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MORPHOMETRIC AND NUTRITIONAL ASSESSMENT OF KOMODO DRAGONS (*Varanus komodoensis*, Ouwens 1912) ON KOMODO ISLAND: IMPLICATIONS FOR SIZE VARIATION AND CONSERVATION

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Abstract. The study employed purposive sampling, selecting eight Komodo individuals who were sampled using manual restraint methods by trained field personnel. The parameters assessed included morphometric data, such as main body weight, extremities and tail, along with nutritional status. This study analyzed 18 morphometric parameters from eight adult Komodo individuals using both descriptive and inferential methods, including correlation, regression and allometric analyses. Data were analyzed using descriptive statistics, Pearson's and Spearman's rank correlations, allometric coefficients and the Body Condition Index (BCI). The results revealed significant variations in body mass, total length and body circumference, with a pattern of positive allometric growth for most variables. A strong correlation between body mass, body length and tail girth was observed, indicating a relationship between body size and predation strategy, as well as spatial dominance. The analysis of nutritional status identified ventral total body length as the primary predictor of Komodo's nutritional condition, making it a practical indicator for field monitoring. These findings highlight the potential of morphometric parameters as noninvasive tools for assessing population health. The conservation implications of this study emphasize the importance of ongoing morphometric monitoring to detect changes in nutritional status, support habitat management and enhance the effectiveness of adaptive conservation strategies.

Keywords: *Varanus komodoensis, morphometrics, allometry, nutritional status, Komodo National Park.*

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1. Introduction

The Komodo dragon (*Varanus komodoensis*, Ouwens 1912), the largest extant lizard species, belongs to the family Varanidae and is endemic to Indonesia (Böhme,

2003). It exists in eight known subpopulations: three isolated groups on the islands of Longos and Ontoloe in Flores and five within Komodo National Park, comprising Komodo Island, Rinca Island, Padar Island, Nusa Kode and Gili Motang (Jessop *et al*., 2021). The species is currently listed as vulnerable on the IUCN Red List and is protected under Appendix I of the CITES Convention, highlighting its high conservation priority (Jessop *et al*., 2021; Shelley & Metz, 2023).

Morphometric traits, such as body length, mass and head and limb dimensions, provide quantitative measures of growth, health and ecological adaptation in reptiles (Andrews, 1982; Harlow *et al*., 2010). In Komodo dragons, these measures also serve as bioindicators of habitat quality, prey availability and anthropogenic disturbance (Jessop *et al*., 2021; Purwandana *et al*., 2016).

Body condition indices (BCIs), derived from body mass-length relationships, are widely applied as non-invasive proxies for health and fitness and are closely linked to survival and reproduction (Jakob *et al*., 1996; Labocha & Hayes, 2012).

Komodo Island, home to a dense and genetically important population of *V. komodoensis* (Purwandana *et al*., 2014), presents distinctive ecological features compared to nearby islands such as Rinca.

Ecological differences in topography, vegetation and human activity, including tourism, may influence morphometric and nutritional attributes of Komodo dragons (Imansyah *et al*., 2008). Understanding these patterns is essential for conservation management, including population monitoring and habitat protection (Ariefiandy *et al*., 2015; Jones *et al*., 2020).

Although substantial research has been conducted on the ecology, behavior and conservation status of Komodo dragons, systematic analyses of morphometric variation and its relationship to body condition remain scarce. In particular, no study has evaluated which morphometric parameters best predict BCIs in wild populations. Bridging this gap is essential for understanding phenotypic variation and guiding conservation strategies.

2. Materials and Methods

Ethical Approval

This study involved the handling of protected wildlife species and was therefore subject to national ethical and legal requirements. Prior to fieldwork, ethical clearance was obtained from the Animal Care and Use Ethics Committee of the National Research and Innovation Agency, under approval number 016/KE.02/SK/01/2024. All procedures were conducted in compliance with established animal welfare standards and observer behavior was standardized to minimize handling time and reduce stress to the animals.

Study Period and Location

Fieldwork was conducted on Komodo Island, one of the largest islands within Komodo National Park, located in West Manggarai Regency, East Nusa Tenggara Province, Indonesia (Figure 1). The island spans approximately 336 km^2, of which 311.5 km^2 constitutes protected Komodo dragon (*Varanus komodoensis*) habitat (Komodo National Park Authority, 2021). The study area included both residential and tourism zones. Data collection was carried out in February 2025, coinciding with the transitional period between the dry and rainy seasons, a time that typically sees increased dragon activity.

Figure 1. Shows the sites designated for data collection on the Komodo Island

Sampling Design and Animal Capture

Komodo dragons were located and sampled from two distinct habitat types: (1) Human-associated areas, defined as zones near settlements where dragons frequently traverse established paths and (2) Tourism areas, zones routinely visited by tourists for wildlife viewing.

At each site, four adult individuals were purposively selected, regardless of sex, using a capture-mark-release-recapture (CMRR) protocol. While the CMRR method is typically used for population estimation, in this study, it was applied solely to avoid repeat sampling of the same individuals across locations or time points.

Captures were conducted following the standard operating procedures outlined in the Ecological and Wildlife Monitoring Manual for Komodo National Park (Jessop *et al*., 2007). Manual restraint was used instead of trapping, given the ease of locating Komodo dragons at the designated sites. The capture team comprised a minimum of seven trained personnel, each assigned a specific role: securing the head, restraining the limbs, controlling the tail and performing measurements and documentation. Dragons were subdued using a lasso technique, ensuring minimal physical struggle and injury.

The inclusion criteria required that each individual be visibly healthy, free from injury or deformity and suitable for full morphometric assessment.

Morphometric Measurement

Once safely restrained, each dragon was subjected to a detailed set of morphometric measurements, including: Body Mass (BM) recorded in kilograms, Ventral Total Body Length (VTBL) from snout to tail tip along the ventral midline, Snout-Vent Length (SVL) from snout to cloacal opening, Head Dimensions, head length (HL) and width (HW), Forelimb and Hindlimb Measurements, right and left upper arm (RAL/LAL), lower arm (RFOL/LFOL), femur (RFL/LFL) and tibia (RTL/LTL), Body Girth Measurements, chest

circumference (CC), body circumference (BC) and hip circumference (HC), Tail Measurements, total length (TL) and tail base circumference (TC).

All length measurements were recorded in centimetres, using a flexible measuring tape and a dial caliper with a precision of 0.1 mm. Body mass was measured using a portable digital scale, in accordance with standard field zoology techniques (Harlow *et al*., 2010). Measurement sites were anatomically defined and standardized across individuals to ensure accuracy and reproducibility (Figure 2).

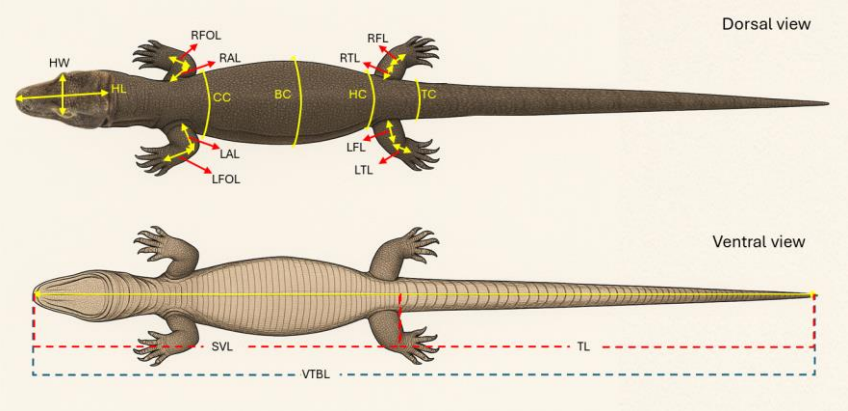

Figure 2. The parts of the Komodo dragon's body that were measured morphometrically

Data Analysis

Morphometric data were analyzed using descriptive and inferential statistical methods. Descriptive statistics included calculation of the mean, standard deviation and range of values. Before conducting the analysis, the data were evaluated for regression assumptions such as linearity, normality and homoscedasticity using diagnostic plots (residual vs. fitted, Q-Q plot) and the Shapiro-Wilk test. To examine the relationships among morphometric parameters, Pearson correlation analysis was conducted with a 95% confidence interval using the critical value of the Pearson Correlation Coefficient ($r = 0.707$, $n = 8$) (if the data distribution was normal) and Spearman rank correlation (if the data distribution was not normal). The allometric coefficient (b) was calculated using log-log regression with the following interpretations: $b \approx 1$ indicates isometry (proportional growth), $b > 1$ indicates positive allometry (where weight increases faster than length) and $b < 1$ indicates negative allometry (where weight increases more slowly than length). The R^2 value indicates the predictive strength of one variable for another.

Assessment of Nutritional Status

The nutritional status of Komodo dragons was assessed using the Body Condition Index (BCI) through a regression residual approach. The BCI for a given species is indicative of the animal's condition by evaluating the correlation between body mass and body length (Jakob *et al*., 1996; Labocha *et al*., 2014). In this study, in addition to analyzing the relationship between body mass (BM) as the dependent variable (Y) and body length (VTBL, SVL) as the independent variable (X), we incorporated additional morphometric variables as predictors, specifically HL, RFL, LFL and TC. This relationship was modeled using the general allometric equation ($Y = aX^b$), with the parameters a (intercept) and b (slope) determined through linear regression based on the log-transformed equation ($\log_{10}Y = \log_{10} a + b \log_{10}X$). The residuals derived from this

model were used as indicators of nutritional status: a positive residual (+) implies that an individual is heavier than anticipated (suggesting a potentially good/fat condition), whereas a negative residual (–) implies that an individual is lighter than anticipated (suggesting a potentially thin/poor condition). All statistical analyses were performed using Microsoft Excel Office 365 and XLSTAT software version 2016.02.28451 (License ID: 34463000).

3. Results and Discussions

Morphometrics, a scientific discipline focused on quantifying the shape and size of organisms, plays a crucial role in various aspects of animal biology, such as species identification, growth assessment and evaluation of the health status of populations (James Rohlf & Marcus, 1993). In Komodo dragons, morphometric differences among individuals are shaped by variables such as age, sex, environmental factors and food availability (Jessop *et al*., 2006; Purwandana *et al*., 2021). Although sexual dimorphism in Komodo dragons has been extensively researched (Harlow *et al*., 2010; Ariefiandy *et al*., 2015), specific morphometric parameters such as BM, VTBL, SVL, HL, HW, RAL/LAL, RFOL/LFOL, RFL/TFL, RTL/LTL, CC, BC, HC, TL and TC have not been documented in previous studies. In the present study, however, sexing of individuals was not feasible and age could not be reliably determined in the field; therefore, part of the observed variation may reflect sex- or age-related differences rather than ecological or nutritional factors. Such data are instrumental in describing the phenotypic diversity and individual growth patterns within a population (Herrel *et al*., 1998).

Body Size of the Komodo dragon

In the present study, morphometric data were obtained from eight adult Komodo dragons irrespective of sex. These measurements provide a preliminary description of body size variation among the sampled individuals (Table 1).

Table 1. Comparison of Morphometric Variables among Komodo dragon Individuals

Variables	Mean	Min	Max	Standard Deviation
BM (kg)	82.04	62.30	120.00	19.95
VTBL (cm)	278.90	249.40	314.00	18.06
SVL (cm)	139.74	133.00	152.30	7.38
HL (cm)	23.38	20.65	34.42	4.49
HW (cm)	11.25	9.91	12.60	0.84
RAL (cm)	12.51	10.00	15.00	1.59
LAL (cm)	12.25	10.00	14.00	1.58
RFOL (cm)	19.03	16.00	23.00	2.26
LFOL (cm)	19.03	17.00	21.00	1.67
CC (cm)	91.09	82.00	110.20	9.61
BC (cm)	48.59	9.91	152.30	47.95
HC (cm)	67.20	61.00	75.40	5.53
RFL (cm)	19.14	17.00	23.20	2.23
LFL (cm)	18.61	15.00	25.10	3.10
RTL (cm)	19.21	16.00	23.00	2.25
LTL (cm)	19.69	13.00	24.00	3.28
TL (cm)	138.45	115.80	160.30	13.07
TC (cm)	55.10	50.00	66.30	5.86

The sampled Komodo dragons exhibited variability in body mass (BM: 82.04 ± 19.95 kg; range: 62.3-120 kg), ventral total body length (VTBL: 278.90 ± 18.06 cm; range: 249.4-314 cm) and body circumference (BC: 48.59 ± 7.95 cm; range: 9.91-152.30 cm). The average snout-vent length (SVL: 139.74 ± 7.38 cm) was approximately half of VTBL, reflecting the anatomical definition of SVL, which extends only to the cloaca. One individual reached a maximum VTBL of 314 cm, a relatively large size that is rarely encountered in the field.

The observed variability in BC values (Table 1) was primarily due to the significant expansion and contraction of the abdominal cavity during the respiratory phases of inspiration and expiration. As it was not feasible to fully control the respiratory cycles during field measurements, the BC values were notably affected by the specific breathing phase of each subject, resulting in substantial variation. Such fluctuations are commonly documented in morphometric studies of large reptiles and mammals, where the thoracoabdominal girth is particularly sensitive to the respiratory state at the time of measurement.

Other morphometric traits, such as head length (HL), head width (HW), arm length (RAL, LAL), forelimb length (FOL), chest circumference (CC), hip circumference (HC), foot length (RFL, TFL), tail length (RTL, LTL) and tail circumference (TC), showed comparatively smaller variation among sampled individuals. Although the limbs (arms and legs) varied only slightly in size, bilateral symmetry was consistently observed between right and left sides.

The current morphometric data underscore the variability in body size among the sampled Komodo dragons, with BM and VTBL exhibiting the greatest ranges. The observation of one exceptionally large individual (VTBL = 314 cm) is noteworthy, as such sizes are infrequently encountered in field studies. Conversely, head dimensions, limb lengths and tail measurements showed limited variation, indicating relative proportional stability in these body regions. However, given that the analysis was restricted to only eight individuals, these findings should be considered preliminary. The variability observed here may not represent the full spectrum of morphometric diversity within the Komodo Island population. Instead, the results serve as pilot data, offering an initial reference point for understanding the body size variation in this species. Larger studies across different populations are necessary to validate and expand upon these preliminary observations.

Correlation Analysis of Morphometric Traits in Komodo Dragons

Correlation analysis of 18 morphometric variables in Komodo dragons revealed several associations between primary body size indicators (BM, TL, SVL and VTBL) and other anatomical measurements. Most of these associations exhibited strong, positive and statistically significant correlation coefficients (Figure 3). Diagnostic evaluation confirmed that the assumptions of normality were satisfied. The Shapiro-Wilk test verified that the residuals did not significantly deviate from normality ($p > 0.05$), with the exception of the associations between the following variable pairs: VTBL-HL, HL-RAL, HL-LAL, HL-RFOL, HL-LFOL, HL-RTL, HL-LTL, HW-TC, RAL-RFOL, RAL-LFOL, LAL-RFOL, RFOL-LFOL, RFOL-CC, CC-BC, RFL-TC, LFL-TC and RTL-LTL. Consequently, associations between variables that did not deviate from normality were analyzed using Pearson's correlation, whereas those that did were analyzed using Spearman's rank correlation. The research findings indicated that the observed associations were strong despite the small sample size. Owing to the limited sample size,

these coefficients may be exaggerated and should be regarded as preliminary and descriptive patterns rather than definitive evidence.

Association of Body Weight with Dimensions of Other Body Parts

In the sampled individuals, body weight (BM) exhibited a tendency to covary with variables such as VTBL (r = 0.88), SVL (r = 0.96), HL (r = 0.80), TL (r = 0.67), TC (r = 0.99), RFL (r = 0.87) and LFL (r = 0.87). These trends suggest a strong association between body mass and the major linear body dimensions. For instance, SVL was positively correlated with RFL, LFL and TC, indicating a potential influence of body length on limb and tail circumference. This pattern aligns with the general framework of ontogenetic allometry, in which different body parts scale relative to overall size. Ecologically, Komodo dragons experience ontogenetic shifts in habitat and feeding strategies; juveniles are more arboreal and insectivorous, whereas adults are terrestrial predators of large animals (Purwandana *et al*., 2016). The tendency toward a larger body size in adults may thus facilitate prey capture and competitive dominance, although confirmation necessitates studies with broader sampling.

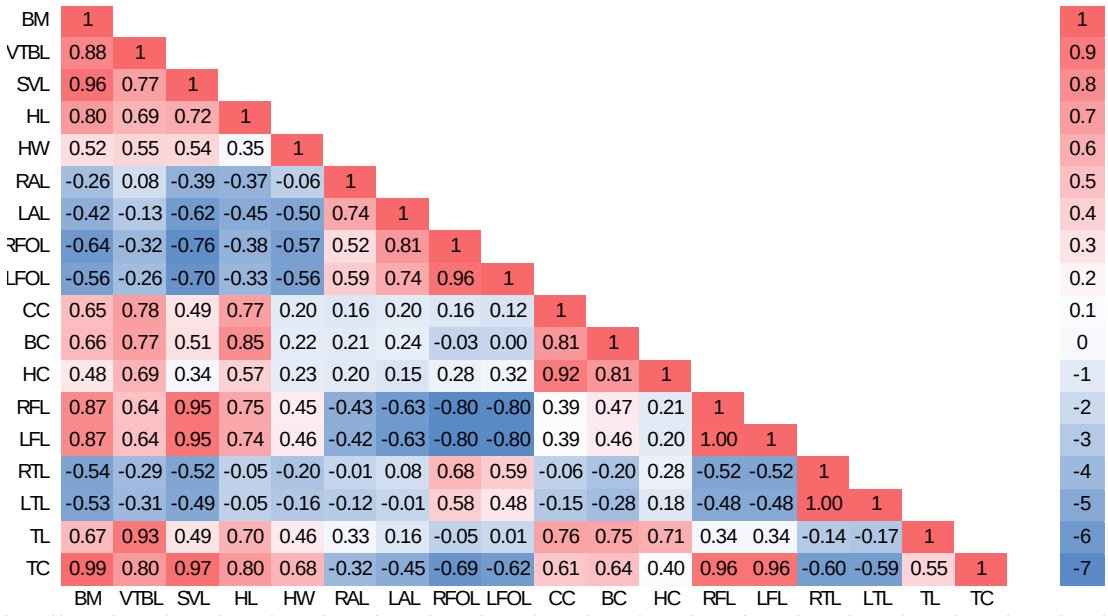

Figure 3. The relationships among the morphometric variables of Komodo dragons

Growth Coordination of Head Size and Main Body Dimensions

Head length (HL) demonstrated moderate to high correlations with BM (r = 0.80), SVL (r = 0.72), CC (r = 0.77), BC (r = 0.85), RFL (r = 0.75), LFL (r = 0.74), TL (r = 0.70) and TC (r = 0.80) (Figure 3). These associations indicate that head proportions scale with the overall body size of sampled Komodo dragons. The stronger correlation between HL and BC/CC may reflect the functional demands related to bite force and feeding capability. Previous research has documented that head size can vary by sex and age (Auffenberg, 1981; Laver *et al*., 2012), with males typically developing larger and more robust heads and females tending to have relatively smaller and more elongated heads. Such variations have been associated with sexual dimorphism and reproductive strategies (Purwandana *et al*., 2014). While our findings appear consistent with these observations, they remain preliminary because of the limited sample size.

Association of Limb Dimensions with Locomotion Strategies

Measurements of paired traits, such as RAL–LAL, RFOL–LFOL, RFL–LFL and RTL–LTL, demonstrated nearly perfect correlations, indicating a pronounced bilateral symmetry among the sampled individuals. For instance, the correlation between RFL and LFL was nearly perfect ($r \approx 1.00$) (Figure 3), suggesting coordinated growth between the right and left limbs of the same individual. This observation aligns with the broader reptilian patterns of limb integration, which are essential for maintaining stability during locomotion (Christian & Garland, 1996). Considering the substantial body mass and terrestrial lifestyle of the Komodo dragon, proportional limb growth likely facilitates effective locomotion and prey-pursuit (Akbar *et al*., 2023). However, these findings should be regarded as preliminary indications rather than definitive biomechanical conclusions.

Negative Correlation between Forelimb and Hindlimb Dimensions

A negative correlation was identified between forearm length (RFOL/LFOL) and overall extremity length (RFL/LFL, RTL/LTL) ($r \approx -0.80$) (Figure 3). This pattern may indicate a biomechanical compensation mechanism, wherein the elongation of one segment is counterbalanced by a reduced proportional investment in another segment. Such a mechanism could contribute to supporting a large body mass while facilitating short bursts of locomotor performance, as opposed to sustained running (Tomańska *et al*., 2025). Although this potential compensatory pattern is intriguing, it necessitates validation using larger datasets.

Contribution of Tail and Limb Morphology to Overall Body Structure

Tail circumference (TC) demonstrated positively correlated with upper limb dimensions, specifically RFL ($r = 0.96$) and LFL ($r = 0.96$) (Figure 3). Anatomically, the base of the tail is intricately connected to the pelvic region and limb girdle, functioning as a structural pivot for balance, communication and defence. A robust tail also facilitates energy storage within the adipose tissue and contributes to body stabilization during locomotion or predatory actions (Tomańska *et al*., 2024; Stawinoga *et al*., 2024). These correlations suggest functional integration between tail and limb morphology; however, the limited sample size restricts the ability to draw definitive conclusions.

Allometry

Allometry describes the disproportionate growth relationship between various body components and the overall size of an organism, typically represented by log-log regression and coefficient b (Fauzia *et al*., 2024; Mangalam *et al*., 2024). Diagnostic evaluation confirmed that the assumptions of linearity, normality and homoscedasticity were satisfied. In the current dataset, log-log regression analysis indicated variations in the estimated allometric coefficient (b). These coefficients were derived from regression models incorporating morphometric predictors (HL, RFL, LFL, CC, BC, TL and TC), which demonstrated positive associations ($r \geq 0.70$) and linier with primary response variables (BM, VTBL and SVL) (Figure 4).

In models that used BM as the response variable, most coefficient values exceeded 1 ($b > 1$), indicating a propensity for positive allometry. For instance, in the BM–SVL ($b = 4.27$), BM–VTBL ($b = 3.09$) and BM–TC ($b = 2.19$) relationships, the body mass appeared to increase at a faster rate than the body length or other linear dimensions. This pattern aligns with the hypothesis that mass gain may surpass length growth, potentially

associated with ontogenetic niche shifts in Komodo dragons, wherein older individuals adopt a more sedentary and ambush-based predatory strategy (Purwandana *et al*., 2016). BM response to certain morphometric traits may suggest relatively rapid growth in specific body parts, potentially enhancing body mass, strength and dominance (Stroud *et al*., 2023). A similar inclination toward positive allometry was observed in the limbs and head of the sampled lizards, which may reflect the functional requirements for strength and endurance (Feldman *et al*., 2016).

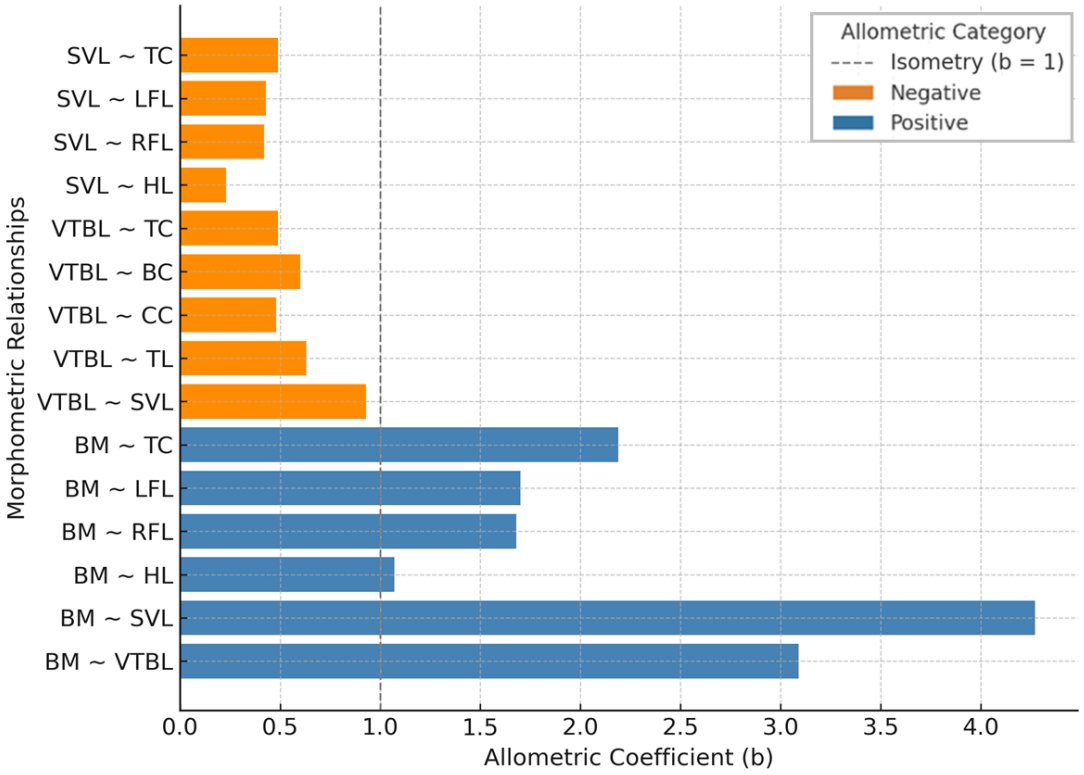

Figure 4. Allometric coefficients from log-log regressions reveal Komodo morphometric relationships and growth patterns

In contrast, negative allometry (b < 1) was observed in several relationships, such as SVL–HL (b = 0.23) and VTBL–TC (b = 0.49), indicating that the head and tail dimensions increased at a slower rate relative to the body length. These patterns may be associated with biomechanical efficiency, as disproportionately long tails or large heads can compromise balance and movement efficiency. The relatively slower growth of head length may also reflect functional adaptation to dietary and behavioral changes with age (Deeming, 2022). In younger Komodo dragons (≤ 20 kg), previous studies have documented that body length growth surpasses mass gain, resulting in slender body forms that are advantageous for arboreal movement and predator avoidance (Purwandana *et al*., 2016). This is in contrast to certain arboreal reptiles, such as *Sceloporus formosus*, where proportional (isometric) growth in VTBL supports balance and locomotion, which are also associated with sexual selection (Pérez-Quintero *et al*., 2019).

The limbs of Komodo dragons, specifically their arms and legs, exhibit positive allometry (b > 1). The relatively larger dimensions of the upper arm, compared to water monitors, may be attributed to variations in hunting strategies and burrow construction (Akbar *et al*., 2023). Positive allometry in limb growth has been extensively documented

in Varanus species and is considered crucial for supporting body weight, enhancing mobility and facilitating predation (Christian & Garland, 1996; Cieri *et al*., 2020; Iijima & Kubo, 2019).

The axial regions encompassing the head and tail demonstrated slower relative growth, indicating functional specialization. A relatively shorter and broader head may enhance the bite force, thereby improving the ability to subdue large prey (Herrel *et al*., 2001, 2002; Openshaw & Keogh, 2014). Similar patterns of positive allometry in head and limb dimensions have been observed in other Varanus species, where they likely contribute to biomechanical stability at larger body sizes (Iijima & Kubo, 2019; Openshaw & Keogh, 2014).

The observation of b values less than 1 for CC and BC indicates that the trunk dimensions of the sampled Komodo dragons expanded at a slower rate relative to their body length. This phenomenon may suggest an energy-efficient body morphology that minimizes the energetic costs associated with movements (Andrews & Pough, 1985). Conversely, herbivorous reptiles, such as turtles, typically exhibit more rapid growth in trunk girth to accommodate larger digestive systems in accordance with the German-Bell principle (Franz *et al*., 2011).

Allometric Patterns and Model Fit

Allometry refers to the disproportionate growth relationship between body components and overall size, typically quantified using log–log regression and the scaling coefficient b (Fauzia *et al*., 2024; Mangalam *et al*., 2024). In the current dataset, log-log regression indicated variation in the allometric coefficient among all Komodo morphometric variables. For instance, the BM–SVL (b = 4.27), BM–VTBL (b = 3.09) and BM–TC (b = 2.19) models demonstrated positive allometry, in which body mass increased at a faster rate than linear body dimensions. Conversely, certain relationships, such as SVL–HL (b = 0.23) and VTBL–TL (b = 0.63), exhibited negative allometry, indicating that the head and tail lengths increased more slowly relative to the trunk length.

The coefficient of determination (R^2) offers valuable insights into the adequacy of these models. Certain regressions demonstrated relatively high R^2 values, such as BM–TC (R^2 = 0.96) and SVL–TC (R^2 = 0.95), indicating that the tail circumference accounted for a substantial proportion of the variation in mass and snout-vent length within the sample. In contrast, SVL ~ HL (R^2 = 0.52) exhibited a lower explanatory power, suggesting that head length alone was not a robust predictor of snout vent length.

Collectively, these patterns indicate heterogeneity in the growth trajectories of different body regions. Mass and limb dimensions generally exhibited positive scaling, whereas axial traits such as head and tail length demonstrated slower growth. These variations may reflect the biomechanical constraints and ecological adaptations observed in Komodo dragons and related Varanid lizards (Purwandana *et al*., 2016; Cieri *et al*., 2020). However, given the limited sample size (n = 8), these findings should be considered exploratory and interpreted with caution until corroborated by larger data sets.

Nutritional Status

A Komodo dragon morphometric study demonstrated a notable internal correlation, particularly between body length and body mass measurements. This correlation underscores the potential utility of the Body Condition Index (BCI) as a tool for assessing the nutritional status of Komodo dragons by linking body mass to linear body dimensions. In the context of BCI, the residuals from the logarithmic regression analysis indicate

individual deviations from the "expected" body mass based on their linear body size. Positive residuals suggest a superior body condition, reflecting good nutrition, whereas negative residuals imply a body mass that is lower than anticipated, indicating poor nutrition.

Nutritional assessment of Komodo dragons was performed using Body Condition Index (BCI) methodology. This approach involved calculating the residuals from a logarithmic regression analysis, where body mass (log BM) served as the dependent variable and various morphometric measurements were used as predictors. The allometric model incorporated several linear predictors, including the VTBL, SVL, HL, RFL, LFL and TC, as illustrated in Figure 5.

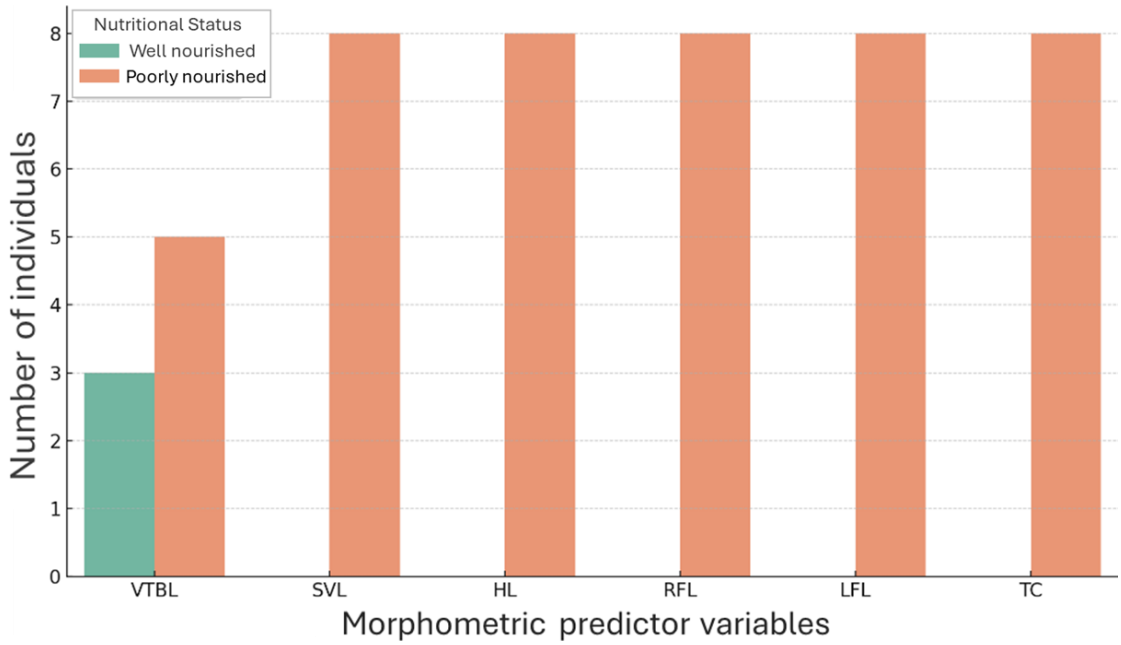

Figure 5. Nutritional status assessed using morphometrics and BCI, with body mass as response

A study of the Body Condition Index (BCI) in Komodo dragons, through regression analysis, revealed that most individuals possess negative residual values of body mass logarithms (log BM) when compared to predicted values derived from various morphometric parameters. These residuals, serving as BCI, imply that a significant portion of the population is in a less-than-optimal nutritional state. VTBL emerged as the most potent predictor of logarithmic body mass (R^2 = 0.74-0.94), with a slope (b) of 3.09, indicating positive allometry. This suggests that body mass increases at a rate disproportionate to vertebral length, establishing the VTBL as a dependable metric for evaluating individual conditions across diverse body sizes. In contrast, the model based on snout-vent length (SVL), despite its high correlation coefficient (R^2 > 0.9), exhibited a steep slope (b = 4.27) and resulted in markedly negative BCI values, with numerous individuals displaying actual body mass significantly below the predicted values (exceeding 1.8 logarithmic units). Similar trends were observed in models utilising head length (HL), tail circumference (TC) and forelimb length, which yielded b values < 2.2 and predominantly negative residual distributions (BCI ranging from -2.09 to +0.08). This inclination towards negative BCI distribution may be indicative of ecological pressures, such as limited food availability, habitat degradation or heightened competition among

individuals. Komodo dragons typically maintain stable body conditions even during the dry season (Purwandana *et al*., 2006, 2014), which might explain the observed decline in physiological health in certain studied populations. Although these variations could be attributed to spatial or temporal factors, the persistent pattern of negative residuals across all models necessitates further ecological investigations.

VTBL exhibits a notable ability to differentiate nutritional status among the six morphometric predictors examined, with three individuals identified as "well-nourished" and five as "poorly nourished". Conversely, the other five predictors (SVL, HL, RFL, LFL and TC) produced uniform results, classifying all individuals as "poorly nourished". These observations imply that VTBL serves as a more sensitive and representative predictor for assessing the body condition of Komodos based on BM. This inference is consistent with the foundational theory of allometry and nutritional status evaluation in animals, which asserts that VTBL is strongly and linearly correlated with actual body weight, especially in species with elongated bodies, such as reptiles (Jakob *et al*., 1996; McCaffrey *et al*., 2023; Stevenson & Woods, 2006). For example, in snakes and large monitor lizards, VTBL is considered a more reliable indicator for estimating body energy status than partial linear measurements, such as SVL or HL (Bonnet *et al*., 2001). However, predictors such as HL and TC seem to lack representativeness for estimating nutritional status, potentially due to their limited morphometric variability or misalignment with body mass fluctuations. This may also be attributed to the morphological roles of the head and girth, which are structurally more stable and less susceptible to changes in body energy conditions (Laurie & Brown, 1990; McCaffrey *et al*., 2023).

The results of this study hold considerable importance for the conservation and health management of Komodo dragons. Implementing a VTBL-based BCI methodology can assist in the prompt detection of individuals with suboptimal nutritional status, potentially leading to metabolic disorders, infections or inadequate food consumption in both natural habitats and captivity. In addition, BCI assessment has proven to be a valuable tool for assessing the welfare of Komodo dragons in ex situ conservation initiatives.

This study indicates that the application of a body condition index (BCI), calculated through log-log allometric regression, is an effective method for assessing the nutritional status of Varanus komodoensis. Among the six morphometric variables analysed, VTBL was the most sensitive and discriminating predictor for estimating body mass in relation to size. This capability is crucial for distinguishing Komodo individuals with varying nutritional statuses, which holds significant importance in both ecological and conservation physiological contexts.

From a morphological perspective, VTBL signifies structural growth and development along the body's longitudinal axis, which is particularly significant in ectothermic animals with elongated forms, such as varanids. In reptiles, body mass serves not only as a measure of energy reserves but also as an indicator of ecological adaptations, including prey availability, thermoregulatory efficiency and activity levels (Angilletta *et al*., 2002; Cox *et al*., 2003). Therefore, fluctuations in body mass relative to VTBL are likely to reflect genuine changes in energy reserves, particularly in natural settings with variable prey distributions, such as those found within Komodo National Park.

The inability of variables such as head length (HL), girth (TC) or limb length (RFL, LFL) to distinguish BCI implies that these variables possess lower allometric sensitivity or are constrained by functions not directly linked to body mass variations. This

phenomenon was similarly observed in the head and limb morphometrics of the lizards Sceloporus and Tiliqua. These morphometrics are evolutionarily conservative owing to their roles in prey capture and locomotion, rendering them unsuitable as indicators of energy status (Feldman & Meiri, 2013; Herrel *et al*., 2001; Meiri, 2010). Additionally, these variables demonstrate limited plasticity in response to short-term changes in body conditions, unlike VTBL, which represents cumulative somatic growth throughout ontogeny.

Residual-based body condition indices (BCI), especially those derived through logarithmic transformation, are extensively recognised as effective tools for correcting nonlinear scaling in body dimensions (Green, 2001; Labocha & Hayes, 2012). This technique addresses the shortcomings of simple mass-to-length ratios, which can often lead to incorrect assessments of body conditions in animals with varying allometric growth patterns. Additionally, log-log transformation plays a crucial role in meeting essential statistical assumptions, such as homoscedasticity and linearity. Although individuals with negative residuals in BCI regression might suggest reduced energy reserves, it is essential to recognize that the interpretation of BCI in reptiles is still debated. Such residual variation could also result from morphological differences, reproductive conditions or hydration status, rather than being solely linked to nutritional factors (Green, 2001; Peig & Green, 2009). Therefore, our findings should be regarded as suggestive rather than definitive and future research that includes dietary, ecological and physiological data is required to accurately determine the nutritional status of the Komodo dragons.

Negative residuals in body condition indices (BCI) should not be interpreted solely as signs of inadequate nutrition. As noted by Green (2001), these residual-based indices may also reflect variations in morphology, reproductive status and hydration levels, suggesting that our findings are preliminary rather than definitive. Future investigations might consider employing alternative methods, such as the scaled mass index (Peig & Green, 2009), to provide a more thorough evaluation of body condition.

In the realm of conservation, particularly for endangered species such as the Komodo dragon, accurately assessing body condition is vital for determining habitat quality, food resources and the overall health of populations in both natural and controlled settings. The proficiency of VTBL in identifying nutritional status underscores its potential as a standard tool for monitoring ecological studies, wildlife health evaluations and breeding initiatives in captivity. Future investigations could refine this method by accounting for seasonal and developmental changes, as nutritional status may vary across different life stages or reproductive periods (Wikelski & Thom, 2000).

4. Conclusion

The Komodo population demonstrated significant variability in body size, particularly concerning body weight, total ventral total body length and body circumference, while other measurements showed only slight differences among individuals. The symmetry observed in the right and left extremities was notable. The maximum recorded total ventral total body length of 314 cm and weight of 120 kg in individual Komodos are exceptional and have rarely been documented. Measurements such as body length (VTBL and SVL), head length and tail circumference are effective indicators for estimating the body weight of komodos. The correlation between body dimensions and extremities is not random but is shaped by evolutionary selection

pressures related to the locomotion, hunting and growth functions of this large predator. The allometric patterns in Komodos reflect a blend of ontogenetic growth and ecological adaptations to environmental pressures and functional demands. These allometric dynamics not only highlight morphological diversity but also reveal adaptive strategies that align with Komodo's life stages and ecological behaviours. Systematic collection and analysis of morphometric data are crucial for assessing conservation strategies, especially in light of climate change and tourism impacts in Komodo National Park. Evaluating the nutritional status of Komodos through morphometric data indicates that total ventral total body length is a key predictor. Utilising a BCI approach based on this measurement can aid in the early identification of individuals with poor nutritional status and serve as a valuable method for monitoring the welfare of Komodos in in situ conservation programs.

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Authors' Contributions

MM contributed to the conceptualization, methodology, software development, validation, formal analysis, investigation, writing original draft preparation, review and editing and visualization.

A.S. was involved in the methodology, software development, validation, formal analysis, writing original draft preparation, review and editing, visualization and supervision.

K.S. contributed to formal analysis, resources, data curation, writing original draft preparation and visualization.

N.S. was responsible for methodology, resources, data curation, writing original draft preparation, visualization and supervision.

Y.J.B. contributed to methodology, validation, investigation, writing original draft preparation, review and editing and visualization.

S.A. was involved in project administration and funding acquisition, as well as conceptualization, methodology, resources, data curation, writing original draft preparation, review and editing, visualization and supervision.

Conflict of interest

The authors declare that they have no conflicts of interest.

Data availability

All data are available in the manuscript.

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