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EDITED BY
Ioannis Hadjigeorgiou,
Agricultural University of Athens,
Greece

*CORRESPONDENCE
Carol Kerven,
carol_kerven@msn.com

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Contribution of goats to climate change: how and where?

Carol Kerven*

Odessa Centre, Great Wolford, United Kingdom

This review examines the contribution of domestic goats (*Capra hircus*) to climate change, particularly through greenhouse gas (GHG) emissions. The review seeks to outline the global numerical importance and physical characteristics of domestic goats; Compare goats with other main livestock species in terms of their climate impacts; Assess the types of environments and farmers most likely to raise goats; Investigate the climate change impacts of raising goats, focusing on variables such as feed sources, management systems (intensive vs. extensive), and methodologies used to measure these impacts. The conclusion is that the negative reputation of goats needs to be re-evaluated, given their importance to poorer farm families and the potential overstatement or misunderstanding of their climate impact. Goats are the third most common ungulate livestock globally, with an estimated population of 1.1 billion. They are particularly suited to harsh environments due to their physiological advantages, such as efficient utilization of fibrous woody material and resilience to extreme climates. Goats are crucial for poorer farmers, especially in lower and middle-income countries in Africa and Asia. They provide milk, meat, and other products, are readily sold and have low labour requirements, making them ideal for families with limited resources. Goats emit less methane per unit body weight compared to other ruminants like cattle and sheep. However, the extent of their greenhouse gas (GHG) emissions varies significantly based on their diet, management system (extensive vs. intensive), and environmental conditions. Extensive systems, where goats forage on natural pastures, may result in low GHG emissions per unit of land area due to carbon sequestration and minimal reliance on high-energy feed. Intensive systems, which use more cultivated energy feed, produce lower methane emissions per unit of product but incur carbon costs arising from feed production. In sum, this review suggests that the negative reputation of goats regarding climate change may be overstated or misunderstood. More research is needed to accurately measure the GHG impacts of goats, considering factors like feed quality, management practices, and carbon sequestration.

KEYWORDS

methane, low income countries, pastoralism, ruminants, green house gases

Introduction

Raising livestock and consuming their products has negative effects for climate change through greenhouse gas (GHG) emissions (Thornton, 2010; Gerber et al., 2013; FAO, 2024). It is safe to say this statement is generally accepted in the scientific community. Policymakers, popular media and activists likewise contend that livestock are having particularly damaging impacts on the environment, especially climate change. Aside from these generalizations, however, little agreement exists on questions of how livestock contribute to climate change, where the problems are most acute, which livestock species are most responsible and under what types of management systems. Here we propose to look at some of these issues.

This review aims to examine the contribution to climate change of one globally significant livestock species – the domestic goat, *Capra hircus*. We begin by outlining the global numerical importance of domestic goats, and identifying the physical characterises which make goats especially suitable for certain environments. Goats are ungulate ruminants - hooved animals whose diets consist of wild or cultivated plants. There are important physiological differences with the other main ruminant livestock species kept. Goats are most likely to be raised in certain types of countries. Some kinds of farmers – mainly poorer families - tend to prefer raising goats in view of the growing global consumption and commercial interest in goat products. Having summarised the global scale of goats in farming, the review examines the climate change GHG impacts of raising goats. Available research data indicates here are several critical variables, beginning with the extent to which roughage constitutes the main source in goats' feed supplies; this is the most consistent variable in explaining livestock GHG emissions when comparing goats with the other main ruminant species. The second critical variable is the extent to which intensive versus extensive goat management affects GHG emissions. The review finally considers the methodologies used to measure the climate change impacts of livestock, including goats. Research is uneven or inconclusive on some of these topics. Nevertheless, there is clear evidence on some of the issues, while other questions remain to be further researched. The review concludes that the negative reputation of goats in some quarters needs to be re-evaluated, as goats make an important contribution to poorer farm families in some of the world's most challenging places, while the climate change impact of goats is either overstated or misunderstood in many instances.

One of the very first animal species to be domesticated by humans some 10,000 years ago (Amills et al., 2017; Hermes et al., 2020), goats of many breeds and usefulness to people are now raised all over the world (Lu, 2023). The number of goats in the world is estimated at 1.1 billion and they are the third most common ungulate livestock after cattle (1.6 billion) and sheep (1.3 billion) (FAOStats, 2024). See Figure 1.

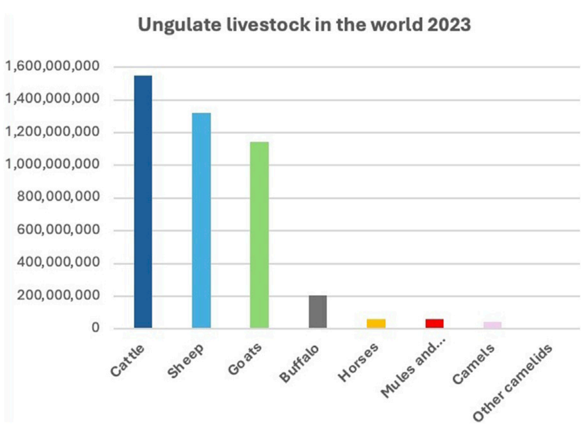

FIGURE 1
Ungulate livestock in the world 2023. Source: FAOstats 2024.

Characteristics of goats compared to other ruminant livestock

Different species of livestock have varied characteristics in relation to their diets. Consequently their usefulness to people and their impacts on the environment and climate is variable. Among livestock, the ruminant group – mainly cattle, sheep and goats - have a unique digestive system, having evolved a specialised stomach which extracts nutrients from plant foods by fermentation, before digestion – hence the process of rumination. Ruminant livestock contribute significantly to the human food chain as they can utilise plant substances such cellulose and other fibrous material in grass and fibrous crop residues which are non-digestible by humans; this material is then converted into meat and milk for human consumption (Silanikove, 2000; Soren et al., 2015). There is a net protein gain for people when calculating the input-output protein balance of ruminant feed intake and ruminant production of food for humans (Mottet et al., 2017). "Typically, ruminant grazing systems consume 0.2 kg human-edible feed protein per kilogram of protein product (0.6 kg kg^{-1} across all ruminant systems)" (Rivero et al., 2021: 2). Cultivation of food crops results in large quantities of crop residues which cannot be eaten by people but can be processed effectively through ruminant guts and subsequently transformed into human food – meat and milk - with a high protein content.

Compared to the world's other main ruminant livestock of cattle and sheep, goats have physiological advantages which determine what they eat, how they eat, where we find them, the nature of their productivity and hence how they are useful, and lastly, the likelihood of potentially damaging impacts on climate.

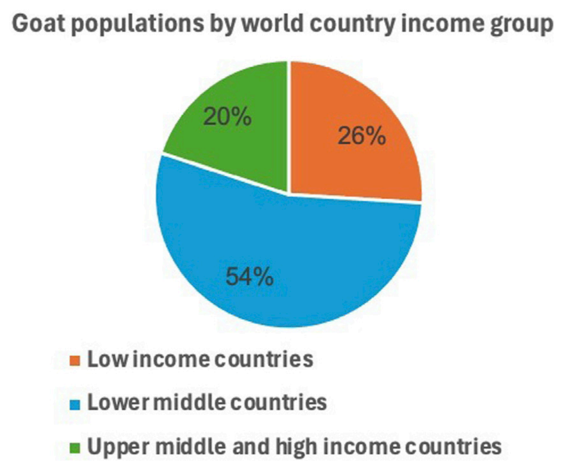

FIGURE 2
Goat populations by world country income group. Source: World Bank 2022, based on gross national income (GNI) *per capita* data in U.S. dollars And FAOStats 2024.

Researchers note that the physiological advantages of goats, for example the anatomy of their upper lips, means they are catholic but selective feeders on mixed herbaceous and woody vegetation. They are efficient in selecting plants and plant parts higher in protein and energy compared to those selected by cows and sheep, but still able to subsist on high fibre diets. Goats also conserve moisture in their gut, minimize water loss, and still produce kids and a relatively good output of milk, meat and manure even when inhabiting deserts (Silanikove, 2000; Pragna et al., 2018). Because of their higher adaptivity and resilience to tough environments, goats are much more likely to be found in certain climatically harsher regions. Goats can thrive in such challenging environments because "Relative to their ruminant counterparts, with a capacity of endocrine control, goats employ greater metabolic adaptations to water deprivation, scarcity of feed, heat stress, cold stress, high altitude, and plant anti-nutritional factors" (Lu, 2023; 107056).

Domestic goats are increasing recognised as having positive environmental impacts on biodiversity when extensively managed on open pastures; see for example Rosa García et al., 2012; Metera et al., 2010), as well having a useful role in brush control to lessen wildfire risks, as demonstrated in Ethiopia and Spain, for instance (Abate et al., 2024; Álverez-Martinez et al., 2016). Goats can help control invasive plant species, prevent the overgrowth of shrubs, maintain open landscapes, and contribute to the diversity of plant species in swards. When allowed to range, their browsing behaviour can create a mosaic landscape structure, which benefits various plant and animal species. Nevertheless, negative biodiversity impacts under certain management conditions are also recognised-see a summary in Lipson et al. (2019). The debate and evidence on whether and how goats are more or less damaging to the land environment is not, however, within the scope of this review focused on climate change impacts of goats.

Global distribution of goats

Some parts of the world have many more goats than others. The lower and middle income countries, principally in Africa and Asia, have around 80% of all goats in the world (Figure 2). Goats predominate in the tropics and sub-tropics, in terms of the number of animals, total production and number of beneficiaries - producers and consumers (Oosting et al., 2014).

The geographical distribution pattern of goats arises from their physiology and anatomy, which makes goats attractive to poorer people in lower income countries. These biological advantages mean that goats are not only prevalent in low-income countries, but furthermore in parts of these countries with more limited animal feed sources. Much of the global goat population is concentrated in the arid and semi-arid agroecological zones of Africa and Asia, subject to heat or extreme winter cold, droughts, and annual or seasonal forage limitations (Koluman Darcan, 2023). See Figure 3. Therefore, "breeds of goats which are indigenous to semi-arid and arid areas are able to utilize low quality high-fibre food more efficiently than other types of indigenous ruminants, or exotic breeds of goats" (Silanikove, 2000: 184). This permits them to exploit both naturally marginal and human degraded environments. Additionally, their climatic adaptability and disease resistance allows them to flourish in diverse conditions while their agility enables them to navigate rugged steep terrains inaccessible to cattle and sheep. Goats also have a higher reproductive rate than other ruminant livestock, with a propensity for twinning, early sexual maturity and high fertility (Lu, 2023). All these factors underlie and reinforce the value of goats to poorer farmers and pastoralists.

Why goats are particularly useful for poorer people in harsh regions

The imbalance in the global distribution of goats is notable, as it underscores the causal link between the physiological advantages of goats and peasant or pastoral agriculture practised in difficult climatic regions.

An early influential catalogue of how goats benefitted people was the global perspective by Peacock and Sherman (2010). They pointed out that goats provide a valuable source of milk to families, even under challenging environmental conditions. Goats are a source of meat for the family, and can be sold, traded or bartered for other foods and goods, such as high calorie grains or household needs. Farmers can sell goat meat, milk, and by-products such as hides and fibre. In some societies, goats have

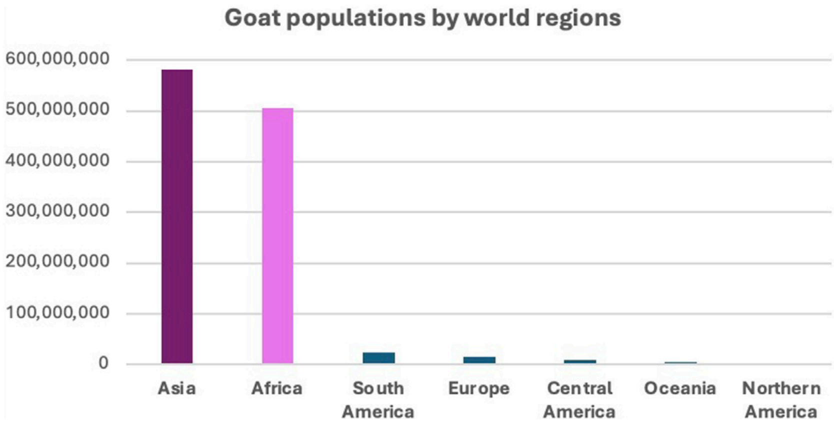

FIGURE 3
Goat populations by world regions. Source: FAOStats 2024.

symbolic significance and are used in cultural events such as marriage and religious ceremonies. Most of these attributes also pertain to other mammalian livestock species – cattle, sheep, camels, buffalos, reindeer, yaks etc. - but what is particularly useful about goats is their capacity to survive, produce and reproduce under the most variable and arduous extreme environments – hot, dry, cold or high. From the deserts of the Sahara, to the high altitude plateau of Tibet, goats are successfully raised by families who depend on their products.

From the aspect of human input efficiency, goats are often the species of choice for rural families with labour constraints (Peacock, 2005). Goats have a lower human labour requirement for herding due to their more diverse dietary selection, since they deploy an ability to forage on a wide range of vegetation and have an efficient digestion. This means that women and the elderly can more easily manage goats, while small children can be entrusted to oversee goats in pastures often nearer to home (Sinn et al., 1999).

Since goats are hardily adapted to survive and prosper in more difficult environments, they are widely preferred by poorer farmers in these places (Peacock, 2005; Pragna et al., 2018). In countries with a greater risk of climate disasters (droughts, floods, freezing snow) or politico-economic upheavals (unstable governments and currencies), resource-poor farmers will choose to keep goats rather than other ruminant livestock, as a cheaper option, faster turnover and quick sales in case of emergencies. For example, in the drylands of East and Southern Africa, goats have lower mortality rates than cattle in the regular droughts that afflict the rangelands (Nkedianye et al., 2011; Vetter et al., 2020). Likewise, after the traumatic socio-economic transformation in Central Asia, when the collapse of the Soviet Union was accompanied by mass rural unemployment and huge loss of livestock from state collective farms (Kerven, 2003), village families began to rebuild their livelihoods by accumulating goats, citing a proverb "If you are poor, you must keep goats" (Kerven et al., 2009).

Given the high population of goats kept by farmers in developing countries, since at least the mid 20th century there have been scientific and development efforts to alleviate poverty by increasing productivity of goats, due to their prevalence and preference among the very poorest farmers and pastoralists (Peters, 1987; Morand-Fehr and Lebbie, 2004). Research and extension on livestock improvement has become more prominent in the tropics of sub-Saharan Africa and southeast Asia (Oosting et al., 2014). Principally these efforts have been aimed at and achieved through raising meat and milk output for home consumption and cash sales by farmers and pastoralists in the world's drylands. The success of these efforts is good news for human nutrition and incomes, but is causing much concern over the impacts on climate change.

Growing consumption and commercialisation of goat products

Goats are not only raised for subsistence and sales by poorer farmers or in climatically harsh regions. Goat products are also increasingly being marketed, sometimes globally, leading to greater public and commercial scrutiny of their environmental impact. The three main products in terms of volume are milk, meat and fibre, while goatskins are also commercially important.

Goat milk is valued among both poorer and richer consumers. "There are far more people consuming goat milk than cow milk in the world", 20 years ago according to Haenlein (2004). For resource-poor farmers and pastoralists in drylands, goats have an advantage in being able to continue lactation even as water availability and forage dwindles (Silanikove, 2000), yielding a small but essential protein supply. Goat milk is also digestible by babies and small children in the absence of mothers' milk, or to people allergic to cows' milk. In high-income countries there is rising demand for gourmet dairy goat products of cheese and yoghurt (Mazinani and Rude, 2020). Globally, there is an ever-increasing number of dairy goats and goat milk production over the last two decades, particularly in Africa and Asia where dairy goat crossbreeds have been developed by researchers and adopted by farmers (Peacock and Sherman, 2010; Lu, 2023).

Considering the increasing world demand for meat as incomes rise (Thornton, 2010), consumers may prefer goat meat compared to other commonly consumed meats of beef, lamb, pork and chicken. Goat meat has less fat, less saturated fat and lower calories but equivalent protein and more iron, compared to other animal meats, based on FAO data cited in Mazinani and Rude (2020). As with increasing world production of goat milk, there is a steady rise in consumption of goat meat (Lu, 2023).

In contrast to the humid or dry hot tropics, in extreme cold continental and temperate climatic regions of Asia, goat fibre (cashmere) is an important source of additional income for millions of often poorer farmers and herders (Kerven et al., 2009). Cashmere goats are raised in deserts, steppes or high altitudes having bitter cold winters of Asia and are not found in Africa, with only an insignificant amount in Europe, the Americas and Australia. The cashmere undercoat protects the goats against extreme cold, and can be harvested and profitably sold by people. The biggest populations of commercially-harvested cashmere goats are in China, Mongolia, Afghanistan, Iran, India and Central Asian countries. In 2018 there were an estimated 700 million cashmere goats in the world (Schneider Group, 2019). Information on the number of cashmere goats in different countries is not officially recorded. As world demand for this valuable product is not abating, consumers and environmentalists are worried about the sustainability of raising goats to sell cashmere, a luxury product (Lindedin, 2024).

With the increase demand for goat products and accompanying supply from producers, more questions are raised about the climate change impacts of bigger goat populations.

Goats' contribution to climate change: What can be measured?

The growing global commercialisation of goat products leads directly to the central question of this review: how does keeping goats contribute to climate change?

The impact of livestock greenhouse gas (GHG) emissions on climate (including methane CH_4) first came to international attention in 2006, with the publication of *Livestock's Long Shadow*, a report by scientists at the UN Food and Agriculture Organization (FAO). The report's conclusions were immediately controversial and remain so, as lobbyists from the meat and dairy industries pressure their governments to object. As a result, scientists responded to challenges of their data and have since refined their methodologies (The Guardian, 2023; Morris and Jacquet, 2024). Furious attacks on the "methane fallacy" from sources like The Western Producer (2019) in Moose Jaw, Saskatchewan, nevertheless continue to rumble through the presses.

Scientists and advocates continue to reach differing conclusions on livestock's role in this global process (Lee et al., 2015; Garnett, 2017; Pitesky et al., 2009; Wolf, 2020). Meanwhile, consumers – at least those surveyed in the USA and Europe - are voting with their wallets, choosing which livestock products to buy or avoid (Sanchez-Sabate and Sabaté, 2019; Stampa et al., 2020). The food and textile industries are responding with alternatives to animal-derived products (McKinsey and Company, 2023; Deloitte, 2023), marketed as less climate damaging. Fashion companies are commissioning detailed life cycle assessments on the impacts of livestock on the environment, hoping to reassure potential buyers of the environmental and climate change neutrality of their animal fibre merchandise (Forbes, 2022; Ecochain, 2024).

The biology and chemistry of livestock GHG emissions is complex, and is still being closely studied. There are some fundamental interactions which need to be understood before rushing into black-and-white conclusions. The main livestock agents that cause GHG emissions are ruminants, including cattle, sheep, goats, buffalos and yaks (Opio et al., 2013; FAO, 2016). This is through the process of rumen enteric fermentation:

> . . .The end products of enteric fermentation are volatile fatty acids which are the primary source of energy in ruminants for both maintenance and production. This process proceeds with the liberation of [four] fermentation gases CO_2, H_2, N_2O, and CH_4 [methane] (Soren et al., 2015:187)

Among these four gases emitted by ruminant livestock, methane (CH_4) particularly contributes to global warming by trapping much more heat in the earth's atmosphere than carbon dioxide (CO_2), although for a shorter time (UNEP, 2024). Because of this, public and scientific attention is sharply focused on methane's impacts on climate change caused by ruminant livestock, including goats.

Broadly, geographic location and climate are known to be the most crucial factors significantly affecting CH_4 production by livestock, according to a widely-cited review (Cottle et al., 2011). That review notes that this is likely due to ambient temperature differences and associated disparities in available feed resources. However, within each different location and climatic zone, there are also many variables which further influence enteric CH_4 production in goats. These variables include type and quality of feed, the physical and chemical characteristics of the feed, feeding level and schedule, the efficiency of feed conversion to products of meat, milk and fibre from goats, the use of feed additives and concentrated feeds to support production efficiency, and the activity, health and genetic make-up of the animal (Soren et al., 2015; Pragna et al., 2018). In other words, even holding environment constant – geography and climate – there are still many other factors that impinge on the output of methane from goats.

In seeking to understand the effects of ruminant livestock on GHG, some of the variables have been precisely measured, some are hard to measure, and other variables are speculative at this stage and need further study. In summary, the key variables are: firstly, the ruminant species, as it is already known that each species emits differently. The next important variable is the extent to which livestock feed depend on roughage versus higher quality feeds. Much reliable data is already available on this question. A third major variable is the distinction between the GHG climate impacts of livestock raised under extensive management versus those raised in more intensive systems. Much less is known about the GHG differences attributable to management. This summary suggests there are complicating factors of species, feed sources and management in sorting out the role of goats in contributing to climate change. Each of these main variables is now considered in more detail.

Ruminant species - goats and others

Research in recent years has clearly shown that emission intensities of the GHG (CO_2, CH_4, and N_20) vary greatly among different livestock species and their products – meat and milk being the principal products considered (FAO, 2016). While FAO closely monitors and updates information on emissions from different livestock species, (including chickens and pigs), unfortunately FAO analyses often group goats together with sheep collectively as small ruminants (Opio et al., 2013). There is a larger sheep population than goats in the world, and sheep produce slightly less CO_2 equivalent (methane) per animal than goats (FAO, 2017). Among the ruminant livestock species it is known that "goats emit less enteric methane (CH_4) than all other domestic ruminant animals per unit body weight" (citing FAO 2017), because "goats have a high feed conversion efficiency, they emit less enteric methane per unit of feed consumed" (Koluman Darcan, 2023:107094). Globally, the world goat population of about 1.01 billion goats (FAOStats, 2024) produced approximately 4.61 million tonnes of enteric methane representing 4.9% of total EME [enteric methane emission] from livestock (FAO, 2016).

Feed sources: The role of roughages

Methane emissions vary according to roughage and concentrates in livestock diets. How much methane is emitted by goats largely depends on what they can eat, where and in what season. A bio-physical relationship has documented since the early 2000s between the content and quality of ruminant forage and feed diets to the consequent methane emissions (Benchaar et al., 2001). The ratio of roughage (principally from pastures) to concentrates in ruminant livestock diets is a fulcrum round which their food intakes vary, and thus the potential GHG emissions.

Roughages in ruminant diets consist of bulky plant materials with a relatively high amount of fibre (digestible cellulose and indigestible lignin) and a lower energy and protein value. Available native roughages include woody shrubs and dried grasses, with plant families and species varying widely between the world's biomes. The ratios of protein and fibre in plants providing roughage will alter considerably by season, plant maturity and local precipitation in different sites grazed and browsed by goats. Cultivated arable plants also produce by-products of roughages fed to ruminants, e.g. maize cobs, rice hulls, grain stalks, cotton, soya and sesame seed cake. Roughages are either grazed in pastures or harvested by humans and fed to the animals (so-called cut-and-carry). "Research shows that different grasses and forages at different stages of development cause ruminants to produce different amounts of CH_4. Forage species of grazing pasture also have a role in influencing enteric CH_4 production in ruminants" (Minson, 1990:350). The inflexion point of differences in methane emissions may occur on whether goats are raised solely on pastures versus more intensively with additional concentrates.

Although involving highly complex sets of relationships, a fundamental result is that "feeding system(s) employed for livestock rearing certainly has an effect on the enteric CH_4 production. Thus, feeding of a high concentrate to low roughage diet produces less enteric CH_4 vis-à-vis low concentrate to high roughage diet" (Soren et al., 2015:187). Since goats are raised and fed in radically dissimilar places and ways around the world according to different production systems, the amount of methane produced by goats will be partially dependent on the feed value of roughages obtained from pastures. The proportion of roughages in the diet changes under extensive or intensive management.

Roughages in diets under extensive management systems

The FAO investigated the question of how GHG emissions varies between different global livestock production systems, using the following classification of extensive systems as "grassland-based livestock production systems in which more than 10 percent of the dry matter fed to animals is farm-produced and in which annual average stocking rates are less than ten livestock units per hectare of agricultural land" (FAO, 1996). Most extensive pastoral systems raise their livestock primarily on available pastures, often communal, as well as crop residues – often *in situ* (Sayre et al., 2013).

Some researchers assume that in arid and semi-arid regions where pastoralists' extensive systems are based on grazing pastures over most or an entire annual cycle, all available feed resources are poor in quality, for example in sub-Saharan Africa (Opio et al., 2013; Graham et al., 2022). In this case, the assumption is that ruminant livestock in these arid and semi-arid regions would therefore have a lower productivity with higher enteric emission per unit output, in comparison to animals given a high quality diet under intensive or semi-intensive management systems in the same or different regions. This assumption can be questioned. If seasonal mobility is practiced, livestock – including goats - are able to reach and consume plants with higher quality feed values at the appropriate season, the strong correlation between GHG climate impact and reliance only on low quality roughage forage sources is less secure.

In many extensive management systems, livestock, including goats, are deliberately herded to or spontaneously seek out the freshest succulent pastures to graze early in the growing season (Coughenour, 1991; Boone et al., 2008; Behnke et al., 2011). While the aim of such seasonal movements is to gain access to plants before they mature and become fibrous roughages, this seasonal movement strategy inadvertently has the benefit of reducing methane emissions. This mobile foraging strategy allows the animals to take advantage of a higher ratio of protein to carbohydrate and fibre forage source, practiced for example in the Sahelian zones of West Africa (Penning de Vries and Djitèye, 1982). The Kazakh long-distance seasonal grazing movements exemplify these functional human-animal relationships: "Livestock migration partially levels out the imbalance between the quality of different forage resources . . . the total biomass output of the dry areas [sandy deserts] is inversely correlated to their nutritional value in the same way as the high level of output from wetter mountain pastures is associated with a lower protein feed value" (Alimaev, 2003:44).

In a very different climate than Central Asia, closely observed studies in Spanish mountain rangelands on seasonal feeding behaviour of feral goats over an annual cycle found that "Browsing use and preference of plant species by feral goats were significantly different across season [and], in general, seasonal fluctuations of diet were consistent with the maximum nutritive value of consumed plants" (Aldezabal and Garin, 2000:133). In another continent and climate, a semi-arid region of South Africa, when comparing the feeding behaviour of free-ranging versus herded goats in a semi-arid communal rangeland area, the goats able to choose their foraging sites were more selective and showed a higher preference for ephemeral herbs and grasses in the wet season; herded goats also preferred legume shrubs with a higher quality feed value (Samuels et al., 2016). Similar findings are recorded for goats under extensive management in other regions, for example, Mongolian Altai (Tsevegemed et al., 2019), Tanzania (Selemani et al., 2013) and Greece (Manousidis et al., 2016). The consumption ratio of roughages to more concentrated protein sources is decreased by such grazing and browsing behaviour by goats. The relatively lower rate of roughage in diets of migratory goats under extensive management practices is an important argument that methane emission per unit of output or animal head may be lower under extensive pastoral livestock management. However, as this relationship is not yet measured it remains speculative.

Adding cultivated feed and concentrates: Intensive management systems

The general conclusion in the research literature is that ruminant livestock raised under intensive concentrate-added systems produce the lowest GHG emissions, because of the ratio of high to low quality feed supplies – roughages to concentrates (Cottle et al., 2011). As already discussed here, the relationship is established that when ruminant livestock are fed low-quality feed (e.g., mainly roughages), they emit higher CH_4 per unit of meat and milk output (Vargas et al., 2022).

Concentrates are comparatively richer than roughages in energy and protein. Concentrates are typically generated by cultivation of cereals, legumes and oil seeds, as well as crop residues and human food processing byproducts such as molasses from sugar, all which frequently depend on inputs such as fossil fuel and agricultural chemicals. Harvesting of roughages can also depend on similar inputs through mechanical methods. In some livestock management practices concentrates are given as supplements, either regularly or in seasons of low pasture availability such as winters or dry seasons.

Some scientists have pointed out that externalities of more intensive management systems may not be properly calculated, such as the embedded emissions associated with producing concentrate diets (Cottle et al., 2011: 503). "For example, feed supplements may improve livestock production and reduce MI [methane intensity relative to production, e.g., kgCH_4 per kg liveweight gain or kg meat or milk] but the impacts of growing and processing these supplements must also be taken into account. Similar considerations apply to feedlot production" (Cottle et al., 2011:492). Concentrates are sometimes transported thousands of km from their source to where livestock are fed. Including the GHG production costs of supplementary feed changes the calculation of GHG emissions for intensive livestock systems (García-Dory et al., 2021).

Comparing GHG impacts of extensive versus intensive management

Certain commentators are asking why the distinction between climate impacts of extensive and intensive livestock management is rarely made (García-Dory et al., 2021; Scoones, 2023). The FAO data models are sometimes challenged by other scientists for being generic and therefore not applicable to all environments, for example:

> "Application of the current prediction equations developed by Food and Agricultural Organization and Intergovernmental Panel on Climate Change overestimated EME [enteric methane emission] from goats, and had low accuracy and precision" and "there is no model for predicting EME in goats developed from a large database emanated from different countries (Patra and Lalhriatpuii, 2016:89).

Two of the key differences at the core of this distinction between extensive and intensive systems centres on feed quality and methane emissions. Firstly, the ratio of roughage feed to concentrates in the diets of selective feeders like goats under extensive mobile systems allows greater access to high quality pasture forage. Secondly, intensive systems appear better in terms of methane emissions due to better quality cultivated feeds, until externalities are factored in.

Recognising that livestock are reared and fed within very different environments and alternative management systems of intensive, extensive and semi-intensive, one study assessed the comparative CH_4 production from these three different livestock feeding systems (Soren et al., 2015). The first major contrast is that developing countries have far greater proportions of livestock raised on locally produced roughages from communal lands as the principal source of feed, while only using minimal supplementation with concentrates. In these extensive management systems, "the quality of the pasture is responsible for the nutrients assimilated by the animal" (ibid: 187). Another notable contrast between management systems was that since goats are the most selective feeders among ruminant livestock, under extensive management conditions, goats were able to exhibit their inherent tendencies to consume a wide variety of plants, compared to sheep with which goats are often herded together in the pastures. In particular, in the dry season goats more than sheep chose to browse more, and have an affinity for protein-rich plants. For goats "the browse often serves as an excellent source of protein in addition to the dry grass" (ibid: 191). The implications of these goat eating habits for methane emissions under extensive management systems have not yet been ascertained. Evidently, it is hard to make accurate calculations of the contribution made by goats to methane emissions. Much depends on where the goats are, what they eat in which season, and how they are managed.

Difficult to establish carbon balances from livestock along the supply chain

There are other GHG effects of livestock apart from methane, however. Comparing emission measures of $C0_2$ versus CH_4 allows a more encompassing measurement of the GHG impacts of producing feed for intensive livestock keeping. An exclusive emphasis on methane – now largely the media focus - makes intensive livestock (and goat) management look better than extensive management, but factoring in $C0_2$ closes the gap.

After the startling messages in FAO's publication of "Livestock's Long Shadow" in 2006, one reaction was that FAO scientists proceeded to look more intently at the associated GHG emissions from different energy sources along the livestock supply chain from production to eventual retail point – i.e., distribution to consumers. Analytical focus turned to life cycle assessments (LCA), which are still being widely conducted on livestock outputs. An early comprehensive global assessment was FAO's publication "*Greenhouse gas emissions from ruminant supply chains*" (Opio et al., 2013).

Certainly the FAO, 2021 global assessment was a huge task, which acknowledged many assumptions, data absences and uncertainties. For assessing the impacts of livestock on GHG emissions, the report only considered human-edible livestock products of meat and milk – in other words, human food – The 2013 FAO calculations did not include GHG emissions associated with livestock's other uses as draught power, fibres, hides, skins and social capital, all of which can be significant components of low-income farm income in cash and in-kind.

Soil carbon sequestration was also not assessed in the 2013 FAO global study, due to a lack of standard criteria and data in all regions. Overlooked in most LCA studies is that ruminant livestock, including goats, contribute to "soil nutrient recycling via excreta . . . enhancing and maintaining soil health (i.e., soil organic C stocks, diverse populations of soil microbes, greater C sequestration" (Chen et al., 2019). Most Life Cycle Assessment (LCA) research has not yet thoroughly investigated the counter-balancing effects of emissions and sequestration from vegetation and soil. The mitigating implications may have a large influence for determining carbon balance, particularly for low-input grazing systems, as Cottle et al. (2011) previously remarked. The focus of LCA research is usually the estimation of CH_4 emission intensity relative to human food production – methane intensity (MI). This is estimated as $kgCH_4$ per kg liveweight gain (LWG) or kg beef or milk product. Accordingly, more weight is attached to CH_4 emissions relative to feed intake and product output (ibid). This methodology is now embedded in international standards often applied by commercial companies to assess the sustainability of their products. We are reminded that methane has an upper limit to the extent it can be stored in soil, reaching equilibrium unless the livestock production system is changed (Wang et al., 2023), but methane is still a powerful source of GHG. On the other hand, $C0_2$ persists for centuries and millennia.

Working out the carbon balance implications of producing high quality feed for concentrate under more intensive ruminant livestock systems is a core question about carbon cost and thus impacts on climate change. Assessing carbon balance requires setting harmful carbon emissions of livestock against carbon benefits to the soil from livestock, as noted above by Chen et al. (2019). Trends around the world are for intensification of livestock production. Pioneer studies which included soil carbon sequestration in assessing ruminant livestock on pastures in USA, for instance Pelletier et al. (2010), reported lower total GHG for pasture-fed beef cows compared with lot-fed beef. A similar early result, also in USA, was found for pasture-fed dairy cows, as when carbon sequestration by grassland was considered, pasture systems reduced net GHG emissions (Belflower et al., 2012). This highlights the possibility of other GHG sinks to counter the higher enteric MI [kgCH_4 per kg liveweight gain] anticipated from pasture grazing management systems. At present, there are apparently no similar studies of carbon sequestration created by goats fed on pasture compared to feed lots.

Nevertheless, concern over climate change consequences of raising ruminant livestock is leading to closer consideration of the carbon balances – or offsets - between ruminant emissions and soil carbon sequestration. So far, field studies are limited to developed countries such as Spain (e.g., Escribano et al., 2020) and Italy (Arca et al., 2021), and the USA results as noted above. Estimations of the carbon balance are lacking or deficient for extensive livestock systems in developing and low income countries (Scoones, 2023). Overlooking the carbon sequestration land use outcomes of raising ruminant livestock is a "blind spot," according to some analysts of the GHG inventory methods (Bellassen et al., 2022).

Evaluating the carbon balances implicated in intensive versus extensive systems depends on how the question is asked. There at least two possible denominators. The conventional LCA approach is to apply the product unit per animal as denominator– meat and milk in weight or protein, per emission of carbon – even when adjusted by carbon sequestration per animal head. Using this denominator leads inexorably to the conclusion that more intensive systems are less climate threatening. Intensively raised animals are individually capable of producing more human food – meat and milk - due to their higher quality diets, breeds and body sizes as well as greater inputs of veterinary drugs, scientific breeding, hormones and other interventions. Therefore, in an intensive system, on average each animal can yield relatively more human food while producing less emissions per animal.

If, on the other hand, carbon emissions are denominated by area of land used per animal – i.e., stocking rate – then as one study shows, "The extensification process shows clear environmental advantage when emission intensity is referred to the area-based functional unit" (Arca et al., 2021). In poorer regions of the world with extreme dry and/or cold winter climates, livestock, including goats, tend to be raised extensively i.e., with a low ratio of animal population per land area. Lacking the inputs of intensive management and spread much more thinly on the ground, their carbon footprint per land area may therefore be lighter. Such a perspective could alter our views about the pros and costs of different livestock management systems around the world. Since goats help to sustain people in some of the most unforgiving landscapes, they deserve to have their role in contributing to climate change re-evaluated. Logically, the next set of questions must be to examine total world quantities of goats and land area involved in these different production systems and climatic regions.

Discussion

Understanding the physiology, eating habits and geographical distribution of goats leads to rethinking how goats fit into the overall concern about livestock's effects on the climate. Since the people who mainly raise goats are among the most economically vulnerable and often live in environments most likely to be affected by global climate shifts, it is time to start re-evaluating the impact of goats on the climate. Not all the questions have clear answers, and there are still many outstanding research conundrums to pursue.

There are indicators that using lesser external inputs under extensive management compared to intensive management systems may foster less GHG emissions. When appraising these questions, one viewpoint has advocated for a more holistic approach, "avoiding the narrow focus on emissions per animal or unit of product" and instead factoring in environmental benefits for biodiversity, ecosystem services, landscape and cultural values (Scoones, 2023:4). These valuable benefits of goats are recognised, but beyond the scope of this review on the contribution of goats to GHG, and not on the broader environmental and societal impacts.

This review has delved into some scientific progress on measuring new variables and measuring more carefully. Some metrics are settled, including that goats emit less methane per head, can find and-compared to other domesticated ruminants - can eat a wider selection of edible nutritious plants. Ruminant livestock – including goats – raised extensively on pastures may less produce less total GHG than when kept under intensive management with a high proportion of cultivated feed and less carbon sequestration.

The extent to which livestock grazed on pastures results in improved biodiversity and adaptation to climate change is now being widely investigated.

Looking backwards, ruminant livestock have been extremely advantageous to humans for the last ten thousand years – goats being one of the earliest domesticated species which yielded meat and milk, as well as skins, for the people who kept them. As ruminants, goats share the facility of being able to derive nutrition efficiently from plants, but more effectively than the other most popular species of cattle and sheep. The physiology of goats allowed the spread of domestic goats to many different environments over time. Yet now we see that goats are more concentrated in some of the world's extreme climates, remote places and in lower income countries, where farmers and herders can derive a more reliable livelihood from them. When raised on pastures in deserts and mountains, goats can provide food for people where few other livestock species can compete. Looking forwards, the trend is for goats to increase in popularity for their milk, fibres and possibly also for meat. This means that the impact of goats on GHG must be considered.

Due to their adaptability, resilience and eating behaviour, goats deserve to be distinguished from other livestock, rather than being lumped together with the world's sheep or with all other livestock, as in the more popular press articles on climate change. People's great dependence on goats in some regions justifies paying better attention to their usefulness. Ultimately, not all the issues are amenable to precise measurement as some issues are inevitably value-laden. This means that the uncertainties, trade-offs and biases must be acknowledged. There is still work to be done.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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