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Impact of soil-conserving strip cropping on ground beetle communities

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Abstract: Soil-conserving strip cropping is increasingly promoted as an effective measure to reduce water erosion on sloping arable land, yet its consequences for biodiversity remain insufficiently understood. We evaluated the effects of strip cropping on ground beetle (Coleoptera: Carabidae) communities during two growing seasons (2023–2024) in South Moravia (Czech Republic), comparing long-term strip-cropped fields with conventionally managed monocultures. Ground beetles were sampled using pitfall traps, and differences in diversity, activity density, and species composition were analysed using univariate statistics, canonical correspondence analysis (CCA), and generalised additive models (GAMs). Strip cropping consistently supported higher ground beetle diversity than conventional management, while significantly higher activity density became evident after longer implementation. Furthermore, this management enhanced diversity at upper erosional positions, indicating reduced environmental stress. Species-specific analyses showed that several xerophilous and conservation-relevant species were associated with habitats promoted by strip cropping. Our findings demonstrate that the ecological benefits of strip cropping extend beyond erosion control. By increasing within-field habitat heterogeneity and improving conditions for ground beetle assemblages, strip cropping simultaneously supports biodiversity and soil conservation. These results highlight its potential as a multifunctional management practice capable of reconciling agricultural production with biodiversity conservation in erosion-prone landscapes.

Keywords: carabids; crop diversification; epigeic arthropods; polycultures

Human exploitation of natural resources strongly influences species living within the affected landscapes. With agricultural land spanning almost 40% of the Earth's land surface and croplands covering about 12% of ice-free land (IPBES 2019; FAO 2025), the management of these areas and their projected expansion are of concern regarding global biodiversity. This is primarily because intensive agriculture, along with the loss of natural habitats due to land conversion, rank among the leading drivers of biodiversity loss across the globe (Kleijn et al. 2009; Jaureguiberry et al. 2022). The main drivers of intensification with considerable impact on the biodiversity of agricultural land include management practices such as fertilisation, irrigation, drainage, ploughing and the application of pesticides and

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herbicides (Holland & Luff 2000; Stoate et al. 2001; Kleijn et al. 2009; Le Provost et al. 2021). Although these practices can have different or even contradicting effects depending on the species of concern as well as the timing of the management (ploughing, pesticide or herbicide application), they have been shown to strongly influence the biodiversity of agro-ecosystems alongside the loss of non-crop habitats and the expansion of large-scale homogeneous monocultures (Stoate et al. 2001; Robinson & Sutherland 2002; Elmquist et al. 2023).

Intensification has been shown to impact insects (Holland & Luff 2000; Wagner 2020), other invertebrates (Tsiafouli et al. 2015), birds (Tucker et al. 1997; Benton et al. 2002; Rigal et al. 2023) together with other vertebrates (Robinson & Sutherland 2002), and also plants (Kleijn et al. 2009; Meyer 2020). On top of that, agricultural intensification poses a threat to the quality of the soil itself (Kopittke et al. 2019), which is also a concern regarding biodiversity, especially the diversity of the soil fauna (Orgiazzi & Panagos 2018) as well as species important for the provision of ecosystem services (Molina et al. 2014; Tsiafouli et al. 2015; Wall et al. 2015; Elmquist et al. 2023).

One of the primary mechanisms of soil degradation is erosion accelerated by inappropriate management practices (Kopittke et al. 2019). In fact, human-induced erosion represents the leading cause of soil degradation worldwide (Lal 2003; Guerra et al. 2020). In the Czech Republic specifically, more than 50% of agricultural land is threatened by water erosion (MoA 2026). Water erosion not only degrades soil itself, but it also has the potential to influence communities of fauna linked to it. Baxter et al. (2013) mention two main pathways by which water erosion impacts soil fauna: (a) direct displacement of individuals transported along with eroded soil particles from upslope to depositional zones (further discussed in Cadet & Albergel 1999), and (b) indirect impacts through the modification of habitats, primarily involving the degradation of upslope sites and the simultaneous enrichment of depositional zones (discussed in Doetterl et al. 2016). Patterns resulting from both of these pathways were recently confirmed in research conducted by Šarapatka et al. (2026), in which the authors found consistently higher abundance of ground-dwelling arthropods in depositional zones compared to erosional sites. However, while abundance followed this pattern across different conditions, significant differences in species richness and diversity were only observed during years with higher precipitation. This suggests that increased rainfall might accelerate soil transport, thus driving more pronounced shifts in community composition.

To address the widespread problem of water erosion, various anti-erosion practices are being implemented on sloped fields within agricultural landscapes. A prominent example is anti-erosion strip cropping (SC). This practice is based on sowing two or more crops in alternating strips along the slope contour. In this system, at least one of the strips consists of a crop with a high soil-protective function. The role of this protective strip is to shield the soil surface with a dense vegetative cover, thereby preventing the destruction of topsoil aggregate structure. It then also intercepts the surface runoff from the strip located upslope, which allows the water – along with direct precipitation – to infiltrate into the soil, thereby preventing the runoff from carrying soil particles to the bottom of the slope (Dumbrovský & Šarapatka 2023).

The goal of mitigating water erosion is primarily to preserve the topsoil as the most vital resource for crop production. However, anti-erosion measures also have the potential to positively impact other ecological aspects, such as the state of soil fauna. SC not only mitigates soil erosion, but also provides the added benefit of increasing heterogeneity within otherwise homogeneous agricultural landscapes. Since different crops support distinct species assemblages (Elmquist et al. 2023), increased crop diversity might foster higher overall biodiversity of associated fauna (Sirami et al. 2019; Alarcón-Segura et al. 2022). Regarding key natural enemies, such as ground beetles, rove beetles, and spiders, strip cropping has been shown to increase their activity-density and species diversity even on flat fields, where erosion is not of concern. These positive effects are likely driven by habitat diversification, increased availability of resources, and the preservation of undisturbed refugia when agricultural interventions occur in adjacent strips (Sirami et al. 2019; Ditzler et al. 2021; Cuperus et al. 2024).

Despite the presumed impact of water erosion on soil fauna, empirical studies evaluating its real-world effect on arthropod communities remain scarce. Furthermore, knowledge regarding the impacts of erosion mitigation through anti-erosion practices is even more limited. Therefore, this study investigated whether soil-conserving strip cropping, a management practice primarily implemented to reduce water erosion, also enhances biodiversity in intensively managed agricultural landscapes. We focused

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on ground beetles (Coleoptera: Carabidae), a widely used indicator group. By comparing strip-cropped and conventionally managed sloping fields, we tested three main hypotheses: (1) strip cropping impacts ground beetle diversity and activity density; (2) strip cropping alters community composition; and (3) the reduction of erosion-related stress under strip cropping promotes more diverse assemblages at upper slope positions where erosion pressure is greatest.

MATERIAL AND METHODS

Locality and experimental design. Field research was conducted in Bošovice (South Moravian Region) during 2023 and 2024. To evaluate anti-erosion strip cropping, two adjacent land blocks were monitored (PB: 3704-0 and 3704-1). The study compared a field transferred to strip cropping management in 2020 (DPB: 3704/14, 49.0644153N, 16.8268356E, slope 5.65°) with a control plot (DPB: 3704/1, 49.0595786N, 16.8269214E, slope 5.36°). After the first season, the original control field was converted to strip cropping as well, necessitating a new control plot for the second year (DPB: 3704/3, 49.0613783N, 16.8259344E, slope 5.62°; MZe 2025). The soil type on the land blocks was Chernozems with varying erosion intensity depending on the location on the slope (erosion and deposition areas). The basic soil characteristics in the erosion and accumulation parts of the slopes are shown in Table 1, which shows a decrease in soil organic matter in the erosion parts of the slopes and, conversely, an increased pH and carbonate content, which indicates the exposure of soil-forming material, loess, as a result of erosion processes.

Crop rotations in the strips included winter oilseed rape and spring barley (2023), followed by spring barley and soybean (2024). The original control plot featured winter barley (2023), followed by strip cropping of maize and two-row winter barley after its conversion (2024), while the new control plot was sown with common sunflower (2024). Due to an accidental application of herbicide in the summer of 2024, the soybean rows were resown later in the season; therefore, the first samples from these strips were taken from bare soil.

Ground beetle sampling. Ground beetles were sampled using pitfall traps (250 mL cups, 4% formaldehyde, metal covers). Traps were arranged in lines of five (15 m spacing). Three pairs of trap lines were positioned within the strip-cropped field; each pair consisted of two trap lines, with each line situated in a different crop strip: one pair at the top of the slope (erosive position), one pair in the middle (erosive position), and one pair at the bottom of the slope (deposition position). Both control sites featured two trap lines: one at the top of the slope (erosive position) and one at the bottom (deposition position).

Sampling took place during the summer of 2023 (two exposure periods) and in both the summer (three periods) and autumn (three periods) of 2024. Exposure periods typically lasted at least 14 days; however, one autumn session in 2024 was limited to 4 days due to agricultural operations. The captured material was preserved in 75% ethanol. Species identification focused on ground beetles (Carabidae) following Hůrka (1996) and Lompe (2025).

Data analysis. All statistical analyses and data visualisations were performed in the R programming

Table 1. Selected soil characteristics at the studied slopes (mean ± SD)

Soil properties	Strip cropping		Control	
	erosion	deposition	erosion	deposition
Silt/clay (%)	18.6 ± 1.8	20.0 ± 1.9	18.7 ± 0.8	19.4 ± 2.1
Fine sand (%)	20.6 ± 5.6	17.5 ± 5.6	20.5 ± 5.1	15.6 ± 3.2
Sand (%)	3.8 ± 2.6	3.0 ± 1.2	3.6 ± 1.6	5.3 ± 1.3
C_{org} (%)	1.5 ± 0.1	2.2 ± 0.4	1.3 ± 0.0	2.4 ± 0.2
N_{tot} (g N/kg)	1.8 ± 0.3	2.8 ± 0.6	1.7 ± 0.1	2.9 ± 0.2
HK/FK	0.5 ± 0.2	1.0 ± 0.4	0.6 ± 0.1	1.3 ± 0.3
pH/$CaCl_2$	7.3 ± 0.0	7.2 ± 0.2	7.5 ± 0.0	7.2 ± 0.1
Carbonates (%)	13.2 ± 1.8	8.0 ± 4.4	15.5 ± 1.0	1.6 ± 0.8

Silt/clay – silt and clay content (particle size < 0.01 mm); fine sand – particle size 0.05–0.25 mm; sand – particle size 0.25–2.0 mm; C_{org} – soil organic carbon; N_{tot} – total nitrogen; HK/FK – humic acids to fulvic acids ratio; pH/$CaCl_2$ – soil reaction measured in calcium chloride; carbonates – calcium carbonate content

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environment (Ver. 4.2.3; R Core Team 2023), and Canoco 5 (Šmilauer & Lepš 2014); data manipulation and visualisation were supported by the *dplyr* (Wickham et al. 2026) and *ggplot2* (Wickham 2016) packages; Claude 3.7 Sonnet assisted with R-coding. Each trap collection from a specific sampling date served as a separate unit to capture temporal dynamics throughout the season. Traps compromised by voles or erosion runoff, as well as traps with insufficient exposure (e.g., 4 days), were excluded from the analysis. To ensure comparability among the remaining samples and to correct for varying exposure periods, the raw trap catches were temporally standardised to a uniform 14-day interval. This standardisation was mathematically calculated in R by adjusting the specific catch counts proportionally to the actual number of trapping days. Following standardisation, we evaluated overall activity density (abundance) and calculated the Shannon-Wiener Diversity Index (H') using the diversity function from the *vegan* package (Oksanen et al. 2026).

Due to a fundamental shift in the experimental design between the two years – specifically, the conversion of the 2023 original control plot into an SC plot in 2024, and the subsequent establishment of a new control plot with a different crop matrix – the data from 2023 and 2024 were analysed separately. Consequently, differences in diversity and abundance were tested using Welch's *t*-test for the 2023 data (comparing two plot types) and ANOVA followed by Tukey's HSD post-hoc test for the 2024 data (comparing three plot types across two seasons), utilising the stats package in R.

Finally, we utilised canonical correspondence analysis (CCA) in Canoco 5. By this multivariate approach, we evaluated the relative impacts of management, crop type, modelled erosion, and soil properties on the carabid community. Generalised additive models (GAMs) were subsequently applied to model the non-linear responses of individual species to these environmental gradients, identifying their specific habitat preferences and niche partitioning along the sloped fields.

RESULTS

A total of 11 424 ground beetle individuals belonging to 41 species were captured over the two years. After filtration and standardisation, the final dataset for analysis consisted of 11 318 individuals. The most abundant species were *Poecilus cupreus* (Linnaeus, 1758) (4 052 individuals), *Pterostichus melanarius* (Illiger, 1798) (3 836), and *Anchomenus dorsalis* (Pontoppidan, 1763) (2 286), together accounting for nearly 90% of the total catch.

Impact of strip cropping on ground beetle diversity. A Welch's *t*-test was used to compare the Shannon–Wiener diversity index between the strip-cropping area and the control plot during the summer of 2023. Diversity was significantly higher in the strip-cropping area (t = 2.0635; df = 35.627; P < 0.05; Figure 1).

For the 2024 season, an ANOVA with a Tukey HSD post-hoc test was applied, incorporating season (summer/autumn) as an additive factor. Both management type (F = 7.935; P < 0.001) and season (F = 92.430; P < 0.001) had a significant effect on diversity. According to the Tukey HSD test, diversity on the new control plot was significantly lower than on both the strip-cropping area (P < 0.001) and the original control plot now under strip cropping (P < 0.01). No significant difference was found between the strip-cropping area and the original control plot (P = 0.9339; Table S1 in Electronic Supplementary Material (ESM), Figure 2).

The interaction between management type and slope position (upper/lower) was also tested for the summer periods of both years. A two-way ANOVA revealed that this interaction significantly influenced ground beetle diversity (F = 8.549; P < 0.01; Figure 3)

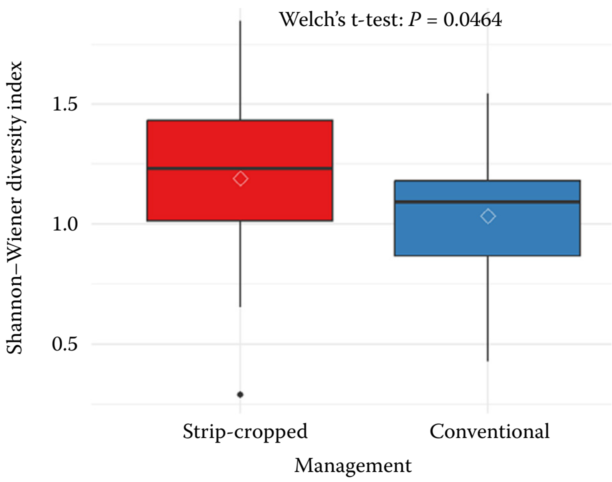

Figure 1. Comparison of Shannon–Wiener diversity index of ground beetle communities between the strip-cropping area (strip-cropped) and the control plot (conventional) during the 2023 summer season

Squares indicate mean values

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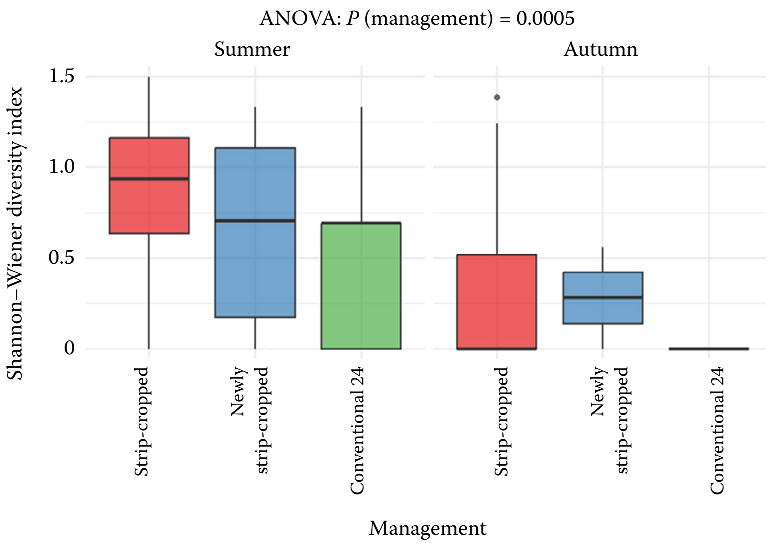

Figure 2. Comparison of Shannon–Wiener diversity index of ground beetle communities across different plot types during the summer and autumn seasons of 2024

Strip-cropped – area with strip cropping; newly strip-cropped – original control plot now under strip cropping; conventional 24 – new control plot

Impact of strip cropping on ground beetle abundance

Ground beetle abundance in the summer of 2023 was compared using Welch's *t*-test. Although the strip-cropping area showed higher mean abundance than the control plot (40.0 vs. 30.0), the difference was not statistically significant (t = 1.6439; df = 32.454; P = 0.11; Figure 4).

For the 2024 season, an ANOVA (without interaction between management and season) followed by a Tukey HSD test was used. Both management type (F = 10.46; P < 0.001) and season (F = 52.31; P < 0.001) significantly affected abundance. The Tukey HSD test showed that abundance in the strip-cropping area was significantly higher than in both control plots. No significant difference was found between the original control plot (now under strip cropping) and the new control plot (Table S2 in ESM; Figure 5).

The interaction between management type and slope position (upper/lower) during the summer periods was also evaluated. While both factors independently had a significant effect (management: F = 13.364, P < 0.001; slope position: F = 4.305, P < 0.05), their mutual interaction was not significant (F = 1.356, P = 0.20; Figure 6).

Community analysis in relation to environmental variables. CCA was used to test the importance of the monitored variables on the ground beetle community. The first axis explains 3.8% of the variability and is significant (pseudo-F = 0.7; P < 0.01); the overall model is also significant (pseudo-F = 2.1; P < 0.01). Individual crops, soil properties modelled erosion, and geographical variables associated with the trap locations had a significant influence (Table S3 andS4 in ESM). When accounting for other variables in conditional effects analysis, the effect

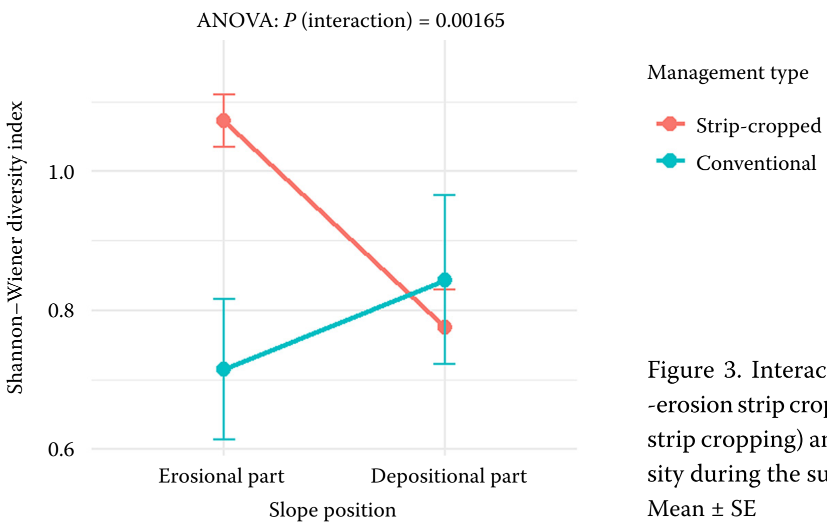

Figure 3. Interaction effect between management (anti-erosion strip cropping, conventional management without strip cropping) and slope position on ground beetle diversity during the summer seasons of 2023 and 2024

Mean ± SE

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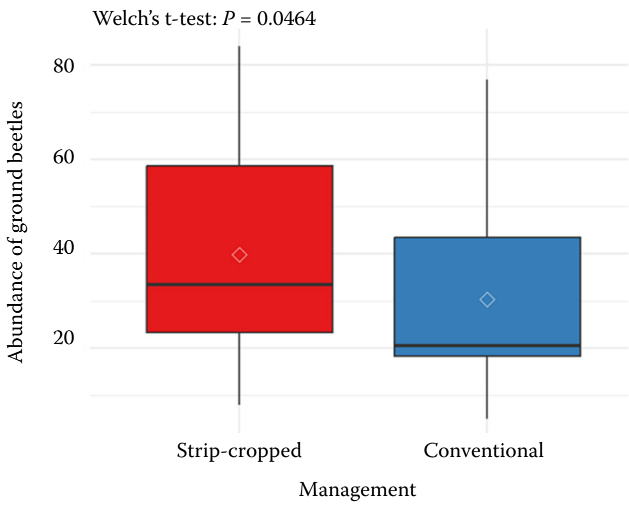

Figure 4. Comparison of ground beetle abundance between the strip-cropping area (strip-cropped) and the control plot (conventional) during the 2023 summer season

Squares indicate mean values

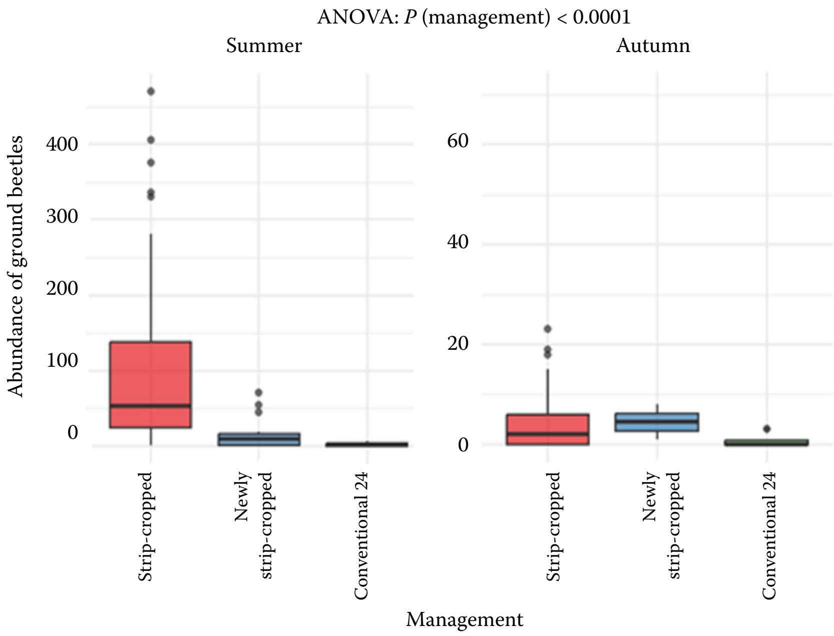

Figure 5. Comparison of ground beetle abundance across different plot types during the summer and autumn seasons of 2024

Strip-cropped – area with strip cropping; newly strip-cropped – original control plot now under strip cropping; conventional 24 – new control plot

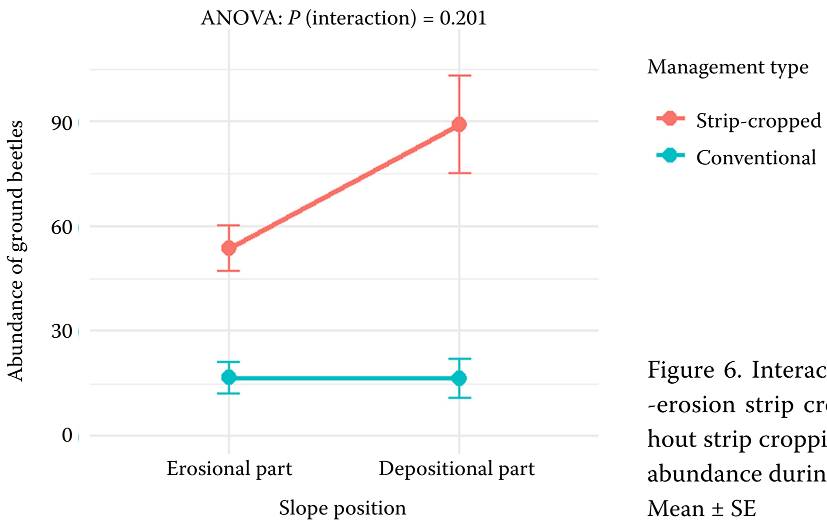

Figure 6. Interaction effect between management (anti-erosion strip cropping, conventional management without strip cropping) and slope position on ground beetle abundance during the summer seasons of 2023 and 2024

Mean ± SE

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of erosion was not statistically significant (Table S5 in ESM; Figure 7).

Ground beetle responses to environmental gradients. GAM were used to visualise the relationships between individual ground beetle species and environmental variables. The figures presented below display only those species that showed a statistically significant response to changes in the values of the respective environmental variables. The dominant and most abundant species, *P. melanarius* and *P. cupreus*, showed a significant response in abundance not only to slope parameters (slope tilt, elevation) but also to nitrogen content and erosion rate (Figure 8). Less abundant species typically showed a significant response to only one or a few of these factors.

DISCUSSION

In addition to reducing water erosion through concurrent cultivation of two crops, anti-erosion strip cropping increases the heterogeneity of agricultural landscapes. Since both landscape homogeneity and erosion can negatively impact associated species, the results of this two-year study in Bošovice demonstrate that ground beetle diversity and abundance were enhanced by both increased heterogeneity and the reduction of water erosion.

In-field heterogeneity increased by soil-conserving strip cropping. Intensive agriculture is associated with vast homogeneous areas featuring low crop diversity, which negatively impacts associated animal species (Robinson & Sutherland 2002; Elmquist et al. 2023). While the primary goal of anti-erosion strip cropping (SC) is soil protection, a significant co-benefit is the increased heterogeneity of the field's vegetative cover.

Our results show that both ground beetle diversity and abundance were higher in SC areas, aligning with studies confirming that increasing crop species richness benefits associated fauna at both the landscape scale (Sirami et al. 2019; Priyadarshana et al. 2021) and within polycultures or strip-cropped fields (Ditzler et al. 2021; Alarcón-Segura et al. 2022; Cuperus et al. 2024).

Interestingly, diversity on the original control plot rose to the level of long-term SC areas within the first year of conversion (Table S1 in ESM). However, abundance followed a different trend, remaining significantly lower than in long-term SC areas and statistically similar to the new control plot. This immediate rise in diversity may be explained by more colonizing species finding suitable conditions and balanced resources due to increased food and cover variety. Conversely, abundance likely remained low

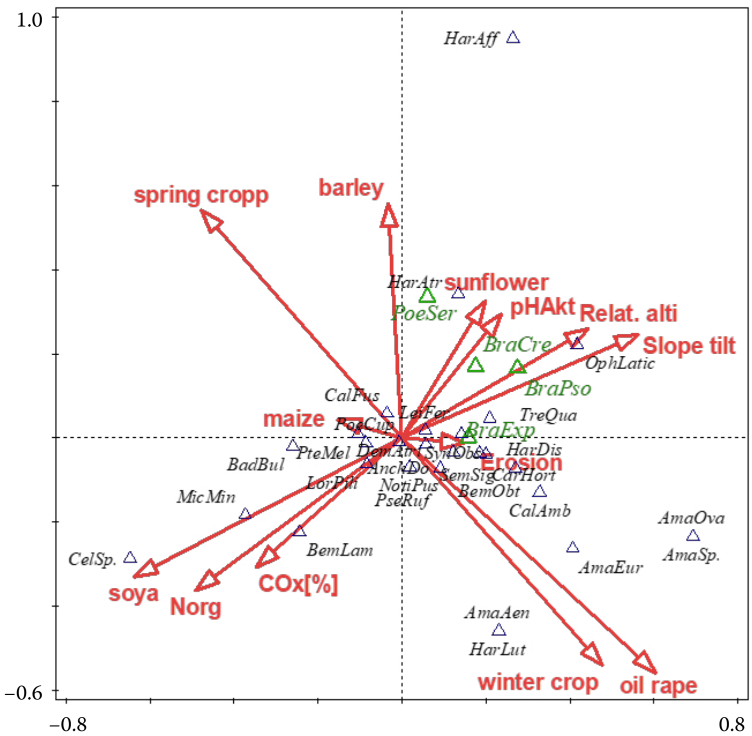

Figure 7. Ordination plot showing the effect of environmental variables on the species composition of ground beetle communities, restricted to production areas only
Species of nature conservation interest are highlighted in green (explained cumulative variation: axis 1 – 3.8%; axis 2 – 5.84%); species of conservation concern are highlighted in green (for abbreviations, see Table S6 in ESM)

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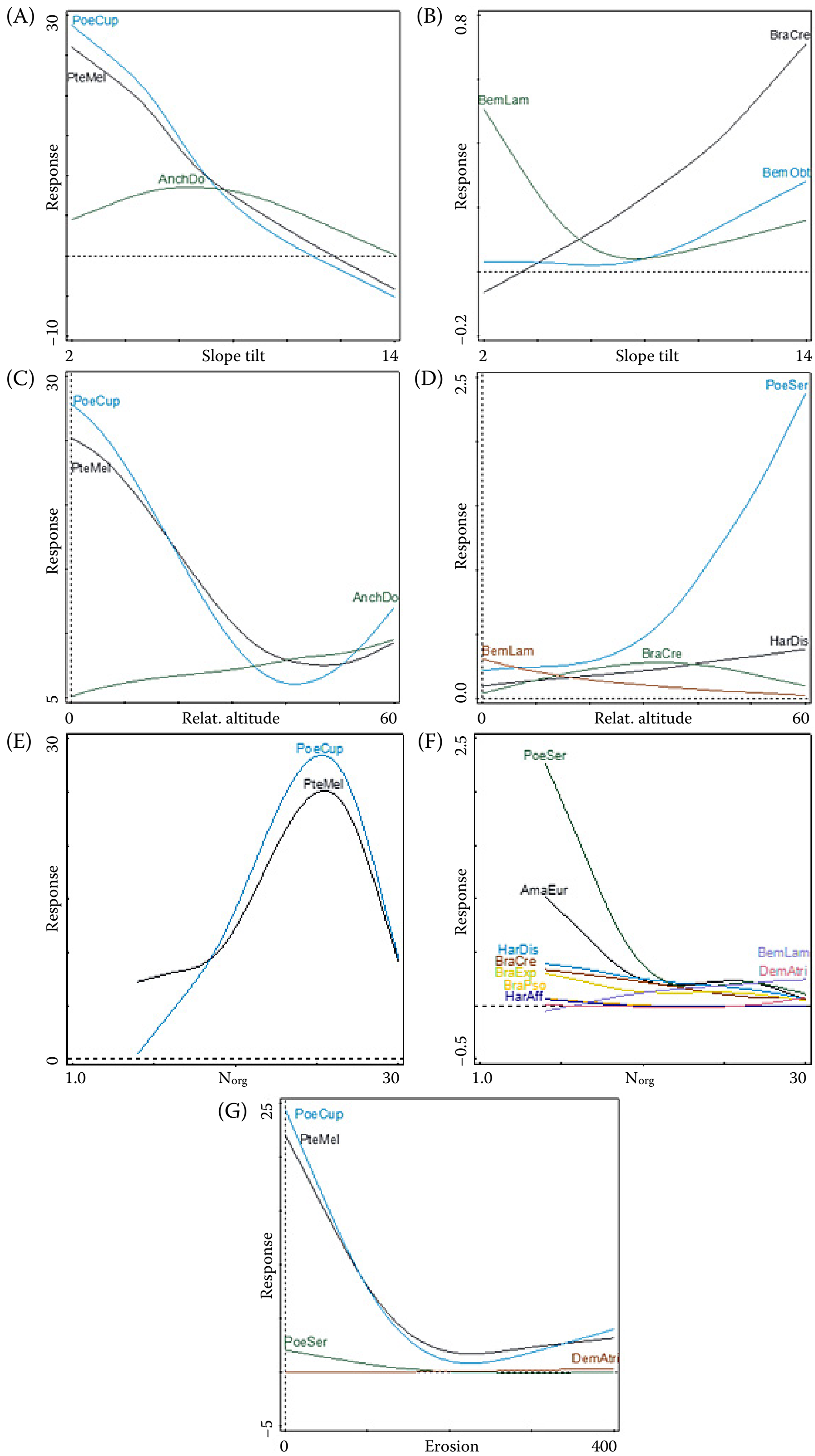

Figure 8. Generalised additive models (GAM) showing response curves of ground beetle species with a significant relationship to the slope gradient (A, B), the relative elevation gradient (C, D), the soil organic nitrogen content gradient (E, F) and long-term potential soil erosion gradient (G)

For abbreviations, and *F* and *P* values see Tables S6 and S7 in ESM

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due to the legacy of conventional management and high erosion rates in previous years, which suppressed population sizes.

Another potential factor for differing abundance is the distance to source habitats, specifically permanent grassland and windbreaks. While these habitats directly bordered the long-term SC field, potentially increasing abundance via the spill-over effect, the nearest trap was approximately 250 m from the boundary. Given that spill-over influence typically drops sharply within dozens of meters (Anjum-Zubair et al. 2010; Boetzl et al. 2018; Jowett et al. 2019), a significant impact on our results is unlikely. It is more probable that the positive effect of SC on abundance, similar to other management changes, requires more time to manifest (MacLeod et al. 2004; Veselý & Šarapatka 2008).

The higher diversity in SC areas likely stems from different crops supporting distinct communities through varying food resources, microclimates, and stand structures. Furthermore, different crops involve specific management timings for fertilisation and pesticide application (Holland & Luff 2000; Smith et al. 2008; Randall & Smith 2020; Elmquist et al. 2023). These strips may enrich each other via spill-over, increasing overall field diversity (Cuperus et al. 2024). Our CCA results confirm this, showing that both crop species and crop type (winter vs. spring) significantly impacted the ground beetle community (Tables S7, S8 in ESM).

Luff (2002) suggests that crop type (spring vs. winter) often has a greater impact on diversity than the specific species, largely due to the timing of disturbances and the phenology of individual beetle species (Holland & Luff 2000; Benton et al. 2002; Smith et al. 2008). This is evident in our 2024 results, where abundance was higher in winter crops. The low abundance in soybean strips, caused by accidental herbicide application and subsequent resowing, further demonstrates that one strip can serve as a refuge during disturbances in the adjacent strip, thereby enhancing ecosystem stability (Gaba et al. 2014; Cuperus et al. 2024).

Impact of erosion reduction by strip cropping. Studies on soil fauna suggest that eroded fields typically exhibit higher abundance at the foot of slopes due to the accumulation of organic matter or the passive transport of individuals by surface runoff (Atlavinytė et al. 1974; Pimentel & Kounang 1998; Tuf et al. 2015). Although anti-erosion SC improves water infiltration and should theoretically reduce such transport, our results showed no significant interaction between management and slope position for ground beetle abundance. The SC area exhibited higher abundance in the lower slope positions (Figure 6).

The lack of this trend on control plots may be due to trap placement, as they were not located at the absolute base of the slope (Figure 1). Since potential erosion was not a significant factor when accounting for other variables (Table S8 in ESM), the higher abundance at the lower slope positions is likely driven by soil properties – specifically increased organic matter, which is closely linked to ground beetle abundance (Pietrasko & De Clercq 1982; Vician et al. 2015; Aldebron et al. 2020). However, the lower abundance at the upper slope positions might still be partly attributed to past erosion and runoff.

In contrast, the interaction between slope position and management significantly influenced diversity (Figure 3). In the SC area, diversity was higher at the upper slope, whereas on control plots, it was lower. This suggests that SC mitigates erosive stress, allowing erosion-sensitive species to persist (Pimentel & Kounang 1998; Baxter et al. 2013; Orgiazzi & Panagos 2018). For example, GAM results showed that *Poecilus sericeus* – xerophilous species, vulnerable according to the national Red List – exhibited a strong affinity for higher altitudes and low potential erosion (Figures 8D, G). This indicates that SC directly supports species of conservation concern by creating stable niches. Other protected species, such as those of the genus *Brachinus*, were also more frequent in long-term SC areas.

GAM also revealed positive correlations between higher relative altitude and xerophilous species such as *Anchomenus dorsalis*, *Brachinus crepitans*, and *Harpalus distinguendus*. Their presence at upper slope positions may be driven by microclimate or competitive exclusion from the more productive lower slopes, where dominant species like *Pterostichus melanarius* and *Poecilus cupreus* thrive due to higher nutrient availability and moisture (Lindroth et al. 1992; Hůrka 1996).

Interestingly, *B. crepitans* showed an affinity for steeper slopes and nitrogen-poor soils (Figures 8B, F). This suggests a preference for sites historically depleted by erosion, which often feature the sparse vegetation this species prefers (Lindroth et al. 1992). While *P. sericeus* prefers nutrient-poor sites with low current erosion risk, *B. crepitans* appears to be a capable colonizer of both currently and historically

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eroded areas. Similarly, *A. dorsalis* showed an affinity for moderate slopes and lower nitrogen content, likely occupying these niches after being competitively excluded from the nutrient-rich lower slopes by *P. melanarius* and *P. cupreus*.

CONCLUSION

This study shows that soil-conserving strip cropping can positively affect ground beetle communities in sloping arable fields. Over two growing seasons, strip-cropped fields supported higher diversity than conventionally managed fields, and long-term implementation was also associated with higher abundance. The observed patterns indicate that the effect of strip cropping is linked not only to erosion mitigation, but also to increased crop heterogeneity within the field.

Our findings also suggest that this management may reduce the negative effects of slope-related environmental stress, particularly at upper slope positions, and may create suitable conditions for species of conservation interest. In this way, strip cropping can enhance the ecological value of intensively managed farmland while maintaining its primary soil-protective function.

By linking erosion control with biodiversity responses, this study extends current knowledge on the multifunctionality of anti-erosion practices in agricultural landscapes. Soil-conserving strip cropping can therefore be considered a promising tool for combining soil protection with the support of aboveground arthropod diversity in erosion-prone cropland.

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