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# Enteric methane emission factors for sheep in Mongolian extensive grazing systems: a Tier 2 approach

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Methane emissions from livestock are a significant contributor to agricultural greenhouse gas outputs, yet region-specific emission factors are often lacking for nomadic pastoral systems. This study determined annual enteric methane emission factors for sheep across three major agro-ecological zones of Mongolia: Desert-steppe, steppe, and forest-steppe, considering animal sex and age categories. Animal performance data were collected for adult males (>3 years), adult females (>3 years), young sheep (1–2 years), and lambs (<1 year). According to the IPCC Tier 1 methodology, the default emission factor for adult sheep is 5 kg $CH_4$/head/year, while lamb values are estimated at approximately 2 kg $CH_4$/head/year. Nevertheless, these generalized values fail to capture country-specific differences in animal productivity, diet quality, seasonal feed availability, and grazing management, thereby introducing significant uncertainty into national greenhouse gas inventories. Results showed that females consistently exhibited higher emission factors than males, with values ranging from 6.0 to 6.1 kg $CH_4$/head/year, compared to 5.40–5.45 kg $CH_4$/head/year for males. Young sheep emitted between 4.3 and 4.9 kg $CH_4$/head/year, while lamb emissions were lowest at 1.6–1.8 kg $CH_4$/head/year. These findings provide updated, region-specific methane emission factors for Mongolian sheep, supporting the refinement of national greenhouse gas inventories and climate change mitigation strategies.

KEYWORDS

**climate change, enteric fermentation, greenhouse gas inventory, IPCC Tier 2 methodology, livestock**

## Introduction

Mongolia sustains a large population of small ruminants, with around 23 million sheep and an equal number of goats (National Statistics Office of Mongolia, 2025). These animals are vital for rural livelihoods, contributing to food security, household income, and traditional cultural practices (Mearns, 2004). Globally, livestock production is a major contributor to agricultural greenhouse gas (GHG) emissions, accounting for roughly 60% of the sector's total output (FAO, 2021). Among GHG emissions, methane ($CH_4$) emissions from grazing ruminants represent about 29% of livestock-related GHG emissions, with 26.4% occurring in arid and semi-arid regions (Clark, 2017). Worldwide, sown pasture (SP) and native pasture (NP) supply nearly half of the feed consumed by grazing animals, supporting the livelihoods of an estimated 1.3 billion people (Belache et al., 2023; IPCC, 2019). Sheep, numbering around 1.2 billion globally, contribute approximately 6.4% of total enteric methane emissions from livestock (Patra, 2014a), making them the third largest ruminant source after cattle and buffalo (FAOSTAT, 2020). The sheep industry plays a role in advancing several United Nations Sustainable Development Goals (SDGs), and maintaining current production levels is considered desirable (Belanche et al., 2021). However, the predicted rise in global demand for meat (+73%) and milk (+58%) poses challenges to achieving $CH_4$ mitigation targets—estimated at up to 47% between 2010 and 2050—while sustaining productivity (Beauchemin et al., 2020). Meeting climate goals, such as limiting warming to 1.5 °C by 2030, will require mitigation strategies that do not compromise animal health, productivity, or welfare (Arndt et al., 2022). Accurate quantification of enteric $CH_4$ emissions across species, production systems, and regions is therefore essential. For sheep, however, comprehensive datasets covering different production environments remain scarce. The Intergovernmental Panel on Climate Change (IPCC) recommends estimating emissions using $CH_4$ conversion factors (Ym), which represent the fraction of gross energy intake lost as methane during enteric fermentation. The 2019 IPCC guidelines suggest a default Ym of 6.7% for all sheep categories and diets, with slightly adjusted values (7.0% or 6.5%) depending on dry matter intake (DMI) levels (Hammond et al., 2011). These estimates are based largely on New Zealand studies using high-quality forage diets (Swainson et al., 2018) and may not reflect the variability in diet quality, rumen fermentation, or animal class (e.g., lambs *versus* adults) in other regions (Moraes et al., 2014). Consequently, applying these default factors directly to grazing sheep in Mongolia could result in significant inaccuracies in national inventories or in cost-benefit analyses of mitigation measures.

Dry matter intake (DMI) is the most important predictor of enteric $CH_4$ production, as it shows a strong positive correlation with $CH_4$ emissions across all databases considered (Ellis et al., 2007). Consequently, forage quality is also a key predictor of greenhouse gas emissions, since it directly influences DMI (Belanche et al., 2023; Xie et al., 2023; Hammond et al., 2009; Patra, 2013). In Mongolia, animal performance is closely linked to both the quantity and quality of natural grasslands. For certain species, up to 98% of annual intake comes from native pasture. These grasslands, covering roughly 128.8 million hectares and hosting around 2,270 grass species (including 600 forage species), are distributed across six main zones:alpine tundra (3%) maintain taiga (4.1%) mountain steppe and desert steppe (25.1%), grass steppe (26.1), desert steppe (25.1) desert (14.5%) (Johnson et al., 2006; Amarsaikhan et al., 2023). Pasture growth is highly seasonal and climate-dependent, with new growth beginning as early as mid-April in forest steppe and steppe regions, and later in other zones. Grazing in early spring consists largely of senescent material, with fresh grass dominating intake from June to September (Munkhzul et al., 2021; Damiran et al., 2009). For roughly 200 days of the year, livestock rely primarily on senescent forage. Some areas are left ungrazed for haymaking or to serve as standing feed during winter (Togtokhbayar, 1995; Hu et al., 2023).

Over 90% of Mongolia's sheep belong to the native "Mongol" breed, which is evenly distributed nationwide. Breeding farms in Bayantsagaan (Tuv aimag), Erdenedalai (Dundgovi aimag), and Hotont (Arkhangai aimag) maintain purebred and improved stock for distribution to more than 70 soums (Chadraabal, 2013; Sambuu, 2003; Nergui et al., 2011). This homogeneity creates an opportunity: even modest improvements in breeding and feeding practices could be scaled nationally, delivering significant mitigation gains while supporting pastoral livelihoods.

The present study aimed to quantify enteric $CH_4$ emissions from major rangeland ecosystems desert-steppe, steppe and mountain forest—in Mongolia using the IPCC Tier 2 methodology. This approach incorporates animal energy requirements based on liveweight, productivity, diet quality, and age sex categories of sheep.

## Materials and methods

This study was conducted in three specific locations in Mongolia. Khotont sum Arhkanhangai province represented forest steppe rangeland (47.369406, 102.473088°E), Bayantsagaan and Sergelen soum of Tuv province represented steppe rangeland (47.692664, 106.997982°E), Shivee-Govi soum of Gobi sumber province (46.157656, 108.545458°E)-represented rangeland sheep systems in semi-arid environments desert-steppe rangeland. For the selected sites, the use of seasonal weight change, energy partitioning calculation, and pasture quality analysis, combined with GPS-tracked locomotion data, ensures improved emission factor (EF) estimation relevant to extensive rangeland systems in the long-term studies.

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## Animal characteristics and performance data

The study followed the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2019) to estimate enteric $CH_4$ emissions. In additions, equations from IPCC (2000) and NRC (2001) were used for the estimation of net energy mobilized due to weight loss and net energy for activity utilizing the daily distance travelled.

Measurements were taken at the beginning and end of each season. Although Mongolia has four seasons, measurements were divided into two periods: summer-autumn (S-A) which is the weight gain season, and winter-spring (W-S), the weight loss season, based on changes in animal body weight.

After the initial visit to herders in early 2024, the researchers conducted repeated herder visits to collect data on live weight and, pasture samples. A representative sub-sample of the herd, 54 sheep in the Khotont, 28 Sheep in the Shivee govi sum, and 46 sheep in the Sergelen and Bayantsgaan sum were considered in the project. The animals were classified into the following age groups: adult male and female sheep (>3 years), young adult (1–2 years), and lamb.

## Live weight measurement and average daily weight gain/loss

Live weights were measured using calibrated sheep weighing scale (dimensions: 1.2 m × 2 m × 1.3 m; YH-T3 Tscale Electronics MFG, Model KW; Kunshan, China) during each visit. The scale was calibrated with known weights before each weighing session in each household. The live weight measurements were taken at the beginning and end of the two distinct seasons in Mongolia: Summer- Autumn (15th August) and Winter-Spring (15th April). Average live weight change (LWC) was computed using the difference in live weight for each animal between seasons and divided by the number of days between measurements. If a live weight was missing, the average LWC of the herd was applied.

## Forage sampling and chemical analysis

Representative forage samples were collected from three locations during the growing season, in mid-May and August, when pasture was fully green. To characterize the senescent forage consumed during winter–spring, additional samples were collected *in situ* in November and April, when sheep predominantly graze on mature or senescent grass. The chemical composition of all samples was analyzed, and the averages of the November and April samples were considered representative of the entire winter–spring season. This approach allows seasonal changes in forage quality to be captured while remaining logistically feasible under extensive grazing conditions.

Samples were dried in hot air oven at 55 °C for 48 h and then ground using a Wiley mill through mm sieve The chemical composition of the study sample was collected at the Nutrition Assessment Laboratory of the Research Institute of Animal Husbandry. The methods employed were moisture and crude ash by weight method (MNS 6548:2015), crude proteins by Kjeldahl method (MNS 6549:2015), fiber and its fractions by ANKOM method (MNS6551:2015), fats by Soxhlet method (MNS6554:2015), macro-microelements (MNS4655:2015). The dry matter digestibility DMD was estimated from the equation of Oddy et al. (1983), as follows:

$$\mathrm{DMD}\ (\mathrm{g}/100\mathrm{g\ DM}) = 83.58 - 0.824 \times \mathrm{ADF}\left(\mathrm{g}/100\mathrm{g\ DM}\right) + \left(2.626 \cdot \mathrm{N}\left(\mathrm{g}/100\mathrm{g\,DM\ 100g\,DM}\right)\right) \quad (1)$$

GE content was estimated according to the equation described by Weiss and Tebbe (2019):

$$\mathrm{GE}\ (\mathrm{MJ/kg\,DM}) = [\mathrm{CP}\,\% \times 0.056 + \mathrm{EE}\,\% \times 0.094 + (100 - \mathrm{CP}\,\% - \mathrm{EE}\,\% - \mathrm{ash}\,\%) \times 0.042] \times 4.187 \quad (2)$$

Subsequently, the DE % was estimated from the DMD using Equation 4 derived from CSIRO (2007), as IPCC methodology utilizes digestible energy (DE, % of gross energy) for the calculation of net energy requirements,

$$DE\% = \frac{DMD\,(\%) \times 0.172 - 1.707}{0.81 \times GE\left(\frac{MJ}{kgDM}\right)} \times 100 \quad (3)$$

Where; DE % is the digestible energy as a percentage of feed gross energy; DMD is seasonal dry matter digestibility%, as estimated in Equation 1, 0.172 and 1.707 are constants used in a formula to convert DMD into megajoules (MJ) of metabolizable energy per kilogram of dry matter (DM); 0.81 is a factor that converts metabolizable energy to digestible energy; GE is gross energy of feed (MJ/kg DM).

## Gross energy calculations

Gross energy (GE) values used in this study were derived from a combination of IPCC default values (IPCC, 2006; IPCC, 2019) and locally measured feed composition. Standard IPCC values were applied for components such as maintenance energy and general feed GE content. For parameters not provided by the IPCC—such as energy content and digestibility of Mongolian pasture species—we used data from chemical analyses of forage samples collected during the study (May, August, November, and April) and supplemented with published regional studies (Yan et al., 2010; Liu et al., 2020; Goopy et al., 2018). This approach ensures that energy intake and expenditure estimates reflect both internationally standardized methods and the specific conditions of Mongolian extensive grazing systems.

*Net energy for maintenance*: (NE m) is the net energy required for maintenance, which is the amount of energy needed to keep the animal in equilibrium where body energy is neither gained nor lost (IPCC, 2006).

$$NEm = Cf^{*}(Weiht)^{0.75} \quad (4)$$

Where:

NE m = net energy required by the animal for maintenance, MJ $day^{-1}$
Cf i = a coefficient for Sheep older than 1 year 0.217, lamb to 1 year 0.236 calculating NEm), MJ $day^{-1}$ $kg^{-1}$
Weight = live-weight of animal, kg

*Net energy for activity*: (NE a) is the net energy for activity, or the energy needed for animals to obtain their food, water and shelter.

$$NEa = Ca^{*}Weight \quad (5)$$

Where:

NEa = net energy for animal activity, MJ $day^{-1}$
Ca = coefficient corresponding to animal's feeding situation 0.0240 for Grazing hilly pasture, MJ day−1 kg −1
weight = live-weight of animal, kg

*Net energy for growth*: (NE g) is the net energy needed for growth (i.e., weight gain).

$$NEg = \frac{WG\,lamb \cdot (a - 0.5b(BWi + BWf))}{365} \quad (6)$$

Where:

NE g = net energy needed for growth, MJ day-1
WG lamb = the weight gain (BW f–BW i), kg yr −1
BW i = the live body weight at weaning, kg
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10.18 2006 IPCC Guidelines for National Greenhouse Gas Inventories
BW f = the live body weight at 1-year old or at slaughter (live-weight) if slaughtered prior to 1 year of age, kg a, b = 2.1, 0.45

Net energy for lactation: (NE l) is the net energy for lactation. Milk production is not known, (Agricultural and Food Research Council, 1990) indicates that for a single birth, the milk yield is about 5 times the weight gain until august of the lamb.

$$NE_l = \left[\frac{(5 \times WGwean)}{365}\right]^{\circ} EVmilk \quad (7)$$

Where:

NEl = net energy for lactation, MJ day-1
WG wean = the weight gain of the lamb between birth and weaning, kg
EV milk = the energy required to produce 1 kg of milk, MJ kg −1. A default value of 4.6 MJ kg −1 (Agricultural and Food Research Council, 1993) can be used.

Net energy for wool production: Wool yield was determined by asking questions to the herdsman. (NE wool) is the average daily net energy required for sheep to produce a year of wool.

$$NE_{wool} = \left[\frac{(EV_{wool} \times Production_{wool})}{365}\right] \quad (8)$$

Where:

NE wool = net energy required to produce wool, MJ day-1
EV wool = the energy value of each kg of wool produced (weighed after drying but before scouring), MJ
kg −1. A default value of 24 MJ kg −1 (Agricultural and Food Research Council, 1993) can be used for this estimate.
Production wool = annual wool production per sheep, kg yr −1

Net energy for pregnancy: (NE p) is the energy required for pregnancy. For sheep, the NE p requirement is similarly estimated for the 147-day gestation period, although the percentage varies with the number of lambs born.

$$NEp = C\,pregnancy^{*}NE\,m \quad (9)$$

Where:

NEp = net energy required for pregnancy, MJ day-1
C pregnancy = pregnancy coefficient 0.007
NEm = net energy required by the animal for maintenance, MJ/day

Net energy for travel: The average daily distance traveled was determined using GPS collars. Collars were attached in the morning before releasing the animals for grazing on randomly selected sheep. Due to the limited number of collars and to obtain data from as many animals as possible per season, collars were changed between animals every 3 days (NRC. ,2001). As the animals were confined at night, only data collected between 8:00 a.m in the morning and 9:00 p.m. were considered.

$$NEt(Mj) = dist(km)^{*}0.0019\left(\frac{MJ/kg}{km}\right)^{*}MLW(kg) + 0.005\left(\frac{MJ}{kg}\right)^{*}MLW(kg) \quad (10)$$

Where: NEt is net energy for travel per day, MJ; Dist. is the average daily distance in km traveled per season, (data obtained from GPS collar); 0.0019 is energy cost of walking per kg body weight per km; MLW is the mean seasonal LW in kg; and 0.005 is the energy (MJ) required per kg LW during grazing.

While Mongolian fat-tailed sheep differ markedly from New Zealand sheep in terms of breed type, grazing management, and mobility, the estimation of energy expenditure for travel and grazing activity is based on fundamental physiological principles linking body weight, locomotion, and metabolic energy use. Currently, no alternative equations have been developed specifically for nomadic or transhumance grazing systems. Therefore, the coefficients derived from New Zealand studies represent the most robust and widely accepted framework for estimating locomotion-related energy requirements in grazing sheep and were applied in this study.

The GEI was calculated using Equation 10 derived from IPCC (2019), with the incorporation of the net energy mobilized (NE mob) due to weight loss as per IPCC (2000) and the calculation of net energy for travel (NEt) instead of net energy for activity (NEa) using the daily distance traveled as per NRC (2001).

$$GEI = \left[ \frac{\frac{NEm+NEa+NEI+NEp+NEt}{REM} + \frac{(NEg+NEwool)}{REG}}{\frac{DE\%}{100}} \right] \quad (11)$$

Where GEI, Gross energy, MJ/day; NE m, Net energy required by the animal for maintenance, MJ/day; NE a, Net energy for animal activity, MJ/day; NE l, Net energy for lactation, MJ/day; NEt Net energy for travel, MJ/day; NEp, Net energy required for pregnancy, MJ/day; REM, Ratio of net energy available in a diet for maintenance to digestible energy consumed following Tier 2 equation from IPCC (2006); NEg, Net energy needed for growth, MJ/day; NEwool, Net energy required to produce a year of wool, MJ/day; REG, Ratio of net energy available for growth in a diet to digestible energy consumed following Tier 2 equation from IPCC (2006); DE%, Digestible energy expressed as a percentage of gross energy.

Enteric $CH_4$ emission. Based on the 2019 Refinement to the IPCC (2006), the daily enteric EF was calculated from gross energy intake (GE) and Ym (the fraction of gross energy intake released in the form of $CH_4$). The following Tier 2 equation (Equation 5) from IPCC (2019) was used to compute seasonal EF and annual EF:

$$EFseason\left[\frac{kgCH4}{season}\right] = \left[\frac{GE\left(\frac{MJ}{day}\right) * \frac{Ym(\%)}{100}}{55.65\left(\frac{MJ}{kgCH4}\right)}\right] * days\, is\, season \quad (12)$$

Where EF season represents the enteric $CH_4$ emission factor (in kg $CH_4$/head/season) estimated from seasonal animal characteristics and performance data based on the IPCC (2019) Tier 2 GE is the gross energy intake (in MJ/d) calculated using IPCC equations, and Ym is the $CH_4$ conversion factor, the IPCC (2019) default value of 6.5% was used due to the absence of site-specific value. The factor 55.65 (MJ/kg CH4) is the energy content of $CH_4$. Equation 12 shows how the annual EF for enteric CH4 emission (kg CH4/head/year) was estimated.

$$Annual\ EF\left[\frac{kgCH4}{season}\right] = \left[\frac{EF\ season1\left(\frac{KgCH4}{season1}\right) + EF\ season\,2\left(\frac{KgCH4}{season1}\right)}{Number\ of\ seasons}\right] \quad (13)$$

## Statistical analysis

Quantitative data analysis used descriptive statistics and oneway analysis of variance (ANOVA). The one-way ANOVA was employed to examine the variation in mean annual live weights, live weight change, and emission factors (EF) across the three locations. A *post hoc* test (Tukey test) was conducted to compare means. The analyses were carried out using Microsoft Excel. In all analyses, p-values less than 0.05 were considered statistically significant.

# Results

## Herd characteristics

Across all animal categories, there were no statistical differences in annual mean LWC among the three locations, except for adult males, where Shivee ovoo exhibited higher annual mean LWC compared to Khotont, Ikh-Tamir and Sergelen (Table 1).

The wool yield was 1.3 kg for male sheep, 1.2 kg for female sheep, 1.1 kg for young sheep, and 0.8 kg for lambs.

## Feed quality

Across all three grazing systems, pasture constituted the primary feed source throughout the year, and supplementary feeding was uncommon. Therefore, feed quality was evaluated solely based on forage composition. The quality of sheep forage, as indicated by various parameters, varied among the three locations. Among the three locations, highest DE values were observed Desert Steppe area (Table 2). Because it has less acid detergent fiber (ADF), and higher nitrogen and protein content than forest steppe and steppe pasture.

Regarding the chemical composition of pasture plants, crude protein content was higher in the desert-steppe region compared than the Mountain-steppe region. Conversely, the Mountain-steppe pastures had higher acid-insoluble fiber, which could contribute to their lower digestibility. In this study, the dry matter digestibility (DMD) of the pasture vegetation ranged from 55% to 62%, falling within the 55%–75% range, as stated in recommended by the IPCC 2006 guidelines.

TABLE 1 Mean live weight, (kg, mean ± SE) for the three study sites in Mongolia.

| Sheep category | Mountain-steppe area | | | Steppe area | | | Desert-Steppe area | | |
|---|---|---|---|---|---|---|---|---|---|
| | Summer-autumn | Winter-spring | Gaining weigh | S-A | W-S | Gaining weigh | S-A | W-S | Gaining weigh |
| Adult male | 48[a] | 36[a] | 12 | 48[b] | 36[a] | 16 | 50[b] | 38[a] | 12 |
| Adult female | 46[a] | 35[a] | 11 | 46[b] | 35[a] | 14 | 46[b] | 35[a] | 11 |
| 2-year-old | 38[a] | 29[a] | 9 | 38[b] | 30[a] | 12 | 40[b] | 32[a] | 8 |
| Lamb | 28[a] | 21[a] | 8 | 25[b] | 21[a] | 4 | 25[b] | 21[a] | 4 |

S-A-summer to autumn, W-S-winter to summer; Adult females (≥3 years); Adult males (≥3 years); 2 years Lamb (≤1 year); Means with different superscript letters in the same row indicate significant differences at $p < 0.05$. NB: IPCC, Tier 1 values are derived from the pasture/range systems mentioned in the IPCC (2019) Guidelines Table 10.10 (New).

TABLE 2 Nutrient composition of pasture grazed by sheep.

| Index | Pasture type in | | | | | | |
|---|---|---|---|---|---|---|---|
| | Desert-steppe | | Steppe | | Forest-steppe | | Winter and spring(senescent grass) |
| | Summer and autumn | | Summer and autumn | | Summer and autumn | | |
| | 15th May | 15th August | 15th May | 15th August | 15th May | 15th August | 15th Nov and 15th April |
| NDF, % | 58.61 ± 0.4 | 57.92 ± 1.3 | 52.8 ± 1.3 | 59.7 ± 1.1 | 52.09 ± 1.5 | 53.40 ± 1.6 | 70.40 ± 1.1 |
| ADF, % | 34.35 ± 1.2 | 37.02 ± 1.4 | 36.8 ± 1.7 | 43.2 ± 1.2 | 36.68 ± 1.4 | 40.92 ± 1.3 | 48.08 ± 1.2 |
| CP,% | 14.25 ± 0.3 | 14.64 ± 0.5 | 13.8 ± 0.6 | 12.5 ± 0.8 | 12.19 ± 0.4 | 10.59 ± 0.8 | 10.09 ± 1.3 |
| N, % | 2.28 ± 0.2 | 2.34 ± 0.6 | 2.17 ± 0.7 | 2.0 ± 0.2 | 2.06 ± 0.2 | 1.69 ± 0.4 | 1.61 ± 0.4 |
| Ether extract,% | 3.1 ± 0.2 | 3.9 ± 0.4 | 3.6 ± 0.4 | 4.01 ± 0.2 | 2.7 ± 0.6 | 3.2 ± 0.2 | 2.7 ± 0.3 |
| Ash,% | 9.2 ± 0.6 | 8.4 ± 0.5 | 10.2 ± 1.1 | 8.1 ± 0.8 | 10.5 ± 0.8 | 9.8 ± 0.5 | 12.7 ± 0.5 |
| GE, Mj/kg DM | 17.46 ± 1.2 | 17.83 ± 1.2 | 17.00 ± 0.8 | 17.38 ±0.9 | 17.14 ± 0.6 | 17.32 ± 1.4 | 16.55 ± 0.5 |
| DMD% | 61.45 ± 1.3 | 59.37 ± 0.8 | 59.05 ± 1.2 | 56.44 ± 1.3 | 59.23 ± 1.2 | 55.23 ± 1.6 | 48.11 ± 1.4 |
| DE% | 62.29 ± 1.2 | 58.87 ± 1.4 | 61.36 ± 1.2 | 56.83 ± 1.2 | 61.06 ± 1.4 | 56.04 ± 1.5 | 48.97 ± 1.1 |

DM, dry matter; NDF, neutral detergent fiber; ADF, acid detergent fiber; N, nitrogen; GE, gross energy; DMD, Dry matter digestibility and DE, feed digestibility expressed as percent of gross energy; NA, no assessment.

We calculated the energy requirements of sheep for maintenance (NEm), walking (NEt), lactation (NEl), pregnancy (NEp), and growth (NEg), based on the gross energy (GE) of their feed. The relative energy for maintenance and other activities (REM) was 0.54 and 0.56 for improved and local sheep in summer–autumn, and 0.34 in winter–spring. The relative energy for growth (REG) was 0.26 and 0.28 in summer–autumn, and 0.28 in winter–spring (Equations 2, 3, 6, 7, 8, 9, 11, 13).

The estimated gross energy (GE) requirements of sheep varied markedly among agroecological zones, seasons, and physiological states (Table 3). Across all zones, GE values were consistently higher in the winter–spring period compared to summer–autumn. This pattern reflects increased maintenance energy (NEm) requirements in colder months, likely due to elevated thermoregulatory demands, as well as lower dietary digestibility during winter grazing.

Despite higher NEm in some summer cases for certain classes (e.g., Gobi steppe females), GE remained higher in winter–spring because of the combined effects of increased activity energy (NEa), pregnancy energy (NEp), and wool energy (NEwool), compounded by lower DE% in winter pastures. For example, Gobi steppe females required 20.61 MJ/day in winter–spring compared to 14.04 MJ/day in summer–autumn, representing a 47% seasonal increase. A similar seasonal gap was evident in forest–steppe females (21.37 vs. 11.02 MJ/day) and steppe females (21.41 vs. 13.63 MJ/day). These trends align with previous reports (Schlecht et al., 2019) that cold-season

TABLE 3 Estimated energy requirement values for different physiological components in sheep.

| Agroecological zone | Season | Sheep | NEm, MJ/day | NEt, MJ/day | NEl, MJ/day | NEp, MJ/day | NEg, MJ/day | $NE_{wool}$, MJ/day | GE, MJ/day |
|---|---|---|---|---|---|---|---|---|---|
| Desert-steppe | W-S | Male | 2.98 | 0.22 | na | na | na | 0.085 | 18.71 |
| | S-A | | 3.83 | 0.53 | na | na | na | | 11.23 |
| | W-S | Female | 2.98 | 0.22 | na | 0.37 | na | 0.078 | 20.61 |
| | S-A | | 3.83 | 0.53 | 0.94 | na | na | | 14.04 |
| | W-S | Young | 2.64 | 0.19 | na | na | na | 0.072 | 13.81 |
| | S-A | | 3.70 | 0.51 | na | na | na | | 6.57 |
| | W-S | Lamb | 0.78 | 0.035 | na | na | na | 0.05 | 16.49 |
| | S-A | | 2.01 | 0.17 | na | na | 0.14 | | 11.01 |
| Steppe | W-S | Male | 2.98 | 0.22 | na | na | na | 0.085 | 18.71 |
| | S-A | | 3.83 | 0.53 | na | na | na | | 11.08 |
| | W-S | Female | 2.98 | 0.22 | na | 0.37 | na | 0.078 | 21.41 |
| | S-A | | 3.83 | 0.53 | 0.94 | na | na | | 13.63 |
| | W-S | Young | 2.64 | 0.19 | na | na | na | 0.072 | 16.63 |
| | S-A | | 3.70 | 0.51 | na | na | na | | 8.47 |
| | W-S | Lamb | 0.78 | 0.035 | na | na | na | 0.05 | 5.2 |
| | S-A | | 2.01 | 0.17 | na | na | 0.14 | | 6.2 |
| Forest-steppe | W-S | Male | 3.12 | 0.22 | na | na | na | 0.085 | 19.47 |
| | S-A | | 2.91 | 0.40 | na | na | na | | 8.85 |
| | W-S | Female | 3.12 | 0.22 | na | 0.37 | na | 0.078 | 21.37 |
| | S-A | | 2.91 | 0.24 | 0.94 | na | na | | 11.02 |
| | W-S | Young | 2.49 | 0.17 | na | na | na | 0.072 | 15.57 |
| | S-A | | 2.42 | 0.17 | na | na | na | | 7.07 |
| | W-S | Lamb | 0.66 | 0.089 | na | na | na | 0.05 | 4.84 |
| | S-A | | 1.61 | 0.026 | na | na | 0.14 | | 5.04 |

NEm, net energy for maintenance; NEt, net energy travel; NEl, net energy for lactation,; NEp, net energy for pregnancy; NEg, net energy for growth; GE, gross energy; REM, used in GE, calculation for improved and local sheep for in the summer-autumn 0.54 and 0.56, respectively; in the winter-spring 0.34 REG, for improved and local sheep were 0.26 and 0.28 in the summer-autumn respectively; in the winter-spring 0.28.

grazing in Mongolia increases maintenance needs by 30%–60% relative to warm seasons due to low ambient temperatures and increased walking distances between sparse forage patches.

Physiological status had a substantial influence on GE requirements. Pregnant females (late gestation) exhibited additional NEp requirements (0.37 MJ/day in winter–spring), while lactating ewes in summer–autumn showed elevated NEl (0.94 MJ/day), contributing to higher total energy demand compared with non-reproductive animals.

For instance, in the steppe zone, summer–autumn GE for females reached 13.63 MJ/day, higher than that of males in the same zone and season (11.08 MJ/day), despite lower NEm, due to lactation energy costs. Wool production also contributed small but consistent amounts (0.072–0.085 MJ/day) to GE across all classes. Young and lamb categories exhibited distinct patterns. Young sheep had GE values ranging from 6.57 MJ/day in Gobi steppe summer–autumn to 16.63 MJ/day in steppe winter–spring, driven largely by higher NEm per unit metabolic weight and substantial seasonal differences in forage digestibility. Lambs in the Gobi steppe showed extremely high GE in winter–spring (16.49 MJ/day) compared with steppe summer–autumn (11.01 MJ/day), indicating greater cold stress susceptibility and faster relative growth rates in early life stages.

Seasonal methane emission factors (EFs) varied substantially among agroecological zones and animal categories (Table 4). Across all zones, methane emissions during the winter–spring period were consistently higher than during summer–autumn,

TABLE 4 Emission factors for sheep in the three agro-ecological zones of Mongolia.

| Agro-ecological zone | Emission factors kg $CH_4$/head/year | | | | IPCC default values |
|---|---|---|---|---|---|
| | Males | Female | 2-year-old sheep | Lambs | |
| Desert-steppe | 5.45 ± 0.4 | 6.1 ± 0.2 | 4.9 ± 0.7 | 1.7 ± 0.2 | 2-lamb<br>5- adult sheep |
| Steppe | 5.43 ± 0.3 | 6.1 ± 0.5 | 4.9 ± 0.3 | 1.8 ± 0.4 | |
| Forest steppe | 5.40 ± 0.5 | 6.0 ± 06 | 4.3 ± 0.7 | 1.6 ± 0.5 | |

reflecting seasonal differences in forage availability, quality, and animal energy requirements.

The estimated enteric methane ($CH_4$) emission factors for Mongolian sheep varied by agro-ecological zone, age, and sex (Table 4). Across all zones, adult females (>2 years) consistently exhibited higher annual methane emissions than adult males, with values ranging from 6.0 to 6.1 kg $CH_4$/head/year compared to 5.40–5.45 kg for males. This difference is likely related to the greater feed intake of females due to pregnancy and lactation demands, which increase gross energy intake and consequently methane production. Young sheep (1–2 years old) showed lower methane emissions (4.3–4.9 kg $CH_4$/head/year) compared to adults, due to their lower body weight and reduced feed intake. Lambs (<1 year) had the lowest emissions (1.6–1.8 kg kg $CH_4$/head/year), consistent with their limited forage consumption and shorter grazing duration per year.

## Discussion

Sheep across the study sites showed marked seasonal fluctuations. Autumn weights were consistently 11–12 kg higher than spring weights for adult males, 13–14 kg higher for adult females, 9–12 kg higher for two-year-olds, and 4–8 kg higher for lambs. These patterns reflect typical live weight dynamics under Mongolia's rangeland conditions, where body reserves are accumulated during summer–autumn and mobilized during winter–spring. Reported organic matter digestibility (OMD) in Mongolian pastures generally varies between 61% and 67% (Nergui et al., 2011; Ariunsuren et al., 2025). However, the digestibility of winter forage is relatively low, around 48%, and and sheep rely on this grass for most of the year (approximately 170–200 days). This may contribute to higher greenhouse gas emissions. The chemical composition of the herbaceous vegetation, including organic matter, crude protein (CP), fiber fractions (NDF and ADF) was within the range typically reported for Mongolian pastures (Daalkhajav, 2009; Tserendash et al., 2011). Vegetation quality reached its peak in summer-autumm season, characterized by high CP and low NDF and ADF, in line with observations by Tserendash et al. (2011), who noted that alpine pasture plants mature in August, leading to decreased CP and increased fiber content due to a higher proportion of stems (Daalkhaijav and Lkagvajav, 1997). Consistent with trends observed in Mongolian forest steppe (Tserendash et al., 2011). Crude protein content was comparable to previous reports for forest steppe, steppe (Otgonjargal, 2012), and desert steppe (Togtohkbayar, 1995), and was similar to values reported for central mountainous regions (Daalkhaijav and Lkagvajav, 1997). The combination of moderately low CP and digestibility, along with elevated fiber levels, suggests a gradual decline in pasture quality from south to nort. Crude protein content was comparable to previous reports for forest steppe, steppe, and desert steppe, and similar to values reported for central mountainous regions. The combination of moderately low CP and digestibility, along with elevated fiber levels, suggests a gradual decline in pasture quality from south to north, consistent with trends observed in Mongolia s forest steppe. For grazing distance, no real difference was observed in the sheep, and they grazed at a distance of 4–7 km in summer and autumn, and 3.5–5 km in spring and winter (Figure 1). Therefore, when calculating the energy expenditure for movement, an average of 6 km was used in summer-autumn and 4 km in winter-spring. The grazing distance of the sheep flock, regardless of age and sex, was the same. Also, since the herders involved in the study did not milk their sheep, the grazing distance of the lambs was the same as that of the flock. Following Lin et al. (2011) we considered our GPS data sufficiently reliable despite the absence of differential correction. The average distance traveled by sheep in our study (6 and 4 km $day^{-1}$) was in the same range of relevant the 4.7–6.4 km $day^{-1}$ reported for sheep grazing Inner Mongolian steppes (Lin et al., 2011). Stocking pressure also played a role: densities of 2.5–7 sheep units (SU) per ha near Tsunkhul Lake and over 13 SU $ha^{-1}$ around camp sites, likely contributed to longer travel distances in July and August. Animut et al. (2005) demonstrated that increased grazing pressure can extend animal itineraries under comparable climatic conditions (Yoshihara et al., 2009). In our case, sheep often had to walk several kilometers each morning to reach high-quality forage, beyond the overgrazed areas close to their camp. Joly et al. (2013) reported average grazing distances of 5.1 km from camp in the Mongolian Gobi, which aligns with our observed mean radius of 6.75 km $day^{-1}$ and the 3.5–6.5 km range previously described for summer herding in Mongolia (Gendaram, 2011). Seasonal convergence in the daily travel distances of sheep is probably linked to the increasing forage availability from spring to early summer. According to Tsevegemed et al. (2019) the effective grazing distance for Mongolian Altai sheep and goats is approximately 10–11 km, which is influenced by the high altitude of the Altai Gobi and the availability of pasture plants. In mobile grazing systems, grazing area and associated energy expenditure are critical drivers of animal productivity and enteric methane emissions (Tsvegemed et al., 2018). Accordingly, the estimates derived from this study are not intended to represent national average conditions. In this context, reliance on IPCC Tier 1 default values constitutes a methodological limitation, as these values do not adequately capture the variability inherent in extensive and mobile grazing systems. Regarding net energy requirements, although seasonal and physiological effects were the main drivers of variation, differences among ecological zones were also evident. Forest–steppe sheep generally exhibited slightly higher NEm values compared with steppe or desert-steppe sheep of similar classes, likely reflecting the cooler and more variable climate as well as terrain-related increases in activity costs. For instance, gross energy intake (GE) of forest–steppe females during winter–spring averaged 21.37 MJ/day, which was comparable to steppe females (21.41 MJ/day) but slightly higher than desert-steppe females (20.61 MJ/day). This difference may be attributable to the availability of relatively better, yet more fibrous, forage in the forest–steppe, which increases energy expenditure for digestion and metabolism.

The estimated enteric methane ($CH_4$) emission factors for Mongolian sheep exhibited pronounced variation across agro-ecological zones (Figure 2), age classes, and sex. Adult females consistently showed higher emission factors than adult males, reflecting the greater nutritional demands associated with pregnancy and lactation. During the winter–spring season, emission factors ranged from 1.67 to 8.70 kg $CH_4$ head$^{-1}$ season$^{-1}$. Adult females exhibited the highest emissions, particularly in the steppe and desert-steppe zones (both 8.46 kg $CH_4$ head$^{-1}$ season$^{-1}$), while adult males showed the highest values in the steppe zone (8.70 kg $CH_4$ head$^{-1}$ season$^{-1}$). Young animals displayed intermediate emission levels (6.42–6.90 kg $CH_4$/head/season), whereas lambs produced substantially lower emissions (1.67–1.76 kg $CH_4$/head/season consistent with their lower body weight, reduced feed intake, and incomplete rumen development. In the summer–autumn season, emission factors declined across all animal categories and agro-ecological zones, ranging from 2.76 to 5.66 kg $CH_4$/head/season. Adult females again exhibited the highest emissions, particularly in the steppe zone (5.66 kg $CH_4$ head$^{-1}$ season$^{-1}$), followed by adult males (4.53–5.18 kg $CH_4$/head/season). Young animals and lambs maintained lower emission levels, consistent with their comparatively lower feed intake and metabolic demand. The overall reduction in methane emissions during summer–autumn likely reflects improved pasture quality, greater digestibility, and increased availability of green forage, which enhance animal productivity and reduce methane yield per unit of intake. Comparable patterns have been reported in small ruminant systems elsewhere, where physiological status strongly influences gross energy intake and subsequent methane production (Goopy et al., 2018; Gurmu et al., 2024; Lokupitiya, 2016). The elevated emissions observed in adult females emphasize the importance of accounting for reproductive status when developing emission factors, as reliance on a single default value may obscure substantial within-species variability. Similarly, age-related declines in emissions have been documented in Ethiopian and Kenyan smallholder sheep systems, where Tier 2 methodologies revealed that lambs contribute disproportionately less to total herd emissions than adult animals (Negussie et al., 2021; Wanjala et al., 2018). These findings highlight the necessity of differentiating age classes when constructing national greenhouse gas inventories, particularly in pastoral systems with high proportions of young animals. Clear spatial differences in emission factors were also observed among the desert-steppe, steppe, and forest-steppe zones. Overall, the steppe zone exhibited the highest methane emission factors, followed by the forest steppe and desert-steppe zones. This pattern likely reflects differences in pasture biomass, botanical composition, grazing intensity, and animal movement. Higher emissions in the steppe zone may be attributed to greater forage availability and intake, resulting in higher gross energy consumption and increased methane production. In contrast, the desert-steppe zone, characterized by limited biomass and poorer forage quality, exhibited lower emission factors, particularly during summer–autumn. Intermediate emission levels in the forest-steppe zone are consistent with its relatively favorable forage conditions and moderate climatic stress. This seasonal and spatial variability contrasts with observations from sub-Saharan Africa, where animals graze more diverse and protein-rich forages during the wet season, leading to greater fluctuations in methane emissions (Alemu et al., 2022; Goopy et al., 2018; Goopy et al., 2020). Collectively, these findings underscore the importance of developing region-specific emission factors rather than relying on global defaults that may not adequately represent local feeding ecology and production systems.

Several methodological and ecological factors must be considered when interpreting enteric methane ($CH_4$) emission estimates derived using the IPCC Tier 2 methodology under Mongolia's nomadic pastoral systems. In extensive grazing environments characterized by high mobility, long-distance seasonal movements, and extreme continental climates, animal energy expenditure varies substantially in response to seasonal temperature fluctuations, forage availability, and grazing distance (IPCC, 2006; NRC, 2001; Goopy et al., 2018). However, the Tier 2 equations do not explicitly incorporate the additional metabolic

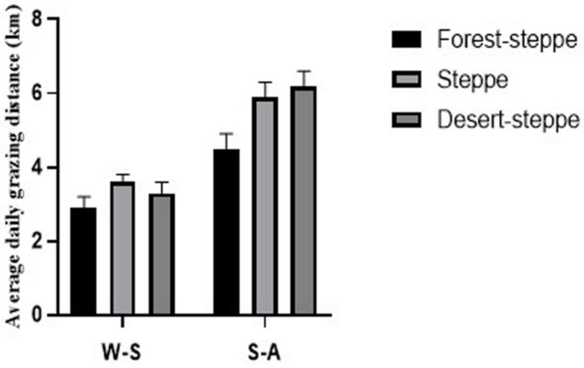


FIGURE 1
Average daily grazing distance (km) of sheep across three regions of Mongolia during Summer-Autumn and Winter-Spring. Bars represent mean values with standard deviations (mean ± SD). Distances were significantly higher in Summer-Autumn, especially in the Desert-steppe (6.2 ± 0.6 km/day). whereas Winter-Spring distances were shorter than Summer-Autumn (3.0–3.3 km/day).

costs associated with cold stress, thermoregulation, and long-distance movement, which are intrinsic features of Mongolian pastoral systems. Consequently, energy requirements and methane emissions may be under- or overestimated, particularly during the winter–spring season, when animals experience severe climatic stress and limited forage availability (Brosh et al., 2006; Fernández-Giménez et al., 2017; Alemu et al., 2022). A further limitation concerns the use of a fixed methane conversion factor (Ym), commonly set at 6.5% of gross energy intake (GEI). Accurate estimation of Ym ideally requires direct methane measurements and detailed assessment of feed digestibility, both of which vary markedly across seasons and rangeland types in mobile grazing systems (IPCC, 2006; Hristov et al., 2013; Moate et al., 2017). Previous studies have reported Ym values of 6.2% for housed sheep in Europe (Zhao et al., 2016), 7.5% for supplemented grazing dairy cattle in the Andes (Muñoz et al., 2018), and 6.9% for grazing beef heifers in temperate North America (Chaves et al., 2006). In contrast, grazing sheep in our study exhibited a higher $CH_4$ energy-to-GEI ratio (~8.0%), exceeding the IPCC default range of 6.5% ± 1%. This likely reflects the combined effects of harsh climatic conditions, extensive mobility, and the relatively low digestibility and high ash content of Mongolian steppe forages (Yan et al., 2010; Rushing et al., 2019; Liu et al., 2020). To reflect the pronounced seasonal dynamics of Mongolian rangelands, we divided the year into two functional periods: a summer–autumn season characterized by green, actively growing pasture and positive live-weight change, and a winter–spring season marked by senescent forage, negative energy balance, and body weight loss. Accordingly, Ym values mean of 6.5%. While this approach captures broad seasonal contrasts, it remains a simplification and may not fully reflect short-term fluctuations in forage quality, intake, and animal metabolism that typify nomadic grazing systems. These limitations highlight the need for seasonally resolved, region-specific Ym values derived from direct field measurements.

Enteric methane ($CH_4$) emissions in Mongolian sheep exhibited clear variation across seasons, ecological zones, and animal categories (Figure 3). Emission factors were highest during the winter–spring season, when animals grazed senescent pasture and experienced body weight loss, and lowest in summer–autumn, when green forage supported higher intake and digestibility. Adult females consistently produced more $CH_4$ than males and young animals, reflecting higher energy requirements associated with reproduction and lactation. These findings highlight the importance of accounting for age, sex, and seasonality in estimating emissions under highly mobile pastoral systems.

We did not collect detailed productivity data, such as slaughter weight, wool yield, or milk production, and therefore any statements regarding emission intensity per unit of product should be considered preliminary. Nevertheless, productivity in Mongolian pastoral systems is strongly influenced by herd structure. Productivity-based emission intensity is shaped by herd structure. Meat is primarily obtained from 2–5-year-old males, whereas most females are retained for breeding until 7–8 years of age. All sheep produce wool, with average yields of 0.8–1.2 kg per year, while meat yield from market-age males averages 16–22 kg per animal (MOFA, 2025; Mongolian Institute of Animal Husbandry, 2011). Milk, although culturally and nutritionally important, is largely consumed locally and was excluded from emission intensity calculations. Given these production patterns, methane emissions per unit of marketed product are likely higher than in intensive systems. Targeted nutritional interventions for breeding females, such as providing higher-quality supplements during periods of high energy demand, could reduce methane emissions per unit of intake while maintaining productivity (Beauchemin and McAllister, 2007; Patra and Yu, 2013; Hristov et al., 2013).

These results underscore the limitations of generalized methane estimation frameworks, such as IPCC Tier 2, when applied to extensive grazing systems. Aggregating all sheep into a single emission factor may misrepresent national emissions, particularly in systems with strong seasonal and ecological variation. The estimated emission factors for Mongolian sheep (1.6–6.1 kg $CH_4$/head/year) are lower than IPCC (2019) defaults for small ruminants in developing countries (8–10 kg $CH_4$/head/year), reflecting lower energy intake and productivity under extensive grazing. While per-head emissions are lower, emission intensity per unit of product may be higher, emphasizing the need to quantify emissions relative to productivity. Overall, developing region- and season-specific emission factors that incorporate animal category, mobility,

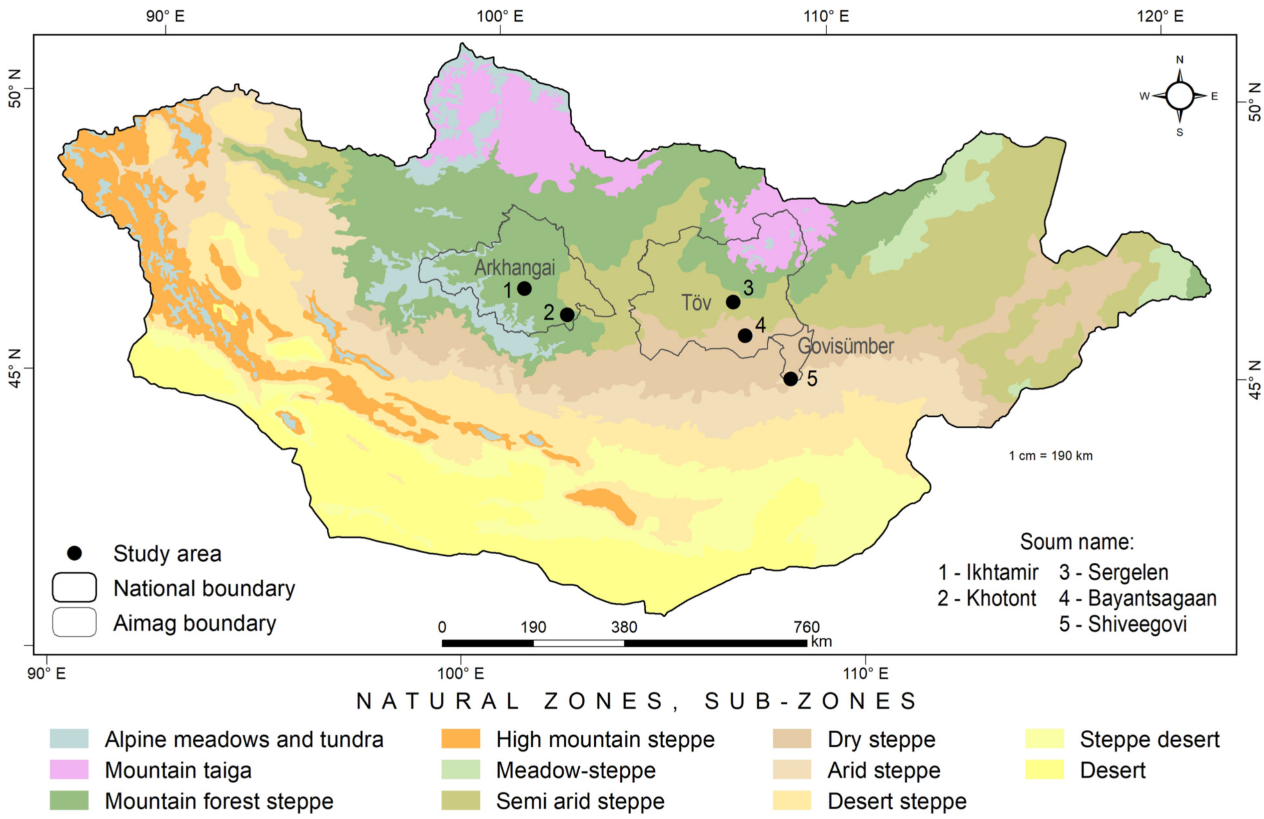


FIGURE 2
Study areas in Mongolia showing the natural zones and sub-zones. Black dots indicate the five study sites: 1 - Ikhtamir, 2 - Khotont, 3 - Sergelen, 4 - Bayantsagaan, and 5 - Shiveegovi. Different colors represent natural zones including alpine meadows and tundra, mountain taiga, mountain forest steppe, high mountain steppe, meadow-steppe, semi-arid steppe, dry steppe, arid steppe, desert steppe, and desert. National and aimag boundaries are outlined. Scale bar represents distance in kilometers.

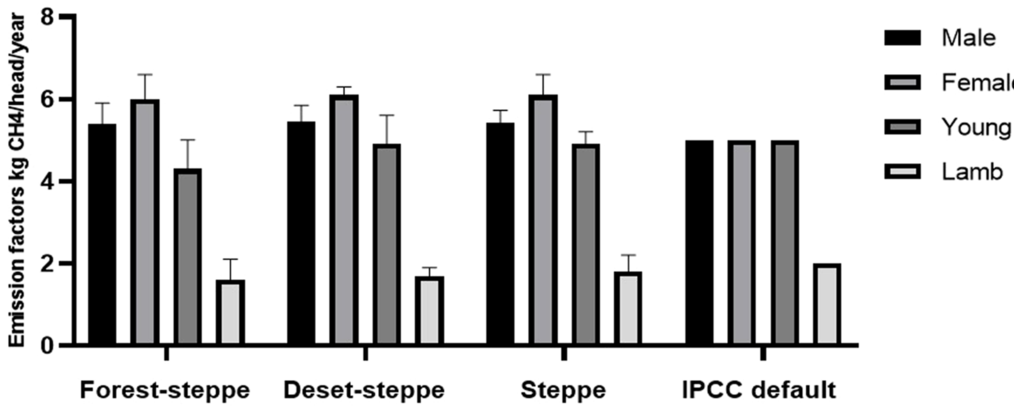


FIGURE 3
Annual methane emission factors (kg CH4 head$^{-1}$ year$^{-1}$) of Mongolian sheep by animal category across three agroecological zones, compared with IPCC default values.

forage quality, and climatic stress is essential for improving the accuracy of national greenhouse gas inventories and informing realistic mitigation strategies in Mongolian pastoral systems.

## Conclusion

Overall, these findings underscore the critical importance of developing region-specific emission factors for improving the accuracy of national greenhouse gas inventories in pastoral livestock systems. The results also emphasize the emission level vary systematically, as a function of physiological status, forage quality, and seasonal energy dynamics, highlighting the limitations of applying global default values in the Mongolian context. By incorporating location specific on diet digestibility, seasonal weight change, and reproductive status, this work provides a more robust basis for Monitoring, Reporting, and Verification (MRV) under the UNFCCC Enhanced Transparency Framework. Beyond the methodological refinement, the results also emphasize that targeted management, particularly improved ewe nutrition during pregnancy and lactation can play vital role in reducing methane intensity. These outcomes bring Mongolia's capacity to design evidence-based mitigation strategies, while offering broader insights for rangeland-based livestock economies engaged in the Global Methane Pledge.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

The animal studies were approved by Ethical Review Guidelines for the Use of Animals in Experiments of Mongolian University of Life Sciences. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent was obtained from the owners for the participation of their animals in this study.

## Author contributions

OS: Writing – original draft, Methodology, Formal Analysis; LG: Data collection; AL: Data collection, NN-O: Data collection Resource mobilization; OG: Data collection Resource mobilization LS: Data cleaning; OS: Writing – review and editing, Methodology; YC: Writing – review and editing, Conceptualization, Methodology; TN: Writing – review and editing, Conceptualization, Methodology, Fund acquisition; JS: Writing – review and editing, Conceptualization, Methodology, Fund acquisition BB: Writing – review and editing, Methodology; MZ: Writing – Conceptualization, Methodology, Fund acquisition CJ: Writing – review and editing, Conceptualization, Methodology, Fund acquisition. All authors contributed to the article and approved the submitted version.

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## Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. While preparing the manuscript AI was utilized to check and improve the language.

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