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Identification and evaluation of agroecosystem compartments as forage sources for free-ranging goats in smallholder farming systems of western Democratic Republic of Congo

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ABSTRACT

Free-ranging goats forage across multiple agroecosystem compartments, thereby contributing to nutrient redistribution. Despite their importance in nutrient flows, little is known about how these compartments support goat diets or about their spatial structure. This study addresses this gap by identifying, mapping, and characterising the agroecosystems exploited by free-ranging goats as forage sources and by assessing the contribution of each compartment to their daily diet. Twelve adult female goats from local herds were monitored during both the dry and rainy seasons for three consecutive days at four sites, using GPS collars combined with drone surveys and direct observations. Two observers were assigned to each goat: one, equipped with a stopwatch and tracking sheet, recorded feeding stations, forages consumed, and biting times; the other, using a Sony HDR-CX405 camera, documented biting behaviour.

Drone-based mapping revealed five distinct compartments of the foraging area: croplands (6.1 %–14.8 %), fallow lands (2.7 %–12.5 %), rangelands (36.4 %–69.7 %), residue supply areas (9.8 %–46.7 %), and hedgerows (0.1 %–5.4 %). The agroecosystem landscapes were highly fragmented (24–54 patches/ha) and exhibited SHDI values ranging from 0.94 to 1.19. Goats consumed 57 forage species, dominated by grasses (17 %) and legumes (9 %), with the remaining 74 % spanning 31 botanical families. The integration of GPS tracks with land-use maps and direct observations revealed that rangelands and agricultural lands were the primary contributors to free-ranging goats' daily dry matter intake and forage species diversity. The marked heterogeneity and floristic richness of these agroecosystem compartments underpin their importance as key forage sources supporting smallholder free-range goat farming in western Democratic Republic of Congo.

1. Introduction

Terrestrial ecosystems have been under increasing human pressure since the Green Revolution, largely owing to rising global food demand (Foley et al., 2011; Barnosky et al., 2012; Bourban, 2019). Subtropical savannahs are among the most intensively exploited ecosystems because of their multifunctional role in supporting food production (Boval et al., 2017; IPBES, 2018; Kuyah et al., 2021). However, they are also highly vulnerable to degradation resulting from unsustainable practices such as slash-and-burn agriculture with short fallow periods (Boval et al., 2017; Mishra et al., 2021), high-intensity fires used for rangeland management, uncontrolled wildfires (McNew et al., 2023), and inappropriate afforestation strategies (Veldman et al., 2015; Fernandes et al., 2016). These practices compromise key ecosystem services—such as nutrient cycling, biodiversity, and food web stability—threatening long-term crop and livestock productivity and the livelihoods of local communities in sub-Saharan Africa (SSA), especially under the pressures of climate change.

Barnosky et al. (2012) emphasise the urgent need to address the root causes of anthropogenic global change and to strengthen biodiversity and ecosystem service management, noting that ecosystems often fail to recover once critical disturbances occur.

In SSA, smallholder farmers rely heavily on extensive agriculture, and livestock production is embedded within natural savannah ecosystems (Callo-Concha et al., 2013; Losch, 2016; Orina et al., 2024). There is a pressing need for research focused on the multifunctional roles of

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these ecosystems (Lemaire et al., 2014; Boval et al., 2017) because significant nutrient export through crop and livestock production leads to soil degradation and loss of fertility. However, free-ranging livestock return a fraction of nutrients through dung and urine while foraging, thereby playing a significant role in maintaining soil fertility (Augustine et al., 2003; Rufino et al., 2006; Grillot et al., 2018; Huruba et al., 2018), although the extent of this contribution remains poorly documented.

Agroecological farming practices that enhance interactions among soil, plants, and animals through efficient nutrient recycling are considered viable strategies for preserving ecosystem health and ensuring sustainable food production (Muramoto et al., 2000; Bonaudo et al., 2014; Altieri et Nicholls, 2020; Altieri et al., 2024; Audouin et al., 2024). Integrated crop–livestock systems (ICLS) exemplify such agroecological practices, supporting sustainable intensification within agroecosystems by improving nutrient recycling through the management of manure and crop residues. These practices reduce dependence on external inputs and enhance resilience to the impacts of climate change (Rufino et al., 2009; Bonaudo et al., 2014; Stark et al., 2016; Grillot et al., 2018, 2018; Steinmetz et al., 2021).

However, livestock management strategies vary across agroecological zones, shaped by differences in land-use allocation and pressure, feed resource availability, and territorial planning (Rufino et al., 2006). This results in diverse ICLS configurations and a range of potential strategies and designs. In the free-ranging systems common in SSA, livestock govern nutrient flows and act as key contributors to soil fertility in both savannah and cultivated lands (Rufino et al., 2006; Audouin et al., 2024). Animal diet composition directly influences the quality and quantity of nutrients returned to the soil via excreta (Rufino et al., 2006). Therefore, assessing forage potential in terms of species diversity, nutritional value, and biomass productivity is critical for developing livestock management strategies that promote the sustainable use of tropical savannah ecosystems (Huruba et al., 2018). Such assessments are particularly important for improving understanding of nutrient transfer from grazing areas to cropland (Audouin et al., 2024), especially in the context of ICLS.

Among livestock, goats are a common species in rural areas of SSA because of their adaptability to diverse and harsh environments, as well as their compatibility with extensive farming systems that require low feed and management inputs (Dossa et al., 2008, 2015; Gasigwa Sabimana et al., 2018; Sejian et al., 2021; Andre Mataveia et al., 2023).

In the Democratic Republic of Congo (DRC), goat farming relies almost entirely on natural forages within agroecosystem landscapes, with herders occasionally providing limited supplementation using crop residues (Gasigwa Sabimana et al., 2018; Wasso et al., 2019; Ndona et al., 2024). Despite this dependence, little is known about the structure of these agroecosystem landscapes and their contribution to the daily diets of free-ranging goats. Addressing this knowledge gap is essential for evaluating the role of free-ranging goats as potential nutrient drivers within an agroecosystem, in line with ICLS principles. We therefore hypothesise that under free-range farming conditions, goats exploit multiple agroecosystem compartments but these compartments contribute unequally to their daily diets.

Accordingly, this study aimed (1) to map and characterise the agroecosystems exploited by free-ranging goats, with particular attention to identifying the main compartments of the foraging area (CoFA); (2) to assess and compare the individual contribution of these CoFA to the goats' daily dry matter intake (DMI); (3) to record and identify the forage species consumed; and (3) to evaluate the quantity and quality of the daily goat diet in terms of DMI, forage species diversity, acid detergent fibre (ADF), neutral detergent fibre (NDF), crude protein (CP) content, and digestibility.

On one hand, these parameters indicate diet quality and act as proxies for nutrient recycling, providing insights into the quantity and quality of nutrients returned to the soil through goat excreta. Such knowledge is crucial for developing sustainable management strategies that enhance nutrient flows within agroecosystem compartments. On the other hand, free-ranging goats often damage crops and provoke land-use conflicts between herders and farmers, as observed in rural areas of the DRC and across SSA. Mapping CoFA and identifying the forages consumed could therefore help inform alternative management strategies that regulate access to these CoFA, secure animal nutrition, and mitigate potential farmer–herder conflicts.

2. Materials and methods

2.1. Study area

Four sites were selected for this study: the Masamuna, Mosango, Ngeba, and Kikola villages, located in the western provinces of the DRC (Fig. 1). The Ngeba village (5°11′ S, 15°12′ E) and the Kikola village (5°06′ S, 15°06′ E) are situated in Kongo Central province, while the Masamuna (4°48′ S, 17°37′ E) and Mosango (4°50′ S, 18°06′ E) villages lie within Kwilu province. These study areas share a similar ecosystem pattern characterised by partly cropped savannahs interwoven with gallery forests that thrive along riverine and wetland habitats (Ndona et al., 2024).

According to the International Vegetation Classification, the biome of these study areas belongs to the West-Central African Mesic Woodland and Savannah division (Faber-Langendoen, 2020). These savannahs constitute an important source of fodder and serve as a vital resource for extensive goat rearing. Following Köppen's classification (Lohmann et al., 1993), the climate is categorised as Aw4. The regions experience a tropical–humid Sudanian climate with two distinct seasons. The dry season lasts for approximately 4 months, from mid-May to mid-September, in Kwilu province (Mosango and Masamuna villages). In Kongo Central province (Ngeba and Kikola villages), it can extend up to 5 months, until mid-October. The rainy season spans roughly 8 months. Mean annual temperatures range between 25 °C and 28 °C, with an average annual rainfall of approximately 1400 mm (Gasigwa Sabimana et al., 2018; Vangu et al., 2023).

2.2. Experimental design

In each village, three female adult goats (27 ± 1.9 kg) were selected from local herds. All had given birth at least once and were raised under typical local free-range farming conditions. Each goat was fitted with a GPS collar (Fastrax UP 501; Fastrax Ltd., Finland) to record its location while foraging across the agroecosystem from 8:00 AM to 5:30 PM each grazing day, over 3 consecutive days, during both the dry (July–August) and rainy seasons (March–April). The GPS recorded the animal's position every 5 min. The University of Liège ethics committee (No. 19–2116, Liège, Belgium) approved the use of tracking devices as appropriate from an animal experimentation perspective (Dumortier et al., 2021).

Additionally, two observers were assigned to monitor and supervise each goat during the three free-grazing days, for approximately 9 h per day (Zampaligré et al., 2013), from 8:00 AM to 5:30 PM, following a 3-day familiarisation period as recommended in previous studies (Agreil & Meuret, 2004; Feldt & Schlecht, 2016; Vandermeulen et al., 2018; Chebli et al., 2020). One observer was equipped with a stopwatch and a daily monitoring sheet to record the duration of biting behaviour at feeding stations, the name and part of the forage plants consumed, and the CoFA where the foraging occurred (e.g. cropland, fallow land, grassland, etc.) (Barroso et al., 2000; Zampaligré et al., 2013). The observer also noted the duration of resting periods.

The second observer simultaneously recorded direct visual observations of goat biting behaviour using a Sony HDR-CX405 2.29 Mpix camera with 60 × optical zoom. Consumed forages were documented under their vernacular or local names as ethnobotanical data (Ayantunde et al., 2008), and specimens were collected for identification in the herbarium of the Plant Ecology and Systematics Laboratory at the University of Kinshasa, Lemba, DRC (Kembelo et al., 2021;

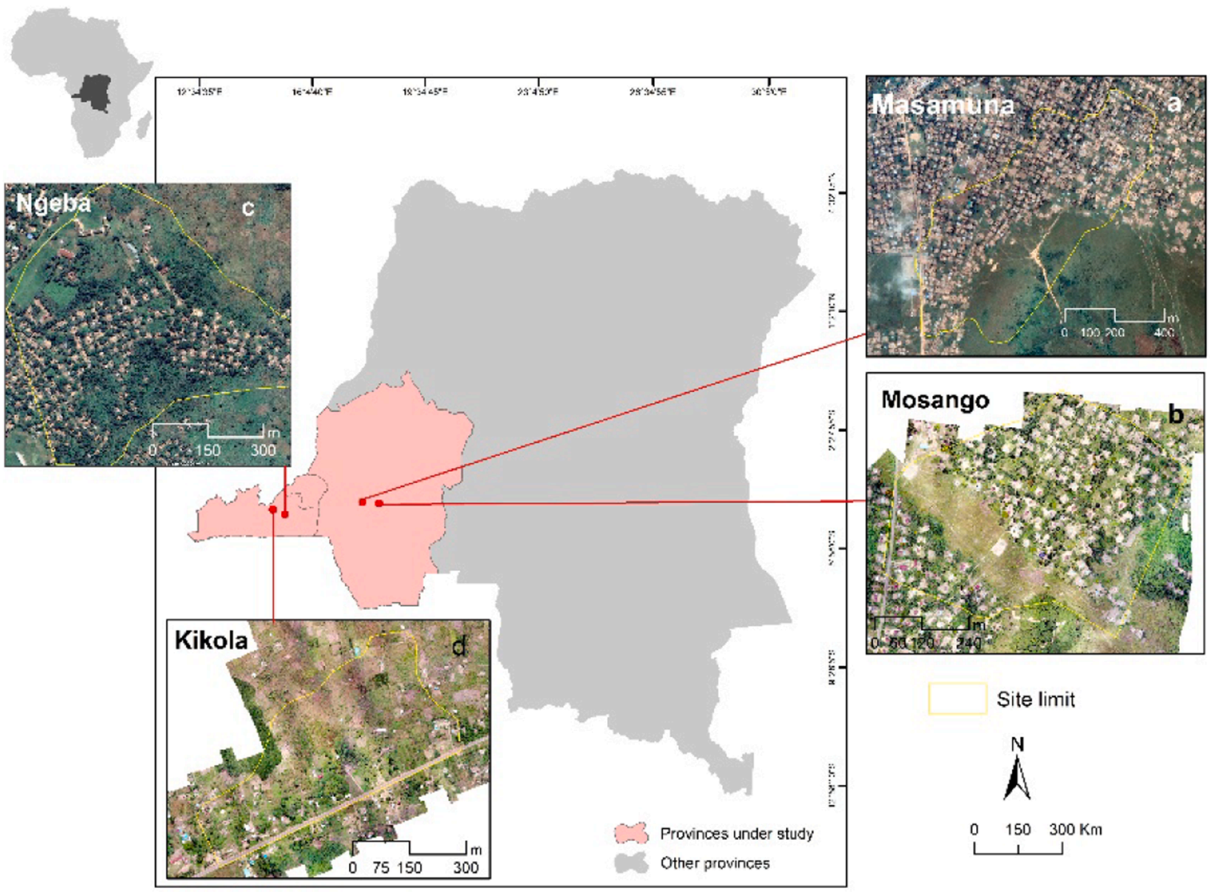

Fig. 1. Study area including the (a) Masamuna, (b) Mosango, (c) Ngeba, and (d) Kikola sites.

Ouachinou et al., 2017).

Finally, on the third day of data collection, an aerial photography survey was carried out at a flight altitude of 80 m using a DJI Mavic Pro 2 unmanned aerial system (UAS) equipped with a 1-inch 20-megapixel CMOS sensor and an adjustable focal aperture ranging from f/2.8 to f/11, along with a 77-degree field of view lens. The purpose of this aerial survey was to complement direct observations by producing high-resolution orthophotos that captured detailed imagery of the foraging areas across the agroecosystems exploited by the goats.

2.3. Data collection and processing

Aerial photographs were processed using Agisoft Metashape photogrammetry software to generate orthomosaics of the surveyed agroecosystems. The main steps included image alignment, generation of a dense point cloud, and extraction of the orthomosaic (Sherwood et al., 2018; Hatcher et al., 2020; Over et al., 2021). The resulting orthomosaics had a spatial resolution of 0.05 m based on the WGS 1984 UTM Zone 33S projected coordinate system. These were then used to map and characterise the agroecosystem compartments.

A land use and land cover (LULC) map of each agroecosystem was produced by digitising the UAS-derived orthomosaics. Automatic classification was not applied because the presence of non-essential objects (e.g. roofs with multiple colours) created radiometric classes that were difficult to distinguish, and some agroecosystem compartments showed strong spectral similarity (e.g. rangelands and fallow lands). Instead, objects were visually and manually labelled during polygon digitisation. A vector layer of polygons was created to represent objects or reference classes irrespective of pixel values (Dupuy et al., 2022; Jolivot & Dupuy, 2023). Houses, trees, and palm stands were digitised as distinct LULC classes but were not considered as CoFA.

The CoFA classes were then characterised using the Patch–Matrix Model (Lausch et al., 2015), which describes the spatial structure of a landscape. Following Plexida et al. (2014), a limited set of six landscape metrics was applied to capture heterogeneity within the agroecosystems exploited by goats: patch density (the number of CoFA patches per hectare), CoFA index (the percentage of the agroecosystem area occupied by a CoFA class), mean patch size ± standard deviation (the area of a CoFA class divided by its number of patches), minimum and maximum patch sizes per CoFA class, CoFA richness (the number of distinct CoFA classes), and Shannon Diversity Index (SHDI).

Goat GPS tracks were then superimposed onto the LULC maps. For each goat, the time spent on each CoFA was calculated from the georeferenced points automatically recorded at 5-minute intervals. Because of land-use dynamics, with frequent shifts between fallow and cropped field classes, both were grouped under the category “agricultural land”.

Daily DMI was estimated indirectly using the hand-plucking method, which mimics the bites taken by grazing goats (Bonnet et al., 2015; Chebli et al., 2020). This method considered three main parameters: feeding time (FT; duration of forage collection), bite mass (BM; average dry mass of forage per bite), and bite rate (BR; number of bites per unit time). DMI was then calculated using Eq. (1):

$$DMI(gd^{-1}) = BM \times BR \times FT \quad (1)$$

Each variable in the equation was determined experimentally. BM for each forage species was estimated using the hand-plucking simulation method, which involved manually collecting portions of forage to replicate goat grazing behaviour. For each recorded forage species, at least 100 hand-plucking repetitions were performed. The collected samples were weighed fresh and then oven-dried at 60 °C until a constant dry weight was achieved. The average BM for each forage species was calculated by dividing the total dry mass by the number of hand-plucking replicates:

$$BM = \frac{Mass\ of\ dried\ sample}{Number\ of\ hand-plucking\ simulations} \quad (2)$$

The BR was determined from direct observation of the videos captured by the second observer. These videos were processed using VSDC professional video editing software (Lee & Kim, 2023). A minimum grazing sequence of 20 s on the forage plant consumed was randomly selected for each goat that had fed on it, resulting in at least 240 s of mixed footage per forage species. By replaying the footage in slow motion, the number of bites taken by the goats on the forage plant in question was accurately counted over the 240-second observation period.

The FT for collecting feed resources was defined as the period during which bites were taken on forage plants. This time excluded all other activities not related to forage collection, such as walking between locations within different CoFA, resting, or ruminating.

The CoFA within the agroecosystem were identified and mapped using UAS-generated orthomosaics. Geolocation data from the goats revealed the time spent on each CoFA, while direct observations confirmed the forage species consumed and recorded the time goats allocated to each species while grazing. Taking the CoFA into account, the data collected allowed the daily intake equation to be adapted as follows:

$$DMIT\left(gd^{-1}\right) = \sum_{i=1}^{n} DMICoFA_i \quad (3)$$

where

- DMIT (g d^{-1}) = total daily DMI (in grams per day)
- DMI $CoFA_i$ = daily DMI within a single CoFA (in grams per day)

Within each CoFA, the daily intake was determined using Eq. (4):

$$DMICoFA\left(gd^{-1}\right) = \sum_{j=1}^{m} DMISp_j \quad (4)$$

where

- $DMISp_j$ = daily intake of each forage species (grams per day) consumed within a single CoFA.

At this step, we referred to Eq. (1) to estimate DMI_Sp_j, expressed using Eq. (5) as follows:

$$DMISp_j = BTSp_j \times BFSp_j \times BMSp_j \quad (5)$$

where

- $BTSp_j$ = total time spent by the animal collecting forage species *j* within the same CoFA during a grazing day (Eq. (6))
- $BFSp_j$ = average bite frequency on forage plant *j* (Eq. (8))
- $BMSp_j$ = mass of a bite on forage plant *j* (Eq. (9)).

The total time spent by the animal collecting forage species *j* within the same CoFA during a grazing day ($BTSp_j$) was calculated using Eq. (6):

$$BTSp_j = \left(\frac{BTvis\ Spj}{\sum_{j=1}^{m} BTvis\ Spj}\right) \times \left(T_{gps}CoFA_i - T_{rest}CoFA_i - T_{walk}CoFA_i\right) \quad (6)$$

where

- BTvis Sp_j = time recorded by the observer (visual observation) that the goat spent in $CoFA_i$ collecting forage species Sp_j
- $\sum_{j=1}^{m} BTvis\ Spj$ = total time recorded by the observer (visual observation) spent in $CoFA_i$ collecting all forage species consumed
- T_{gps} $CoFA_i$ = time recorded by the goat's GPS collar within a single $CoFA_i$ while foraging
- $T_{rest}CoFA_i$ = non-grazing and/or resting time recorded by the observer within $CoFA_i$
- $T_{walk}CoFA_i$ = time allocated to walking within $CoFA_i$ (Eq. (7))

The walking time within a CoFA ($T_{walk}CoFA_i$) was calculated using Eq. (7):

$$T_{walk}CoFA_i = \frac{Dgps}{S} \quad (7)$$

where

- Dgps = distance walked within $CoFA_i$, recorded automatically by the goat's GPS collar
- S = walking speed of the goat when not collecting forage, estimated at 50 m min^{-1} (Meuret et al., 1985)

The average bite frequency on forage plant *j* ($BFSp_j$) was then determined using Eq. (8):

$$BFSp_j = \frac{NBSpj}{t} \quad (8)$$

where

- $NBSp_j$ = number of bites counted on forage plant *j* by replaying the grazing footage in slow motion using VSDC Video Editor
- t = time spent making these bites

Finally, the mass of a bite on forage plant *j* ($BMSp_j$) was obtained using Eq. (9):

$$BMSp_j = \frac{\sum_{k=1}^{l} BMsimul}{l} \quad (9)$$

where

- l = number of hand-plucking repetitions performed on the consumed part of forage plant *j*
- $\sum_{k=1}^{l} MBsimul$ = total dry weight (g) of the l hand-plucking repetitions for forage plant *j*

2.4. Forage sample analyses

Hand-plucked forage samples, previously collected to estimate BM and oven-dried at 60 °C, were subsequently ground to pass through a 1-mm mesh sieve (Cyclotec 1093 Sample Mill; FOSS Electric, A/S, Hillerød, Denmark). The samples were then sent to the Laboratory of Precision Livestock and Nutrition, Gembloux Agro-BioTech (Liège University), for chemical analysis. NDF and ADF values were determined following the methodology outlined by Van Soest et al. (1991). The in vitro digestibility of organic matter was assessed using an enzymatic procedure involving pepsin and cellulase, according to the method described by Aufrere (1982). Total nitrogen content was determined using the Kjeldahl method (AOAC, 1990), and CP was calculated as $N \times 6.25$.

2.5. Statistical analysis

Descriptive statistics were used to characterise the agroecosystems exploited by free-ranging goats. To assess the effects of site, season, and their interaction on daily DMI, diet quality (CP, ADF, NDF, and digestibility), and the daily number of forage species consumed, a two-way analysis of variance (ANOVA) was performed, provided that the assumptions of normality and homogeneity of variances were met (using the Kolmogorov–Smirnov and Levene tests), with the *car* package implemented in R Core Team (2024) RStudio version 4.4.2. If these assumptions were violated, a two-way aligned rank transform (ART) ANOVA was conducted using the *ARTool* package as an alternative to the F-test (Kay & Wobbrock, 2016). Following either the ANOVA or ART ANOVA, Tukey's post-hoc test was applied to identify significant differences ($p < 0.05$) within site and season groups.

To evaluate and compare the contribution of different CoFA to daily DMI, grazing time, and consumed forage diversity, a three-way ART ANOVA was performed, considering season, site, and CoFA as fixed factors, including the interaction term season × CoFA. Tukey's post-hoc test was again used to detect significant differences ($p < 0.05$) between CoFA classes.

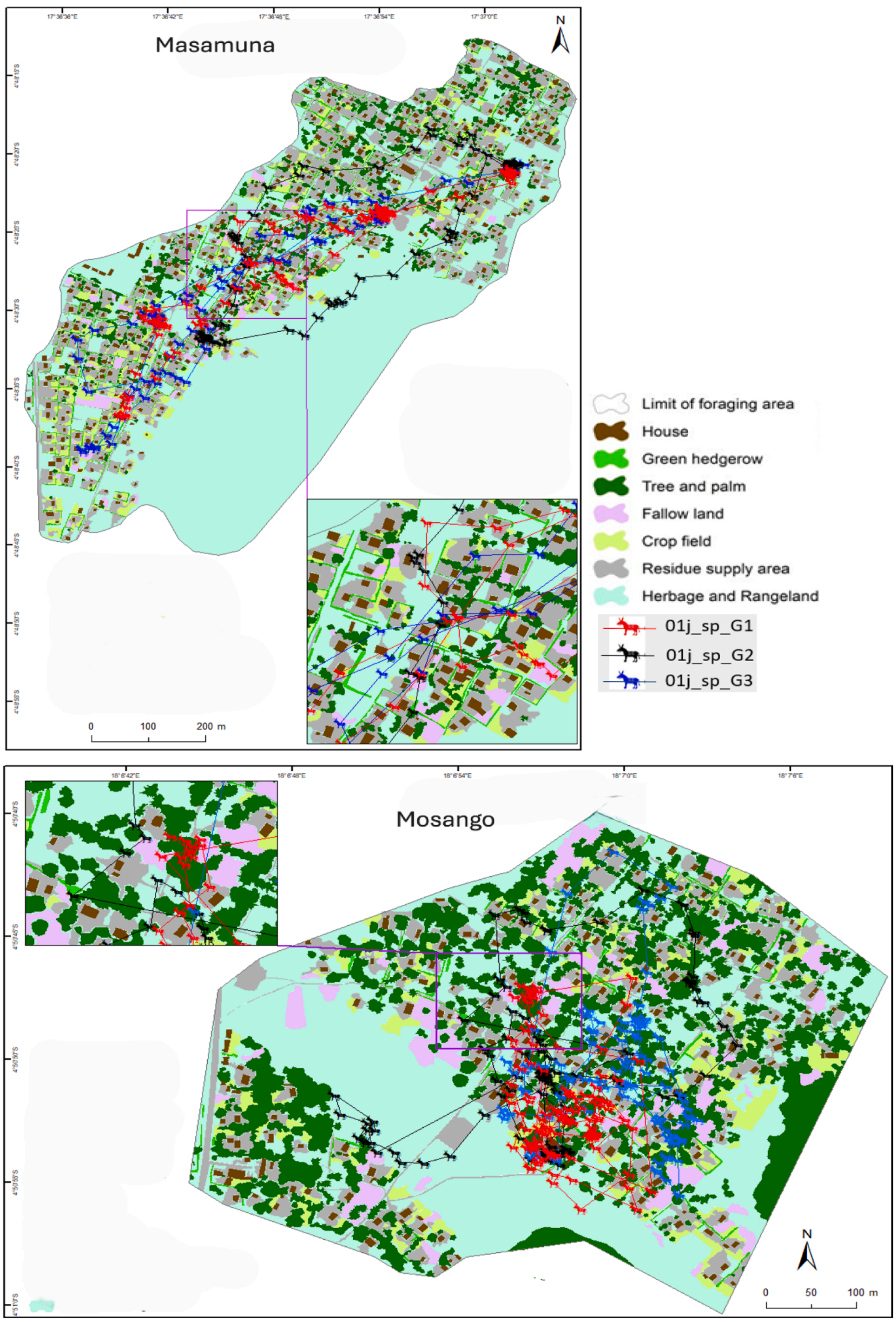

Fig. 2a. Land use and land cover maps illustrating the spatial configuration of compartment of foraging area (CoFA) within the agroecosystems exploited by free-ranging goats. The red, blue, and black lines exemplify georeferenced movement tracks recorded by GPS-collared goats (G1, G2, and G3) on day 1 of monitoring in rainy season at the Masamuna and Mosango sites.

3. Results

The spatial structure of the agroecosystems across the four study sites (Fig. 2a, Fig. 2b) revealed five distinct land-use classes exploited by free-ranging goats as CoFA. These compartments, described in Table 1, were croplands (comprising annual crops and vegetable gardens under active cultivation); fallow lands (post-cultivation areas), both of which constituted agricultural land; rangelands and natural vegetation (dominated by herbaceous species); green hedgerows (featuring woody or herbaceous perennial species used as plot borders); and residue supply areas (areas lacking vegetation cover, such as house halls, front or back yards, where goats consumed crop residues or household organic waste). Despite a moderate diversity of compartments, as indicated by SHDI values close to 1 (Table 1), the agroecosystems exploited by the goats were heterogeneous across all sites. Masamuna showed the highest fragmentation index (54 CoFA patches per hectare), whereas the other sites ranged between 24 and 31 patches per hectare (Fig. 2a).

Goats in free-range systems consumed a total of 57 forage species, including grasses (17 %, $n = 10$) and legumes (9 %, $n = 5$), which were the most frequently consumed botanical groups. The remaining 74 % ($n = 42$) of species were distributed across 31 distinct botanical families. Detailed information on life forms, plant parts consumed, seasonal consumption patterns, and nutritional profiles of these species is presented in Tables 2a and 2b for the Kongo Central and Kwilu provinces, respectively.

Goat diet composition varied across sites and seasons (Table 3). DMI, forage species diversity, and diet digestibility all showed significant effects of site and season ($p < 0.05$). By contrast, NDF content did not differ significantly between sites or seasons ($p > 0.05$), while ADF exhibited spatial but not seasonal variation ($p > 0.05$).

Goat diets were more species-diverse and contained higher DMI and CP content during the rainy season than during the dry season across all sites ($p < 0.05$). Across sites, Masamuna and Mosango showed the greatest species diversity in the goats' daily diets

($p < 0.05$), although CP content did not differ significantly among sites ($p > 0.05$).

The contribution of each CoFA to daily DMI, forage species richness, and time spent foraging (Fig. 3) differed significantly among CoFA ($p < 0.01$). Within a given CoFA, species richness varied significantly between seasons ($p < 0.01$), whereas DMI and grazing time were more stable. Tukey's post-hoc test indicated that agricultural land contributed the highest proportion of daily DMI during the rainy season (38 % ± 9 %), which declined in the dry season (28 % ± 10 %), while the contribution from rangelands increased from 34 % ± 10 % in the rainy season to 36 % ± 13 % in the dry season. Residue supply areas became more important in the dry season (31 % ± 12 %) than in the rainy season (23 % ± 9 %), while green hedgerows contributed minimally in both seasons (5 % ± 3 % in the rainy season and 6 % ± 3 % in the dry season).

The number of forage species consumed per CoFA was significantly higher in the rainy season, except in the residue supply areas and green hedgerows. The most species-rich compartments were agricultural land (8 ± 3 forage species in the rainy season and 5 ± 2 in the dry season) and rangelands (7 ± 2 and 5 ± 2, respectively), compared with the residue supply areas (5 ± 2 in both seasons) and green hedgerows (2 ± 1 in both seasons). In terms of grazing time allocation, goats spent the most time in the rangelands (38 % ± 14 % of total time in the rainy season and 41 % ± 12 % in the dry season) and agricultural lands (38 % ± 10 % in the rainy season and 29 % ± 7 % in the dry season), with considerably less time spent in the other compartments.

4. Discussion

In free-range goat farming, little is known about how agroecosystem landscapes are structured and how they contribute to goats' daily diets. This study was conducted under typical traditional free-range goat farming conditions, characterised by small herd sizes (<15 goats) composed mainly of females and unweaned kids (Airs et al., 2023; Alexandre et al., 2012; Namonje-Kapembwa et al., 2022; Seleka et al., 2024; Tchouamo et al., 2005; Wasso et al., 2019). Adult males and growing young goats were not included because they are generally sold or consumed early. The limited sample size (12 female goats monitored for 3 days across 4 sites) constrains the generalisation of the findings to the wider goat population, given natural variability in grazing behaviour and nutritional requirements.

Table 1
Characterisation of CoFA and agroecosystem landscape heterogeneity metrics.

Site	CoFA Class	Frequence of patch	Patch area range (m^2) (Min-Max)	Average area (m^2) ± Std	CoFA area (m^2)	Percentage (%)	CoFA Richness	Patch density (n/ha)	Shannon diversity index
Kikola	Cropland	63	3 - 4271	461.4 ± 738.2	29,069	14.8			
	Fallow land	34	3 - 3222	720.6 ± 922.1	24,501	12.5			
	Range land	372	5 - 86,048	330.6 ± 4480	122,985	62.8	5	28	1.0705
	Residue supply area	78	4 - 9687	245.7 ± 1095.9	19,164	9.8			
	Green hedgerow	9	4 - 68	25 ± 19.2	225	0.1			
Masamuna	Cropland	347	4 - 519	79.5 ± 79.7	27,581	8.9			
	Fallow land	58	14 - 1263	143.1 ± 172.3	8301	2.7			
	Range land	372	4 - 17,486	106.7 ± 660.2	113,185	36.4	5	54	1.1928
	Residue supply area	525	11 - 11,083	276.6 ± 689.5	145,229	46.7			
	Green hedgerow	389	2 - 435	43.3 ± 52.2	16,832	5.4			
Mosango	Cropland	152	4 - 1504	126.6 ± 172	19,248	6.1			
	Fallow land	50	30 - 1758	363.6 ± 374	18,178	5.7			
	Range land	470	4 - 98,988	469.8 ± 4634.1	220,804	69.7	5	31	0.9427
	Residue supply area	212	10 - 3265	257.9 ± 328.2	54,694	17.3			
	Green hedgerow	100	5 - 172	38.6 ± 34.9	3857	1.2			
Ngeba	Cropland	185	5 - 9027	257.4 ± 868.6	47,613	12.7			
	Fallow land	23	61 - 6034	861.3 ± 1357.8	19,809	5.3			
	Range land	298	4 - 160,668	853.6 ± 9328.4	254,381	67.8	5	24	1.0027
	Residue supply area	291	2 - 1631	166.2 ± 181.6	48,375	12.9			
	Green hedgerow	117	4 - 234	43 ± 47.3	5030	1.3			

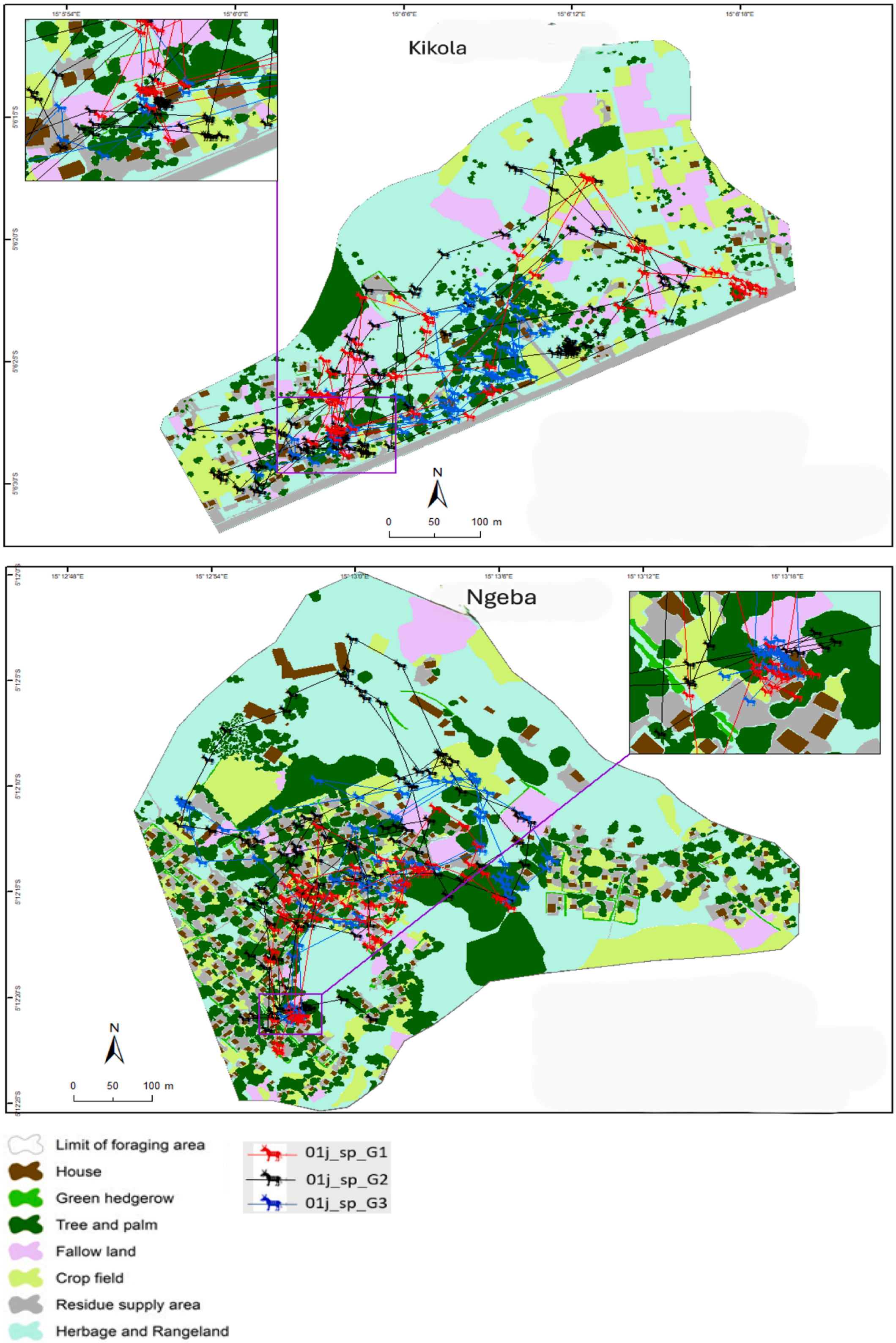

Fig. 2b. Land use and land cover maps illustrating the spatial configuration of compartment of foraging area (CoFA) within the agroecosystems exploited by free-ranging goats. The red, blue, and black lines exemplify georeferenced movement tracks recorded by GPS-collared goats (G1, G2, and G3) on day 1 of monitoring in rainy season at the Kikola and Ngeba sites.

Table 2a
Forage consumed by goats at Ngeba and Kikola sites, Kongo Central region, DRC.

Category[1]	Species[2]	Part consumed[3]	Botanical family[4]	Live form[5]	Season of consumption[6]	CP[7] (% of DM)		NDF[8] (% of DM)		ADF[9] (%of DM)		Digestibility[10] (%of DM)	
						RS	DS	RS	DS	RS	DS	RS	DS
Grass and grass-like plant	*Cynodon dactylon (L.) Pers.*	leaves	Poaceae	Herbaceous	RS and DS	16.2	13.8	68.1	72.9	29.7	36.4	44.5	40.2
	Cyperus esculentus L.	leaves	Cyperaceae	Herbaceous	RS	25.3	–	47.4	–	26.6	–	75.6	–
	Digitaria horizontalis Willd.	leaves	Poaceae	Herbaceous	RS	9.9	–	45.6	–	30.5	–	47.5	–
	Eleusine indica (L.) Gaertn.	leaves	Poaceae	Herbaceous	RS and DS	19.8	14.4	61.8	68.8	28.3	32.1	57.5	49.9
	Panicum maximum Jacq.	leaves	Poaceae	Herbaceous	RS and DS	20.8	15.6	58.5	67.1	32.4	34.1	62.4	46.1
	Paspalum notatum Alain ex Flüggé	leaves	Poaceae	Herbaceous	RS and DS	17.4	15.1	62.6	68.5	32.1	36.4	53.3	40.5
Legume	*Centrosema virginianum (L.) Benth.*	leaves	Fabaceae	Herbaceous	RS	32.1	–	39.7	–	22.6	–	70.5	–
	Acacia auriculiformis A. Cunn. ex Benth.	seed	Fabaceae	Tree	DS	–	27.2	–	34.3	–	25.3	–	68.2
	Acacia auriculiformis A. Cunn. ex Benth.	leaves	Fabaceae	Tree	RS and DS	16.9	16.3	56.5	57.9	48.7	50.1	39.4	36.5
	Psophocarpus scandens (Endl.) Verdc.	leaves	Fabaceae	Herbaceous	RS	39.9	–	38.7	–	17.8	–	81.2	–
	Calopogonium mucunoides Desv.	leaves	Fabaceae	Herbaceous	RS	30.0	–	43.2	–	26.7	–	58.2	–
Others	*Amaranthus blitum* L.	Leaves and stem	Amaranthaceae	Herbaceous	RS	32.2	–	25.8	–	13.9	–	69.7	–
	Boerhavia diffusa L.	leaves	Nyctaginaceae	Herbaceous	RS	30.9	–	32.9	–	18.1	–	70.5	–
	Oncoba welwitschii Oliv. Syn. *Caloncoba welwitschii* (Oliv.) Gilg	leaves	Salicaceae	Shrub	RS and DS	19.9	17.1	49.4	51.2	27.9	32.3	54.1	50.2
	Carica papaya L.	leaves	Caricaceae	Herbaceous	RS and DS	15.8	15.1	20.3	21.1	19.6	20.9	80.1	79.6
	Chromolaena odorata (L.) R.M. King & H. Rob.	leaves	Asteraceae	Herbaceous	RS and DS	32.0	21.4	33.6	39.9	17.1	26.9	82.3	63.1
	Combretum racemosum P. Beauv.	leaves	Combretaceae	Shrub	RS and DS	13.9	13.1	40.2	38.5	27.4	26.8	56.7	57.1
	Commelina diffusa Burm. f.	Leaves and stem	Commelinaceae	Herbaceous	RS and DS	27.5	25.1	37.5	39.1	22.9	23.4	80.2	79.4
	Erigeron sumatrensis Retz. Syn. Conyza sumatrensis (Retz.) E. Walker	leaves	Asteraceae	Herbaceous	RS and DS	20.3	16.6	32.7	35.1	28.2	29.7	53.4	51.4
	Costus phyllocephalus K. Schum.	leaves	Costaceae	Herbaceous	RS and DS	21.1	18.9	51.9	55.5	27.2	29.3	43.8	40.2
	Croton hirtus L'Hér.	Leaves and stem	Euphorbiaceae	Herbaceous	RS and DS	26.9	21.9	32.9	36.8	22.8	23.5	75.6	73.0
	Cyathula prostrata (L.) Blume	Leaves and stem	Amaranthaceae	Herbaceous	RS and DS	24.4	24.7	37.7	36.5	15.7	18.9	62.7	54.8
	Dacryodes edulis (G. Don) H.J. Lam	leaves	Burseraceae	Tree	RS and DS	11.3	9.8	43.7	46.5	35.8	37.1	40.5	39.6
	Elaeis guineensis Jacq.	leaves	Arecaceae	Herbaceous	RS and DS	19.8	17.9	59.4	61.9	33.3	35.7	52.5	49.3
	Euphorbia hirta L.	Leaves and stem	Euphorbiaceae	Herbaceous	RS	14.2	–	19.9	–	17.0	–	33	–
	Ficus bubu Warb.	leaves	Moraceae	Shrub	RS and DS	17.8	14.5	37.4	39.1	24.5	27.4	64.2	59.1
	Gymnanthemum coloratum (Willd.) H. Rob. & B. Kahn	leaves	Asteraceae	Shrub	DS	–	30.1	–	26.5	–	21.2	–	70.7
	Hymenocardia ulmoides Oliv.	leaves and twig	Phyllanthaceae	Shrub	RS and DS	29.9	25.7	48.6	50.5	31.6	35.3	68.7	65.2
	Phragmanthera usuiensis (Oliv.) M.G. Gilbert subsp. *Usuiensis Syn. Loranthus albizziae De Wild.*	leaves	Loranthaceae	Shrub	RS and DS	11.6	11.9	38.2	37.8	31.6	34.9	52.5	51.3
	Mangifera indica L.	leaves	Anacardiaceae	Tree	RS and DS	9.3	10	43.7	45.0	33.5	32.7	54.5	54.1
	Manihot esculenta Crantz Syn. Manihot utilissima Pohl	tuber	Euphorbiaceae	Shrub	RS and DS	1.1	0.9	1.1	1.1	0.7	0.6	99.1	98.9
	Manihot esculenta Crantz Syn. Manihot utilissima Pohl	leaves	Euphorbiaceae	Shrub	RS and DS	30.5	28.9	33.5	34.1	17.3	18.1	76.7	77.1
	Manihot esculenta Crantz Syn. Manihot utilissima Pohl	tuber peels	Euphorbiaceae	Shrub	RS and DS	5.8	6.1	20.8	21.6	17.2	17.5	73.6	74.2
	Megaphrynium macrostachyum (Benth.) Milne-Redh.	leaves	Marantaceae	Herbaceous	RS and DS	14.7	16.6	66.4	63.8	37.9	36.6	32.3	33.8

(*continued on next page*)

Table 2a (*continued*)

Category[1]	Species[2]	Part consumed[3]	Botanical family[4]	Live form[5]	Season of consumption[6]	CP[7] (% of DM)		NDF[8] (% of DM)		ADF[9] (%of DM)		Digestibility[10] (%of DM)	
						RS	DS	RS	DS	RS	DS	RS	DS
	Morinda morindoides (Baker) Milne-Redh.	leaves	Rubiaceae	Shrub	RS and DS	24.4	24.9	49.2	50.5	40.6	39.9	56.1	55.4
	Musa acuminata Colla	leaves	Musaceae	Herbaceous	RS and DS	13.6	14.1	47.5	50.1	27.1	26.4	45.1	45.5
	Passiflora edulis Sims	Leaves and stem	Passifloraceae	Herbaceous	RS and DS	35.3	28.9	22.5	27.4	17.9	18.7	91.3	85.9
	Persea americana Mill.	leaves	Lauraceae	Tree	RS and DS	12.1	11.8	44.3	45.6	35.3	33.9	36.5	38.3
	Psidium guajava L.	leaves	Myrtaceae	Tree	RS and DS	13.4	12.9	44.8	46.3	34.3	35.1	37.2	35.6
	Rhabdophyllum arnoldianum (De Wild. & T. Durand) Tiegh.	leaves	Ochnaceae	Shrub	RS and DS	9.1	9.8	44.3	45.1	28.3	29.6	40.1	39.7
	Sida acuta Burm. f.	Leaves and stem	Malvaceae	Herbaceous	RS and DS	29.2	22.3	36.1	41.7	19.2	23.3	87.2	79.1
	Smilax anceps Willd.	Leaves	Smilacaceae	Herbaceous	RS and DS	12.3	13.9	52.5	50.1	37.3	36.5	38.7	41.5
	Urena lobata L.	Leaves and stem	Malvaceae	Herbaceous	RS and DS	19.4	18.8	44.9	45.7	29.9	31.1	50.5	49.7
	Tithonia diversifolia (Hemsl.) A. Gray	Leaves	Asteraceae	Shrub	DS	–	22.9	–	33.4	–	27.2	–	58.6

[1] Category denotes the primary taxonomic classification of the consumed forage species within plant community hierarchies.
[2] Species specifies the binomial nomenclature (genus and species) of the taxonomically identified forage consumed.
[3] Plant part consumed indicates the specific anatomical structure of the forage ingested.
[4] Botanical family classifies the consumed forage species according to its taxonomic family.
[5] Live form describes the physiognomy of the consumed forage.
[6] Season of consumption is the period of forage utilisation, defined as dry season (DS), rainy season (RS), or both (RS and DS).
[7] CP is the crude protein content expressed as grams per 100 g of dry matter (g/100 g DM).
[8] NDF (neutral detergent fibre) measures hemicellulose, cellulose, and lignin content, reported as grams per 100 g of dry matter (g/100 g DM).
[9] ADF (acid detergent fibre): measures cellulose and lignin content reported as grams per 100 g of dry matter (g/100 g DM).
[10] Digestibility represents the proportion of dry matter digested (DMD) (g/100 g DM ingested).

Despite these limitations, the combined use of GPS tracking, drone-based mapping, and direct observation provided valuable insights into smallholder free-range goat farming. This integrated approach linked goat movement patterns to the structural heterogeneity of agro-ecosystems, providing more accurate insights into compartment use and forage availability than traditional monitoring methods.

Agricultural lands (cropped fields and fallows) and rangelands emerged as the main compartments of the agroecosystem exploited by goats (Fig. 3). Their higher forage diversity and richness likely attracted goats, reflecting the animals' selective foraging behaviour and strategies to meet daily nutritional needs. Residue supply areas and hedgerows contributed less overall but still served as supplementary forage sources. The UAS-based maps and GPS tracks align with earlier findings from the DRC (Wasso et al., 2019; Ndona et al., 2024), which highlighted the importance of rangelands and crop residues as feed resources for extensive goat farming systems.

The drone-based maps revealed strong structural heterogeneity within the agroecosystems, with 24–54 CoFA patches per hectare, indicating high landscape fragmentation (Table 1) driven by anthropogenic activities (Molinario et al., 2017). Land use consisted of small crop plots, scattered farm structures, and livestock shelters interspersed with natural savannah. This fragmentation explains the landscape diversity indices (0.94–1.19) and species richness observed, with goats consuming 57 different forage species (Tables 2a, 2b). The plant diversity included both cultivated species (in croplands and hedgerows) and a predominance of spontaneous grasses and legumes (in rangelands and fallows), together contributing to a diverse forage base. The Aw4 Köppen climate subtype, characterised by an 8- to 9-month rainy season and high temperatures (Lohmann et al., 1993), favours and explains this floristic richness. Similar associations between rainfall, temperature, plant diversity, and biomass productivity have been reported in Venezuelan tropical ecosystems (Marín et al., 2001).

Savannah-type rangelands dominated the agroecosystem landscape, covering 36 %–70 % of the total area (Table 1). Their extensive coverage reflects the low population density in rural areas of the DRC, driven largely by rural–urban migration (Loola, 2025), rather than by deliberate land-use management strategies. Such rangeland availability underpins extensive livestock farming systems, as shown in earlier studies (Augustine et al., 2003; Zampaligré et al., 2013; Boval et al., 2017; Ouédraogo et al., 2021).

GPS tracking data also confirmed the functional importance of rangelands and croplands, where goats spent most of their time and obtained the highest proportion of their daily DMI. These CoFA likely play a significant role in nutrient recycling, with nutrients returned directly via goat excreta during foraging or indirectly through manure collected from night corrals and later applied to croplands (Audouin et al., 2024). Although nutrient fluxes within these compartments were not directly quantified, this assumption of recycling is realistic. Schlecht et al. (2006) demonstrated that excreta deposition by free-ranging herbivores is proportional to the time spent in specific areas. Thus, prolonged goat presence in agricultural land, rangelands, and night corrals likely contributes to nutrient transfer through faeces and urine, supporting ICLS by enhancing soil fertility and reducing dependence on external inputs.

Green hedgerows, though marginal contributors to DMI, showed potential as valuable supplementary forage sources. Their contribution could be enhanced by enrichment with high-fodder-value perennials such as *Leucaena, Albizia, Gliricidia, Acacia* trees, and vetiver or elephant grasses. These species, known for their high productivity and year-round palatability, could increase both forage diversity and the DMI contribution from hedgerows. This finding aligns with Zampaligré et al. (2013) and Ouédraogo et al. (2021), who emphasised the agroecological importance of woody perennials in alleviating dry-season forage shortages. A greater availability of woody forages may also help improve the relatively low daily DMI observed in this study (20–25 g DM kg^{-1} live weight [LW] across seasons) (Table 3). These values are close to the minimum requirement (19 g kg^{-1} LW) but remain below the average (30 g kg^{-1} LW) and maximum (41 g kg^{-1} LW) reported under similar subtropical conditions in Brazil (Almeida et al., 2019). Increasing DMI through hedgerow forage supply could also allow for longer goat confinement, facilitating manure collection and enhancing nutrient recycling into croplands. Moreover, hedgerows restrict goat access to croplands, thereby helping to reduce crop damage and mitigate

Table 2b
Forage consumed by goats at Masamuna and Mosango sites, Kwilu region, DRC.

Category[1]	Species[2]	Part consumed[3]	Botanical family[4]	Live form[5]	Season of consumption[6]	CP [7] (% of DM)		NDF[8] (% of DM)		ADF[9] (% of DM)		Digestibility[10] (% of DM)	
						RS	DS	RS	DS	RS	DS	RS	DS
Grass and grass-like plant	*Anthephora cristata (Döll) Hack. ex De Wild. & T.Durand*	leaves	Poaceae	Herbaceous	RS	19.9	–	45.5	–	26.6	–	65.2	–
	Cynodon dactylon (L.) Pers.	leaves	Poaceae	Herbaceous	RS and DS	16.7	8.1	63.9	77.2	30.8	35.5	49.1	29.3
	Cyperus esculentus L.	leaves	Cyperaceae	Herbaceous	RS and DS	16.3	16.1	62.1	63.6	31.8	33.7	46.2	43.8
	Digitaria horizontalis Willd.	leaves	Poaceae	Herbaceous	RS	9.9	–	44.5	–	31.5	–	47.1	–
	Eleusine indica (L.) Gaertn.	leaves	Poaceae	Herbaceous	RS and DS	*18.2*	13.6	55.6	61.7	30.2	32.5	62.6	43.8
	Hyparrhenia diplandra	leaves	Poaceae	Herbaceous	RS and DS	8.1	15.0	66.7	57.1	38.4	25.9	33.5	46.7
	Panicum maximum Jacq.	leaves	Poaceae	Herbaceous	RS and DS	*16.5*	15.7	64.7	67.5	36.4	39.1	50.3	44.1
	Paspalum notatum Alain ex Flüggé	leaves	Poaceae	Herbaceous	RS and DS	15.8	11.1	55.7	60.1	31.7	33.3	55.1	49.3
	Pennisetum setaceum	leaves	Poaceae	Herbaceous	RS	*13.9*	–	57.7	–	38.2	–	65.2	–
	Phyllostachys viridiglaucescens	leaves	*Poaceae*	Herbaceous	RS and DS	27.9	22.3	58.1	65.9	28.3	32.7	55.9	47.5
Legume	*Calopogonium mucunoides* Desv.	leaves	Fabaceae	Herbaceous	RS	30.1	–	30.7	–	24.3	–	58.8	–
	Psophocarpus scandens (Endl.) Verdc.	leaves	Fabaceae	Herbaceous	RS	31.1	–	49.7	–	30.9	–	55.1	–
	Zornia latifolia	Leaves and stem	Fabaceae	Herbaceous	RS	25.3	–	32.1	–	26.9	–	72.1	–
Others	*Aframomum alboviolaceum* (Ridl.) K. Schum.	leaves	Zingiberaceae	Herbaceous	RS and DS	19.8	17.1	58.7	62.1	32.3	32.9	30.4	28.2
	Amaranthus blitum L.	Leaves and stem	*Amaranthaceae*	*Herbaceous*	*RS*	*32.2*	–	*25.8*	–	*13.9*	–	*69.6*	–
	Asystasia gangetica	Leaves and stem	*Acanthaceae*	Herbaceous	RS and DS	*19.9*	*14.9*	*15.4*	*36.0*	*12.1*	*30.1*	*51.6*	*27.8*
	Boerhavia diffusa L.	leaves	Nyctaginaceae	Herbaceous	RS	23.4	–	27.1	–	17.2	–	70.0	–
	Breynia disticha J.R. Forst. & G.Forst.	leaves and twig	Phyllanthaceae	Shrub	RS and DS	24.7	23.2	31.7	33.3	18.6	20.4	77.9	70.1
	Carica papaya L.	leaves	Caricaceae	Herbaceous	RS and DS	21.0	20	24.3	25.7	19.9	20.6	74.2	69.7
	Chromolaena odorata (L.) R.M. King & H. Rob.	leaves	Asteraceae	Herbaceous	RS and DS	27.6	24.6	35.8	39.8	33.9	35.8	53.5	52.8
	Commelina diffusa Burm. f.	Leaves and stem	Commelinaceae	Herbaceous	RS and DS	22.3	19.1	31.6	35.8	23.7	24.5	62.3	55.1
	Croton hirtus L'Hér.	Leaves and stem	Euphorbiaceae	Herbaceous	RS and DS	19.8	13.4	30.8	37.9	12.6	30.1	54.1	27.3
	Cyathula prostrata (L.) Blume	Leaves and stem	Amaranthaceae	Herbaceous	RS and DS	19.7	18.8	32.6	30.6	16.2	17.1	47.4	46.7
	Dacryodes edulis (G. Don) H.J. Lam	leaves	Burseraceae	Tree	RS and DS	10.9	9.8	41.2	44.5	36.3	37.6	41.3	40.9
	Dracaena fragrans (L.) Ker Gawl.	leaves	Asparagaceae	Herbaceous	RS and DS	19.8	20.1	44.1	43.4	32.3	33.7	55.7	51.2
	Elaeis guineensis Jacq.	leaves	Arecaceae	Herbaceous	RS and DS	16.5	13.2	56.4	64.7	34.8	37.2	45.3	39.1
	Euphorbia hirta L.	Leaves and stem	Euphorbiaceae	Herbaceous	RS	13.6	–	17.1	–	14.4	–	32.9	–
	Ficus bubu Warb.	leaves	Moraceae	Shrub	RS and DS	18.2	15.1	49.9	56.4	40.1	43.5	54.1	46.3
	Gymnanthemum coloratum (Willd.) H. Rob. & B. Kahn	leaves	Asteraceae	Shrub	DS and DS	29.5	20.2	24.5	31.9	20.7	24.9	71.6	59.4
	Hymenocardia acida Tul.	leaves and twig	Phyllanthaceae	Shrub	RS and DS	21.8	22.9	70.1	64.5	64.8	55.3	21.1	26.3
	Ipomoea batatas (L.) Lam.	leaves and twig	Convolvulaceae	Herbaceous	RS and DS	25.2	20.1	24.2	30.1	21.5	23.6	74.0	68
	Phragmanthera usuiensis (Oliv.) M.G. Gilbert subsp. *Usuiensis Syn. Loranthus albizziae De Wild.*	leaves	Loranthaceae	Shrub	RS and DS	10.9	10.5	55.1	53.9	49.6	51.1	34.3	32.1
	Mangifera indica L.	leaves	Anacardiaceae	Tree	RS and DS	11.3	10.1	42.1	42.9	30.9	40.2	57.1	54.6
	Manihot esculenta Crantz Syn. Manihot utilissima Pohl	tuber	Euphorbiaceae	Shrub	RS and DS	0.8	1	1.7	1.9	1.5	1.5	97.9	98.7
	Manihot esculenta Crantz Syn. Manihot utilissima Pohl	leaves	Euphorbiaceae	Shrub	RS and DS	32.2	29.4	34.3	37.7	28.1	31.2	68.9	68.4
	Manihot esculenta Crantz Syn. Manihot utilissima Pohl	tuber peels	Euphorbiaceae	Shrub	RS and DS	9.5	8.7	21.7	20.9	18.2	19.1	51.4	47.1

(*continued on next page*)

Table 2b (*continued*)

Category[1]	Species[2]	Part consumed[3]	Botanical family[4]	Live form[5]	Season of consumption[6]	CP[7] (% of DM)		NDF[8] (% of DM)		ADF[9] (% of DM)		Digestibility[10] (% of DM)	
						RS	DS	RS	DS	RS	DS	RS	DS
	Megaphrynium macrostachyum (Benth.) Milne-Redh.	leaves	Marantaceae	Herbaceous	RS and DS	15.3	13.1	69.3	65.1	44.2	41.8	22.1	24.5
	Musa acuminata Colla	leaves	Musaceae	Herbaceous	RS and DS	16.6	17.3	61.3	60.7	34.4	33.8	31.5	30.2
	Parinari capensis Harv.	leaves	Chrysobalanaceae	Shrub	RS and DS	9.5	11.1	71.9	69.4	64.7	60.8	15.4	18.8
	Passiflora edulis Sims	Leaves and stem	Passifloraceae	Herbaceous	RS and DS	41.3	40.5	20.8	21.5	18.5	19.9	86.6	81.3
	Persea americana Mill.	leaves	Lauraceae	Tree	RS and DS	12.2	11.9	42.1	40.4	32.6	31.9	41.2	42.5
	Rumex usambarensis	Leaves and stem	Polygonaceae	Herbaceous	RS and DS	27.1	29.4	31.5	30.9	20.2	20.7	75.4	72.8
	Sida acuta Burm. f.	Leaves and stem	Malvaceae	Herbaceous	RS and DS	26.5	23.7	22.4	34.0	18.1	17.1	74.3	76.2
	Spermacoce latifolia Aubl.	Leaves	Rubiaceae	Herbaceous	RS	20.9	–	23.6	–	18.9	–	73.1	–
	Urena lobata L.	Leaves and stem	Malvaceae	Herbaceous	RS and DS	22.2	13.9	33.4	40.1	28.8	31.5	65.4	40.5
	Talinum triangulare (Jacq.) Willd.	Leaves and stem	Talinaceae	Herbaceous	RS and DS	16.4	14.1	21.9	35.4	13.3	17.7	52.4	45.1
	Tithonia diversifolia (Hemsl.) A. Gray	Leaves	Asteraceae	Shrub	DS	–	25.4	–	34.5	–	33.2	–	58.6

[1] Category denotes the primary taxonomic classification of the consumed forage species within plant community hierarchies.
[2] Species specifies the binomial nomenclature (genus and species) of the taxonomically identified forage consumed.
[3] Plant part consumed indicates the specific anatomical structure of the forage ingested.
[4] Botanical family classifies the consumed forage species according to its taxonomic family.
[5] Live form describes the physiognomy of the consumed forage.
[6] Season of consumption is the period of forage utilisation, defined as dry season (DS), rainy season (RS), or both (RS and DS).
[7] CP is the crude protein content expressed as grams per 100 g of dry matter (g/100 g DM).
[8] NDF (neutral detergent fibre) measures hemicellulose, cellulose, and lignin content, reported as grams per 100 g of dry matter (g/100 g DM).
[9] ADF (acid detergent fibre): measures cellulose and lignin content reported as grams per 100 g of dry matter (g/100 g DM).
[10] Digestibility represents the proportion of dry matter digested (DMD) (g/100 g DM ingested).

Table 3
Goat's daily diet quantity and quality across seasons and sites.

		Dry mater intake (g $DMI.kg^{-1}$ LW^{-1})	Number species consumed	CP (% of DM)	ADF (% of DM)	NDF (% of DM)	Digestibility (% of DM)
Kikola	Rainy season daily diet	22.1 ± 2.6	12±3	20.1 ± 1.4	24.2 ± 1.9	42.1 ± 2.9	66.1 ± 2.5
	Dry season daily diet	20.4 ± 1.6	9 ± 1	17.8 ± 2.6	24.6 ± 1.5	43.3 ± 2.1	63.9 ± 3.1
Ngeba	Rainy season daily diet	23.9 ± 1.7	13±3	20.2 ± 1.6	22.8 ± 1.8	40.4 ± 3	66.1 ± 3.3
	Dry season daily diet	20.6 ± 2.3	13±1	18.0 ± 1.4	24.3 ± 1.9	42.4 ± 5.3	64.7 ± 3.2
Masamuna	Rainy season daily diet	25.2 ± 1.3	22±2	19.3 ± 1.4	27.1 ± 1.3	39.6 ± 2.6	56.8 ± 2.4
	Dry season daily diet	21.7 ± 1.7	15±2	16.9 ± 1.2	32.9 ± 2.4	46.5 ± 5.3	52.9 ± 3.8
Mosango	Rainy season daily diet	25.4 ± 1.5	22±3	18.9 ± 0.9	28.7 ± 1.4	42.9 ± 1.5	53.9 ± 2.4
	Dry season daily diet	21.1 ± 1.5	20±2	18.4 ± 1.3	28.9 ± 1.2	43.6 ± 2.5	55.3 ± 3.2
P-value	Site	0.0018	< 0.001	0.205	< 0.001	0.347	< 0.001
	Season	< 0.001	< 0.001	< 0.001	0.062	0.067	0.0016
	Site x Season	0.1899	< 0.001	0.245	< 0.001	0.005	0.4339

farmer–herder conflicts—an ongoing challenge in African agro-pastoral systems (Barrière & Barrière, 2002; Azalou et al., 2023).

Because forage nutritional value is a key determinant of diet quality and, consequently, of the nutrient composition of excreta (Rufino et al., 2006; Piñeiro-Vázquez et al., 2017; Wang et al., 2018), the goats' daily diet also varied according to the nutritional value of the forage species (Tables 2a, 2b), the phenological stage of the consumed plant parts, the season, and the site. For instance, *Manihot esculenta* showed pronounced contrasts in CP content between tubers (approximately 1 % CP), peelings (6.0 %–9.5 % CP), and leaves (approximately 30 % CP). Legumes consistently exhibited the highest CP content (25 %–40 % CP), attributable to symbiotic nitrogen fixation (Prell & Poole, 2006; Barbieri et al., 2023). As ruminants use nitrogen inefficiently, excess intake of protein-rich legumes leads to nitrogen-rich excreta. Both unassimilated dietary protein and nitrogen released by ruminal microbiota are largely excreted as urinary urea (Rotz et al., 2006; Nasiru et al., 2014).

Surprisingly, several non-leguminous species (*Passiflora* spp., *Amaranthus blitum, Chromolaena odorata, Hymenocardia ulmoides, Gymnanthemum coloratum*, and *Boerhavia diffusa*) also exhibited high CP contents (≥30 %), likely due to the presence of non-protein nitrogen in immature leaves with low C/N ratios (Lu et al., 2005; Zeng & Chen, 2018; Baath et al., 2024). The goats' selective feeding behaviour (Lee and Kim, 2023; Dias-e-Silva & Abdalla Filho, 2020)) favoured tender, nutrient-rich foliage, though they also consumed fibrous, mature plants (NDF/ADF > 30 %, digestibility < 70 %). This mixed foraging strategy helps balance rumen microbiome function and nutrient intake, consistent with findings from other studies on ruminant feeding behaviour (Fedele et al., 1993; Lu et al., 2005; Zampaligré et al., 2013; Claps et al., 2020).

The high CP values observed in grasses (Tables 1a, 1b) were comparable to those reported for fertilised pastures at early growth stages (Hirata et al., 2016; Muntifering et al., 2000; Matta et al., 2023; F. D. Fernandes et al., 2014; Paciullo et al., 2017; Pedreira et al., 2024; Sokupa et al., 2024), possibly reflecting soil fertility and post-fire regrowth effects (McNew et al., 2023), which promote young, protein-rich shoots often preferred by grazers (Augustine et al., 2003).

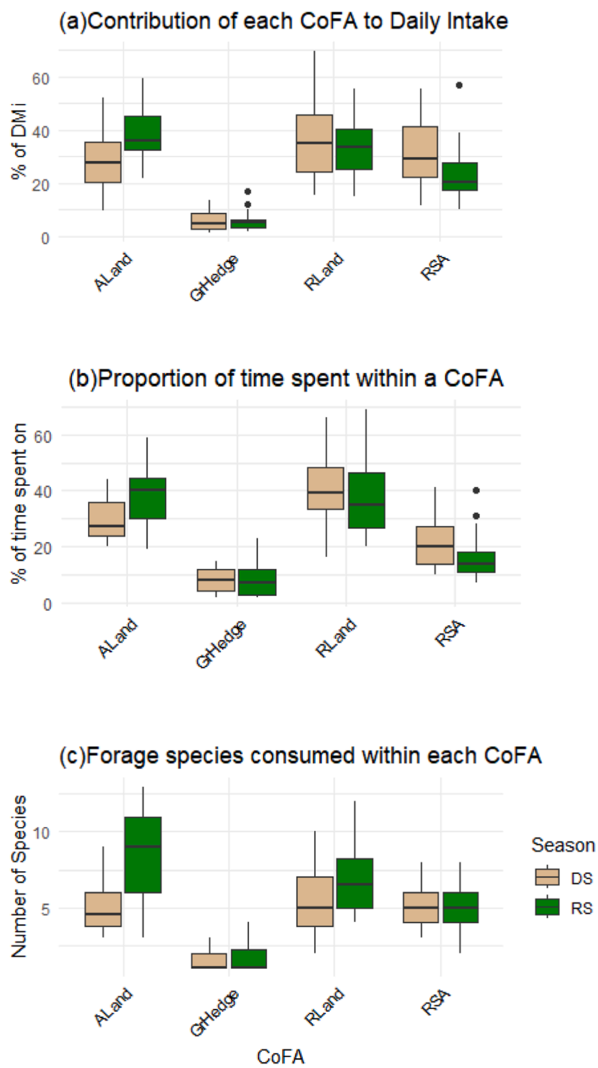

Fig. 3. The importance of each compartment of foraging area (ALand: agricultural land including crop and fallow land; GrHedge: living green hedgerow used as plot boundary or crop field protection; RLand: rangeland comprising savanna and/or natural herbage) in terms of their contribution to daily dry matter intake (a), proportion of time goat spent on each one (b) and number of different forage species consumed (c), during the rainy (RS) and dry (DS) season.

Conversely, lower CP values reported in other studies Alsunaydi et al., 2024; Foster et al., 2011; Hare et al., 2015) may result from differences in climate, soil, or sampling protocols, as those studies often collected mature forages (>30 days post-emergence) with higher lignin content (Zeng & Chen, 2018; Baath et al., 2024).

Even under similar geo-climatic conditions, seasonal patterns in forage quality were evident. CP content and digestibility peaked during the rainy season, while NDF and ADF increased in the dry season due to rapid lignification under water stress and rising C/N ratios, as noted by Ephrem et al. (2015). These seasonal shifts negatively affected forage quality and, consequently, the goats' daily diets during the dry season.

Although CP contents were generally high (Tables 2a, 2b), they do not necessarily reflect protein bioavailability or digestibility because of the presence of antinutritional compounds such as alkaloids and tannins (Alavarse et al., 2022), which bind dietary proteins and inhibit enzymatic hydrolysis and subsequent nutrient assimilation (Ebrahimi et al., 2009; Sá et al., 2020). Moreover, non-protein nitrogen compounds—commonly found in immature or rapidly growing vegetative tissues—differ from those in other plant parts and may artificially inflate CP estimates without increasing the availability of usable amino acids.

The proportion of plant parts consumed reflects individual differences in goats' selective grazing behaviour. Such selectivity directly shapes daily diet composition and, consequently, the nutrient profile of excreta (Rufino et al., 2006; Piñeiro-Vázquez et al., 2017; Wang et al., 2018). However, this study did not quantify the proportion of plant parts within total DMI. Combined with the small sample size (three goats per site) and short monitoring period (3-days across four sites), this limits the extent to which the findings can be generalised. In addition, the nutrient recycling potential within agroecosystems was inferred rather than directly measured through excreta collection and analysis, which introduces uncertainty due to individual variability in grazing behaviour and potential nutrient losses.

Despite these limitations, the integration of GPS tracking, direct observation, and drone mapping provided valuable insights into the spatial dynamics of free-ranging goats and their foraging patterns across agroecosystem compartments. Even with the availability of forage in rangelands, free-ranging goats obtained a substantial portion of their daily DMI from croplands. This dependence increases competition between livestock and humans for food resources and exacerbates farmer–herder conflicts.

Future research should expand the sample size to include other goat groups (e.g., adult males and young goats), extend the monitoring duration, and quantify both the proportions of plant parts consumed and the nutrient composition of excreta. Such work would offer a more comprehensive understanding of free-ranging goat diets and their potential contribution to nutrient recycling within ICLS.

5. Conclusions

This study examined the structure of agroecosystem landscapes and their contribution to the daily diets of free-ranging goats. The results show that, in smallholder farming systems of western DRC, free-ranging goats exploit multiple agroecosystem compartments and consume a diverse range of 57 forage species of varying nutritional quality, without relying on external feed inputs. Among the exploited compartments, agricultural lands and rangelands contributed most to daily DMI and forage diversity.

Although green hedgerows contributed little to the goats' daily diets, their role could be strengthened through enrichment with high-value forage species, such as woody and perennial grass fodders. Doing so could provide a dual benefit: reducing goat intrusion into croplands while supplying substantial forage biomass year-round.

The spatial heterogeneity of agroecosystem compartments, combined with their floristic diversity and variable nutritional quality, supports their role as key forage sources for free-ranging goats in western DRC.

These findings, however, should be interpreted with caution. The small sample size, limited representativeness of goat populations, and short observation period may have introduced uncertainties. Nonetheless, direct observations combined with GPS tracking and drone mapping have yielded valuable insights into smallholder free-range goat farming systems.

Future research should therefore involve larger and more diverse goat populations, extended monitoring periods, and a broader range of agroecosystem contexts. Such investigations would provide stronger evidence on the compartments exploited, forage diversity, and the nutritional quality of goats' daily diets. These parameters are critical for understanding free-ranging goat dynamics and their potential role in nutrient recycling, which is essential for designing appropriate ICLS. Advancing knowledge of nutrient fluxes within agroecosystem compartments will be key to developing sustainable ICLS tailored to the diverse farming systems of SSA.

Ethical statement

All animals were cared for in accordance with acceptable practices and experimental protocols approved by the University of Liège ethical committee (No. 19–2116, Liège, Belgium).

CRediT authorship contribution statement

Alain Ndona: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Anthony Kikufi Batoba:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis. **Eric Lutete:** Writing – review & editing, Validation, Methodology, Formal analysis. **Bienvenu Kambashi Mutiaka:** Writing – review & editing, Validation, Investigation. **Charles-Henri Moulin:** Writing – review & editing, Visualization, Validation, Methodology, Data curation, Conceptualization. **Yves Beckers:** Writing – review & editing, Visualization, Validation. **Jérôme Bindelle:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request

References

Agreil, C., & Meuret, M. (2004). An improved method for quantifying intake rate and ingestive behaviour of ruminants in diverse and variable habitats using direct observation. *Small Ruminant Research, 54*(12), Article 99113. https://doi.org/10.1016/j.smallrumres.2003.10.013

Airs, P. M., Ventura-Cordero, J., Gwiriri, L. C., Tinsley, J. H. I., Mvula, W., Lee, M. R. F., … Safalaoh. (2023). Goat health and management for improved smallholders' livelihoods in central Malawi – A socioeconomic analysis of rural households. *Small Ruminant Research, 229*, 107114. https://doi.org/10.1016/j.smallrumres.2023.107114

Alavarse, A. C., Frachini, E. C. G., Da Silva, R. L. C. G., Lima, V. H., Shavandi, A., & Petri, D. F. S. (2022). Crosslinkers for polysaccharides and proteins : Synthesis conditions, mechanisms, and crosslinking efficiency, a review. *International Journal of Biological Macromolecules, 202*, Article 558596. https://doi.org/10.1016/j.ijbiomac.2022.01.029

Almeida, A. K. D., Tedeschi, L. O., De Resende, K. T., Biagioli, B., Cannas, A., & Teixeira, I. A. M. D. A (2019). Prediction of voluntary dry matter intake in stall fed growing goats. *Livestock Science, 219*, 19. https://doi.org/10.1016/j.livsci.2018.11.002

Alexandre, G., Arquet, R., Fleury, J., Troupé, W., Boval, M., Archimède, H., Mahieu, M., & Mandonnet, N. (2012). Systèmes d'élevage caprins en zone tropicale : Analyse des fonctions et des performances. *INRAE Productions Animales,, 25*(3), Article 305316. https://doi.org/10.20870/productions-animales.2012.25.3.3218

Alsunaydi, S., Alharbi, A. B., Al-Soqeer, A. A., & Motawei, M. I. (2024). Nutritional Composition and Productivity of Panicum maximum cv. "Mombasa" Under Different Levels of Nitrogen Fertilization and Water Deficit. *Life, 14*(12), 1614. https://doi.org/10.3390/life14121614

Altieri, M. A., & Nicholls, C. I. (2020). Agroecology : Challenges and opportunities for farming in the Anthropocene. *International Journal of Agriculture and Natural Resources, 47*(3), Article 204215. https://doi.org/10.7764/ijanr.v47i3.2281

Altieri, M. A., Nicholls, C. I., Dinelli, G., & Negri, L. (2024). Towards an agroecological approach to crop health : Reducing pest incidence through synergies between plant diversity and soil microbial ecology. *Npj Sustainable Agriculture, 2*(1), 6. https://doi.org/10.1038/s44264-024-00016-2

Andre Mataveia, G., Visser, C., & Sitoe, A. (2023). Smallholder goat production in Southern Africa : A review. Éd. In S. Kukovics (Ed.), *Goat science—Environment, health and economy*. IntechOpen. https://doi.org/10.5772/intechopen.97792.

AOAC. (1990). In A. O. A. Chemists (Ed.), *Official Methods of Analysis* (15th). Arlington: Association Official Analytical Chemists.

Audouin, E., Odru, M., Masse, D., Dorégo, G. S., Delaunay, V., Lecomte, P., & Vayssières, J. (2024). A methodology based on territorial metabolism analysis to assess the multi-criteria sustainability of African village terroirs with contrasted crop-livestock systems. *Agricultural Systems, 213*, Article 103781. https://doi.org/10.1016/j.agsy.2023.103781

Aufrere, J. (1982). Etude de la prévision de la digestibilité des fourrages par une méthode enzymatique. *Annales De Zootechnie, 31*(2), Article 111130. https://doi.org/10.1051/animres:19820202

Augustine, D. J., McNaughton, S. J., & Frank, D. A. (2003). Feedbacks between soil nutrients and large herbivores in a managed savanna ecosystem. *Ecological Applications, 13*(5), Article 13251337. https://doi.org/10.1890/02-5283

Ayantunde, A. A., Briejer, M., Hiernaux, P., Udo, H. M. J., & Tabo, R. (2008). Botanical knowledge and its differentiation by age, gender and ethnicity in Southwestern Niger. *Human Ecology, 36*(6), Article 881889. https://doi.org/10.1007/s10745-008-9200-7

Azalou, M., Assani, S. A., Assogba, B. G. C., Idrissou, Y., Alabi, C. D., Yabi, J. A., & Alkoiret, T. I. (2023). Dynamics of transhumant livestock systems in West African coastal countries : A review. *Journal of Livestock Science, 14*(2). https://doi.org/10.33259/JLivestSci.2023.109-121

Baath, G. S., Sarkar, S., Sapkota, B. R., Flynn, K. C., Northup, B. K., & Gowda, P. H. (2024). Forage yield and nutritive value of summer legumes as affected by row spacing and harvest timing. *Farming System, 2*(1), Article 100069. https://doi.org/10.1016/j.farsys.2023.100069

Barbieri, P., Starck, T., Voisin, A.-S., & Nesme, T. (2023). Biological nitrogen fixation of legumes crops under organic farming as driven by cropping management : A review. *Agricultural Systems, 205*, Article 103579. https://doi.org/10.1016/j.agsy.2022.103579

Barnosky, A. D., Hadly, E. A., Bascompte, J., Berlow, E. L., Brown, J. H., Fortelius, M., Getz, W. M., Harte, J., Hastings, A., Marquet, P. A., Martinez, N. D., Mooers, A., Roopnarine, P., Vermeij, G., Williams, J. W., Gillespie, R., Kitzes, J., Marshall, C., Matzke, N., & Smith, A. B. (2012). Approaching a state shift in Earth's biosphere. *Nature, 486*(7401), 5258. https://doi.org/10.1038/nature11018

Barrière, O., & Barrière, C. (2002). Un droit à inventer : Foncier et environnement dans le delta intérieur du Niger. IRD Éditions. https://doi.org/10.4000/books.irdeditions.14471.

Barroso, F. G., Alados, C. L., & Boza, J. (2000). Social hierarchy in the domestic goat : Effect on food habits and production. *Applied Animal Behaviour Science, 69*(1), 3553. https://doi.org/10.1016/S0168-1591(00)00113-1

Bonaudo, T., Bendahan, A. B., Sabatier, R., Ryschawy, J., Bellon, S., Leger, F., Magda, D., & Tichit, M. (2014). Agroecological principles for the redesign of integrated crop–livestock systems. *European Journal of Agronomy, 57*, 4351. https://doi.org/10.1016/j.eja.2013.09.010

Bonnet, O. J. F., Meuret, M., Tischler, M. R., Cezimbra, I. M., Azambuja, J. C. R., & Carvalho, P. C. F. (2015). Continuous bite monitoring : A method to assess the foraging dynamics of herbivores in natural grazing conditions. *Animal Production Science, 55*(3), 339. https://doi.org/10.1071/AN14540

Bourban, M. (2019). Croissance démographique et changement climatique : Repenser nos politiques dans le cadre des limites planétaires: La Pensée écologique, N° 3(1), 1937. https://doi.org/10.3917/lpe.003.0019.

Boval, M., Angeon, V., & Rudel, T. (2017). Tropical grasslands : A pivotal place for a more multi-functional agriculture. *Ambio, 46*(1), 4856. https://doi.org/10.1007/s13280-016-0806-5

Callo-Concha, D., Gaiser, T., Webber, H., Tischbein, B., Müller, M., & Ewert, F. (2013). Farming in the West African Sudan Savanna : Insights in the context of climate change. *African Journal of Agricultural Research, 8*(38), Article 46934705. https://doi.org/10.5897/AJAR2013.7153

Chebli, Y., Otmani, S. E., Chentouf, M., Hornick, J.-L., Bindelle, J., & Cabaraux, J.-F. (2020). Foraging behavior of goats browsing in southern Mediterranean forest rangeland. *Animals,, 10*(2), 196. https://doi.org/10.3390/ani10020196

Claps, S., Mecca, M., Di Trana, A., & Sepe, L. (2020). Local small ruminant grazing in the Monti Foy Area (Italy) : The relationship between grassland biodiversity maintenance and added-value dairy products. *Frontiers in Veterinary Science, 7*, Article 546513. https://doi.org/10.3389/fvets.2020.546513

Dias-e-Silva, T. P., & Abdalla Filho, A. L. (2020). Sheep and goat feeding behavior profile in grazing systems. *Acta Scientiarum. Animal Sciences, 43*, Article e51265. https://doi.org/10.4025/actascianimsci.v43i1.51265

Dossa, L. H., Rischkowsky, B., Birner, R., & Wollny, C. (2008). Socio-economic determinants of keeping goats and sheep by rural people in southern Benin. *Agriculture and Human Values, 25*(4), 581. https://doi.org/10.1007/s10460-008-9138-9

Dossa, L. H., Sangaré, M., Buerkert, A., & Schlecht, E. (2015). Production objectives and breeding practices of urban goat and sheep keepers in West Africa : Regional analysis and implications for the development of supportive breeding programs. *SpringerPlus, 4*(1), 281. https://doi.org/10.1186/s40064-015-1075-7

Dumortier, P., Gourlez De La Motte, L., Andriamandroso, A. L. H., Aubinet, M., Beckers, Y., Bindelle, J., De Cock, N., Lebeau, F., & Heinesch, B. (2021). Beef cattle methane emission estimation using the eddy covariance technique in combination with geolocation. *Agricultural and Forest Meteorology, 297*, Article 108249. https://doi.org/10.1016/j.agrformet.2020.108249

Dupuy, S., Jolivot, A., Lebourgeois, V., & Lelong, C. (2022). *Guide technique pour la construction d'une base de données de vérité-terrain pour l'apprentissage et la validation des algorithmes de classification d'images satellites :Principes de base et manuel pratique mobilisant le logiciel qgis et l'application QField*. Cirad, Département Environnement et Société /Unité Mixte de Recherche. https://agritrop.cirad.fr/602409/.

Ebrahimi, S. R., Nikkhah, A., Sadeghi, A. A., & Raisali, G. (2009). Chemical composition, secondary compounds, ruminal degradation and in vitro crude protein digestibility of gamma irradiated canola seed. *Animal Feed Science and Technology, 151*(3-4), 184–193. https://doi.org/10.1016/j.anifeedsci.2009.01.014

Ephrem, N., Tegegne, F., Mekuriaw, Y., & Yeheyis, L. (2015). Nutrient intake, digestibility and growth performance of Washera lambs supplemented with graded levels of sweet blue lupin (Lupinus angustifolius L.) seed. *Small Ruminant Research, 130*, 101–107. https://doi.org/10.1016/j.smallrumres.2015.07.019

Faber-Langendoen, D. (2020). Tropical, temperate, and Mediterranean grasslands of the world. *Encyclopedia of the World's Biomes*. , Article 424433. https://doi.org/10.1016/B978-0-12-409548-9.12093-7

Fedele, V., Pizzillo, M., Claps, S., Morand-Fehr, P., & Rubino, R. (1993). Grazing behavior and diet selection of goats on native pasture in Southern Italy. *Small Ruminant Research, 11*(4), Article 305322. https://doi.org/10.1016/0921-4488(93)90002-Y

Feldt, T., & Schlecht, E. (2016). Analysis of GPS trajectories to assess spatio-temporal differences in grazing patterns and land use preferences of domestic livestock in southwestern Madagascar. *Pastoralism : Research, policy and practice, 6*(1), 5. https://doi.org/10.1186/s13570-016-0052-2

Fernandes, F. D., Ramos, A. K. B., Jank, L., Carvalho, M. A., Martha, G. B., Jr., & Braga, G. J (2014). Forage yield and nutritive value of Panicum maximum genotypes in the Brazilian savannah. *Scientia Agricola, 71*(1), 2329. https://doi.org/10.1590/S0103-90162014000100003

Fernandes, G. W., Coelho, M. S., Machado, R. B., Ferreira, M. E., Aguiar, L. M. D. S., Dirzo, R., Scariot, A., & Lopes, C. R. (2016). Afforestation of savannas : An impending ecological disaster. *Natureza & Conservação, 14*(2), Article 146151. https://doi.org/10.1016/j.ncon.2016.08.002

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., O'Connell, C., Ray, D. K., West, P. C., Balzer, C., Bennett, E. M., Carpenter, S. R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., & Zaks, D. P. M (2011). Solutions for a cultivated planet. *Nature, 478* (7369), Article 337342. https://doi.org/10.1038/nature10452

Foster, J. L., Carter, J. N., Sollenberger, L. E., Blount, A. R., Myer, R. O., Maddox, M. K., … Adesogan, A. T. (2011). Nutritive value, fermentation characteristics, and in situ disappearance kinetics of ensiled warm-season legumes and bahiagrass. *Journal of Dairy Science, 94*(4), 2042–2050. https://doi.org/10.3168/jds.2010-3800

Gasigwa Sabimana, R., Baenyi Simon, P., & Kizungu Vumilia, R. (2018). Paramètres de reproduction et de dynamique de population de la chèvre locale de Mbanza-Ngungu en république démocratique du Congo. *Revue D'élevage Et De Médecine Vétérinaire Des Pays Tropicaux, 70*(3), 9397. https://doi.org/10.19182/remvt.31522

Grillot, M., Guerrin, F., Gaudou, B., Masse, D., & Vayssières, J. (2018). Multi-level analysis of nutrient cycling within agro-sylvo-pastoral landscapes in West Africa using an agent-based model. *Environmental Modelling & Software, 107*, Article 267280. https://doi.org/10.1016/j.envsoft.2018.05.003

Hare, M. D., Phengphet, S., Songsiri, T., & Sutin, N. (2015). Effect of nitrogen on yield and quality of Panicum maximum cvv. Mombasa and Tanzania in Northeast Thailand. *Tropical Grasslands - Forrajes Tropicales, 3*(1), 27. https://doi.org/10.17138/TGFT(3)27-33

Hatcher, G. A., Warrick, J. A., Ritchie, A. C., Dailey, E. T., Zawada, D. G., Kranenburg, C., & Yates, K. K. (2020). Accurate bathymetric maps from underwater digital imagery without ground control. *Frontiers in Marine Science, 7*, 525. https://doi.org/10.3389/fmars.2020.00525

Hirata, M., Okuma, T., Tanaka, Y., & Tobisa, M. (2016). Sward characteristics, nutritive value and choice by cattle of conterminous monocultures of centipedegrass (Eremochloa ophiuroides) and bahiagrass (Paspalum notatum). *Animal Science Journal, 87*(5), Article 674680. https://doi.org/10.1111/asj.12474

Huruba, R., Mlambo, T., Mundy, P. J., Sebata, A., & MacFadyen, D. N. (2018). Short duration overnight cattle kraaling in natural rangelands : Implications for grass composition, quality, above ground biomass, species diversity and basal cover. *Agriculture, Ecosystems & Environment, 257*, Article 144151. https://doi.org/10.1016/j.agee.2018.02.004

IPBES. (2018). The IPBES assessment report on land degradation and restoration. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Zenodo. https://doi.org/10.5281/ZENODO.3237392.

Jolivot, A., & Dupuy, S. (2023, février). Formation à la réalisation d'une carte d'occupation du sol à partir d'images Sentinel2. Travaux pratiques avec OTB et QGIS. Cirad, Département Environnement et Société, Unité Mixte de Recherche Territoire Environnement Télédétection et Information Spatiale. https://agritrop.cirad.fr/604433/.

Kay, M., & Wobbrock, J. (2016). ARTool : 0.10.0 (Version v0.10.0) [Logiciel]. Zenodo. https://doi.org/10.5281/ZENODO.44586.

Kembelo, P. K., Bakwaye, F. N., Katula, H. B., Vanhove, W., & Van Damme, P. (2021). Ethnobotanical characterization of medicinal plants used in Kisantu and Mbanza-Ngungu territories, Kongo-Central Province in DR Congo. *Journal of Ethnobiology and Ethnomedicine, 17*(1), 5. https://doi.org/10.1186/s13002-020-00428-7

Kuyah, S., Sileshi, G. W., Nkurunziza, L., Chirinda, N., Ndayisaba, P. C., Dimobe, K., & Öborn, I. (2021). Innovative agronomic practices for sustainable intensification in sub-Saharan Africa. A review. *Agronomy for Sustainable Development, 41*(2), 16. https://doi.org/10.1007/s13593-021-00673-4

Lausch, A., Blaschke, T., Haase, D., Herzog, F., Syrbe, R.-U., Tischendorf, L., & Walz, U. (2015). Understanding and quantifying landscape structure – A review on relevant process characteristics, data models and landscape metrics. *Ecological Modelling, 295*, 3141. https://doi.org/10.1016/j.ecolmodel.2014.08.018

Lee, S., & Kim, Y. (2023). Non-invasive measurement of circadian clock activity in the turquoise killifish. *STAR Protocols, 4*(2), Article 102261. https://doi.org/10.1016/j.xpro.2023.102261

Lemaire, G., Franzluebbers, A., Carvalho, P. C. D. F., & Dedieu, B. (2014). Integrated crop–livestock systems : Strategies to achieve synergy between agricultural production and environmental quality. *Agriculture, Ecosystems & Environment, 190*, 48. https://doi.org/10.1016/j.agee.2013.08.009

Lohmann, U., Sausen, R., Bengtsson, L., Cubasch, U., Perlwitz, J., & Roeckner, E. (1993). The Köppen climate classification as a diagnostic tool for general circulation models. *Climate Research, 3*, Article 177193. https://doi.org/10.3354/cr003177

Loola, B. (2025). Développement rural comme frein à l'exode rural et levier à l'exode urbain en République Démocratique du Congo. In Revue Internationale de la Recherche Scientifique (Revue-IRS) - ISSN: 2958-8413. Zenodo. https://doi.org/10.5281/zenodo.17073422.

Losch, B. (2016). Structural transformation to boost youth labour demand in sub-Saharan Africa : The role of agriculture, rural areas and territorial development. *International Labour Office. Employment Policy Dept, 204*, 65.

Lu, C. D., Kawas, J. R., & Mahgoub, O. G. (2005). Fibre digestion and utilization in goats. *Small Ruminant Research, 60*(12), 4552. https://doi.org/10.1016/j.smallrumres.2005.06.035

Marín, D., Martino, G.D., Guenni, O., & Guédez, Y. (2001). Biomasse et productivité de la strate herbacée des savanes de l'Etat de Guarico (Venezuela).

Matta, F. D. P., Fávero, A. P., Vigna, B. B. Z., Pozzobon, M. T., De Medeiros, S. R., Júnior, W. B., & Cavallari, M. M. (2023). Agronomic, nutritive value, reproductive, cytogenetic, and molecular aspects of Paspalum accessions : Contribution to the development of new forage cultivars. *Grass and Forage Science, 78*(1), Article 101118. https://doi.org/10.1111/gfs.12600

McNew, L. B., Dahlgren, D. K., & Beck, J. L. (2023). *Rangeland wildlife ecology and conservation*. Springer International Publishing. https://doi.org/10.1007/978-3-031-34037-6

Meuret, M., Bartiaux-Thill, N., Bourbouze, A., Rosenberger, S., Vernerey, M., Sourbier, Y., Ninane, V., Trojan, M., Trojan, M., Rouchy, N., & André, J.-F. (1985). Evaluation de la consommation d'un troupeau de chèvres laitières sur parcours forestier—Méthode d'observation directe des coups de dents—Méthode du marqueur oxyde de chrome. *Annales De Zootechnie, 34*(2), Article 159180. https://doi.org/10.1051/animres:19850203

Mishra, G., Giri, K., Jangir, A., Vasu, D., & Rodrigo-Comino, J. (2021). Understanding the effect of shifting cultivation practice (slash-burn-cultivation-abandonment) on soil physicochemical properties in the north-eastern Himalayan region. *Investigaciones Geográficas, 76*, 243. https://doi.org/10.14198/INGEO.17820

Molinario, G., Hansen, M. C., Potapov, P. V., Tyukavina, A., Stehman, S., Barker, B., & Humber, M. (2017). Quantification of land cover and land use within the rural complex of the Democratic Republic of Congo. *Environmental Research Letters, 12* (10), Article 104001. https://doi.org/10.1088/1748-9326/aa8680

Muntifering, R. B., Crosby, D. D., Powell, M. C., & Chappelka, A. H. (2000). Yield and quality characteristics of bahiagrass (Paspalum notatum) exposed to ground-level ozone. *Animal Feed Science and Technology, 84*(34), Article 243256. https://doi.org/10.1016/S0377-8401(00)00124-3

Muramoto, J., Ellis, E., Li, Z., Machado, R., & Gliessman, S. (2000). Field-scale nutrient cycling and sustainability : Comparing natural and agricultural ecosystems. Éd. In S. Gliessman (Ed.), *Agroecosystem sustainability: 20002349. Agroecosystem sustainability*. CRC Press, Article 121134. https://doi.org/10.1201/9781420041514.ch8.

Namonje-Kapembwa, T., Chiwawa, H., & Sitko, N. (2022). Analysis of goat production and marketing among smallholder farmers Zambia. *Small Ruminant Research, 208*, Article 106620. https://doi.org/10.1016/j.smallrumres.2022.106620

Nasiru, A., Ibrahim, M. H., & Ismail, N. (2014). Nitrogen losses in ruminant manure management and use of cattle manure vermicast to improve forage quality. *International Journal of Recycling of Organic Waste in Agriculture, 3*(2), 57.

Ndona, A., Kambashi, B., Beckers, Y., Moulin, C.-H., & Bindelle, J. (2024). Contribution of traditional goat farming systems to the sustainable intensification of smallholder agriculture in sub-Saharan Africa : The example of the western part of the Democratic Republic of Congo. *Farming System, 2*(2), Article 100079. https://doi.org/10.1016/j.farsys.2024.100079

Orina, P. S., Chepkirui, M., Orina, T., Olala, M., & Oluwole, F. (2024). A review on Africa's agricultural Farming systems and potential for transition. *Collective Journal Of Agricultural Sciences*, 0108. https://doi.org/10.70107/collectjagricsci-ART0032

Ouachinou, J. M.-A. S., Adomou, A. C., Dassou, G. H., Yedomonhan, H., Tossou, G. M., & Akoegninou, A. (2017). Connaissances et pratiques ethnobotaniques en médecines traditionnelles vétérinaire et humaine au bénin : Similarité ou dissemblance ? *Journal of Applied Biosciences, 113*(1), Article 11174. https://doi.org/10.4314/jab.v113i1.6

Ouédraogo, K., Zaré, A., Korbéogo, G., Ouédraogo, O., & Linstädter, A. (2021). Resilience strategies of West African pastoralists in response to scarce forage resources. *Pastoralism : Research, policy and practice, 11*(1), 16. https://doi.org/10.1186/s13570-021-00210-8

Over, J.-S.R., Ritchie, A.C., Kranenburg, C.J., Brown, J.A., Buscombe, D., Noble, T., Sherwood, C.R., Warrick, J.A., & Wernette, P.A. (2021). Processing Coastal Imagery with Agisoft Metashape Professional Edition, version 1.6—Structure from motion workflow documentation (nos. 2021–1039; U.S. Geological Survey open-file report 2021–1039, p. 46p).

Paciullo, D. S. C., Gomide, C. A. M., Castro, C. R. T., Maurício, R. M., Fernandes, P. B., & Morenz, M. J. F. (2017). Morphogenesis, biomass and nutritive value of Panicum maximum under different shade levels and fertilizer nitrogen rates. *Grass and Forage Science, 72*(3), Article 590600. https://doi.org/10.1111/gfs.12264

Pedreira, B. C., Yasuoka, J. I., Helwig, D., Farney, J. K., & Sassenrath, G. F. (2024). Forage accumulation and nutritive value of 'Wrangler' bermudagrass hayfield in response to nitrogen and harvesting management. *Crop, Forage & Turfgrass Management, 10*(2), Article e70016. https://doi.org/10.1002/cft2.70016

Piñeiro-Vázquez, A. T., Jiménez-Ferrer, G. O., Chay-Canul, A. J., Casanova-Lugo, F., Díaz-Echeverría, V. F., Ayala-Burgos, A. J., Solorio-Sánchez, F. J., Aguilar-Pérez, C. F., & Ku-Vera, J. C. (2017). Intake, digestibility, nitrogen balance and energy utilization in heifers fed low-quality forage and Leucaena leucocephala. *Animal Feed Science and Technology, 228*, Article 194201. https://doi.org/10.1016/j.anifeedsci.2017.04.009

Plexida, S. G., Sfougaris, A. I., Ispikoudis, I. P., & Papanastasis, V. P. (2014). Selecting landscape metrics as indicators of spatial heterogeneity—A comparison among Greek landscapes. *International Journal of Applied Earth Observation and Geoinformation, 26*, 2635. https://doi.org/10.1016/j.jag.2013.05.001

Prell, J., & Poole, P. (2006). Metabolic changes of rhizobia in legume nodules. *Trends in Microbiology, 14*(4), Article 161168. https://doi.org/10.1016/j.tim.2006.02.005

R Core Team. (2024). *A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing. https://www.R-project.org.

Rotz, C. A., Oenema, J., & Van Keulen, H. (2006). Whole farm management to reduce nutrient losses from dairy farms : A simulation study. *Applied Engineering in Agriculture, 22*(5), Article 773784. https://doi.org/10.13031/2013.21992

Rufino, M. C., Hengsdijk, H., & Verhagen, A. (2009). Analysing integration and diversity in agro-ecosystems by using indicators of network analysis. *Nutrient Cycling in Agroecosystems, 84*(3), Article 229247. https://doi.org/10.1007/s10705-008-9239-2

Rufino, M. C., Rowe, E. C., Delve, R. J., & Giller, K. E. (2006). Nitrogen cycling efficiencies through resource-poor African crop–livestock systems. *Agriculture, Ecosystems & Environment, 112*(4), Article 261282. https://doi.org/10.1016/j.agee.2005.08.028

Sá, A. G. A., Moreno, Y. M. F., & Carciofi, B. A. M. (2020). Food processing for the improvement of plant proteins digestibility. *Critical Reviews in Food Science and Nutrition, 60*(20), 3367–3386. https://doi.org/10.1080/10408398.2019.1688249

Schlecht, E., Hiernaux, P., Kadaouré, I., Hülsebusch, C., & Mahler, F. (2006). A spatio-temporal analysis of forage availability and grazing and excretion behaviour of herded and free grazing cattle, sheep and goats in Western Niger. *Agriculture, Ecosystems & Environment, 113*(14), Article 226242. https://doi.org/10.1016/j.agee.2005.09.008

Sejian, V., Silpa, M. V., Chauhan, S. S., Bagath, M., Devaraj, C., Krishnan, G., Nair, M. R. R., Anisha, J. P., Manimaran, A., Koenig, S., Bhatta, R., & Dunshea, F. R. (2021). Eco-intensified breeding strategies for improving climate resilience in goats. Éds. In M. K. Jhariya, R. S. Meena, & A. Banerjee (Eds.), *Ecological intensification of natural resources for sustainable agriculture*. Singapore: Springer, Article 627655. https://doi.org/10.1007/978-981-33-4203-3_18.

Seleka, T. A., Senyolo, M. P., & Mokhaukhau, J. P. (2024). Exploring socioeconomic determinants of goat herd size : A case study of smallholder farmers in Lephalale local municipality, Limpopo, South Africa. *Journal of Infrastructure, Policy and Development, 8*(13), 8091. https://doi.org/10.24294/jipd8091

Sherwood, C. R., Warrick, J. A., Hill, A. D., Ritchie, A. C., Andrews, B. D., & Plant, N. G. (2018). Rapid, remote assessment of Hurricane Matthew impacts using four-dimensional structure-from-motion photogrammetry. *Journal of Coastal Research, 34*(6), 1303. https://doi.org/10.2112/JCOASTRES-D-18-00016.1

Sokupa, M. I., Mupangwa, J. F., Washaya, S., Tikwayo, S. E., & Mopipi, K. (2024). The nutritive value of Panicum maximum and, Brachiaria brizantha grass species. *Acta Agriculturae Scandinavica, Section A — Animal Science,, 73*(12), 19. https://doi.org/10.1080/09064702.2023.2249903

Stark, F., Fanchone, A., Semjen, I., Moulin, C.-H., & Archimède, H. (2016). Crop-livestock integration, from single practice to global functioning in the tropics : Case studies in Guadeloupe. *European Journal of Agronomy, 80*, 920. https://doi.org/10.1016/j.eja.2016.06.004

Stark, F., González-García, E., Navegantes, L., Miranda, T., Poccard-Chapuis, R., Archimède, H., & Moulin, C.-H. (2018). Crop-livestock integration determines the agroecological performance of mixed farming systems in Latino-Caribbean farms. *Agronomy for Sustainable Development, 38*(1), 4. https://doi.org/10.1007/s13593-017-0479-x

Steinmetz, L., Veysset, P., Benoit, M., & Dumont, B. (2021). Ecological network analysis to link interactions between system components and performances in multispecies livestock farms. *Agronomy for Sustainable Development, 41*(3), 42. https://doi.org/10.1007/s13593-021-00696-x

Tchouamo, I. R., Tchoumboué, J., & Thibault, L. (2005). Caractéristiques socio-économiques et techniques de l'élevage de petits ruminants dans la province de l'ouest du Cameroun. *Topicultura, 4*(23), Article 2012011.

Van Soest, P. J., Robertson, J. B., & Lewis, B. A. (1991). Methods for dietary Fiber, neutral detergent Fiber, and nonstarch polysaccharides in relation to animal nutrition. *Journal of Dairy Science, 74*(10), Article 35833597. https://doi.org/10.3168/jds.S0022-0302(91)78551-2

Vandermeulen, S., Ramírez-Restrepo, C. A., Marche, C., Decruyenaere, V., Beckers, Y., & Bindelle, J. (2018). Behaviour and browse species selectivity of heifers grazing in a temperate silvopastoral system. *Agroforestry Systems, 92*(3), Article 705716. https://doi.org/10.1007/s10457-016-0041-x

Vangu, G. P., Mobambo, K. N., Omondi, B. A., & Staver, C. (2023). Evaluation des performances du plantain en systèmes de cultures associées pérennes en zone savanicole au Kongo central en République Démocratique du Congo. *International Journal of Biological and Chemical Sciences, 17*(4), Article 14431455. https://doi.org/10.4314/ijbcs.v17i4.13

Veldman, J. W., Overbeck, G. E., Negreiros, D., Mahy, G., Le Stradic, S., Fernandes, G. W., Durigan, G., Buisson, E., Putz, F. E., & Bond, W. J. (2015). Where tree planting and forest expansion are bad for biodiversity and ecosystem services. *BioScience,, 65*(10), Article 10111018. https://doi.org/10.1093/biosci/biv118

Wang, J., Wang, D., Li, C., Seastedt, T. R., Liang, C., Wang, L., Sun, W., Liang, M., & Li, Y. (2018). Feces nitrogen release induced by different large herbivores in a dry grassland. *Ecological Applications, 28*(1), Article 201211. https://doi.org/10.1002/eap.1640

Wasso, D. S., Akilimali, J. I., Patrick, B., & Bajope, J. B. (2019). Élevage caprin : Situation actuelle, défis et impact socioéconomique sur la population du territoire de Walungu, République Démocratique du Congo. *Journal of Applied Biosciences, 129*(1), Article 13050. https://doi.org/10.4314/jab.v129i1.8

Zampaligré, N., Dossa, L. H., & Schlecht, E. (2013). Contribution of browse to ruminant nutrition across three agro-ecological zones of Burkina Faso. *Journal of Arid Environments, 95*, 5564. https://doi.org/10.1016/j.jaridenv.2013.03.011

Zeng, L., & Chen, C. (2018). Using remote sensing to estimate forage biomass and nutrient contents at different growth stages. *Biomass and Bioenergy, 115*, 7481. https://doi.org/10.1016/j.biombioe.2018.04.016