



Application of multilayer perceptron neural networks in classifying management effects based on morphometric traits of *Carabus granulatus*

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Morphometric traits are essential tools for understanding the variability of organisms and their responses to environmental conditions. They provide valuable insights into ecological processes, as changes in body size and proportions often reflect adaptations to habitat characteristics and environmental pressures. During the years 2020–2023, we conducted research in 6 study areas falling under three habitats (willow-poplar floodplain forest, poplar nursery, alluvial meadow) in the Danube Floodplains Protected Landscape Area (CHKO Dunajské Luhy). This study examined the variability of nine morphometric characters (body length, body height, body width, head length, head width, pronotum length, pronotum width, right elytron, left elytron) in the ground beetle *Carabus granulatus* Linnaeus, 1758 in relation to management, habitat, and sex. A total of 992 individuals (440 males, 552 females) were analyzed. Individuals from the managed sites showed slightly higher values in body width, head width, and pronotum width, whereas those from unmanaged habitats exhibited greater body length, body height, and elytral length. Generalized linear models revealed that habitat and sex were the main factors influencing morphometric variability, while management had a weaker effect. Habitat significantly affected multiple traits, with lower values observed in more disturbed environments. Sex had a strong influence on most traits, with males consistently smaller than females, confirming sexual dimorphism. A Multilayer Perceptron model demonstrated high classification performance (accuracy = 0.925), indicating that morphometric traits effectively distinguish individuals based on management. Overall, morphometric variability is primarily driven by habitat conditions and sex, with management playing a secondary role. Morphometric traits can be applied in environmental monitoring as sensitive indicators of habitat quality and ecological changes. Their analysis enables more effective assessment of land management practices and supports conservation strategies aimed at maintaining biodiversity and ecosystem stability.

Keywords: Carabidae; *Carabus granulatus*; management; Danube floodplains; Slovakia.

Introduction

Morphometric traits represent a key tool for studying the variability of organisms and their adaptation to environmental conditions. In invertebrates, particularly epigeic beetles of the family Carabidae, body size and proportions are closely linked to ecological functions such as locomotor activity, dispersal ability, reproductive potential, and resource use (Basedow, 1990; Bengtsson et al., 2005). Morphometrics thus enables not only the description of population variability but also the interpretation of ecological processes that shape this variability (Kotze, 2011; Magura et al., 2017).

In recent years, morphometric traits have been increasingly used as sensitive indicators of environmental change, as they respond to environmental conditions more rapidly than changes in species composition (Brygadyrenko & Korolev, 2015). Studies have shown that alterations in land-use intensity, habitat fragmentation, or anthropogenic disturbances can lead to systematic changes in body size and proportions of organisms (Gossner et al., 2016; Seibold et al., 2019). One of the main factors influencing morphometric traits is habitat. Differences in vegetation structure, moisture, temperature, or food availability can significantly affect individual growth and final body size. For example, individuals inhabiting more stable and less disturbed habitats often reach larger sizes, whereas individuals from disturbed or fragmented environments may exhibit smaller body sizes or altered body proportions (Benton et al., 2003; Fahrig, 2003; Hole et al., 2005; Langraf et al., 2025). Moreover, some morphometric traits were found to be linked to physiological and functional characteristics, such

as the ability to accumulate energy reserves or withstand stressful conditions (Parhomenko et al., 2022).

An important factor influencing morphometric traits is sexual dimorphism. This dimorphism can be reflected in various morphometric traits, and its consideration is essential for the interpretation of morphological variability (Fairbairn, 1997; Blanckenhorn, 2005). In epigeic beetles of the family Carabidae, these differences are often expressed in basic morphometric traits, which may reflect different ecological and reproductive strategies of the two sexes (Stillwell et al., 2010). In general, females of many invertebrate species tend to reach larger body sizes than males. This phenomenon is most commonly explained by so-called fecundity selection, i.e., selection favoring larger females that are capable of producing more eggs. Thus, larger body size in females is directly linked to their reproductive success. By contrast, males may be smaller and more mobile, allowing them to search more efficiently for mates and increase their chances of mating (Brygadyrenko & Reshetniak, 2014).

In addition to natural factors, land management also plays an important role. It can influence morphological traits indirectly through changes in habitat conditions such as vegetation structure, food availability, moisture, or microclimate. Studies suggest that individuals from managed sites may exhibit different body proportions compared with individuals from more natural or less disturbed habitats, with these differences often relating primarily to body robustness and the relative dimensions of individual body parts (Ribera et al., 2001).

Morphometric traits do not only reflect current environmental conditions, but also longer-term evolutionary and ecological processes

ses. Variability in body proportions may result from selective pressures that favor certain traits depending on the type of environment, for example, more efficient mobility in open habitats or greater resistance in moist and stable environments (Desender et al., 1994; Kotze et al., 2011; Carbonne et al., 2021).

The species *Carabus granulatus* represents a suitable model organism for the study of morphometric variability, as it is a widely distributed species primarily associated with moist lowland habitats (Putchikov et al., 2019, 2020). Its morphological traits are influenced by local environmental conditions and may reflect differences among populations exposed to varying levels of disturbance or management. Morphometric analysis of this species thus allows for the identification of subtle differences in population responses to environmental changes (Koivula, 2011). The objective of this study was to analyze the variability of morphometric traits of the *Carabus granulatus* in relation to the factors of management, habitat, and sex.

Materials and methods

Between 2020 and 2023, fieldwork was carried out across six selected sampling locations. The study was conducted within the Danube Floodplains Protected Landscape Area (CHKO Dunajské Luhy), an area of European significance situated in western Slovakia. This protected region spans approximately 122.8 km² and is a part of the Alpine-Himalayan system within the Danubian Lowland. From a climatic perspective, the locality is classified as a warm zone characterized by relatively mild winters, with mean summer temperatures around 25 °C and winter averages near -3 °C. The prevailing soil type is clay-loam, developed from sediments deposited by the Danube River.

Within the forest habitat (specifically willow-poplar lowland floodplain) the applied restoration measures included the establishment of new side canals within the Danube Delta, as well as the artificial induction of flooding events twice annually (in spring and summer). By contrast, in open habitats such as poplar plantations and alluvial meadows, different management practices were implemented. These involved mowing vegetation between rows of trees in the poplar stands twice per year (spring and summer), regular annual cutting of meadow vegetation, seasonal inundation of meadow areas once a year, and cattle grazing.

The study areas where the research was conducted were as follows:

1) willow-poplar floodplain forest; 119 metres above sea level; geographic coordinates: 47°54'36.0" N 17°27'51.3" E, without management;

2) willow-poplar floodplain forest; 106 metres above sea level; geographic coordinates: 47°45'17.0" N 17°56'59.9" E, without management;

3) willow-poplar floodplain forest; 115 metres above sea level; geographic coordinates: 47°53'28.5" N 17°28'56.9" E, with management;

4) poplar nursery; 118 metres above sea level; geographic coordinates: 47°53'51.5" N 17°27'25.5" E, with management;

5) poplar nursery; 127 metres above sea level; geographic coordinates: 47°58'22.9" N 17°22'02.9" E, with management;

6) alluvial meadow; 108 metres above sea level; geographic coordinates: 47°45'00.0" N 17°56'09.2" E, with management;

The individuals of *C. granulatus* were sampled using pitfall traps at monthly intervals between April and October over the period 2020–2023. A 4% formalin solution served as the preservative fluid. At each sampling location, five traps were arranged in a linear transect, spaced 10 m apart, forming a total transect length of 40 m. Altogether, 75 pitfall traps were deployed during the study period. Species identification was carried out according to the identification key by Hürka (1996).

For each individual of *C. granulatus*, nine morphometric traits were measured. Measurements were taken using a digital LCD microscope Koolertron (the model ADSM301, manufactured by Shenzhen Andonstar Technology Co., China, in 2017) with an accuracy of 0.1 mm. The morphometric characters were as follows:

1) head length – distance between the labrum and the the juncture of the occiput and postgena;

2) head width – distance between the innermost sides of eyes;

3) pronotum length – measured along the central furrow pronotum;

4) pronotum width – distance between posterior corners of the pronotum;

5) right elytra – distance between posterior end of scutellum and terminus of right elytron;

6) left elytra – distance between posterior end of the scutellum and the terminus of left elytron;

7) body length – the distance from the anterior margin of the clypeus to the end of the elytra;

8) body width – the maximum transverse distance between the lateral margins of the elytra;

9) body height – the maximum dorsoventral thickness of the body at the middle of the elytra.

The effects of management, habitat, and sex on morphometric traits were analyzed using a generalized linear model (GLM). Individual morphometric traits (body length, body height, body width, head length, head width, pronotum length, pronotum width, right elytron, left elytron) were treated as dependent variables, while management, habitat, and sex were included as explanatory variables. Statistical significance was assessed at the $P = 0.05$ level. To complement the analysis, a Multilayer Perceptron (MLP) neural network model was used to classify individuals according to management based on morphometric traits. Model performance was evaluated using accuracy, balanced accuracy, precision, recall, and F1-score. To visualize the differences between the groups, the morphometric traits were standardized (z-scores) and displayed using a heatmap, allowing comparison of traits measured on different scales. The results of the GLM model were visualized using boxplots. All the analyses were performed in Python version 3.12 (2023, Python Software Foundation Legal Statements Privacy Notice).

Results

During the study, we recorded 992 individuals of *C. granulatus* (440 males and 552 females). The individuals from the managed sites showed slightly higher mean values for body width, head width, and pronotum width, whereas the individuals from the unmanaged conditions exhibited somewhat higher mean values for body length, body height, and elytral length (Table 1).

The effects of management, habitat, and sex on the morphometric traits were analyzed using a generalized linear model (GLM). Body length was significantly influenced by all examined variables. The beetles from the unmanaged sites displayed higher values of body length (coef = 0.2271; $P = 0.015$). Habitat showed a strong negative effect, with lower values recorded in poplar nursery (coef = -1.6204; $P < 0.001$) and willow-poplar lowland floodplain forest (coef = -1.1718; $P < 0.001$). Sex also had a significant effect (coef = -0.9062; $P < 0.001$), with males being smaller than females (Fig. 1). Body height was not significantly affected by management (coef = -0.0310; $P = 0.610$) or sex (coef = 0.0861; $P = 0.557$). However, habitat showed a significant negative effect, with lower values in poplar nursery (coef = -0.6079; $P < 0.001$) and willow-poplar lowland floodplain forest (coef = -0.8568; $P < 0.001$, Fig. 2). Body width was not influenced by management (coef = 0.0804; $P = 0.135$) or habitat ($P > 0.05$). Meanwhile, sex had a strong negative effect (coef = -1.0702; $P < 0.001$), indicating that males exhibited lower body width values (Fig. 3). Head length was not significantly affected by management (coef = 0.0012; $P = 0.963$) or habitat ($P > 0.05$). A significant effect was observed only for sex (coef = -0.3124; $P < 0.001$), with males having smaller head length (Fig. 4).

Head width was not influenced by management (coef = 6.953×10^{-5} ; $P = 0.997$) or by habitat in the case of poplar nursery (coef = 0.0109; $P = 0.812$). However, the values were lower in willow-poplar lowland floodplain forest (coef = -0.1681; $P < 0.001$). Sex also had a significant effect (coef = -0.0920; $P = 0.023$), with males being smaller (Fig. 5). Pronotum length was not significantly affected by management (coef = 0.0242; $P = 0.172$). Habitat had a strong negative effect (poplar nursery: coef = -0.1894; $P < 0.001$; willow-poplar lowland floodplain forest: coef = -0.2649; $P < 0.001$), with lower

values compared with the willow-poplar lowland floodplain forest habitat. Sex had a significant effect (coef = -0.1554; $P < 0.001$), with males showing smaller values (Fig. 6).

Table 1
Average values of morphometric characters of *Carabus granulatus*

Management	Male		Female	
	without management	with management	without management	with management
Body length	20.64	20.58	21.33	21.07
Body height	6.86	6.34	7.34	7.10
Body width	4.66	5.31	4.83	5.19
Head length	3.22	3.08	3.20	3.22
Head width	2.10	2.16	2.08	2.16
Pronotum length	3.62	3.63	3.60	3.63
Pronotum width	4.78	4.96	5.01	5.05
Right elytron	12.39	12.68	13.33	13.09
Left elytron	12.39	12.71	13.37	13.12

Table 2
Výsledky GLM model of morphometric character

Morphometric character	Coefficient	SE	z	P
Body length				
Management [without management]	0.2271	0.094	2.428	0.015
Habitat [poplar nursery]	-1.6204	0.255	-6.352	<0.001
Habitat [willow-poplar lowland floodplain forest]	-1.1718	0.223	-5.252	<0.001
Sex [male]	-0.9062	0.226	-4.006	<0.001
Body height				
Management [without management]	-0.0310	0.061	-0.510	0.610
Habitat [poplar nursery]	-0.6079	0.166	-3.671	<0.001
Habitat [willow-poplar lowland floodplain forest]	-0.8568	0.145	-5.916	<0.001
Sex [male]	0.0861	0.147	0.587	0.557
Body width				
Management [without management]	0.0804	0.054	1.493	0.135
Habitat [poplar nursery]	-0.2014	0.147	-1.372	0.170
Habitat [willow-poplar lowland floodplain forest]	0.0629	0.128	0.490	0.624
Sex [male]	-1.0702	0.130	-8.217	<0.001
Head length				
Management [without management]	0.0012	0.027	0.046	0.963
Habitat [poplar nursery]	0.0245	0.073	0.336	0.737
Habitat [willow-poplar lowland floodplain forest]	-0.0122	0.064	-0.190	0.849
Sex [male]	-0.3124	0.065	-4.824	<0.001
Head width				
Management [without management]	6.953e-05	0.017	0.004	0.997
Habitat [poplar nursery]	0.0109	0.046	0.238	0.812
Habitat [willow-poplar lowland floodplain forest]	-0.1681	0.040	-4.221	<0.001
Sex [male]	-0.0920	0.040	-2.277	0.023
Pronotum length				
Management [without management]	0.0242	0.018	1.364	0.172
Habitat [poplar nursery]	-0.1894	0.048	-3.912	<0.001
Habitat [willow-poplar lowland floodplain forest]	-0.2649	0.042	-6.255	<0.001
Sex [male]	-0.1554	0.043	-3.620	<0.001
Pronotum width				
Management [without management]	0.0060	0.025	0.239	0.811
Habitat [poplar nursery]	-0.1878	0.069	-2.732	0.006
Habitat [willow-poplar lowland floodplain forest]	-0.2186	0.060	-3.638	<0.001
Sex [male]	-0.1502	0.061	-2.465	0.014
Right elytron				
Management [without management]	0.1740	0.070	2.483	0.013
Habitat [poplar nursery]	-1.4549	0.191	-7.611	<0.001
Habitat [willow-poplar lowland floodplain forest]	-0.8973	0.167	-5.368	<0.001
Sex [male]	-0.7467	0.170	-4.405	<0.001
Left elytron				
Management [without management]	0.1842	0.070	2.631	0.009
Habitat [poplar nursery]	-1.4774	0.191	-7.737	<0.001
Habitat [willow-poplar lowland floodplain forest]	-0.9765	0.167	-5.848	<0.001
Sex [male]	-0.8176	0.169	-4.829	<0.001

Pronotum width was not influenced by management (coef = 0.0060; $P = 0.811$). Habitat had a significant negative effect (poplar nursery: coef = -0.1878; $P = 0.006$; willow-poplar lowland floodplain forest: coef = -0.2186; $P < 0.001$), with lower values compared with the willow-poplar lowland floodplain forest habitat. Sex also had a significant effect (coef = -0.1502; $P = 0.014$), with males exhibiting smaller values (Fig. 7). Right elytron length was influenced by all the variables. Individuals from unmanaged sites showed higher values (coef = 0.1740; $P = 0.013$). Habitat had a strong negative effect (poplar nursery: coef = -1.4549; $P < 0.001$; willow-poplar lowland floodplain forest: coef = -0.8973; $P < 0.001$), with lower values compared with the willow-poplar lowland floodplain forest habitat. Males exhibited lower values (coef = -0.7467; $P < 0.001$). Similarly, left elytron length was influenced by all factors. Higher values were recorded in unmanaged sites (coef = 0.1842; $P = 0.009$). Habitat had a significant negative effect (poplar nursery: coef = -1.4774; $P < 0.001$; willow-poplar lowland floodplain forest: coef = -0.9765; $P < 0.001$), with lower values compared with the willow-poplar lowland floodplain forest habitat. Males also showed lower values (coef = -0.8176; $P < 0.001$, Table 2).

The GLM analysis showed that the morphometric traits were primarily influenced by habitat and sex, while the effect of management was less pronounced. Habitat had a significant negative impact on several traits, including body length, body height, pronotum length, pronotum width, and the lengths of the right and left elytra, with individuals from poplar nursery and willow-poplar lowland floodplain forest exhibiting lower values. In addition, habitat was also a significant factor for head width in the willow-poplar lowland floodplain forest. Sex was an important factor for most morphometric traits, including body length, body width, head length, head width, pronotum length, pronotum width, and the lengths of the right and left elytra, with males consistently showing lower values than females. By contrast, sex did not influence body height. The effect of management was statistically significant only for body length and the lengths of the right and left elytra, where individuals from unmanaged sites exhibited higher values. The remaining morphometric traits (body height, body width, head length, head width, pronotum length, and pronotum width) were not significantly affected by management. Overall, the results suggest that variability in morphometric traits is primarily determined by habitat conditions and sexual dimorphism, while management plays a secondary role and affects only selected traits.

Using a Multilayer Perceptron (MLP) model, we analyzed morphometric traits (body length, body height, body width, head length, head width, pronotum length, pronotum width, right elytron, left elytron) separately in relation to management, without considering the effects of sex and habitat. Several standard metrics were used to evaluate model performance, allowing a comprehensive assessment of its quality. The overall accuracy reached 0.925, indicating that the model correctly classified approximately 92.5% of all cases, reflecting the proportion of correct predictions. Balanced accuracy reached 0.91, suggesting good performance of the model for both the majority and minority classes. Precision reached 0.95, indicating the proportion of correctly classified cases among all predicted cases. Recall reached 0.94, meaning that the model successfully identified most of the actual positive cases. The F1-score reached 0.98, indicating a very good balance between precision and recall.

The heatmap of standardized morphometric traits reveals clear differences between individuals originating from sites with and without management. Individuals from the managed study areas show higher values particularly for body height, head width, pronotum length, and pronotum width. In other words these individuals are, on average, taller, and have more robust anterior body parts. Slightly higher values can also be observed for some other traits, although these differences are less pronounced. By contrast, lower values in these individuals were recorded for body width, body length, and head length, suggesting a more slender body structure. On the other hand, individuals from unmanaged study areas exhibit the opposite trend. Higher values were observed for body width, body length, head length, and elytral length, indicating an overall more robust and broader body structure. Conversely, lower values were found for body

height, head width, pronotum length, and pronotum width, meaning that these individuals are relatively lower and less “tall” than those from the managed sites. The values of the left and right elytra were balanced between the management types (Fig. 9).

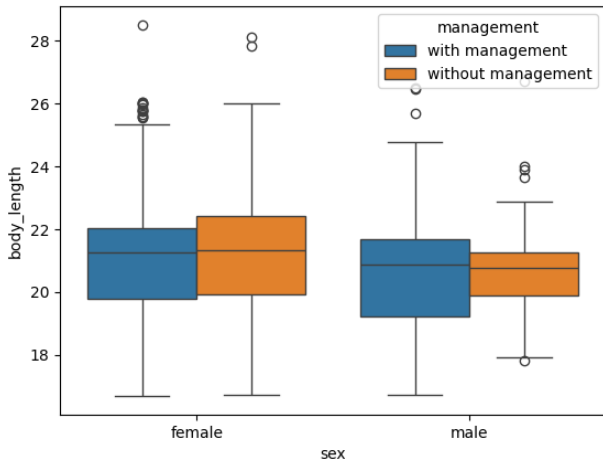


Fig. 1. Differences in body length between management and sex

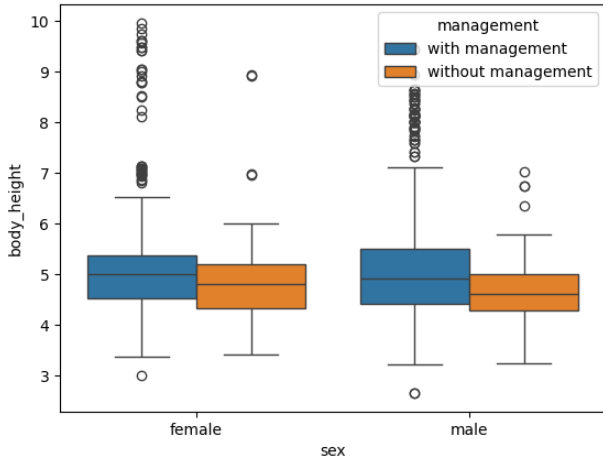


Fig. 2. Differences in body height between management and sex

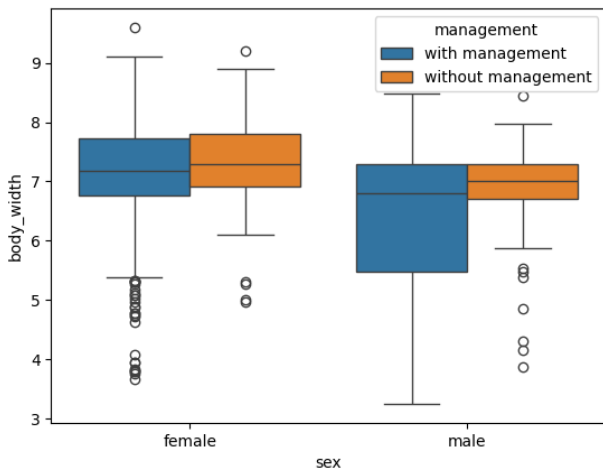


Fig. 3. Differences in body width between management and sex

Discussion

The results of this study confirm that the variability of morphometric traits in *Carabus granulatus* is primarily determined by habitat conditions and sexual dimorphism, while the effect of management is less pronounced. The significant influence of habitat on several traits (body length, body height, pronotum, and elytra) indicates that local environmental conditions play a key role in shaping body size and proportions of individuals. Similar findings were reported by García-

Tejero & Taboada (2016), who demonstrated that changes in habitat structure lead to substantial shifts in arthropod morphological traits, particularly those related to body size. Likewise, Davis et al. (2013) emphasized that human-induced habitat changes can significantly affect functional traits of organisms, including their morphometry.

The negative effect of certain habitats (particularly poplar nurseries and floodplain forests) on the studied traits may be related to lower environmental quality or a higher level of disturbance, leading to restricted individual growth. This trend is consistent with the findings of Ghannem (2017), who reported that fragmented and disturbed environments often produce smaller individuals due to limited resources and increased stress. Similarly, Jelaska & Durbes (2009) noted that ground beetles respond to changes in landscape structure through shifts in body size and ecological strategies.

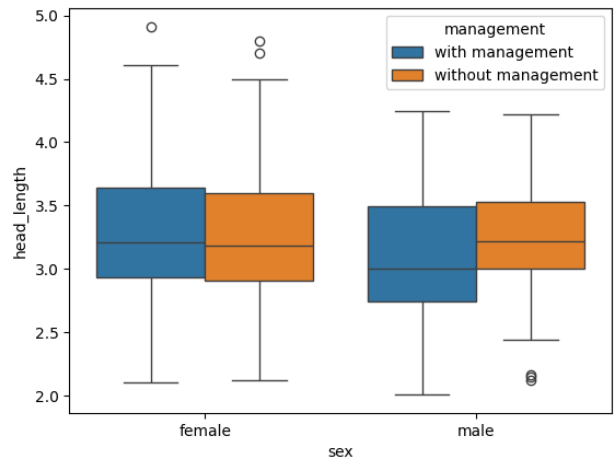


Fig. 4. Differences in head length between management and sex

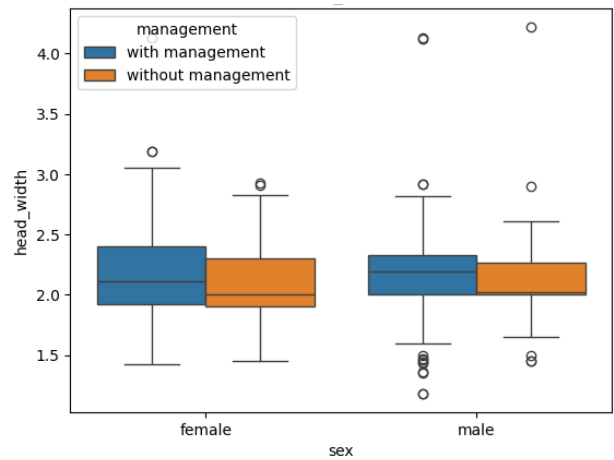


Fig. 5. Differences in head width between management and sex

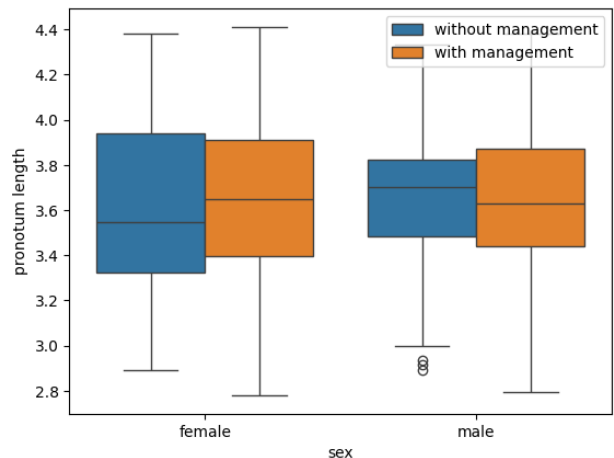


Fig. 6. Differences in pronotum length between management and sex

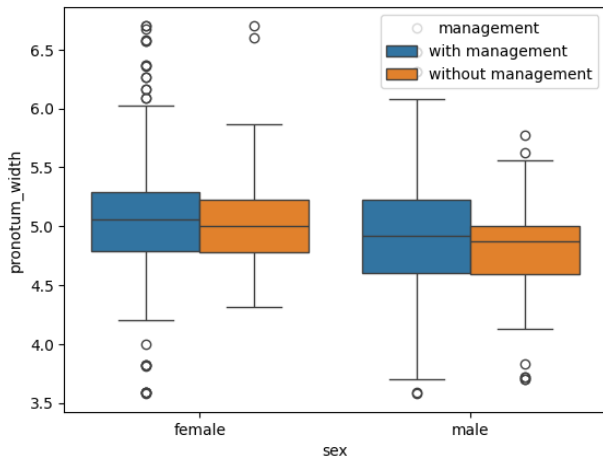


Fig. 7. Differences in pronotum width between management and sex

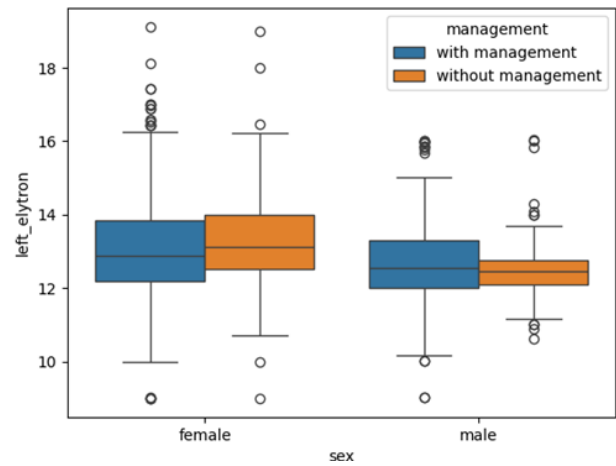


Fig. 9. Differences in left elytron between management and sex

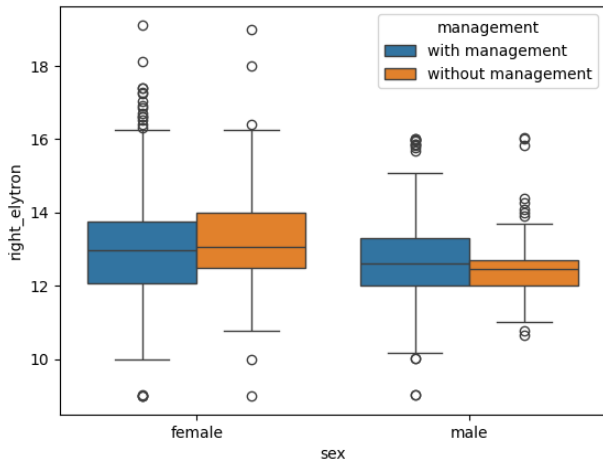


Fig. 8. Differences in right elytron between management and sex

The significant effect of sex on most morphometric traits, with males exhibiting lower values than females, confirms the presence of sexual dimorphism. This phenomenon is widely documented in invertebrates and is often explained by selection for higher reproductive capacity in females. Females achieve greater reproductive success, whereas smaller males benefit from higher mobility; thus, sexual dimorphism results from a combination of ecological and evolutionary pressures (Fairbairn et al., 2007; Eyre & Luff, 2004; Benítez, 2013).

By contrast, the relatively weak effect of management on most traits suggests that short-term or moderate interventions in the landscape may not have an immediate impact on the morphological characteristics of individuals. A significant effect was observed only for body length and elytral length, which may reflect specific responses to resource availability or microclimatic conditions. Similar conclusions were reported by Komlyk & Brygadrenko (2019, 2020), who stated that the morphological response of Carabidae to management is often less pronounced than their response to habitat factors.

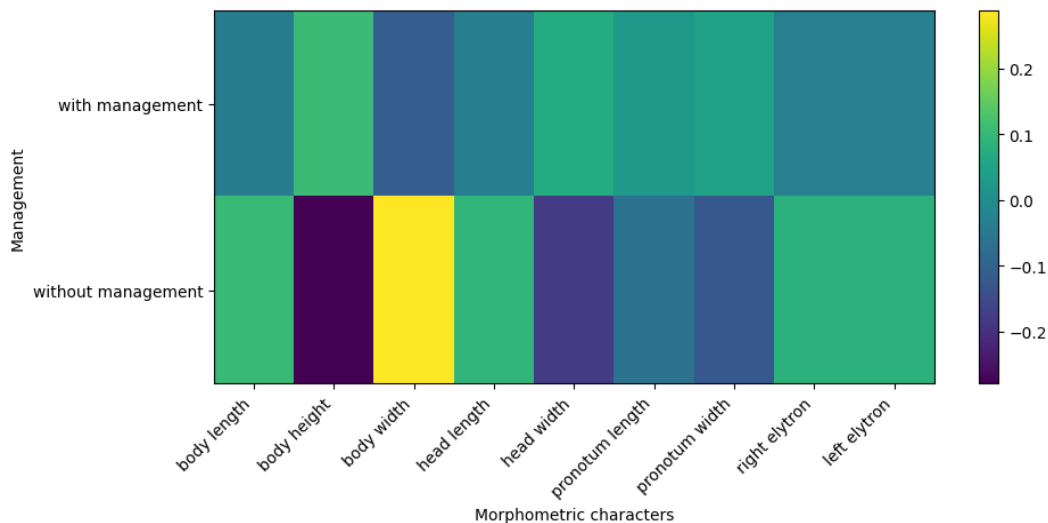


Fig. 10. MLP report comparing morphometric characters between management

The results of the analysis using the Multilayer Perceptron (MLP) model indicate a high potential of morphometric traits for distinguishing individuals of *C. granulatus* from sites with different management regimes. The high model performance (accuracy = 0.925; F1-score = 0.98) suggests that morphometric traits carry important ecological information and can be used as reliable indicators of environmental conditions. Similar conclusions were reported by Sukhodolskaya et al. (2021), who highlighted the importance of functional and morphological traits in assessing landscape changes and emphasized their sensitivity to environmental gradients.

The observed differences between individuals from managed and unmanaged sites (particularly in traits such as body height, pronotum,

and head dimensions) indicate different adaptive strategies depending on environmental conditions. Individuals from managed sites exhibited greater robustness of the anterior body parts, whereas individuals from unmanaged areas showed higher values of overall body length and width, which may reflect differences in resource availability and microclimatic conditions. This trend is consistent with the study by Barton et al. (2011), who demonstrated that changes in land management lead to modifications in functional traits of arthropods, including body size.

The heatmap analysis confirms that morphometric traits respond to environmental conditions, with different groups of traits showing distinct patterns of variability. The greater robustness of individuals

from managed sites may be associated with higher levels of disturbance or more frequent interventions, which favor individuals with more resilient morphology. Meanwhile, individuals from unmanaged sites reach larger body sizes, which may result from more stable conditions and greater resource availability. This phenomenon was also described by Gobbi & Fontaneto (2008), who reported that land-use intensification leads to changes in functional traits of organisms, including body size and proportions.

The results also suggest that individual morphometric traits do not respond uniformly to environmental factors but represent a complex system of organismal responses to a combination of ecological conditions. According to Schirmel et al. (2015) and Ghannem et al. (2017), ground beetles are sensitive bioindicators, and their morphological traits reflect not only current environmental conditions but also longer-term ecological processes.

Overall, it can be concluded that the combination of classical statistical approaches and modern modeling methods, such as MLP, represents an effective tool for studying morphometric variability and its environmental determinants. These approaches enable a better understanding of population responses to environmental changes and support the use of morphometric traits as indicators of habitat quality and the effects of management.

Conclusions

The results of this study confirmed that the morphometric variability of *C. granulatus* is primarily influenced by habitat conditions and sexual dimorphism, whereas the effect of management plays a secondary role. The generalized linear model revealed that most of the analyzed morphometric traits, including body length, pronotum length, pronotum width, and elytral length, were significantly affected by habitat, with individuals from certain habitat types exhibiting lower values. Sex was identified as a significant factor for the majority of the analyzed traits, with females reaching higher values than males, confirming the presence of sexual dimorphism. The effect of management was statistically significant only for selected traits, specifically body length and elytral length, where individuals from unmanaged sites exhibited higher values. The remaining traits were not significantly influenced by management, suggesting that its effect is likely indirect and mainly mediated through changes in habitat conditions. The results of the Multilayer Perceptron (MLP) model further confirmed that morphometric traits contain sufficient information for reliable classification of individuals according to management. The model achieved high performance metrics (accuracy 0.925; balanced accuracy 0.91; precision 0.95; recall 0.94; F_1 -score 0.98), indicating a very good ability to distinguish between groups based on morphometric parameters. These findings support the conclusions of the GLM analysis and suggest that even though the effect of management is not always directly significant for individual traits, it is reflected in the combined variation of multiple morphometric characteristics. From a practical perspective, these results highlight the importance of morphometric analyses as a tool for environmental monitoring. Morphological traits can serve as sensitive indicators of changes in environmental quality and may reveal environmental impacts before they become evident at the level of species diversity. In practice, this implies that effective landscape management should primarily focus on maintaining habitat quality, as these conditions have the most pronounced influence on the morphological variability of populations.

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