Science of the Total Environment 953 (2024) 176100

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

An unconventional approach to evaluating the environmental role of a productive system: An environmental assessment of beef farms in North-West Italy

Davide Biagini [a,*], Marco Betta [b]

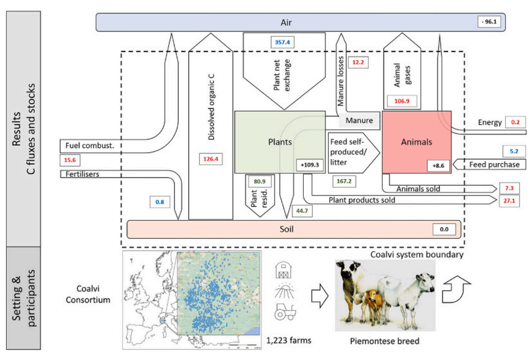
[a] Dipartimento di Scienze Agrarie, Forestali e Alimentari, Università di Torino, Largo Paolo Braccini 2, 10095 Grugliasco, TO, Italy

[b] Cosiqua, Consorzio di Allevatori per i Sistemi di Qualità della Razza Piemontese, Strada Trinità 32/a, 12061 Carrù, CN, Italy

HIGHLIGHTS

- Environmental assessments tend to misrepresent less intensive agriculture.
- Canonical Carbon balance put in evidence the ecological role of a productive system.
- Carbon fluxes of 1223 livestock members of a consortium were analysed.
- The productive processes removed 9.6 10^4 t year^{-1} of carbon from atmosphere.
- An integrated production system can help to reduce GHG emissions from livestock.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Antonella Petrillo

Keywords:
Beef cattle
Carbon balance
Carbon gases
Carbon fluxes
Carbon storage
Integrated system

ABSTRACT

The environmental impact of livestock is often evaluated separately from the other agricultural activities involved in an integrated system, such as that of the rearing of Piemontese cattle in the area of origin of the breed. The most frequently used assessment methods (e.g. Footprint approaches or a Life Cycle Assessment) are in fact often used, through a product-based approach, to analyse a single productive process, but such methods do not consider the production of agro-ecological services, and they neglect the interactions that characterise complex systems. Moreover, such methods often only consider the negative aspects of the environmental impact and misrepresent less intensive agriculture practices. However the current gaps in knowledge about the carbon sequestration of agricultural ecosystems, which are complex and integrated systems, require further investigation and other types of analysis tools. A carbon (C) balance of 1223 Piemontese breed beef farms, located in North-West Italy, has been calculated to evaluate whether such a method could be applied to overcome the aforementioned limitations, to evaluate whether it could be used to describe a complex and integrated system, to

Abbreviations: AA, agricultural area; ARA, arable lands; CSRD, Corporate Sustainability Reporting Directive; DMI, dry matter intake; FA, farm area; GHG, greenhouse gases; GWP, Global Warming Potential; IFS, integrated farming system; LCA, Life Cycle Assessment; LW, live weight; NEE, net ecosystem exchange; NUAA, unutilised agricultural area; KG, kitchen gardens; OL, other land; PECR, permanent crops; PEGR, permanent grasslands; SAA, special holding area; UAA, utilised agricultural area; WA, wooded area.

* Corresponding author.
E-mail address: davide.biagini@unito.it (D. Biagini).

https://doi.org/10.1016/j.scitotenv.2024.176100
Received 13 May 2024; Received in revised form 4 September 2024; Accepted 5 September 2024
Available online 8 September 2024

highlight the relationships that exist between rearing and agricultural activities and to characterise their environmental roles. Conducting a mass balance involves considering the input and output material flows and their accumulation within a system. Thus, the data necessary to quantify the C input, output and internal fluxes of a system at the farm gate, pertaining to the vegetable and animal production processes (productive factors, crop yields, animal performances, productions and sales, reuses), were collected from official documentation, and were then completed and verified through site visits. The mass balance of the system was transformed into C fluxes using stoichiometric coefficients. The fluxes evaluated for the balance were then used to estimate the changes in the C stocks to highlight not only the C emissions or losses from the system, but also their contributions towards reducing environmental hazards. A sensitivity analysis was carried out to evaluate the uncertainty and the robustness of the obtained results. The net C exchange from plants was the flux that contributed the most, amounting to 94.3 % of the inputs, and this was followed by soil losses and animal gases released through respiration and enteric fermentation, which amounted to 42.8 and 36.2 % of the outputs, respectively. The C stored and released by the considered system was calculated considering the C fluxes. Plant, animal and soil storage sites were included in the system, whereas the air site was left out. A constant C content was assumed for the soil. The productive activities of the selected group of beef farms in the Consortium were calculated to remove 96.1 10^3 t of C from the atmosphere (air site) over a period of one year, and that this amount of C was transferred to plant growth and agricultural products (plant site) and to an increase in live weight (LW) of the animals (animal site). The rates of the stored C to agricultural and wooded areas and to the LW of the animals slaughtered in one year were 1.18 t ha^{-1} and 2.24 t C t^{-1} LW, respectively. The sensitivity analysis demonstrated that the C balance was always positive, even for the worst scenario. This study has shown that the examined beef production system, when analysed as an integrated and complex system, can be considered an important C sink and that it is necessary to reconsider the role that livestock, and ruminants in particular, play in the global greenhouse effect.

1. Introduction

Livestock, whenever it is taken into account separately from the productive context in which it is involved, is considered one of the most significant contributors to global greenhouse gas (GHG) emissions (FAO, 2006; EPA, 2019), and it has been suggested reducing the overall number of reared animals to mitigate climate change (Ripple et al., 2014). Livestock farming activities, especially those pertaining to cattle, are closely linked to cultivation activities, and not only to the production of forages and crops to feed animals but also, through the spreading of manure on fields, to those not specifically intended for livestock feed production. These relationships are often not considered in assessment methods that focus on the single production process of a product or a service. Such methods often analyse the entire life cycle, through a product-based approach, but do not consider ecosystem services or agro-ecological aspects (soil health, biodiversity, etc.) and neglect the interactions that characterise complex systems. Motloch (2019) defined such systems as entities that have many components that interact closely with each other. Agricultural and livestock systems can undoubtably be defined as complex systems. Furthermore, the main methods used to assess productive systems generally focus on the negative aspects of the environmental impact and neglect the positive ones, or consider them separately, as in the case of the Carbon Footprint method, which involves counting C sequestration separately from C emissions (ISO 14067, 2018). Furthermore, the most frequently applied environmental assessment methods tend to misrepresent less intensive agriculture production systems (van der Werf et al., 2020). Thus, the current gaps in knowledge about the carbon sequestration of agricultural ecosystems requires further investigation and more analysis tools.

Livestock farms can differentiate their productions, and it is thus necessary to consider the overall production activities and their roles in a more general livestock or environmental system to fully assess the environmental effect of these activities. Livestock systems differ throughout the world, depending on the availability of natural resources, the agro-ecological forces, and the endeavours of farmers to produce efficiently and sometimes following local traditions. It is therefore important to highlight the specific characteristics of each production system to establish the potential environmental role of each system.

In Italy, the rearing of Piemontese cattle is mainly restricted to the region from which the breed derives its name (Piedmont). All the different types of production systems, i.e. whole-cycle system, cow-calf system, growing-finishing system, and mixes of the aforementioned production systems, are carried out by farmers in the area. Over 270 thousand heads have been registered in the herd book (Anaborapi, 2022), but their overall number exceeds 300 thousand heads, which makes the Piemontese breed the most important autochthonous breed in Italy. Breeders typically manage their farms at a family level, and although rearing is their main activity, the farmers also have a variety of other productions. Most of these farms are members of Coalvi, a Consortium that was set up for the protection and valorisation of the breed, whose headquarters are in Carrù (Italy), a hilly area where the Piemontese breed is part of the historical and cultural heritage. The Consortium groups together approximately 1300 farms that raise more than 130 thousand heads, that is, about one third of the Piemontese cattle reared in Italy. Many farms raise their animals on grasslands or mountain pastures for a part of the year, and these lands are enriched with organic matter, while the other farm fields are fertilised with manure obtained from animals raised in confined rearing systems.

These production methods differ from other beef rearing systems in Italy, and they can be considered, on the basis of the characteristics described above, as a more complex system than other agricultural production systems. Since this difference could affect the carbon (C) fluxes and storage, a balance was drawn up to estimate the changes in the C stocks of the system.

It should be recalled that Odum (1956) and Woodwell and Whittaker (1968) introduced the principles of the material and energy balance to the ecological system. This approach has been widely used in agricultural and livestock systems to evaluate the management of nutrients, crop residues and manure, or to evaluate the feed efficiency and nutrient excretion of livestock (e.g. the European Commission and FAO established calculation criteria to evaluate the nitrogen content in animal manure using the mass balance; Ketelaars and Van Der Meer, 2000; ERM/AB-DLO, 2002; FAO-IAEA, 2008). It has also been used to evaluate sustainable practices, and this has involved estimating C sequestration by extending the material balance to assess C cycling in agroecosystems (Schapendonk et al., 1997; Byrne et al., 2007; Oates and Randall, 2014; Rutledge et al., 2015; Viglizzo et al., 2019; Wang et al., 2024a) or developing simulation models (Kröbel et al., 2016). Thus, the mass balance can be considered an important tool in the environmental science and engineering field, and it also plays a crucial role in evaluating the environmental impact of farm systems.

A mass balance involves accounting for the input and output flows of material and their accumulation within a system. In the environmental impact assessment context, a mass balance helps to quantify substances of interest in various environmental compartments. Therefore, a mass balance could be used as an alternative or as an additional tool to other environmental assessment methods as it can be utilised to conduct the assessment from a different point of view and in a systemic way. Indeed, it can be used to highlight certain aspects of biological production processes, such as those carried out simultaneously and in an integrated way on non-intensive and multi-purpose livestock farms.

In order to evaluate whether a C mass balance can be used to describe the complex system that underlies the relationship between the different productive sectors of a farm with a diversified production and to characterise the environmental role of a productive system such as Coalvi, the Authors decided to quantify the C fluxes of the Consortium farms with the aim of: i) using a systemic approach to highlight the relationship that exists between rearing and agricultural activities in order to evaluate how much C is stored and released over one year of activity; ii) overcoming the limitations of other assessment methods that only focus on emissions, and do not consider material captures; iii) providing further information to that obtainable through the use of other assessment methods in order to highlights the particular features of each production system, including low intensity and integrated systems.

This paper presents the results obtained from a C balance regarding the C storage capacity of the Coalvi productive system, which were obtained considering the C stored in the potential accumulation sites (plants, soil, air, and animals) and the C fluxes.

2. Materials and methods

The consortium chosen for this study (Coalvi) is the largest Piemontese beef cattle breeder association and, because of the large number of members, it ensures the representativeness of the breeding systems. The farms in the sample are evenly distributed over different altitude zones (56 % are located in the plain and 44 % in hilly or mountain areas); 99 % of these farms are managed at a family level; 44, 25, 5, and 26 % of the farms adopt a whole-cycle system, a growing-finishing system, a cow-calf system, and a mixed system, respectively.

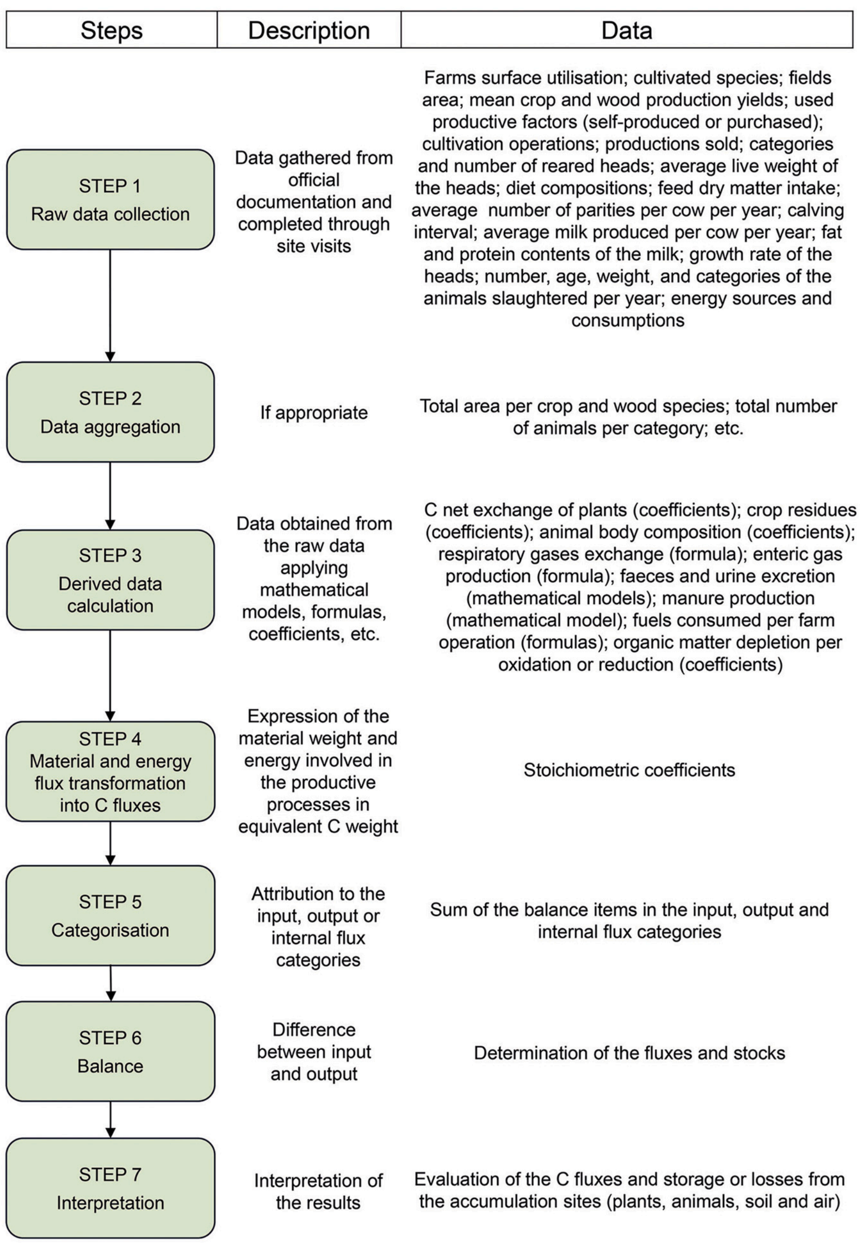


Fig. 1. Description of the steps involved in the calculation of the carbon balance of the collected data and of the elaboration methods.

All the farms in the sample have differentiated productions. These include not only animal production, but also different types of cultivation for the livestock (crops, grasslands, pastures) and/or for the market (crops, orchards, vineyards, woods, etc.). Furthermore, the consortium is responsible for the traceability and voluntary labelling of the meat obtained from Piemontese cattle. Thus, many of the data that we needed to draw up the C balance were already available, although collaboration with the association was useful to collect and/or verify the data obtained from the various farms. The calculation steps of the C balance and their descriptions are summarised in Fig. 1.

The feeding systems, diets, and manure management procedures of the considered Coalvi farms are similar, and the farms are all located in the same climatic area (Piedmont region, North-West Italy; Latitude N 44.12–45.82, Longitude E 7.12–8.98). The area has an average rainfall of 1050 mm $year^{-1}$ and an annual daily mean temperature of 9.1 °C (ARPA, 2023). At the end of 2023, the Consortium included 1278 farms, some of which are small livestock farms for which it is not easy to obtain reliable data. Thus, sample of farms considered to calculate the Coalvi C fluxes was reduced to 1223 (96 % of the total number of farms).

The farms in the sample are representative of the Piemontese breed rearing systems and constitute a homogeneous group of livestock farms, but, at the same time, they are complex and integrated farm systems. Thus, the sample was considered suitable to test the C mass balance as an environmental assessment method as it could avoid misrepresenting the less intensive and multi-purpose production activities.

2.1. General data and assumptions

The information required for the C balance was collected from farm dossiers or from official data recorded by the herd book association (Anaborapi, 2022). When necessary, this information was completed and verified through farm visits and interviews with the farmers. The data on the single farms were than categorised and aggregated (Fig. 1). The available agronomic data referred to surface utilisation, which was classified as: total farm area (FA), and was divided into agricultural area (AA), wooded area (WA) and other land (OL); AA was in turn divided into utilised agricultural area (UAA), unutilised agricultural area (NUAA), and special holding area (SAA). UAA was divided into arable lands (ARA), permanent grasslands (PEGR), permanent crops (PECR), and kitchen gardens (KG). Moreover, specification on the cultivated species, the mean production yield and the quantity of some productive factors (e.g., mineral fertilisers) was available.

The information on the livestock referred to the categories of reared heads, their overall number, the average live weights, and the dry matter intake (DMI) of the feeds; the diet compositions; the average parities per cow per year; the calving interval; the average milk produced per cow per year, and the qualitative characteristics of the milk (fat and protein contents); the growth rate; the number, age, weight and categories of the animals slaughtered per year. The animals were divided into subgroups (suckler calves, 0–6 months; replacement calves, 6–12 months; fattening calves, 6–12 months; heifers, 12–26 months; bulls, over 12 months; dry and lactating cows, over 26 months) and characterised according to their age, weight, diet and production (i.e., milk production, pregnancy, growth rate). The data collected from the farmers were adopted for the DMI because the data calculated from the feed intake estimation, using the IPCC (2019) simplified Tier 2 method, were found to overestimate the assumed feed consumption of the Piemontese breed. It was assumed, on the basis of the values collected from the farmers, that the live weight of the animals and DMI were within ±15 % and ±10 %, respectively (Table 1).

When data were not available, they were estimated or calculated as described in the following sections. Two assumptions were made to calculate the C fluxes: i) the quantity of C in the soil was considered constant (supplies equal to volatilisations), because no recent changes in land use or management had been reported; ii) the system on the farms that were members of the Consortium were considered to ensure the supply of replaced animals. The farm gate was considered as the system boundary for the purposes of this study. A positive sign was conventionally adopted for the C fluxes for the inputs while a negative one was adopted for the outputs. The C fluxes were calculated as explained in the following sections.

2.2. Internal carbon fluxes

Some C fluxes, such as self-produced feeds and litter materials, crop residues incorporated in the soil, manure used as a fertiliser for the farm fields, cow's milk used for the suckler calves, and replaced animals, were assumed within the considered system.

The widely employed value of 50 % was considered for the C content of the plants. This value was originally calculated from an average molecular formula, that is, $CH_{1.44}O_{0.66}$ (Bert and Danjon, 2006; Ma et al., 2018), and it was used to estimate the average C content of the forages and concentrates self-produced on the Coalvi farms and used as cattle feeds, as well as the litter materials obtained from the farm crop by-products. The same percentage was used to calculate the C of the crop residues incorporated into the soil.

Piemontese cattle are reared on litter, and the resulting manure is used as a fertiliser for the crops on the Consortium farms. The manure was quantified by referring to regional regulation DPGR 10/R, which acknowledges the European Directive concerning the protection of water bodies against pollution caused by nitrates from agricultural sources (Dir. 676/91/EEC), with the adjustments legislated through Italian Interministerial Decree no. 5046 issued on 25 February 2016, to consider the specificity of Italian livestock management (Biagini et al., 2007; Biagini, 2010). The same C content as that of the plants used for the self-produced feeds (50 %) was adopted to estimate the average C content of the manure, while considering the origin of this organic waste (prevalently straw plus digested and indigested feeds of vegetal origin).

Cow's milk is used on the farms to feed suckler calves, and it therefore represents another internal flux of C of the considered system. The average quantity of produced milk per cow per year (±standard deviation) was 1567 ± 712 L and on average contained 3.70 ± 0.66 % of fat and 3.51 ± 0.36 % of protein (AIA, 2023). Therefore, assuming an average sugar content of the milk of 4.80 %, the C content of the milk was estimated, on the basis of stoichiometric relationships, to be 6.80 %.

The Coalvi farms were assumed to be autonomous as far as the supply of replacement animals is concerned, which was therefore considered an internal flux. The Piemontese breed is a hypertrophied breed, and their body composition is therefore affected by a reduced body fat content. The skeleton of Piemontese cattle is light and their muscular hypertrophy increases the protein content per unit of live weight. Considering the empty live body weight composition of beef cattle (Honig et al., 2022), corrected for the Piemontese characteristics (Biagini and Lazzaroni, 2011), average contents of 19 % protein, 13 % fat and 1 % carbohydrate were assumed; the C content per kilogram of live weight gain was stoichiometrically estimated to be 19.75 %. It was assumed, on the basis

Table 1
The live performances of animals according to the cattle category.

	Cows	Heifers	Calves 0–6 mth	Replac. calves 6–12 mth	Fattening calves 6–12 mth	Bulls
Average live weight (kg)	560.0 ± 84.0	375.0 ± 56.3	97.5 ± 14.6	200.0 ± 30.0	265.0 ± 39.8	515.0 ± 77.3
Dry matter intake (kg d^{-1})	9.1 ± 0.9	6.5 ± 0.7	2.0 ± 0.2	3.5 ± 0.4	4.0 ± 0.4	8.0 ± 0.8
Daily weight gain (kg)	0.013 ± 0.001	0.520 ± 0.052	0.583 ± 0.058	0.556 ± 0.56	1.278 ± 0.128	1.500 ± 0.150

of the values reported by the farmers, that the live weight gain varied within ±10 % (Table 1).

2.3. Carbon inputs

The net carbon exchanges of farms AA and WA, determined as the difference between the carbon dioxide (CO_2) uptake through photosynthesis and the CO_2 loss through respiration, were estimated considering bibliographic values taken from studies carried out on the Italian environment or from the most similar agri-ecosystems possible. The net C exchange was evaluated considering the data of Carvajal (2011) and Mathew et al. (2017) for crops (values ranging between 3.55 and 11.74 t C ha^{-1} $year^{-1}$, according to the species), of Soussana et al. (2010) and Mathew et al. (2017) for grasslands and rangelands (values ranging between 0.71 and 3.27 t C ha^{-1} $year^{-1}$), of Iandolo (2008), Carvajal (2011) and Zanotelli et al. (2018) for orchards and vineyards (values ranging between 2.46 and 7.73 t C ha^{-1} $year^{-1}$), and of APAT (2002), Marchetti et al. (2012), Neri et al. (2020), and Magnani and Raddi (2021) for woodlands and wood crops (values ranging between 4.09 and 75.13 t C ha^{-1} $year^{-1}$). Grassing was also considered for orchards as an additional net C exchange component.

As explained in Section 2.2, most of the feeds were self-produced, thereby representing internal C fluxes, but the farmers also purchased a quota of protein concentrates and commercial feedstuffs, prevalently for those fattening animals that are mainly responsible for the C inputs. The main ingredients of the diets are shown in Table 2. The Consortium provided the average purchased percentage of DMI intake of the feeds per category of head (cows 2 %; heifers 6 %; calves 6–12 months 6 %; fattening animals 11 %). These quotas were estimated as C fluxes by adopting a value of 50 % in the same way as for the calculation of the C in the plants.

Among the chemical fertilisers used by the farmers for crop fertilisation, only urea contains C. The C stoichiometric coefficient of the CH_4N_2O formula was used to calculate the C introduced by the urea fertilisers.

Atmospheric CH_4 oxidation from the soils was considered negligible, according to Boeckx and Van Cleemput (2001), and was therefore not considered for the C balance.

The farmers purchase diesel oil as fuel for the vehicles used for the preparation of the soil, seeding, fertilisation, irrigation, plant treatments, haymaking, harvesting and for livestock feeding and management operations. The quantity of the fuel introduced into the considered system was estimated by consulting the regional tables on the allocation of petroleum products considered for agriculture tax relief purposes (APAT, 2003), and quantified according to the Resolution of the Regional Council, December 29, 2021, no. 35-4488. A stoichiometric approach was used to estimate this C input.

Table 2
The main ingredients used (X) for the diets of the different animal categories.

Ingredient	Cows	Heifers	Repl. calves 6–12 mth	Calves 6–12 mth	Bulls
Polyphyte hay I-II cut	X	X	X	X	X
Polyphyte grass I-II cut	X	–	–	–	–
Perennial ryegrass hay	X	X	–	X	X
Perennial ryegrass grass	X	X	–	–	–
Clover spp. hay	X	–	–	–	–
Clover spp. grass	X	–	–	–	–
Alfalfa hay	X	–	–	–	–
Alfalfa grass	X	–	–	–	–
Corn silage	X	X	X	X	X
Ground corn silage	X	–	–	–	X
Wheat bran	X	X	X	X	X
Cereal straw	–	–	–	–	X
Soybean meal	X	X	–	X	X
Faba beans	–	–	–	–	X
Corn	X	X	–	X	X
Barley	X	X	–	X	X
Dried beet pulp	X	–	–	X	X
Complementary feedstuff	X	X	X	X	X
Minerals	X	X	–	X	X

2.4. Carbon outputs

The respiratory gas exchange of the animals was estimated considering the physiological characteristics of beef cattle (number of respiratory acts at rest, gas exchanges per respiratory act; Aguggini et al., 1997), and was corrected on the basis of the specific chest length and circumference of the Piemontese breed and on the head category, characteristics which were obtained from morphological measurements conducted during experimental studies carried out over the previous four decades by the Department of Agricultural, Forest and Food Sciences of the University of Torino (Pagano Toscano et al., 1990; Lazzaroni and Pacher, 1995; Lazzaroni et al., 2001; Lazzaroni and Biagini, 2005; Biagini and Lazzaroni, 2019).

The faecal productions were estimated by considering the feed digestibility, which was calculated from the average characteristics of the rations prepared for the different animal categories (feed digestibility ranging between 65 and 76 %) and on the basis of experimental data collected on Piemontese cattle (Biagini, 2010; Biagini and Lazzaroni, 2022). The urine productions were estimated from bibliographic data (Aguggini et al., 1997; Misselbrook et al., 2016).

The enteric release of C was calculated as the difference between the C input (feed), C retention (average weight gain) and C output (milk, calves, breathing, faeces and urine) to consider the production of both carbon dioxide and methane.

The C emissions from dung were estimated, between the excretion of the faeces and the spreading of manure on the fields, on a dry weight basis, as the net loss of organic matter, considering the average animal production of faeces and urine plus the average quantity of litter distributed per animal category, minus the manure spread on the fields, which was quantified as the internal C flux, as described in Section 2.2.

The yearly live weight of all the slaughtered animal categories was taken from the traceability system of the Consortium to calculate the animal C outputs of the productive system. As assumed for the replacement animals, the C content per kilogram of live weight was estimated to be 19.75 %. The live weight (LW) of the slaughtered animals was considered to calculate the index of the weight of C captured per weight of LW slaughtered.

The same C content as that of the plants used for the self-produced feeds (50 %) was adopted to estimate the average C content of the plant products sold annually.

The diesel oil used as fuel, quantified as described in Section 2.3, once burned, releases carbon dioxide into the atmosphere. A stoichiometric approach was used to estimate this C output, whereby it was assumed that the carbon content of the fuel was all oxidised at a maximum oxidation state or to carbon dioxide (APAT, 2003). The conversion coefficient used to obtain the C output was 711 g C L^{-1} diesel.

The average power used for the rearing phase per head was estimated, according to the livestock category, to quantify the C fluxes imputable to electric consumption. The electricity consumed for zootechnical purposes was evaluated considering the average energy consumption for barn lighting, environmental conditioning (fans), and for barn equipment (manure removal). The thus obtained value was arbitrarily increased by 10 % to consider all the other electric consumptions on the farms. The emission factor for the Italian power sector, per kWh produced in Italy from fossil fuels in 2022 (482.2 g CO_2 kWh^{-1}; ISPRA, 2023), which refers to the mix of fuels used for thermoelectric productions, was applied to quantify the CO_2 emissions. The value was reduced by deducting the share of electricity obtained from renewable sources from the final gross consumption of electricity in Italy (39.4 %; ISPRA, 2022). The CO_2 emissions were calculated as C on the basis of the stoichiometric relationships.

2.5. Carbon storage and losses

It is possible to calculate the C stored and released by a given system from the C fluxes, by only considering the phases involved in the productive processes i.e., without considering the emissions related to the transport and processing of raw materials.

The C stored by the system was considered to be net of the sold products, which represent an outflow of C from the considered system, even though they do not release their C into the environment until they are completely degraded in the subsequent use phases. The considered storage or depletion sites of the farm systems were plants, soil and animals, whereas the air site was considered to be outside the system. The C fluxes (losses or enrichments) in the considered system sites and outside the system boundary were fertilisers and purchased feeds, plant and animal sold products, the net plant C exchanged with the atmosphere, and gases produced by bovine respiration and enteric fermentation, manure storage and spreading, organic matter degradation of soil and energy sources (electricity and fuel). The difference in the C stock changes in the plant, animal, and soil components, and thus the system losses, net of the outside input fluxes of the farms, represent the enrichment or depletion of the air component. A schematic representation of the C fluxes and the considered storage sites is shown in Fig. 2.

2.6. Sensitivity analysis

A sensitivity analysis was carried out to evaluate the uncertainty and the robustness of the obtained results. Such an analysis allow an estimation to be made, over a reasonable range, of how the changes in some of the variables affect the results of the tested model. The first step was to clarify the uncertainty space of the model, i.e. how many and what factors were considered uncertain and could affect the output and the drawn inferences. The second step involved choosing the most suitable method to conduct the sensitivity analysis. In this study, the C input and output variables were considered to affect the C balance. Thus a two-way analysis was chosen, first because it allowed two factors to be changed at the same time and to observe how they affected the outcomes, and second because it could be applied when there was a correlation between two tested factors. From a mathematical point of view:

$$Z_{i,j} = f\left(x_i, y_j\right) \tag{1}$$

where: $Z_{i,j}$ is the output, and x_i and y_j are the variables that affect the output.

The following C balance was used:

$$Z = x - y \tag{2}$$

where: Z is the balance, x is the input and y is the output.

In order to calculate the most probable range of variation of the variables, once the C balance had been calculated, a weighted mean was introduced using the range of variations of the single components of the C inputs and outputs, respectively, and their different contributions (weights) to the final value of these variables. The variations of the C input and output components were assumed by referring to bibliographic references or were taken from information obtained from the Coalvi Consortium, which collects the annual production data of its members and has knowledge of the specific rate of change of these variables in the sample of farms involved in this study. The sensitivity range obtained from the bibliographic sources, which generically refer to bovine species, was reduced to one third when the component in this study referred to the specific characteristics of the Piemontese breed. The range of variation considered for the C input included: Plant exchange ±10 % (adjusted according to Jaksic et al., 2006 on the basis of the annual yield variations recorded by Coalvi); Feedstuffs ±5 % (range calculated by the Coalvi Consortium on the basis of its technical assistance on feeding); Fertilisers ±10 % (calculated by the Coalvi Consortium from direct investigations); Fuel ±8 % (calculated by the Coalvi Consortium from direct investigations). The range of variation

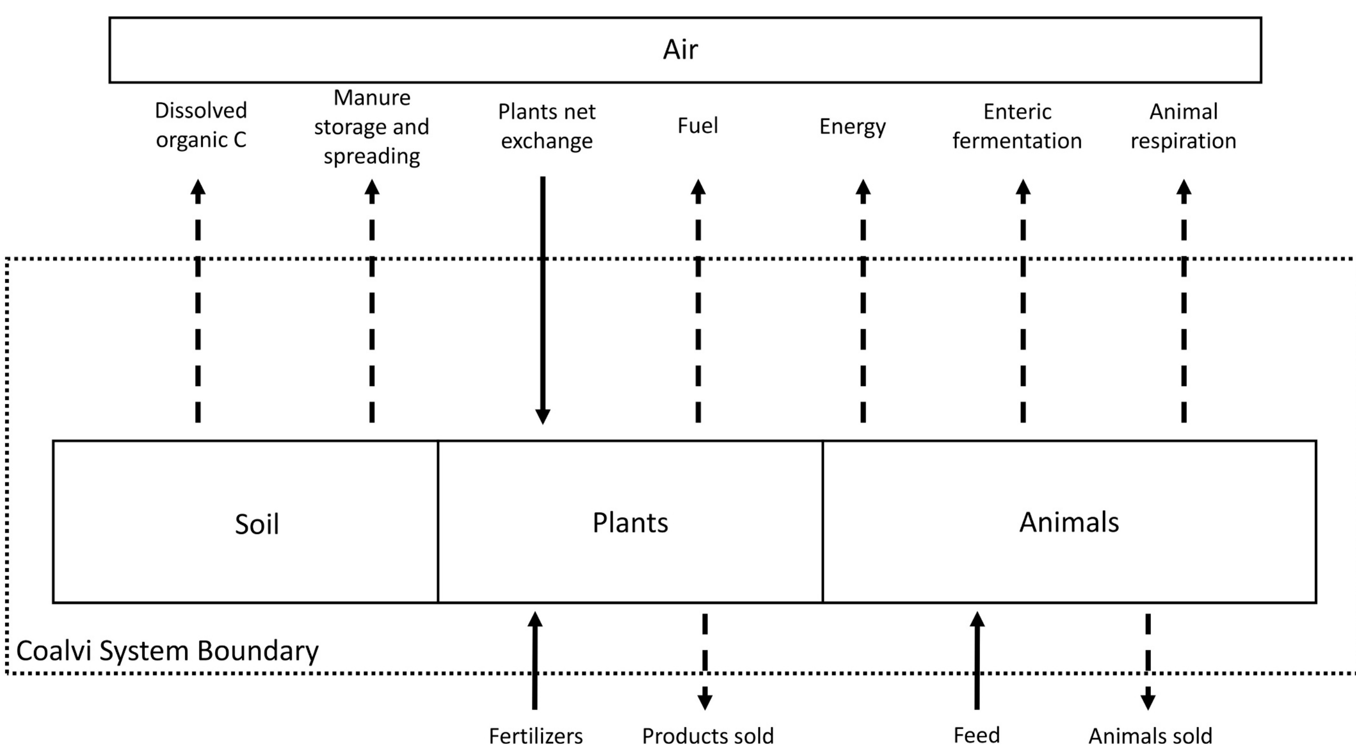


Fig. 2. Schematic representation of the C fluxes and the considered storage sites. The carbon inputs are represented by solid arrows, the C outputs by broken arrows, while the squares represent the storage sites.

considered for the C output included: Soil losses ±15 % (adjusted according to Lei et al., 2022); Manure losses ±8 % (adjusted according to Amon et al., 2001); Animal respiration ±5 % (adjusted according to Aguggini et al., 1997); Enteric fermentation ±10 % (adjusted according to IPCC, 2019); Fuel combustion ±10 % (calculated by the Coalvi Consortium from direct investigations); Electric energy consumptions ±8 % (calculated by the Coalvi Consortium from direct investigations); Animals sold ±5 % (calculated by the Coalvi Consortium on the basis of its product traceability activity); Plant products sold ±10 % (calculated by the Coalvi Consortium on the basis of the annual yield variations).

3. Results

The presented results refer to the year 2023. The collected raw data allowed the case study to be described and characterised. The raw data and its interpretation are presented in separate sections.

3.1. Characterisation of the case study

The locations of the Coalvi farms involved in this study are shown in Fig. 3 and their surface utilisation is shown in Fig. 4. The cultivation list includes 139 different types of cultivation, divided into categories (annual crops, permanent crops, orchards, vineyards, grasslands, pastures, woods, etc.) and species. There are also areas left fallow or designated for the pollinating of insects.

The average herd size (mean and, in brackets, range of values, mode and median, respectively) of the member farms of the Consortium is 112.8 heads (10–1287; 27; 84). The herd composition, considered as the average number of heads, is cows 50.1 (1–321; 1; 38), heifers 17.7 (1–321; 2; 11), calves 0–6 months 16.8 (1–222; 2; 12), calves 6–12 months 23.2 (1–406; 3; 16), bulls 12–24 months 20.6 (1–371; 4; 11), bulls over 24 months 3.2 (1–71; 1; 2). The numbers of cattle reared and slaughtered in 2023 are shown in Table 3, together with the specific slaughter weights. The stocking rate is 1.55 livestock units (LU) per hectare. These aspects were all considered to characterise the C fluxes and balance.

3.2. Elaboration of the raw data

The C fluxes of the studied system are shown in Table 4. The net C exchange of the plants is the largest component of the C inputs, amounting to 94.3 %. Of this C flux, 46.8 and 22.6 % supply the farm self-produced feeds plus litter for the reared animals, and organic matter in the soil as crop residues, respectively. The remaining percentage represents the fixed C in the saleable production and in the organic matter that is produced from the annual growth of woody or pluriannual plants. The feedstuffs and urea fertilisers contribute less to the C inputs, that is by 1.4 and 0.2 %, respectively.

Regarding the C outputs, soil losses account for the largest flux (42.8 %), and this is followed by animal gases released through respiration, which is a significant source of C, and enteric fermentation (36.2 % in total). The C fixed in the sold plants and animal productions amounts to 11.6 % of the C output. The C balance shows a positive value, thus demonstrating the environmental role of the Consortium in capturing 1.18 t C ha^{-1} or 2.24 t C t^{-1} of live weight slaughtered (37,240 t).

The C balance was conducted with the purpose of highlighting the environmental exchanges of C that occur during farm production activities. In other words, it was aimed at determining how much C is used,

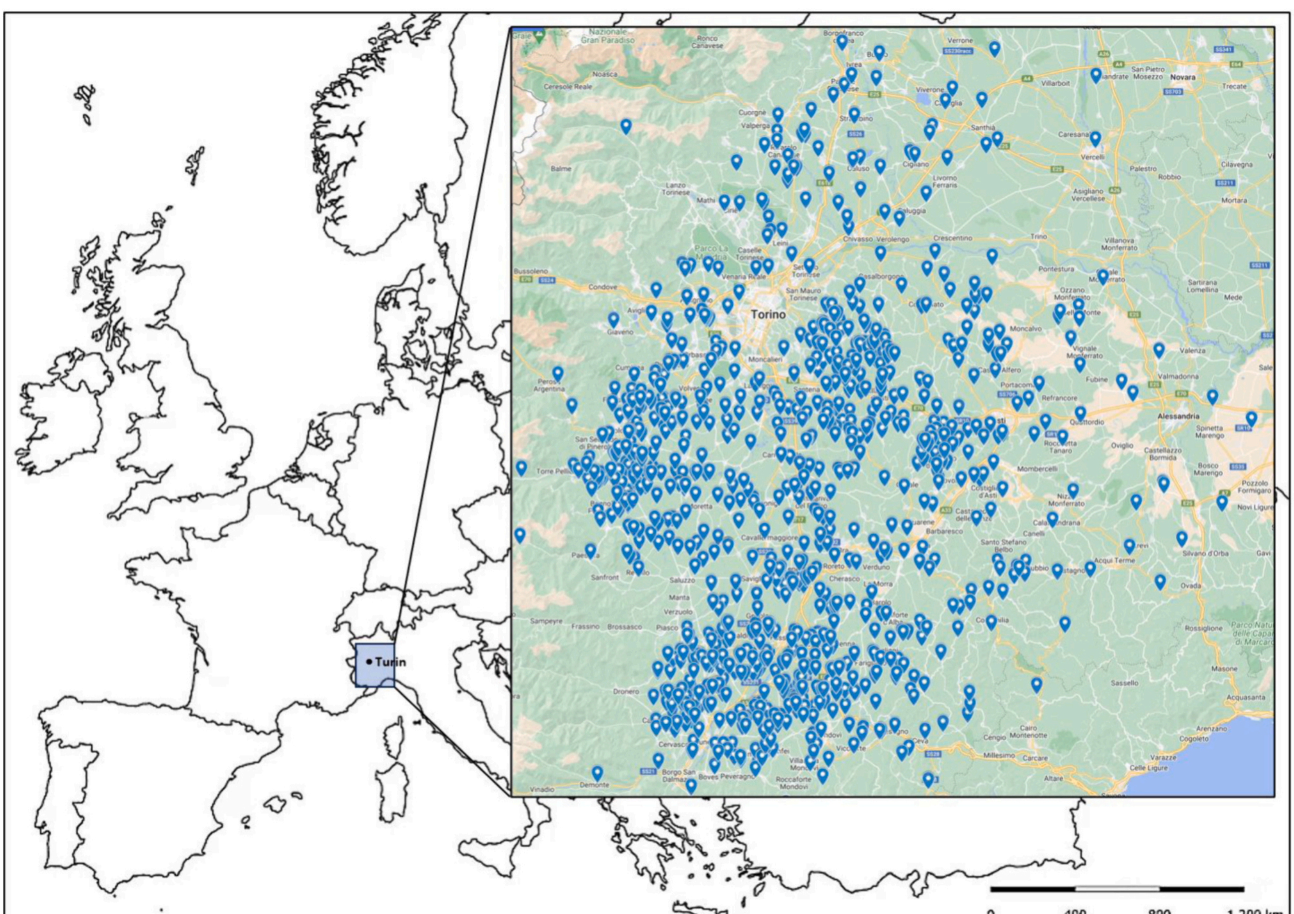


Fig. 3. Location of the Coalvi farms involved in the study.

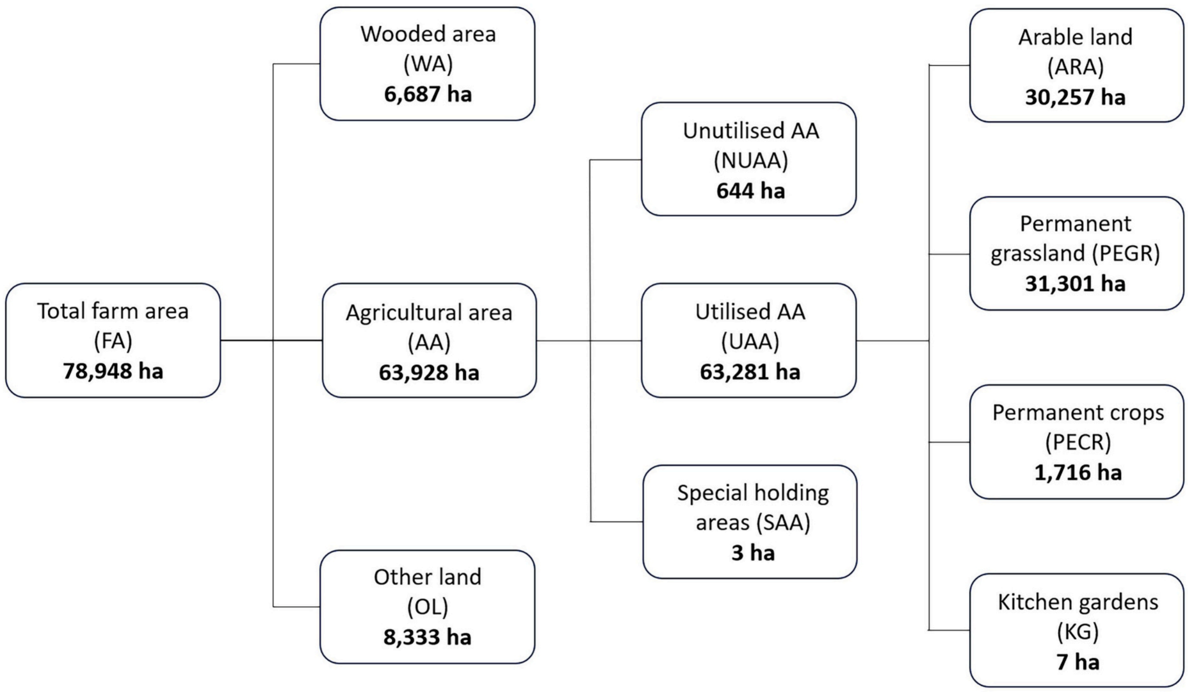


Fig. 4. Farm area utilisation classified as: the total farm area (FA); agricultural area (AA); wooded area (WA); other land (OL); utilised agricultural area (UAA); unutilised agricultural area (NUAA); special holding area (SAA); arable lands (ARA); permanent grasslands (PEGR); permanent crops (PECR); and kitchen gardens (KG).

Table 3
The live and slaughtered animals of the Consortium, with reference to 2023.

	Cows	Heifers	Suckler calves	Calves	Bulls
Heads reared (no.)	50,365	19,631	17,874	26,855	23,253
Heads slaughtered (no.)	4653	14,978	–	–	36,770
Slaughtering weight (kg)	685	534	–	–	641

fixed and released during a year of agricultural activities. Therefore, this balance involved quantifying the flows of the considered system, with reference to such components as plants, soil, air and animals; Fig. 5 shows the results. The set of productive activities of the farms that are member of the Consortium, was found to remove 96.1 10^3 t of C from the atmosphere during one year of operation and to transfer it to plant growth, agricultural products, and meat.

The weighted means of the range of variation of the C inputs and outputs, calculated from the range of variability of the single components of the C fluxes, as described in Section 2.6, and their quantification (weight), as shown in Table 4, were ± 10.4 and ± 9.9, respectively; both the variables were rounded to a range of variability of ±10 %, and were then used to carry out the sensitivity analysis shown in Table 5. Thus, the C balance was found to range over ±81 % and to be positive, even for the worst scenario (C input −10 % and C output +10 %).

4. Discussion

The environmental sustainability of the Consortium involved in this study (Coalvi) can be appreciated by considering its productive differentiation (139 different agricultural productions), which help to enrich the rural landscape through a variety of elements, and also makes it enjoyable from a tourist perspective. This significant crop diversity ensures that the degree of productive circularity and self-supply of feeds for livestock is very high for the available land, but could be further increased in the case of adverse market conditions or because of international political scenarios. The weight of the C inputs on the considered categories is an indication of the high level of self-supply of the farms that are members of the Consortium, particularly concerning the feeds. Indeed, the purchased feeds and feedstuffs are responsible for only 3.1 % of the C introduced into the livestock production with the animal rations. In this regard, Byrne et al. (2007) affirmed that it is important to

Table 4
Carbon fluxes and balance presented as the absolute value (total) and relative values (per Agricultural Area plus Wooded Area hectares and per ton of live weight slaughtered, LW).

Category	Absolute value	Relative value	Relative value
	(,000 t C)	(t C ha^{-1})	(t C t^{-1} LW)
Internal carbon fluxes			
Forages, concentrates and litter	167.2	2.37	4.49
Milk	4.6	0.07	0.12
Manure	44.7	0.63	1.20
Crop residues	80.9	1.15	2.17
Carbon inputs			
Net plant exchange	357.4	5.06	9.60
Feedstuffs	5.2	0.07	0.14
Urea	0.8	0.01	0.02
Fuel	15.6	0.22	0.42
Sub-total	379.0	5.36	10.18
Carbon outputs			
Soil losses	−126.4	−1.79	−3.39
Manure losses	−12.2	−0.17	−0.33
Animal respiration	−87.7	−1.24	−2.35
Enteric fermentation	−19.2	−0.27	−0.52
Fuel combustion	−15.6	−0.22	−0.42
Electric energy consumption	−0.2	−0.003	−0.005
Animal sold	−7.3	−0.10	−0.20
Plant products sold	−27.1	−0.38	−0.73
Sub-total	−295.7	−4.19	−7.94
Net carbon balance	83.3	1.18	2.24

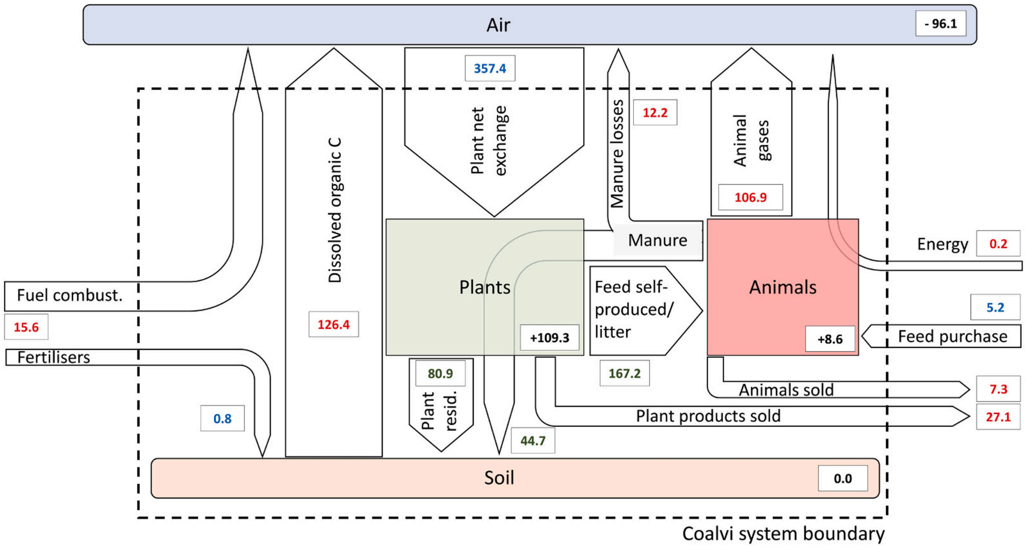


Fig. 5. C flows of the Coalvi system and changes in the of C stock for the environmental (air, soil, plants and animals) components (,000 t). The C inputs, outputs, internal fluxes and storage quantities are written in blue, red, green and black, respectively.

Table 5
The most likely range of variation of the C balance for different scenarios obtained from a sensitivity analysis.

	C input	-10.0%	-7.5%	-5.0%	-2.5%	0%	2.5%	5.0%	7.5%	10.0%
C output		341.10	350.58	360.05	369.53	379.00	388.48	397.95	407.43	416.90
-10.0%	266.13	74.97	84.44	93.92	103.40	112.87	122.35	131.82	141.30	150.77
-7.5%	273.52	67.58	77.05	86.53	96.00	105.48	114.95	124.43	133.90	143.38
-5.0%	280.92	60.18	69.66	79.13	88.61	98.09	107.56	117.04	126.51	135.99
-2.5%	288.31	52.79	62.27	71.74	81.22	90.69	100.17	109.64	119.12	128.59
0%	295.70	45.40	54.87	64.35	73.83	83.30	92.78	102.25	111.73	121.20
2.5%	303.09	38.01	47.48	56.96	66.43	75.91	85.38	94.86	104.33	113.81
5.0%	310.49	30.62	40.09	49.57	59.04	68.52	77.99	87.47	96.94	106.42
7.5%	317.88	23.22	32.70	42.17	51.65	61.12	70.60	80.07	89.55	99.02
10.0%	325.27	15.83	25.31	34.78	44.26	53.73	63.21	72.68	82.16	91.63

Colour of the cells: white = starting value; green = variation > +20 %; light green = variation within +20 %; yellow = variation within −20 %; orange = variation > −20 %.

take cognisance of any feeds of external origin in the C balance of a farm, because this C flux reduces the C sequestration potential of other ecosystems. The large quantity of food self-produced by the farms in the examined Consortium underlines the ecosystemic role of this productive system in preserving the C stocks of other ecosystems.

The Coalvi farms are all managed through a traditional approach, which can be described as an integrated farming system (IFS). It has recently been proposed that different livestock systems could be managed through an IFS, as it can reduce or compensate for C emissions from agriculture, while simultaneously improving production efficiency (Oliveira et al., 2018). From this point of view, it is possible to state that the Coalvi livestock farms have a high degree of resilience and are unlike typical intensive specialised farms, as confirmed by the low number of LU per hectare.

This aspect also affects the C balance because the C gas emissions from livestock are mitigated by the subtraction of atmospheric carbon dioxide through plant photosynthesis. Indeed, the result of the C balance suggests that the Coalvi farm system could be considered, in agreement with the definition of Byrne et al. (2007), as a so-called "carbon sink" and confirms that, in this case, the dominant pathway of C input is through photosynthesis. The average net plant exchange (5.06 t C ha^{-1}) is much higher than those of other livestock systems where, however, the net ecosystem exchange (NEE) has been calculated. NEE measures the respiration of the C of an ecosystem, which is the difference between canopy photosynthesis and ecosystem respiration during daytime and at night (Luo and Zhou, 2006). Unlike the net C plant exchange, which is obtained as the difference between the CO_2 uptake through photosynthesis and the CO_2 loss through respiration, NEE also considers respiration of the soil ecosystem (that is, it subtracts the heterotrophic respiration of soil, animals and microbes from the net photosynthesis). From this point of view, the average net C plant exchange index represents a novel approach to the evaluation of the carbon fluxes of a productive system. If these differences are taken into account, the average value of the net plant exchange calculated in this C balance seems to be proportionate to those found in studies related to NEE. Byrne et al. (2007), for example, considering grassland in Ireland found an NEE of 2.9 t C ha^{-1} for extensive cattle rearing systems, a value that is similar to that found by Schapendonk et al. (1997), that is, of 3 t C ha^{-1}, reported for *L. perenne* grassland in the Netherlands. Indeed, with reference to the assumptions on the calculation of the C fluxes reported in Section 2.1, and to similar cultivations, when we subtracted the C of the non-harvested plant residues from the net C plant exchange as soil respiration losses, the obtained value, that is, 2.61 and 3.00 t C ha^{-1} for grassland and *L. multiflorum*, respectively, were similar to the NEE calculated by the other authors. It is important to recall that the grassland NEE value has been found to reach values of over 7 t C ha^{-1} for different ecosystems (Novick et al., 2004). Jaksic et al. (2006) reported a great variability (over 40 %) of the grassland NEE between wet (1.9 t C ha^{-1}) and dry years (2.6 t C ha^{-1}) and confirmed that the net plant exchange accounted for the largest proportion of C inputs, thereby impacting the annual C balance of a farm to a great extent. Abdalla et al. (2013) found, for other Northwestern European ecosystems, that the C of forest plantations was an order of magnitude larger (9.04 t C ha^{-1}) than that of grasslands (1.89 t C ha¯1) and arable ecosystems (2.12 t C ha^{-1}). These values are in agreement with the weighted average net plant exchange value estimated in the present trial.

These differences in NEE, and therefore in the net plant exchange, are surely affected by both climate and management variables, in the same way that carbon fluxes from agricultural soils are affected by the crop (species, yield and rotation), climate (temperature, rainfall and evapotranspiration) and soil characteristics (carbon content and water retention capacity; Vleeshouwers and Verhagen, 2002). The climatic characteristics of the North-West of Italy affect the length of the vegetative season of the plants and support organic matter mineralisation and C volatilisation as methane or carbon dioxide, as recognised in the EU environmental regulation (Dir. 676/91/EEC), where a manure nitrogen loss as gas of 28 % was indicated for Italy vs 10 % for north European countries. Furthermore, approximately half of the UAA of the Consortium farms is occupied by permanent grasslands. The role of grasslands and pastures in temperate areas as C sequestration sites was pointed out by Mudge et al. (2011), who, albeit under different climatic conditions, found values for the net ecosystem C balance that ranged between 590 and 900 kg C ha^{-1}. As far as farm management is concerned, a large part of the forage sources on the considered farms was silage maize, a C4 species with a high C capture efficiency through photosynthesis. Hollinger et al. (2005), in a study on the C budget of a maize and soybean rotational system, found that at the local scale maize was a sink for 5.76 t C ha^{-1} $year^{-1}$. However, it should be considered that maize can lead to rather large soil C losses and/or a lower soil C equilibrium than grassland, if long-term cropped. In addition to these sources of data uncertainty, the use of bibliographic coefficients to process the collected information or to estimate some components of the C balance, such as the net carbon exchange of plants and fuel consumption, could be a source of approximation, distortion, and uncertainty. However, when working with a large number of farms, as in this study, a compensating effect of the errors should be considered.

The Consortium farms are not only based on grasslands. Indeed, they have large areas that exceed those considered strictly necessary for livestock production, which allows significant amounts of carbon dioxide to be sequestered from fast-growing and highly carbon-absorbing perennial plants. Moreover, the rearing systems adopted by most of the members of the Consortium can be defined as moderately intensive, with the fattening animals reared in confined conditions, but the members also sometimes resort to the use of non-intensive grazing on grasslands and alpine pastures in the summer-autumn seasons, which could affect the net C plant exchange.

The results obtained in this work can be considered to confirm the effect of the management variables on the C balance and the validity of the latter as an instrument that could be used to characterise different agricultural systems. In fact, when considering the net C balance, the differences from systems based on grasslands are less marked than the net C plant exchange vs NEE and are similar to the values obtained by other authors (2.05–2.15 t C ha^{-1}, Byrne et al., 2007).

The role of Coalvi in removing C from the atmosphere, as can be seen from their C balance of the selected group of beef farms, confirms the results obtained by other authors and for other cattle systems. Indeed, the annual C balance drawn up by Byrne et al. (2007) for dairy farms based on grassland suggests that this production system was net of C sinks, thereby reducing its Global Warming Potential (GWP). Other studies that have carried out mass balances to estimates the C sink/source of livestock farms can be found in the literature (e.g. Nieveen et al., 2005; Jaksic et al., 2006; Lloyd, 2006; Wang et al., 2024b), but a comparison with the results presented in this paper is difficult because the aforementioned studies did not fully represent the farm level C balance, since they did not address all the C input and output pathways, such as the release of respiratory gases, the exporting of meat and milk and/or the importing of concentrate feeds. Taking these differences into account, the conclusions drawn up by the aforementioned authors support the results of this paper. For example, the agricultural production system examined by Wang et al. (2024b) has proved to be a carbon sink with an average annual absorption intensity of 1.8 t C ha^{-1} $year^{-1}$.

The results obtained in the present study lead to different conclusions from those that would have been obtained with other assessment methods, such as a Life Cycle Assessment (LCA) analysis. There are few studies in the literature that have applied an LCA analysis to the breeding of Piemontese cattle. One of these (Bonnin et al., 2021), calculated the GWP of 10 closed-cycle farms over a four-year period, and reached the conclusion that such a system emits 15 kg of CO_2 equivalent per kg of live weight, which is equivalent to 4.1 kg of C. Other studies carried out on beef rearing systems in Italy, but with different production intensities, have obtained similar results (4.8–7.2 kg of C per kg of live weight; Bragaglio et al., 2018), thereby leading to the conclusion that livestock is a net emitter of GHG. Even when nitrous oxide is considered in the LCA calculation of the greenhouse effect, which has not been done in the present study as it does not contain C, it is clear that LCA studies suffer from some limitations as they adopt a product-based approach. In fact, by not considering the immobilisation of material in the organic matter that occurs during the production process (e.g. by means of the addition of organic fertilisers to the soil or by the particulate fallout or bacterial fixation of atmospheric N, even for crops not specifically intended for livestock feed production), the LCA method is not able to evaluate the positive effects of an integrated production system, as it gives a partial representation of a complex reality.

Soussana et al. (2007), who accounted for GHG (CO_2, CH_4 and N_2O) in grassland sites, obtained a result, starting from their NEE and considering the N_2O and CH_4 emissions that occurred within the grassland plots and the off-site emissions of CO_2 and CH_4 produced from enteric fermentation of the herbage cut to feed the cattle, that was not significantly different from zero, and which was close to the one obtained in the present work. Kay et al. (2019), who examined the potential of suitable agroforestry systems for carbon sequestration on European farmlands, concluded that agroforestry could contribute to achieving zero-emissions from agriculture. Livestock farms, and ruminants in particular, are essential in such a scenario to preserve areas with a large C storage, such as grasslands or pastures, and soil organic matter. A mass balance, despite its limitations, which are discussed hereafter, can offer a clearer vision of the interactions that take place within a complex system, such as a livestock farm.

The sensitivity analysis has demonstrated that when certain uncertainties were incorporated into the analysis, the results did not change, and that the productive system of the Coalvi consortium always showed a positive C balance, thus confirming the ecological role of this group of farms.

Some limitations of the proposed method have emerged, and they are now discussed in detail. The first and most important limitation concerns the fact that the method does not analyse the system pertaining to the different categories of environmental impact and only highlights the flows and storage of the materials of the system. Same materials could have different environmental impacts, or different materials could have the same effect on the environment, but this does not emerge from the mass balance. However, it is possible, with the proposed method, to evaluate whether the system is depleted or enriched by a certain resource.

Moreover, the C balance adopted in this study fails to consider the previously discussed effects of climate, management and soil variables on the actual C fluxes, because the model is unable to correlate the variables and their interactions with the fluxes. The method instead provides an average evaluation, which is similar to Tier 1 or Tier 2 of the LCA method, that is useful for generic comparisons between different production choices and/or different production systems. Climatic, management and pedological forecasting models could eventually be introduced into the balance, but with reference to specific climatic areas.

The drawing up of the C balance requires that a large number of different types of raw data are collected from more or less complex production systems, but these data need to be critically evaluated, processed and correctly interpreted by multidisciplinary experts (e.g. agronomists, zootechnicians, soil scientists, agricultural engineers, etc.). In other words, the application of this assessment method is not simple, and the results could change according to the species-specific data elaboration process that is carried out to evaluate the material and energy fluxes (e.g. the precision level of information regarding the anatomical and/or physiological characteristics of the animals could be different for different animal breeds). This aspect would make a comparison between studies conducted by different research groups difficult, but this is a problem that is common to other assessment methods, such as the Life Cycle Assessment, and depends on the subjective methodological assumptions, e.g. the system boundary, the allocation method or which Tier level is adopted (1, 2 or 3).

Furthermore, the C balance is calculated by referred to a system with defined boundaries and it is not suitable for a life cycle approach study, unless the boundaries of the system are expanded and the amount of information needed is exponentially increased. In the latter case, compensatory elements would need to be introduced, which could limit the level of differentiation in a comparison among production systems. This compensation effect could be avoided if the C balance were carried out at the farm boundary. For these reasons, it should be considered that the C balance offers complementary environmental indexes that can be used to complete the information provided by other assessment methods.

The net C balance was able to show the measured or estimated C fluxes of the system, and the storage balance was able to point out the potential role of the Consortium in reducing atmospheric carbon gases during productive processes carried out over a period of one year. This calculation was certainly underestimated, as it did not consider the potential carbon accumulation in the soil. In fact, because of a lack of information, this value was cautiously assumed equal to zero, but considering the use of organic fertilisers, and the results of long-term studies on the grassland C balance of beef farms (Fornara et al., 2016), it is plausible to assume that a part of the organic C from manure added to the soil or derived from pasture management would accumulate in this site. Soussana et al. (2004) suggested that grassland management may increase C stocks in soil by 0.2–0.5 t C ha^{-1} $year^{-1}$. Therefore, it would be appropriate to detect short-term changes in the C stocks in soil by using rapid and/or new measurement methods proposed as new technologies combined with a precision agriculture approach (Zhou et al., 2023).

4.1. Practical impacts and policy implications

The results presented in this paper suggest some practical impacts and policy implications. First, the possibility of having an environmental impact assessment method which, if extended to other flows (nitrogenous, phosphoric, energetic, etc.), could increase the objectivity of technical evaluations and political choices. In the proposed approach, the mass balance allows the problem to be viewed from a different perspective from that of other assessment methods. In fact, the mass balance, by considering the farm as a whole and not just as a production process, is able to assess the real impact derived from a multi-functional production activity. It provides information on to what extent a farm is able to mitigate its environmental impacts, and, in the specific case considered here, on those related to C flows, on the GWP effect and on keeping the organic matter in the stocking site as soil. Thus, production processes, such as ruminant farming, take on a different role when they are considered in the real productive context, that is, integrated with other farm production activities.

Second, the tool allows the overall efficiency of both intensive and extensive systems to be evaluated. In the former case, it can be useful to direct choices towards what is defined as "sustainable intensification", that is, to condition choices not only on technical efficiency but also on environmental efficiency, e.g. by measuring the self-sufficiency or the role of agricultural conservation techniques. It is possible to imagine the creation of associations between zootechnical and non-zootechnical farms to exchange products or by-products such as manure for feeds, straw or other production residues to increase the sustainability and circularity of the system.

From a political point of view, it could be possible to encourage agreements between companies by means of legislative or financial instruments, subject to having a C mass balance equal to zero or negative, i.e. with C storage, to ensure that the livestock sector achieves the goal of zero emissions. Furthermore, the proposed assessment method could be used by farmers to deal with the carbon farming initiatives introduced by the EU concerning the so-called "agricultural carbon credits", because it can highlight the effect of mitigation strategies adopted to reduce C emissions or to improve its sequestration.

Moreover, considering the new Corporate Sustainability Reporting Directive, (CSRD - EU Directive 2022/2624) that entered into force on 5 January 2023, which introduced new rules that will be mandatory from 2024 onwards for companies regarding sustainability reporting, the carbon balance could be a simpler tool than other assessments methods to measure the environmental impact of companies. In this regard, Coalvi will use the results of this study to draw up their sustainability balance. The Consortium has proposed digitising the carbon balance to make it available to individual farms so that the farmers can self-assess the effect of their productive choices.

5. Conclusions

This study has used C balance data to evaluate the changes in the C stocks of the different environmental and biological components involved in the productive processes of the Coalvi consortium: soil, plants, air and animals. It was found that the examined beef production system is an important C sink, and this makes it necessary to reconsider the outcome livestock, and ruminants in particular, have on the global greenhouse effect. Indeed, livestock play a fundamental role in an integrated production system, regarding C recycling and sequestration, as cattle can be used to improve soil fertility and crop yields, produce nutrient-dense food sources for less land utilisation, and reduce the carbon dioxide released into the atmosphere.

On the basis of these preliminary results, it appears that the method is able to describe a complex and integrated system and to highlight the relationship that exists between rearing and agricultural activities in order to characterise their environmental roles. For these reasons, the method lends itself to being used as a sustainability assessment tool (to measure farm sustainability), a farm development tool (to increase sustainability), a policy making tool (to reach or improve policy objectives), and/or a communication tool (as a commercial message). However, further adaptations of the method may be necessary to achieve these goals.

In short, the case study presented in this paper represents a virtuous example in which the air C was reduced by 2.2 kg per kilogram of live weight slaughtered, although a comparison with other livestock systems will be necessary to evaluate this performance more precisely. Moreover, although these results are already informative, further studies (e.g., soil C measurements) are necessary to improve the precision of the results pertaining to the environmental role of the Consortium involved in this work. Therefore, a future development of the proposed method will include using data obtained from direct measurements instead of from databases or research activities carried out under similar conditions. However, this preliminary study will be useful to evaluate the changes in the environmental role of the Consortium in the coming years, as determined by the new markets and/or political directions that will influence the actions of the farmers and the Consortium, but also to compare different rearing systems with different levels of integration of farm activities.

The approach proposed in this paper could be extended to include other materials and/or the energy level to derive useful indexes or benchmarks that could then be used at a technical, political and/or commercial level.

Ethical approval

The study was based on a dataset obtained from the Coalvi Consortium and did not include any direct handling of animals to take measurements or samples and did not require authorisation by the University Ethical Committee.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Davide Biagini: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Marco Betta:** Investigation, Formal analysis.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

Data availability

Data will be made available on request.

Acknowledgements

We would like to thank the Consorzio di Tutela della Razza Piemontese (Coalvi), Carrù (CN), Italy, for granting authorisation to use the data of the farm members of the Consortium and in particular the agronomist Dr. Luca Varetto.

References

Abdalla, M., Saunders, M., Hastings, A., Williams, M., Smith, P., Osborne, B., Lanigan, G., Jones, M.B., 2013. Simulating the impacts of land use in Northwest Europe on Net Ecosystem Exchange (NEE): the role of arable ecosystems, grasslands and forest plantations in climate change mitigation. Sci. Total Environ. 465, 325–336. https://doi.org/10.1016/j.scitotenv.2012.12.030.

Aguggini, G., Beghelli, V., Giulio, L.F., 1997. Fisiologia degli animali domestici con elementi di etologia [Domestic Animals Physiology With Ethology Elements]. UTET, Torino.

AIA, 2023. Bollettino controlli funzionali 2022 [Functional controls bulletin 2022]. AIA, Roma. http://bollettino.aia.it/#contenuti (accessed 10 September 2023).

Amon, B., Amon, T., Boxberger, J., Alt, C., 2001. Emissions of NH_3, N_2O and CH_4 from dairy cows housed in a farmyard manure tying stall (housing, manure storage, manure spreading). Nutr. Cycl. Agroecosyst. 60, 103–113.

Anaborapi, 2022. Relazione tecnica e statistiche [Technical Report and Statistics]. Anaborapi, Carrù. https://www.anaborapi.it/index.php?option=com_content&view=category&layout=blog&id=26&Itemid=28 (accessed 10 September 2023).

APAT, 2002. Assorbimento e fissazione di carbonio nelle foreste e nei prodotti legnosi in Italia [Carbon uptake and fixation in forests and wood products in Italy], APAT Rapporti 21/2002, Roma. https://www.isprambiente.gov.it/contentfiles/00003800/3886-rapporti-02-21.pdf (accessed 10 October 2023).

APAT, 2003. Analisi dei fattori di emissione di CO_2 dal settore dei trasporti. Metodo di riferimento IPCC, modello COPERT ed analisi sperimentali [Analysis of CO_2 emission factors from the transport sector. IPCC reference method, COPERT model and experimental analyses], APAT Rapporti 28/2003, Roma. https://www.isprambiente.gov.it/contentfiles/00003900/3906-rapporti-03-28.pdf (accessed 10 October 2023).

ARPA, 2023. Il clima in Piemonte, 2022 [The climate in Piedmont, 2022], ARPA Piemonte. https://www.arpa.piemonte.it/rischinaturali/tematismi/clima/rapporti-di-analisi/annuale_pdf/anno_2022.pdf (accessed 10 October 2023).

Bert, D., Danjon, F., 2006. Carbon concentration variations in the roots, stem and crown of mature Pinus pinaster (Ait.). Forest Ecol. Manag. 222, 279–295. https://doi.org/10.1016/j.foreco.2005.10.030.

Biagini, D., 2010. Controllo dell'impatto ambientale degli allevamenti intensivi di bovini da carne [control of the environmental impact of beef cattle intensive rearing]. In: Crovetto, M., Sandrucci, A. (Eds.), Allevamento animale e riflessi ambientali [Livestock and environmental impact]. Fondazione Iniziative Zooprofilattiche e Zootecniche, Brescia, pp. 65–99.

Biagini, D., Lazzaroni, C., 2011. Male pre- and post-pubertal castration effect on liveweight, components of empty body weight, estimated nitrogen excretion and efficiency in Piemontese hypertrophic cattle. Ital. J. Anim. Sci. 10 (e16), 78–82. https://doi.org/10.4081/ijas.2011.e16.

Biagini, D., Lazzaroni, C., 2019. Cow-calf morphometric relationships and birth dystocia in Piemontese breed. Ital. J. Anim. Sci. 18 (Suppl. 1), 140–141.

Biagini, D., Lazzaroni, C., 2022. Modelling manure production in beef calves: development, evaluation, and application of a complete vs. simplified prediction model. J. Agric. Sci. Technol. 12, 84–95. https://doi.org/10.17265/2161-6256/2022.02.005.

Biagini, D., Kaijun, G., Lazzaroni, C., Zoccarato, I., 2007. Relazione finale del progetto: valutazione dell'escrezione azotata degli allevamenti zootecnici; approfondimenti per il Piemonte [Final report of the project: evaluation of nitrogen excretion from livestock farms; insights for Piedmont Region], Regione Piemonte.

Boeckx, P., Van Cleemput, O., 2001. Estimates of N_2O and CH_4 fluxes from agricultural lands in various regions in Europe. Nutr. Cycl. Agroecosyst. 60, 35–47. https://doi.org/10.1023/A:1012604032377.

Bonnin, D., Tabacco, E., Borreani, G., 2021. Variability of greenhouse gas emissions and economic performances on 10 Piedmontese beef farms in North Italy. Agric. Syst. 194, 103282 https://doi.org/10.1016/j.agsy.2021.103282.

Bragaglio, A., Napolitano, F., Pacelli, C., Pirlo, G., Sabia, E., Serrapica, F., Serrapica, M., Braghieri, A., 2018. Environmental impacts of Italian beef production: a comparison between different systems. J. Clean. Prod. 172, 4033–4043. https://doi.org/10.1016/j.jclepro.2017.03.078.

Byrne, K.A., Kiely, G., Leahy, P., 2007. Carbon sequestration determined using farm scale carbon balance and eddy covariance. Agric. Ecosyst. Environ. 121, 357–364. https://doi.org/10.1016/j.agee.2006.11.015.

Carvajal, M., 2011. Investigation into CO_2 absorption of the most representative agricultural crops of the region of Murcia. Research report. In: CSIC (Consejo Superior de Investigaciones Cientificas), Spain.

EPA, 2019. Inventory of the U.S. greenhouse gas emissions and sinks 1990–2017. U.S. Environmental Protection Agency. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2017.

ERM/AB-DLO, 2002. Estabilishment of Criteria for the Assessment of Nitrogen Content in Animal Manures. European Commission, Final Report, Bruxelles.

FAO, 2006. Livestock Long Shadow: Environmental Issues and Options. FAO, Rome.

FAO-IAEA, 2008. Guidelines for Sustainable Manure Management in Asian Livestock Production Systems. IAEA-TECDOC-1582, Vienna, Austria. https://www-pub.iaea.org/MTCD/Publications/PDF/TE_1582_web.pdf (accessed 15 October 2023).

Fornara, D.A., Wasson, E.A., Christie, P., Watson, C.J., 2016. Long-term nutrient fertilization and the carbon balance of permanent grassland: any evidence for sustainable intensification? Biogeosciences 13, 4975–4984. https://doi.org/10.5194/bg-13-4975-2016.

Hollinger, S.E., Bernacchi, C.J., Meyers, T.P., 2005. Carbon budget of mature no-till ecosystem in North Central Region of the United States. Agric. For. Meteorol. 130, 59–69. https://doi.org/10.1016/j.agrformet.2005.01.005.

Honig, A.C., Inhuber, V., Spiekers, H., Windisch, W., Gotz, K.U., Schuster, M., Ettle, T., 2022. Body composition and composition of gain of growing beef bulls fed rations with varying energy concentrations. Meat Sci. 108685 https://doi.org/10.1016/j.meatsci.2021.108685.

Iandolo, F., 2008. Le colture arboree da frutto per la mitigazione dell'effetto serra: potenzialità di uso dei residui di potatura (BSc thesis). University of Pisa, Scienze e Tecnologie per l'Ambiente.

IPCC, 2019. Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4 Agriculture, Forestry and Other Land Use. Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarizem S., Osakom, A., Pyrozhenko, Y., Shermanau, P., Federici, S. (Eds.), IPCC, Switzerland.

ISO 14067, 2018. Greenhouse Gases - Carbon Footprint of Products - Requirements and Guidelines for Quantification. International Organization for Standardization, Vernier (Geneva) Switzerland.

ISPRA, 2022. Indicatori di efficienza e decarbonizzazione del sistema energetico nazionale e del settore elettrico [Efficiency and decarbonisation indicators of the national energy system and the electricity sector]. ISPRA Rapporti 363/2022. https://www.isprambiente.gov.it/files2022/pubblicazioni/rapporti/r363-2022.pdf (accessed 15 September 2023).

ISPRA, 2023. Efficiency and decarbonization indicators in Italy and in the biggest European Countries. ISPRA Rapporti 386/2023. https://www.isprambiente.gov.it/files2023/pubblicazioni/rapporti/r386-2023.pdf (accessed 15 September 2023).

Jaksic, V., Kiely, G., Albertson, J., Oren, R., Katul, G., Leahy, P., Byrne, K.A., 2006. Net ecosystem exchange of grassland in contrasting wet and dry years. Agric. For. Meteorol. 139, 323–334. https://doi.org/10.1016/j.agrformet.2006.07.009.

Kay, S., Rega, C., Moreno, G., den Herder, M., Palma, J.H.N., Borek, R., Crous-Duran, J., Freese, D., Giannitsopoulos, M., Graves, A., Jäger, M., Lamersdorf, N., Memedemin, D., Mosquera-Losada, R., Panteran, A., Paracchini, M.L., Paris, P., Roces-Díaza, J.V., Rolo, V., Rosati, A., Sandor, M., Smith, J., Szerencsits, E., Varga, A., Viaud, V., Wawer, R., Burgess, P.J., Herzog, F., 2019. Agroforestry creates carbon sinks whilst enhancing the environment in agricultural landscapes in Europe. Land Use Policy 83, 581–593. https://doi.org/10.1016/j.landusepol.2019.02.025.

Ketelaars, J.J.M.H., Van Der Meer, H.G., 2000. Establishment of criteria for the assessment of the nitrogen content of animal manures. In: Final Report to DG XI of the European Commission, Report 14, 64 pp. + Annexes, Plant Research International, Wageningen, The Netherlands.

Kröbel, R., Bolinder, M.A., Janzen, H.H., Little, S.M., Vandenbygaart, A.J., Kättere, T., 2016. Canadian farm-level soil carbon change assessment by merging the greenhouse gas model Holos with the Introductory Carbon Balance Model (ICBM). Agric. Syst. 143, 76–85. https://doi.org/10.1016/j.agsy.2015.12.010.

Lazzaroni, C., Biagini, D., 2005. Influence of rearing system on body measurements in Piemontese young bulls. Ital. J. Anim. Sci. 4 (Suppl. 2), 287.

Lazzaroni, C., Pacher, F., 1995. La valutazione dei vitelloni da carne. Prima parte: misure in vita e sulle carcasse [Evaluation of beef bulls. First part: measurements on live animals and on carcasses]. La Razza Bovina Piemontese 26, 23–26.

Lazzaroni, C., Toscano Pagano, G., Andrione, A., Biagini, D., 2001. Body and carcass measurements in Piemontese and Belgian Blue young bulls. In: Recent Progress in Animal Production Science. University of Firenze, pp. 287–289.

Lei, N., Wang, H., Zhang, Y., Chen, T., 2022. Components of respiration and their temperature sensitivity in four reconstructed soils. Sci. Rep. 12, 6107. https://doi.org/10.1038/s41598-022-09918-y.

Lloyd, C.R., 2006. Annual carbon balance of a managed wetland meadow in the Somerset Levels, UK. Agric. For. Meteorol. 138, 168–179. https://doi.org/10.1016/j.agrformet.2006.04.005.

Luo, Y., Zhou, X., 2006. Soil Respiration and the Environment. Academic Press. https://doi.org/10.1016/B978-012088782-8/50000-0.

Ma, S., He, F., Tian, D., Zou, D., Yan, Z., Yang, Y., Zhou, T., Huang, K., Shen, H., Fang, J., 2018. Variations and determinants of carbon content in plants: a global synthesis. Biogeosciences 15, 693–702. https://doi.org/10.5194/bg-15-693-2018.

Magnani, F., Raddi, S., 2021. Afforestation and CO_2 fixation: a few reference figures from scientific research. Forest@ 18, 60–63. https://doi.org/10.3832/efor3928- 018.

Marchetti, M., Sallustio, L., Ottaviano, M., Barbati, A., Corona, P., Tognetti, R., Zavattero, L., Capotorti, G., 2012. Carbon sequestration by forests in the National Parks of Italy. Plant Biosyst. 146, 1001–1011. https://doi.org/10.1080/11263504.2012.738715.

Mathew, I., Shimelis, H., Mutema, M., Chaplota, V., 2017. What crop type for atmospheric carbon sequestration: results from a global data analysis. Agric. Ecosyst. Environ. 243, 34–46. https://doi.org/10.1016/j.agee.2017.04.008.

Misselbrook, T., Fleming, H., Camp, V., Umstatter, C., Duthie, C.A., Nicoll, L., Waterhouse, T., 2016. Automated monitoring of urination events from grazing cattle. Agric. Ecosyst. Environ. 230, 191–198. https://doi.org/10.1016/j.agee.2016.06.006.

Motloch, J., 2019. Complex systems and sustainable development. In: Leal Filho, W. (Ed.), Encyclopedia of Sustainability in Higher Education. Springer Cham.

Mudge, P.L., Wallace, D.F., Rutledge, S., Campbell, D.I., Schipper, L.A., Hosking, C.L., 2011. Carbon balance of an intensively grazed temperate pasture in two climatically contrasting years. Agric. Ecosyst. Environ. 144, 271–280. https://doi.org/10.1016/j.agee.2011.09.003.

Neri, E., Pulselli, R.M., Marchi, M., 2020. Assorbimento di CO_2 di un bambuseto gestito da Forever Bambù e coltivato in Italia [CO_2 absorption of a bamboo grove managed by Forever Bambù and cultivated in Italy]. Report INDACO (INDicatori Ambientali e CO_2). https://foreverzeroco2.it/wp-content/uploads/2022/03/Indaco-FB-REPORT-ASSORBIMENTI-BAMBU_DEF-2020-1.pdf (accessed 15 September 2023).

Nieveen, J.P., Campbell, D.I., Schipper, L.A., Blair, I.J., 2005. Carbon exchange of grazed pasture on a drained peat soil. Glob. Chang. Biol. 11, 607–618. https://doi.org/10.1111/j.1365-2486.2005.00929.x.

Novick, K.A., Stoy, P.C., Katul, G., Ellsworth, D.S., Siqueira, M.B.S., Juang, J.R., Oren, R., 2004. Carbon dioxide and water vapor exchange in a warm temperate grassland. Oecologia 138, 259–274. https://doi.org/10.1007/s00442-003-1388-z.

Oates, L.G., Randall, D.J., 2014. Livestock management strategy affects net ecosystem carbon balance of subhumid pasture. Rangel. Ecol. Manag. 67, 19–29. https://doi.org/10.2111/REM-D-12-00151.1.

Odum, H.T., 1956. Primary production in flowing waters. Limnol. Oceanogr. 1, 102–117. https://doi.org/10.4319/lo.1956.1.2.0102.

Oliveira, J.D., Madari, B.E., Carvalho, M.T.D., Assis, P.C.R., Silveira, A.L.R., Lima, M.L., Wruck, F.J., Medeiros, J.C., Machado, P.L.O.A., 2018. Integrated farming systems for improving soil carbon balance in the southern Amazon of Brazil. Reg. Environ. Chang. 18, 105–116. https://doi.org/10.1007/s10113-017-1146-0.

Pagano Toscano, G., Lazzaroni, C., Zoccarato, I., 1990. Relationships between on live and carcass measures in young bulls of different breeds. In: 41st Annual Meeting of the European Association for Animal Production, Touluse (France), 2, C.IIIA.12.

Ripple, W.J., Smith, P., Haberl, H., Montzka, S.A., McAlpine, C., Boucher, D.H., 2014. Ruminants, climate change and climate policy. Nat. Clim. Chang. 4, 2–5. https://doi.org/10.1038/nclimate2081.

Rutledge, S., Mudge, P.L., Campbell, D.I., Woodward, S.L., Goodrich, J.P., Wall, A.M., Kirschbaum, M.U.F., Schipper, L.A., 2015. Carbon balance of an intensively grazed temperate dairy pasture over four years. Agric. Ecosyst. Environ. 206, 10–20. https://doi.org/10.1016/j.agee.2015.03.011.

Schapendonk, A.H.C.M., Dijkstra, P., Groenwold, J., Pot, C.S., Van de Geijn, S.C., 1997. Carbon balance and water use efficiency of frequently cut Lolium perenne L. swards at elevated carbon dioxide. Glob. Chang. Biol. 3, 207–216. https://doi.org/10.1046/j.1365-2486.1997.00099.x.

Soussana, J.F., Loiseau, P., Vuichard, N., Ceschia, E., Balesdent, J., Chevallier, T., Arrouays, D., 2004. Carbon cycling and sequestration opportunities in temperate grasslands. Soil Use Manag. 20, 219–230. https://doi.org/10.1111/j.1475-2743.2004.tb00362.x.

Soussana, J.F., Allard, V., Pilegaard, K., Ambus, P., Ammann, C., Campbell, C., Ceschia, E., Clifton-Brown, J., Czobel, S., Domingues, R., Flechard, C., Fuhrer, J., Hensen, A., Horvath, L., Jones, M., Kasper, G., Martin, C., Nagy, Z., Neftel, A., Raschi, A., Baronti, S., Rees, R.M., Skiba, U., Stefani, P., Manca, G., Sutton, M., Tuba, Z., Valentini, R., 2007. Full accounting of the greenhouse gas (CO_2, N_2O, CH_4) budget of nine European grassland sites. Agric. Ecosyst. Environ. 121, 121–134. https://doi.org/10.1016/j.agee.2006.12.022.

Soussana, J.F., Tallec, T., Blanfort, V., 2010. Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grassland. Animal 3, 334–350. https://doi.org/10.1017/S1751731109990784.

Viglizzo, E.F., Ricard, M.F., Taboada, M.A., Vázquez-Amábile, G., 2019. Reassessing the role of grazing lands in carbon-balance estimations: Meta-analysis and review. Sci. Total Environ. 661, 531–542. https://doi.org/10.1016/j.scitotenv.2019.01.130.

Vleeshouwers, L.M., Verhagen, A., 2002. Carbon emission and sequestration by agricultural land use: a model study for Europe. Glob. Chang. Biol. 8, 519–530. https://doi.org/10.1046/j.1365-2486.2002.00485.x.

Wang, B., Smith, B., Waters, C., Feng, P., Liu, D.L., 2024a. Modelling changes in vegetation productivity and carbon balance under future climate scenarios in southeastern Australia. Sci. Total Environ. 924, 171748 https://doi.org/10.1016/j.scitotenv.2024.171748.

Wang, J., Chang, G., Liu, H., Yin, Z., Liu, P., Zhao, Y., Li, K., Gao, T., 2024b. Carbon balance analysis of agricultural production systems in oasis areas. Sci. Rep. 14, 16698. https://doi.org/10.1038/s41598-024-66972-4.

van der Werf, H.M.G., Knudsen, M.T., Cederberg, C., 2020. Toward better representation of organic agriculture in life cycle assessment. Nat. Sustain. 3, 419–425. https://doi.org/10.1038/s41893-020-0489-6.

Woodwell, G.M., Whittaker, R.H., 1968. Primary production in terrestrial communities. Am. Zool. 8, 19–30 (doi:10/1093/icb/8.1.19).

Zanotelli, D., Vendrame, N., López-Bernal, A., Caruso, G., 2018. Carbon sequestration in orchards and vineyards. Italus Hortus 25, 13–28. https://doi.org/10.26353/j.itahort/2018.3.1328.

Zhou, T., Jia, C., Zhang, K., Yang, L., Zhang, D., Cui, T., He, X., 2023. A rapid detection method for soil organic matter using a carbon dioxide sensor in situ. Measurement 208, 112471. https://doi.org/10.1016/j.measurement.2023.112471.