Morphological variability within the indigenous sheep population of Benin

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Abstract

Knowledge of both the genetic diversity and geographical distribution of animal genetic resources is a prerequisite for their sustainable utilization, improvement and conservation. The present study was undertaken to explore the current morphological variability within the sheep population in Benin as a prelude for their molecular characterization. From November 2018 to February 2020, 25 quantitative linear body measurements and 5 qualitative physical traits were recorded on 1240 adult ewes from the 10 phytogeographic zones that comprise the three vegetation zones of Benin. Fourteen morphological indices were calculated based on the linear body measurements. The collected data were first analyzed using multiple comparisons of least-square means (LSmeans), followed by generalized linear model (GLM) procedures, to explore the relationships among the measured morphometric traits and the 10 phytogeographic zones. Next, the presence of any genetic sub-populations was examined using multivariate analytical methods, including canonical discriminant analysis (CDA) and ascending hierarchical clustering (AHC). Univariate analyses indicated that all quantitative linear body measurements varied significantly (P < 0.05) across the phytogeographic zones. The highest values (LSmean ± standard error) of withers height (68.3 ± 0.47 cm), sternum height (46.0 ± 0.35 cm), and rump height (68.8 ± 0.47 cm) were recorded in the Mekrou-Pendjari zone, the drier phytogeographic zone in the North, whereas the lowest values, 49.2 ± 0.34, 25.9 ± 0.26, and 52.0 ± 0.35 cm, respectively, were recorded in the Pobe zone in the South. Multivariate analyses revealed the prevalence of four distinct sheep sub-populations in Benin. The sub-population from the South could be assimilated to the short-legged and that from the North to the West African long-legged sheep. The two other sub-populations were intermediate and closer to the crossbreds or another short-legged sub-breed. The proportion of individuals correctly classified in their group of origin was approximately 74%. These results uncovered a spatial morphological variation in the Beninese sheep population along a South-North phytogeographic gradient.
Introduction

Small ruminants play important socio-economic and cultural roles [1, 2] and contribute to improved livelihoods in both rural and peri-urban areas [3, 4]. For millions of rural households, the holding of these animal genetic resources, notably sheep, represents a pathway to poverty reduction and an increase in financial security [2, 5, 6]. Furthermore, they make an important contribution to the protein consumption of smallholder households [7]. In West Africa, sheep populations are raised under harsh and diverse ecological conditions, which may have led to the evolution of diversified adaptive traits for their survival [2, 8]. This valuable diversity of livestock is increasingly exposed to socio-economic and ecological changes that threaten their genetic integrity. Indeed, changes in production systems, breed preferences of farmers and market demands are the main drivers of their genetic dilution through poorly planned or indiscriminate crossbreeding, while their potential for further genetic improvements remains largely unknown.

In Benin, as in most West African countries, indigenous sheep populations are not sufficiently characterized, and little reliable data are available [9]. It is commonly accepted that two main sheep breeds, the Djallonké (S1 and S2 Figs) and the Sahelian (S3 and S4 Figs), are widely distributed throughout Benin [10–12]. Djallonké, also named West African Dwarf (WAD) sheep, seems to originate from the breed of fine-tailed and hairy sheep native to Western Asia, having migrated to Africa through the Isthmus of Suez and Bab el Mandeb. Moreover, Djallonké sheep were the only sheep breed in the African continent until the third millennium BC [13]. Widely distributed in West Africa, Djallonké sheep are mainly raised for meat [10, 11, 14]. Moreover, Djallonké sheep are particularly adapted to coastal areas [15] because of their resistance to trypanosomiasis [12, 16]. However, Djallonké sheep may have undergone significant phenotypic changes over time [9, 12]. Generally, Djallonké/WAD sheep are small-sized animals with straight facial profiles, small narrow-erected ears, and a hairy short coat [14, 17]. In contrast to ewes, rams are horned and have a heavy white or pied mane black forequarters and white hindquarters. Two sub-breeds of Djallonké sheep have been identified based on size [18, 19]: the larger breed is found in the Sudanian zone, and the smaller breed in the Guinean zone further south [9, 18].

Sahelian sheep include all long-legged sheep breeds known under different ethnic and local names in the semi-arid and arid zones of the West African Sahel [9]. Similar to Djallonké sheep, Sahelian sheep are thought to have descended from the fine-tailed and hairy sheep [9]. Although Sahelian sheep are not known to survive in humid areas [20], they are increasingly encountered in different humid localities of West Africa, including Benin, over the past few years [11, 12], reflecting their progressive adaptation to less dry climates. Sahelian sheep are raised for meat and milk production in Sahelian pastoral and agro-pastoral production systems [14]. Sahelian sheep have a convex facial profile, long pendulous ears, a long thin tail, and diverse coat color [9]. A typical characteristic of the Sahelian ram is the absence of mane. As in several West African countries, many crossbreeds between Sahelian and Djallonké sheep (S5 and S6 Figs) are present in Benin with various intermediate body sizes.

The lack of knowledge on the genetic diversity of West African sheep populations and their specific traits constitutes a major constraint for implementing sound programs for their genetic improvement and sustainable use. Moreover, the presence of unknown sub-breeds within each of these two known breeds of sheep and the occurrence of crossbreeding can lead to certain ambiguities when it comes to distinguishing certain individuals according to well-defined breed/genetic type standards. According to the Food and Agriculture Organization Agency (FAO) [21], phenotypic and molecular characterizations are important tools for documenting breeds, which is the first step towards the development of strategies for their
sustainable use, management and conservation. To date, neither of these characterization tools have not been covered in depth to describe the diversity existing within the Beninese sheep population. Hence, in this study, to further document this existing diversity and to explore the actual spatial distribution within the indigenous sheep population of Benin, we primarily characterized their morphology based on a large panel of collected morphological/phenotypic traits. We hypothesized that the sheep population of Benin is highly diverse and unevenly distributed according to ecological conditions.

The current study aimed to establish the relationships among sheep morphometric traits and the 10 phytogeographic zones of Benin using univariate analyses and then explore the presence of sheep sub-populations in the Beninese indigenous sheep population using multivariate analyses. The findings of this study will provide the basis for a comprehensive molecular study on the same samples, based on both simple sequence repeat and single nucleotide polymorphism marker genotyping. Morphological data could then be compared with molecular data and association analyses (i.e., genome-wide association studies) to appropriately address possible breeding strategies for the indigenous sheep population of Benin.

Material and methods

Ethical statement

This study was conducted as part of the ARES-PRD Project (Amélioration des systèmes traditionnels d’élevage de petits ruminants (ovins et caprins) dans un contexte de mutation environnementale et sociétale au Bénin https://www.ares-ac.be/fr/cooperation-au-developpement/pays-projets/projets-dans-le-monde/item/150-prd-amelioration-des-systemes-traditionnels-d-elevage-de-petits-ruminants-ovins-et-caprins-dans-un-contexte-de-mutation-environnementale-et-societale-au-benin). The Scientific Committee has approved these protocols. Furthermore, the study involved recording body measurements from sheep with oral consent and in the presence of their owners. Due to the absence of specific legislation for body measurements, no approval was necessary.

Study area

This study was conducted in the 10 phytogeographic zones (Fig 1) that comprise the three vegetation zones of Benin [22, 23], namely the Guinea-Congolian (GCZ), the Guineo-Sudanian transition (GSZ) zone and the Sudanian zone (SZ). The characteristics of the 10 phytogeographic zones, such as climatic conditions, temperature, humidity index, soil characteristics, and predominant vegetation, are presented in Table 1.

Sampling procedure

A longitudinal survey was conducted from November 2018 to February 2020 in the 10 phytogeographic zones of Benin. In each zone, two to five communes were selected depending on the presence or abundance of sheep flocks. Thirty-two out of the 77 communes of Benin were included in the survey. At least four distinct villages were randomly chosen from each commune. In each village, 5 to 20 individual flocks were selected based on farmers’ willingness to participate in the study. Approximately four or more unrelated animals were sampled per flock based on farmers’ knowledge of the individual animals present in their sheep flocks. Thus, a total of 1240 ewes that were at least two years old and multiparous (at least two lambings) were randomly selected, described and phenotypically characterized. The age of animal estimated by the farmers was ascertained by examining their teeth according to the procedure described in [25, 26]. The sampling distribution across the vegetation and phytogeographic
Fig 1. Map of the vegetation zones and phytogeographic zones of Benin showing the 32 communes sampled to assess the morphological variability within the indigenous sheep population of Benin. The map was made using QGIS 3.8 [24].

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zones is presented in Table 1. All individuals sampled in a phytogeographic zone were considered as a sub-population.

### Data collection procedure

A total of 25 quantitative linear body measurements (Fig 2 and Table 2) and 5 qualitative physical traits drawn from the FAO guidelines [25] and from a previous study [27], were used to describe the morphological characteristics of each animal. To minimize collecting biases, all measurements were taken by a young researcher and a trained field assistant. The live body-weight of each animal was measured using a scale. The other 24 body measurements were taken using a flexible measuring tape and a measuring stick, early in the morning before the animals were fed to avoid biases on certain traits due to feed intake. In addition, the reproductive history of each sampled animal, including the number and type of parities (single, twins, triplet and quadruplets), was recorded from its owner. The geographical position of the herds in which the sheep individuals were sampled was recorded using a Garmin GPS (etrex vista TM).

### Data analysis

Fourteen morphological indices (Table 3) were calculated based on the collected quantitative linear body measurements (or morphometric traits). All statistical analyses were conducted using SAS version 9.4 (SAS Institute Inc., Cary, NC, USA). Descriptive statistics for the quantitative linear body measurements and qualitative physical traits were obtained using the procedures PROC UNIVARIATE and PROC FREQ, respectively. The frequencies and Pearson chi-

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**Table 1. Characteristics of the 10 phytogeographic zones of Benin and sample size (sheep).**

| Vegetation zone | Phytogeographical zones | Climate | Humidity index | Annual rainfall (mm) | Major soil type | Main vegetation | Sample size |
|-----------------|-------------------------|---------|----------------|----------------------|----------------|----------------|-------------|
| GC Coastal (CZ) | Subequatorial            | 4.6 to 5.8 | 900–1300 | Sandy                | Dense humid forest, marshy forest, light forests and savannah | 105 |
| Pobe (PoZ)      | Subequatorial            | 4 to 5.8  | 1100–1300 | Ferrallitic and without concretions | Dense humid semi-deciduous forest | 96 |
| Oueme Valley (VOZ) | Subequatorial          | 4.9      | 1100–1300 | Hydromorphous with sandy loam to clay loam texture | Marshy forest, forest and sections of dense semi-deciduous forest | 103 |
| Plateau (PIZ)   | Subequatorial            | 3.8 to 4.9 | 900–1300 | Red ferrallitic soil and without concretions | Dense semi-deciduous forest | 110 |
| GS Zou (ZZ)     | Subhumid tropical        | 2.8      | 1100      | Tropical ferruginous | Dense dry forest and light forests | 147 |
| Bassila (BZ)    | Typical subhumid         | 2.7 to 3.9 | 1200–1300 | Tropical ferruginous type with ferrallitic soil intrusions with concretions | Dense semi-deciduous forest, gallery forests, dense dry forests, light forests and wooded savannahs | 167 |
| Borgou-Sud (BSZ) | Tropical with tendency to unimodal | 2.9      | 1200      | Ferruginous soils on crystalline rocks | Light forest and wooded savannahs | 112 |
| S Borgou-Nord (BNZ) | Typically dry tropical | 1.9      | 1000–1150 | Ferruginous soils on crystalline rocks | Wooded savannahs | 124 |
| Chaîne Atacora (CAZ) | Typically dry tropical | 2.1      | 1000–1200 | poorly developed, with unrefined minerals | Savannah and Pockets of dense dry Forest and light forests | 148 |
| Mekrou-Pendjari (MPZ) | Typically dry tropical | 1.9 to 1.4 | 900–1000 | Ferruginous type washed with concretion | Dense dry forests, light forests and wooded savannahs | 128 |

Total 1240

GC, Guineo-Congolese zone; GS, Guineo-Sudanian zone; S, Sudanian zone.

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Fig 2. Illustration of the 25 linear body measurements taken on each sampled sheep. WH, withers height; RH, rump height; SH, sternum height; BH, back height; CD, chest depth; RD, rump depth; CW, chest width; SIL, scapulo-ischial length; BL, body length; HL, head length; HW, head width; EL, ear length; MD, muzzle diameter; NL, neck length; NG, neck girth; TL, tail length; HG, heart girth; CC, chest circumference; AG, abdominal girth; BD, bicostal diameter; RW, rump width; RL, rump length; TC, cannon bone circumference; HC, hock circumference; BW, body weight.

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square ($\chi^2$) tests were used for qualitative physical traits to explore the relationships among qualitative variables. The least-square means (LSmeans), their standard errors (SEs), and the
coefficients of variation (CVs) of the morphometric traits were calculated for each phytogeographic zone. The comparison of LSmeans between phytogeographic zones was performed using Tukey’s test multiple mean comparison tests. Subsequently, the general linear model procedure (PROC GLM) was used to analyze the relationship between phytogeographic zones and morphometric traits.

A stepwise discriminant analysis was performed using PROC STEPDISC to identify the most useful morphometric traits and morphological indices for further discriminant analyses. The relative discriminatory ability of a quantitative variable was assessed using the partial R-square, F value, and level of significance (Pr>F). Then, the canonical discriminant analysis (CDA) function (PROC CANDISC) was used to perform univariate and multivariate one-way analyses, derive canonical functions and linear combinations of the quantitative variables that summarize variation between populations, and calculate the associated Mahalanobis distances. The ability of the computed canonical functions to classify each individual animal into its a priori phytogeographic zone was measured using the discriminant procedure (PROC DISCRIM). The degree of morphological similarity or dissimilarity among individuals from the different phytogeographic zones was determined based on the ascending hierarchical clustering (AHC) analysis procedure (PROC CLUSTER). The PROC TREE procedure was used to build a dendrogram displaying the interrelationships among individuals within and across phytogeographic zones. Finally, a multiple correspondence analysis (MCA) using the PROC CORRESP procedure was used to associate the qualitative physical traits with the phytogeographic zones.

Results
Relationships among sheep morphometric traits and the 10 phytogeographic zones of Benin using univariate analyses

The result of the univariate analysis showed significant differences (P<0.05) among the 10 phytogeographic zones for all measured quantitative morphometric variables (S1 Table) and the
calculated morphological indices (S2 Table). Overall, most of the quantitative linear body traits, except ear length (EL), tail length (TL) and body weight (BW), had relatively high CVs, whereas the quantitative variables chest depth (CD), scapulo-ischial length (SIL), body length (BL), muzzle diameter (MD), heart girth (HG), and cannon bone circumference (TC) had relatively low CVs. High values of CVs were observed for most of the quantitative variables in the Borgou-Nord and Chaîne Atacora zones in the North. Most of the morphological indices, except mass index (MI), balance index (Ba), and auricular index (IAT), showed relatively low CVs with the least variation for body ratio (BR), pelvic index (IP), sternum index (USI), body (IBR), size index (SI), chest depth index (CDI), and boniness index (BI). However, for most of the measured morphometric traits and indices, the highest mean values were observed in the Mekrou-Pendjari zone in the North and the lowest mean values in the Oueme Valley and Pobe zones in the South. The highest mean values recorded for withers height (WH), rump height (RH), BL, and SIL were respectively 68.3, 68.8, 63.2 and 91.2 cm, and the lowest were 49.2, 50.9, 50.9 and 69.3 cm respectively. The highest mean values of the slenderness (IGS) and IAT indices were 1.36 and 0.61, respectively, and the lowest mean values were 1.16 and 0.37, respectively (S2 Table).

Significant differences in the frequencies (P < 0.0001) were observed among the 10 phyto-geographic zones for certain qualitative traits, such as head profile, coat color and patterns, hair type, back profile, and ear orientation (Table 4). A composite coat color (88.1%) was more frequently observed regardless of the phyto-geographic zone, with a dominance of spotted white (75.6%), black (6.6%) and brown (5.9%) colors. It was followed by the plain/uniform white (9.0%) and piebald (2.9%) colors, which appeared to be present almost exclusively in the Mekrou-Pendjari, Borgou-Nord, and Chaîne Atacora phyto-geographic zones. Long hair (61.9%) and erected/pendulous ears (72.6%) were more common than short hair (38.1%) and dropped ears (27.4%), which also predominated in the Mekrou-Pendjari, Borgou-Nord, and Chaîne Atacora zones. Additionally, animals with dipped back (44.0%) were relatively more common than those with slopes up towards the rump (31.9%) and straight back (24.1%). Irrespective of the phyto-geographic zone, the most commonly observed facial profile was the straight type (60.1%), followed by the convex type (37.5%).

The proportion of birth type varied significantly (p < 0.0001) among the 10 phyto-geographic zones (S3 Table). Irrespective of the zone, single-born lambs were the most common. The highest percentages of twin-born lambs were recorded in the Oueme Valley, Pobe, and Zou zones, whereas the highest proportions of triplets and quadruplets were recorded in the Pobe zone. The percentage of multiple births appeared to increase with the parity number of ewes.

Identification of sheep sub-populations using multivariate analyses

The results of the stepwise discriminant analysis (Table 5) showed that 38 out of the 39 quantitative variables (i.e., 25 quantitative linear body traits and 14 morphological indices) included in the analysis significantly contribute to discrimination between the phyto-geographic zones (P < 0.0001). The traits rump width (RW) and sternum height (SH) showed higher partial R² and F values, illustrating their greater discriminant power than the other variables used to assess the morphological diversity in the Benin sheep population. Nevertheless, the use of the 32 significant (P < 0.0001 for column Pr > F) quantitative variables (i.e., 22 quantitative linear body traits and 10 morphological index) in the CDA generated two significant (P < 0.0001) canonical variables (CAN 1 and CAN 2) that explain 76% of the total variation, as revealed by the standardized coefficients for the discriminant function, the canonical correlation, the eigenvalue, and the share of total variance taken into account (Table 6). Canonical loadings that measure the simple linear correlations between each independent variable and canonical variables are reported in Table 6. CAN 1 was dominated by positive loadings of head length
In contrast, CAN 2 was dominated by positive loadings of BL, TL, back height (BH), RH, WH, CD, BW, HG, TC, rump depth (RD), head width (HW), MI and neck length (NL).

The plot of the centroid values of the first two canonical discriminant functions (CAN1 and CAN2) showed many distinct and homogenous sheep sub-populations with overlapping events (Fig 3).

The Mahalanobis distances among the 10 phytogeographic zones are presented in Table 7. All pairwise distances were significant (P<0.0001). The two largest measured squared Mahalanobis distances were between the Mekrou-Pendjari and Pobe zones (69.02) and between the Oueme Valley and Bassila zones (61.65). The closest distance (2.85) was between the Chaı̂ne Atacora and Borgou-Nord zones. The discriminant functions accurately classified a relatively high proportion (74.59%) of the individual sheep into their a priori group (Table 8).

Based on the squared Mahalanobis distances, AHC generated a dendrogram that indicated four distinct sub-groups or sub-populations of sheep (Fig 4). The first sub-population was composed of Borgou-Nord and Chaı̂ne Atacora zones joined by the Borgou-Sud zone, the second was only composed of the Mekrou-Pendjari zone, the third was composed of the Pobe and Costal zones joined by the Bassila zone, and the fourth was composed of the Oueme Valley, Zou, and Plateau zones.

Table 4. Frequency (%) of qualitative traits in sheep population of the 10 phytogeographic zones of Benin.

| Zones          | BSZ n = 112 | BZ n = 167 | BNZ n = 124 | CAZ n = 148 | MPZ n = 128 | PIZ n = 110 | PoZ n = 96 | VOZ n = 103 | CZ n = 105 | ZZ n = 147 | Overall n = 1240 | Chi² | P   |
|----------------|-------------|------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------------|------|-----|
| Facial profile |             |            |             |             |             |             |             |             |             |             |                   | 498.85 | 0.0001 |
| Convex        | 47.3        | 9.0        | 46.8        | 75.7        | 77.3        | 19.1        | 42.2        | 26.2        | 1.0          | 17.7        | 33.6              |      |      |
| Ultra-convex  | 1.8         | 0.0        | 5.6         | 5.4         | 9.4         | 0.0         | 0.0         | 0.0         | 0.7          | 0.7         | 2.4               |      |      |
| Straight      | 50.9        | 91.0       | 47.6        | 18.9        | 13.3        | 80.9        | 95.8        | 73.8        | 99.1         | 81.6        | 64.0              |      |      |
| Coat color    |             |            |             |             |             |             |             |             |             |             |                   | 166.06 | 0.0001 |
| Spotted white | 79.5        | 71.9       | 78.2        | 75.7        | 67.2        | 84.5        | 78.1        | 71.8        | 67.6         | 81.6        | 75.6              |      |      |
| Spotted brown | 6.3         | 1.8        | 5.6         | 5.4         | 7.8         | 5.5         | 5.2         | 11.7        | 6.7          | 5.4         | 5.9               |      |      |
| Spotted black | 7.1         | 5.4        | 4.0         | 6.1         | 3.9         | 3.6         | 11.5        | 8.7         | 19.0         | 1.4         | 6.6               |      |      |
| Zoned pie     | 2.7         | 1.2        | 4.8         | 3.4         | 14.8        | 0.0         | 0.0         | 0.0         | 0.7          | 0.7         | 2.9               |      |      |
| Plain/Uniform white | 4.5        | 19.8       | 7.3         | 9.5         | 6.3         | 6.4         | 5.2         | 7.8         | 6.7          | 10.9        | 9.0               |      |      |
| Hair length   |             |            |             |             |             |             |             |             |             |             |                   | 395.67 | 0.0001 |
| Long          | 43.8        | 76.6       | 16.9        | 33.8        | 28.1        | 81.8        | 91.7        | 83.5        | 93.3         | 83.0        | 61.9              |      |      |
| Short         | 56.3        | 23.4       | 83.1        | 66.2        | 71.9        | 18.2        | 8.3         | 16.5        | 6.7          | 17.0        | 38.1              |      |      |
| Back profile  |             |            |             |             |             |             |             |             |             |             |                   | 1004.33 | 0.0001 |
| Straight      | 13.4        | 4.2        | 31.5        | 36.5        | 10.9        | 45.5        | 8.3         | 52.4        | 1.9          | 38.1        | 24.1              |      |      |
| Curved/Dipped | 78.6        | 5.4        | 62.1        | 52.0        | 85.5        | 50.0        | 1.0         | 20.4        | 4.8          | 58.5        | 44.0              |      |      |
| Slopes up towards the rump | 8.0        | 90.4       | 6.5         | 0.7         | 3.1         | 4.5         | 90.6        | 27.2        | 93.3         | 3.4         | 31.9              |      |      |
| Ear orientation|             |            |             |             |             |             |             |             |             |             |                   | 392.51 | 0.0001 |
| Erected/ Pendulous | 76.8    | 77.2       | 54.8        | 47.3        | 17.2        | 91.8        | 94.8        | 94.2        | 96.2         | 91.8        | 72.6              |      |      |
| Dropped      | 23.2        | 22.8       | 45.2        | 52.7        | 82.8        | 8.2         | 5.2         | 5.8         | 3.8          | 8.2         | 27.4              |      |      |

MPZ, Mekrou-Pendjari zone; CAZ, Chaı̂ne Atacora zone; BNZ, Borgou-Nord zone; BSZ, Borgou-Sud zone; BZ, Bassila zone; CZ, Coastal zone; PoZ, Pobe zone; PIZ, Plateau zone; VOZ, Oueme Valley zone; ZZ, Zou zone.
P is the probability observed for the qualitative traits; Chi² expresses independence between variables at 5% level.

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Table 5. Summary of the stepwise selection of quantitative traits obtained from the stepwise discriminant analysis performed on 39 morphometric variables.

| Step | Number of traits | Partial R2 | F value | Pr > F | Wilks' lambda (λ) | Pr < Lambda (λ) | Average squared canonical correlation | Pr > ASCC |
|------|------------------|------------|---------|--------|-------------------|----------------|--------------------------------------|----------|
| 1    | RW               | 0.7377     | 384.46  | <.0001 | 0.26225           | <.0001         | 0.082                               | <.0001   |
| 2    | SH               | 0.6708     | 278.31  | <.0001 | 0.08632           | <.0001         | 0.143                               | <.0001   |
| 3    | HC               | 0.3351     | 68.76   | <.0001 | 0.05740           | <.0001         | 0.175                               | <.0001   |
| 4    | HL               | 0.3240     | 65.36   | <.0001 | 0.03880           | <.0001         | 0.203                               | <.0001   |
| 5    | TL               | 0.2567     | 47.05   | <.0001 | 0.02884           | <.0001         | 0.222                               | <.0001   |
| 6    | Ba               | 0.2359     | 42.02   | <.0001 | 0.02203           | <.0001         | 0.243                               | <.0001   |
| 7    | SI               | 0.1744     | 28.73   | <.0001 | 0.01819           | <.0001         | 0.259                               | <.0001   |
| 8    | CC               | 0.1615     | 26.16   | <.0001 | 0.01525           | <.0001         | 0.273                               | <.0001   |
| 9    | IAT              | 0.1620     | 26.24   | <.0001 | 0.01278           | <.0001         | 0.288                               | <.0001   |
| 10   | TD               | 0.1560     | 25.08   | <.0001 | 0.01079           | <.0001         | 0.301                               | <.0001   |
| 11   | BH               | 0.1294     | 20.14   | <.0001 | 0.00939           | <.0001         | 0.307                               | <.0001   |
| 12   | HG               | 0.1112     | 16.94   | <.0001 | 0.00835           | <.0001         | 0.315                               | <.0001   |
| 13   | EL               | 0.1146     | 17.53   | <.0001 | 0.00739           | <.0001         | 0.325                               | <.0001   |
| 14   | MI               | 0.1132     | 17.26   | <.0001 | 0.00655           | <.0001         | 0.331                               | <.0001   |
| 15   | CW               | 0.1290     | 20.01   | <.0001 | 0.00571           | <.0001         | 0.338                               | <.0001   |
| 16   | IC               | 0.1054     | 15.91   | <.0001 | 0.00511           | <.0001         | 0.347                               | <.0001   |
| 17   | CM               | 0.0873     | 12.89   | <.0001 | 0.00466           | <.0001         | 0.352                               | <.0001   |
| 18   | IP               | 0.0823     | 12.08   | <.0001 | 0.00428           | <.0001         | 0.358                               | <.0001   |
| 19   | CD               | 0.1190     | 18.19   | <.0001 | 0.00377           | <.0001         | 0.366                               | <.0001   |
| 20   | BW               | 0.0754     | 10.97   | <.0001 | 0.00349           | <.0001         | 0.370                               | <.0001   |
| 21   | WH               | 0.1452     | 22.84   | <.0001 | 0.00298           | <.0001         | 0.377                               | <.0001   |
| 22   | TC               | 0.0784     | 11.42   | <.0001 | 0.00275           | <.0001         | 0.381                               | <.0001   |
| 23   | NG               | 0.0642     | 9.22    | <.0001 | 0.00257           | <.0001         | 0.385                               | <.0001   |
| 24   | NL               | 0.0497     | 7.01    | <.0001 | 0.00244           | <.0001         | 0.390                               | <.0001   |
| 25   | BD               | 0.0475     | 6.68    | <.0001 | 0.00233           | <.0001         | 0.393                               | <.0001   |
| 26   | HW               | 0.0387     | 5.39    | <.0001 | 0.00224           | <.0001         | 0.397                               | <.0001   |
| 27   | RD               | 0.0372     | 5.18    | <.0001 | 0.00215           | <.0001         | 0.399                               | <.0001   |
| 28   | USI              | 0.0321     | 4.43    | <.0001 | 0.00208           | <.0001         | 0.400                               | <.0001   |
| 29   | IBR              | 0.0309     | 4.25    | <.0001 | 0.00202           | <.0001         | 0.403                               | <.0001   |
| 30   | BL               | 0.0307     | 4.23    | <.0001 | 0.00196           | <.0001         | 0.406                               | <.0001   |
| 31   | SIL              | 0.0273     | 3.75    | 0.0001 | 0.00190           | <.0001         | 0.408                               | <.0001   |
| 32   | AG               | 0.0261     | 3.58    | 0.0002 | 0.00185           | <.0001         | 0.410                               | <.0001   |
| 33   | IGS              | 0.0238     | 3.24    | 0.0007 | 0.00181           | <.0001         | 0.412                               | <.0001   |
| 34   | BI               | 0.0220     | 3.00    | 0.0015 | 0.00177           | <.0001         | 0.413                               | <.0001   |
| 35   | PI               | 0.0155     | 2.69    | 0.0276 | 0.00174           | <.0001         | 0.414                               | <.0001   |
| 36   | RH               | 0.0363     | 5.00    | <.0001 | 0.00168           | <.0001         | 0.416                               | <.0001   |
| 37   | BR               | 0.0284     | 3.88    | <.0001 | 0.00163           | <.0001         | 0.418                               | <.0001   |
| 38   | RL               | 0.0147     | 1.98    | 0.0387 | 0.00161           | <.0001         | 0.418                               | <.0001   |

Number of traits is the number of variables in the model; F, F value for entering or removing the variable; Pr > F, the probability level for the Fstatistic; Pr < Lambda is based on the F approximation to Wilks' lambda; Pr > ASCC is based on the F approximation to Pillai's trace.

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Multiple correspondence analysis of sheep qualitative traits

Multiple correspondence analysis (MCA) highlighted the association between the different qualitative physical traits and phytogeographic zones (Fig 5). The first two dimensions (Dim 1 and Dim 2) explained 68.88% and 18.21% of the total variation, respectively. On the right-hand side of the plot, the Zou, Plateau and Oueme Valley zones were closely associated with
sheep with a straight back, long hair, a predominant coat color of spotted white and brown patterns. Animals from the Pobe, Coastal, and Bassila zones were characterized by back profile slopes up towards the rump and either a plain/uniform white or a composite coat color with predominantly spotted black or white patterns. Moreover, the left-hand side shows that the Mekrou-Pendjari zone was plainly associated with sheep that had dropping ears, flush hairs, an ultra-convex head profile, and pie-black or pie-brown coat color. Conversely, the zones of Borgou-Sud, Borgou-Nord and Chainé Atacora were associated with sheep that have a convex

Table 6. Total canonical coefficients for the canonical function, the adjusted canonical correlation, the eigenvalue, the approximate standard error of the canonical correlations and the percentage total variance accounted for obtained from the canonical discriminant analysis performed on 32 morphometric variables.

| Variables | Can1  | Can2  |
|-----------|-------|-------|
| WH        | 0.43  | 0.64  |
| RH        | 0.30  | 0.65  |
| SH        | 0.72  | 0.41  |
| BH        | 0.30  | 0.65  |
| CD        | 0.26  | 0.60  |
| RD        | 0.26  | 0.55  |
| CW        | -0.27 | 0.27  |
| BL        | 0.07  | 0.72  |
| HL        | 0.74  | 0.41  |
| HW        | 0.03  | 0.55  |
| EL        | 0.49  | 0.47  |
| CM        | 0.53  | 0.25  |
| NL        | 0.57  | 0.50  |
| NG        | 0.14  | 0.46  |
| TL        | 0.28  | 0.69  |
| HG        | 0.13  | 0.58  |
| CC        | 0.02  | 0.38  |
| BD        | 0.39  | 0.47  |
| RW        | -0.80 | 0.45  |
| TC        | 0.22  | 0.57  |
| HC        | -0.18 | -0.07 |
| BW        | 0.25  | 0.59  |
| MI        | 0.08  | 0.52  |
| IAT       | 0.52  | 0.30  |
| IS        | 0.42  | 0.28  |
| IP        | -0.73 | 0.34  |
| SI        | 0.68  | 0.28  |
| Ba        | -0.80 | 0.18  |
| IBR       | -0.24 | 0.00  |
| IC        | -0.83 | 0.02  |
| BR        | 0.70  | 0.13  |
| TD        | -0.82 | -0.08 |

Adjusted Canonical Correlation 0.942 0.871
Approximate Standard Error of the canonical correlations 0.003 0.007
Eigenvalue 8.0952 3.2562
Proportion of the eigenvalue sum 0.54 0.08
Cumulative proportion of the eigenvalue sum 0.54 0.84

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head profile, a dipped back profile and a coat color with predominantly spotted white and brown patterns (Fig 5).

**Discussion**

In this study, we aimed to further document the existing diversity and spatial distribution within the sheep population raised in Benin based on a large panel of qualitative and quantitative traits. Univariate analyses revealed significant differences among phytogeographic zones for all measured morphological traits and derived indices, suggesting the possible influence of these zones on the evolutionary adaptation of the sheep population in terms of these
morphological traits. This result is in line with the finding of a previous study [16], who reported a significant impact of the breeding area on morphological traits in the sheep population from Ivory Coast. The mean values of thoracic development (TD), greater than 1.2,
indicated that all measured animals had good thoracic development, regardless of the phytogeographic zone. However, following the classification based on the body index (IBR) [27], the sheep from the phytogeographic zones of Borgou-Nord, Chaîne Atacora, Plateau, and to some extent Borgou-Sud, can be considered as of the brevigline breed (mean values of IBR < 0.85), whereas those of Bassila, Mekrou-Pendjari, Pobe, Oueme Valley, Coastal and Zou zones are of the medigline breed (mean values of IBR > 0.85). The overall calculated cephalic index (IC) of 51.20% indicated that sheep from Benin are dolichocephalic, regardless of the phytogeographic zone. This result is considerably lower than that reported in a previous study [35] for sheep breeds in Nigeria. Based on the main qualitative traits generally used for breed description (i.e., coat color, facial profile, ear orientation), the composite coat color with a dominance of spotted white associated with both straight facial profile, long hairs, and erected ears, most frequently recorded in the Southern zones (i.e., BZ, PIZ, PoZ, CZ, ZZ and VOZ) are physical characteristics of Djallonké/WAD sheep, as described in previous studies [10, 16, 36]. This result suggests that the sheep in the aforementioned zones are closer to the Djallonké sheep. In contrast, specific physical traits of the long-legged Sahelian sheep breed, such as convex facial profile, short hair, and dropped ears orientation, were more common in the sub-populations surveyed in the Northern zones (i.e., BSZ, BNZ, CAZ, and MPZ). Some individuals from the Sahelian sheep breed presented a bicolored coat (the front being brown or black and the rear white), mainly in Mekrou-Pendjari (MPZ). These characteristics are specific to Fulani sheep, also known as Oudah. Notably, in these Northern zones, some of the long-legged Sahelian sheep breed’s physical characteristics were also observed in crossbreeding products between Sahelian and West...
African Dwarf sheep. This distribution of sheep populations along the South-North gradient was confirmed by the results of the multiple correspondence analysis for qualitative physical traits. This finding could be explained either by the increasing introgression of Sahelian long-legged sheep from the Sahel through transhumance and trade or by the selection pressure for specific traits. The mobility of herders with diverse sheep breeds in West Africa could favor genetic introgression and be a dynamic factor of animal genetic diversity. According to a recent report on sheep transhumance between Niger and Benin [37], transhumant sheep herders move from Niger towards localities of the Alibori department in North Benin and stay for about six months to ensure feeding and watering of their animals. Therefore, many exchanges are made between transhumant and local breeders favoring the mixture of Sahelian or long-legged type sheep (i.e., Oudah, Bali-Bali, and Balami) with WAD sheep. The distribution gradient could also result from an adaptive response to changing local environments since morphological adaptations (body size and shape, coat and skin color, and hair type) are physical changes in the animal that enhance its fitness in a given environment [38, 39].

The multivariate discriminant analyses confirmed the significant morphological variability among sheep from most of the 10 phytogeographic zones of Benin. The proximity between sheep from CZ, PoZ, and BZ and their farness from those of VOZ, MPZ, BNZ, BSZ, CAZ, ZZ, and PlZ (Fig 3) could be explained by the geographic proximity and exchange of animals, as well as by similarities or dissimilarities in their ecologies [7]. Nonetheless, the low proportion of individuals from CAZ (55.4%) and BNZ (64.5%) correctly classified in their origin groups, as well as the low values of Mahalanobis distance between these two zones, revealed some overlap among sheep breeds of these phytogeographic zones with those from other zones except for BZ, PoZ, CZ, and VOZ. These overlaps could be the result of crossbreeding, especially in the BNZ and CAZ phytogeographic zones that host transhumant sheep flocks. Additionally, the subdivision of the sheep population into four sub-populations in the hierarchical cluster analysis (Fig 4) seems to reflect differences in the type of vegetation, climate, and humidity among phytogeographic zones. This result is likely to confirm the effect of environmental factors on the morphology of sheep [40–43] and transhumance and management practices. Many convergences with other reports on the measured morphological traits were found in the current study. For example, the mean values of the two quantitative body linear traits, WH and HG, obtained for the sheep from the Southern zones (i.e., PlZ, ZZ, and VOZ), (53.2±3.40 cm and 60.9±1.67 cm, respectively), were highly similar to previously reported values (52.3 ± 1.07 cm and 65.0 ± 1.60 cm, respectively) for the Djallonké/WAD sheep in Nigeria [44], and to the WH mean value of 56.5± 0.22 cm reported for the Djallonké/WAD sheep in Burkina Faso [31]. Therefore, the sheep sub-population found in these zones appeared to be an ecotype of the Djallonké sheep (WAD). Likewise, the mean value of these traits (HW and HG) obtained for the sheep from PoZ, CZ and BZ (52.9±5.07 cm and 73.6±3.72 cm, respectively) were highly similar to those (54.6 ± 8.23 cm and 74.7 ± 8.28 cm, respectively) reported for the Djallonké/WAD sheep in Togo [36]. Thus, the sheep from PoZ, CZ, and BZ might represent another ecotype of Djallonké/WAD sheep with a size relatively larger than the first sheep sub-group of PlZ, ZZ, and VOZ. As for the sheep population from MPZ, which is dominated by individuals with physical characteristics of the Sahelian long-legged sheep, the mean value of WH obtained in the current study (i.e., 68.4±0.47 cm) was similar to that (69.1 ± 0.12 cm) reported for the Sahelian sheep in Burkina Faso [31]. The mean values of WH and HG for the sheep from BNZ, CAZ, and BSZ (61.2±0.92 cm and 68.9±0.90 cm, respectively) were intermediate between those for the sheep from MPZ and each of the two other groups of Southern zones (PlZ, ZZ, and VOZ; PoZ, CZ, and BZ) (Figs 3 and 4), suggesting that these zones may be considered as very favorable zones for crossbreeding. This result also suggests the co-existence of several sheep morphotypes in these zones.
This study highlights a highly diverse sheep population in Benin, as in other African countries (e.g., Burkina Faso, Ivory Coast, Togo, and Nigeria), within which the distribution of individuals is affected by natural and also anthropogenic factors. Thus, the sheep subgroups observed in the different phytogeographic zones of Benin also exist in other African countries in similar or different environments [16, 31, 36, 44]. The most important natural factors at the origin of the recorded sheep diversity across the 10 investigated phytogeographic zones might be climate-related factors (temperature, humidity, and/or vegetation cover), which affect the availability of feed resources and induce natural selection pressures. Anthropogenic factors mainly concern animal management practices in different zones, cultural preferences, and livestock marketing systems. Thus, the phenotypic traits (small size, stocky appearance, small ears, and long hair) of the Djallonké/WAD sheep, which are predominantly found in Southern Benin, are likely a response to natural selection over several generations under the influence of the constraints of the environment in which the animals are raised. Furthermore, the larger phenotypic traits of the Djallonké ecotype in the PoZ, CZ, and BZ could be explained, in addition to the influence of the environment, by changes in sheep farmers’ breeding practices in these phytogeographic zones, especially the practice of crossbreeding short-legged with long-legged animals from the North. This is undoubtedly influenced by the annual flow of Sahelian animals to these regions during the Aid El-Kebir cultural ceremonies when sheep sacrifice takes place in Muslim households. In addition, the breeders of these areas would try to adapt to new consumer demands, as expressed by their preference for animals that possess larger physical features than the Djallonké during ceremonies and festivals. Likewise, the Sahelian sheep, which are predominant in the MPZ in northern Benin, are larger and slender, with varied but predominantly light coats, short hair, a long tail, dropped, and larger ears. Several hypotheses about the adaptive value of these traits have been put forth. For instance, [45] argue that these specific traits might allow them to reflect solar radiation better, and thus, to be less prone to heat stress. In addition, according to these authors their long legs might predispose them to travel long distances when searching for pastures. Moreover, their large height might allow them to feed easily in tree and shrubs savannah pastures, which are predominant in these regions [22, 23]. But confirmation of these hypotheses requires further study and remains inconclusive.

The BNZ and CAZ, with their intermediate climatic gradient between the humid south and the dry north, promote, on the one hand, the extension of the distribution area of the Sahelian types, and on the other hand, the cross-border sheep transhumance practices that are at the origin of the admixture of sub-populations observed in these two zones. Referring to transhumance, it is worth noting that during the migratory period, and to meet their own subsistence needs, transhumant shepherders often sell or exchange a few heads of animals in their herds for food and salt [37]. In contrast, the attraction of certain sheep farmers for large animals in areas hosting transhumant herds sometimes encourages them to herd their animals to the same grazing areas in the hope of mating their animals with those kept by the transhumant herders.

Although morphological variation is largely under genetic control [30], it is subject to the influence of the environment and management practices [46, 47]. Thus, the preservation of local populations that adapt to their environment is essential. This calls for the development of new management strategies for sheep farming in Benin as well as in other African countries aiming to improve farm profitability by improving animal performance while preserving the diversity within the local sheep populations. In this way, sheep farming would overcome current and future challenges in production systems in Africa, including climate change and market demand.

**Conclusion**

This study aimed to explore the morphological variability of indigenous sheep reared in different phytogeographic zones of Benin. The results showed significant variations in phenotypic
traits, both qualitative and quantitative, among phytogeographic zones. Four sheep sub-populations were identified. Animals in the phytogeographic zones of Southern Benin could be identified as short-legged (Djallonké/WAD) sheep, whereas those from the zones located in the northern regions of the country were much closer to the long-legged Sahelian sheep breed. The intermediate sub-populations included an ecotype of Djallonké/WAD sheep and various crossbreeds. These results could be due to several factors, such as adaptation of animals or natural selection, changes in farmers’ breeding practices, and gene flow. Further research is ongoing to better understand the genetic, environmental, and socio-economic determinants of these recorded morphological variations. Thereafter, a breeding program could be developed and implemented for better management of the diversity existing between and within recorded sheep sub-populations and for the sustainable production of this livestock species in Benin.

Supporting information
S1 Fig. Djallonké ewe and lambs.
(TIFF)

S2 Fig. Djallonké ram.
(TIFF)

S3 Fig. Sahelian ewe.
(TIFF)

S4 Fig. Sahelian ram.
(TIFF)

S5 Fig. Crossbreed ewe.
(TIFF)

S6 Fig. Crossbreed ram.
(TIFF)

S1 Table. Least squares means (LSmeans), standard errors (SEs) and coefficients of variation (CVs) of morphological measurements (cm) across phytogeographic zones.
(PDF)

S2 Table. Least squares means (LSmeans) standard errors (SEs) and coefficients of variation (CVs) of morphological indices across phytogeographic zones.
(PDF)

S3 Table. Incidence of phytogeographic zones and number of parity on the type of parity.
(PDF)

S1 Database.
(XLSX)

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References

1. Boutrais J, Duteurtre G, Faye B. L'élevage, richesse des pauvres; stratégies d'éleveurs et organisations sociales face aux risques dans les pays du Sud. J. Afr. 2014; 84(2):306–309. French.

2. Food and Agriculture Organization. The Second Report on the State of the World’s Animal Genetic Resources for Food and Agriculture, edited by B.D. Pilling. FAO commission on Genetic Resources for Food and Agriculture Assessments. Rome, Italy; 2015. Available from: http://www.fao.org/3/a-i4787e/index.html.

3. Dossa LH, Rischkowsky B, Birner R, Wolny C. Socio-economic determinants of keeping goats and sheep by rural people in southern Benin. Agric. Hum. Values. 2008; 25, 581–592. https://doi.org/10.1007/s10460-008-9138-9

4. Food and Agriculture Organization. La situation mondiale de l’alimentation et de l’agriculture: Le point sur l’élevage. Organisation des Nations unies pour l’alimentation et l’agriculture, FAO, Rome, Italy; 2009.

5. Zewdu E, Haile A, Tibbo M, Sharma AK, Sölkner J, Wurzinger M. Morphological characterization of Bonga and Horro indigenous sheep breeds under smallholder conditions in Ethiopia. Eth. J. Anim. Prod. 2009; 9(1):117–133.

6. Yaye Abdou H, Dayo G-K, Issa M, Mani M, Idi I, Marichatou H. Etude des pratiques d’élevage des moutons Peulh du Niger: le Peulh blanc et le Peulh bicolore. Int. J. Biol. Chem. Sci. 2019; 13(1): 83–98. French. https://doi.org/10.4314/jbcs.v13i1.f8

7. Melesse A, Banerjee S, Lakew A, Mersha F, Hailemariam F, Tsegaye S, et al. Morphological characterization of indigenous sheep in southern Regional State, Ethiopia. Anim. Genet. Resour. Inf. 2013; 52: 39–50. https://doi.org/10.1017/S207863612000513

8. Diaha-Kouame ACA, Tian-Bl TYN, Yao KP, Achi YL, Dupraz M, Kouakou K, et al. Apport de la morphométrie géométrique dans la lutte contre Rhipicephalus (Boophilus) microplus (Canestrini, 1888) sur le couloir de transhumance Ivoir-Burkinabé. Int. J. biol. chem. sci. 2018; 11(6): 2630–2648. French.

9. Molina-Flores B, Manzano-Baena, P, Coulibaly MD. The role of livestock in food security, poverty reduction and wealth creation in West Africa. FAO, Accra, Ghana; 2020. https://doi.org/10.4060/eb985en.
10. Wilson RT. Small ruminants production and the small ruminants genetic resources in tropical Africa. Anim. Prod. Health Paper 88. FAO, Rome, Italy; 1991. 231 pp.
11. Meyer C. Races d'ovins, de caprins et de caméliens: aires de répartition en Afrique [Diaporama]. In: Mémento de l’agronome. CIRAD, GREM, France-MAE. Montpellier: CIRAD, 1 CD-Rom ISBN 2-86844-130-0; 2002. 17pp.
12. Gbangboche AB, Hornich JL, Adamou-N’diaye M, Edorh AP, Fanir F, Abiola FA, et al. Caractérisation et maîtrise des paramètres de la reproduction et de la croissance des ovins Djallonké (Ovis amin aries). Ann Méd Vét. 2005; 149: 170–182. French.
13. Epstein H. The origin of the domestic animals of Africa Volume I. Africana Publishing Corporation. New York. London. Munich; 1971. pp. 201–204.
14. Food and Agriculture Organization (FAO). Sub regional report on animal genetic resources: North and West Africa. Annex to The State of the World’s Animal Genetic Resources for Food and Agriculture. Rome, Italy; 2007.
15. Mason IL. Classification and distribution of goat breeds. In: Maijala K. ed., Genetic resources of pig, sheep and goat. Amsterdam, The Netherlands. Elsevier. 1991, pp. 405–411.
16. N’Goran KE, Kouadja GS, Kouassi NC, Loukou NE, Eka JY, Dayo GKC, et al. Caractéristiques phe notypiques des ressources génétiques de moutons et chèvres du sahel au Niger par analyse des indices de primarité et des paramètres qualitatifs. Anim Genet Resour. 2014; 54;21–32. French. https://doi.org/10.1017/S207863614000046
17. Doutresoule G. L'élevage en Afrique Occidentale Francaise. Larose, Paris, France; 1947. pp. 298.
18. Rombaut D, Van Vlaenderen G. Le mouton Djallonké de Côte-d'Ivoire en milieu villageois : Comportements et alimentation. Rev. élev. méd. vét. pays trop. 1976; 29 (2): 157–172. French. https://doi.org/10.19182/remvt.189362
19. Vallerand F, Branckaert R. La race ovine Djallonké au Cameroun: Potentialités zootechniques, conditions d'élevage, avenir. Rev. élev. méd. vét. pays trop. 1975; 28 (4): 523–545. French. PMID: 1230890
20. CIRAD. Les races ovines et caprines de l'Afrique occidentale europé. Conférence de LUKNOW. 13–22 Février 1950. pp. 193–201. Available from: https://agritrop.cirad.fr/433550/1/ID433550.pdf
21. Food and Agriculture Organization (FAO). Phenotypic characterization of Animal Genetic Resources. FAO Animal Production and Health Guidelines No. 11. FAO, Rome, Italy; 2012. Available from: www.fao.org/docrep/015/i2686e/i2686e00.pdf
22. Adomou AC. Vegetation patterns and environmental gradient in Benin: Implications for biogeography and conservation. PhD thesis, University of Wageningen. 2005. Available from: https://edepot.wur.nl/121707
23. Sinsin B, Kampmann D. Biodiversity Atlas of West Africa, Volume I: Benin. Cotonou and Frankfurt/Main; 2010. https://doi.org/10.1186/1746-4266-6-12 PMID: 20302642
24. QGIS. QGIS Geographic Information System. Version 3.8 Zanzibar [Software]. 2021. Available from: https://qgis.org/tr/site/download.
25. Food and Agriculture Organization (FAO). Caractérisation phénotypique des ressources génétiques animales. Directives FAO sur la production et la santé animales No. 11. Rome, Italy; 2013.
26. Ali TM. A manual for the primary animal health care worker. Food and Agriculture Organization (FAO); 1994.
27. Chacón J, Macedo F, Velázquez F, Paiva SR, Pineda E, Manus M. Morphological measurements and body indices for Cuban Creole goats and their crossbreds. Rev. Bras. Zootec. 2011; 40(8): 1671–1679. https://doi.org/10.1590/S1516-35982011000800007
28. Crimella C, Barbieri S, Giuliani MG, Zecchini M. Body measurements and morphological indexes of a cattle population in the Adamawa region (Cameroon). Ital. J. Anim. Sci. 2003; 2:sup1, 243–253. https://doi.org/10.4081/ijas.2003.11676005
29. Bourzat D, Souvenir Zafindraona P, Lauvergne JJ, Zeuh V. Comparaison morpho-biométrique de chèvres au Nord Cameroun et au Tchad. Rev. élev. méd. vét. pays trop. 1993; 46 (4): 667–674. French. https://doi.org/10.19182/remvt.9423.
30. Dossa LH, Wolny C, Gauly M. Spatial variation in goat populations from Benin as revealed by multivariate analysis of morphological traits. Small Rumin. Res. 2007; 73: 150–159. https://doi.org/10.1016/j.smallrumres.2007.01.003
31. Traoré A, Tamboura HH, Kaboré A, Royo L, Fernandez I, Álvarez I, et al. Multivariate characterization of morphological traits in Burkina Faso sheep. Small Rumin. Res. 2008; 80(1–3): 62–67.
32. Mani M, Marichatou H, Issa M, Chaibou I, Sow A, Chaibou M, et al. Caractéristiques phénotypiques de la chèvre du sahel au Niger par analyse des indices de primarité et des paramètres qualitatifs. Anim Genet Resour. 2014; 54: 21–32. French. https://doi.org/10.1017/S207863614000046
33. Bene S, Nagy B, Nagy L, Kiss B, Polgár JP, Szabó F. Comparison of body measurements of beef cows of different breeds. Arch. Anim. Breed. 2007; 50: 363–373. https://doi.org/10.5194/aab-50-363-2007

34. Salako AE. Application of morphological indices in the assessment of type and function in Sheep. Int. J. Morphol. 2006; 24 (1), 13–18. http://doi.org/10.4067/S0717-95022006000100003

35. Popoola MA, Oseni SO. Multifactorial discriminant analysis of cephalic morphology of indigenous breeds of sheep in Nigeria. Slovak J. Anim. Sci. 2018; 51 (2): 45–51.

36. Dayo G-K., Alfa E., Talaki E., Soedji K., Sylla S., Dao B. Caractérisation phénotypique du mouton de Vogan du Togo et relation avec le mouton Djallonké et le mouton sahelien. Anim. Genet. Resour. 2015; 56, 63–78. https://doi.org/10.1017/S207863361500003X

37. PASEL7. Concertations transfrontalières pour une transhumance apaisée: L’expérience réussie de la région de Dosso au Niger et du département d’Alibori au Bénin; 2018. Available from: https://veterinairessansfrontieres.be/mediatheque/concertations-transfrontalières-pour-une-transhumance-apaisée/

38. Chedid M, Jaber LS, Giger-Reverdin S, Duvaux-Pontier C, Hamadeh SK. Review: Water Stress in Sheep Raised under Arid Conditions. Can. J. Anim. Sci. 2014; 94 (2): 243–257. https://doi.org/10.4141/cjas2013-18.

39. Berihulay H, Abied A, He X, Jiang L, Ma Y. Adaptation Mechanisms of Small Ruminants to Environmental Heat Stress. Animals. 2019; 9(3): 1–9. https://doi.org/10.3390/ani9030075 PMID: 30823364

40. Gizaw S, Van Arendonk JA, Komen H, Windig JJ, Hanotte O. Population structure, genetic variation and morphological diversity in indigenous sheep of Ethiopia. Anim. Genet. 2007; 38(6): 621–628. https://doi.org/10.1111/j.1365-2052.2007.01659.x PMID: 18028516

41. Desta TT, Ayalew W, Hegde BP. Breed and trait preferences of Sheko cattle keepers in southwestern Ethiopia. Trop Anim Health Prod. 2010; 43(4): 851–856. https://doi.org/10.1007/s11250-010-9772-2 PMID: 21181495

42. Rauw WM, Gomez-Raya L. Genotype by environment interaction and breeding for robustness in livestock. Front. Genet. 2015; 6:1–15. https://doi.org/10.3389/fgene.2015.00310 PMID: 25674101

43. Ahozonlin MC, Dossa LH, Dahouda M, Gbangboche AB. Morphological divergence in the West African shorthorn Lagune cattle populations from Benin. Trop Anim Health Prod. 2020; 52(2): 803–814. https://doi.org/10.1017/s11250-019-02071-1 PMID: 31617051

44. Agaviezor BO, Peters SO, Adefenwa MA, Yakubu A, Adebambo OA, Ozoje M, et al. Morphological and microsatellite DNA diversity of Nigerian indigenous sheep. J. Anim. Sci. Biotechnol. 2012; 3(1):1–16. https://doi.org/10.1186/2049-1891-3-3-38 PMID: 22958360

45. Gaughan JB, Sejian V, Mader TL, Dunshea FR. Adaptation strategies: ruminants. Anim. Front. 2019; 9 (1): 47–53. https://doi.org/10.1093/af/vfy029 PMID: 32002239

46. Mirkena T, Duguma G, Haile A, Tibbo M, Okeyo M A, Wurzinger M, et al. Genetics of adaptation in domestic farm animals: A review. Livest. Sci. 2010; 132(1–3): 1–12. https://doi.org/10.1016/j.livsci.2010.05.003

47. Leroy G, Besbes B, Boetcher P, Hoffmann I, Capitan A, Baumung R. Rare phenotypes in domestic animals: unique resources for multiple applications. Anim. Genet. 2015; 47(2): 141–153. https://doi.org/10.1111/age.12393 PMID: 26662214