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Seasons, herd mobility and management drive feed intake and digestibility in grazing cattle in West African landscapes

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Estimating the daily diet of grazing cattle from available feed resources in pastoral and mixed crop-livestock systems in tropical West Africa remains a challenge. The objective of this study was to describe the relevance of cattle diet monitoring across the seasons to better assess the livestock-resources interactions in its local environment in the region. We analyzed seasonal profiles of the diet of grazing cattle in five sites distributed along the Sudano-Sahelian climate gradient from an arid to a sub-humid bioclimate. In the five sites (ranked from the driest to the wettest: Widou, Dahra, Niakhar, Koumbia, Kolda), the feeding behavior of grazing cattle was monitored and feces were collected monthly for one year to estimate dietary intake and digestibility. All the conserved dry samples (n = 1,186) underwent near infrared spectroscopy (NIRS) analyses. The resulting spectral data were compared with a large set of spectral reference data (n=4,138) to predict dry matter intake (DMvi_Fnir DM; g.kgMW^{-1}) and digestibility (dMO_Fnir,%OM) using an updated NIRS "local calibration" procedure. Daily fodder intake ranged from 38.90 ± 6.35 in the hot dry season to 83.86 ± 8.73 gDM.kgMW^{-1}.d^{-1} in the late wet season. Estimated diet organic matter digestibility ranged from 53.6 ± 8.51% in the hot dry season to 74.3 ± 3.52% in the early wet season. Estimated by aggregation, the total annual intake of a tropical livestock unit (TLU, i.e. a standard 250 kg live weight animal) ranged from 1,236 ± 255 kgDM.TLU^{-1}.year^{-1} in Dahra to 1,560 ± 142 kgDM.TLU^{-1}.year^{-1} in Widou. This was well below the 2,281 Kg.DM annual estimate derived from a standard intake of 2.5% LW in DM. Taking digestibility into account, the summed annual metabolizable energy (ME) intake values ranged from 9,858 ± 2,077 Mj.TLU^{-}1.year^{-1} in Dahra to 13,929 ± 2,345 Mj.TLU^{-1}.year^{-1} in Koumbia. While important gaps appear during the dry season in some locations, this covered the annual basal maintenance requirements of a TLU, which, based on international standards, are estimated at 7,819 Mj.TLU^{-}1.year^{-1} (21.4 Mj.day^{-1}). This leaves ME at

varying extend, to cover the needs for growth, milk production and reproduction. Tested in a GLM, the variations in in the dependent variables (the daily DM intake, diet digestibility, and ME intake) were analyzed in relation to the independent factors location (study site) and season, as well as their interaction. Results showed that, seasonal effects largely explained the observed variability across the five sites, while differences in herd management practices modulated these effects.

KEYWORDS

fecal NIRS, grazing cattle, pastoral and agro-pastoral systems, intake, diet digestibility, Sudano-Sahelian zone, climate season, tropical West Africa

1 Introduction

The Sudano-Sahelian (Su-Sa) belt covers an area of some 4.5 million sq.km on the southern fringe of the Sahara Desert and stretches 6,000 km from the Atlantic Ocean to the Red Sea, in a strip ranging from 600 to 1,200 km in width (Le Houerou, 1989). The zone hosts some 117 million cattle and 36 million smallholders in both pastoral and agro-pastoral livestock systems. The herbaceous and woody leaf mass growing on the rangelands represent the main feed resources of the grazing cattle (Senock, 1990). Vegetation production is mostly driven by rainfall distribution. Livestock production depends directly on the herd's access to grazing resources, including crop residues, and on grazing practices. Climate is characterized by highly seasonal rainfall produced by the convective storms of the West African (WA) monsoon that reaches the region in summer in a window extending between April-June and September-October depending on the latitude of the site, with peak rainfall in mid-August (Nicholson, 2013). Mean annual rainfall decreases with increasing latitude. However, rainfall events are also patchy (Ali et al., 2003) and vary considerably between years (Lebel and Ali, 2009). In contrast with the short hot wet season, the dry season lasts six to 10 months with low air humidity associated with mild temperatures from November to February and increasing temperatures and humidity from March to the first rains (Guichard et al., 2009). In accordance with the regular rainfall seasonality, solar radiation, temperature and air humidity, the herbaceous vegetation is dominated by short cycle annual plants associated with varying densities of mostly deciduous woody plants, in addition to a smaller proportion of evergreens in the Sahelian arid and semiarid landscapes (Hiernaux and Le Houerou, 2006). Moving toward the sub-humid landscape, perennial Andropogoneae, and Paniceae grasses and deciduous trees with a long foliage cycle progressively predominate (Savadogo et al., 2009).

Livestock production in the arid, semi-arid and sub-humid WA is largely based on pastoralist husbandry, which is traditionally nomadic or transhumant with selective free grazing and limited feed supplementation (Ayantunde et al., 2000). Family livestock is typically composed of a multi-species mix of cattle, sheep, goats, camels, horses and donkeys. The quantity and quality of grazing resources are key factors in cattle productivity. In that context, livestock feeding depends on rangelands grazed all year round. The diet is a mix of grasses and selected forbs, and, depending on the herder's practices. The livestock also occasionally browses the foliage and fruits of bushes, shrubs and pruned trees; while for six to eight months in the dry season, they also graze weeds, crop stubble, crop residues and crop by-products either in the field or stocked by the agro-pastoralists (Sanon, 2007).

Today, the most widely used standard in the region sets the daily dry matter intake (DMi) of cows at 2.5% of live weight (LW) per day often expressed in standard tropical livestock units (TLU, i.e. 250 kgLW) as 6.25 kgDM/TLU per day. This standard was first proposed by Boudet and Rivière (1968) based on measurements performed on cattle fed cut-and-carry tropical grasses placed in troughs at the Sotuba (Mali) research station, and confirmed by assessments of grazing cattle, for which values ranged between 20 and 30 $gDM.kgLW^{-1}.d^{-1}$. The use of this standard was then generalized to all ruminant species and popularized by being recommended in the widely distributed in hard cover manuals that were often updated and reprinted several times (Boudet, 1975; Rivière, 1977; Boudet, 1975, 1991).

In our study region, this standard is applied to the total live weight of the livestock population on an annual basis, but does not account for the different regardless of animal species, of seasonal changes in selective grazing behavior, and of the aptitude of different types of livestock to cope with periodic weight loss and compensatory growth (Ayantunde et al., 1999) by adapting to cyclic fodder availability (Chirat et al., 2014).

The aim of the present study is to describe the relevance of the indirectly estimated daily fodder intake, digestibility and resulting metabolizable energy intake by cattle depending on the season and on herd management. Two questions are specific to the Sudano-Sahelian environment:

- What is the best seasonal division to most accurately estimate the feed intake and digestibility of grazing cattle?Either consider the two contrasted but unequal duration seasons of the monsoonal climate: the rainy and the dry season, or three more equal size seasons by splitting the dry long dry

season in two based temperature and air humidity: the cool dry season (CDS) and the hot dry season (HDS), or else in five seasons following local population perception splitting the rainy season in three with the early wet season (EWS), the core (CWS) and late wet season (LWS).

- Does the norm commonly used for feed intake by cattle in this region adequately reflect the annual mean feed intake by grazing cattle across the seasons and along a climate gradient ranging from arid to sub-humid?

The motivation for designing a systematic method to divide the year into two, three or five seasons is the latitudinal shift in the monsoon climate, as it is not appropriate to use the same calendar along the latitudinal gradient.

Improving the comprehensive appraisal of fodder intake and digestibility variations across the seasons will help to fit the best adapted measure to improve the productive efficiency, it will also improve the modelling of livestock-driven organic matter use and of the spatial nutrient transfers that determine crop production and soil fertility management in West Africa (Manlay et al., 2004; Schlecht et al., 2004; Grillot et al., 2018). It will further improve the assessment of the impact of livestock on climate change as fodder intake and digestibility determine methane emissions caused by enteric fermentation (Doreau et al., 2016) and feces are one of the key inputs that explain soil carbon sequestration (Abdalla et al., 2018) and N_2O emissions (Assouma et al., 2017a).

2 Materials and methods

2.1 The five locations

The study was carried out in five sites along the Sudano-Sahelian bioclimatic gradient bounded by the 150 mm and 1,200 mm rainfall isohyets (Figure 1). The whole region is characterized by a single rainy season, the duration of which decreases with increasing latitude, mostly due to the later onset of the rainy season. Vegetation growth begins between May and July and ends between September and October.

As shown on the map in Figure 1, the five study locations are:

- The sylvo-pastoral area within the Widou-Thiengoly borehole Service Area, WTSA, (15.32°W; 15.99°N; alt. 20 m asl) in the Ferlo region, in North Senegal (Assouma et al., 2019) where mean (± standard deviation) annual rainfall in the 1971–2000 period was 291 ± 124 mm;
- The sylvo-pastoral area of the National Center for research in Animal Husbandry of Dahra-Djoloff (15.48°W; 15.35°N;

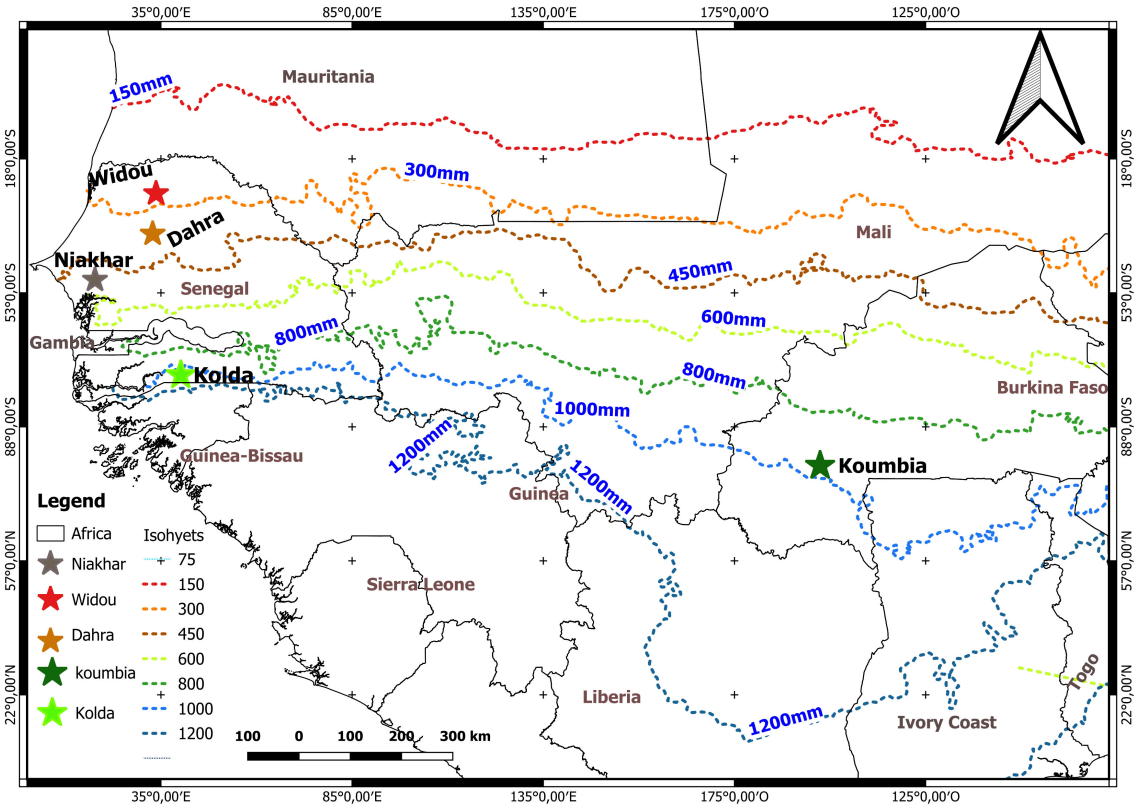


FIGURE 1
Location of the 5 study sites relative to the Sudano-Sahelian bioclimatic gradient in West Africa. The isohyets are means for the period 1981-2014. Source: Climate Hazards Group InfraRed Precipitation with Station data, CHIRPS, (ftp://ftp.chg.ucsb.edu/pub/org/chg/products/CHIRPS-2.0).

alt. 40 m asl) in the Ferlo in North Senegal (Ndiaye et al., 2014) where mean annual rainfall in the 1971–2000 period was 407 ± 116 mm;

- The agropastoral village of Niakhar (16.40°W-14.48°N; alt. 0 m asl), in the Fatick region in the core of the groundnut basin of Senegal, in the center of Senegal (Abat et al., 2016) where mean annual rainfall in the same period was 589 ± 151mm;
- The agropastoral village of Koumbia (3.41°W-11.14°N; alt. 320 m asl), 67 km West of Bobo-Dioulasso in south-western Burkina Faso (Dongmo et al., 2012), where mean annual rainfall in the same period was 919 ± 130 mm;
- The agropastoral village of Sare Yoro Bana (14.95°W-12.88° N; alt. 20 m asl), in the Kolda region, Casamance, southern Senegal (Chirat et al., 2014) where the mean annual rainfall in the same period was 1011 ± 489 mm.

2.2 The climate and seasons

The climate of the Sudano-Sahelian belt is driven by the West African monsoon. According to the Köppen-Geiger classification (Peel et al., 2007) it varies between classes: Aw in Koumbia and Kolda (A, Equatorial Climate; w savannah with dry winter), BSh in Niakhar (B, Arid Climate; S, steppe; h, hot), to BWh in Widou, Dahra (B, Arid Climate; D, desert; h, hot). As mentioned above, it is marked by highly contrasted seasons in terms of rainfall distribution, as well as in air temperature and humidity. The rains fall almost exclusively in the monsoon season that starts between April and June and ends between September and October depending location on the sub-humid to arid gradient. This rainfall pattern divide thus the year in two seasons a shorter wet season and a long dry season. However taking day length, air temperature and humidity into account help split the long dry season in two halves: the first shorter days, mid temperature and dry air cool dry seasons (CDS) followed by longer days, high temperature and more humid hot dry season (HDS), resulting in a three season model. Moreover, the ancestral agropastoral calendar widely shared among West African populations divide the year in five seasons of variable duration (Bonfiglioli, 1988; Thébaud, 2002; Vall and Diallo, 2009). In this paper, these seasons are named in *Fulfuldé or Pulaar*, the language of the *Fulani* people whose pastoral culture extends across all the countries of the Sudano-Sahelian belt. The agropastoral calendar unfolds according to an annual cycle that depends on the distribution of rainfall, temperature and air humidity. These parameters have an impact on the vegetation cycle and on the corresponding cropping cycle as well as on pastoral management practices. For crop farmers, the calendar of seasons refers to preparing the field, sowing, weeding, heading, flowering and maturing of crops, and harvesting plus the long vegetation resting period. Herders face two main constraints: (i) the availability and accessibility of drinking water, which is often managed using livestock paths and resting spots "*billé*", (ii) the quantity and quality of standing forage resources and their rules of access, especially for the cropland stubbles. The monsoon comprises three seasons, it starts with the early wet season (EWS) "*Gataaje*" characterized by the first rainfall events that are generally sporadic, unevenly distributed, risky for crop sowing decisions and for decisions concerning the northward transhumance of the livestock. The EWS season is the most critical period for livestock: water is still rare, croplands become less accessible as soon as farmers begin sowing and in addition, the only available good quality fodder is the slow growing limited mass of annual seedlings that emerge with first rains, and a few early leafing browsing species. The core wet season (CWS) "*Ndugu*" is the key period in the calendar as it determines the human food and livestock feed resources until the following year. Indeed, the distribution and amount of rainfall in the wet season determine crop yields and exploitable herbage mass; croplands are not accessible to grazing livestock during this period. The late wet season (LWS) "*Yaamde*" is the period just after the last rainfall events in the wet season. Crop harvesting begins, livestock grazes the neighboring rangelands and fallows. The dry season occupies the longest period of the year and is subdivided into two parts: the cool dry season (CDS) "*Dabbude*", when the days are shorter, the temperatures are lower and air humidity decreases. Harvesting is over, and the remaining stubble, crop residues and weeds in crop fields are all available for grazing; off-season crops (onions, water melons, bell pepper, tomatoes, cabbages, etc.) are now being cultivated under irrigation in home gardens that are protected from livestock; open water progressively dries out; animals graze the large standing herbaceous mass in rangelands and/or progressively enter croplands and graze post-harvest residues and weeds, while simultaneously manuring the fields. Next comes the hot dry season (HDS) "*Ceedu*" with progressively longer days, increasing temperatures and air humidity, standing straw in the rangeland decays rapidly, livestock have to walk farther each day in search of forage and to exploit the remaining crop residues left in the fields or stockpiled for supplementation. The herds eventually leave on transhumance either southwards or towards regrowth of green grass in a local wetland (the Senegal, Gambia and Niger alluvial plains, the inner delta of the Niger river, Lake Chad, etc.).

There are several sources of climate data in the region, but they are not always evenly documented and easily accessible. The FAO New_LocClim V 1.10 database and tool (Grieser et al., 2006) provide a freely accessible generic framework to characterize the main climate variables and make it possible to identify the start and end date of each of the five local seasons in each location. The FAO Database covers a 30-year period (1971-2000). For each location, data from the surrounding stations were interpolated according to the inverse weighted distance average (IWDA) method to recalculate the best estimated mean, minimum and maximum values (with a 95% confidence level) for rainfall, air temperature, humidity and potential evapotranspiration (PET) at each particular location. The average starting and ending dates of each of the five seasons (Figure 2) were determined based on decadal data arrangement respecting the following rules:

- "*Gataaje*", the early wet season (EWS) starts when decadal rainfall is greater than 10 mm
- "*Ndungu*", the core wet season (CWS) starts when decadal rainfall is either greater than decadal PET or than 20 mm
- "*Yaamde*", the late wet season (LWS) starts when decadal rainfall falls below decadal PET or to 20 mm but remains above 10 mm.
- "*Dabbude*" the cool dry season (CDS) starts when decadal rainfall falls below 10 mm
- "Ceedu", the hot dry season (HDS) starts when the temperature humidity index (THI) falls below the threshold value of 72. The THI is a widely used indicator in livestock bioclimatology Kibler (1964), calculated (NRC, 2001) based on mean temperature (T in °C) and relative humidity (RH in%) calculated as follows:

$$THI = (1.8T + 32) - (0.55 - 0.0055RH)(1.8T - 26)$$

The average dates in the calendar of seasons for the 1971 to 2000 period and the main climate parameters for each location are summarized in Figure 2; additional details are listed in Table 1.

2.3 Livestock management practices to make best use of water and forage resources

The livestock management practices in the region are highly dependent on the spatial and temporal variability and accessibility of forage and water resources. To adapt to the spatial and temporal variability of resources, livestock move locally along daily grazing orbits and migrate seasonally in transhumance out of the main pastoral settlement area. Both scales of herd mobility are essential traits of pastoral management. In addition, herders and livestock breeders combine different practices throughout the year to meet cattle feed requirements. Transhumance, sometimes over very long distances (> 500 km) is one way of adapting to variations in the availability of rangeland fodder and of exploiting the ecological complementarity between the Sahelian and Sudanian rangeland and cropland, upland and wetland ecosystems. Moreover, periodic pastoral interactions with cropping, as evidenced by the rules governing seasonal access of herds to cropped fields to graze and/or to manure cropped fields, implies high complementarity between cropping and livestock breeding practices both of which are framed by the seasonal calendar. The livestock breeding practices in the five locations are locally defined for each season along with the availability of drinking water and forage resources (Table 1). They determine herd mobility, watering practices, cattle management during the day and at night, the grazing of stubble, crop residues, browsing and feed supplementation. Further details on these elements are provided in the form of descriptive monographs for each study site in Supplementary Material. Furthermore, it should be noted that the pastoral management of the cattle herd in the Dahra research station (CRZ) is non-farmer management (timing of grazing, supplementation) meaning this site is interesting but is an outlier in the regional comparison.

2.4 Intake and digestibility databases

To address the profile of the variation of the vegetation use and the nutritive value for animals along a yearly cycle of seasons in different environment in the zone, a data base was built using

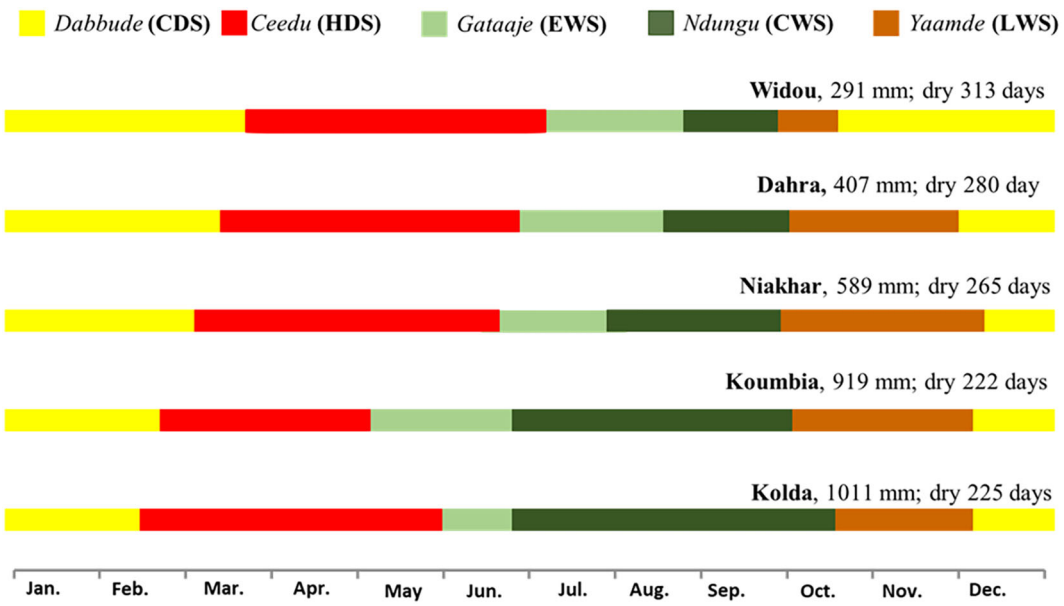


FIGURE 2
Calendar of the bioclimate seasons as named by the Fulani pastoralists in each of the 5 study sites. The calendar is based on FAO New_LocClim data (1971 to 2000), the criteria are described in the text.

TABLE 1 Seasonal climate parameters and main seasonal livestock practices in the five locations in SSA.

	Locations	Widou	Dahra	Niakhar	Koumbia	Kolda	Widou	Dahra	Niakhar	Koumbia	Kolda	Widou	Dahra	Niakhar	Koumbia	Kolda
	Systems	*P*	*P*	*AP*	*AP*	*AP*	*P*	*P*	*AP*	*AP*	*AP*	*P*	*P*	*AP*	*AP*	*AP*
		N° (+/-days)					Rain (mm)					THI>78 (days)				
Climate	*Gataaje*; (EWS)	54 ± 27	57 ± 17	43 ± 5	77 ± 10	30 ± 5	120.2	138	103	206	77	51	33	37	53	30
	Ndungu; (CWS)	34 ± 25	23 ± 17	61 ± 5	97 ± 4	113 ± 9	122.6	134	368	637	882	41	20	60	13	77
	Yaamde; (LWS)	22 ± 7	79 ± 16	71 ± 8	64 ± 9	48 ± 13	26.5	109	95	70	63	10	30	37	7	13
	Dabbude; (CDS)	158 ± 60	107 ± 24	90 ± 26	81 ± 29	74 ± 29	9.6	4	4	6	2	0	0	0	0	0
	Ceedu; (HDS)	97 ± 31	99 ± 21	100 ± 22	46 ± 27	100 ± 22	12.7	13	9	25	6	10	27	13	10	47
	Total	–	–	–	–	–	291.6	398.4	578	944.7	1030	112	110	147	83.3	167
		Fodder mass					Browse					Feeds Suppl.				
Fodder resources	*Gataaje*; (EWS)	-/+		+	+	+	++	+	+++	–	++	+	-/+	+/++	+/-	–
	Ndungu; (CWS)	+++	-/+	+++	+++	+++	–	–	–	–	–	–	–	–	–	–
	Yaamde; (LWS)	+++	+++	+++	+++	+++	–	–	–	–	–	–	–	–	–	–
	Dabbude; (CDS)	++/-	+++	++	++	++/-	–	–	–	–	–	–	–	–	–	–
	Ceedu; (HDS)	+/-	++	+/-	++/-	+/-	+++	++	++	+	++	+/++	-/+	+/++	+/++	–
		Regional mobility					Access to Water					Night				
Management options	*Gataaje*; (EWS)	**	*	*	*	*	2-WD	1-WD	1-AW	1-NP	1-AW	FG	Cconf	HFmS	Cconf	HFmS
	Ndungu; (CWS)	*	*	*	*	*	1-NP	1-WD	1-NP	1-NP	1-AW/ NP	FG	Cconf	NFc	Cconf	Cconf
	Yaamde; (LWS)	*	*	*	*	*	1-NP	1-WD	1-NP	1-NP	1-AW/ NP	FG	Cconf	NFc	Cconf	Cconf
		**	*	*	*	*	1-WD	1-WD	1-AW	1-AW/NP	1-AW	FG	Cconf	DFc	Cconf	HFmS

(Continued)

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TABLE 1 Continued

	Locations	Widou	Dahra	Niakhar	Koumbia	Kolda	Widou	Dahra	Niakhar	Koumbia	Kolda	Widou	Dahra	Niakhar	Koumbia	Kolda
	Systems	*P*	*P*	*AP*	*AP*	*AP*	*P*	*P*	*AP*	*AP*	*AP*	*P*	*P*	*AP*	*AP*	*AP*
		Regional mobility					Access to Water					Night				
	Dabbude; (CDS)															
	Ceedu; (HDS)	*/***	*	*	*	*	2-WD	1-WD	1-AW	1-AW/NP	1-AW	FG	Cconf	DFc	FG	HFmS

Parameters: Seasons, N° (days); the Fulani seasons and length in days.//THI; >78, days: the temperature humidity index and the number of days with a value above a high stress threshold of 78 (Nidumolu et al., 2014)//Fodder mass: the local expert's general assessment of the available and accessible fodder mass for grazing livestock: +, early growing annuals and perennial regrowth spots; ++, generalized green growth landscape; +++, tall standing grass and leguminous? mass; ++/-, senescent and decaying but still standing biomass; +/- 50% bare soil; - crop residues and straw//Mobility: *, local displacement< 10 km; **, temporary move to adjacent zones > 10–<50 km; ***, long distance transhumance//Access to water: rhythm and type: once a day 1; every two days only 2; - borehole, WD; artisanal well, AW; ponds, streams, NP//Night: Herd management at night: herder present to monitor grazing, MG; free roaming grazing, FG; corral confinement, Cconf.; Home Field mobile stakes, HFmS; Distant Field corralling, DFC; night fallow corralling, NFc//Browse: interaction with trees and forest resources; +, browsing; ++, browsing and limited tree pruning for weak and exhausted animals; +++ daily tree pruning due to lack of standing herbaceous forage//Feed Suppl.: supplementation of animals with market or farm made agricultural by-products (hay, cakes, haulms, grains etc.): +/- limited to milking cows and exhausted animal, +,< 500 g adults, ++ > 500 g/d.

information collected in previous surveys carried out by ISRA, CIRAD and CIRDES over the 2014–2015 annual cycle in Dahra, Widou-Thiengoly, Niakhar and Koumbia, and over the 1993–1994 cycle in Kolda. In each location, one to 10 herds were monitored for 24/48 h each month using similar protocols. In addition to recording feeding behavior (fodder intake, forage selection, nutritive value, distance and duration of pasture), samples of freshly excreted feces of seven to 35 cattles were systematically collected and dried at 70 °C for 48 h.

The collected samples (n = 1,186) were submitted to near-infrared spectroscopy (NIRS) analysis. The NIR reflectance (R) spectrum between 1,100 and 2,498 nm wavelength was recorded at 2 nm intervals, as log 1/R with a Foss NIRS-system 6500 monochromator. WINISI III calibration software (FOSS Tecator Infrasoft International LCC, Hillerød, Denmark), described by Shenk et al. (1997) was used to predict feed intake and digestibility. Indeed several authors (Boval et al., 2004; Tran et al., 2010; Coates and Dixon, 2011; Decruyenaere et al., 2013; Johnson et al., 2017; Andueza et al., 2019; Peters et al., 2023) describe the relevant assessments of forage intake and selected feed digestibility when near infrared spectroscopy is directly applied to the feces emitted by the animal (F-NIRS). Feces composition reflect the diet recently consumed, the feces can be sampled in large numbers on the field and F-NIRS method are easily applied at very low cost. The spectral reference library used in the "local procedure" is the one introduced and described by Decruyenaere et al. (2009) and Decruyenaere et al. (2013).

It contains a large spectral data set of dry scanned feces from ruminants subjected to *in vivo* trials in several temperate and tropical contexts and was incremented with a recent set of 90 fecal references of daily dry matter intake collected in the Widou site (Assouma et al., 2018) to obtain a final set of 4,633 reference spectra. The two parameters referenced in the spectra database are *in vivo* organic matter digestibility (dMO_Fnir,%; N: 3166; mean ± s.d.: 65.06 ± 10.51) and/or the mean daily dry matter voluntary intake, expressed as g DM per kg MW (DMvi_Fnir; N: 3407; mean ± s.d: 64.78 ± 28.51) of the diet consumed by the animal.

According to Assouma (2016) the prediction performance of the global calibration models calculated in cross validation as R squared coefficient (R^2cv) and standard error (SEcv) values are: 0.89 and 3.52 for dMO_Fnir: while for DMvi_Fnir values are 0.84 and 11.49, a quite large standard errors for DM intake although remaining in the range (18.7%) of the biological error generally occurring in such measures. Even less precise, such models appear particularly interesting as they may be applied to large series of repeated samplings for which averaged predictions provide the most relevant estimates.

Further as stated by Tran et al. (2010) when large referenced database are available, "Local" calibration techniques represent an alternative promising method that generally performs better then classical "Global" techniques and further increases (15-20%) the accuracy (SE and R^2) of the prediction. Here, following this local procedure, a subset of references spectrally similar to the analyzed sample was selected in the database. The subset of spectra was then used to develop a specific calibration equation, and the procedure was

then repeated for each sample and parameter. The local NIRS models were built with a modified partial least square regression, using the second derivative mode spectrum with scatter correction based on standard normal variate and detrend data. The population boundaries for the calibration were set with a maximum standardized H (Mahalanobis distance) value of 4.0 (Shenk and Westerhaus, 1991). Like in Tran et al. (2010), and Andueza et al. (2019), the local procedure was optimized by a number of samples selected from the spectral library set to 200, a maximum number of PLS terms of 10, and a number of factors removed from the prediction of 2.

2.5 Statistical analysis

The 1,181 predicted intake DMvi_Fnir (g.kgMW^{-1})with MW metabolic weight equal to liveweight exponent 0.75 (kgMW) and digestibility dMO_Fnir (%OM) were coded per month, site and season. The seasons considered are the five seasons of the local calendars specific to each site and named in Fufuldé-Pulaar corresponding to the codes EWS (early wet season), CWS (core wet season), LWS (late wet season), CDS (cool dry season), HDS (hot dry season). The five seasons were also arranged in a three-season group in which WS (wet season) includes the three components of the wet season EWS, CWS, LWS. The seasons were further grouped in only two main seasons: the wet season (WS) and the dry season (DS) by merging the two parts of the dry season CDS and HDS.

Averaged intake values were transformed into TLU_DMint kgDM.day^{-1} ingested by a tropical livestock unit of 250 kg liveweight (standard weight for cattle in this region). According to a standard of 90.4% organic matter content in the intake DM and the fecal dMO_Fnir, the daily average metabolizable energy intake (TLU_MEint, Mj.d^{-1}) was calculated (NRC, 2016) for each season of the different calendars and finally aggregated over the year to calculate annual feeding balances.

To compare the three seasonal schemes, the statistical evaluation of the series was undertaken with Minitab (v15, 2007; Minitab, State College, PA). The results were analyzed using a GLM model procedure:

$$Y = \mu + \text{location}_j + \text{season}_k + \text{location} - \text{season}_{jk} + e$$

where μ is the overall mean, location is the study site and the herd is managed by a herder, who selects the daily grazing route, the seasons are analyzed separately for the different calendars (5, 3 or 2 seasons); location-season$_{jk}$ is the interaction between seasons and locations due to varying herd management practices in the different locations, month is treated as repeated within the season factor and *e* is the residual error. Significance was $p<0.05$.

3 Results

3.1 Diet, daily dry matter intake

There were highly significant ($p< 0.005$) variations between seasons and differences between sites in monthly averaged predicted daily dry matter intake (gDM.kgMW^{-1}.d^{-1}) and corresponding daily dry matter intake per tropical livestock unit (in kgDM.TLU^{-1}.d^{-1}) (Table 2; Figure 3). In all the sites, feed intake peaked in the core or late wet season when forage availability was high. However, the peak in August was sharper, was followed by a marked decrease in pastoral systems, and occurred later (in October-November) in Koumbia. There were notable differences in the feed intake profiles in the dry season: feed intake decreased markedly to less than 3 kgDM.TLU^{-1}.d^{-1} in the hot dry season in the wetter Sudanian sites up to April in Koumbia, and up to June in Kolda. The low intake observed in Kolda could be related to the systematic practice of night corralling, i.e. preventing night grazing, in order to manure the fields in the vicinity of the village. Feed supplementation is scarce and during *Ceedu*, cropland resources are exhausted and accidental burning of the surrounding savannas also reduces natural resources availability. In the three drier sites, after the steady decrease following the wet season peak, feed intake increased until January, levelled off from February to March and then decreased slightly at the end of the dry season as the volume of straw and litter decreased, except in Dahra where the decrease worsened until August. This prolonged decrease in intake could be linked to the limited daytime grazing time linked with no night grazing. In Niakhar, the noticeable increase in feed intake in middle of the dry season could be due to the opening of millet straw stockpiles and night grazing in the communal fallow, while in Widou and Dahra, the higher feed intake in the middle of the dry season could be linked with access to foliage and *Acacia raddiana* pods. During the wet season, cattle opportunely select feed from a wide range of species and plant organs, while during the dry season feed intake decreases with the progressively increasing scarcity of the straw and litter and the progressive loss of feed quality. However, this was highly variable depending on herd management and on the timing of day/night grazing, availability of browsable vegetation and supplementation practices of the herders that are particularly restrictive in Dahra and Kolda, as detailed in Table 1 and Supplementary Material.

Calculated across the five locations and five seasons, feed intake ranged between 39.4 ± 6.8 gDM.kgMW^{-1}.d^{-1} (2.4 ± 0.4 kgDM.TLU^{-1}.d^{-1}) in HDS in Kolda and 84,8 ± 11,3 gDM.kgMW^{-1}.d^{-1} (5.3 ± 0.7 kgDM.TLU^{-1}.d^{-1}) in LWS in Koumbia. Tested in a GLM, the subdivision into 5, 3 or 2 seasons explained respectively and decreasingly 32%, 26% and 14% of the daily feed intake across all the five locations (see details in Supplementary Table S2). The interaction between seasons and locations reflecting the seasonal herd management practices explained 60%, 47% and 30% of interactions with 5, 3 and 2 seasons, respectively (Supplementary Table S2).

Finally, the average annual intake in the five locations was estimated at 60.9 ± 8.5 gDM.kgMW^{-1}.d^{-1} equivalent to (3.8 ± 0.53 kgDM.TLU^{-1}.d^{-1}), far below (-39%) the 6.25 kgDM.TLU^{-1}.d^{-1} common standard. The summed total annual intake varied between 1,236 kgDM.TLU^{-1}.year^{-1} in Dahra to 1,560 kgDM.TLU^{-1}.year^{-1} in Widou, all below the 2,280 kgDM.TLU^{-1}.year^{-1} estimated from the common standard, and emphasize the marked differences between two pastoral (restricted or free grazing) practices. However, averaged annual intake in the two pastoral and the three agro-pastoral systems

TABLE 2 Predicted annual values and deviations along the different seasonal patterns for the intake, digestibility and metabolizable energy ingested across the five sites and respective local seasons.

	TLU_Daily Fodder Intake						Organic Matter Digestibility						TLU Metabolizable Energy intake					
Locations	Widou	Dahra	Niakhar	Koumbia	Kolda	*p*	Widou	Dahra	Niakhar	Koumbia	Kolda	*p*	Widou	Dahra	Niakhar	Koumbia	Kolda	*p*
Systems	P	P	AP	AP	AP		P	P	AP	AP	AP		P	P	AP	AP	AP	
	Kg DM/day						% OM						MJ/day					
Five seasons																		
Gataaje; (EWS)	$4.8^{a,A}$	$2.5^{c,B}$	$3.9^{b,AB}$	$3.6^{b,C}$	$2.6^{c,C}$	*<0.001*	$60.7^{c,AB}$	$57.9^{c,AB}$	$67.3^{b,AB}$	$74.3^{a,A}$	$63.1^{bc,B}$	*<0.001*	$41.5^{a,A}$	$19.9^{c,C}$	$36.6^{b,BC}$	$37.5^{b,B}$	$22.9^{c,D}$	*<0.001*
s.d.	*0.69*	*1.21*	*0.44*	*0.95*	*0.47*		*5.89*	*3.86*	*7.07*	*3.52*	*8.95*		*8.51*	*9.12*	*5.30*	*9.57*	*6.27*	
Ndungu; (CWS)	$4.8^{a,A}$	$3.6^{c,AB}$	$4.6a^{b,A}$	$4.4^{b,B}$	$4.2^{b,A}$	*5.4E-11*	$64.0^{b,A}$	$59.4^{c,A}$	$69.7^{ab,A}$	$69.4^{ab,B}$	$70.4^{a,A}$	*<0.001*	$42.8^{a,A}$	$30.8^{b,A}$	$45.6^{a,A}$	$42.6^{a,A}$	$42.0^{a,A}$	*1.0E-11*
s.d.	*0.54*	*0.94*	*0.49*	*0.46*	*0.49*		*4.91*	*4.98*	*4.72*	*4.89*	*4.58*		*5.33*	*9.56*	*5.95*	*4.87*	*6.02*	
Yaamde; (LWS)	$4.7^{ab,A}$	$4.2^{b,A}$	$4.0^{b,AB}$	$5.3^{a,A}$	$4.3^{b,A}$	*5.8E-08*	$63.6^{a,AB}$	$54.2^{c,B}$	$62.9^{a,BC}$	$62.2^{a,C}$	$59.5^{b,C}$	*3.9E-09*	$42.4^{ab,A}$	$31.5^{c,A}$	$35.2^{bc,BC}$	$46.6^{a,A}$	$36.3^{bc,B}$	*7.3E-10*
s.d.	*0.38*	*1.29*	*0.43*	*0.71*	*0.79*		*2.23*	*4.16*	*2.04*	*4.00*	*4.09*		*3.77*	*9.13*	*3.93*	*7.39*	*7.88*	
Dabbude; (CDS)	$4.1^{a,B}$	$3.2^{b,B}$	$3.6^{b,B}$	$4.0^{a,BC}$	$3.7^{b,B}$	*4.8E-06*	$58.2^{b,B}$	$55.6^{c,AB}$	$60.7^{ab,C}$	$63.3^{a,C}$	$56.2^{c,D}$	*<0.001*	$33.3^{a,B}$	$24.8^{b,B}$	$30.9^{ab,C}$	$36.0^{a,B}$	$29.2^{b,C}$	*2.5E-10*
s.d.	*0.32*	*0.47*	*0.81*	*1.16*	*0.83*		*3.83*	*4.52*	*2.79*	*4.23*	*3.17*		*4.18*	*4.39*	*7.27*	*10.81*	*7.43*	
Ceedu; (HDS)	$4.0^{a,B}$	$3.1^{b,B}$	$4.2^{a,A}$	$2.6^{bc,D}$	$2.4^{c,C}$	*<0.001*	$53.6^{d,C}$	$57.6b^{c,AB}$	$63.8^{a,ABC}$	$61.6^{ab,C}$	$55.6^{c,D}$	*5.9E-16*	$30.5^{b,C}$	$24.9^{c,B}$	$37.9^{a,B}$	$22.7^{cd,C}$	$19.3^{d,E}$	*<0.001*
s.d.	*0.57*	*0.80*	*0.57*	*0.77*	*0.43*		*8.51*	*4.13*	*5.07*	*5.41*	*3.26*		*6.92*	*6.54*	*5.22*	*7.08*	*3.83*	
p	*<0.001*	*2.3E-03*	*3.5E-03*	*<0.001*	*<0.001*		*<0.001*	*2.0E-02*	*5.7E-04*	*<0.001*	*<0.001*		*<0.001*	*7.6E-03*	*3.0E-05*	*<0.001*	*<0.001*	
Three seasons																		
WS	$4.8^{a,A}$	$3.7^{c,A}$	$4.1^{bc,AB}$	$4.2^{b,A}$	$4.1^{bc,A}$	*2E-15*	$61.9^{c,A}$	$57.4^{d,A}$	$65.9^{b,A}$	$69.9^{a,A}$	$67.2^{b,A}$	*<0.001*	$42.0^{a,A}$	$30.1^{c,A}$	$37.7^{b,A}$	$41.4^{a,A}$	$38.5^{b,A}$	*2.3E-12*
s.d.	*0.62*	*1.17*	*0.52*	*0.99*	*0.78*		*5.59*	*5.12*	*5.58*	*6.18*	*6.93*		*7.39*	*9.65*	*6.18*	*8.41*	*8.89*	
CDS	$4.1^{a,B}$	$3.2^{b,AB}$	$3.6^{b,B}$	$4.0^{a,A}$	$3.7^{b,B}$	*4.8E-06*	$58.2^{b,B}$	$55.6^{c,A}$	$60.7^{ab,B}$	$63.3^{a,B}$	$56.2^{c,B}$	*<0.001*	$33.3^{a,B}$	$24.8^{b,B}$	$30.9^{ab,B}$	$36.0^{a,B}$	$29.2^{b,B}$	*2.5E-10*
s.d.	*0.32*	*0.47*	*0.81*	*1.16*	*0.83*		*3.83*	*4.52*	*2.79*	*4.23*	*3.17*		*4.18*	*4.39*	*7.27*	*10.81*	*7.43*	
HDS	$4.0^{a,C}$	$3.1^{b,B}$	$4.2^{a,A}$	$2.6^{bc,B}$	$2.4^{c,C}$	*<0.001*	53.6d,C	$57.6b^{c,A}$	$63.8^{a,AB}$	$61.6^{ab,B}$	$55.6^{c,B}$	*5.9E-16*	$30.5^{b,C}$	$24.9^{c,B}$	$37.9^{a,A}$	$22.7^{cd,C}$	$19.3^{d,C}$	*<0.001*
s.d.	*0.57*	*0.80*	*0.57*	*0.77*	*0.43*		*8.51*	*4.13*	*5.07*	*5.41*	*3.26*		*6.92*	*6.54*	*5.22*	*7.08*	*3.83*	
p	*<0.001*	*2.0E-02*	*1.6E-02*	*4.4E-08*	*<0.001*		*<0.001*	*3.1E-01*	*6.0E-03*	*5.8E-15*	*<0.001*		*<0.001*	*1.7E-02*	*2.0E-03*	*1.2E-13*	*<0.001*	
Two seasons																		
WS	$4.8^{a,A}$	$3.7^{d,A}$	$4.3^{bc,A}$	$4.4^{b,A}$	$4.0^{cd,A}$	*<0.001*	$61.9^{b,A}$	$58.4^{c,A}$	$67.3^{a,A}$	$70.1^{a,A}$	$69.3^{a,A}$	*<0.001*	$42.0^{a,A}$	$30.6^{c,A}$	$41.0^{ab,A}$	$42.7^{a,A}$	$39.2^{b,A}$	*6.1E-11*
s.d.	*0.62*	*1.16*	*0.45*	*0.70*	*0.77*		*5.59*	*4.56*	*6.32*	*5.57*	*5.99*		*7.39*	*10.15*	*5.64*	*6.03*	*9.07*	
DS	$4.0^{a,B}$	$3.2^{b,B}$	$3.9^{a,B}$	$3.9^{a,A}$	$3.1^{b,B}$	*<0.001*	$56.1^{c,B}$	$56.1^{c,B}$	$62.9^{b,B}$	$65.8^{a,B}$	$56.3^{c,B}$	*<0.001*	$32.1^{b,B}$	$25.2^{c,B}$	$34.4^{ab,B}$	$35.9^{a,B}$	$24.6^{c,B}$	*<0.001*

(Continued)

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TABLE 2 Continued

		TLU_Daily Fodder Intake						Organic Matter Digestibility						TLU Metabolizable Energy intake					
Locations		Widou	Dahra	Niakhar	Koumbia	Kolda	*p*	Widou	Dahra	Niakhar	Koumbia	Kolda	*p*	Widou	Dahra	Niakhar	Koumbia	Kolda	*p*
Systems		P	P	AP	AP	AP		P	P	AP	AP	AP		P	P	AP	AP	AP	
		Kg DM/day						% OM						MJ/day					
Two seasons																			
	s.d.	*0.45*	*0.78*	*0.66*	*1.28*	*0.96*		*6.74*	*4.63*	*4.28*	*6.64*	*3.59*		*5.73*	*5.80*	*6.15*	*11.56*	*8.62*	
	p	*<0.001*	*2.9E-02*	*1.0E-02*	*1.7E-03*	*<0.001*		*3.9E-13*	*4.1E-02*	*1.7E-03*	*1.0E-06*	*<0.001*		*<0.001*	*5.0E-03*	*1.5E-04*	*5.0E-07*	*<0.001*	
Annual																			
	Sum	1 560[a]	1 236[c]	1 458[b]	1 480[b]	1 246[c]	*<0.001*							12 893[a]	9 858[b]	13 348[a]	13 929[a]	11 044[b]	*<0.001*
	s.d.	*142*	*255*	*154*	*235*	*189*		*6.8*	*4.6*	*4.1*	*6.5*	*7.7*		*1714*	*2077*	*1631*	*2345*	*1934*	
	Daily mean	*4.3*	*3.4*	*4.0*	*4.1*	*3.4*		58.6[d]	56.9[d]	64.2[b]	67.5[a]	60.6[c]	*<0.001*	36.3	27.16	36.3	38.6	29.38	
	s.d	*0.67*	*0.96*	*0.64*	*1.1*	1.0		6.88	4.70	5.29	6.56	7.60		8.13	8.01	6.68	10.28	11.13	

P; Pastoral; AP, agropastoral; Values in the table are means (x, X) where x is Location (line) effect coef. and X is Seasonal (column) effect coef; p, p value.

were similar 1,398, 1,395 kgDM.TLU^{-1}.year^{-1} respectively (Supplementary Table S1).

3.2 Digestibility of diet organic matter

The overall year-round dietary digestibility mean for the five sites was 61.87 ± 1.27% OM, and, like for intake, there were significant seasonal variations and differences among the sites. Annual average diet digestibility was generally lower in the Sahelian pastoral sites (58.6 and 56.9% OM in Widou and Dahra) than in the agropastoral south-Sahelien and Sudanian sites (64.2, 67.5 and 60.6 respectively in Niakhar, Koumbia and Kolda) (Figure 4). The higher average digestibility in the wetter sites was mainly due to 8.5% higher digestibility of the selected diet in *Ceedu* (HDS), *Gataaje* (EWS) and *Ndugu* (CWS). However, the temporal profiles of diet digestibility at the three wetter sites diverged considerably in the dry season: digestibility decreased rapidly after the wet season and remained below 56% until April in Kolda, while it remained above 60% and increased strongly from March on in Koumbia and more progressively in Niakhar (Figure 4). The early marked increase in diet digestibility in Koumbia matched the regrowth of perennial herbaceous vegetation. Feed supplementation in agropastoral systems also helped maintain high diet digestibility during the dry season especially in Niakhar and Koumbia where herders manage and exploit all available crop by-products. In the two drier pastoral sites, unlike for feed intake, the seasonal profiles of diet digestibility were close. Yet diet digestibility decreased more rapidly during *Yaamde* (LWS) and remained low during *Dabbude* (CDS) in Dahra. In contrast, diet digestibility was slightly higher in Dahra during *Ceedu* (HDS) probably thanks to higher feed supplementation than in Widou.

The digestibility of the selected diet averaged over five, three or two seasons significantly explained respectively 41%, 32% and 27% of daily feed digestibility across the five locations. The interaction between seasons and locations explained, respectively, 62%, 42% and 38% for five, three and two seasons (Supplementary Table S2).

3.3 Metabolizable energy intake

The product of the fodder DM intake and diet digestibility estimates daily metabolizable energy intake (MEI). Here it was calculated for standard cattle of 250 kg Live weight, equivalent to one TLU. Compared to the TLU basal maintenance requirements, referenced at 21.4 Mj.day^{-1} (NRC, 2016) the MEI of the daily diet varied largely across the five sites and seasons (Figure 5; Table 2).

Daily MEI varied between 17.8 ± 0.39 in Kolda (May, HDS) and 45.91 ± 3.44 in Niakhar, (August, WS). Summed over the year, MEI ranged from 9,858 ± 2,077 Mj.TLU^{-1}.year^{-1} in Dahra to 13,929 ± 1,631 Mj.TLU^{-1}.year^{-1} in Koumbia. While important gaps appear for several days in the dry season, over the year this largely covered the annual basal maintenance requirements of a TLU estimated at 7,819 Mj.TLU^{-1}.year^{-1}, leaving in varying extend additional energy to cover milk production, reproduction, growth and the reconstitution of body reserves.

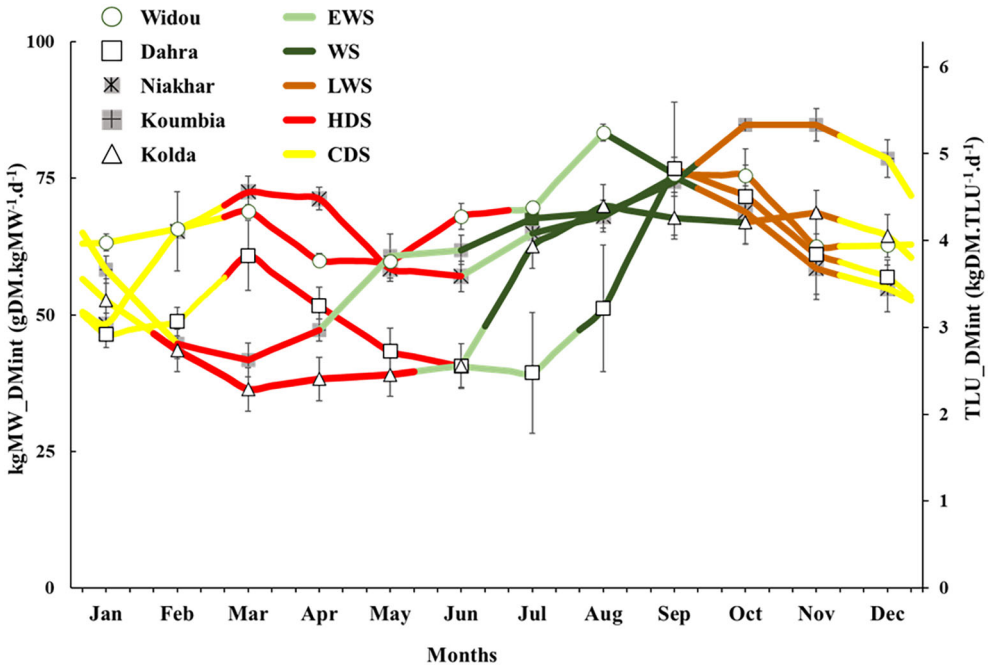


FIGURE 3
Monthly variations in the daily DM intake expressed per kgMW and TLU (means and s.d.) in the five locations and local seasons (the names of the seasons are in Pulaar-Fulfulde).

The cyclic variation of MEI with varying marked drops during the hot dry period reflected the seasonal variations in forage resources and herd management. Indeed, MEI was below basal metabolic requirements in two sites: during most of the dry season from February to May in the agro-pastoral Sudanian site of Kolda, and just at the onset of the rains in June-July in the pastoral Sahelian site of Dahra. In both cases, the failure to satisfy basal needs in a context of poor seasonal availability of quality forage is attributable to herd management that limited cattle grazing time both in the day and at night. Likewise, the gap in diet digestibility observed between drier pastoral sites and wetter agropastoral sites was largely offset by higher feed intake, although only late (September) in the wet season in Dahra. A general drop in MEI occurred at the onset of the dry season except in Koumbia where the drop was delayed to (CDS) at the time of the bush fires. The MEI then improved in the middle of the dry season, at the transition between (CDS-HDS) in the pastoral site of Widou as well as in the agropastoral site of Niakhar.

Subdividing the year into five, three and two seasons significantly explained respectively 42%, 37% and 26% of the variations in MEI across the five locations. The interactions between seasons and locations explained 62%, 52% and 41% of this variation with five, three and two seasons respectively (Supplementary Table S2).

4 Discussion

The analysis of fecal samples by near infrared spectroscopy (F-NIRS) and using the "local calibration technique" provided an original description of intake and selected diet digestibility in five case study sites distributed along the semi-arid to sub-humid bioclimatic gradient in the Sudano-Sahelian zone of sub-Saharan Africa. Fecal NIRS is an indirect method to predict intake and digestibility and apart from statistical cross validation and spectral distance measurement techniques there is no easy alternative direct method to validate predictions. The direct methods used with cattle grazing in Sahelian and Sudanian rangelands are generally much more laborious and costly. However, when observing the evolution of the parameters one can rely on the consistency of the values and the coherence of the profiles to support predicted intake and diet digestibility of grazing cattle in these particularly constrained pastoral and agropastoral systems. Moreover, several studies using F-NIRS have demonstrated the relevance of the technique in both the humid and dry tropics (Boval et al., 2004; Dixon et al., 2007; Tran et al., 2010; Decruyenaere et al., 2013; Assouma et al., 2017; Parra-Forero et al., 2023). The large number of samples collected here in huge experimental field trials in different locations enabled us to build a large dataset of NIRS predicted intake and digestibility values at limited analytical cost.

Compared to the feeding values reported in the literature for SSA environments, rainy and early dry season prediction of intake and digestibility are compatible with standard described in tables (INRA, 1989; 2018) and values observed in experimental stations (Guérin et al., 1986; Ouédraogo-Koné et al., 2008; Kouazounde et al., 2015). They are also comparable with the observations made by Ayantunde et al. (1999); Ickowicz and Mbaye (2001); Schlecht et al. (2004) and Assouma et al. (2018) in similar situations using marker based, oesophageal fistula or hand plucking methods. None

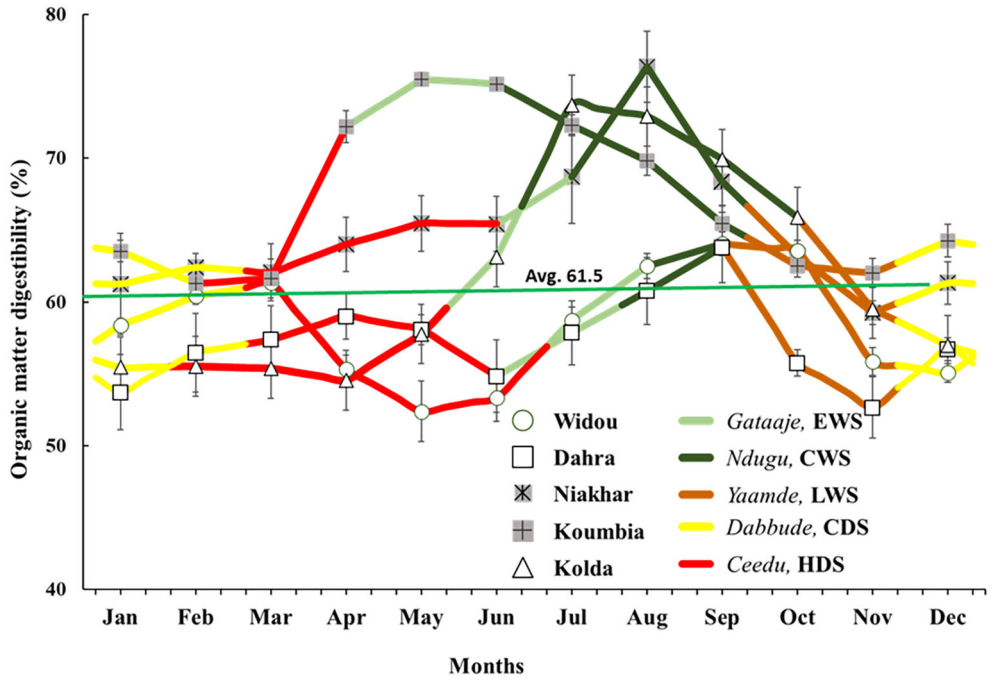


FIGURE 4
Monthly variations in *in-vivo* organic matter digestibility of the voluntarily ingested diet (dMO_Fnir; means and s.d.) in the five SSA locations and Fulani seasons.

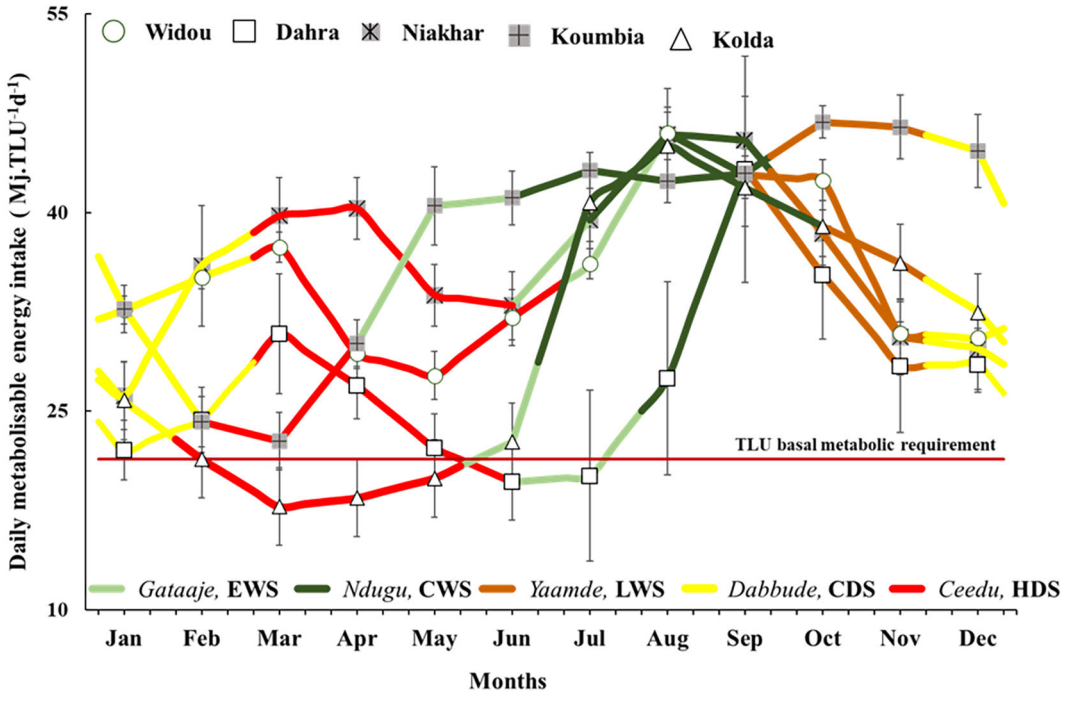


FIGURE 5
Monthly variations in the TLU voluntary metabolizable energy intake (MEI_TLU; means and s.d.) in the five SSA locations and Fulani seasons, compared to the basal metabolic need of a TLU.

of the seasonal feed intake means come close to the common standard of 6.25 kgDM.TLU.d^{-1} as the largest feed intake observed reached 5.3 kgDM.TLU.d^{-1} in the late wet season in Koumbia. Moreover, the annual feed intake observed at the five sites ranged between 3.4 and 4.1 kgDM.TLU.d^{-1}, far below the standard feed intake commonly used to assess livestock nutrition in sub-Saharan Africa. Instead, the alternative reference proposed by analyzing cattle (and sheep and goats), feed intake in Widou Thiengoly (Assouma et al., 2018) better reflects the annual mean observed in Widou, as well as in the other four sites. Indeed, the alternative norm proposed to assess feed intake of grazing cattle is 73 gDM.kgMW^{-1} or 18 gDM.kgLW^{-1}, equivalent to 4.6 and 4.5 kgDM.day^{-1} for one TLU. This estimation is still more than 10% higher that the annual mean intake observed in Widou, Niakhar and Koumbia and about 25% higher than that recorded in Dahra and Kolda. If the plus or minus 13% seasonal modulation of the alternative norm is applied, cattle feed intake should vary seasonally between 4.0 and 5.2 kgDM.TLU^{-1}.d^{-1} in the dry and the wet season respectively. These seasonal norms were close to the intake observed in the dry season in Widou, Niakhar and Koumbia, but higher than observed intake in Dahra and Kolda. The wet season norms were about 13% above the norms at the three former sites and above the intake observed at the two latter sites.

The cattle herd we studied in Widou is representative of the most common free grazing pastoral system in arid to semi-arid regions in SSA. However, the sample feces were only collected from cattle that remained in the Widou perimeter all year round, whereas in practice a large fraction (75%) of the cattle leave the area, mainly in the *ceedu* (HDS), in a transhumance toward wetter areas. Further work should be conducted with the transhumant animals, to assess the impact of seasonal mobility on intake and diet digestibility. On the other hand, the cattle herd in Dahra has access to similar rangeland resources but is sedentary. The extremely low intake values observed in the late dry and in the early wet season are linked to the constrained grazing time, particularly due to station management. If Dahra is excluded from the comparison for that reason, annual mean feed intake in arid pastoral Widou is 11% higher than the mean of three wetter agropastoral sites where grazing time was restricted for different reasons including lack of skilled herding labor, no tradition of night grazing, and priority given to manure collection in corrals.

The supposedly better nutritional quality of arid rangelands in the wet season often used to justify the pro-active wet season transhumance of livestock to the north (Breman and De Ridder, 1991; Schlecht et al., 2001; Turner et al., 2014) was not confirmed by the dietary digestibility of cattle in Widou and Dahra, as it was lower than that in the three wetter sites. However, higher feed intake offset the reduced digestibility of selected feed so that wet season MEI in Widou was close to the MEI in wetter sites. Agropastoral systems in the dry season in semi-arid and sub-humid zones manage the quality of the feed intake by grazing perennial regrowth and supplementing cattle with stored or purchased crop by-products that reached higher MEI except in Kolda. Crop and livestock systems are often presented as competing for resources, and hence leading to conflict. However, it is noteworthy that a positive interaction between them was observed here.

The formalization of the climate parameters along the local seasonal calendar in Pulaar-Fulfulde provides a comprehensive explanation for the practices within and between the cropping and the livestock systems. Although the climate data derived for each site and year by geographic interpolation (from the open access FAO New_LocClim V 1.10 database) could probably be improved, they already allowed us to characterize the five seasons across the five sites using a common model. This useful, easily accessible tool would just need to be updated with recent and evolving climate data. In the future, it will certainly be helpful to use alternative data sets in order to address climatic fluctuations and changes in the Sahel, particularly concerning seasonality (e.g (Biasutti and Sobel, 2009)). Taken together, these results underline the importance of accounting for seasonal variations for more detailed estimations of variations of the intake, diet digestibility and ME needs cover in grazing cattle. Using a standard annual intake reference is not appropriate to assess the nutrition of grazing cattle and its environmental impact. The different seasonal arrangements based on the local five season calendar explain the temporal variations across the five sites sampled along the Sudano-Sahelian bioclimatic gradient better (Supplementary Table S2). Yet, a notable proportion of these variations linked to the specific practices of each herder in each site are largely seasonal specific, as revealed by the superiority of the variations explained by the interactions between seasons and sites (Supplementary Table S2). To inter-compare livestock breeding systems, the three-season scheme integrating a THI threshold is a good compromise between five local seasons and two main seasons (one wet and one dry) that are usually recognized based on rainfall distribution alone. Indeed, dividing the year into two seasons (wet and dry) still explained 27% of the monthly variations of diet digestibility in the five sites, but only 14% of the variations in intake (Supplementary Table S2). Adding the division of the dry season into cool dry and hot dry increases these shares to 32% and 26% respectively, closer to the 41% and 32% reached when five local seasons are taken into account. Whatever the number of seasons considered, they always explained a larger proportion of the digestibility of the selected diet than did variations in intake. Adding herd management to the GLM model by considering the interaction between seasons and sites improved the rate of variation explained. Indeed, site interaction with two seasons explained 52% and 30% of diet digestibility and intake variations versus 49% and 47% with three seasons and 62% and 54% with the five local seasons.

The higher proportion (30-62%) of variations explained by the seasons versus about 18% of diet digestibility and intake variations explained by site alone, underlines the seasonality of most herd management options. Again, more variations in diet digestibility were explained by season*site interactions than by feed intake, but the gap was reduced especially if five or even three seasons were considered. This reduction in the gap is an evidence for the possibility to compensate for inadequate cattle nutrition due to

seasonal contrasted forage availabilities by site specific livestock management and seasonal migration.

Reliable statistics on seasonal feed intake and diet digestibility of grazing cattle are crucial to assess vegetation mass flows, nutrient and carbon cycling, and more generally, to evaluate the impact of cattle on the environment and their contribution to climate change. Based on the data provided in this paper, enteric methane and CO_2 emissions by grazing cattle in the context of the pastoral and agropastoral systems studied here are currently under assessment. New emission factors will be proposed in a separate paper to provide more precise references for West Africa, for IPCC guidelines for instance. As such, statistics on seasonal feed intake and diet digestibility should not be extrapolated to the whole cattle population of South Saharan West Africa because of the marked variations observed with local agroecological and management particularities. However, these data help target sites, seasons and practices characterized by stresses in MEI, highlight gaps in the feed intake of grazing cattle, and enlight the potential of improved interactions between cropping and livestock breeding systems.

5 Conclusion

In this study, we defined a generic method that crosses local farmers' knowledge and quantitative climate criteria (decadal rainfall, potential evapotranspiration, mean air temperature and air humidity) in order to divide the year into seasons in tight relation with local knowledge. This method successfully captured the five seasons recognized by the local farmers and herders along the Sudano-Sahelian climate gradient.

The annual feed intake observed in the five sites distributed along the bioclimate gradient in West Africa ranged between 3.4 and 4.1 kgDM.TLU^{-1}.d^{-1}, far below the standard feed intake norm of 6.25 kgDM.TLU^{-1}.d^{-1} widely used in sub-Saharan Africa. What is more, none of the seasonal feed intake means approaches that standard. One can thus conclude that this standard does not reflect the annual mean cattle feed intake. Instead, the alternative reference of 73 g.kgMW^{-1} proposed in the literature for grazing cattle, sheep and goats in North Senegal reflects the annual mean observed in the five sites studied here far better.

Our study also revealed highly significant ($p< 0.005$) variations between seasons and between sites. The annual intake reference standard is thus not sufficient to assess the nutrition of grazing cattle across the bioclimatic gradient.

The herders' different seasonal arrangements show that the local calendar with five seasons explains a larger proportion of the variations in cattle feed intake and diet digestibility recorded across the five sites sampled along the Sudano-Sahelian bioclimatic gradient than a calendar with only two seasons.

Whatever the number of seasons used, they always explained a larger proportion of variation in selected diet digestibility than variation in feed intake. Yet the interaction between seasons and sites considerably increased (62%) the share of variation explained, underlining the seasonality of most herd management options and to the extent to which they can complete the nutritional requirements of livestock facing seasonally contrasted forage availability.

Summed over the year, the metabolizable energy intake of grazing cattle varied considerably covering the basal annual maintenance requirements to a greater or lesser extent. Yet in two sites, periods with deficient nutrition were identified in the late dry season and early wet season that resulted from the combination of poor seasonal grazing resources and inappropriate grazing management practices. During these two periods of deficit, the metabolizable energy intake of grazing cattle was well below the annual energy required for basal maintenance exept for Koumbia and Kolda. This underlines the feed gap in these two seasons and the need to upscale organizational schemes between the crop and livestock sectors to fill the gap.

The results of our study will improve assessments of the impact of grazing cattle on the environment, especially impacts on nutrient and carbon fluxes, and assessments of methane emissions caused by enteric fermentation. These parameters play a determining role in assessing livestock-driven nutrient transfers for soil fertility management, soil carbon sequestration and the carbon balance between livestock systems and products. Their improvement should thus help design improved pastoral management policies in West Africa.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

MA: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. PL: Conceptualization, Data curation, Formal analysis, Methodology, Writing – review & editing. PH: Conceptualization, Data curation, Methodology, Supervision, Validation, Visualization, Writing – review & editing. AI: Methodology, Supervision, Writing – review & editing. VD: Investigation, Supervision, Writing – review & editing. MB: Conceptualization, Data curation, Investigation, Writing – review & editing. CW: Data curation, Investigation, Methodology, Writing – review & editing. BB: Conceptualization, Data curation, Investigation, Methodology, Writing – review & editing. CC: Formal analysis, Methodology, Project administration, Resources, Writing – review & editing. FG: Data curation, Formal analysis, Methodology, Writing – review & editing. JV: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Visualization, Writing – review & editing.

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Conflict of interest

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

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Supplementary material

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