

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



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### ABSTRACT

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<sub>4</sub>) emissions, there are very few references based on *in vivo* measurements of eCH<sub>4</sub> 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<sub>4</sub> in ruminants. Thus, eCH<sub>4</sub> 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 ( $\pm$  SD) initial BW of 138  $\pm$  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<sub>4</sub> (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<sub>4</sub> 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<sub>4</sub> emissions for steers amounted to 68.1 g/d (24.6 g/kg DM intake per day, 46.7  $\pm$  3.34 kg of eCH<sub>4</sub>/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<sub>4</sub> data for ruminants in Sub-Saharan Africa.

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### 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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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) (Balehgn 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<sub>4</sub>) 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<sub>4</sub> 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<sub>4</sub> have been performed in the context of Sub-Saharan African livestock production. In addition, none of these studies addressed the seasonal variation in eCH<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> emission factors are affected by season in order to improve regional and national eCH<sub>4</sub> inventories.

## Material and methods

### Experimental site

The experiment was conducted at the experimental station of the Centre International de Recherche-Développement sur l'Élevage 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<sup>2</sup> each and an area of 48 m<sup>2</sup> where the eCH<sub>4</sub> 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*.

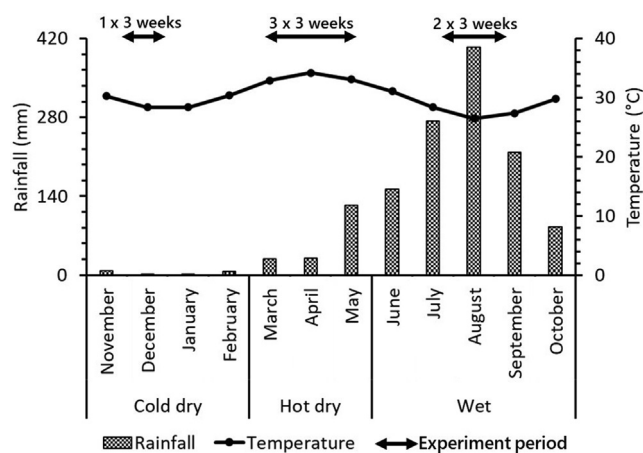


Fig. 1. Rainfall and temperature of Bobo-Dioulasso over the last 10 years (2013–2022), and experiment periods in Sudanese Fulani zebu steers (Historique-Météo, 2023).

**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 <sup>c</sup>	30.7 <sup>b</sup>	31.5 <sup>b</sup>	32.5 <sup>b</sup>	35.5 <sup>a</sup>	36.2 <sup>a</sup>	<0.001	28.6 <sup>C</sup>	31.6 <sup>B</sup>	35.8 <sup>A</sup>	0.43	<0.001
BW (kg)	139.4 <sup>ab</sup>	147.6 <sup>a</sup>	144.5 <sup>ab</sup>	143.7 <sup>ab</sup>	129.8 <sup>b</sup>	131.1 <sup>b</sup>	0.042	139.4 <sup>AB</sup>	145.3 <sup>A</sup>	130.4 <sup>B</sup>	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 <sup>ab</sup>	123.4 <sup>a</sup>	123.6 <sup>a</sup>	123.3 <sup>a</sup>	117.6 <sup>b</sup>	120.8 <sup>ab</sup>	0.016	118.7 <sup>B</sup>	123.4 <sup>A</sup>	119.2 <sup>B</sup>	0.62	0.002
Scapulo ischial length (cm)	109.4 <sup>b</sup>	116.6 <sup>a</sup>	115.2 <sup>a</sup>	117.2 <sup>a</sup>	111.0 <sup>b</sup>	115.5 <sup>a</sup>	<0.001	109.4 <sup>C</sup>	116.3 <sup>A</sup>	113.3 <sup>B</sup>	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

<sup>a,b,c</sup>Values within a row with different superscripts differ significantly at  $P < 0.05$ : comparison between trials.

<sup>A,B,C</sup>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<sub>4</sub>.

#### 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<sup>®</sup> 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:

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

##### Enteric methane and carbon dioxide emissions measurements

The eCH<sub>4</sub> and carbon dioxide (CO<sub>2</sub>) emissions were measured using a GreenFeed<sup>®</sup> (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<sup>®</sup> 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<sup>®</sup> per measurement. The GreenFeed<sup>®</sup> 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<sub>4</sub>: 0.509 ppmv, CO<sub>2</sub>: 4.993 ppmv, H<sub>2</sub>: 0.010 ppmv and O<sub>2</sub>: 0.021 ppmv; Air Liquide, C-Lock Inc., USA). Twice a week, at the beginning and end of each trial, a CO<sub>2</sub> 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<sup>-1</sup> (8 cm<sup>-1</sup> 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<sup>®</sup> 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<sub>4</sub> and CO<sub>2</sub> 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<sub>4</sub>.P.i) for each gas flow according to Eq. (2) as follows:

$$\begin{aligned} \text{eCH}_4.\text{P.i (g/d)} &= 0.5 * [(\text{eCH}_4.1000 \text{ h} + \text{eCH}_4.1400 \text{ h} \\ &+ \text{eCH}_4.1800 \text{ h}) / 3] + 0.5 \\ &* [(\text{eCH}_4.0630 \text{ h} + \text{eCH}_4.0000 \text{ h}) / 2] \end{aligned} \quad (2)$$

With eCH<sub>4</sub>.P.i: average eCH<sub>4</sub> 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:

$$\text{Intake.Year} = [\Sigma(\text{Intake.S}_i * \text{D}_i)] / 365 \quad (3)$$

With Intake.Year: average daily intake (g/d) over a year, Intake.S<sub>i</sub>: average intake (g/d) for the i<sup>th</sup> season, and D<sub>i</sub>: number of days for the i<sup>th</sup> 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<sub>4</sub> over a year (eCH<sub>4</sub>.P.Year) was calculated using Eqs. (4) and (5) as follows:

$$\text{eCH}_4.\text{P.Year} = [\Sigma(\text{eCH}_4.\text{P.S}_i * \text{D}_i)] / 365 \quad (4)$$

with eCH<sub>4</sub>.P.Year: average daily emissions over a year (in g/d), eCH<sub>4</sub>.P.S<sub>i</sub>: average emissions for the i<sup>th</sup> season (in g/d) and D<sub>i</sub>: number of days of the i<sup>th</sup> season.

$$\text{eCH}_4.\text{BW.Year} = [\Sigma(\text{eCH}_4.\text{BW.S}_i * \text{D}_i)] / 365 \quad (5)$$

with eCH<sub>4</sub>.BW.Year: average daily emissions over a year (in g/kg BW), eCH<sub>4</sub>.BW.S<sub>i</sub>: average emissions for the i<sup>th</sup> season (in g/kg BW) and D<sub>i</sub>: number of days of the i<sup>th</sup> season.

The average daily eCH<sub>4</sub> yields over a season (eCH<sub>4</sub>.Y.S<sub>i</sub>) and a year (eCH<sub>4</sub>.Y.Year) were calculated using Eqs. (6) and (7) as follows:

$$\text{eCH}_4.\text{Y.S}_i = \text{eCH}_4.\text{P.S}_i / \text{Intake.S}_i \quad (6)$$

With eCH<sub>4</sub>.Y.S<sub>i</sub>: average daily emissions (g/kg intake per day) over a season, eCH<sub>4</sub>.P.S<sub>i</sub>: average emissions (g/d) for the i<sup>th</sup> season, and Intake.S<sub>i</sub> is the intake (either DM intake or OM intake: kg/d) for the i<sup>th</sup> season.

$$\text{eCH}_4.\text{Y.Year} = [\Sigma(\text{eCH}_4.\text{P.S}_i * \text{D}_i)] / [\Sigma(\text{Intake.S}_i * \text{D}_i)] \quad (7)$$

With eCH<sub>4</sub>.Y.Year: average daily emissions (g/kg intake per day) over a year, eCH<sub>4</sub>.P.S<sub>i</sub>: average emissions (g/d) for the i<sup>th</sup> season, D<sub>i</sub>: number of days in the i<sup>th</sup> season, and Intake.S<sub>i</sub>: intake (either DM intake or OM intake in kg/d) for the i<sup>th</sup> season.

#### Statistical analysis

All statistical analyses were performed using R software version 4.1.2. (R Core Team, 2021). Intake, digestibility, CO<sub>2</sub> and eCH<sub>4</sub> 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<sub>2</sub> and eCH<sub>4</sub> 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<sub>ijk</sub> = variable of interest (offered feed component, intake, digestibility, CO<sub>2</sub>, eCH<sub>4</sub>);

μ = overall average;

S<sub>i</sub> = fixed effect representing the different seasons during which the study was conducted (CDS, HDS and WS);

T<sub>j</sub> = 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 <sup>b</sup>	928.1 <sup>a</sup>	934.3 <sup>a</sup>	952.0 <sup>a</sup>	321.8 <sup>c</sup>	330.2 <sup>c</sup>	<0.001	828.2 <sup>B</sup>	938.1 <sup>A</sup>	326.0 <sup>C</sup>	0.47	<0.001
OM (g/kg DM)	886.7 <sup>a</sup>	865.9 <sup>b</sup>	874.2 <sup>ab</sup>	880.7 <sup>a</sup>	851.1 <sup>c</sup>	861.0 <sup>bc</sup>	<0.001	886.7 <sup>A</sup>	873.7 <sup>B</sup>	856.1 <sup>C</sup>	2.40	<0.001
CP (g/kg DM)	41.0 <sup>c</sup>	28.4 <sup>d</sup>	26.5 <sup>d</sup>	26.0 <sup>d</sup>	73.1 <sup>a</sup>	57.7 <sup>b</sup>	<0.001	41.0 <sup>B</sup>	27.0 <sup>C</sup>	65.4 <sup>A</sup>	3.22	<0.001
NDF (g/kg DM)	746.9 <sup>a</sup>	725.9 <sup>a</sup>	744.9 <sup>a</sup>	753.7 <sup>a</sup>	647.5 <sup>b</sup>	672.3 <sup>b</sup>	<0.001	746.9 <sup>A</sup>	741.5 <sup>A</sup>	660.0 <sup>B</sup>	7.35	<0.001
ADF (g/kg DM)	455.1 <sup>b</sup>	451.9 <sup>b</sup>	466.1 <sup>ab</sup>	475.1 <sup>a</sup>	387.3 <sup>d</sup>	406.6 <sup>c</sup>	<0.001	455.1 <sup>A</sup>	464.4 <sup>A</sup>	397.0 <sup>B</sup>	5.47	<0.001
GE (MJ/kg DM)	17.7 <sup>bc</sup>	17.4 <sup>c</sup>	17.4 <sup>c</sup>	17.5 <sup>c</sup>	18.1 <sup>ab</sup>	18.3 <sup>a</sup>	0.001	17.7 <sup>B</sup>	17.4 <sup>B</sup>	18.2 <sup>A</sup>	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.

<sup>a,b,c,d</sup>Values within a row with different superscripts differ significantly at P < 0.05: comparison between trials.

<sup>A,B,C</sup>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

$\epsilon_{ijk}$  = 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  $21.2 \pm 1.52$  g DM/kg BW per day or  $5.3 \pm 0.38$  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 <sup>a</sup>	4.9 <sup>a</sup>	3.4 <sup>b</sup>	2.0 <sup>d</sup>	3.0 <sup>bc</sup>	2.9 <sup>c</sup>	<0.001	4.7 <sup>A</sup>	3.4 <sup>B</sup>	2.9 <sup>C</sup>	0.16	<0.001
DM refused (kg)	1.4 <sup>b</sup>	2.0 <sup>a</sup>	1.3 <sup>c</sup>	0.4 <sup>d</sup>	0.05 <sup>d</sup>	0.09 <sup>d</sup>	<0.001	1.4 <sup>A</sup>	1.2 <sup>A</sup>	0.07 <sup>B</sup>	0.25	<0.001
DMI (kg)	3.3 <sup>a</sup>	2.4 <sup>c</sup>	2.4 <sup>c</sup>	2.0 <sup>d</sup>	3.1 <sup>a</sup>	2.7 <sup>b</sup>	<0.001	3.3 <sup>A</sup>	2.3 <sup>C</sup>	2.9 <sup>B</sup>	0.07	<0.001
DMI (g/kg BW)	23.9 <sup>a</sup>	16.4 <sup>c</sup>	16.8 <sup>c</sup>	13.9 <sup>d</sup>	22.8 <sup>ab</sup>	21.8 <sup>b</sup>	<0.001	23.9 <sup>A</sup>	15.7 <sup>C</sup>	22.3 <sup>B</sup>	0.53	<0.001
OMI (kg)	2.9 <sup>a</sup>	2.2 <sup>c</sup>	2.1 <sup>c</sup>	1.8 <sup>d</sup>	2.6 <sup>b</sup>	2.4 <sup>bc</sup>	<0.001	2.9 <sup>A</sup>	2.0 <sup>C</sup>	2.5 <sup>B</sup>	0.06	<0.001
OMI (g/kg BW)	20.9 <sup>a</sup>	14.9 <sup>c</sup>	14.5 <sup>c</sup>	12.5 <sup>d</sup>	19.5 <sup>b</sup>	18.8 <sup>b</sup>	<0.001	20.9 <sup>A</sup>	14.0 <sup>C</sup>	19.2 <sup>B</sup>	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.

<sup>a,b,c,d</sup>Values within a row with different superscripts differ significantly at  $P < 0.05$ : comparison between trials.

<sup>A,B,C</sup>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 <sup>b</sup>	906 <sup>a</sup>	4.0	<0.001	887 <sup>a</sup>	863 <sup>b</sup>	3.6	<0.001	853 <sup>b</sup>	887 <sup>a</sup>	3.1	<0.001
CP (g/kg DM)	49 <sup>a</sup>	27 <sup>b</sup>	2.6	<0.001	28	25	0.4	0.080	68 <sup>a</sup>	41 <sup>b</sup>	2.4	<0.001
NDF (g/kg DM)	704 <sup>b</sup>	819 <sup>a</sup>	14.0	<0.001	757	733	4.5	0.251	652 <sup>b</sup>	749 <sup>a</sup>	8.7	<0.001
ADF (g/kg DM)	427 <sup>b</sup>	503 <sup>a</sup>	9.5	<0.001	474	463	3.6	0.127	390 <sup>b</sup>	480 <sup>a</sup>	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.

<sup>a,b</sup>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 <sup>b</sup>	0.46 <sup>c</sup>	0.47 <sup>c</sup>	0.46 <sup>c</sup>	0.61 <sup>a</sup>	0.53 <sup>b</sup>	<0.001	0.50 <sup>B</sup>	0.46 <sup>C</sup>	0.57 <sup>A</sup>	0.008
OM (kg/kg OM)	0.53 <sup>b</sup>	0.50 <sup>c</sup>	0.49 <sup>c</sup>	0.49 <sup>c</sup>	0.61 <sup>a</sup>	0.53 <sup>b</sup>	<0.001	0.53 <sup>B</sup>	0.49 <sup>C</sup>	0.57 <sup>A</sup>	0.007	<0.001
CP (kg/kg CP)	0.04 <sup>b</sup>	0.00 <sup>b</sup>	0.14 <sup>ab</sup>	0.11 <sup>ab</sup>	0.30 <sup>a</sup>	0.29 <sup>a</sup>	0.009	0.04 <sup>B</sup>	0.08 <sup>B</sup>	0.29 <sup>A</sup>	0.030	0.002
NDF (kg/kg NDF)	0.54 <sup>ab</sup>	0.52 <sup>b</sup>	0.51 <sup>b</sup>	0.51 <sup>b</sup>	0.62 <sup>a</sup>	0.57 <sup>ab</sup>	0.020	0.54 <sup>B</sup>	0.51 <sup>B</sup>	0.60 <sup>A</sup>	0.005	0.001
ADF (kg/kg ADF)	0.59 <sup>ab</sup>	0.56 <sup>b</sup>	0.54 <sup>b</sup>	0.54 <sup>b</sup>	0.62 <sup>a</sup>	0.56 <sup>b</sup>	<0.001	0.59 <sup>A</sup>	0.54 <sup>B</sup>	0.58 <sup>A</sup>	0.006	<0.001
GE (kg/kg GE)	0.55 <sup>c</sup>	0.51 <sup>d</sup>	0.49 <sup>de</sup>	0.47 <sup>e</sup>	0.65 <sup>a</sup>	0.58 <sup>b</sup>	<0.001	0.55 <sup>B</sup>	0.48 <sup>C</sup>	0.61 <sup>A</sup>	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.

<sup>a,b,c,d,e</sup>Values within a row with different superscripts differ significantly at  $P < 0.05$ : comparison between trials.<sup>A,B,C</sup>Values within a row with different superscripts differ significantly at  $P < 0.05$ : comparison between seasons.**Table 6**  
Emissions of CO<sub>2</sub> and eCH<sub>4</sub> 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 <sub>2</sub> (g/d)	2 127 <sup>a</sup>	1 868 <sup>b</sup>	1 781 <sup>b</sup>	1 781 <sup>b</sup>	1 840 <sup>b</sup>	1 835 <sup>b</sup>	0.003	2127 <sup>A</sup>	1810 <sup>B</sup>	1838 <sup>B</sup>	7.0
eCH <sub>4</sub> (g/d)	83.2 <sup>a</sup>	73.2 <sup>ab</sup>	72.2 <sup>ab</sup>	68.2 <sup>ab</sup>	56.7 <sup>b</sup>	60.4 <sup>b</sup>	0.002	83.2 <sup>A</sup>	71.2 <sup>A</sup>	58.6 <sup>B</sup>	2.15	<0.001
eCH <sub>4</sub> (g/kg BW)	0.60 <sup>a</sup>	0.50 <sup>ab</sup>	0.50 <sup>ab</sup>	0.48 <sup>ab</sup>	0.42 <sup>b</sup>	0.48 <sup>ab</sup>	0.018	0.60 <sup>A</sup>	0.49 <sup>B</sup>	0.45 <sup>B</sup>	0.024	0.001
eCH <sub>4</sub> (g/kg DMI)	25.2 <sup>bc</sup>	30.6 <sup>ab</sup>	30.3 <sup>ab</sup>	34.5 <sup>a</sup>	18.7 <sup>c</sup>	22.2 <sup>c</sup>	<0.001	25.2 <sup>B</sup>	31.8 <sup>A</sup>	20.5 <sup>C</sup>	1.09	<0.001
eCH <sub>4</sub> (g/kg OMI)	28.8 <sup>bc</sup>	33.9 <sup>ab</sup>	34.4 <sup>ab</sup>	39.0 <sup>a</sup>	21.9 <sup>c</sup>	25.7 <sup>bc</sup>	<0.001	28.8 <sup>B</sup>	35.8 <sup>A</sup>	23.8 <sup>B</sup>	1.21	<0.001
eCH <sub>4</sub> (g/kg dDMI)	50.4 <sup>b</sup>	66.4 <sup>a</sup>	66.1 <sup>a</sup>	74.7 <sup>a</sup>	30.8 <sup>c</sup>	42.3 <sup>bc</sup>	<0.001	50.4 <sup>B</sup>	69.1 <sup>A</sup>	36.6 <sup>C</sup>	2.69	<0.001
eCH <sub>4</sub> (g/kg dOMI)	53.9 <sup>bc</sup>	67.5 <sup>ab</sup>	70.8 <sup>a</sup>	80.0 <sup>a</sup>	35.8 <sup>d</sup>	48.2 <sup>cd</sup>	<0.001	53.9 <sup>B</sup>	72.8 <sup>A</sup>	42.0 <sup>C</sup>	2.73	<0.001
eCH <sub>4</sub> (% GEI)	7.9 <sup>bc</sup>	9.3 <sup>ab</sup>	9.6 <sup>ab</sup>	11.0 <sup>a</sup>	5.8 <sup>c</sup>	6.8 <sup>c</sup>	<0.001	7.9 <sup>B</sup>	10.0 <sup>A</sup>	6.3 <sup>C</sup>	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<sub>2</sub> = carbon dioxide; eCH<sub>4</sub> = enteric methane; DMI = DM intake; dDMI = digestible DM intake; OMI = organic matter intake; dOMI = digestible organic matter intake; GEI = gross energy intake.<sup>a,b,c,d</sup>Values within a row with different superscripts differ significantly at  $P < 0.05$ : comparison between trials.<sup>A,B,C</sup>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 col-

lected 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<sub>4</sub> 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 (Keedy 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<sub>4</sub> 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<sub>4</sub>, but in the current study, eCH<sub>4</sub> 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<sub>4</sub> values would have been higher, as reported by Perry et al. (2017).

The eCH<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> if ruminal metabolism is improved, primarily through nitrogen supplementation (Archimède et al., 2011). The eCH<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> were observed in CDS and WS, respectively, compared with HDS. These drops in eCH<sub>4</sub> 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<sub>4</sub> emissions from Fulani zebu cattle–fed natural fodder throughout the year. The seasonally weighted average annual eCH<sub>4</sub> emissions from steers in this study (eCH<sub>4</sub>.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<sub>4</sub> 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<sub>4</sub>/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<sub>4</sub> 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<sub>4</sub> yield value recorded in CDS (25.2 g/kg DM intake) corroborates that IPCC value, the HDS eCH<sub>4</sub> 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<sub>4</sub> measurement methods have reported variable eCH<sub>4</sub> emissions from cattle. van Wyngaard et al. (2018) obtained 323 g/d, equating to 29.1 g eCH<sub>4</sub>/kg DM intake per day, using the SF<sub>6</sub> method in 391 kg of BW Jersey cows grazing predominantly *Penisetum clandestinum* during the summer in South Africa. In the same country, Slayi et al. (2023) measured eCH<sub>4</sub> with a laser methane detector in 381 kg of BW cows on a natural pasture and reported 26.42 g of eCH<sub>4</sub>/kg DM intake per day. In Kenya, eCH<sub>4</sub> measurements carried out on-station with a methane chamber on 148 kg Holstein × Boran heifers fed wheat stalks and Rhodes hay revealed 93.1 g of eCH<sub>4</sub>/day and 30.6 g of eCH<sub>4</sub>/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<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> 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.

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