Animal 18 (2024) 101320

Contents lists available at ScienceDirect

Animal

The international journal of animal biosciences

Enteric methane emissions from zebu cattle are influenced by seasonal variations in rangeland fodder quality and intake

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A R T I C L E I N F O

Article history:
Received 11 October 2023
Revised 26 August 2024
Accepted 27 August 2024
Available online 2 September 2024

Keywords:
Greenhouse gases
Natural pasture
Ruminant livestock
Seasonal variability
Sub-Saharan Africa

A B S T R A C T

Rangeland fodder resources used to feed ruminants in the Sahel decline considerably in both quantity and quality from the wet to dry seasons. While it is widely assumed worldwide that this seasonality of fodder supply impacts intake levels and therefore enteric methane (**eCH_4**) emissions, there are very few references based on *in vivo* measurements of eCH_4 in this region. The purpose of this study was to test the assumption that the seasonality of fodder supply impacts intake levels and consequently eCH_4 in ruminants. Thus, eCH_4 was measured *in vivo* in Sudanese Fulani zebu cattle during three main seasons of the year (wet season: **WS**, cold dry season: **CDS**, and hot dry season: **HDS**). The experiment was carried out on 10 steers aged 32 months with an average (± SD) initial BW of 138 ± 5.8 kg (i.e. 0.55 Tropical Livestock Unit – **TLU**) and kept in individual pens. Animals were fed with natural rangeland fodder harvested each season following herders' practices, i.e. green fodder in the WS and dry fodder hay in the CDS and HDS. Different levels of fodder were offered to the animals to reproduce the gradient of fodder availability on rangelands over the year (six trials): 3.3% BW during the CDS; 3.3, 2.3, and 1.4% BW successively during the HDS; and 2.3% in two sequential studies in the WS. Each trial lasted 3 weeks, split into 2 weeks of fodder adaptation and 1 week of data collection. The BW, quantity of voluntary DM intake, digestibility of DM digestibility and of OM digestibility, and eCH_4 (GreenFeed® system) were measured for each animal. Fodder composition varied considerably between seasons ($P < 0.05$). The DM intake (g/kg BW per day) varied from 23.9 in CDS to 15.7 in HDS and 22.3 in WS ($P < 0.001$). The DM digestibility varied from 0.50 in CDS to 0.46 in HDS and 0.57 in WS. The eCH_4 yields (g/kg DM intake per day) varied significantly from 25.2 in the CDS to 31.8 in the HDS and 20.5 in the WS. When extrapolated over a full year and irrespective of season, eCH_4 emissions for steers amounted to 68.1 g/d (24.6 g/kg DM intake per day, 46.7 ± 3.34 kg of eCH_4/TLU per year). Variations in the various parameters recorded in different areas and during the main seasons must therefore be accounted for in national inventories to refine eCH_4 data for ruminants in Sub-Saharan Africa.

Implications

Extensive cattle production systems worldwide are based on natural pastures subject to seasonal variations in terms of availability and quality. The current study provides evidence that these variations affect feed intake, apparent digestibility, and enteric methane emissions in ruminants fed fodder from natural pastures. This study makes a significant contribution by providing the first quantitative assessment of the effects of seasonality on cattle enteric methane emissions. These findings will help tropical countries, especially those in Sub-Saharan Africa, improve their national greenhouse gas inventories for the livestock farming sector, particularly for enteric methane, by accounting for seasonal variations.

Introduction

Pastoral rangelands account for more than 25% of the Earth's land surface, and more specifically, around 40% of Africa's land mass (Tagesson et al., 2015). In Sub-Saharan Africa, these are

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https://doi.org/10.1016/j.animal.2024.101320

regions subject to severe climatic constraints, where pastoralism, the extensive grazing of livestock on natural rangelands, is the dominant agricultural activity. The main livestock species are cattle, sheep, goats, and camels (Vall et al., 2014). High herd mobility is an optimal strategy of pastoralists for adapting to seasonal livestock watering and fodder resource scarcity (McGahey et al., 2014; Manzano et al., 2021). In West African pastoral areas, the availability of both these resources is highly dependent on rainfall, which can vary greatly in both space and time (Sanogo et al., 2015). West Africa's climate is generally characterised by alternating wet (**WS**) and dry seasons. In the literature, the dry season is further divided into cool dry season (**CDS**) and hot dry season (**HDS**).

During the WS, fodder in natural rangelands is green and available in both quantity and quality. During the CDS, the fodder dries out, with a drop in quality but still a sufficient quantity in the form of hay. During the HDS, fodder quality and quantity in the form of hay and litter decline (Linstädter et al., 2013). This seasonal divergence in natural vegetation attributes is exacerbated by both observed and predicted changes in rainfall patterns (Wittig et al., 2007; Sylla et al., 2016). This seasonality leads to instability in fodder supply, whether in terms of species, quantity, quality, or spatial distribution (Amole et al., 2022), and influences the level of fodder intake by grazing animals (Rahimi et al., 2021). In addition, very few farmers have implemented fodder storage and conservation practices. As a result, fodder recovery occurs mostly directly on rangelands (Djohy et al., 2022), and animal productivity is therefore seasonal, with improved performance (milk, meat, reproduction) in the WS and poorer performance in the HDS.

Under these conditions, extensive livestock systems in Sub-Saharan Africa are, rightly or wrongly, regarded as generating the world's highest intensity levels of greenhouse gas emissions (emissions per unit of animal product) (Balehegn et al., 2021), despite the region's modest contribution to global emissions (Assouma et al., 2019). According to Watts et al. (2021), ruminant livestock contributes more than 50% of agricultural greenhouse gas emissions. Depending on the type of ruminant livestock system, enteric methane can contribute up to 51–61% of total carbon emissions from a livestock system (de Figueiredo et al., 2017).

It is recognised that enteric methane (**eCH_4**) emissions are closely linked to the quality and quantity of feed intake (Blaxter and Clapperton, 1965). Compared with cattle breeds raised in temperate environments, local African cattle breeds are considered to produce higher eCH_4 yields and intensities (Assouma et al., 2019) due both to their lower feed intake and production levels, and the methanogenic potential of the feed they ingest. However, these statements are not sufficiently supported by accurate data, as very few direct measurements of eCH_4 have been performed in the context of Sub-Saharan African livestock production. In addition, none of these studies addressed the seasonal variation in eCH_4 emissions in relation to the high seasonal changes in feed quality, quantity, and intake (Amole et al., 2022).

Although a number of studies based on the Intergovernmental Panel on Climate Change (**IPCC**) Tier 2 methodology addressed the issue of eCH_4 seasonality in Sub-Saharan Africa, they were mainly based in East Africa, particularly in Kenya (Goopy et al., 2018, 2021; Ndung'u et al., 2021, 2022), Tanzania, Uganda, and Ethiopia (Korir et al., 2022). None of these studies have been conducted in West Africa. Cattle breeds differ in these two parts of the continent (Strucken et al., 2017; Ouédraogo et al., 2021a) and eCH_4 yields could vary according to the breed and season (Islam et al., 2022). National livestock greenhouse gas inventories in Africa use either the IPCC Tier 1 method with default emission factors or the IPCC Tier 2 method with more detailed approaches based on assumed intake (IPCC, 2019). It is important to validate the resultant eCH_4 emissions using direct and accurate measurement methods.

In this context, the purpose of this study was to compare, across different seasons of the year, the actual intake, digestibility, and eCH_4 emissions from a West African cattle breed (the Sudanese Fulani zebu cattle) kept indoors and fed natural rangeland fodder available in each season. The research question was whether eCH_4 emission factors are affected by season in order to improve regional and national eCH_4 inventories.

Material and methods

Experimental site

The experiment was conducted at the experimental station of the Centre International de Recherche-Développement sur l'Elevage en zone Subhumide (**CIRDES**) located in Bobo-Dioulasso (11°10′37″ latitude North and 4°17′52″ longitude West) in southwestern Burkina Faso (Mapcarta, 2023). The area lies in the Southern Sudanian Savannah zone characterised by a tropical subhumid climate with three seasons: a wet season from May to October, a cold dry season from November to February, and a hot dry season from March to May. The experimental periods are marked by arrows in Fig. 1. The average annual temperature and rainfall were 30 ± 2.5 °C and 1 333 mm, respectively. The study was conducted in a ventilated barn (25 m long × 10 m wide) housing 10 individual pens of 9 m^2 each and an area of 48 m^2 where the eCH_4 measuring unit (GreenFeed® system) was set up.

Animals, feed, and experimental design

Ten steers of the Sudanese Fulani zebu breed with an average (± SD) initial weight of 138 ± 5.8 kg were used. Table 1 outlines the prestudy physical characteristics of the animals over different trials and seasons.

The feed used in this study was natural rangeland fodder (predominantly *Andropogon gayanus* Kunth). It originated from a grazing area (rural commune of Bama) located 20 km from Bobo-Dioulasso (11°23′59″ North, 4°25′46″ West). The fodder was harvested every 2 days during WS and CDS. In HDS, it was harvested and stored at the beginning of the season to ensure its availability at the end of the season. Half of the daily ration was offered to the animals at 0830 h and the other half at 1630 h. Access to mineral licking stone (Reva mineral block®) and drinking water was *ad libitum*.

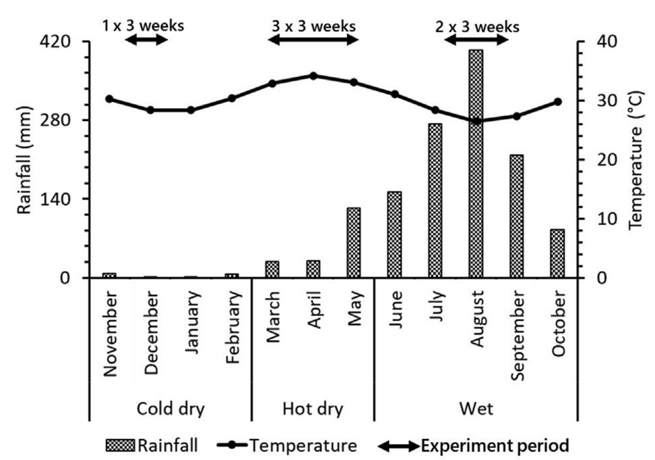

Fig. 1. Rainfall and temperature of Bobo-Dioulasso over the last 10 years (2013–2022), and experiment periods in Sudanese Fulani zebu steers (Historique-Météo, 2023).

Table 1
Average of initial physical characteristics of Sudanese Fulani zebu steers in the different trials and seasons of the year.

Item	Trials							Seasons				
	CDS_3.3	HDS_3.3	HDS_2.3	HDS_1.4	WS1_2.3	WS2_2.3	*P*-value	CDS	HDS	WS	SEM	*P*-value
Age (month)	28.6 [c]	30.7 [b]	31.5 [b]	32.5 [b]	35.5 [a]	36.2 [a]	<0.001	28.6 [C]	31.6 [B]	35.8 [A]	0.43	<0.001
BW (kg)	139.4 [ab]	147.6 [a]	144.5 [ab]	143.7 [ab]	129.8 [b]	131.1 [b]	0.042	139.4 [AB]	145.3 [A]	130.4 [B]	2.09	0.008
Withers height (cm)	106.8	109.7	109.0	109.5	108.8	108.9	0.743	106.8	109.4	108.8	0.53	0.270
Thoracic perimeter (cm)	118.7 [ab]	123.4 [a]	123.6 [a]	123.3 [a]	117.6 [b]	120.8 [ab]	0.016	118.7 [B]	123.4 [A]	119.2 [B]	0.62	0.002
Scapulo ischial length (cm)	109.4 [b]	116.6 [a]	115.2 [a]	117.2 [a]	111.0 [b]	115.5 [a]	<0.001	109.4 [C]	116.3 [A]	113.3 [B]	0.61	<0.001

CDS = cold dry season including 1 trial; HDS = hot dry season including 3 trials; WS = wet season including 2 trials; CDS_3.3 = 3.3% BW of DM offered in cold dry season; HDS_3.3 = 3.3% BW of DM offered in hot dry season; HDS_2.3 = 2.3% BW of DM offered in hot dry season; HDS_1.4 = 1.4% BW of DM offered in hot dry season; WS1_2.3 = 2.3% BW of DM offered during full wet season; WS2_2.3 = 2.3% BW of DM offered tending towards the end of the wet season
[a,b,c]Values within a row with different superscripts differ significantly at $P < 0.05$: comparison between trials.
[A,B,C]Values within a row with different superscripts differ significantly at $P < 0.05$: comparison between seasons.

Seasonal fodder availability was simulated by offering different quantities of fodder during the experiment. Six trials (feeding conditions), spread over the three main seasons of the year, were conducted in this study. In CDS, animals were given a quantity of DM equivalent to 3.3% of their BW (CDS_3.3), as suggested by Ku-Vera et al. (2018). Two consecutive trials of 2.3% BW of feed each were conducted in the WS, at full season (WS1_2.3) and towards the end of season (WS2_2.3), to ensure representativeness due to that season's length. Feed was gradually reduced in the HDS (Tensaba et al., 2023) and spread over three consecutive trials (3.3% BW – HDS_3.3, 2.3% BW – HDS_2.3, and 1.4% BW – HDS_1.4) because of the wide variation in available fodder between the beginning and end of the season. The quantity of feed offered to animals during the WS was probably lower than their ingestion capacity due to logistical constraints during this season. Each trial lasted 3 weeks, split into 2 weeks of feed adaptation and 1 week of data collection, covering BW, feed intake, nutrient digestibility, and gas emissions, including eCH_4.

Measurement and sampling

Body weight, feed intake, and apparent digestibility measurements

Body weight was recorded individually at the beginning and end of each trial. Fodder intake was measured daily by weighing the fodder offered and refused per animal in each trial. Representative samples (300 g) of feed offered and refused (per animal) were collected daily for each animal. Similarly, a sample of the bait used by the GreenFeed® was also collected (see following section below).

Each animal was fitted with a faecal collection bag to which they were accustomed during the feed adaptation phase. During each trial, the bag was placed on the animals on the eve of the experiment and emptied the next day just before the first feed distribution. During each trial, the bags were emptied twice a day (at 1700 h and the following day at 0800 h before the morning feed distribution). A representative sample of 800 g faeces per animal was collected each day. Samples (n_1 = 7 offered, n_2 = 70 refused and n_3 = 70 faeces per trial) were labelled and oven-dried directly at 55 °C for 72 h. The samples were then ground to 1 mm (mill: SM 100, Retsch GmbH, Hann, Germany) and stored individually before being analysed for their chemical composition. The apparent digestibility was calculated as follows:

$$\text{Apparent DM digestibility} = (\text{quantity of DM intake} - \text{quantity of DM excreted}) / \text{quantity of DM intake} \quad (1)$$

Enteric methane and carbon dioxide emissions measurements

The eCH_4 and carbon dioxide (**CO_2**) emissions were measured using a GreenFeed® (ID: 252, C-Lock Inc., SD, USA). The unit was calibrated to dispense a 34-g drop of bait every minute during each animal visit (i.e., a maximum of 0.42 kg of pellets per animal per day). To reduce its effects on intake and emissions, the bait was made up of rangeland fodder and molasses (90:10 ratio). The fodder was ground to pass through a 1-mm sieve before being mixed with molasses. The homogeneous mixture was then pelleted to 8-mm diameter. Refused bait was removed and weighed after each visit to determine the quantity of ingested bait included in the daily feed intake.

Measurement times were tailored to the feeding behaviour of the animals: 0630 h (overnight fast), 1000 h (immediately after feed intake), 1400 h (during rumination), and 1800 h (immediately after feed intake and at sunset). An additional measurement was performed at 0000 h (during total rest) on the 7th day of each trial. In total, each animal visited the GreenFeed® 29 times per trial, exceeding the number of 20 visits recommended by Manafiazar et al. (2017). Each animal spent an average of 3min ± 31s (Min = 2min02s, Max = 4min28s) at the GreenFeed® per measurement. The GreenFeed® was automatically calibrated every day for each gas (at 0400 h, with no animals attending), with a gas mixture being injected at certified concentrations (CH_4: 0.509 ppmv, CO_2: 4.993 ppmv, H_2: 0.010 ppmv and O_2: 0.021 ppmv; Air Liquide, C-Lock Inc., USA). Twice a week, at the beginning and end of each trial, a CO_2 recovery test was conducted and the filter was changed when the airflow fell below 27 L/s. Over the course of the experiment, the average values for airflow, recovery rate, and wind direction were 38.3 ± 2.75 L/s (Min = 28.35, Max = 40.50), 96.5 ± 1.22% (Min = 92.88, Max = 99.89) and 136.3 ± 56.72° (Min = 3.15, Max = 353.83), respectively.

Determination of feed and faecales chemical components

Feed and faecal chemical compositions were predicted using near-IR spectroscopy. The near-IR spectroscopy spectra for all samples were collected on a reflectance spectrometer (Tango model, Bruker Optics GmbH, Ettlingen, Germany), with scanning wavelengths ranging from 11 536 to 3 952 cm^{-1} (8 cm^{-1} step). Calibration models based on 1 890 fodder samples were used to predict fodder ash, CP, NDF, ADF and gross energy. Calibration models based on 690 faecal samples were used to predict faecal ash, nitrogen, NDF, ADF and GE. Standard errors of cross-validation of fodder composition predicting models were 3.0, 1.7, 5.7, 4.5, and 2.3% for ash, CP, NDF, ADF and GE, respectively. The SEs of cross-validation of faecal composition predicting models were 4.7, 0.2, 5.85.7 and 3.1% for ash, nitrogen, NDF, and ADF and GE, respectively. NDF reference analyses following the method suggested by Van Soest et al. (1991) were performed using an Ankom fibre analyser (Ankom® Tech. Co., Fairport, NY, USA). The mineral content was determined by incineration in a muffle furnace for 5 h at 550°C. Total nitrogen content was determined using the Kjeldahl method, and the CP content was calculated as total nitrogen × 6.25. Gross energy reference analyses followed bomb calorimetry measure (IKA calorimeter model C2 000; IKA-Werke GmbH, Staufen, Germany). The chemical composition of the natural rangeland fodder offered in the different trials and seasons of the year is shown in Table 2.

Data preprocessing, annual extrapolation, and statistical analyses

Daily gas emissions calculation

The raw data (n = 1 740) generated by the GreenFeed® were uploaded to the C-Lock website. A total of 74 measurements was removed because of too short visits to the GreenFeed® (< 3 min), bad head position, or head proximity (< 800 raw) to sensors during the monitoring period. The data file acquired from C-Lock included eCH_4 and CO_2 spot measurements (g/d) for each visit and each animal (n = 1 666 data per gas). Subsequently, the outlier gas data, which accounted for 0.36% of the total dataset, were removed following the linear regression approach described by Coppa et al. (2021), resulting in 1 660 data per gas for further analysis. Data from each visit were then averaged per animal and per day to produce individual daily values (eCH_4.P.i) for each gas flow according to Eq. (2) as follows:

$$eCH_4.P.i\,(g/d) = 0.5 * [(eCH_4.1000\ h + eCH_4.1400\ h + eCH_4.1800\ h)/3] + 0.5 * [(eCH_4.0630\ h + eCH_4.0000\ h)/2] \quad (2)$$

With eCH_4.P.i: average eCH_4 emissions (g/d) for visits over the same i period.

Because there were two night-time readings (0000 h and 0630 h) and three daytime readings, the average was weighted by assigning them equal weights.

Data extrapolation over a year

To estimate animal emissions over a year, data measured in the trial were extrapolated to a full year, with weighting based on season length. The average daily intake of DM over a year (Intake.Year) was calculated using Eq. (3) as follows:

$$Intake.Year = [\Sigma(Intake.S_i * D_i)]/365 \quad (3)$$

With Intake.Year: average daily intake (g/d) over a year, Intake.Si: average intake (g/d) for the i^{th} season, and D_i: number of days for the i^{th} season. The Intake.S is the intake (either DM intake or OM intake: kg/d) for a season.

The WS lasts for 5 months (153 days), CDS for 4 months (120 days), and HDS for 3 months (92 days) (Fig. 1).

The average daily production of eCH_4 over a year (eCH_4.P.Year) was calculated using Eqs. (4) and (5) as follows:

$$eCH_4.P.Year = [\Sigma(eCH_4.P.S_i * D_i)]/365 \quad (4)$$

with eCH_4.P.Year: average daily emissions over a year (in g/d), eCH_4.P.S_i: average emissions for the i^{th} season (in g/d) and D_i: number of days of the i^{th} season.

$$eCH_4.BW.Year = [\Sigma(eCH_4.BW.S_i * D_i)]/365 \quad (5)$$

with eCH_4.BW.Year: average daily emissions over a year (in g/kg BW), eCH_4.BW.S_i: average emissions for the i^{th} season (in g/kg BW) and D_i: number of days of the i^{th} season.

The average daily eCH_4 yields over a season (eCH_4.Y.S_i) and a year (eCH_4.Y.Year) were calculated using Eqs. (6) and (7) as follows:

$$eCH_4.Y.S_i = eCH_4.P.S_i / Intake.S_i \quad (6)$$

With eCH_4.Y.S_i: average daily emissions (g/kg intake per day) over a season, eCH_4.P.S_i: average emissions (g/d) for the i^{th} season, and Intake.S_i is the intake (either DM intake or OM intake: kg/d) for the i^{th} season.

$$eCH_4.Y.Year = [\Sigma(eCH_4.P.S_i * D_i)]/[\Sigma(Intake.S_i * D_i)] \quad (7)$$

With eCH_4.Y.Year: average daily emissions (g/kg intake per day) over a year, eCH_4.P.S_i: average emissions (g/d) for the i^{th} season, D_i: number of days in the i^{th} season, and Intake.S_i: intake (either DM intake or OM intake in kg/d) for the i^{th} season.

Statistical analysis

All statistical analyses were performed using R software version 4.1.2. (R Core Team, 2021). Intake, digestibility, CO_2 and eCH_4 data were analysed using the GLM procedure with lme4 (Bates et al., 2015) and lmerTest (Kuznetsova et al., 2017) packages. The model was used to test differences in intake, digestibility, CO_2 and eCH_4 averages between seasons and trials nesting (fixed effects). The random effect of individual animals was also considered, making it possible to control for inter-individual variations. The least squares means and their SEMs were generated for all variables analysed for each factor. These means were compared using the Duncan test (duncan.test) via the agricolae package (de Mendiburu, 2023) in the event of a significant difference ($P < 0.05$). The following statistical model was used for the variance data analysis:

$$Y_{ijk} = \mu + S_i + T_j + (1|A_k) + \epsilon_{ijk}$$

where Y_{ijk} = variable of interest (offered feed component, intake, digestibility, CO_2, eCH_4);

μ = overall average;

S_i = fixed effect representing the different seasons during which the study was conducted (CDS, HDS and WS);

T_j = fixed effect representing trials nesting within each season (1 in CDS, 3 in HDS, and 2 in WS);

Table 2
Chemical composition of natural rangeland fodder offered in the different trials and seasons of the year to Sudanese Fulani zebu steers.

Item	Trials							Seasons				
	CDS_3.3	HDS_3.3	HDS_2.3	HDS_1.4	WS1_2.3	WS2_2.3	*P*-value	CDS	HDS	WS	SEM	*P*-value
DM (g/kg FM)	828.2 [b]	928.1 [a]	934.3 [a]	952.0 [a]	321.8 [c]	330.2 [c]	<0.001	828.2 [B]	938.1 [A]	326.0 [C]	0.47	<0.001
OM (g/kg DM)	886.7 [a]	865.9 [b]	874.2 [ab]	880.7 [a]	851.1 [c]	861.0 [bc]	<0.001	886.7 [A]	873.7 [B]	856.1 [C]	2.40	<0.001
CP (g/kg DM)	41.0 [c]	28.4 [d]	26.5 [d]	26.0 [d]	73.1 [a]	57.7 [b]	<0.001	41.0 [B]	27.0 [C]	65.4 [A]	3.22	<0.001
NDF (g/kg DM)	746.9 [a]	725.9 [a]	744.9 [a]	753.7 [a]	647.5 [b]	672.3 [b]	<0.001	746.9 [A]	741.5 [A]	660.0 [B]	7.35	<0.001
ADF (g/kg DM)	455.1 [b]	451.9 [b]	466.1 [ab]	475.1 [a]	387.3 [d]	406.6 [c]	<0.001	455.1 [A]	464.4 [A]	397.0 [B]	5.47	<0.001
GE (MJ/kg DM)	17.7 [bc]	17.4 [c]	17.4 [c]	17.5 [c]	18.1 [ab]	18.3 [a]	0.001	17.7 [B]	17.4 [B]	18.2 [A]	0.07	0.025

CDS = cold dry season including 1 trial; HDS = hot dry season including 3 trials; WS = wet season including 2 trials; CDS_3.3 = 3.3% BW of DM offered in cold dry season; HDS_3.3 = 3.3% BW of DM offered in hot dry season; HDS_2.3 = 2.3% BW of DM offered in hot dry season; HDS_1.4 = 1.4% BW of DM offered in hot dry season; WS1_2.3 = 2.3% BW of DM offered during full wet season; WS2_2.3 = 2.3% BW of DM offered tending towards the end of the wet season
FM = fresh matter; OM = organic matter; GE = gross energy.
[a,b,c,d]Values within a row with different superscripts differ significantly at $P < 0.05$: comparison between trials.
[A,B,C]Values within a row with different superscripts differ significantly at $P < 0.05$: comparison between seasons.

A_k = random effect representing individual variations among animals (n = 10); and

ϵ_{ijk} = residual error.

However, the interaction between seasons and trial nesting could not be estimated because of the unequal number of trials conducted in each season. The main objective of this analysis was to assess the effects of seasons and trials nesting on the variables of interest. Despite the absence of an interaction, the main effects of seasons or trials nesting provide further insights into the observed variations, which was crucial for our analysis. The results of all trials are shown in tables. For each season (HDS and WS), the means calculated from the trial data were presented as seasonal data.

Results

Seasonal quality of rangeland fodder

The quality of the rangeland fodder offered to the animals varied significantly (Table 2) between the different seasons of the year (P < 0.001) for all parameters except gross energy. No significant differences were observed within the same season. The WS fodder contained 1.6–2.4 times more CP than the fodder from both dry season periods, with the HDS fodder having the lowest CP value. In contrast, the NDF and ADF contents of WS fodder were lower than those of fodder harvested in both dry season periods.

Seasonal and annual extrapolation of intake, and apparent digestibility of rangeland fodder

The DM intake varied (P < 0.001) between 15.7 and 23.9 g/kg BW across the different seasons of the year (Table 3). Average animal intake was 97% of the feed offered in the WS, 71% in CDS, and 66% in HDS. Within trials, the lowest DM intake was recorded at the end of HDS and the highest in the CDS. Regarding the refusal rate (3% of offered) in the WS, the average quantity intake in this season refers to a lower feed quantity provided to the animal per day compared to the normal they could find in a real environment. The chemical compositions of the feed offered and of the refusals were significantly different (Table 4). The average daily DM intake per animal over a year was 2.9 kg/d, which equates to 21.2 ± 1.52 g DM/kg BW per day or 5.3 ± 0.38 kg/tropical livestock unit (**TLU**) per day.

There was a positive correlation between DM digestibility, OM digestibility, and gross energy digestibility both within trials and between seasons. The lowest values for these parameters were recorded in the HDS (Table 5). The CP apparent digestibility values were very low, close to 0 in CDS (0.04) and HDS (0.08). The digestibility of fibres (NDF and ADF) was significantly lower in HDS than in the other two seasons.

Seasonal gas emissions and annual extrapolation

The eCH_4 emissions per animal varied from 58.6 g/d in the WS to 83.2 g/d in the CDS (Table 6). There were no significant differences within the same season. This production increased significantly by 42 and 21.5%, respectively, in the CDS and HDS, compared with the WS. The amounts of CO_2 produced in the WS and the HDS were not markedly different, whereas the value recorded in the CDS was 14.3% higher than that in the WS. The seasonal eCH_4 yield (g/kg DM intake) was also the lowest in the WS but increased by 23.2 and 55.6%, in the CDS and HDS, respectively. The average annual value of eCH_4 emissions was 68.1 g/d, which equals to 24.85 kg/year, 0.50 g/kg BW per day, 24.6 g/kg DM intake per day, 28.3 g/kg OM intake per day or 46.7 kg/TLU per year.

Discussion

Seasonal quality of rangeland fodder

In Sub-Saharan Africa, rangeland fodder is the main feed source for ruminants on extensive farms (Hiernaux and Le Houerou, 2006). In the Sudanian area of Burkina Faso, it mostly consists of species of the Andropogon genus, (Ouédraogo et al., 2021b; Sawadogo et al., 2005). The nutritional value of the rangeland fodder used in this study significantly varied between seasons.

During vegetative growth (WS), when there are adequate levels of feed for ruminants in Sub-Saharan Africa (Linstädter et al., 2013), fodder quality remains relatively low, with an average CP content of 6.54 and an OM digestibility of 0.57. The quality of this fodder is lower than that of rangeland fodder found in dry tropical regions in the WS (CP: 13.6% DM, NDF: 66.7% DM, ADF: 33.2% DM), as reported by INRA (2018). However, it is close to that of 8-week-old regrowth of irrigated green *Panicum maximum* (K 187B Orstom variety) (CP: 6.9% DM, NDF: 76% DM, ADF: 44.1% DM, OM digestibility: 0.54) reported by INRA (2018) in a dry tropical area during the HDS. A sharp decline in the quality of rangeland fodder can be expected at the end of WS, as documented by Müller et al. (2019) in South Africa. By the CDS, CP content decreased by 37% in this study, with an OM digestibility of 0.53. This is due to rangeland plant senescence (Sbrissia et al., 2020). In HDS, the CP content decreased by a further 34%, down around 60% in WS. The OM digestibility value obtained in the current study for WS fodder is lower than that reported by INRA (2018) for standing rangeland fodder at the vegetative stage during the month of August in the dry tropics.

Table 3
Daily intake by Sudanese Fulani zebu steers in the different trials and seasons of the year.

Item	Trials							Seasons				
	CDS_3.3	HDS_3.3	HDS_2.3	HDS_1.4	WS1_2.3	WS2_2.3	P-value	CDS	HDS	WS	SEM	P-value
DM offered (kg)	4.7 ^{a}	4.9 ^{a}	3.4 ^{b}	2.0 ^{d}	3.0 ^{bc}	2.9 ^{c}	<0.001	4.7 ^{A}	3.4 ^{B}	2.9 ^{C}	0.16	<0.001
DM refused (kg)	1.4 ^{b}	2.0 ^{a}	1.3 ^{c}	0.4 ^{d}	0.05 ^{d}	0.09 ^{d}	<0.001	1.4 ^{A}	1.2 ^{A}	0.07 ^{B}	0.25	<0.001
DMI (kg)	3.3 ^{a}	2.4 ^{c}	2.4 ^{c}	2.0 ^{d}	3.1 ^{a}	2.7 ^{b}	<0.001	3.3 ^{A}	2.3 ^{C}	2.9 ^{B}	0.07	<0.001
DMI (g/kg BW)	23.9 ^{a}	16.4 ^{c}	16.8 ^{c}	13.9 ^{d}	22.8 ^{ab}	21.8 ^{b}	<0.001	23.9 ^{A}	15.7 ^{C}	22.3 ^{B}	0.53	<0.001
OMI (kg)	2.9 ^{a}	2.2 ^{c}	2.1 ^{c}	1.8 ^{d}	2.6 ^{b}	2.4 ^{bc}	<0.001	2.9 ^{A}	2.0 ^{C}	2.5 ^{B}	0.06	<0.001
OMI (g/kg BW)	20.9 ^{a}	14.9 ^{c}	14.5 ^{c}	12.5 ^{d}	19.5 ^{b}	18.8 ^{b}	<0.001	20.9 ^{A}	14.0 ^{C}	19.2 ^{B}	0.44	<0.001

CDS = cold dry season including 1 trial; HDS = hot dry season including 3 trials; WS = wet season including 2 trials; CDS_3.3 = 3.3% BW of DM offered in cold dry season; HDS_3.3 = 3.3% BW of DM offered in hot dry season; HDS_2.3 = 2.3% BW of DM offered in hot dry season; HDS_1.4 = 1.4% BW of DM offered in hot dry season; WS1_2.3 = 2.3% BW of DM offered during full wet season; WS2_2.3 = 2.3% BW of DM offered tending towards the end of the wet season
DMI = DM intake; OMI = organic matter intake.
[a,b,c,d]Values within a row with different superscripts differ significantly at P < 0.05: comparison between trials.
[A,B,C]Values within a row with different superscripts differ significantly at P < 0.05: comparison between seasons.

Table 4
Chemical composition of intake and refusal fodder by Sudanese Fulani zebu steers across different seasons of the year.

Item	Season											
	CDS				HDS				WS			
	Intake	Refusal	SEM	*P*-value	Intake	Refusal	SEM	*P*-value	Intake	Refusal	SEM	*P*-value
OM (g/kg DM)	875 [b]	906 [a]	4.0	<0.001	887 [a]	863 [b]	3.6	<0.001	853 [b]	887 [a]	3.1	<0.001
CP (g/kg DM)	49 [a]	27 [b]	2.6	<0.001	28	25	0.4	0.080	68 [a]	41 [b]	2.4	<0.001
NDF (g/kg DM)	704 [b]	819 [a]	14.0	<0.001	757	733	4.5	0.251	652 [b]	749 [a]	8.7	<0.001
ADF (g/kg DM)	427 [b]	503 [a]	9.5	<0.001	474	463	3.6	0.127	390 [b]	480 [a]	8.2	<0.001
GE (MJ/kg DM)	18	18	0.1	0.254	18	17	0.1	0.263	18	18	0.1	0.457

CDS = cold dry season including 1 trial; HDS = hot dry season including 3 trials; WS = wet season including 2 trials;
OM = organic matter; GE = gross energy; MJ = megajoule.
[a,b]Values within a row and season with different superscripts differ significantly at $P < 0.05$.

Table 5
Apparent digestibility of feed intake by Sudanese Fulani zebu steers across different trials and seasons of the year.

Item	Trials							Seasons				
	CDS_3.3	HDS_3.3	HDS_2.3	HDS_1.4	WS1_2.3	WS2_2.3	*P*-value	CDS	HDS	WS	SEM	*P*-value
DM (kg/kg DM)	0.50 [b]	0.46 [c]	0.47 [c]	0.46 [c]	0.61 [a]	0.53 [b]	<0.001	0.50 [B]	0.46 [C]	0.57 [A]	0.008	<0.001
OM (kg/kg OM)	0.53 [b]	0.50 [c]	0.49 [c]	0.49 [c]	0.61 [a]	0.53 [b]	<0.001	0.53 [B]	0.49 [C]	0.57 [A]	0.007	<0.001
CP (kg/kg CP)	0.04 [b]	0.00 [b]	0.14 [ab]	0.11 [ab]	0.30 [a]	0.29 [a]	0.009	0.04 [B]	0.08 [B]	0.29 [A]	0.030	0.002
NDF (kg/kg NDF)	0.54 [ab]	0.52 [b]	0.51 [b]	0.51 [b]	0.62 [a]	0.57 [ab]	0.020	0.54 [B]	0.51 [B]	0.60 [A]	0.005	0.001
ADF (kg/kg ADF)	0.59 [ab]	0.56 [b]	0.54 [b]	0.54 [b]	0.62 [a]	0.56 [b]	<0.001	0.59 [A]	0.54 [B]	0.58 [A]	0.006	<0.001
GE (kg/kg GE)	0.55 [c]	0.51 [d]	0.49 [de]	0.47 [e]	0.65 [a]	0.58 [b]	<0.001	0.55 [B]	0.48 [C]	0.61 [A]	0.009	<0.001

CDS = cold dry season including 1 trial; HDS = hot dry season including 3 trials; WS = wet season including 2 trials; CDS_3.3 = 3.3% BW of DM offered in cold dry season; HDS_3.3 = 3.3% BW of DM offered in hot dry season; HDS_2.3 = 2.3% BW of DM offered in hot dry season; HDS_1.4 = 1.4% BW of DM offered in hot dry season; WS1_2.3 = 2.3% BW of DM offered during full wet season; WS2_2.3 = 2.3% BW of DM offered tending towards the end of the wet season;
OM = organic matter; GE = gross energy.
[a,b,c,d,e]Values within a row with different superscripts differ significantly at $P < 0.05$: comparison between trials.
[A,B,C]Values within a row with different superscripts differ significantly at $P < 0.05$: comparison between seasons.

Table 6
Emissions of CO_2 and eCH_4 by Sudanese Fulani zebu cattle across different trials and seasons of the year.

Item	Trials							Seasons				
	CDS_3.3	HDS_3.3	HDS_2.3	HDS_1.4	WS1_2.3	WS2_2.3	*P*-value	CDS	HDS	WS	SEM	*P*-value
CO_2 (g/d)	2 127 [a]	1 868 [b]	1 781 [b]	1 781 [b]	1 840 [b]	1 835 [b]	0.003	2127 [A]	1810 [B]	1838 [B]	7.0	0.025
eCH_4 (g/d)	83.2 [a]	73.2 [ab]	72.2 [ab]	68.2 [ab]	56.7 [b]	60.4 [b]	0.002	83.2 [A]	71.2 [A]	58.6 [B]	2.15	<0.001
eCH_4 (g/kg BW)	0.60 [a]	0.50 [ab]	0.50 [ab]	0.48 [ab]	0.42 [b]	0.48 [ab]	0.018	0.60 [A]	0.49 [B]	0.45 [B]	0.024	0.001
eCH_4 (g/kg DMI)	25.2 [bc]	30.6 [ab]	30.3 [ab]	34.5 [a]	18.7 [c]	22.2 [c]	<0.001	25.2 [B]	31.8 [A]	20.5 [C]	1.09	<0.001
eCH_4 (g/kg OMI)	28.8 [bc]	33.9 [ab]	34.4 [ab]	39.0 [a]	21.9 [c]	25.7 [bc]	<0.001	28.8 [B]	35.8 [A]	23.8 [B]	1.21	<0.001
eCH_4 (g/kg dDMI)	50.4 [b]	66.4 [a]	66.1 [a]	74.7 [a]	30.8 [c]	42.3 [bc]	<0.001	50.4 [B]	69.1 [A]	36.6 [C]	2.69	<0.001
eCH_4 (g/kg dOMI)	53.9 [bc]	67.5 [ab]	70.8 [a]	80.0 [a]	35.8 [d]	48.2 [cd]	<0.001	53.9 [B]	72.8 [A]	42.0 [C]	2.73	<0.001
eCH_4 (% GEI)	7.9 [bc]	9.3 [ab]	9.6 [ab]	11.0 [a]	5.8 [c]	6.8 [c]	<0.001	7.9 [B]	10.0 [A]	6.3 [C]	0.35	<0.001

CDS = cold dry season including 1 trial; HDS = hot dry season including 3 trials; WS = wet season including 2 trials; CDS_3.3 = 3.3% BW of DM offered in cold dry season; HDS_3.3 = 3.3% BW of DM offered in hot dry season; HDS_2.3 = 2.3% BW of DM offered in hot dry season; HDS_1.4 = 1.4% BW of DM offered in hot dry season; WS1_2.3 = 2.3% BW of DM offered during full wet season; WS2_2.3 = 2.3% BW of DM offered tending towards the end of the wet season
CO_2 = carbon dioxide; eCH_4 = enteric methane; DMI = DM intake; dDMI = digestible DM intake; OMI = organic matter intake; dOMI = digestible organic matter intake; GEI = gross energy intake.
[a,b,c,d]Values within a row with different superscripts differ significantly at $P < 0.05$: comparison between trials.
[A,B,C]Values within a row with different superscripts differ significantly at $P < 0.05$: comparison between seasons.

The NDF content increased by an average of 13% in the dry season compared with that in WS. Fournier (1991) showed in southern Burkina Faso that the first evolutionary phase of rangeland fodder during its cycle is the vegetative growth, which lasts until July-August (in the middle of WS). Flowering begins in August and signals the end of fodder stem elongation. However, fodder blooms and bears fruit later, in September and October (at the end of WS), and all seeds drop by November (beginning of CDS). Senescence, which refers to the process by which fodder dries out and loses part of its living matter, begins shortly after fruiting (at the end of the CDS), according to this author. It should be noted that at the end of HDS, rangeland fodder consists of hay and litter, hence its poor nutritional quality.

The gross energy value recorded in the current study is consistent with that reported by Pathot and Berhanu (2023), who collected fodder at different stages (growth, anthesis and maturity) in Ethiopia. Similar to our observations, these authors found no significant difference in gross energy between the different stages of fodder development. OM and DM apparent digestibilities decline from WS to dry season. In principle, the feed's degradation potential remains the same, but ruminal metabolism, which is severely disrupted by the lack of nitrogen, reduces *in vivo* degradation efficiency. The apparent digestibility of CP is low, particularly in the dry season, when feed CP flow is very limited. Recycling and catabolism resulting from underfeeding led to faecal nitrogen loss. The slight decrease in fibre (NDF and ADF) digestibility in HDS is consistent with progressing plant maturity and the onset of senescence (Xu et al., 2023).

This study found a positive correlation between DM digestibility and OM digestibility, in agreement with Dilaga et al. (2022). For the different constituents, the digestibility values recorded in CDS generally lie between those recorded in WS and HDS. This is probably due to the moderate fibre and protein quality of rangeland fodder during that season compared with other seasons.

Seasonal and annual intake

Data from this study are based on trials conducted in a barn under controlled conditions. Animals were fed with natural rangeland resources across different seasons, and intake conditions did not account for animal movements for fodder selection, which is a feature of pastoral livestock systems (Ayantunde et al., 1999). Intake levels depend as much on the animal (size of its digestive tract, its needs for maintenance, its production) as on the feed (nutrient concentrations, morphological characteristics, offered quantity) and the environment (resource abundance, climate) (Decruyenaere et al., 2009).

In the dry season, *ad libitum* intake was low. In the CDS, the refusal rate was approximately 30% (3.35% BW DM offered vs 2.38% BW DM intake), proving that the animals were being fed *ad libitum* (Boval et al., 1996). Intake was approximately 2.4% BW, which is consistent with the standard of 2.5% BW suggested by Rivière (1991) and used in Sub-Saharan Africa to estimate intake by grazing ruminants. In the HDS, refusal rates were over 50% during the first two trial periods, with an average intake of only 1.6% BW. The composition of the refusals did not vary from that of the fodder offered. This was therefore not the result of diet selection by the animals but rather of their reduced intake capacity linked to the ration's fill capacity and lower quality. During the 3rd period, quantities offered were greatly reduced (1.4% BW) and refusal rates were very low, suggesting a slight dietary restriction. On average, the DM intake was 1.6% BW over the entire HDS (2.36% BW DM offered vs 1.57% BW DM intake), which has to be seen in relation to the very low quality of fodder and in particular its low CP content. The lower CP content of the feed most likely resulted in nitrogen limitation in the rumen, leading to a reduced microbial activity. This has consequences on the capacity of degradation or structural carbohydrates (Beckers, 2013), and on the microbial protein production. Ruminal function is disrupted and feed degradation is low, as reported by Fanchone et al. (2012), leading to high fodder fill (Beckers, 2013). This is the season during which the animals draw on their body reserves and lose a considerable amount of BW. During the experiment, water was provided and consumed by the animals *ad libitum*, whereas in real-life rangeland conditions, water is consumed once a day or sometimes every 2 days. This could be a limiting factor for feed intake. Water availability in this study could lead to higher digestibility than in real-life conditions.

In the WS, the quantities of fodder offered (2.3% BW) were probably much lower than the *ad libitum* quantity because there were virtually no refusals (< 5%). The small amount of residual feed (2.28% BW DM offered vs 2.23% BW DM intake) with a very different composition to that offered shows that the selection process only eliminates some of the less palatable and more lignified parts of the fodder. Differences in intake were affected by the amount offered, for WS and for the lower levels fed in the end of HDS, consequence of the feeding rules in the study. The lower feed offered could lead to lower eCH_4 emissions in WS. Consequently, the emissions factor found in this season must be used with caution.

The initial weights of the animals during the HDS and WS trials clearly indicate that they were experiencing compensatory growth in the WS. The age at which the restriction is imposed and its severity and duration are factors that can influence compensatory growth (Hoch et al., 2003). In addition, the animals in our study were in the middle of growth. Their metabolism and intake capacity were probably increased in the WS (Keady et al., 2021; Moura et al., 2022). The increase in intake during the compensatory phase can range from 3 to 24% and last up to 100 days (Hoch et al., 2003). Local cattle are subjected to this feeding pattern (abundance-restriction-abundance) throughout the year and are therefore suited or accustomed to it in Sub-Saharan Africa.

For tropical cattle, Rivière (1991) set a standard of 6.25 kg DM intake per TLU (250 kg BW cattle) per day. Assouma et al. (2018) reported 115–140 kg grazing steers 9.6–26.1 g DM intake/kg BW daily that corresponds to the intake range we identified. The annual mean value obtained in the current study is consistent with the 20–30 g DM/kg BW equivalence reported by Boudet and Rivière (1968).

Seasonal enteric methane emissions

This research was conducted with a view to mimicking the quality and quantity of fodder available on rangelands over a year. Strong variations in feed intake due to fodder quality led to large seasonal variations in eCH_4 production. Alvarado-Bolovich et al. (2021) reported that higher DM intake and dietary DM digestibility lead to greater carbohydrate degradation and higher production of eCH_4, but in the current study, eCH_4 production was highest during CDS despite the lowest digestibility (of DM and OM) compared with WS. This is due to feed restriction during the WS. If the feed intake had been greater (*ad libitum*) in WS, eCH_4 values would have been higher, as reported by Perry et al. (2017).

The eCH_4 yield (g/kg DM intake) was greater by 23 and 36% in CDS and HDS, respectively, compared with WS. It is commonly known that high digestibilities of ADF and NDF are associated with a high daily eCH_4 yield (Benaouda et al. 2023), as is the case in CDS and HDS compared with WS. This observation was likely due to impaired ruminal function, with a high retention time but low degradation efficiency. Lower values of DM digestibility between CDS and HDS may mainly be due to differences in their CP, NDF, and ADF contents, which are related to fodder quality. There is therefore significant scope for action on eCH_4 if ruminal metabolism is improved, primarily through nitrogen supplementation (Archimède et al., 2011). The eCH_4 seasonal emission response curve needs to be studied more closely so that predictive models can be developed considering DM intake and CP content. The recorded eCH_4 yields are close to those reported by Díaz-Céspedes et al. (2021) for Brahman steers fed on tropical pastures in Peru.

According to Boadi et al. (2002), eCH_4 emissions per unit of digestible DM intake and digestible OM intake can decline as DM digestibility and OM digestibility increase. Our results reflect these findings as significant decreases of 27 and 47% (g/kg digestible DM intake per day) in eCH_4 were observed in CDS and WS, respectively, compared with HDS. These drops in eCH_4 amounted to 25 and 42% (g/kg digestible OM intake per day), respectively, in CDS and WS compared with HDS.

Extrapolation of enteric methane to an annual time scale

Extrapolation to an annual time scale provides the magnitude of eCH_4 emissions from Fulani zebu cattle–fed natural fodder throughout the year. The seasonally weighted average annual eCH_4 emissions from steers in this study (eCH_4.Year) was 68.1 g/d (i.e. 24.85 kg/year or 0.50 g/kg BW per day or 24.63 g/kg DM intake per day or 28.29 g/kg OM intake per day or 46.69 kg/TLU per year). According to the IPCC Tier 1 (2019), the estimated value is 52 kg/TLU per year per growing animal. These default emission factors used in the inventories of some Sub-Saharan African countries exceed the annual average obtained in the current study. This discrepancy is due to differences in the measurement method, weight of the animals, and feed quantity offered. In addition, Tier

1 uses default eCH_4 emission factors that provide fixed values for each animal species in different regions of the world, regardless of variations in the physiological state of the animal or the level of production.

Under IPCC Tier 2, the average annual emissions are estimated at 23.3 g of eCH_4/kg DM intake per day for non-dairy cattle on a forage-based diet (>70%) with a DM digestibility < 0.62. This value is close to ours (100% fodder and DM digestibility < 0.58) and confirms the strength of the IPCC Tier 2 references, which could be used over a year but not for each season in contexts where no references based on direct measurements are available. However, a limitation of the current study was the feed intake below *ad libitum* in the WS. The eCH_4 yield value (20.4 g/kg DM intake) recorded in this season must be improved despite the green fodder having the characteristics proposed by the IPCC for diets with greater than 70% forage and DM digestibility less than 0.62. Even if the eCH_4 yield value recorded in CDS (25.2 g/kg DM intake) corroborates that IPCC value, the HDS eCH_4 yield (31.8 g/kg DM intake) is higher and could lead us to say that IPCC Tier 2 value, although accurate over the year is not accurate over all seasons. The feeding restriction applied towards the end of the HDS was intended to mimic the availability of fodder on rangeland during this season and cannot be considered equivalent to the WS restriction that was an experimental outcome. To a certain extent, the IPCC Tier 2 value can be used in Sub-Saharan Africa in HDS with a great caution.

A few studies conducted in Sub-Saharan Africa using different eCH_4 measurement methods have reported variable eCH_4 emissions from cattle. van Wyngaard et al. (2018) obtained 323 g/d, equating to 29.1 g eCH_4/kg DM intake per day, using the SF_6 method in 391 kg of BW Jersey cows grazing predominantly *Pennisetum clandestinum* during the summer in South Africa. In the same country, Slayi et al. (2023) measured eCH_4 with a laser methane detector in 381 kg of BW cows on a natural pasture and reported 26.42 g of eCH_4/kg DM intake per day. In Kenya, eCH_4 measurements carried out on-station with a methane chamber on 148 kg Holstein $\times$ Boran heifers fed wheat stalks and Rhodes hay revealed 93.1 g of eCH_4/day and 30.6 g of eCH_4/kg DM intake per day (Ali et al., 2019). Wolz et al. (2022) reported 75.4 kg/year for mature females weighing 420 kg on-station in a Kenyan park using a micro-meteorological method (backward Lagrangian Stochastic). Within direct measurements, factors such as methods used (Münger et al., 2018), breed and season in those studies compared with our conditions could also affect eCH_4 yield (Islam et al., 2022).

Comparing our results with some estimations using IPCC Tier 2 in Sub-Saharan African grazing steers fed 100% rangeland fodder, Gwatibaya et al. (2023) found similar eCH_4 productions over a year (kg/TLU) (DM digestibility = 539 g/kg DM). In contrast, du Toit et al. (2013), Kouazounde et al. (2015), and Tongwane and Moeletsi, 2020 reported higher eCH_4 production over a year (kg/TLU) with DM digestibility values of 558, 540, and 549 g/kg DM, respectively. These differences support the hypothesis that direct measurement of eCH_4 emission does not yield the same results as estimation methods. The fodder used in the current study and its chemical composition are linked to season in Sub-Saharan Africa livestock systems, justifying the importance of this study in measuring seasonal emissions. However, the absolute values recorded in the current study can still be improved given that many factors differ between the experimental conditions and the field conditions.

Our eCH_4 measurements were scheduled for different periods to include times of a ruminant behaviour (fasting, after eating, rest, rumination) on pasture. This methodology is different from that of Hristov et al. (2015) who performed eight measurements in 3 days for 24 h. *Ad libitum* intake on pasture during the WS would probably be higher if the animals had easy access to fodder, without having to make long journeys. In the dry season, the animals were fed *ad libitum* (except marginally at the end of the HDS), but their feed consumption on pasture would undoubtedly have been different. It would probably be lower because the animals would have walked for long distances and hours in search of fodder. Intermittent watering can also decrease intake and digestibility. However, under actual conditions, a slight supplementation could occur in some cases, either through the selection of more nitrogen-rich plants (shrubs, woody species) or through a supplementation provided by the farmer. Although limited, such supplementation could have a significant impact on ruminal metabolism, digestibility, and voluntary intake.

In conclusion, this study was conducted to compare the actual intake, digestibility, and eCH_4 emissions across different seasons of the year. It showed that the quality of natural rangeland fodder in Sub-Saharan Africa is poorer in HDS and better in WS. In CDS, this fodder is of moderate quality, offering an intermediate quality between those of the other two seasons and resulting in a higher DM intake than that of WS because the animals were restricted. The eCH_4 production and yields in steers fed with this fodder were therefore lower in the WS. The data obtained in this study for annual emissions are therefore indicative. A potential underestimation of eCH_4 yield cannot be discarded because of the unanticipated feed restriction. Therefore, it is necessary to feed the animals *ad libitum* during the WS and consider the seasonality of both resources and emissions to improve the annual emissions values obtained in the current study, to align estimates as closely as possible with ruminant feeding practices and compare them with the IPCC default value. This experiment was carried out on-station, and its findings relate to the value of fodder available for grazing rather than value of fodder grazed by animals on rangelands. Given the feeding behaviour of cattle on pasture (free choice, movement, group effect, influence of the environment, etc.), on-station intake during the various seasons of the year could differ from that of animals on natural rangelands. The current study must be reproduced using both different cattle categories and pasture types during all seasons of the year to further improve the emission factors for use in agricultural greenhouse gas inventories in the region.

Ethics approval

Approval from the CIRDES Ethics Committee for Animal Experiments dated 15/04/2021 for application No. 006/Mars/2021/CE-CIRDES.

Data and model availability statement

None of the data were deposited in an official repository. All data are available from the authors upon request.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) did not use any AI and AI-assisted technologies.

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Declaration of interest

None.

Acknowledgements

The authors wish to thank Florentin SANOU, Kaoussarath ADAMOU and Saïdou BOLI (CIRDES, 454 Bobo-Dioulasso, Burkina Faso) for their support during data collection; Yvanne ROCHETTE (INRAE, UMR 1213 Herbivores, 63122 Saint-Genès-Champanelle, France) and Michel OROUNLADJI (CIRDES, 454 Bobo-Dioulasso, Burkina Faso) respectively for assistance with data quality assurance and analysis; and Donato Andueza (INRAE, UMR 1213 Herbivores, 63122 Saint-Genès-Champanelle, France) for advice on spectral data.

Financial support statement

This study was made possible through the support of the "Carbon Sequestration and greenhouse gas emissions in (agro) Sylvopastoral Ecosystems in the sahelian CILSS States" (CaSSECS) regional project funded by the European Union (European DeSIRA programme, under grant agreement No. FOOD/2019/410-169).

References

Ali, A.I.M., Wassie, S.E., Korir, D., Merbold, L., Goopy, J.P., Butterbach-Bahl, K., Dickhoefer, U., Schlecht, V., 2019. Supplementing tropical cattle for improved nutrient utilization and reduced enteric methane emissions. Animals 9, 1–17. https://doi.org/10.3390/ani9050210.

Alvarado-Bolovich, V., Medrano, J., Haro, J., Castro-Montoya, J., Dickhoefer, U., Gomez, C., 2021. Enteric methane emissions from lactating dairy cows grazing cultivated and native pastures in the high Andes of Peru Víctor. Livestock Science 243, 104385. https://doi.org/10.1016/j.livsci.2020.104385.

Amole, T., Augustine, A., Balehegn, M., Adesogoan, A.T., 2022. Livestock feed resources in the West African Sahel. Agronomy Journal 114, 26–45. https://doi.org/10.1002/agj2.20955.

Archimède, H., Eugène, M., Magdeleine, C.M., Boval, M., Martin, C., Morgavi, D.P., Lecomte, P., Doreau, M., 2011. Comparison of methane production between C3 and C4 grasses and legumes. Animal Feed Science and Technology 166–167, 59–64. https://doi.org/10.1016/j.anifeedsci.2011.04.003.

Assouma, M.H., Lecomte, P., Hiernaux, P., Ickowicz, A., Corniaux, C., Decruyenaere, V., Diarra, A.R., Vayssieres, J., 2018. How to better account for livestock diversity and fodder seasonality in assessing the fodder intake of livestock grazing semi-arid sub-Saharan Africa rangelands. Livestock Science 216, 16–23. https://doi.org/10.1016/j.livsci.2018.07.002.

Assouma, M.H., Lecomte, P., Corniaux, C., Hiernaux, P., Ickowicz, A., Vayssieres, J., 2019. Pastoral landscapes in the Sahel: a carbon balance with unexpected potential for climate change mitigation. Perspective 52, 1–4 https://hal.science/cirad-02384064.

Ayantunde, A.A., Hiernaux, P., Fernández-Rivera, S., van Keulen, H., Udo, H.M.J., 1999. Selective grazing by cattle on spatially and seasonally heterogeneous rangeland in Sahel. Journal of Arid Environments 42, 261–279. https://doi.org/10.1006/jare.1999.0518.

Balehegn, M., Kebreab, E., Tolera, A., Hunt, S., Erickson, P., Crane, T.A., Adesogan, A.T., 2021. Livestock sustainability research in Africa with a focus on the environment. Animal Frontiers 11, 47–56. https://doi.org/10.1093/af/vfab034.

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. Journal of Statistical Software 67, 1–48. https://doi.org/10.18637/jss.v067.i01.

Beckers, Y., 2013. A balanced diet for bovines: strategies to improve the efficiency of nitrogen use. Biotechnology, Agronomy, Society and Environment 17, 243–250.

Benaouda, M., González-Ronquillo, M., Avilés-Nova, F., Vázquez-Carrillo, M.F., Castelán-Ortega, O.A., 2023. Effect of fiber digestibility on methane emission, milk production and quality in dairy cattle. Archivos Latinoamericanos de Producción Animal 31, 213–220 www.doi.org/10.53588/alpa.310538.

Blaxter, K.L., Clapperton, J.L., 1965. Prediction of the amount of methane produced by ruminants. British Journal of Nutrition 19, 511–522. https://doi.org/10.1079/BJN19650046.

Boadi, D.A., Wittenberg, K.M., McCaughey, W.P., 2002. Effects of grain supplementation on methane production of grazing steers using the sulphur (SF6) tracer gas technique. Canadian Journal of Animal Science 82, 151–157.

Boudet, G., Rivière, R., 1968. Practical use of fodder analysis to assess the value of tropical pastures. Revue D'elevage et De Médecine Vétérinaire Des Pays Tropicaux 21, 227–266.

Boval, M., Peyraud, J.l., Xande, A., Aumont, G., Coppry, O., Saminadin, G., 1996. Evaluation of faecal indicators to predict digestibility and voluntary intake of Dichanthium sp by cattle. Annales de Zootechnie 45, 121–134 https://hal.science/hal-00889547.

Coppa, M., Jurquet, J., Eugene, M., Dechaux, T., Rochette, Y., Lamy, J.M., Ferlay, A., Martin, C., 2021. Repeatability and ranking of long-term enteric methane emissions measurement on dairy cows across diets and time using GreenFeed system in farm-conditions. Methods 186, 59–67. https://doi.org/10.1016/j.ymeth.2020.11.004.

de Figueiredo, E.B., Jayasundara, S., de Oliveira Bordonal, R., Berchielli, T.T., Reis, R.A., Wagner-Riddle, C., La Scala Jr., N., 2017. Greenhouse gas balance and carbon footprint of beef cattle in three contrasting pasture-management systems in Brazil. Journal of Cleaner Production 142, 420–431. https://doi.org/10.1016/j.jclepro.2016.03.132.

de Mendiburu, F., 2023. Agricolae: Statistical Procedures for Agricultural Research. R package version 1.3-3. Accessed 14 May 2023 on: https://CRAN.R-project.org/package=agricolae.

Decruyenaere, V., Buldgen, A., Stilmant, D., 2009. Factors affecting intake by grazing ruminants and related quantification methods: a review. Biotechnologie, Agronomie Société et Environnement 13, 559–573.

Díaz-Céspedes, M., Hernández-Guevara, J.E., Gómez, C., 2021. Enteric methane emissions by young Brahman bulls grazing tropical pastures at different rainfall seasons in the Peruvian jungle. Tropical Animal Health and Production 53, 421. https://doi.org/10.1007/s11250-021-02871-4.

Dilaga, S.H., Putra, R.A., Pratama, A.N.T., Yanuarianto, O., Amin, M., Suhubdy, S., 2022. Nutritional quality and in vitro digestibility of fermented rice bran based on different types and doses of inoculants. Journal of Advanced Veterinary and Animal Research 9, 625–633. https://doi.org/10.5455/javar.2022.i632.

Djohy, G.L., Sounon Bouko, B., Dossou, P.J., Yabi, J.A., 2022. Productivity of natural pastures and pastoral mobility practices in a context of climate change in West Africa. Revue Marocaine Des Sciences Agronomiques et Vétérinaires 10, 92–105.

du Toit, C.J.L., Meissner, H.H., van Niekerk, W.A., 2013. Direct methane and nitrous oxide emissions of South African dairy and beef cattle. South African Journal of Animal Science 43, 320–339. https://doi.org/10.4314/sajas.v43i3.7.

Fanchone, A., Nozière, P., Portelli, J., Duriot, B., Largeau, V., Doreau, M., 2012. Effects of nitrogen underfeeding and energy source on nitrogen ruminal metabolism, digestion, and nitrogen partitioning in dairy cows. Journal of Animal Science 91, 895–906. https://doi.org/10.2527/jas2012-5296.

Fournier, A., 1991. The phenology, growth and production of plants in some savannahs of West Africa. Variation in terms of a Climate Gradient. PhD Thesis. Editions Orstom Collection Study and Theses, Paris, France.

Goopy, J.P., Onyango, A.A., Dickhoefer, U., Butterbach-Bahl, K., 2018. A new approach for improving emission factors for enteric methane emissions of cattle in smallholder systems of East Africa – results for Nyando, Western Kenya. Agricultural Systems 161, 72–80. https://doi.org/10.1016/j.agsy.2017.12.004.

Goopy, J.P., Ndung'u, P.W., Onyango, A., Kirui, P., Butterbach-Bahl, K., 2021. Calculation of new enteric methane emission factors for small ruminants in western Kenya highlights the heterogeneity of smallholder production systems. Animal Production Science 61, 602–612. https://doi.org/10.1071/AN19631.

Gwatibaya, S., Murungweni, C., Mpofu, I., Jingura, R., Tigere, A.T., Tererai, B., 2023. Enteric methane emission estimates for the Zimbabwean Sanga cattle breeds of Tuli and Mashona. Tropical Animal Health and Production 55, 111. https://doi.org/10.1007/s11250-023-03539-x.

Hiernaux, P., Le Houerou, H.N., 2006. The Rangelands of the Sahel. Sécheresse 17, 51–71.

Historique-Météo, 2023. Historique météo : archives météo pour le monde entier. Accessed 06 July 2023 on https://www.historique-meteo.net/afrique/burkina-faso/bobo-dioulasso/.

Hoch, T., Begon, C., Cassar-Malek, I., Picard, B., Savary-Auzeloux, I., 2003. Mechanisms and consequences of compensatory growth in ruminants. INRA Productions Animales 16, 49–59.
Hristov, A.N., Oh, J., Giallongo, F., Frederick, T., Weeks, H., Zimmerman, P.R., Hristova, R.A., Zimmerman, S.R., Branco, A.F., 2015. The use of an automated system (GreenFeed) to monitor enteric methane and carbon dioxide emissions from ruminant animals. Journal of Visualized Experiments 103, e52904.
INRA feeding system for ruminants: Specific feeding of ruminant in hot regions. Editions Quæ, Versailles, France. https://doi.org/10.3920/978-90-8686-292-4.
IPCC, 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (ed. Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S.). IPCC, Switzerland, CH. ISBN 978-4-88788-232-4.
Islam, M., Kim, S.H., Son, A.R., Lee, S.S., Lee, S.S., 2022. Breed and season-specific methane conversion factors influence methane emission factor for enteric methane of dairy steers. Sustainability 14, 7030. https://doi.org/10.3390/su14127030.
Keady, S.M., Keane, M.G., Waters, S.M., Wylie, A.R., O'Riordan, E.G., Keogh, K., Kenny, D.A., 2021. Effect of dietary restriction and compensatory growth on performance, carcass characteristics, and metabolic hormone concentrations in Angus and Belgian Blue steers. Animal 15, 100215. https://doi.org/10.1016/j.animal.2021.100215.
Korir, D., Marquardt, S., Eckard, R., Sanchez, A., Dickhoefer, U., Merbold, L., Butterbach-Bahl, K., Jones, C., Robertson-Dean, M., Goopy, J., 2022. Weight gain and enteric methane production of cattle fed on tropical grasses. Animal Production Science 63, 120–132. https://doi.org/10.1071/AN21327.
Kouazounde, J.B., Gbenou, J.D., Babatounde, S., Srivastava, N., Eggleston, S.H., Antwi, C., Baah, J., McAllister, T.A., 2015. Development of methane emission factors for enteric fermentation in cattle from Benin using IPCC Tier 2 methodology. Animal 9, 526–533. https://doi.org/10.1017/S1751731114002626.
Ku-Vera, J.C., Valencia-Salazar, S.S., Piñeiro-Vázquez, A.T., Molina-Botero, I.C., Arroyave-Jaramillo, J., Montoya-Flores, M.D., Lazos-Balbuena, F.J., Canul-Solís, J.R., Arceo-Castillod, J.I., Ramírez-Cancino, L., Escobar-Restrepo, C.S., Alayón-Gambo, J.A., Jiménez-Ferrer, G., Zavala-Escalante, L.M., Castelán-Ortega, O.A., Quintana-Owend, P., Ayala-Burgosa, A.J., Aguilar-Pérez, C.F., Solorio-Sánchez, F. J., 2018. Determination of methane yield in cattle fed tropical grasses as measured in open-circuit respiration chambers. Agricultural and Forest Meteorology 258, 3–7. https://doi.org/10.1016/j.agrformet.2018.01.008.
Kuznetsova, A., Brockhoff, P.B., Christensen, R.H.B., 2017. lmerTest package: tests in linear mixed effects models. Journal of Statistical Software 82, 1–26. https://doi.org/10.18637/jss.v082.i13.
Linstädter, A., Kemmerling, B. (equally contributing), Baumann, G., Kirscht, H., 2013. The importance of being reliable – Local ecological knowledge and management of forage plants in a dryland pastoral system (Morocco). *Journal of Arid Environments* 95, pp. 30–40. https://doi.org/10.1016/j.jaridenv.2013.03.008.
Manafiazar, G., Zimmerman, S., Basarab, J.A., 2017. Repeatability and variability of short-term spot measurement of methane and carbon dioxide emissions from beef cattle using GreenFeed emissions monitoring system. Canadian Journal of Animal Science 97, 118–126 10.1139/cjas-2015-0190.
Manzano, P., Burgas, D., Cadahía, L., Eronen, J.T., Fernández-Llamazares, Á., Bencherif, S., Holand, Ø., Seitsonen, O., Byambaa, B., Fortelius, M., Fernandez-Gimenez, M.E., Galvin, K.A., Cabeza, M., Stenseth, N.C., 2021. Toward a holistic understanding of pastoralism. One Earth 4, 651–665. https://doi.org/10.1016/j.oneear.2021.04.012.
Mapcarta, 2023. Location in Bobo-Dioulasso region: CIRDES. Accessed 06 July 2023 on https://mapcarta.com/W441415995.
McGahey, D., Davies, J., Hagelberg, N., Ouedraogo, R., 2014. Pastoralism and the Green Economy – a natural nexus? IUCN and UNEP, Nairobi, Kenya.
Moura, F.H., Fonseca, M.A., Macias-Franco, A., Archilia, E.C., Batalha, I.M., Pena-Bello, C.A., Silva, A.E.M., Moreira, G.M., Schütz, L.F., Norris, A.B., 2022. Characterization of body composition and liver epigenetic markers during periods of negative energy balance and subsequent compensatory growth in post pubertal beef bulls. Journal of Animal Science 100, 1–14. https://doi.org/10.1093/jas/skac047.
Müller, L., Samuels, M.I., Cupido, C.F., Swarts, M.B.V., Amary, N.M., Hattas, D., Morris, C., Cyster, L.F., Boatwright, J.S., 2019. The impacts of season and livestock management strategy on the quality of diets selected by goats and sheep in the semi-arid rangelands of Namaqualand, South Africa. African Journal of Range and Forage Science 36, 105–114. https://doi.org/10.2989/10220119.2018.1552622.
Münger, A., Denninger, T., Martin, C., Eggerschwiler, L., 2018. Methane emission from grazing dairy cows: comparison of methods. Recherche Agronomique Suisse 9, 180–185.
Ndung'u, P.W., Kirui, P., Takahashi, T., du Toit, C.J.L., Merboldf, L., Goopy, J.P., 2021. Data describing cattle performance and feed characteristics to calculate enteric methane emissions in smallholder livestock systems in Bomet County, Kenya. Data in Brief 39, 107673. https://doi.org/10.1016/j.dib.2021.107673.
Ndung'u, P.W., du Toit, C.J.L., Takahashi, T., Robertson-Dean, M., Butterbach-Bahl, K., Merbold, L., Goopy, J.P., 2022. A simplified approach for producing Tier 2 enteric-methane emission factors based on East African smallholder farm data. Animal Production Science 63, 227–236. https://doi.org/10.1071/AN22082.
Ouédraogo, D., Soudré, A., Yougbaré, B., Ouédraogo-Koné, S., Zoma-Traoré, B., Khayatzadeh, N., Traoré, A., Sanou, M., Mészáros, G., Burger, P.A., Mwai, O.A., Wurzinger, M., Sölkner, J., 2021a. Genetic improvement of local cattle breeds in West Africa: a review of breeding programs. Sustainability 13, 2125. https://doi.org/10.3390/su13042125.
Ouédraogo, K., Zaré, A., Korbéogo, G., Ouédraogo, O., Linstädter, A., 2021b. Resilience strategies of West African pastoralists in response to scarce forage resources. Pastoralism: Research, Policy and Practice 11, 16. https://doi.org/10.1186/s13570-021-00210-8.
Pathot, Y.D., Berhanu, W.T., 2023. Effect of harvesting stage on yield and nutritive value of antelope grass (*Echinochloa pyramidalis*) hay under natural pasture in Nuer zone of Gambella, Ethiopia. African Journal of Agricultural Research 19, 374–379. https://doi.org/10.5897/AJAR2022.16274.
Perry, L.A., Jassim, A.l.R., Gaughan, J.B., Tomkins, N.W., 2017. Effect of feeding forage characteristic of wet- or dry-season tropical C4 grass in northern Australia, on methane production, intake and rumen outflow rates in Bos indicus steers. Animal Production Science 57, 2033–2041. https://doi.org/10.1071/AN15314.
R Core Team, 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL: https://www.R-project.org/.
Rahimi, J., Haas, E., Grote, R., Kraus, D., Smerald, A., Laux, P., Goopy, J., Butterbach-Bahl, K., 2021. Beyond livestock carrying capacity in the Sahelian and Sudanian zones of West Africa. Scientific Reports 11, 22094. https://doi.org/10.1038/s41598-021-01706-4.
Rivière, R., 1991. Manuel d'alimentation des ruminants domestiques en milieu tropical, Institut de l'élevage et de médecine vétérinaire des pays tropicaux. Ministère de la coopération et du Développement, collection manuels et précis d'élevage, Paris, France.
Sanogo, S., Fink, A.H., Omotosho, J.A., Ba, A., Redl, R., Ermert, V., 2015. Spatio-temporal characteristics of the recent rainfall recovery in West Africa. International Journal of Climatology 35, 4589–4605. https://doi.org/10.1002/joc.4309.
Sawadogo, L., Tiveau, D., Nygård, R., 2005. Influence of selective tree cutting, livestock and prescribed fire on herbaceous biomass in the savannah woodlands of Burkina Faso, West Africa. Agriculture, Ecosystems and Environment 105, 335–345. https://doi.org/10.1016/j.agee.2004.02.004.
Sbrissia, A.F., Schmitt, D., Duchini, P.G., Da Silva, S.C., 2020. Unravelling the relationship between a seasonal environment and the dynamics of forage growth in grazed swards. Journal of Agronomy and Crop Science 206, 630–639. https://doi.org/10.1111/jac.12402.
Slayi, M., Kayima, D., Jaja, I.F.J., Mapiye, C., Dzama, K., 2023. Enteric methane output and weight accumulation of Nguni and Bonsmara cows raised under different grazing conditions. Pastoralism 13, 12. https://doi.org/10.1186/s13570-023-00275-7.
Strucken, E.M., Al–Mamun, H.A., Esquivelzeta-Rabell, C., Gondro, C., Mwai, O.A., Gibson, J.P., 2017. Genetic tests for estimating dairy breed proportion and parentage assignment in East African crossbred cattle. Genetics Selection Evolution 49, 67. https://doi.org/10.1186/s12711-017-0342-1.
Sylla, M.B., Elguindi, N., Giorgi, F., Wisser, D., 2016. Projected robust shift of climate zones over West Africa in response to anthropogenic climate change for the late 21st century. Climatic Change 134, 241–253. https://doi.org/10.1007/s10584-015-1522-z.
Tagesson, T., Fensholt, R., Cropley, F., Guiro, I., Horion, S., Ehammer, A., Ardö, J., 2015. Dynamics in carbon exchange fluxes for a grazed semi-arid savanna ecosystem in West Africa. Agriculture, Ecosystems and Environment 205, 15–24. https://doi.org/10.1016/j.agee.2015.02.017.
Tensaba, R.S., Kiema, A., Zongo, M., Gnanda, B.I., Tiema, A.K.P., 2023. Feed resources and feeding strategies of small ruminants in the North Center region of Burkina Faso. Journal of Applied Biosciences 182, 19007–19017 10.35759/JABs.182.3.
Tongwane, M.I., Moeletsi, M.E., 2020. Emission factors and carbon emissions of methane from enteric fermentation of cattle produced under different management systems in South Africa. Journal of Cleaner Production 265, 121931. https://doi.org/10.1016/j.jclepro.2020.121931.
Vall, E., Salgado, P., Corniaux, C., Blanchard, M., Dutilly, C., Alary, V., 2014. Changes and innovations in livestock systems in Africa. In: Special number, Which innovations for which livestock systems? Ingrand, S., Baumont, R. (Eds). INRA Productions Animales 27, pp. 161–174. https://doi.org/10.1016/j.jclepro.2020.121931.
Van Soest, P.J., Robertson, J.B., Lewis, B.A., 1991. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. Journal of Dairy Science 74, 3583–3597.
van Wyngaard, J.D.V., Meeske, R., Erasmus, L.J., 2018. Effect of concentrate level on enteric methane emissions, production performance, and rumen fermentation of Jersey cows grazing kikuyu-dominant pasture during summer. Journal of Dairy Science 101, 9954–9966. https://doi.org/10.3168/jds.2017-14327.
Watts, N., Amann, M., Arnell, N., Ayeb-Karlsson, S., Beagley, J., Belesova, K., Boykoff, M., Byass, P., Cai, W., Campbell-Lendrum, D., Capstick, S., Chambers, J., Coleman, S., Dalin, C., Daly, M., Dasandi, N., Dasgupta, S., Davies, M., Napoli, C.D., Dominguez-Salas, P., Drummond, P., Dubrow, R., Ebi, K.L., Eckelman, M., Ekins, P., Escobar, L.E., Georgeson, L., Golder, Su., Grace, D., Graham, H., Haggar, P., Hamilton, I., Hartinger, S., Hess, J., Hsu, S., Hughes, N., Mikhaylov, S.J., Jimenez, M.P., Kelman, I., Kennard, H., Kiesewetter, G., Kinney, P.L., Kjellstrom, T., Kniveton, D., Lampard, P., Lemke, B., Liu, Y., Liu, Z., Lott, M., Lowe, R., Martinez-Urtaza, J., Maslin, M., McAllister, L., McGushin, A., McMichael, C., Milner, J., Moradi-Lakeh, M., Morrissey, K., Munzert, S., Murray, K., Neville, T., Nilsson, M., Sewe, M.O., Oreszczyn, T., Otto, M., Owfi, F., Pearman, O., Pencheon, D., Quinn, R., Rabbaniha, M., Robinson, E., Rocklöv, J., Romanello, M., Semenza, J.C., Sherman, J., Shi, L., Springmann, M., Tabatabaei, M., Taylor, M., Triñanes, J., Shumake-Guillemot, J., Vu, B., Wilkinson, P., Winning, M., Gong, P., Montgomery, H., Costello, A., 2021. The 2020 report of The Lancet Countdown on health and

climate change: responding to converging crises. The Lancet 397, 129–170. https://doi.org/10.1016/S0140-6736(20)32290-X.

Wittig, R., König, K., Schmidt, M., Szarzynski, J., 2007. A study of climate change and anthropogenic impacts in West Africa. Environmental Science and Pollution Research 14, 182–189. https://doi.org/10.1065/espr2007.02.388.

Wolz, K., Leitner, S., Merbold, L., Wolf, B., Mauder, M., 2022. Enteric methane emission estimates for Kenyan cattle in a night time enclosure using a backward Lagrangian Stochastic dispersion technique. Theoretical and Applied Climatology 147, 1091–1103. https://doi.org/10.1007/s00704-021-03868-7.

Xu, Z., Heuschele, D.J., Lamb, J.F.S., Jung, H.J.G., Samac, D.A., 2023. Improved forage quality in Alfalfa (*Medicago sativa* L.) via selection for increased stem fiber digestibility. Agronomy 13, 770. https://doi.org/10.3390/agronomy13030770.