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Morphometric differences in ground beetle populations in managed and natural habitats

V. Langraf*, K. Petrovičová**, V. V. Brygadyrenko***, ****

*Constantine the Philosopher University in Nitra, Nitra, Slovakia
**University of Agriculture in Nitra, Nitra, Slovakia
***Oles Honchar Dnipro National University, Dnipro, Ukraine
****Dnipro State Agrarian and Economic University, Dnipro, Ukraine

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Department of Zoology and Anthropology, Constantine the Philosopher University in Nitra, Tr. A. Hlinku, 1, Nitra, 94901, Slovakia. Tel.: +421-910-340-204. E-mail: langrafvladimir@gmail.com

Institute of Plant and Environmental Sciences, University of Agriculture in Nitra, Tr. A. Hlinku, 2, Nitra, 94901, Slovakia. Tel.: +421-915-349-669. E-mail: kornelia.petrovicova@gmail.com

Oles Honchar Dnipro National University, Nauky av., 72, Dnipro, 49010, Ukraine. Tel.: +38-050-93-90-788. E-mail: brigad@ua.fm

Dnipro State Agrarian and Economic University, Serhii Efremov st., 25, Dnipro, 49010, Ukraine. Tel.: +38-050-93-90-788. E-mail: brigad@ua.fm

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The impacts of anthropogenic activity and environmental factors on ecosystems are also reflected in the morphometric variable of ground beetles, based on which we can determine the state of habitat quality. During 2020–2022, we recorded 1,304 individuals belonging to 24 species of ground beetles in forest habitats located in an agrarian landscape and the Dunajské Luhy Protected Landscape Area (important European habitats), using pitfall traps. For each individual, we measured the following morphometric characters: head length, head width, pronotum length, pronotum width, right elytra, and left elytra. Using PCA analysis, we confirmed the connection of morphometric characters to study areas belonging to the Dunajské Luhy Protected Landscape Area. Based on the flight ability of ground beetles under different land use conditions, we found that morphometric variability is greater in agrarian landscape conditions compared to the Dunajské Luhy Protected Landscape Area. In habitats exposed to higher anthropogenic impact, ground beetles do not have their food optimum, and there is greater variability in morphometric characters. On the contrary, the habitats in the Dunajské Luhy Protected Landscape Area provided sufficient food supply and a stable environment, so the variability was lower. We also found higher median values in this area, which indicates larger individuals compared to habitats in the agrarian landscape. For the preservation of habitats of European importance, it is important to determine the interactions between the ecosystem and species from the Carabidae family, which are important bioindicators of the environment.

Keywords: Carabidae; Dunajské Luhy; diversity; agrarian landscape; morphometric characters; variability.

Introduction

Morphometric variability refers to the differences in the shapes and sizes of body structures of organisms. In ground beetles, this variability is key to understanding their adaptations to different ecological conditions and can serve as an indicator of environmental change. It also represents a key aspect of their ecology, evolution, and adaptation to different environmental conditions. This variability reflects not only genetic factors, but also environmental influences, such as changes in soil properties, urbanisation, and agricultural practices (Schirmel et al., 2015; Elek et al., 2022).

Morphometric variability in Carabidae is intricately linked to a multitude of environmental variables, including soil properties, urbanisation, microclimatic conditions, and geographic factors. Understanding these relationships is essential for understanding beetle ecology, assessing the impacts of environmental changes, and informing conservation strategies. Morphometric responses of ground beetles to environmental variables indicate their adaptive mechanisms and ecological significance (Davis et al., 2014; Cadotte & Tucker, 2017). Environmental conditions profoundly impact the morphometric traits of ground beetles. Soil chemistry, for example, plays an significant role. Research indicates that soil magnesium (Mg), manganese (Mn), total nitrogen (N), and pH levels are strongly correlated with variations in ground beetle morphometry. Industrial and agricultural activities that alter these soil properties can lead to notable changes in beetle size and shape, reflecting the adaptability to modified habitats (Fountain-Jones et al., 2014; Sun et al., 2023). Soil characteristics, including salinity, moisture content, and nutrient composition, significantly impact the morphometry of ground beetles. Studies have shown that soil salinization affects morphological variability, with implications for development and reproductive success (Komlyk & Brygadyrenko, 2020).

Morphometric assessments in ground beetles are essential for understanding their ecological roles and adaptive strategies. Variations in body dimensions can influence dispersal abilities, predation efficiency, and habitat preferences. For example, larger body sizes may confer advantages in predation and competitive interactions, while smaller sizes might enhance survival in resource-limited environments. Furthermore, morphometric analyses can serve as bioindicators, reflecting habitat stability and environmental health. Studies have shown that changes in morphometric variables of ground beetles indicate the state of biotopes, particularly in response to anthropogenic activities such as forestry, agriculture, and urbanisation (Brandmayr & Talarico, 2021; Ornaghi et al., 2023).

Analysing morphometric traits in Carabidae is essential to understand their ecological adaptability and evolutionary responses to environmental pressures. Variations in body dimensions can affect dispersal abilities, predation strategies, and habitat preferences, making morphometric studies crucial for assessing the impact of environmental changes on beetle populations. For example, changes in morphometric variables and the ellipsoidal biovolume of ground beetles have been linked to biotope stability, influenced by anthropogenic activities such as forest, agriculture, and urbanization. Urbanisation introduces habitat fragmentation and environmental stressors that influence the morphometric profile of ground beetles. Studies along urban–suburban–rural gradients have observed a decrease in the average ellipsoid biovolume (EV) and other morphometric characteristics (length, height, and width) of ground beetles moving from rural to urban areas. This trend suggests that urban environments can favor smaller-bodied individuals, possibly due to factors such as habitat fragmentation and altered microclimates (Sukhodolskaya & Saveliev, 2016; Langraf et al., 2020). Morphometric variability can also occur on microgeographical scales, reflecting localized adaptations. Research by Alivert et al. (2001) has demonstrated significant morphological differentiation among populations separated by short distances. These variations are often attributed to factors such as habitat heterogeneity and limited gene flow, underscoring the importance of fine-scale environmental influences on morphological traits.

Morphometric traits serve as valuable indicators of habitat disturbance and ecosystem health. In protected areas, assessing the morphological variability of invertebrates, particularly ground beetles, can reveal the impact of environmental changes. Variations in body length, coefficients of variation, and morphometric indices can signal shifts in population dynamics and habitat quality, helping conservation efforts (Parhomenko et al., 2022).

Morphometric variability in ground beetles offers deep insight into their adaptive strategies, ecological roles, and responses to environmental changes. By examining variations in body size and shape, researchers can infer the impacts of factors such as soil chemistry, urbanisation, and habitat disturbance (Cvetkovska-Gjorgjievska et al., 2017). Morphometric variability in Carabidae is intricately linked to a multitude of environmental variables, including soil properties, urbanisation, microclimatic conditions, and geographic factors. Understanding these relationships is essential to understand beetle ecology, assessing the impacts of environmental changes, and inform conservation strategies. Ongoing research on the morphometric responses of ground beetles to environmental variables continues to shed light on their adaptive mechanisms and ecological significance (Porhajašová et al., 2018; Gobbi, 2020).

In this paper, we evaluate changes in morphometric characters (head length, head width, pronotum length, pronotum width, right elytra and left elytra) and flight ability in ground beetles in the conditions of an agricultural landscape and the Dunajské Luhy PLA.

Materials and methods

During three years (2020–2022), we collected ground beetles in six study areas in forest habitats and willow-poplar floodplain forest and regenerating poplar forests. Three study areas fell under the agrarian landscape and the other three under the Dunajské Luhy Protected Landscape Area. We placed five pitfall traps in each study area, arranged in a line and with a distance of 10 m between each pitfall trap. We collected the obtained material at regular monthly intervals and used 4% formaldehyde solution as a fixative. The species were determined and the nomenclature was adjusted according to Hůrka (1996). The first three study areas (1–3) were within an area of intensive agriculture. The following agricultural crops were grown in the vicinity of the studied forest stands: *Zea mays* L., *Brassica napus* L., *Medicago sativa* L. and *Triticum aestivum* L. Climatically, the area is characterised by a very dry climate with dry winters. The soil type is fluvisol cultismecarbonate. The study areas are (Fig. 1):

1) willow-poplar floodplain forest: 110 metres above sea level; geographic coordinates: 47°54’40” N 18°01’19” E;

2) willow-poplar floodplain forest: 111 metres above sea level; geographic coordinates: 47°55’29” N 17°59’42” E;

3) regenerated poplar forest: 109 metres above sea level; geographic coordinates: 47°55’32” N 17°59’52” E.

Study areas (4–6) fell under the Danube Floodplains Protected Landscape Area, which is part of the "Natura 2000" list, which includes the most endangered habitats in Europe. Climatically, the area is dominated by a very dry climate with dry winters. The type of soil is carbonate floodplain sediments or clay-loamy river soil. The investigated study areas are (Fig. 2):

4) willow-poplar floodplain forest: 114 metres above sea level; geographic coordinates: 47°53’3” N 17°30’25” E;

5) willow-poplar floodplain forest: 115 metres above sea level; geographic coordinates: 47°53’29” N 17°28’57” E;

6) regenerated poplar forest: 118 metres above sea level; geographic coordinates: 47°53’52” N 17°27’26” E.

We measured the following morphometric character using a Koolerton (model: ADSM301, Company: Shenzhen Andonstar Technology Co., Country: China,year 2017) LCD digital microscope (accuracy 0.1 mm):

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.

Using principal component analysis (PCA), we determined the correspondence of morphometric characters (head length, head width, pronotum length, pronotum width, right elytra, left elytra) with study areas (agrarian landscape – 1–3; Dunajské Luhy Protected Landscape Area – 4–6) in the Canoco5 programme (Ter Braak & milauer, 2012).

In Python 3.12. we tested the normality of the distribution of the data of the measured morphometric characters using the Shapiro-Wilk (SW) test. We tested the differences between flight ability and land use in morphometric characters using the Kruskal-Wallis test.

Fig. 1. Study areas 1–3 in agrarian landscape

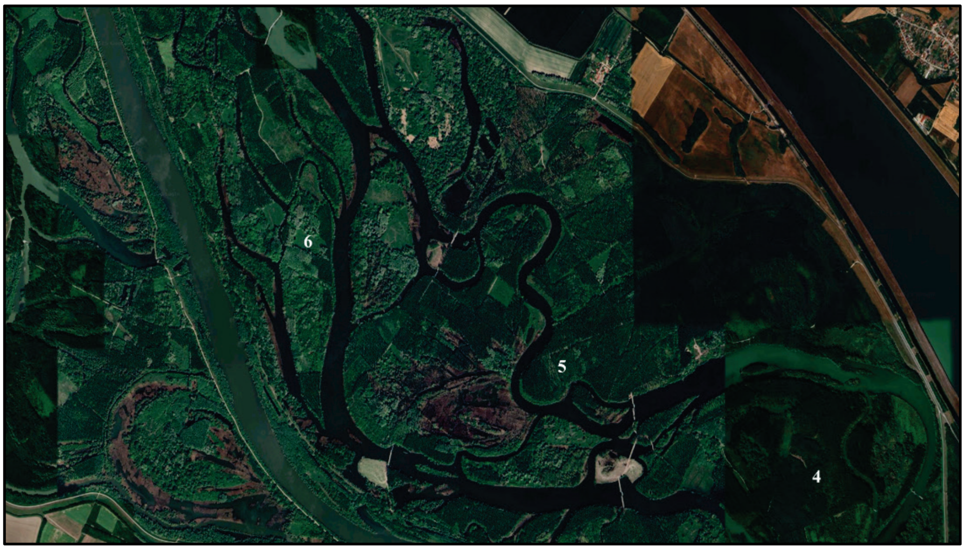

Fig. 2. Study areas 4–6 in Danube Floodplains Protected Landscape Area

Results

In total, we recorded 1,304 individuals belonging to 24 taxa in the areas studied. We confirmed 18 macropterous species, 3 apterous and brachypterous species. We confirm the eudominant representation in the species *Pseudoophonus rufipes* (28.5%), *Carabus granulatus* (25.0%), *Pterostichus niger* (15.6%). The average values of the studied morphometric characters studied in the detected species are listed in Table 1.

By principal component analysis (PCA, SD = 2.2 on the first ordination axis) we expressed the relationship of morphometric characters (head length, head width, pronotum length, pronotum width, right eaves, left eaves) to study areas (1–6). The explained variability in the samples was 88.8% on the first ordination axis and 99.6% on the second cumulative ordination axis. From the results of the analysis we see a closer relationship of these morphometric characters with study areas 5 and 6 belonging to the Dunajské Luhy Protected Landscape Area. This relationship points to a more stable environment and less variability in the morphometric character data. The ground beetle species had a better food optimum in these study areas and therefore their morphometric characteristics were similar (Fig. 3).

The Shapiro-Wilk (SW) test confirmed the violation of the normality of the data distribution (P = 0.00001) for all morphometric characters. Based on this, we used the nonparametric Kruskal Wallis test, which confirmed a significant difference between land use for head length (P = 0.0199, Fig. 4), pronotum length (P = 0.0163, Fig. 5), right elytra (P = 0.05, Fig. 6) and left elytra (Fig. 7). We did not confirm a significant difference for head width (P = 0.7028, Fig. 8) and pronotum width (P = 0.4915, Fig. 9).

A significant difference between flight ability (A – apterous, B – brachypterous, M – macropterous) in the agrarian landscape was confirmed for head length (P = 0.0057), head width (P = 0.0099), pronotum length (P = 0.0066), pronotum width (P = 0.0269), right elytra (P = 0.0121) and left elytra (P = 0.0115). In the conditions of the Dunajské Luha Protected Landscape Area, we confirm a significant difference between flight ability for head length (P = 0.0397), head width ($P = 3.0*10^{-8}$), pronotum length (P = 0.00001), pronotum width (P = 0.0047), right elytra (P = 0.0095) and left elytra (P = 0.0114).

Table 1
Recorded species with average values of morphometric characters

Species	Flight ability	Number of individuals	Head length	Head width	Pronotum length	Pronotum width	Right elytra	Left elytra
Amara aenea (De Geer, 1774)	M	12	1.02	1.10	1.91	2.91	4.88	4.90
Amara familiaris (Duftschmid, 1812)	M	35	1.19	1.11	2.08	3.39	5.59	5.57
Amara ingenua (Duftschmid, 1812)	M	37	1.09	0.88	1.75	2.64	4.43	4.42
Amara saphyrea Dejean, 1828	M	23	1.63	1.16	2.12	3.40	5.29	5.30
Amara similata (Gyllenhal,1810)	M	6	1.19	1.07	2.27	3.19	5.80	5.81
Anchomenus dorsalis (Pontoppidan, 1763)	M	6	1.20	0.97	1.62	1.50	4.10	4.13
Asaphidion austriacum (Schweiger, 1975)	M	2	0.60	0.50	0.89	0.93	2.45	2.44
Brachinus crepitans (Linnaeus, 1758)	M	6	1.87	1.07	1.73	1.69	5.76	5.70
Brachinus explodens Duftschmid, 1812	M	2	1.52	0.82	1.74	1.35	5.08	5.15
Calathus fuscipes (Goeze, 1777)	M	39	1.74	1.42	2.55	3.51	7.02	7.00
Carabus coriaceus Linnaeus, 1758	A	2	5.58	4.28	7.11	9.89	24.40	24.32
Carabus granulatus Linnaeus, 1758	B	326	3.12	2.00	3.56	4.85	12.76	12.66
Carabus violaceus Linnaeus, 1758	A	46	4.43	2.75	5.37	6.92	17.65	17.68
Cychrus caraboides (Linnaeus, 1758)	A	17	2.78	1.47	3.75	3.78	9.90	9.87
Harpalus rubripes (Duftschmid, 1812)	M	29	1.47	1.66	2.11	3.01	5.07	5.07
Leistus rufomarginatus (Duftschmid, 1812)	M	1	1.27	1.47	1.62	2.78	5.80	5.78
Nebria brevicollis (Fabricius, 1792)	M	43	1.61	1.54	2.37	3.52	8.20	8.17
Notiophilus biguttatus (Fabricius, 1799)	B	3	1.23	1.21	1.24	1.62	3.28	3.32
Platyderus rufus (Duftschmid, 1812)	B	20	0.95	0.76	1.47	1.79	3.35	3.34
Platynus assimilis Paykull, 1790	M	64	1.76	1.67	2.09	3.05	7.40	7.40
Poecilus cupreus (Linnaeus, 1758)	M	6	2.12	1.34	2.40	3.20	5.50	5.82
Poecilus versicolor (Sturm, 1824)	M	4	1.45	1.14	2.76	3.35	7.20	7.11
Pseudoophonus rufipes (DeGeer, 1774)	M	372	2.43	2.02	3.28	4.54	8.91	8.87
Pterostichus niger (Schaller, 1783)	M	203	2.92	2.30	4.00	4.89	11.37	11.39

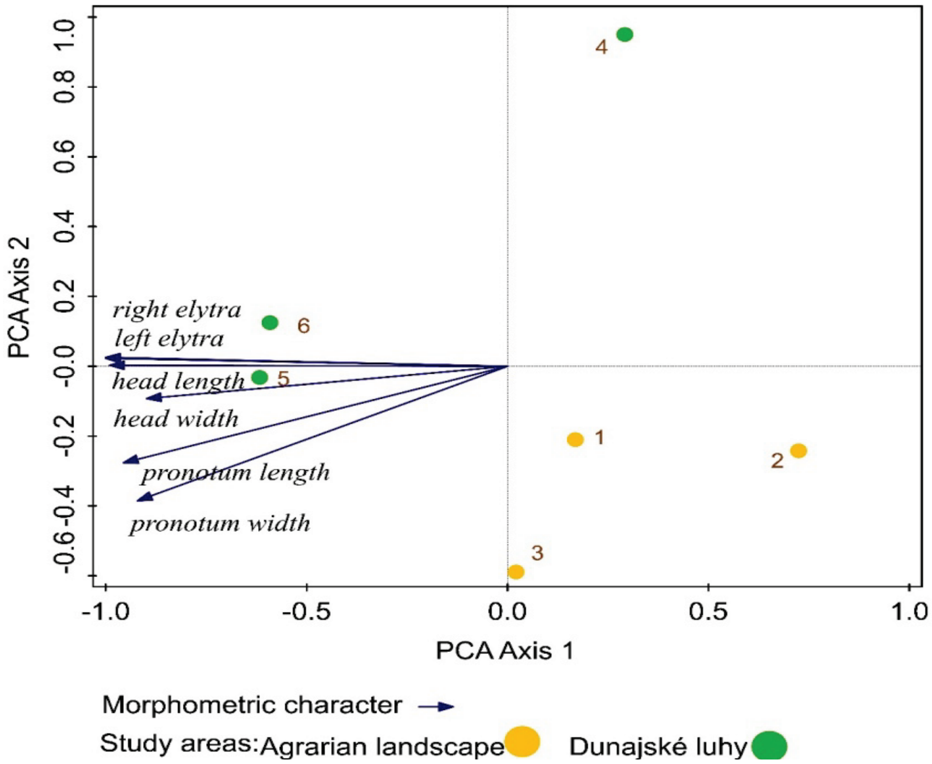

Fig. 3. Linkage of morphometric characters to study areas (1-6)

From the results of the analysis, we can say that in the agrarian landscape conditions, the value of all morphometric characters increased in the direction of brachypterous, macropterous, and apterous species. The variability of the measured values also increased in this direction, which we can see in the maximum and minimum values of the boxplots. Under the conditions of the Dunajské Luhy Protected Landscape Area, the variability of the measured values for morphometric characters was not as significant compared to the agrarian landscape. The median values of the morphometric characters of all flight ability groups are higher in the conditions of the Dunajské Luhy, which indicates the predominance of larger individuals in these conditions. These results indicate a stable environment in the Dunajské Luhy Protected Landscape Area, where there is not much variability of values and ground beetles have their food optimum in their habitats. In the agrarian landscape, habitats are disturbed by agricultural activity in the vicinity of forest habitats, so beetles do not have their food optimum in their habitats and must fly for food, which also results in a larger range of variability of the values of morphometric characters.

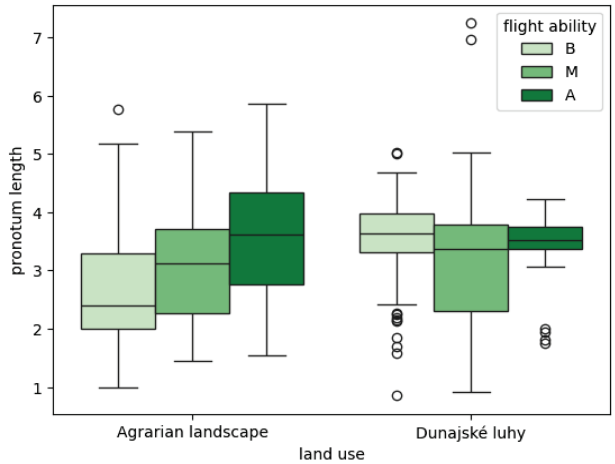

Fig. 5. The difference in pronotum length between land use and flight ability

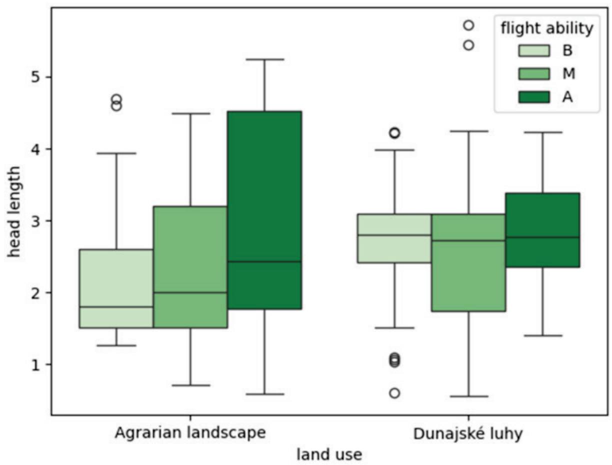

Fig. 4. The difference in head length between land use and flight ability

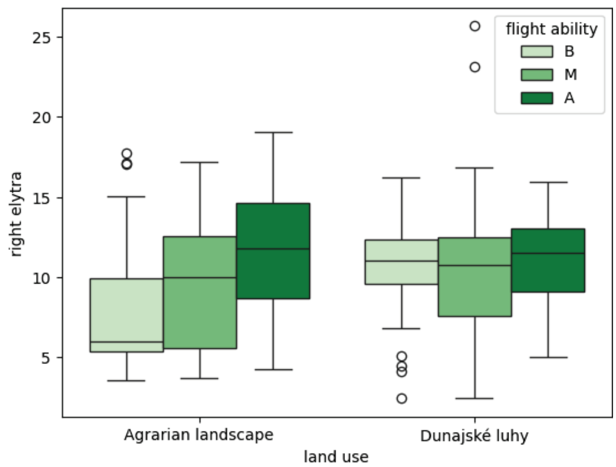

Fig. 6. The difference in right elytra between land use and flight ability

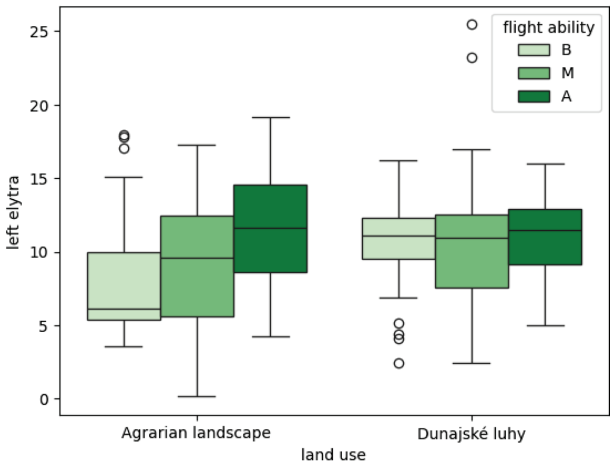

Fig. 7. The difference in right elytra between land use and flight ability

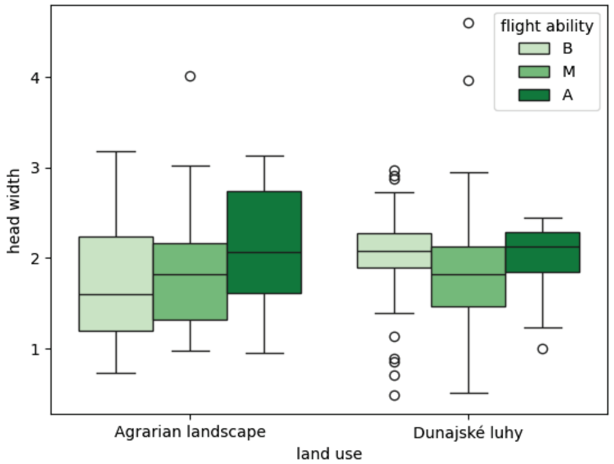

Fig. 8. The difference in head width between land use and flight ability

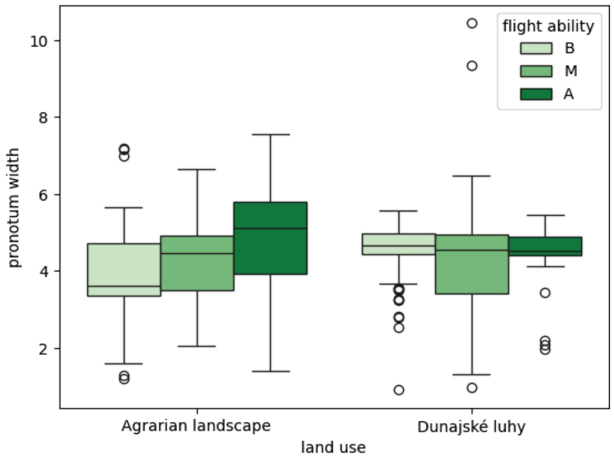

Fig. 9. The difference in pronotum width between land use and flight ability

Discussion

Comparison of beetle morphometric traits in agricultural landscapes and protected areas provides valuable information about the impact of various environmental factors on their populations. In agricultural landscapes, where intensive land use occurs, habitats can be fragmented and exposed to various forms of disturbance, which affect the morphometric traits of beetles. On the contrary, protected areas, such as the Dunajské Luhy Protected Landscape Area, provide a more stable environment with a lower level of anthropogenic interference, which may be reflected in different morphometric parameters of these organisms. Therefore, beetle morphometry represents an important tool for studying ecological interactions between organisms and their environment. This approach is often used to assess the impact of environmental factors, such as landscape fragmentation (Brygadyrenko, 2015; Putchkov et al., 2019), food availability (Brygadyrenko & Reshetniak, 2014), climatic conditions (Avtaeva et al., 2021) and the impact of anthropogenic activities on the morphological traits of beetles (Jelaska & Durbes, 2013; Brygadyrenko & Reshetniak, 2014; Komlyk & Brygadyrenko, 2019a, 2019b; Litavský et al., 2021). Given the importance of morphometric variability, due to the influence of environmental factors, we also focus on this type of research.

Agricultural landscapes are characterised by a high level of anthropogenic impact, which leads to habitat fragmentation and population declines for many species of beetles. Studies show that in these areas there is increased variability in morphometric traits, which may indicate adaptation to unstable conditions. The impact of pesticides and herbicides also has a significant impact on their populations (Kozak et al., 2020). Research shows that in agricultural landscapes there is increased variability in the morphometric traits of beetles. This variability may be a consequence of adaptation to diverse and frequently changing environmental conditions, where beetles have to face disturbances caused by agricultural activities (Gobbi et al., 2021; Sukhodolskaya et al., 2021). In our study carried out in an agricultural landscape, significant differences in head length (P = 0.0057), head width (P = 0.0099), pronotum length (P = 0.0066), pronotum width (P = 0.0269), right elytra (P = 0.0121) and left elytra (P = 0.0115) were recorded between individual groups of beetles with different flight abilities and a large variability of the measured values. These differences indicate that beetles in these areas must be morphologically adaptive to cope with environmental changes.

Compared to agrarian landscapes, protected areas, such as the protected landscape area of the Danube Plain, provide more stable ecosystems. Studies suggest that beetles in these areas have more homogeneous morphometric characteristics, which is evidence of lower evolutionary pressure on morphological diversity. The influence of climate, such as temperature extremes and humidity, is less intense in stable habitats. Therefore, less variability in beetle morphometric characteristics is recorded in these areas. The more stable environment of these areas provides beetles with more consistent living conditions, which is reflected in more homogeneous morphological parameters (Garcia-Tejero al., 2016; Galle al., 2018; Ghannem al., 2018). Our study carried out in this area confirmed significant differences between the flight ability of beetles and morphometric characteristics such as head length (P = 0.0397), head width ($P = 3.0*10^{-8}$), pronotum length (P = 0.00001), pronotum width (P = 0.0047), right elytra (P = 0.0095) and left elytra (P = 0.0114); however, the variability of the measured values was smaller. These results indicate that in stable conditions in protected areas, there is less morphological variability between beetles.

The availability of food in stable ecosystems allows an increase in body size of individuals. Studies conducted in various ecosystems have confirmed that individuals in less disturbed ecosystems have, on average, larger dimensions than those in agrarian areas. In protected areas, where the ecosystem is less disturbed, beetles have better access to food, which can lead to larger body sizes (Hendrickx et al., 2007; Long et al., 2019). We noted that the median values of morphometric characters of all flight ability groups were higher in the conditions of the Danube floodplains, which indicates the predominance of larger individuals in these areas. In contrast, in agrarian landscapes, where habitats are often disturbed by agricultural activities, beetles have to search for food in a wider environment, which may lead to greater variability of morphometric characters.

Conclusions

In our study, we assessed the impact of land use on the morphometric variability of ground beetles. During 2020–2022, we recorded 1,304 individuals belonging to 24 species of the Carabidae family using pitfall traps in 6 study areas (1–3 – agrarian landscape, 4–6 – Dunajské Luhy Protected Landscape Area). For each individual, we measured the following morphometric traits: head length, head width, pronotum length, pronotum width, right elytra and left elytra. Using

PCA analysis, we pointed out the connection of morphometric traits to study areas belonging to the Dunajské Luhy Protected Landscape Area. Based on the flight ability of species in different land use conditions, we found that morphometric variability is greater in agrarian landscape conditions compared to the Dunajské Luhy Protected Landscape Area. The findings suggest that environments with high levels of anthropogenic impact induce increased morphological variability in beetles, while structured and stable environments promote morphological consistency. The results of our study highlight the importance of protecting natural habitats and minimising anthropogenic interference to maintain the morphological integrity and diversity of beetles. They also highlight the need for more research aimed at understanding the mechanisms by which environmental factors influence the morphometric traits of these important indicators of ecosystem health.

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