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The effect of management in agroecosystems on the histomorphological variability of epigeic beetles

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Monitoring the impact of agricultural management on epigeic beetles is important for assessing the stability of agroecosystems. Beetles represent suitable bioindicators, as they respond sensitively to environmental changes. We analyzed histomorphometric traits (area, perimeter, maximum and minimum diameter) of the cecal crypts of the beetles *Pterostichus niger* (Schaller, 1783), *Calathus fuscipes* (Goeze, 1777), and *Silpha obscura* Linnaeus, 1758 living under organic and conventional management conditions. The results showed higher median values of the histomorphological features of *P. niger* and *S. obscura* under organic management, and a similar trend was observed for *C. fuscipes*. Conventional management was associated with lower median values of the histomorphological features, indicating the presence of individuals that were lacking food. The most pronounced reaction to management was confirmed in *P. niger* and *S. obscura*, and the lowest in *C. fuscipes*, which corresponds to its preference for warmer and more disturbed habitats. The obtained results point to the importance of organic management for supporting favorable histomorphological structures of epigeic beetles and emphasize their usefulness in monitoring anthropogenic impacts and setting effective agroenvironmental measures.

Keywords: Coleoptera; Carabidae; Silphidae; agroecosystem; management; histology; soil fauna.

Introduction

Soil communities in agroecosystems represent dynamic organic environments, where interactions among invertebrates, soil structure, and management practices play a key role in regulating biotic processes and maintaining system functionality. Within this dynamic, the family Carabidae of the order Coleoptera is a significant bioindicator, as their morphology reflects the adaptation to environmental conditions, as well as the impact of agrochemical interventions or management intensity (Brygadyrenko, 2016a, 2016b; Putchkov et al., 2020). At the optimum food level, when there is enough food, the cecal crypts are larger than when there is a lack of food (Turin, 2022; Makwela et al., 2023).

The digestive system of beetles (Coleoptera) is a complex structure that is adapted to different organic materials and feeding strategies. In many species, the digestive tract is divided into three main parts: the foregut, the midgut, and the hindgut. The hindgut often contains specialized structures such as cryptonephridial systems or deep intestinal crypts intended for efficient reabsorption of water and ions, which helps minimize water loss in the body and maintain the body's ionic balance (Candan et al., 2021; Koçakoğlu et al., 2025). Histologically, the midgut contains columnar epithelial cells with numerous invaginations or protrusions increasing the absorptive surface area, which is especially important in a diet with a higher proportion of plants. At the same time, the most posterior part of the intestine (ileum, colon, rectum) is equipped with a thicker muscle layer and is often connected to it by the cryptonephridial system, i.e. a narrow space where the distal ends of the Malpighian tubules are attached to the wall of the hindgut, which allows for efficient reabsorption of water and ions before the elimination of digestive residues, thereby minimizing water loss in the body and maintaining the body's ionic balance (Irvine, 1969; Toni et al., 2022). The digestive system of predatory species is histologically adapted for the rapid digestion of captured prey; the stomach is highly glandular and acidic; and the intestine is relatively short. Phytophagous species have a longer and more voluminous digestive tract to allow slow microbial degradation of fiber. Their epithelium and mucosa are adapted for the fermentation of plant material, either in foreguts lined with stratified squamous epithelium or in a markedly developed cecum and large intestine. Necrophagous species have a highly acidic stomach and a resistant mucosa, which serves to destroy pathogens ingested with decomposing food. Species inhabiting dry or food-poor habitats have well-developed cryptonephridial systems and a hindgut adapted for intensive water and ion resorption, thus minimizing water loss (Candan et al., 2020; Toni et al., 2022).

In relation to agroecosystems, these histological features are extremely important, as changes in management practices (e.g. organic or conventional) modify soil structure, food availability, and microbial community, which can affect the course of digestion, gut structure or reabsorption intensity (Carbonne et al., 2022; Makwela et al., 2025). Histological studies show that deep intestinal crypts or enlarged cavities may be present in the hindgut (colon, rectum), which are located near the junction with the Malpighian tubules and serve to maximize reabsorption, especially under conditions of limited water supply during years of poor rainfall or increased need for metabolic regulation in the environment of altered agroecosystems. Agroecosystems differ markedly in the availability and quality of food as well as in exposure to chemical substances. In conventional farming systems, organisms are more frequently exposed to pesticides and fertilizers, which increases the demands on detoxification and regulatory metabolic pathways (Faly & Brygadyrenko, 2024; Faly et al., 2025). By contrast, in organic or less intensive systems, nutrient availability may fluctuate, requiring flexible regulation of energy metabolism (Dow & Davies, 2006; Dow, 2009; Douglas, 2009; Jing et al., 2015). Given this adaptability, it can be assumed that species living in more stable ecosystems with less intensive interventions will have histological features leading to more efficient absorption, deeper crypts or less variability, while in conventional systems with higher disturbance, these changes may not occur (Chapman, 2012). The study of histomorphological features of the digestive tract therefore represents a valuable approach to assessing the impact of management methods on soil fauna not only in terms of biodiversity, but also in terms of histological performance and species adaptation. In our research, we tested the hypothesis of whether there is an increase in histomorphological features (area, perimeter, minimum and maximum diameter) in individuals living in the field under organic farming (where they have a greater food optimum) compared with those living under conventional farming (where there is a lack of food).

Materials and methods

The study areas are located in the cadastral territory of Nitra (geographical coordinates: 48°17′19.6″ N, 18°06′48.1″ E). The area lies at an altitude of 130 m a.s.l., the soil type is Cambisol, and the climate is warm with mild winters.

Organic tillage was based on annual tillage plowing, incorporating crop residues and weeds into the soil. The soil was ploughed three times and turned. Presowing preparation and sowing were combined. Machines with driven working tools were used in conjunction with a seed drill. When sowing, it was possible to use seed coulters with an obtuse angle of penetration into the soil. No spraying (pesticides, insecticides) was used in organic farming. In conventional soil tillage, standard deep ploughing was carried out, followed by the use of various pesticide products intended to protect plants against diseases and weeds (Hurricane, Promir, Adengo SC, Arrat Šaman). In addition, at a rate of 0.1 L/ha, the following insecticides were applied: Lambada, Karate Zeon 5 CS, and Delmetros 100 SC.

During the year 2023, we captured specimens of the species *Pterostichus niger* (Schaller, 1783), *Calathus fuscipes* (Goeze, 1777), and *Silpha obscura* Linnaeus, 1758 in wheat (*Triticum aestivum*) crops grown organically and conventionally. The beetle collection took place in two fields. A total of 20 individuals of each species were collected. Only females were selected due to the easier removal of the tracheostomy system where the cecal crypt is located. Four histological preparations of the cecal crypt were made from each individual. Subsequently, we selected the 33 best preparations for measuring histomorphological features of the cecal crypt.

The species *C. fuscipes* and *P. niger* are predatory beetles from the Carabidae family. These epigeic beetles play an important role in regulating populations of small invertebrates in the soil. The body length of the species *P. niger* reaches 12–18 mm and that of *C. fuscipes* reaches 9–13 mm. Both species feed on small invertebrates such as insect larvae, worms, snails, aphids, and eggs of other species. *Silpha obscura* is a necrophagous beetle from the Silphidae family, which feeds on decaying organic matter, especially dead animals. It plays an important role in the decomposition and cycling of nutrients in nature. The body length is 12–18 mm.

We captured the beetles using pitfall traps, five of which were placed in a line. There was a 10 m distance between each pitfall trap. The first trap was placed 20 m from the edge of the field. The collection of individuals in both fields took place from May to July. There was no fixing fluid in the pitfall traps and we collected samples every 3–4 days. The specimens were identified to species level, and nomenclature was verified according to Zahradník (Hurka 1996; Zahradní 2017).

After collecting the individuals in the field, they were immediately transported (within 20 minutes) to the laboratory where they were subsequently killed using chloroform. Then, a necropsy was performed and the digestive system was removed, after which we performed fixation and dehydration of the samples. Histological processing of the samples followed standard laboratory procedures. Fixed samples were dehydrated through an ascending series of ethanol-benzene solutions, cleared in xylene, and infiltrated with paraffin using a tissue processor Intelsint TP300 – RVG/1 (INTELSINT, Italy). After embedding in paraffin blocks, the samples were sectioned at a thickness of 3.0–4.5 μm using a rotary microtome HistoCore Autocut 1 (Leica, Germany) and dried in a thermostat at 37 °C. The sections were stained with hematoxylin–eosin using the automated staining system Stainer AUS 124 (Bio Optica Milano SPA, Italy) and mounted with Pertex (HistoLab, Sweden). Qualitative analysis of the digestive system was performed under a polarizing microscope DM750P (Leica, Germany) at 20× and 40× magnifications, with expert verification of the identified structures. Quantitative analysis of the cecal crypts included measurements of area (μm^2), perimeter (μm), and minimum and maximum diameter (μm) using ImageJ software (Fig. 1).

We analyzed the histomorphological features of the cecal crypts of the appendix (area, perimeter, minimum and maximum diameter) in three species (*Pterostichus niger* (Schaller, 1783), *Calathus fuscipes* (Goeze, 1777), *Silpha obscura* Linnaeus, 1758) under two types of management (organic, conventional). Using the Shapiro–Wilk test, we confirmed a violation of normal data distribution for the examined histomorphometric traits: area ($P < 0.001$), perimeter ($P < 0.001$), maximum diameter ($P < 0.001$), and minimum diameter ($P < 0.001$). Based on the not normally distributed data, we applied the nonparametric Friedman test to assess the differences in histomorphological traits in the species (*P. niger*, *C. fuscipes*, *S. obscura*) under different management types (organic, conventional). Using the K-nearest neighbor (KNN) algorithm (machine learning), we predicted the development similarity groupings in histomorphological features of perimeter and area between *P. niger*, *C. fuscipes*, and *S. obscura* under organic and conventional management. These two histomorphological features best indicate the size of the cecal crypt, which should be larger under organic farming compared with conventional farming. The analyses were performed in Python version 3.12.

Results

From the results of the analysis, we confirmed a significant difference in the histomorphological features in the species under different types of crop management. The results are as follows: area ($P < 0.001$, Fig. 2), perimeter ($P < 0.001$, Fig. 3), maximum diameter ($P < 0.001$, Fig. 4), and minimum diameter ($P < 0.001$, Fig. 5). Based on the results, we observed that in the species *P. niger* and *S. obscura*, higher median values of histomorphological features were confirmed under organic management compared with conventional management. In *C. fuscipes*, we also confirmed higher median values of histomorphological features, which are located in the upper quartile, indicating a predominance of higher values under organic management. By contrast, under conventional management, the median values of histomorphological features are located in the lower quartile, which indicates a predominance of lower values in the dataset. However, under conventional management, higher maximum and outlier values of histomorphological features occur, suggesting the presence of a smaller number of larger values compared with organic management. Moreover, the difference between the medians of histomorphological features is not as pronounced as in *P. niger*, indicating only a small difference between in *C. fuscipes* under different management types. From the results, we can infer that beetles in organically managed field have a greater food supply and food abundance than beetles in conventionally managed field.

Using the K-nearest neighbor (KNN) algorithm, we predicted the development of clusters of histomorphological parameters of area and perimeter of the species *P. niger*, *C. fuscipes*, and *S. obscura* under organic and conventional management. The performance of the KNN classifier is presented using a confusion matrix. The results show that most cases are correctly classified into their respective classes, as indicated by the diagonal frequency of cases (Fig. 6). Therefore, we subsequently created a KNN model that divided the states (1 – conventional management and *P. niger*, 2 – organic management and *P. niger*, 3 – organic management and *C. fuscipes*, 4 – conventional management and *C. fuscipes*, 5 – organic management and *S. obscura*, 6 – conventional management and *S. obscura*) into groups based on the histomorphological characteristics of area and perimeter. The data were standardized using Z-score normalization. Value $K = 3$, the ratio of trained data to tested data, is 20% / 80%. The model accuracy is 60%, which means that 60% of the test examples were correctly classified by the model. Thus, most of the predictions correspond to the actual classes, indicating that the model exhibits moderate strength.

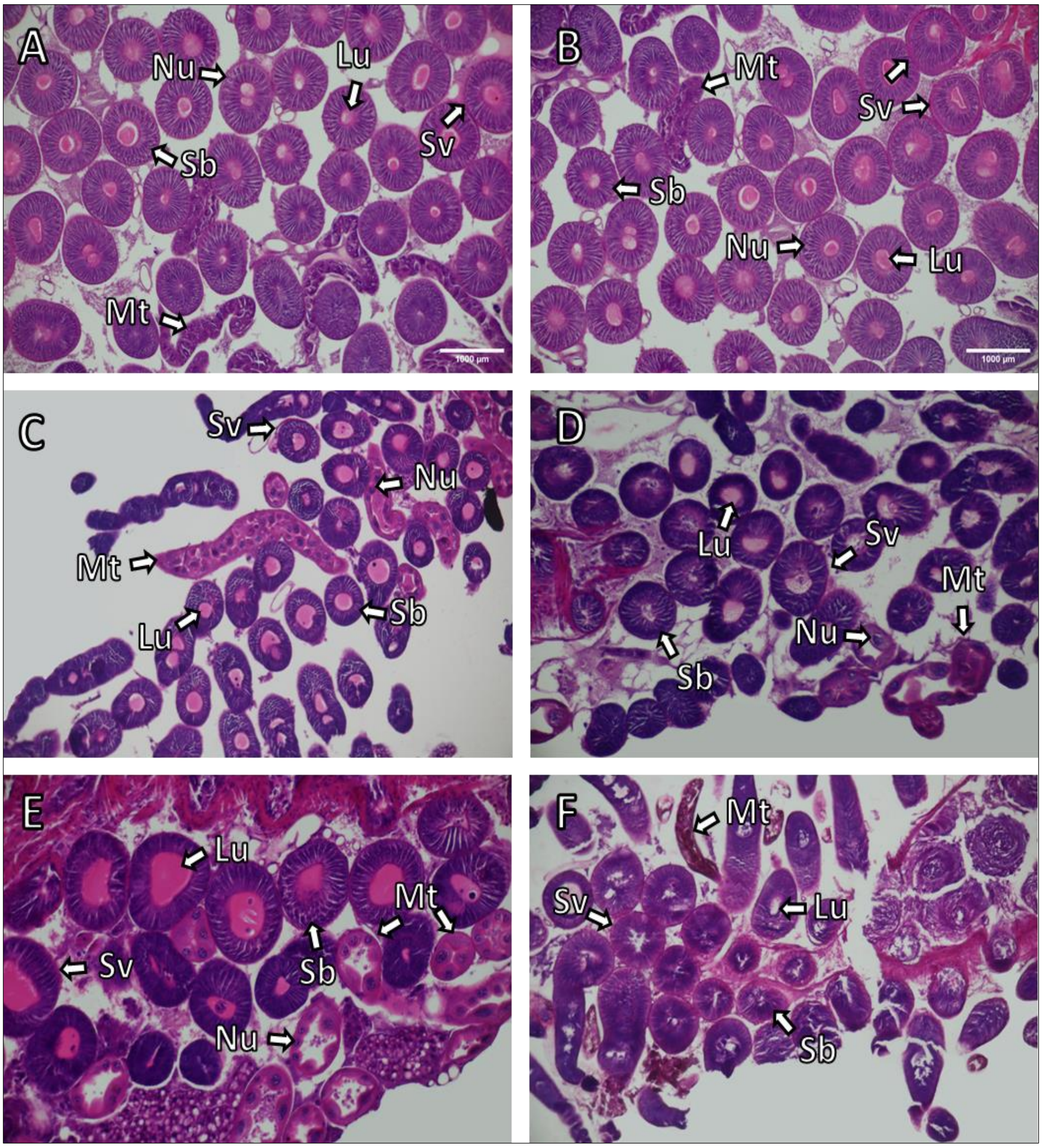

Fig. 1. Representative image of the cecal crypts of *Silpha obscura* Linnaeus, 1758 from the organic group (*A*) and conventional group (*B*), representative image of the cecal crypts of the beetle *Pterostichus niger* (Schaller, 1783) from the organic group (*C*) and conventional group (*D*), representative image of the cecal crypts of the beetle *Calathus fuscipes* (Goeze, 1777) from the organic group (*E*) and conventional group (*F*): Nu – nuclei, Lu – lumen, Sv – musculature, Sb – secretory cells, Mt – Malpighian tubules

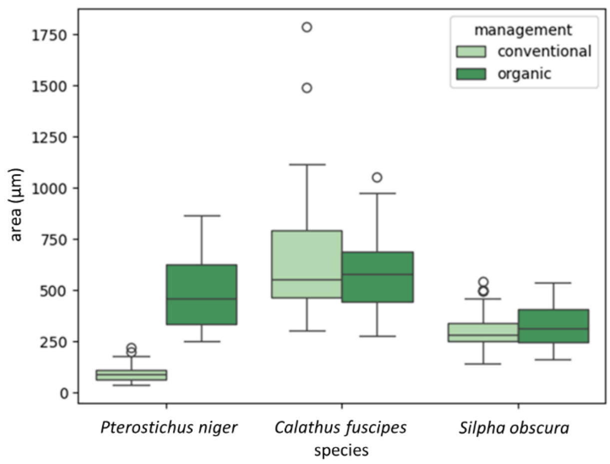

Fig. 2. Difference in area of cecal crypt in the species under different types of crop management

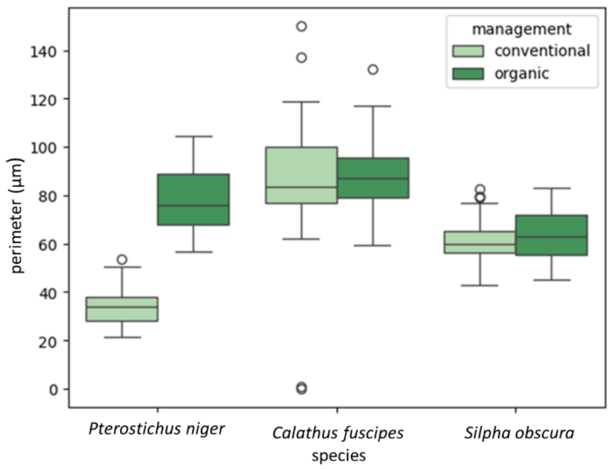

Fig. 3. Difference in perimeter of cecal crypt in the species under different types of crop management

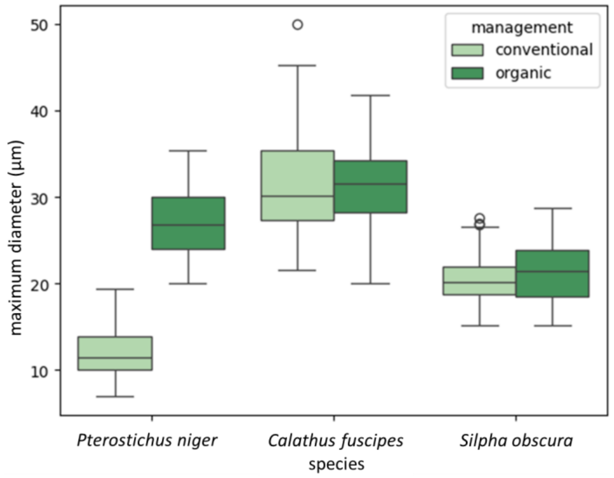

Fig. 4. Difference in maximum diameter of cecal crypt in the species under different types of crop management

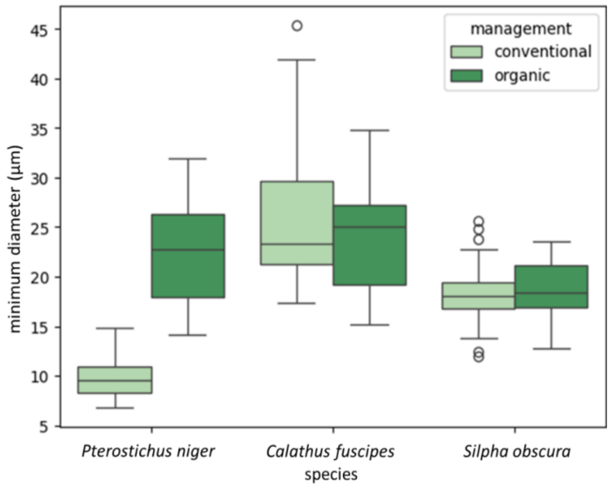

Fig. 5. Difference in minimum diameter of cecal crypt in the species under different types of crop management

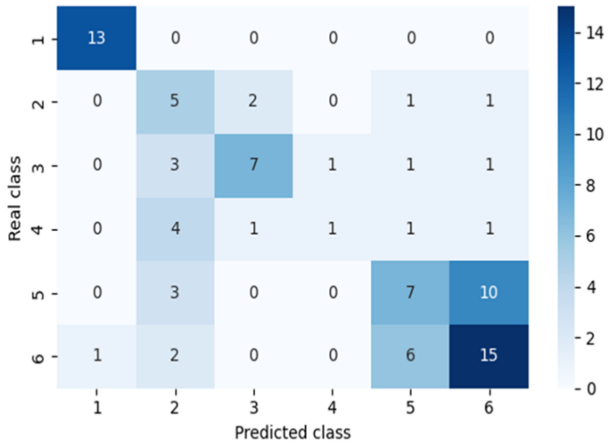

Fig. 6. Confusion matrix of KNN classification showing case classification assignment: the number of correct classifications is listed diagonally; 1 – conventional management and *Pterostichus niger* (Schaller, 1783), 2 – organic management and *P. niger*, 3 – organic management and *Calathus fuscipes* (Goeze, 1777), 4 – conventional management and *C. fuscipes*, 5 – organic management and *Silpha obscura* Linnaeus, 1758, 6 – conventional management and *S. obscura*

The visualization of the results shows how the model divides the space according to the area and perimeter values. The colored regions illustrate how the KNN model predicts the classification of the space based on the histomorphological parameters of area and perimeter. *Pterostichus niger* is classified into two clusters: one under conventional management (state 1), where both area and perimeter values are lower, and another under organic management (state 2), where these values are higher. This indicates that the species has more favorable conditions, such as more food, under organic management. *Calathus fuscipes* is also classified into two clusters, one under organic management (state 3) and one under conventional management (state 4). These clusters partially overlap, suggesting only a small difference between the two management types. The species *S. obscura* is distributed into one cluster under organic management (state 5) and another under conventional management (state 6). These clusters alternate but do not overlap as strongly as in the case of *C. fuscipes*. The clustering ends with the organic management cluster, indicating that differences between management types can be expected, though not as pronounced as in *P. niger*. The effect of management was not the same across all three species: *P. niger* was the most sensitive, followed by *S. obscura*, while *C. fuscipes* proved to be more resistant to changes caused by anthropogenic activity, preferring warmer and more frequently disturbed habitats (Fig. 7).

Discussion

The results of our research show that the lack of food under conventional farming compared with organic farming affects the size of the cecal crypt, which is important in digestion, nutrient acquisition, and detoxification of the individual with the help of symbiotic microorganisms. The results of the histomorphometric analyses of the three beetles *P. niger*, *C. fuscipes*, and *S. obscura* indicate that agroecosystem management practices affect influenced histomorphological parameters (area, perimeter, minimum diameter, maximum diameter). The confirmation of significant differences in all the examined parameters (area, perimeter, maximum diameter, minimum diameter) suggests that conventional conditions represent a significant selective pressure of food shortage acting on histological structures. Such responses are consistent with the findings that soil beetles react to habitat changes sensitively and rapidly (Lövei & Sunderland, 1996; Rainio & Niemelä, 2003).

The clear predominance of higher median values of histomorphological parameters in *P. niger* and *S. obscura* under organic management confirms the findings that low intensity and organic practices support better conditions for food availability, resulting in larger cecal crypts. They participate in the detoxification of the body through microorganisms that are able to enzymatically degrade pesticides or other xenobiotics into less toxic or nontoxic compounds. The cecal crypts function as a separate compartment that prevents direct contact of toxic substances with the host tissues (Bengtsson et al., 2005; Hole et al., 2005; Lundgren et al., 2007; Lundgren & Lehman, 2010; Philipp et al., 2013). The demonstrated higher variability under conventional systems, especially in *C. fuscipes*, may indicate a stressful environment with occasional selection for more extreme phenotypes, as also confirmed by the study by Basedow (1990). Organic management is typically characterized by greater soil heterogeneity, higher organic matter content, and lower chemical disturbance, creating more favorable conditions for the development of robust individuals (Bentonová et al., 2003). By contrast, conventional management may act selectively and sometimes promote the occurrence of extreme values, which was reflected in the detection of higher maximum and extreme values, particularly in *C. fuscipes*. This species is ecologically tolerant (eurytopic), often prefers warmer and disturbed habitats (Kotze et al., 2011), and therefore it is logical that its morphometric responses to management are not as pronounced.

The identified differences between the agroecosystems confirm that the response to management is not uniform. *Pterostichus niger* showed the highest sensitivity to management (organic, conventional), which is consistent with its organic preferences for wetter, cooler, and less disturbed environments. *Silpha obscura* responded with moderate intensity, while *C. fuscipes* proved to be a more typical of warmer and disturbed habitats, which is consistent with the findings of previous studies (Thiele, 1977; Desender et al., 2013).

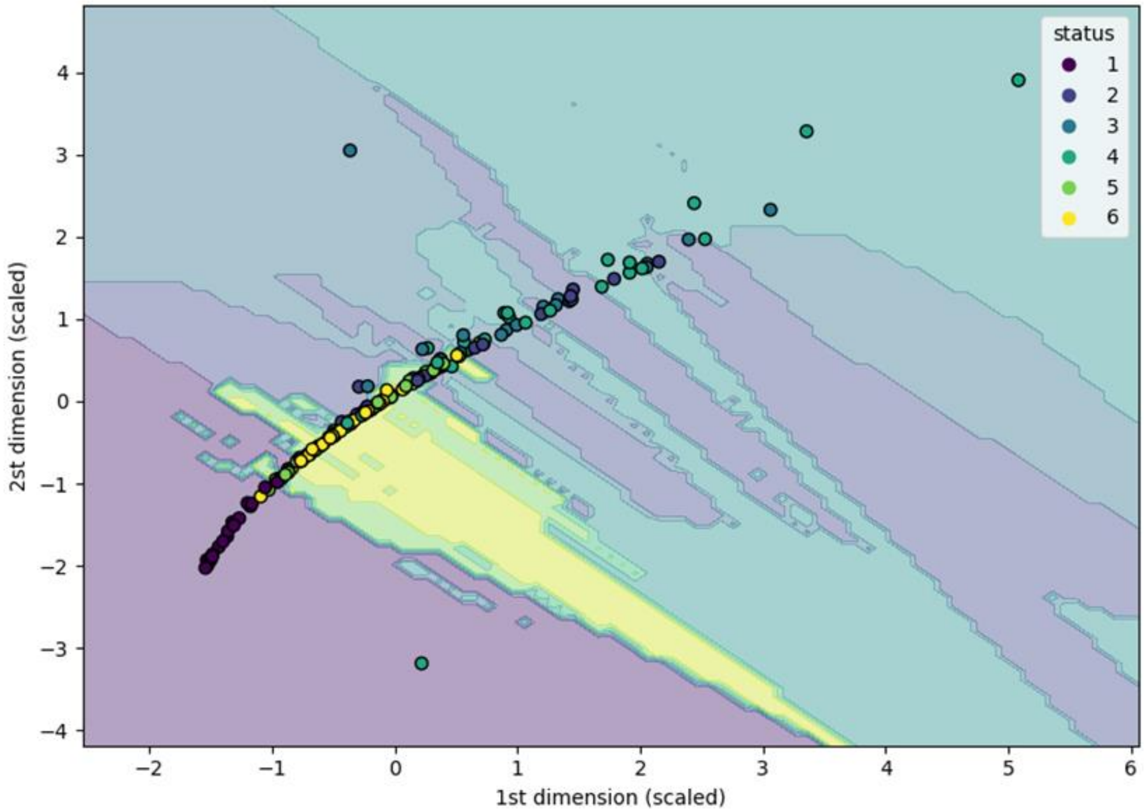

Fig. 7. KNN analysis expressing the evolution of *Pterostichus niger* (Schaller, 1783), *Calathus fuscipes* (Goeze, 1777) and *Silpha obscura* Linnaeus, 1758 species between organic and conventional management: state 1 – conventional management and *P. niger*, state 2 – organic management and *P. niger*, state 3 – organic management and *C. fuscipes*, state 4 – conventional management and *C. fuscipes*, state 5 – organic management and *S. obscura*, state 6 – conventional management and *S. obscura*

The predictive analysis using the K-nearest neighbors (KNN) algorithm suggests that histomorphometric traits can serve as useful indicators for estimating habitat condition and management type. Based on the clustering of histomorphometric traits, we can state that under organic farming, the beetles had larger cecal crypts, which indicates a greater source of nutrition under this type of farming. The predicted classes in the data indicate practical applicability, which is supported by other studies applying machine learning in biodiversity assessment (Edwards et al., 2005; Edwards et al., 2006; Cutler et al., 2007; Potapov et al., 2022). The visualization of classification spaces clearly shows population segregation, especially in *P. niger*, which again highlights the high sensitivity of this species to organic-farming conditions.

Our results show that organic farming creates more suitable feeding conditions for epigeic groups, supporting higher biodiversity and consequently ecosystem services (Diekötter et al., 2010; Tuck et al., 2013). Moreover, histomorphometric traits are emerging as suitable bioindication tools for distinguishing environmental states across agroecosystems. The present findings thus contribute to the increasing need to integrate model-based approaches in assessing the impacts of anthropogenic activity on epigeic fauna.

Conclusions

The results of the analysis of histomorphometric traits of three beetle species *P. niger*, *C. fuscipes*, and *S. obscura* confirmed the influence of management type on their histomorphological parameters. We demonstrated significant differences in all examined traits (area, perimeter, maximum diameter, minimum diameter) in the beetles in fields under organic and conventional management. Under organic management, higher median values were recorded for *P. niger* and *S. obscura*, with a similar trend observed in *C. fuscipes*. By contrast, under conventional management, lower median values were observed, indicating the presence of smaller individuals compared with organic management. *Pterostichus niger* was the most sensitive species to changes in the management, whereas *C. fuscipes* appeared to be the most resistant, which may be related to its organic preference for warmer and more disturbed habitats. *Silpha obscura* showed a medium level of sensitivity. The obtained results have significant practical importance for assessing management practices and their impact on epigeic beetles, valuable bioindicators of soil quality and ecosystem stability. The sensitivity of certain species (especially *P. niger*) to the type of management can be used in monitoring the effects of anthropogenic activities, particularly agricultural intensification. Identifying the sensitivity of individual species allows for more precise targeting of agri-environmental measures, optimizing landscape interventions, and minimizing the negative impacts of conventional practices.

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