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Review article

Climate change: Production performance, health issues, greenhouse gas emissions and mitigation strategies in sheep and goat farming☆

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ABSTRACT

Climate change is transforming the planet's ecosystem and threatening the well-being of current and future generations. The livestock sector plays an important role in climate change contributing with a significant share to the anthropogenic greenhouses gases (GHG) emissions. In particular, small ruminant farming plays a crucial socio-economic role in many countries and there is strong interest in measuring and improving environmental performance and production. This review provides an integrated overview on the effect of climate change on small ruminant production and health. Measurement and prediction of sheep and goat emissions and opportunities to mitigate GHG emissions from small ruminants are also discussed. The relationships among climate change, small ruminant production and health and GHG emissions are highlighted using the system thinking of analysis.

1. Introduction

Climate change represents one of the greatest threats faced by our planet, its population and economies (Skuce et al., 2013). The rate of change in climate is faster now than in any period in the last 1000 years. According to the forecast of the International Panel of Climate Change (IPCC) in the next 90 years the average global temperatures will increase between 1.8 °C and 4.0 °C (Yatoo et al., 2012). This change will have a direct and indirect impact on livestock farming systems as well as on human and animal health. The impact of climate change on animal health is not covered in the IPCC report but – as is the case for human well-being – it is potentially devastating, especially regarding zoonotic infectious and parasitic diseases caused by viruses, bacteria, protozoa, helminths and arthropod vectors.

The small ruminant sector is of worldwide importance, sheeps and goats represent 56% of global ruminant domestic population with 1178 million of sheeps and 1000 million of goats on the total of 3.872 million heads (FAOSTAT, 2013). The global sheep numbers are expected to increase 60% by 2050 (Foresight, 2011). In 2013, the world flock of sheeps and goats produced more than 13 million tons of meat and 28 million tons of milk, showing an increase of 1.7 and 1.3% per year, respectively, during the past 20 years (FAOSTAT, 2013). About 56 percent of the world's small ruminants are located in arid zones and 27 percent and 21 percent in the temperate and humid zones, respectively. Small ruminant farming plays a crucial socio-economic role contributing to the management of landscapes and preserved ecosystems to the conservation of biodiversity, and to provide niche products on the market. Therefore, regarding on small ruminant sector there is strong interest in measuring and improving environmental performance.

With emissions estimated at 7.1 Gt/year of CO_2-eq representing 14.5% of human-induced GHG emissions, the livestock sector plays an important role in climate change (Gerber et al., 2013). The small ruminant sector is of worldwide importance, sheeps and goats represent 56% of global ruminant domestic population with 1178 million of sheeps and 1000 million of goats on the total of 3.872 million heads (FAOSTAT, 2013). The global sheep numbers are expected to increase 60% by 2050 (Foresight, 2011). In 2013, the world flocks of sheep and goats produced more than 13 million tons of meat and 28 million tons of milk, showing an increase of 1.7 and 1.3% per year, respectively, during the past 20 years (FAOSTAT,

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2013). About 56% of the world's small ruminants are located in arid zones and 27% and 21% in the temperate and humid zones, respectively. With emissions estimated at 7.1 Gt/year of CO_2-eq, representing 14.5% of human-induced GHG emissions, the livestock sector plays an important role in climate change (Gerber et al., 2013). Small ruminants contribute for about 6.5%, corresponding to 475 million tons CO_2eq, of which 299 million tons are allocated to meat production and 130 million tons to milk. However, estimates of small ruminant GHG emissions are often based on different methods or assumptions, difficult to compare, and not easy to obtain in practice due to a lack of data, especially for the dairy sector.

A detailed understanding on the contribution of sheep and goat farming to greenhouse gas emissions and on the effects of climate change on small ruminant production and health is useful for sector's stakeholders in order to strengthen existing knowledge and to avoid oversimplifications.

This review aimed to provide a broad, integrated overview on: (i) measurement and prediction of sheep and goat emission; (ii) source of variation and opportunities to mitigate GHG emissions from small ruminant; (iii) perspective of the effects of climate change on small ruminant production and health.

2. Small ruminant greenhouse gas emissions

Small ruminants GHG emissions are mainly related to methane (CH_4) from both enteric fermentation and manure management while regarding the nitrous oxide (N_2O) seems to depend only from manure management (Opio et al., 2013). The percentage of each category of emission from global emissions for small ruminant productions is shown in Fig. 1. Over 55% of emissions from small ruminant milk and meat production were attributed to enteric fermentations and about 35% to feed production, whereas emissions from manure were very low because excreta are deposited on pasture (Gerber et al., 2013).

The total emission flow of the entire production process can be estimated by the Life Cycle Assessment (LCA) approach. LCA considers the life of a product or process starting from the raw materials used ("from cradle") continuing with the production system, transport, distribution, use or consumption, eventual reuse and its final disposal ("to grave"). Standard methodology and guidelines for quantifying greenhouse gas (GHG) emissions and fossil fuel demand from sheep and goat supply chains covering the system boundary of the cradle-to-primary-processing-gate were recently developed by the Livestock Environmental Assessment and Performance (LEAP) Partnership (LEAP, 2014).

A schematic representation of sheep farming systems aimed to estimate the emissions of lamb production following LCA principles was reported by Jones et al. (2014) and is shown in Fig. 2. The carbon footprints accounted for all major sources of CH4, N_2O and CO2 gases emissions, encompassing both on farm and off-farm emissions. On-farm emissions directly occur on farm (e.g., animal emissions, fuel combustion for crop cultivation on farm), while off farm emissions can be attributed to the farm, but occur elsewhere (emissions related to the purchased feeds or other inputs).

As reported by Chianese et al. (2009), the carbon footprint estimation can also include emissions resulting from land use change mainly based on the long term variation in carbon soil stocks due to changes in land destination or crop type.

According to the LCA approach, FAO published a detailed report of the animal emissions on a global scale (Opio et al., 2013), from this report is possible to deduce an overview of the small ruminants sharing of global warming. Small ruminants contribute for about 6.5%, corresponding to 475 million tons CO_2eq, of which 299 million tons are allocated to meat production and 130 million tons to milk as shown in Table 1. Small ruminants not only produce edible products, but also important non-edible products (natural fiber) including wool, cashmere and mohair. Globally, 45 million tons CO2-eq are allocated to fiber production; in regions where natural fiber production is important and has high economic value, a substantial share of emissions can be attributed to these products, reducing the share of emissions attributed to milk and meat production (Gerber et al., 2013).

World emissions attributed to milk production are quantitatively similar for sheeps and goats, whereas emissions from meat production are much higher for sheeps than goats. However, considering the emission intensity in terms of CO_2eq. emitted per kg of small ruminant product, sheep milk reaches higher values than goats (8.4 vs 5.4) due to their lower production levels and the higher milk solid content (Opio et al., 2013). It is worth to note that global average of the carbon footprint for milk production for small ruminants is more than double compared to cattle and buffalo milk production (6.5 vs 2.8 and 3.4CO_2eq. emitted per kg of milk, respectively) while small ruminant meat has a lower carbon footprint than cattle and buffalo meat (23.8 vs 46.2 and 53.4 kg of CO_2eq./kg of carcass weight, Opio et al., 2013). These differences are mainly due to: (i) higher production levels for dairy cattle rather than for small ruminants; (ii) higher fecundity, reproduction cycles and average growth rates in small ruminants meat production than in beef cattle.

Several differences were observed by FAO (Opio et al., 2013) among geographical regions, agro ecological zones (classified by climate) and grassland or mixed based production systems. In particular, emission intensities for sheep and goat milk production ranged from 1.6 kg of CO_2eq. to 14.2 kg of CO_2eq. (in humid grassland areas of West Europe and in arid grassland areas of North Africa respectively), while, emission intensities for lamb and goat meat production ranged from 7.4 kg of CO_2eq. to 57.5 kg of CO2eq. (in mixed areas of West Europe and in temperate grassland areas of North Africa, respectively). The range of reported values is the threshold of the lowest and the highest 10% of world values. Emission attributed to milk production is higher in developing countries like Africa and Asia mainly due to poorer production conditions and livestock system oriented to human subsistence, whereas emission intensities is lower in industrialized countries due to specialization of production.

3. Prediction of sheep and goat emissions

The choice of the GHG estimation method depends on emission source, on experiment purposes, on estimation accuracy level and on the availability of economic resources (Bhatta et al., 2007). Direct measurements are not always feasible, especially when estimations are referred to big areas like regions, countries or even continents. Indirect methods are preferred for large areas inventories, equations and mathematical models allow estimating GHGs emissions when a great amount of animals and farms are considered (Storm et al., 2012).

The IPCC guidelines (IPCC, 2006) are the considered standard of emission estimation for each productions sector. The IPCC method presents three level of analysis called Tier 1, Tier 2 and Tier 3, the choice of the Tier depends on the availability of the information that are requested for the calculations, and on the dimension of the considered system. Estimations referred to big areas such as continents and nations are generally realized by the application of Tier 1 and Tier 2, whereas, Tier 3, is often applied on restricted areas or even on single elements, such as industries or farms. Considering that the high variability exists in small ruminants production systems (due to breeds, specialization, geographic and environmental conditions, available feeds, management, etc.) a simple approach

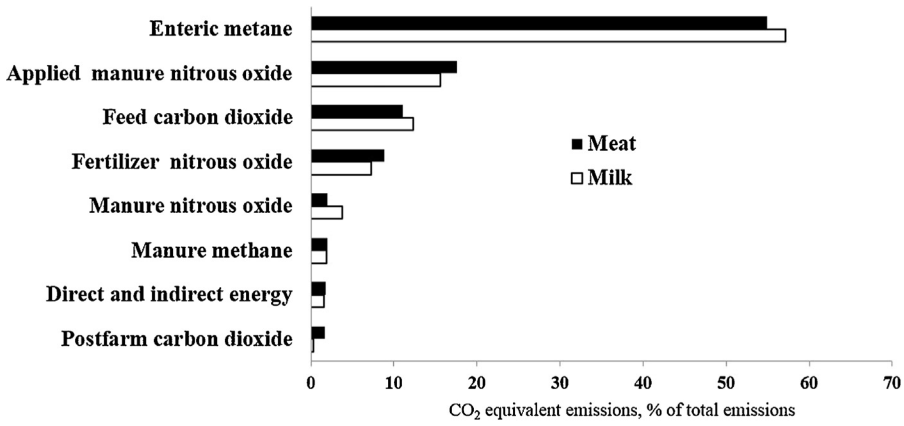

Fig. 1. Global emissions for small ruminant milk and meat production, percentage of each emissions category.

(source Gerber et al., 2013)

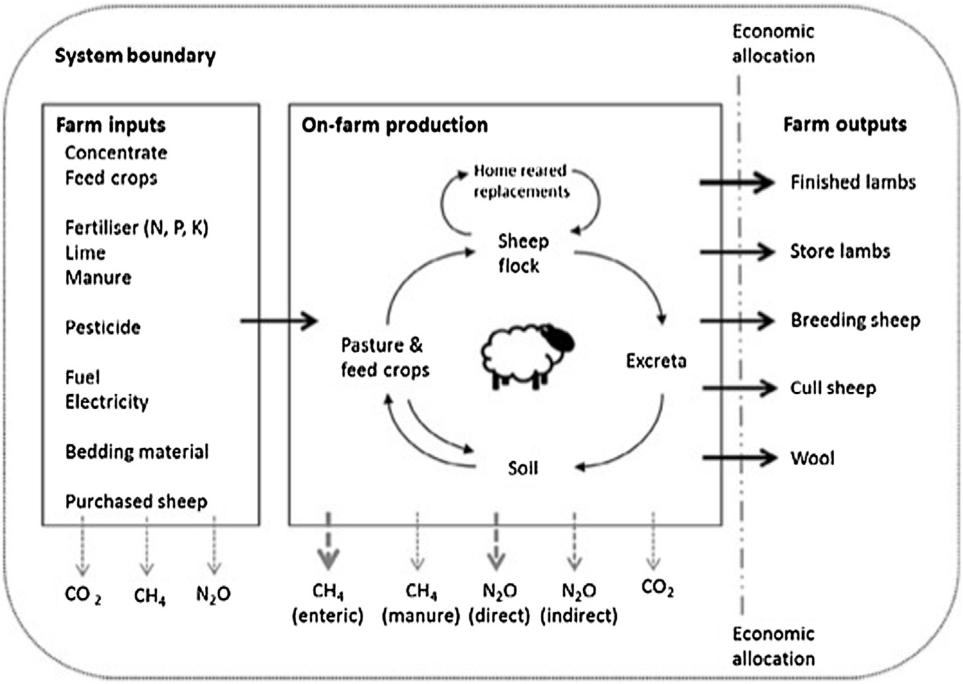

Fig. 2. Schematic representation of sheep farming systems.

(source Jones et al., 2014)

Table 1
Milk and meat production (x year) from small ruminants and their CO_2 equivalent emissions.

Species	Production		Emissions of CO_2 eq.			
	Milk	Meat	Milk	Meat	Milk	Meat
UM	Million tons		Million tons		kg/kg of product	
Sheep	8	7.8	67.4	186.9	8.4	24.4
Goats	11.9	4.8	62.4	112.5	5.2	23.5
Total	20	12.6	129.8	299.2	6.5	23.8

(source Opio et al., 2013)

like the TIER 1 should be adequate for initial estimations in most countries (Zervas and Tsiplakou, 2012). A large methane emission inventory, based on a detailed TIER 3 approach, was carried out by Vermorel et al. (2008) for French livestock. They found that values of methane emission suggested by the IPCC Tier 1 for sheep (8 kg/year per head) are lower and different than those obtained using a more detailed approach which shows high variability (ranging from 0.8 to 14.4 and 14.7 kg/year for lamb with high concentrate diets, lactating sheep and male sheep, respectively). Considering the level of details pursued in this inventory and similarities among breeds and production systems, the values of Vermorel et al. (2008) might be considered more reliable than the values suggested by TIER 1 in order to provide estimations in the Western Europe and Mediterranean production conditions for sheeps and goats. Following the example of Vermorel, an emission inventory for the Italian sheep sector was recently performed by Atzori et al. (2013a). In this study the estimation considered the population profile of Italian sheep population accounting for differences at regional level of: consistency, incidence of milk and/or meat production specialization, morphological and productive characteristics of raised sheep breeds, livestock systems and dietary factors. The inventory confirmed the values of Vermorel regarding enteric emissions of methane per ewes.

A summary of the published studies with carbon footprint estimates for sheeps and goats and the methodology used is reported in Table 2. More studies have been carried out on sheep meat whereas a limited number of studies quantified emissions of dairy sheep and very few researches (e.g., Robertson et al., 2015) have been carried out to estimated GHG emissions from goat productions. However, the results obtained in different studies are hardly comparable because of differences in system boundaries, used methods, functional units, allocation criteria and number of surveyed farms.

4. Mitigation strategies

Previous studies (Kumar et al., 2014; Knapp et al., 2014) highlighted many opportunities for reducing enteric methane and other greenhouse gas emissions in ruminants. Mitigation strategies can be classified into 3 broad categories: (1) options related to nutrition, feed supplements and feed/feeding management (for CH_4 only); (2) options for rumen control and modifiers; (3) animal breed selection and intensiveness of production. The first two mitigation options include strategies that directly or indirectly affect the ruminal metabolism. However, not all of these options have practical interest because of the high costs or inconsistent effects.

4.1. Feeding strategies

As for the feeding management, all measures that increase feed efficiency and animal performance are generally associated to lowered CH_4 emissions (Hegarty, 1999). Feeding strategies that increase voluntary feed intake and limit ruminal fermentation, such as the utilization of less ruminally degradable starch, are likely to increase the extent of post-ruminal digestion and decrease CH_4 emissions. A high proportion of concentrates in the diet or the use of maize silage as main forage, decrease ruminal pH and improves propionate production in the rumen (Patra, 2012). This shift in metabolic hydrogen sink reduces the amount of CH_4 produced (Ungerfeld, 2015). The choice of a particular forage type can affect CH_4 ruminal production as well. For instance, forages of the Fabaceae family, and especially, warm climate species may be characterized by low CH_4 ruminal emissions, when compared to grasses (Archimède et al., 2011). This appears to be related to their high content in condensed tannins, known to inhibit methanogenesis, and the high ruminal digestibility (Bhatta et al., 2009; Patra, 2012). As regards to feed supplements, lipids are effective in inhibiting the growth of both methanogens and protozoa. Vegetable oils rich in medium chain fatty acids, such as coconut oil for instance, are known to decrease rumen methanogenesis (Dohme et al., 2000). High levels of dietary unsaturated lipids usually decrease CH_4 emissions because of the reduced dry matter degradability and the ruminal hydrogenation of fatty acids, which act as hydrogen sink (Johnson and Johnson, 1995).

Among the plant secondary constituents, saponins, tannins and essential oils are the most promising compounds for their CH_4 mitigation potentials. Besides their direct influence on methanogens, they have an anti-protozoal effect and decrease rumen degradability (Patra and Saxena, 2009, 2010). However, their efficacy in vivo is not conclusively confirmed and results can be affected by the basal diet and the chemical composition of the extracts, which may substantially vary according to harvesting season and phenological stage of the plant (Patra and Saxena, 2010). Major components of essential oils are terpenes and terpenoids (20–70%) and phenylpropanoids, which determine their activity addressed mainly against Gram-positive bacteria (Bakkali et al., 2008) and methanogenic archaea. However, most promising CH_4 inhibitors (*Origanum vulgare, Thymus vulgaris, Eucalyptus globulus, Cinnamomum zeylanicum, Anethum graveolens* and *Menta piperita*) (Patra et al., 2010; Evans and Martin 2000) can decrease ruminal digestibility as a side effect of their antimicrobial activity (Cobellis et al., 2015).

4.2. Rumen modifiers

A number of rumen modifiers have been proposed and tested in the past decade.

a) Ionophores antibiotics such as monensin are not common in commercial small ruminant production but their effect on rumen metabolism (increased acetate-to-propionate ratio and decreased CH_4 production) is well known (Tomkins et al., 2015). Nevertheless, the inhibition of methanogenesis seems not to persist over time (Bell et al., 2015) and the use of antibiotics as feed additives, being a public health concern, has been banned in the EU since 2006.
b) The use of yeast feed additives, *Saccharomyces cerevisiae* in particular, is widespread in most ruminant species for the long-known beneficial effect on digestion and animal performance (Nagpal et al., 2015). However, their efficacy in decreasing CH_4 production by ruminal microbial population is still uncertain and most data were obtained under in vitro conditions.
c) Finally, various chemicals have been proposed as feed additives for their anti-methanogenic activity but again, due to public concerns over the use of synthetic molecules in livestock production, it is unlikely that this research field will be pursued in the future. A number of alternative strategies, such as the use of methylotrophs or bacteriophages, are theoretically usable but further studies are needed to confirm their validity under field conditions (Patra, 2012; Poulsen et al., 2013). Promising results were recently obtained with vaccines against methanogens (Subharat et al., 2015).

In conclusion, more research is needed to deepen the understanding of the relationships between the ruminal ecosystem and the mitigation options proposed. A sustainable decrease of CH_4 production is likely to be obtained only by the combined use of several feeding strategies, according to animal species, basal diet and costs of the proposed supplements.

4.3. Rearing system and animal breed selection

Intensive rearing system is generally advocated to mitigate GHG intensification consider the use of selected breeds, with enhanced productivity, associated with significant reductions in CH_4 emissions, related to larger use of concentrates rather than forages (Steinfeld and Gerber, 2010). On the contrary, especially in Mediterranean areas, sheep and goat farming systems are characterized by extensive rearing system linked to natural and semi-natural areas through grazing or shrubs, forest pasture and alpine grasslands. It is known that extensive system contribute to biodiversity preservation, management of renewable natural sources, conservation of cultural landscapes to the socio-economic viability of many rural areas, especially in marginal areas or less favored areas. This important function of small ruminant farming system is often neglected when comparing emissions of greenhouse gases among different rearing systems. In a recent study, Ripoll-Bosch et al. (2013) evaluated greenhouse gases emissions of three contrast-

Table 2
Summary of the carbonfootprint of small ruminants from published studies in different countries (LEAP, 2014 modified).

Reference	Country	Animal category	Data source	System boundary	Functional unit (FU)	Enteric methane	Allocation method	Carbon footprint (kg CO2-eq/FU)
Peters et al. (2010)	Australia	Lamb	1 Case farm	Farm gate	1 kg CW	Tier 2	Mass	10.2–10.8
Eady et al. (2012)	Australia	Lamb	1 Case farm	Farm gate	1 kg CW	Tier 2	System expansion	12.6
EBLEX (2012)	England	Lamb	57 Case farm	Farm gate	1 kg LW	Tier 2	Economic	6–20
Gac et al. (2012)	France	Lamb	Survey 104 farms	Farm gate	1 kg LW	Tier 1	Mass	12.9
Benoit and Dakpo (2012)	France	Lamb	Survey 1180 farms	Farm gate	1 kg CW	Tier 1-2	Mass	15–82
Ledgard et al. (2011)	New Zealand	Lamb	Survey 437 farms	Farm gate	1 kg CW	Tier 2	Biophysical, economic	19
Ripoll-Bosch et al. (2013)	Spain	Lamb	3 Systems	Farm gate	1 kg LW	Tier 2	Economic	19–26
Wallman et al. (2012)	Sweden	Lamb	10 Case farm	To retail	1 kg CW	Tier 2	Mass/economic	16
Williams et al. (2008)	UK	Lamb	Uk model	To retail	1 kg CW	Tier 2	Economic	14.1
Edwards-Jones et al. (2009)	Wales	Lamb	2 Case farm	To grave	1 kg LW	Tier 1	Economic	8–144
Jones et al. (2014)	UK	Lamb	Lowland-27 farms	Farm gate	1 kg LW	Tier 1	Economic	5.4–21.5
	UK	Lamb	Upland-12 farms	Farm gate	1 kg LW	Tier 1	Economic	8.3–18.3
	UK	Lamb	Hill-21 farms	Farm gate	1 kg LW	Tier 1	Economic	8.8–33.3
Biswas et al. (2010)	Australia	Meat sheep	3 Systems	Farm gate	1 kg LW	Tier 2	Economic	5.45
	Australia	Meat sheep	3 Systems	Farm gate	1 kg wool	Tier 2	Economic	6.58–16.59
Harrison et al. (2014)	Australia	Lamb	3 Fecundity rates	Farm gate	1 kg LW	Tier 3	No allocation	7.2–9.3
Bell et al. (2012)	Australia	Lamb	Model of actual and future scenario	Farm gate	1 kg LW	Tier 2	Biophysical	10.1–21.7
Vagnoni et al. (2015)	Italy	Dairy sheep	3 Systems	Farm gate	1 kg FPCM	Tier 1	Economic	2.0–2.3
Atzori et al. (2013a)	Italy	Dairy sheep	1 Case farm	Farm gate	1 kg CW	Tier 2	Economic	16.13
	Italy	Dairy sheep	1 Case farm	Farm gate	1 kg FPCM	Tier 2	Economic	2.27
Atzori et al. (2013b)	Italy	Dairy sheep	4 Simulated scenario	Farm gate	1 kg FPCM	Tier 3	No allocation	2.45–3.16
Batalla et al. (2014)	Spain	Dairy Sheep	Survey 12 farm	Farm gate	1 kg of ECM	Tier 3	Economic	23.35–5.35
Robertson et al. (2015)	New Zealand	Dairy goat	5 Case farm	Farm gate	1 kg of FPCM	Tier 3	Economic	0.81–1.03

Methodologies used; CW—carcass weight; Lw—Live weight; FPCM—fat and protein corrected milk; ECM—energy corrected milk.

ing meat-sheep farming systems in Spain, which differed in their degree of intensification (reproduction rate, land use and grazing management: pasture based, mixed, zero grazing). Results of this study showed that GHGs emissions varied from 39.0–51.7 kg CO_2-eq per kg of lamb meat, with highest values referring to the pasture based livestock system. On the contrary, the same authors highlight that when accounting for multifunctionality (including the cultural ecosystems services), GHGs emission per kg of lamb live weight among the sheep farming systems was reversed: with lowest values for the pasture-based system and highest for zero-grazing system (13.9 kg CO_2-eq vs 19.5 kg CO_2-eq per kg of lamb live weight). Therefore, as claimed by the authors of this study, a comparison of GHGs emissions among different farming system should account for the multifunctionality of pasture-based livestock systems. Similar results were reported by Vagnoni et al. (2015) in a study on environmental performance of dairy sheep production systems at different input levels. Results show that input/output values reflect the differences between the three productive systems: low input showed the lowest values for all the impact categories while high input farms showed the highest.

Genetic could be used to reduce emissions per kg product by improving productivity and feed efficiency, reducing wastage at flock level (e.g., premature losses, poor fertility and health), reducing emission through direct selection if or when individual animal emission can be measured or accurately predicted (Lambe et al., 2014). Differences between individual animals in plant selection during grazing, rumen digestion retention rate, and host-microbe interactions may be heritable and this amenable to genetic selection for animal with less enteric CH_4 emission per-day or per DMI basis (Knapp et al., 2014). The high individual variability in CH_4 measurements and the poor repeatability of the data obtained, could limit the selection schemes based on this. Anyway widespread consensus exists that increasing the productivity of an animal will decrease the proportion of CH_4 per unit of product. The Environmental Protection Agency has stated that "*Improving livestock productivity, so that less CH_4 is emitted per unit of product, is the most promising and cost-effective technique for reduce emission*" (EPA, 2005). Production efficiency can be improved by genetic selection and management practices but it is important to evaluate this aspect in terms of herd-productivity basis and not only examined on an individual animal. The classical breeding selection methods can allow ameliorating milk or meat yield per sheep for example selection for residual feed intake or residual solid production but could dilutes the maintenance energy cost and increase gross energy efficiency (Knapp et al., 2014). To date there are numerous molecular biology methods and molecular markers to study genome diversity in sheep and in microbioma. The availability of high throughput sequencing tools offer the opportunity to deeply investigate animal genome and transcriptome, describing more in details the variable structure of genotype among animals of the same species. The biological basis of the novel traits and of nutritional and hygienic quality of milk and meat are investigated at a molecular, cellular and genome levels, including microbiota evaluation. The availability of the Illumina OvineBead Chip, containing more than 50 K SNPs allows scientist to practice association studies between the markers and phenotype, but moreover this tool could be used to predict the breeding value of selection candidates based on linkage disequilibrium between markers and the polymorphisms that cause variation in important traits. GHG emissions are very difficult to directly measure accurately on a large number of animals, especially in an extensive grazing environment, therefore models incorporating information from predictor traits are increasingly used to estimate GHG emissions (Lambe et al., 2014). A set of biomarkers already considered in literature as indexes of feed and metabolic efficiency can be used ad indirect measures (e.g., beta hydroxybutyrate and urea in plasma and milk, purine derivatives, in plasma and urine), but they also have to be taken judiciously and a genetic nucleus could be the right solution in animal like sheep and goats using a multi-trait genetic selection index to improve sustainability and profitability combining growth, carcass, maternal characteristics. Other biomarkers for stress response and animal efficiency can also be considered, according to new information published in the literature. The description of the new phenotypes is completed with productive data, as milk yield, milk quality and hygiene, body condition score. Many researchers in many countries are involved in projects, mostly in the cow, to investigate novel phenotype to indirect measure CH4 or different methods to measure directly the phenotype associated with this trait. Pinares-Patiño et al. (2013) studied the heritability of methane emission from sheep. They showed that g CH_4 per day and g CH_4 per unit of ingested feed (expressed in kg) are both heritable and repeatable traits. Even though variation in intake has accounted for a significant fraction of the phenotypic and genetic variation in CH_4 emissions, there remains a component that is independent of intake and offers hope for genetic selection as potential option to reduce emissions.

5. Climate changes and small ruminants production and health

Climate change affects sheep and goat production and the ruminants' health in different ways. In particular, this occurs through: (a) the impact of changes in small ruminants' pasture availability; (b) the impacts on pastures and forage crop production and quality; (c) changes in the distribution of diseases and pests; and (d) the direct effects of weather and extreme events on health, growth, production and reproduction parameters (Sejian et al., 2013).

5.1. Small ruminant production

Therefore due to climate change, numerous stresses, other than the heat stress, can counteract sheep and goat farming with severe consequences on their production. Both the quantity and the quality of the available pastures are affected during extreme environmental conditions, consequently, animals have to graze for long distances in search of pastures. If the animals are exposed to more than one stress at the same time, the summated effects of the different stressors might prove detrimental to these animals. The animal's body reserves are not sufficient to effectively counter multiple environmental stressors (Sejian et al., 2013). The main changes caused by heat stress in small ruminants are depression in feed intake efficiency and utilization; disturbances in the metabolism of water and protein; alteration in energy, mineral balances, enzymatic reactions, hormonal secretions and blood metabolites (Marai et al., 2007). Even if sheeps and goats are considered to be among the most heat tolerant species, the above mentioned changes result in the impairment of production and reproduction performance. A summary of the published studies on the effects of high temperature on yield and quality of ewes and goats milk is reported in Table 3. Heat stress condition can negatively affect milk yield both in ewes and goats. The extent of milk production decline observed seems to be quite different among breeds of sheep (Finocchiaro et al., 2005). Exposure to high temperature seems to have a great effect on yield of fat and casein in milk of several breeds of sheeps and goats. High temperature has deleterious effects on coagulating properties of sheep milk. Deteriorated coagulating behavior of milk from sheeps exposed to high temperature is primarily due to the use of fat and nitrogen reserves to supply energy through gluconeogenesis at the expense of the mammary gland and to increased milk pH, due to high amounts of CO2 dissi-pated via the panting (Amaral-Phillips et al., 1993). The plasma mineral unbalance, especially caused by a reduction in sodium, potassium, calcium and phosphorus and to an increase in chloride concentrations also contributes to the worsening of milk coagulating ability (Kume et al., 1987).

Exposure to high ambient temperatures has also a detrimental impact on milk nutritional properties. Sevi et al. (2002b), found that the exposition to direct solar radiation led to a reduction of the levels of unsaturated fatty acids and to an increase of saturated fatty acids. In particular, the authors observed an increase of short chain and saturated fatty acids and a decreased contents of oleic, linoleic and linolenic acids. Reduced energy availability for galactopoiesis may have a detrimental effect on the synthesis and assembly of milk long-chain lipids because the lengthening of the fatty acid chain requires great amounts of energy to synthesize NADPH in the mammary tissue from glucose oxidation (Kaufmann and Hagemeister, 1987). Milk from sheep exposed to high temperature resulted in increased concentrations of neutrophils leucocytes and to an increase in capillary permeability resulting in an increase of lypolitic and proteolytic enzyme into milk (Sevi and Caroprese, 2012). It is known that milk is an important source of vaccenic acid, which is an intermediate of rumen biohydrogenation of linoleic and linolenic acid, and is converted to rumenic acid, the major isomer of total conjugated linoleic acid (CLA) by Δ^9 desaturase in the mammary gland. Both vaccenic and rumenic acids are considered heath promoting fatty acids (McGuire and McGuire, 2000). In ewe milk, Nudda et al. (2005) observed a reduction of these fatty acids with the advancement of lactation with the lowest values recorded in hot summer.

However, several studies (Sevi et al., 2001, 2003; Sevi and Caroprese 2012; Caroprese et al., 2011; Todaro et al., 2015) highlighted that adequate management (e.g., proper ventilation regime, provision of shade, shift the time of feeding to afternoon) and nutritional strategies (e.g., whole flaxseed supplementation) are able to reduce the negative effects of thermal stress on sheep and goat milk production and can also improve small ruminants immunological functions and udder health.

Related to meat production, Nardone et al. (2010) reported a remarkable reduction in body weight and wither height in different sheep and goat breeds from European, Asian and African Mediterranean area suggesting that with global warming there be a risk of reduction in average carcass weight in ruminants. Kadim et al. (2004) found negative effects of the hot season on the organoleptic characteristics of cattle meat.

5.2. Small ruminant health

From a health point of view, it is noteworthy that the distribution and expression of many livestock infections/diseases are known to be climate dependent. Climate change has well documented effects on the life cycle and geographical distribution of insects and ticks and, therefore, on arthropod-borne infections (mainly virus, bacteria and protozoa). That climate change will affect vector-borne diseases is widely recognized, especially because arthropods are ectothermal and the extrinsic incubation of pathogens is widely temperature dependent (Medlock and Leach, 2015). Then, biological restrictions that limit the survival of the infective agent(s) in the vector population also determine the limits for disease transmission (Martin et al., 2008). A relevant example is the widespread emergence of the Schmallenberg virus (SBV) (Medlock and Leach, 2015). SBV is a novel *Orthobunyavirus*, a member of the Simbu serogroup, closely related to Akabane and Shamonda viruses; during 2011 and 2012, SBV spread widely

Table 3
Summary of the effects of high temperature on yield, nutritional and technological quality of ewes and goat milk.

Effects	Assumption(s)	References
Reduced milk yield	Reduced feed intake; greater energy waste for thermoregolatory purpose	Hamzaoui et al. (2012); Salama et al. (2014); Peana et al. (2007); Sevi et al. (2001, 2003)
Reduced total protein content	Amino acids utilisation for glyconeogenesis; reduced uptake and secretory ability by the mammamy gland epitelium	Sevi et al. (2001, 2002a); Hamzaoui et al. (2012)
Reduced casein content	Reduced amount of phosphorylation fractions due to reduced P availability	Sevi et al. (2002a, 2003)
Reduced fat content	Utilisaton of fat body reserve for energy purpose	Sevi et al. (2001, 2002a); Hamzaoui et al. (2012)
Worsening of milk coagulating ability	Use of fat and nitrogen reserves to supply energy through gluconeogenesis at the expense of the mammary gland; plasma mineral unbalance	Albenzio et al. (2005); Todaro et al. (2014)
Increase of saturated fatty acids and decrease of oleic, rumenic, vaccenic, linoleic and linolenic acids	Reduced energy availability for galactopoiesisi; increase of lypolitic and proteolytic enzyme into milk	Sevi et al. (2002b); Caroprese et al. (2011); Nudda et al. (2005)

in cattle, sheep and goat populations over large parts of North-Western Europe (Garigliany et al., 2012; Lievaart-Peterson et al., 2012; Bessell et al., 2014), including Belgium, Denmark, Germany, France, Italy, Luxembourg, the Netherlands, Spain and the United Kingdom. The disease has re-emerged, at least in France, Germany and the United Kingdom during the vector-active season in 2012 and recently spread to Austria, Finland, Poland, Switzerland and Sweden (Conraths et al., 2013). Clinical signs are characterized by pyrexia, reduced milk production, abortions and congenital malformations among offspring whose mothers are infected during a particular period of pregnancy (Doceul et al., 2013). SBV genetic material has been detected in different species of *Culicoides* biting midges (*Culicoides obsoletus*, *C. obsoletus* complex, *Culicoides dewulfi*, *Culicoides chiopterus, Culicoides pulicaris, Culicoides sonorensis*). This strongly suggests the role of these midge species in the transmission of the SBV (Rasmussen et al., 2012; Veronesi et al., 2013; Koenraadt et al., 2014). The reliance on midge vectors for disease transmission means that disease spread is limited seasonally by the duration of the adult vector season (Bessell et al., 2014). A relevant characteristic observed in *Culicoides*, in particular in *C. sonorensis*, is the "leaky gut phenomenon" which results in higher infection rates at higher temperatures. This phenomenon indicates that successful dissemination and transmission of a virus is temperature-dependent (Koenraadt et al., 2014). In recent years, studies have been carried out to assess the ability of other arthropods, such as mosquitoes, to act as vectors for the transmission of SBV. However, the role of mosquitoes in SBV transmission has not been demonstrated so far (Manley et al., 2015). Knowledge of the ecology of the vector species is important in predicting the likelihood of the virus continuing to circulate. A recent study modeled the likely impacts of SBV following introduction into Scotland, a country that saw only sporadic case of SBV during 2012 and 2013 (Bessell et al., 2014). The study found that the ability of the virus to spread within Scotland is highly sensitive to the temperature as it determines the incubation within the vector. Moreover, the capability of *Culicoides* species to overwinter and serve as reservoir for new infections during the next year is of relevance to the transmission of SBV. Unfortunately, given factor such as climate change, SBV is unlikely to be the last 'exotic' vector- borne disease to affect European livestock (Tarlinton et al., 2012). The 21st century has been characterized, in fact, by the outbreaks, across the Europe, of several vector-borne diseases, such as Bluetongue, Lyme disease, Chikungunya virus, West Nile virus, tick-borne encephalitis, Crimean-Congo hemorrhagic fever viruses, etc. (Medlock and Leach, 2015).

The examples above reported evidenced that the impact of climate change appears to be more pronounced for vector-borne diseases, while less attention has been given so far to the effects of climate changes on helminth infections, as those caused by gastrointestinal nematodes (GIN) and liver flukes (Rinaldi et al., 2015a,b,c). These parasitic infections remain one of the main constraint on health and productivity in sheep farms worldwide (Rinaldi et al., 2015c). Also, some of these parasitic species may also provoke high mortality rates, particularly in young animals. Different species of GIN (e.g., *Haemonchus contortus*) and liver flukes (e.g., *Fasciola hepatica*) are highly prevalent in sheep farms in Europe (Rinaldi et al., 2015c). The distribution and abundance of livestock helminths has been shifting and increasing in temperate regions, with climate change implicated as one of the main drivers (Fox et al., 2015). As an example, GIN infections in temperate regions were historically limited to species better adapted to colder climes (e.g., *Ostertagia ostertagi*, *Teladorsagia circumcincta*, *Cooperia* spp., *Trichostrongylus* spp. and *Nematodirus* spp.). However, helminth abundance and species composition have changed in temperate regions, with an increase in tropically adapted species such as *H. contortus*, which typically dominates in regions with hot summers (Fox et al., 2015).

Levels and seasonal patterns of parasites challenge to livestock are likely to be affected by climate change, through direct effects on life cycle stages (eggs and larvae) and intermediate hosts (snails for flukes) outside the definitive host (Morgan and van Dijk, 2012). An increased number of generations and prolonged periods during which conditions are favorable for survival and transmission would be expected to increase potential parasite temporal availability. Similarly, warmer temperatures might be expected to change the geographic distributions of *H. contortus* and other species of GIN (Bolajoko et al., 2015) and flukes (Caminade et al., 2015). In addition, a number of studies have aimed to link changes in helminths distributions and abundance with climate change (Morgan et al., 2013; Skuce et al., 2013). For example, Bosco et al. (2015) have recently demonstrated changes in the epidemiology of *F. hepatica* in sheep in southern Italy as consequence of climatic changes. An outbreak of fasciolosis was related to significant changes in temperature, rainfall and rainy days observed in the study period compared to earlier periods; these conditions likely resulted in an increase of the distribution of humid areas in the pastures, which constitute the ideal habitats for the development of external stages of *F. hepatica*.

The impact of climate change on the distribution of helminths is therefore a growing concern and different models have been developed to predict climate-driven spatial and temporal changes in the distribution of these parasites and consequent disease risk on broad spatial and temporal scales (e.g., Bolajoko et al., 2015; Caminade et al., 2015). Nevertheless, it is impossible to understand and, therefore, much less to predict, the pattern of any infection/disease without taking into account sheep management systems and husbandry, which also vary spatially and are them-

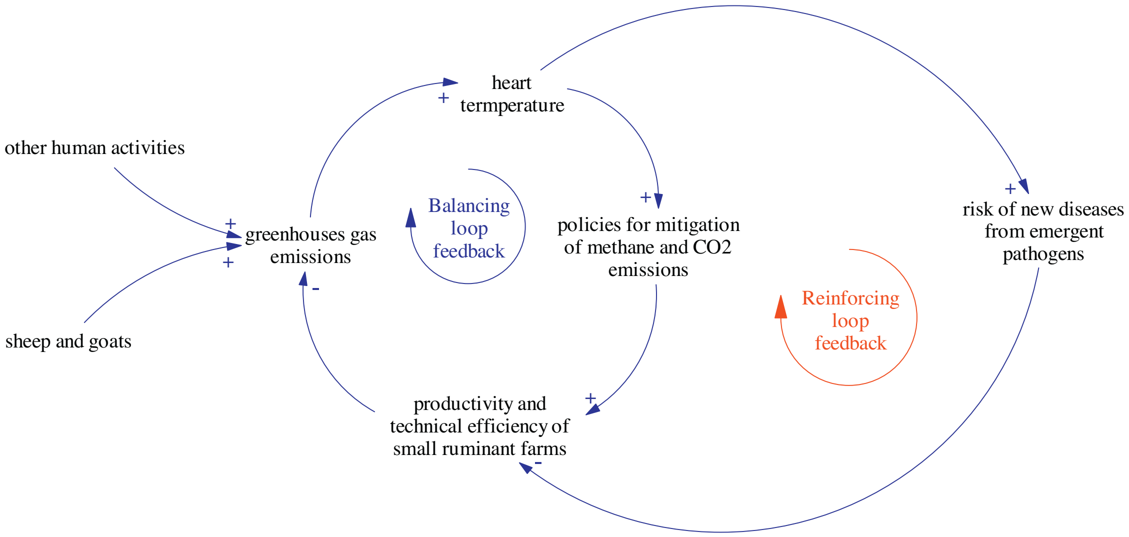

Fig. 3. Causal loop diagram of relationships among small ruminant farming climate change. The balancing loop represents the dynamics of the mitigation strategies on small ruminants contribution to climate change whereas the reinforcing loop represents the contrasting effect due to a suffered condition. The arrowhead represents the causality direction and the polarity indicates the correlation sign of the connection.

selves strongly influenced by climate (Morgan and van Dijk, 2012). In fact, host-parasites interactions will not only be directly affected by climate change but also through alterations to farm management (Morgan et al., 2013).

Geospatial tools (e.g., geographical information systems, remote sensing, virtual globes, ecological niche models, etc.) are very useful for mapping, monitoring and modeling parasite distribution in livestock farms in the era of climate changes (Cringoli et al., 2013; Rinaldi and Cringoli, 2014; Rinaldi et al., 2015c). Geospatial tools have now become an integral part of epidemiology and surveillance by driving systematic collection, analysis and interpretation of health data. The advantage of mapping the location of livestock farms and of studying the spatial distribution of infections is clear since it enable to understand the effects of climate changes and to focus intervention strategy in a sustainable way (Cringoli et al., 2013). Due to the effect of climate change on small ruminant production and health, improved surveillance strategies tailored at various multi-scale levels by the use of geospatial tools should be seriously considered by small ruminant health authorities.

6. Ruminant production efficiency and climate change from a system thinking perspective

From the previous sections is possible to highlight several feedback loops (defined as circular sequence of cause-effect events), which involve climate change, animal production, health and GHG emissions.

A qualitative representation of these feedbacks can be drawn using the causal diagram annotation used for system thinking analysis (Sterman, 2001; Tedeschi et al., 2011). It assumes that in a long run, with reference to each involved variable, balancing feedback loops cause counteractive effects whereas reinforcing feedbacks loops cause their exponential growth (or decay).

In Fig. 3, the information flow that describes the relationships among small ruminant farming and climate change is shown. As temperature raise, there is more human emphasis on mitigation policies that result on increases in efficiency use of the resources (even in the small ruminant sector) to counteract emissions and the temperature raise. The whole action flow is actually driven by a balancing feedback loop that aims to reach temperature equilibrium (desired pattern of behavior). At the opposite, we can describe a side effect of temperature raise that increases the risks of negative effect on the livestock health. Depression on animal health will cause reduction in animal production efficiency and thus a consequent increases of emissions and further temperature raise. The whole action flow is actually driven by a reinforcing feedback loop that could push an exponential growth of global warming (undesired pattern of behavior). The consequent behavior over time will be driven by the feedback loop that dominates the system.

7. Concluding remarks

The small ruminant production system is affected by climate change and at the same time, itself contributes to global warming with GHG emissions representing a challenge to the development of the sheep and goat sector.

Accurate estimations of GHG emissions are crucial to plan effective mitigation strategies within different area and livestock systems. On the other side, climate change is not only due to small ruminants thus the detrimental effect of global warming caused by other sources might reduce the small ruminant performances contrasting the efficacy of implemented mitigation strategies for which a large impact on the animal response is expected. Therefore, for sustainable small ruminant production, it will be necessary to focus on both mitigation, so to reduce the level of emission of GHG contributing to global warming, and on adaptation, to reduce the effect of climate change on small ruminant production and health. Genomic tools and support of the new technologies could help in developing climate change adaptation strategies and to predict influences of climate change on small ruminants' health.

Conflict of interest

The authors declare that they have no conflict of interest.

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