors observed that the intensification does not produce variations on emission intensity per kg of normalized milk (mass FU), whereas higher values of emission intensity per ha (area-based FU) were observed in more intensive systems. In addition, Baldini et al. (2017) showed that the choice of the FU produces different results in terms of environmental output, advantaging in some case the more intensive systems and in other case the more extensive ones. Moreover, Escribano et al. (2020) stated that the use of the area-based FU and the inclusion of soil C_{seq} in the emission intensity estimate are more appropriate for environmental assessment of extensive farming systems based on permanent grasslands. Finally, as observed by Gislon et al. (2020), few numbers of LCA studies on milk production are based on specific farm data and considered soil C_{seq} in the environmental profile of farming system. The main aim of this work was to evaluate the environmental implication of a Mediterranean dairy sheep farm, before and after the transition from a semi-intensive to a semi-extensive production system. For this purpose, we carried out an LCA study of a Sardinian dairy sheep farm including the contribution of soil C_{seq} and using both mass and area-based FUs.

Materials and methods

In our research, a single case study approach was adopted. This approach was in accordance with the recommendations from Horrillo et al. (2021), who stated that the case study is a tool that allowed to analyse in detail a specific phenomenon that occurred in a well-defined real context. Moreover, Fedele et al. (2014) demonstrated that an impacts assessment based on the LCA methodological approach can support a comparative environmental impact evaluation between contrasting production systems in a single farm. Ultimately, this methodology was suitable for our scope and, although it was limited to providing non-statistical results, it can contribute to scientific development with valid results when extrapolated from appropriate case studies (Flyvbjerg, 2006).

Case study

The study was carried out in a dairy sheep farm located in Osilo, Sardinia (Italy) (40°45'11" N and 8°38'43" E, elevation 364 m a.s.l.) (Figure 1). The area has typical Mediterranean climate conditions with warm and dry summers, mild and wet winters (Chessa and Delitala, 1997). The average annual rainfall was approximately 760 mm, with 72 rainy days per year, mostly concentrated in October-November, and a drought period usually lasting from May to October. Minimum and maximum mean monthly temperatures were about 10 °C and 26 °C, respectively, with an average annual temperature of 16.5 °C. The landscape was characterized by hilly morphologies on volcanic rocks that occupied the fertile lowland, along a fluviokarstic valley that cuts a carbonate plateau (Biddau and Cidu, 2005). The surrounding area was characterized by dairy sheep farms with feed resources on tilled lands and grazing on permanent grasslands in areas unsuitable to crop production, which were neither inorganically fertilized nor irrigated, with small patches of native Mediterranean maquis. Permanent grasslands were grazed from autumn to spring, while temporary grasslands, such as annual crops, were grazed until the end of winter to allow the hay or grain production. Summer grazing was also carried out mainly on upland fields and on dry residuals of cereals and annual hay crops, after harvest/haymaking. During browsing, manure remained in the fields and contributed to replenish soil fertility levels. Native grasslands on neutral-subalkaline soils were characterized by annual species, with a dominant contribution of grasses.

Up until 2008, the case study farm was characterized by a foraging system based mainly on temporary grasslands such as grain-cereal crops (winter wheat, *Triticum durum* Desf.), annual forage crops (oat, *Avena sativa.*, and Italian ryegrass, *Lolium multiflorum* Lam.), both for grazing and hay production, and irrigated crop (silage maize, *Zea mays* L.) (Figure 1 and Table 1). The whole milk production was sold to the dairy industry. Since 2008, the farmer decided to change progressively the management strategy, with the aim of destining all milk production to the on-farm manufacturing of semi-artisanal cheeses. As a result, most of the arable land has been converted from temporary grasslands to permanent grasslands, both natural and semi-natural (Figure 1 and Table 1). Natural grasslands were established exploiting the germination of native seedbank, while semi-natural grasslands through the overseeding of annual self-reseeding legumes and grasses. The extensification of the production system, completed in 2011, was part of a wider farm management strategy oriented to increase the milk's added value, represented by the cheese selling, and to reduce its production costs (especially for self-produced forage). Therefore, this farm was characterized by the switching between two contrasting production systems that can be defined as "semi-intensive" (SI, pre-2008) and "semi-extensive" (SE, post-2008), respectively. The general characteristics of these dairy systems adopted by the farm during the two periods are reported in Table 2. Both farming systems used Sarda sheep breed. During the transition from SI to SE, the farmer slightly reduced flock size (340 and 320 productive ewes in SI and SE, respectively) and varied the animal diet (Tables 2 and 3). In the process of extensification, land management was changed (Table 1). The SI farming system managed 69.4 ha of utilized agricultural area (UAA), as temporary grasslands (30%, 35%, 22% and 9% for grazing, hay, grain and silage production, respectively), and 3 ha as permanent grasslands (natural grassland for grazing) (Table 1). In the SE production system (69.7 ha), only 13% of the UAA was occupied by temporary grasslands (7% of Italian ryegrass-oat mixture and 6% of irrigated meadows - alfalfa, *Medicago sativa* L., and white clover, *Trifolium repens* L. - for grazing), while 87% was occupied by permanent grasslands, both natural and semi-natural (76% and 11%, respectively) (Table 1). Approximately 23% of natural grasslands were used for hay production, the remaining 77% for grazing. Semi-natural grasslands were used as grazing lands (Table 1). On-farm feed resources were integrated with about 92 and 85 Mg of concentrates in SI and SE, respectively.

Life cycle assessment methodology

A comparative LCA was performed, according to the International Organization of Standardization LCA rules (14040 and 14044) (ISO 2006a, b). In order to have a more comprehensive view of the environmental impacts of sheep farming systems, soil C_{seq} was included in greenhouse gas (GHG) emissions balance, adopting two FUs: *i)* a mass-based FU, fat protein corrected milk (FPCM), where *FPCM* (kg) = *raw milk* (kg) x (0.25 + 0.085 *fat%* + 0.035 *protein%*) (Pulina and Nudda, 2002); *ii)* an area-based FU, expressed in ha of UAA. The use of both FUs allowed to combine productive and economic results with depletion of natural resources, reflecting, in other terms, the two main functions of agricultural production systems: the production of market goods and the provision of public services and externalities, associated with the environmental role of farming systems (Basset-Mens and van der Werf, 2005; Gutiérrez-Peña et al., 2019). By this way, global and local effects of climate change were included in the perspective of the analysis, giving back a more balanced assessment of the results. Specific farm data were referred to the years 2001 and 2011, when the farm has been characterized by two different production systems. The system boundary of the analysis was from "cradle-to-farm-gate". In particular, system boundary of the study included: i) amount of hay, green forage and concentrated consumed by the flock, comparing the biomass yields of grasslands and the nutritional needs of each animal category (based on gender, age, weight, physiological stage and production level of animals), ii) water and energy use; iii) machineries and equipment (tractors included); iv) milking parlour, barns and other manufactured goods linked with the farm structure; v) consumable materials (agrochemicals, packaging materials, etc.); vi) distances and mode of transportations. We collected primary data, representing more than 90% of the inventory data, through farm's register examination, several field visits and interviews to farmer. All representative secondary data were taken from Ecoinvent Centre v3.6 database (Moreno Ruiz et al., 2018), except for the dataset of sunflower meal and soybean feed, taken from Agri-footprint 4.0 (2017) database. No generic data were used. The estimation of enteric CH_4 emission (F_{CH4}) was based on the use of the CH_4 emission factor (Y_m), calculated as function of Metabolizable Energy Intake (MEI) (Vermorel et al., 2008):

$$F_{CH4} = MEI \times Y_m/55.65 \qquad (1)$$

Where:

F_{CH4} represented the kg of emitted CH_4/day per head; MEI was expressed in MJ/day per head; the coefficient 55.65 represented the energy content of 1 kg of CH_4 and was expressed in MJ; Y_m, the methane conversion factor (%), which expressed the proportion of ration gross energy lost as CH_4, was calculated as:

$$Y_m = -0.15 \times DE + 21.89 \quad (2)$$

where DE was the Digestible Energy (DE in %) of the diet.

The monthly diets of each animal category were defined through farm data collection. Type and amount of feed utilized in the diet were collected as primary data, except for the intake of grazed biomass. For the composition of each feed type we used the database elaborated by LAORE Sardegna (the Regional Agency for Agriculture Development) (Sardegna Agricoltura, 2013). In order to calibrate the diet, based on the nutritional needs of each animal category and the nutritional value of each feed type, the Small Ruminant Nutrition System Software (SRNS - Tedeschi et al., 2008) was adopted using amount, type and composition of the feed as inputs. The intake of grazed biomass was estimated by difference between total dry matter intake (DMI), calculated with the SRNS software, and the sum of the amounts of the other feeds.

Emissions related to pesticide and fertilizer applications were assessed according to the following approaches: equations reported in Ecoinvent report No.15 (Nemecek and Kägi, 2007) for *i)* emissions of NO_x to air, *ii)* emissions of heavy metals, PO_{3-}, P and NO_{3-} to water and *iii)* emissions of heavy metals to soil; Tier 1 IPCC method (IPCC, 2019) for both N_2O direct and indirect and CO_2 emissions to air; Tier 2 IPCC method (IPCC, 2019), using national emission factor proposed by ISPRA (2011) for NH_3 emissions to air. The impacts related to manure management excluded CH_4 emissions and included only the N_2O emitted through animal excreta, with the rationale that in both farming systems sheep were not confined in small or covered spaces. This type of animal emission was estimated following the IPCC (2019) approach and using the default emission factor for sheep and "other animals" [0.003 kg N_2O-N (kg N)$^{-1}$]. In addition, daily N excretion of animal categories was estimated based on empirical equations (Decandia et al., 2011) for ewes (lactating, dry, pregnant and replacements), rams and lambs. Final and intermediate transports were inventoried considering means of transport, distances and transported mass. To calculate distances, primary data were used when available (internet researches were done to find production plants and logistic chain). Big size machineries road transport was modelled referring to the corresponding Ecoinvent processes. In case of lack of primary data, logistic and distances were traced utilizing Searates website (Searates, 2021). Fossil fuel consumptions were estimated by adding up consumptions of all the agricultural operations. For the year 2001, fossil fuels consumption included also the use of the power generator. Electricity consumption for the year 2011 (in the year 2001 the farm used an electric generator as power supply) was calculated considering the average annual consumption reported in the supply bills of the electric company, excluding consumption for family and external uses. In addition, consumptions of major utilities (such as irrigation, milking and milk refrigeration) were estimated based on installed power and by checking literature data. Finally, the estimated data were compared with those reported in the bills to identify any discrepancies. Electricity datasets were built based on the energetic mix declared by the electric company for the reference year, starting from the Ecoinvent process "Electricity, high voltage {IT}| market for | Cut-off, U".

In line with several LCA investigations on dairy sector (Pirlo et al., 2014; Baldini et al., 2017), we performed an economic allocation procedure in order to partitioning all inputs and outputs, considering that: *i)* milk, the "main" product, had a very higher economic value than co-products such as meat, live rams (only in SI system) and wool; *ii)* in similar cases, allocation mode did not affect the LCA results (Salou et al., 2017). In SI system, the economic allocation resulted as follows: 76% to milk, 13% to rams, 10% to meat and 1% to wool. Similarly, in SE system, it resulted in 91% to milk, 8% to meat and 1% to wool. We used SimaPro software (PRé Consultants, 2018) to model the life cycle and for impact analysis. The LCA analysis focused exclusively on Climate Change impact category, expressed as emission intensity. We calculated emission intensity using the IPCC (2013) evaluation method, based on Global Warming Potential (GWP) indicator (100-year time horizon)~~,~~ expressed in kg of CO_2 equivalents (CO_2-eq), and with the latest values of CH_4 characterization factor (34.00 and 36.75 kg CO_2-eq/kg for biogenic and fossil CH_4, respectively).

Estimation of soil carbon sequestration

We calculated the soil C_{seq}, referring to the total area actually used to feed sheep (both for grain and forage supply), according to the method suggested by Petersen et al. (2013). This model was designed exclusively for agricultural LCA studies for estimating the soil C changes as a consequence of the C input from above- and belowground crop residues and manure added to the soil. This approach was based on the modelling of two C fluxes: i) from the soil to the atmosphere, where the soil organic matter mineralization was modelled using the soil C model C-TOOL (Petersen, 2010); ii) from the atmosphere to the soil, where the atmospheric CO_2 decay was modelled using the Bern Carbon Cycle model (IPCC, 2007). Petersen et al. (2013) observed that 9.7% of C added to the soil as organic C input in the first year would be sequestered in a 100-year perspective. This method, although being simplistic, was based on site-specific data of soil C input and field conditions, whereas the other available models to estimate the soil C_{seq} in agricultural LCA were based on default values per ha of grassland, as highlighted by Batalla et al. (2015). In addition, the 100-year time horizon was in line with the time perspective of GWP indicator. Therefore, other authors used this method to estimate soil C_{seq} in LCA studies on dairy systems under Mediterranean conditions (Batalla et al., 2015; Gutiérrez-Peña et al., 2019; Escribano et al., 2020), as well as in regions of Western Europe (Knudsen et al., 2019). In order to estimate soil C_{seq}, the same coefficient (9.7%) was applied to the amount of soil C input, composed of two distinct fractions: *i)* the C derived from crop residues, and *ii)* the C contained in manure deposited by sheep during grazing (Batalla et al., 2015). The C derived from crop residues included both C from aboveground crop residues and from belowground biomass, left on the soil at the end of the first year. The estimation of above- and belowground residues was based on the available data of each grassland yield, expressed in Mg of dry matter (DM) ha^{-1} (Table 4). For all grasslands, we converted the amounts of residues into C using a coefficient of C content equal to 0.40 (Burle et al., 1997; dos Santos et al., 2011), except for silage maize and Italian ryegrass-oat mixture destined to the hay production, for which we estimated the C derived from crop residues as percentage of the harvested DM, 11% and 44.7%, respectively, following Lai et al. (2017). Aboveground residues were estimated using different equations, by applying coefficients to the total aboveground biomass or yield, depending on the grassland type and use destination of the biomass, as reported in Table 5. The belowground residues included roots and rhizodeposition biomass. We computed the root biomass by applying a specific shoot-root or root-shoot ratio index (see Table 6 for literature details) to the relative total aboveground biomass, estimated for each grassland as sum of yield and aboveground residues. Rhizodeposition was calculated as fraction of the entire root system biomass, using an index equal to 0.65 (Bolinder et al., 2007) for each grassland. In natural grasslands and irrigated meadows (alfalfa and white clover), we estimated roots as annual biomass increase and rhizodeposition as a fraction of the entire root system. By contrast, in semi-natural grasslands and temporary grasslands, such as cereal crops and annual forage crops, both roots and rhizodeposition were estimated as annual biomass production. Finally, C:N ratio index equal to 13.4 (Escudero et al., 2012) was used for estimating the amount of C input derived from sheep manure during grazing.

Results

Farming systems

Both SE and SI farming systems had almost the same number of lactating ewes (320 versus 340 heads) and slightly different values of stocking rate (4.6 versus 4.7 head ha^{-1}) (Table 2). During transition to SE, the diet of productive ewes varied (Table 3), with an increase of the green forage fraction and a reduced use of conserved forages (0.57 and 0.12 kg DMI^{-1} in SE, 0.24 and 0.48 kg DMI^{-1} in SI, respectively). The DMI of ewes in SE was lower for about 88 kg DM ewe^{-1} (565 versus

653 kg DM ewe^{-1} year^{-1} in SE and SI, respectively) (Table 2). The fraction of concentrates in the diet slightly increased from SI to SE (0.28 and 0.31 kg concentrate kg DMI^{-1}) (Table 2), while individual concentrate consumptions of ewes were similar in both farming systems (184 versus 176 kg ewe^{-1} year^{-1}) (Table 3). Consequently, ewe milk productivity was lower in SE compared with SI (227 versus 303 kg FPCM ewe^{-1} year^{-1}) (Table 2). Feed efficiency (FE) of productive ewes was lower in SE than SI: 0.40 versus 0.46 kg FPCM kg DMI^{-1}, respectively. Annual feed production in SE was about 67% of SI (Figure 2), while annual FPCM production was lower by 30% (Table 2). Furthermore, despite the lower amount of total purchased feeds (85.33 versus 97.38 Mg DM year^{-1} in SE and SI, respectively), feed self-sufficiency in SE was lower than in SI (62% versus 68%, respectively) (Table 3).

Life cycle assessment

As reported in Table 7, by excluding soil C_{seq}, we observed higher values of emission intensity per kg FPCM in SE than in SI (for about 5%), whereas opposing results were obtained using the area-based FU. Specifically, the emission intensity per kg FPCM was equal to 3.54 and 3.37 kg CO_2-eq kg FPCM^{-1} in SE and SI, respectively. However, considering the area-based FU, the emission intensity assessed without soil C_{seq} was lower in SE than in SI (4,030 versus 6,257 kg CO_2-eq ha UAA^{-1}, respectively).

In the calculation of emission intensity that includes the contribution of soil C_{seq}, the GHG emissions per kg of FPCM and per ha of UAA showed a reduction by about 18% and 7% in SE and SI farming systems, respectively (Table 7). The values of emission intensity including soil C_{seq} were equal to 2.90 versus 3.12 kg CO_2-eq kg FPCM^{-1} and 3,299 versus 5,793 kg CO_2-eq ha UAA^{-1} in SE and SI, respectively.

The contribution analysis (Table 7) shows animal emissions as the main source of GHG emissions, with much more than 50% of contribution in both farming systems. Animal emissions included enteric CH_4 and faecal N_2O emissions, and the latter were by far the lowest impacting, representing less than 1% of total emission intensity. Immediately after animal emissions, off-farm and on-farm feed productions accounted for a relevant hotspot, representing on average more than 19% of total emission intensity in both production systems, including and excluding soil C_{seq} (Table 7). As expected, the contribution of purchased feed was higher in the SE farm management and the difference between the two production systems mainly concerned the role of on-farm feeds, since in SI represented on average 15% of total feed contribution, while in SE accounted by only 1%.

Carbon sequestration in soil

In the transition from SI to SE dairy sheep system, we estimated changes in soil C_{seq}, with a value in SE almost twice than in SI (55.30 versus 33.90 Mg CO_2 year^{-1}), although the total grasslands area actually utilized in both systems was similar (69.7 ha versus 72.4 ha) (Figures 2 and 3). Annual soil C_{seq} from manure during grazing was similar in both farming systems (2.57 versus 3.36 Mg CO_2 year^{-1} in SE and SI, respectively). However, annual soil C_{seq} from crop residues was higher in SE than SI (52.73 versus 30.55 Mg CO_2 year^{-1}, respectively), representing the main input of the total soil C_{seq} (Figure 2).

Taking into account the grassland use destination, the soil C_{seq} contribution of grazed grasslands in SI was almost the same of grasslands for hay, silage and grain purposes (15.06 versus 15.49 Mg CO_2 year^{-1}), while in SE soil C_{seq} from grazed grasslands was 39.38 Mg CO_2 year^{-1}, accounting for 75% of the total (Figure 3).

In SI, natural permanent grasslands contributed for about 16% of soil C_{seq} from crop residues, even though they covered only 4% of UAA (Figure 3). By contrast, in SE the amount of soil C_{seq} due to permanent grasslands (both natural and semi-natural) and irrigated meadows (alfalfa and white clover) contributed for about 90% of the soil C_{seq} from crop residues, while temporary grasslands such as annual forage crops sequestered the remaining 10% (Figure 3).

Overall, by referring soil C_{seq} to 1 kg of FCPM, the values were 0.76 and 0.33 kg of CO_2 sequestered in SE and SI, respectively. When soil C_{seq} was referred to the unit of area, the values were equal to

793 and 469 kg CO_2 per ha of UAA.

Discussion

Life cycle assessment

The extensification of the production system showed contrasting environmental effects, depending on the FU used and the inclusion or exclusion of soil C_{seq} in LCA system boundaries (Table 7). Gutiérrez-Peña et al. (2019) and Escribano et al. (2020) reported similar findings in a comparison between Spanish dairy goat and sheep systems with different grazing regimes, respectively.

Excluding soil C_{seq}, the difference of emission intensity per kg of FPCM between SI and SE can be explained by the decrease of FPCM production in SE. This observation is consistent with data from previous studies that showed how extensive livestock systems have a greater environmental impact than intensive systems, due to their less productive and less efficient management (Gerber et al., 2013). Moreover, by conducting the LCA analysis using the kg $FPCM^{-1}$ as FU and excluding soil C_{seq}, our results are similar to those reported by other investigations (Atzori et al., 2015; Vagnoni et al., 2017) and comparable with those observed by Batalla et al. (2015). The latter, who carried out a study in dairy sheep systems under similar conditions to ours, found emission intensity ranging from 2.87 to 3.19 kg CO_2-eq kg $FPCM^{-1}$ in three semi-intensive systems, and from 2.76 to 5.17 kg CO_2-eq kg $FPCM^{-1}$ in six semi-extensive systems. However, our results differ, in some aspects, from those of Escribano et al. (2020), who stated that emission intensity values followed a trend corresponding to the increasing level of extensification (four farming systems in total), ranging from 1.77 (most intensive farm) to 4.09 (most extensive farm) kg CO_2-eq kg $FPCM^{-1}$. This lower emission intensity per kg of FPCM could be associated to the lower values of enteric CH_4 emissions factors (25 instead of 34 kg CO_2-eq/kg CH_4) and to the higher fraction of concentrate in the diet (on average 1.26 instead 0.66 kg per L of milk) considered in Escribano et al (2020), resulting finally in lower overall enteric CH_4 emissions per ewe (8.64 versus 9.01 kg CH_4 ewe-1 $year^{-1}$).On the other hand, when the ~~GWP~~ emission intensity was referred to 1 ha of UAA and soil C_{seq} was not included, our results are in line with those of Escribano et al. (2020), where the emission intensity values were inversely related to the extent of permanent grasslands.

The percentage reduction of emission intensity with inclusion of soil C_{seq} observed in our study was consistent with results of Knudsen et al. (2019), that observed similar trends in dairy systems located in Western Europe. The inclusion of soil C_{seq} in the emission intensity estimate has allowed to highlight better environmental performance in SE, regardless of the FU used. Indeed, emission intensity per kg FPCM and per ha of UAA in SE was 7% and 43% lower than SI, respectively, in accordance to what stated by other studies on extensive dairy sheep and goat systems based on permanent grasslands (Batalla et al., 2015; O'Brien et al., 2016; Gutiérrez-Peña et al., 2019). Furthermore, Batalla et al. (2015) observed a significantly higher environmental performance of Mediterranean semi-intensive dairy sheep systems only when soil C_{seq} was excluded from the assessment. In their study, the inclusion of soil C_{seq}, estimated according to Petersen et al. (2013), determined an average decrease of 38% in emission intensity per kg of FPCM in sheep farms with Latxa breed. These farming systems were comparable with our case study in terms of stocking rate and feed supply. By contrast, in Escribano et al. (2020), extensive farming systems always showed the highest emission intensity per kg FPCM, even when soil C_{seq} was included. These contrasting results between Escribano et al. (2020) and our study may be due to the difference of soil C_{seq} values. In their study, in fact, the positive effect of C_{seq} soil from natural grasslands did not seem sufficient to compensate for the increase in enteric emissions of CH_4, due to the lower digestibility of the grass-based diet. On the other hand, in our study, the use of irrigated meadows and semi-natural grasslands, mainly based on legume species with high digestibility, certainly limited the negative effects of enteric CH_4 emissions.

In our study, enteric CH_4 emissions have been shown to be the largest contributor to GHG emissions, as demonstrated by several studies on ruminant livestock sector worldwide (González-García et al., 2013; Marino et al., 2016; O'Brien et al., 2016). The different feeding strategies applied in the two production systems of our study influenced the environmental performance in terms of enteric emissions of CH_4 per kg of FPCM. Indeed, despite the lower amount of fibrous feed ingested by ewes, the lower milk yield in SE (determined by lower DMI) resulted in higher enteric CH_4 emissions per unit of FPCM than SI, with 67 versus 58 g of CH_4 kg $FPCM^{-1}$, respectively. As a consequence, enteric CH_4 emissions had a larger contribution to the total emission intensity in SE than in SI (Table 7). In other terms, the FE of productive ewes in conjunction with digestibility represents the most important driver for enteric fermentation (Cottle et al., 2011). Indeed, the value of FE was 15% higher in SI than in SE. The different contribution of purchased feeds and on-farm feeds indicated that feed supply chain and land use strategies strongly influenced the environmental performances of the two production systems, as already stated by Gislon et al. (2020).

In summary, the switch from SI to SE system resulted in a clear environmental advantage when ~~GWP~~ emission intensity was referred to 1 ha of UAA, while the use of mass-based FU determined less pronounced differences between the two production systems (Salvador et al., 2017; Escribano et al., 2020). In this manner, we assessed the effect of the extensification with two contrasting perspectives and we observed that the use of less inputs per ha of UAA led to a clear environmental benefit. Considering that UAA was similar for both farming systems, this conclusion was not obvious and confirmed that using only a mass-based FU the environmental assessment did not provide a balanced view of the intensification impacts (Escribano et al., 2020).

Soil carbon sequestration

The values of soil C_{seq} per kg FPCM observed in our study were in line with the results obtained by Gutiérrez-Peña et al. (2019) in three different Spanish dairy goat systems, where C_{seq} per kg FPCM ranged from 0.15 to 0.81 kg CO_2, with the highest values observed in extensive farms. Similarly, Escribano et al. (2020) showed analogous trend of soil C_{seq} moving from more intensive to more extensive Spanish dairy sheep farms, with values ranging between 0.09 and 2.04 kg CO_2 sequestered per kg of FPCM. The higher amount of soil C_{seq} in SE can be in part associated with the contribution of grazed grasslands, that occupied 83% of the UAA in SE compared to 35% in SI (Tables 1 and 3).

For instance, according to Stanley et al. (2018), the increase of grazing surface together with the improvement of grazing management in SE contributed to enhance the soil C_{seq} of production system. The permanent grasslands and irrigated meadows also contributed considerably to the increase of soil C_{seq} in SE (Table 3). Thanks to their abundant root systems, high root turnover and rhizodeposition, the high amount of biomass residues left on the soil by these grasslands may explain higher soil C_{seq} values in SE (Beniston et al., 2014; Lorenz and Lal, 2018). The increase of "persistent" grasslands, such as irrigated meadows and permanent grasslands that persist undisturbed in the soil for a long time, could lead to an improvement of soil C input and soil C stock, if compared with temporary grasslands such as annual crops (King and Blesh, 2018; Gislon et al., 2020). In addition, the soil disturbance caused by tillage in annual croplands can favour the soil organic matter mineralization (Six et al., 2004; Acar et al., 2018). Hence, the use of "persistent" grasslands allowed to reduce the soil tillage intensity in SE. In this sense, Paustian et al. (1997) reported that management practices that can improve the soil C stock may increase the soil C input or decrease soil organic matter decomposition rates. Considering that a suitable forage system provides benefits in terms of soil C_{seq}, it can be considered as a climate change mitigation strategy of the whole dairy production system (Gislon et al., 2020).

As mentioned before, similar studies conducted by Batalla et al. (2015), Gutiérrez-Peña et al. (2019) and Escribano et al. (2020) estimated soil C_{seq} of semi-extensive and semi-intensive Mediterranean small ruminant dairy systems adopting the model of Petersen et al. (2013). When soil C_{seq} was referred to 1 ha of UAA, these authors obtained similar values between production systems with different intensification levels. Contrarily, we estimated a soil C_{seq} value in SE nearly 70% greater than in SI. The values observed in our study were in line with the range of values showed by Gutiérrez-Peña et al. (2019), but they were lower than the average values observed by Batalla et al. (2015) and higher than those showed by both Eldesouky et al. (2018) and Escribano et al. (2020). The cropping system productivity and the equations used for crop residues estimation can explain these different values of soil C_{seq}. The estimation of above- and belowground residues based on grassland type and destination use allowed to highlight the differences between SE and SI in terms of soil C_{seq} per ha, therefore confirming the potential of soil C_{seq} capacity of livestock systems based on permanent grasslands (Salvador et al., 2017). Thus, the results of our study lead to suggest the need of detailed information about soil C_{seq} from cropping systems characterized by temporary and permanent grasslands, in LCA studies on small ruminant dairy farms. Obviously, it is essential that the models and coefficients used for estimating grazed biomass and crop residues are carefully adopted to obtain reliable soil C_{seq} values.

Conclusions

Accounting for soil C_{seq} in emission intensity estimation, the transition from semi-intensive to semi-extensive Mediterranean dairy sheep farming led to better environmental performance of the production system. By not counting soil C_{seq} within the LCA system boundaries, the adoption of semi-extensive system showed a clear environmental benefit only when emission intensity was expressed per ha of UAA, whereas semi-intensive systems resulted less impacting when ~~GWP~~ emission intensity was referred to the kg of normalized milk.

Enteric CH_4 emissions were confirmed by far as the main source of GHG emissions with direct implications in feed supply strategies.

The soil C_{seq} was favoured by the presence of large areas covered by permanent grasslands and destined to the grazing in the semi-extensive production system. The improvement of soil organic C stock associated to the permanent grasslands would contribute effectively to mitigate GHG emissions in Mediterranean dairy sheep farms, highlighting the positive role of ecosystem services provided by extensive farming systems.

However, being the estimation of soil C_{seq} in our study was influenced by the methods used to estimate grazed biomass and crop residues, further investigations based on direct field measurements are advisable in order to improve data quality and results reliability.

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Table 1. Grassland type, use of the biomass and surface area (ha) in the semi-intensive (SI) and semi-extensive (SE) farming systems.

Semi-intensive system (SI)				
Temporary or permanent grassland	**Type of grassland**	**Species or mixture**	**Use**	**Surface (ha)**
Temporary grasslands	Cereal crop	Winter wheat	Grain	16.0
	Annual forage crops	Oat	Grazing	2.0
		Italian ryegrass-oat mixture	Grazing	20.0
			Hay	25.0
	Irrigated crop	Maize	Silage	6.4
Permanent grassland	Natural grassland	Native vegetation	Grazing	3.0
Semi-extensive system (SE)				
Temporary or permanent grassland	**Type of grassland**	**Species or mixture**	**Use**	**Surface (ha)**
Temporary grasslands	Annual forage crop	Italian ryegrass-oat mixture	Grazing	4.9
	Irrigated meadows	Alfalfa	Grazing	2.6
		White clover	Grazing	1.7
Permanent grasslands	Semi-natural grasslands	Type I: mixture of *Lolium rigidum*, *Trifolium subterraneum*	Grazing	1.0
		Type II: mixture of *Lolium rigidum*, *Medicago polymorpha*	Grazing	1.9
		Type III: mixture of *Lolium rigidum*, *Medicago polymorpha*, *Trifolium subterraneum*	Grazing	4.9
	Natural grassland	Native vegetation	Grazing	40.6
			Hay	12.1

Table 2. Main characteristics of the two production systems, namely semi-intensive (SI) and semi-extensive (SE), adopted to the same farm in different years.

Characteristics of dairy sheep farm	UM	SI	SE
Heads (number of mature ewes) [(1)]	n	340	320
Stocking rate [(1)]	head ha^{-1}	4.7	4.6
Milk total annual production	kg	104,234	82,214
Milk per capita annual production	kg ewe^{-1} $year^{-1}$	307	257
Fat and Protein Corrected Milk (FPCM), per capita annual production	kg ewe^{-1} $year^{-1}$	303	227
Dry Matter Intake (DMI) of mature ewes [(1)]	kg DM ewe^{-1} $year^{-1}$	653	565
Fraction of concentrate in the diet of mature ewes [(1)]	kg DM DMI^{-1}	0.28	0.31
Temporary grasslands (cereal and annual forage crops)	ha	63.0	4.9
Temporary grasslands (irrigated silage maize)	ha	6.4	0
Temporary grasslands (irrigated meadows of alfalfa and white clover)	ha	0	4.3
Permanent grasslands (natural and semi-natural)	ha	3.0	60.5
Mineral N-fertilizing	kg ha^{-1}	68.9	0.5
Mineral P_2O_5-fertilizing	kg ha^{-1}	104.4	1.7

[(1)] Rams and replacement are not considered.

Table 3. Main input (feed, diesel, electricity and water consumptions) and output (feed production and feed self-sufficiency) in semi-intensive (SI) and semi-extensive (SE) production systems, adopted to the same farm in different years.

Item	Unit	Value	
		SI	SE
Input			
Hay/silage consumption [(1)]	kg DM ewe^{-1} $year^{-1}$	314	70
Green forage consumption [(1)]	kg DM ewe^{-1} $year^{-1}$	155	320
Concentrate consumption [(1)]	kg DM ewe^{-1} $year^{-1}$	184	176
Purchased feed per kg FPCM	kg DM kg $FPCM^{-1}$	0.90	1.18
Unit diesel consumption [(2)]	kg diesel 100 kg $FPCM^{-1}$	6.93	4.56
Unit electricity consumption [(3)]	kWh 100 kg $FPCM^{-1}$	0	9.75
	kg diesel 100 kg $FPCM^{-1}$	6.71	0
Unit water consumption	m^3 100 kg $FPCM^{-1}$	19.67	11.48
Output			
Hay/silage production	Mg DM $year^{-1}$	120.49	26.48
Grazing production	Mg DM $year^{-1}$	60.77	110.13
Concentrate production	Mg DM $year^{-1}$	22.5	0
Feed self-sufficiency [(4)]	%	69	62

[(1)] Consumptions of rams and replacement are not included;
[(2)] Diesel use includes the fossil fuel consumption for agricultural operations;
[(3)] Electricity use expressed as kg of fossil fuel from power generator in SI and kWh from electric company in SE;
[(4)] Ratio feed production/feed consumption.

Table 4. Annual biomass yield and total residues (above- and belowground) for each grassland type in both production systems adopted to the same farm in different years.

Item	Yield (Mg DM ha^{-1})	Total residues (Mg DM ha^{-1})
Semi-intensive system		
Oat (grazing)	2.12	2.55
Italian ryegrass-oat mixture (grazing)	2.41	3.33
Italian ryegrass-oat mixture (hay)	1.01	1.23
Maize (silage)	14.61	4.02
Winter wheat (grain)	1.41	3.28
Natural grassland (grazing)	2.77	11.36
Semi-extensive system		
Italian ryegrass-oat mixture (grazing)	5.57	7.69
Alfalfa (grazing)	10.2	15.52
White clover (grazing)	2.21	11.94
Semi-natural grassland (grazing) (1)	3.06	8.12
Natural grassland (grazing)	0.66	2.72
Natural grassland (hay)	2.18	7.71

(1) Mean values of the three type of semi-natural grasslands are reported.

Table 5. Equations and coefficients used to estimate the aboveground residues depending on grassland type and use destination of the biomass.

Type of grassland	Use	Equation	Acronym	Index	Source
Temporary grasslands - annual forage crops (1) - irrigated meadows (2) Permanent grasslands - semi-natural grasslands (3) - natural grassland	Grazing	$AbRes_{grz} = TAbB_{grz} \times i_{grz}$ $TAbB_{grz} = Yie_{grz} \times (1-i_{grz})^{-1}$	• $AbRes_{grz}$ = Aboveground Residues after sheep grazing • $TAbB_{grz}$ = Total Aboveground Biomass of grazed grassland • Yie_{grz} = dry Yield (green forage) of grazed grassland (available data) • i_{grz} = index of aboveground residues after sheep grazing	$i_{grz} = 0.25$	Seddaiu et al. (2018)
Temporary grassland - cereal crops (4)	Grain	$AbRes_{grain} = (Yie_{grain} \times HI_{cer}^{-1}) - Yie_{grain}$	• $AbRes_{grain}$= Aboveground Residues after grain harvest • Yie_{grain} = dry grain Yield of cereal (available data) • HI_{cer} = harvest index of cereal (winter wheat)	$HI_{cer} = 0.4322$	Bolinder et al. (1997)
Permanent grassland - natural grassland	Hay	$AbRes_{hay} = Yie_{hay} \times iLos_{hay}$	• $AbRes_{hay}$ = Aboveground Residues after hay harvest • Yie_{hay} = dry hay Yield of natural pasture (available data) • $iLos_{hay}$ = index of hay harvest losses	$iLos_{hay} = 0.185$	Lai et al. (2017)

(1) Oat and Italian ryegrass-oat mixture;
(2) Alfalfa and white clover;
(3) Mixtures of annual self-seeding species (rigid ryegrass, burr medic and subterranean clover);
(4) Winter wheat.

Table 6. Equations and coefficients applied to estimate the belowground residues depending on the type and duration time of the grassland.

Type of grassland	Duration (year)	Equation	Acronym	Index
Temporary grasslands - annual forage crops • oat • Italian ryegrass-oat mixture (grazed) - cereal crop • winter wheat	1 1 1	$BelRes_{an} = [TAbB \times i(S:R)_{an}^{-1} \times (1+iRz)]$	• $BelRes_{an}$ = Belowground Residue of annual crop • $i(S:R)_{an}$ = Shoot-Root ratio index of annual crop • iRz = index of Rhizodeposition as fraction of root biomass • TAbB = Total Aboveground Biomass (1)	• $i(S:R)_{an}$ = 2.53 (oat) (2) • $i(S:R)_{an}$ = 3.76 (winter wheat) (2) • $i(S:R)_{an}$ = 2.1 (Italian ryegrass- oat mixture) (3) • iRz = 0.65 (2)
Temporary grassland - irrigated meadows • alfalfa • white clover Permanent grassland - natural grassland	4 4 50	$BelRes_{per} = [TAbB \times i(R:S)_{per} \times t^{-1}] + [TAbB \times i(R:S)_{per} \times iRz]$	• $BelRes_{per}$ = Belowground Residue of perennial crop • $i(R:S)_{per}$ = Root - Shoot ratio index of perennial crop • t = time of crop duration • iRz = index of Rhizodeposition as fraction of root biomass • TAbB = Total Aboveground Biomass (1)	• $i(R:S)_{per}$ = 0.9901 (alfalfa) (2) • $i(R:S)_{per}$ = 4.224 (white clover and natural pasture) (4) • iRz = 0.65 (2)
Permanent grassland - semi-natural grassland • annual self-seeding mixtures	4	$BelRes_{ss} = [TAbB \times i(R:S)_{ss} \times t^{-1}] \times (1 + iRz)$	• $BelRes_{ss}$ = Belowground Residue of self-seeding crop • $i(R:S)_{ss}$ = Root - Shoot ratio index of self-seeding crop • t = time of crop duration • iRz = index of Rhizodeposition as fraction of root biomass • TAbB = Total Aboveground Biomass (1)	• $i(R:S)_{ss}$ = 4.224 (4) • iRz = 0.65 (2)

(1) TAbB = AbRes + Yie, for each grassland Total Aboveground Biomass (TAbB) is estimated summing Aboveground Residues (AbRes, Table 5) and Yield (Yie, Table 4);
(2) Bolinder et al., 2007;
(3) Lai et al., 2017;
(4) Mokany et al., 2005.

Table 7. Process contributions for the Climate Change impact category. Emission and contribution of the processes to the total greenhouse gas emissions of semi-intensive (SI) and semi-extensive (SE) production systems, calculated including and excluding soil C sequestration (soil C_{seq}), for both 1 kg of fat and protein corrected milk (FPCM) and 1 ha of utilised agricultural area (UAA) functional units.

Climate Change	Soil C_{seq} exluded		Soil C_{seq} included	
	SI	SE	SI	SE
kg CO_2-eq per kg FPCM	3.37	3.54	3.12	2.90
kg CO_2-eq per ha UAA	6,257	4,030	5,793	3,299
Process contribution (%)				
Animal emissions	56	65	61	80
Purchased feeds	12	18	13	22
On-farm feeds	15	1	16	1
Power supply	6	3	7	4
Transport (lorry and/or transoceanic freight ship)	3	4	3	5
Infrastructures	1	0	1	0
Tractor and agricultural machinery production	0	3	0	3
Soil C sequestration	0	0	-8	-22
Remaining processes [(1)]	7	6	7	7

[(1)] All processes with a percentage contribution lower than 0.35% are included.

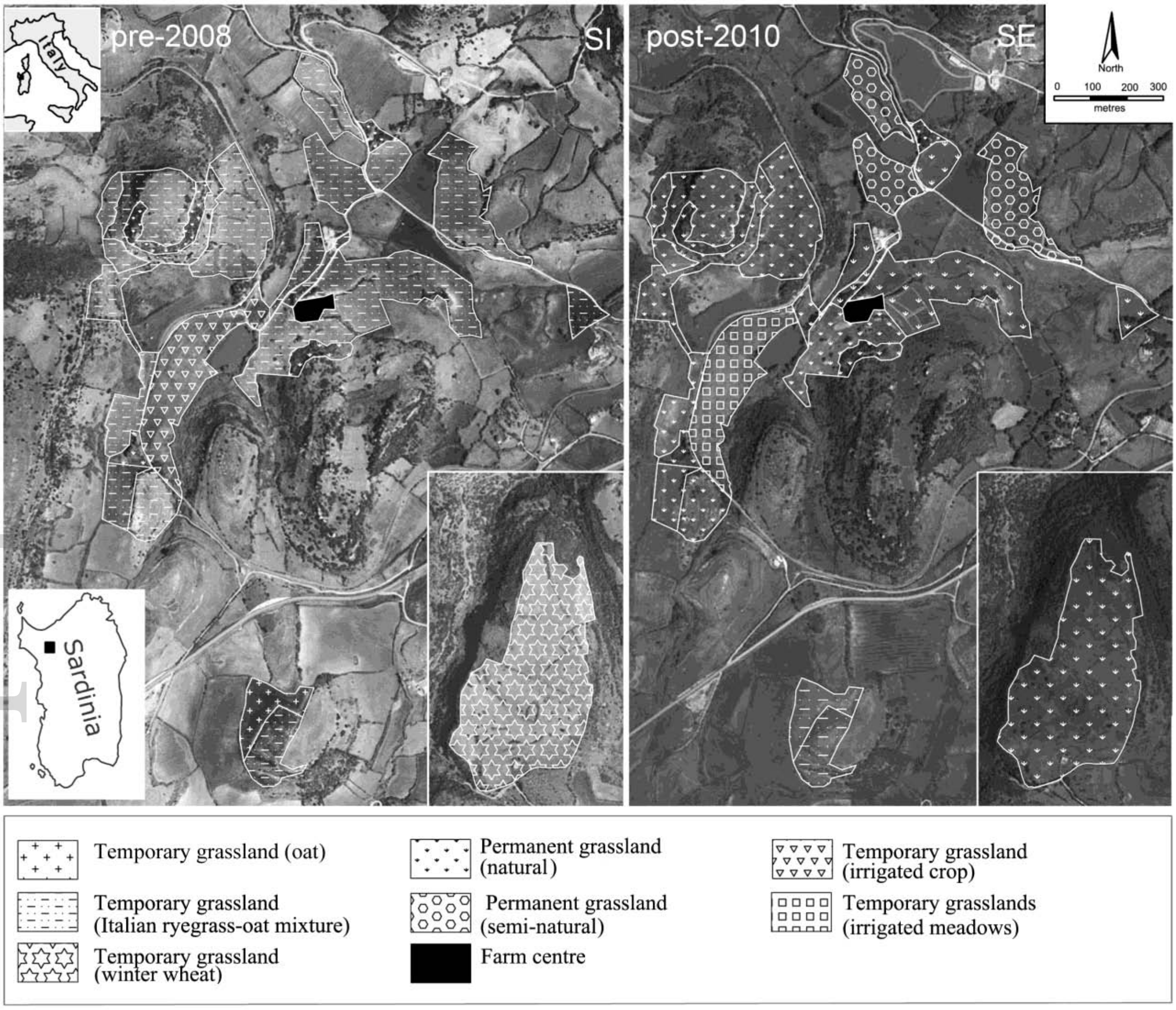

Figure 1. Overview of the case-study farmland in North Sardinia (Italy). The two farming systems (semi-intensive, SI, and semi-extensive, SE) are overlaid with a land use map during the analysed period (based on satellite imageries of SardegnaFotoAeree: 2006 for semi-intensive system and 2013 for semi-extensive system).

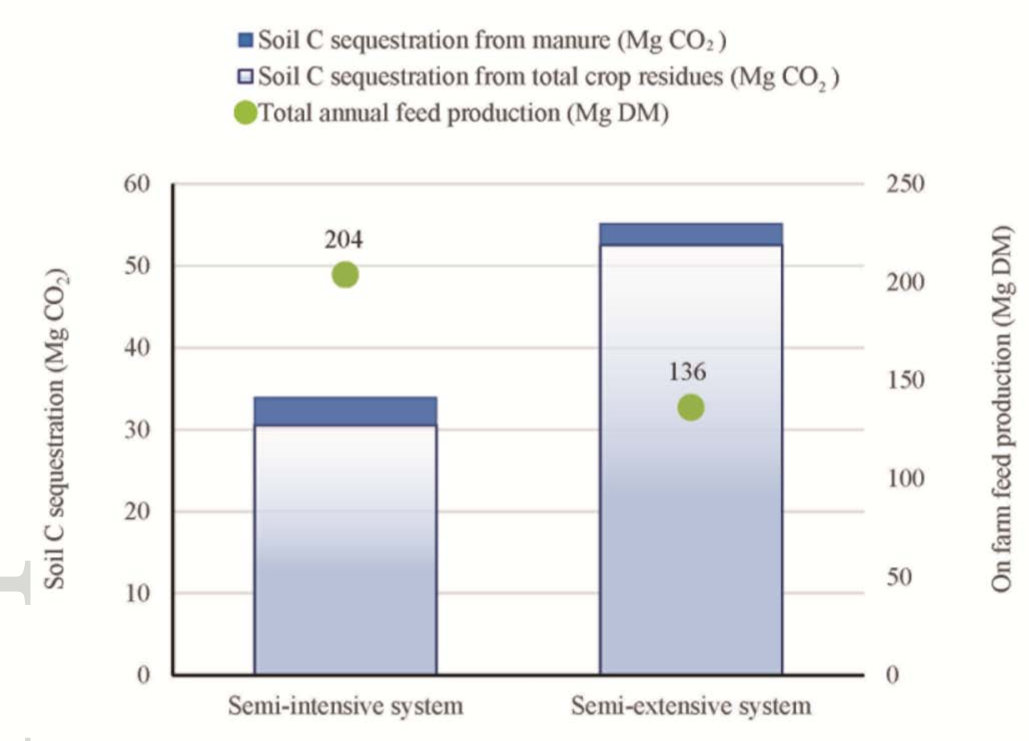

Figure 2. Feed production and soil C sequestration. Total on-farm feed production (Mg DM of grain and forages) and soil C sequestration (Mg CO_2) from crop residues and manure in the semi-intensive and semi-extensive systems. The label values indicate the total on farm feed production (Mg DM).

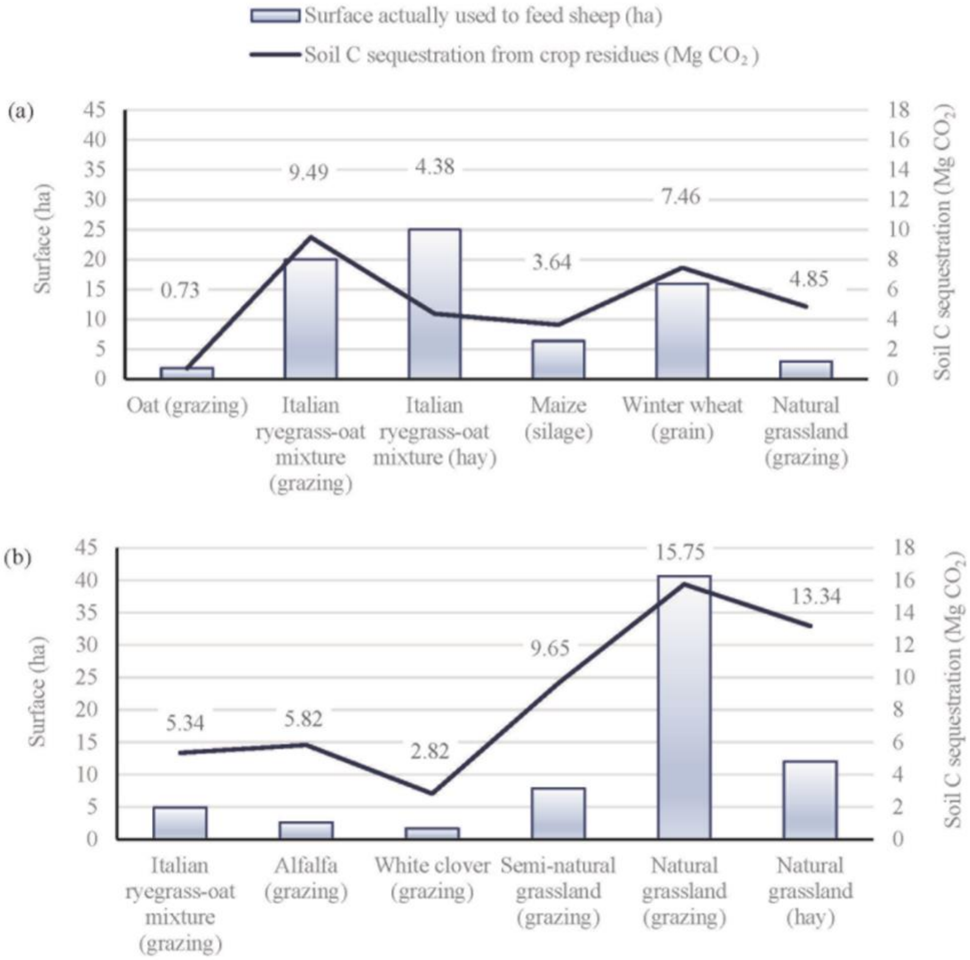

Figure 3. Land use and soil C sequestration. Surface actually used to feed sheep (ha) and soil C sequestration (Mg CO_2 per total surface occupied) deriving from crop residues, based on grassland type and use destination of the biomass, in the semi-intensive (a) and semi-extensive (b) system. The label values indicate the C sequestered (Mg) per whole surface of each grassland.