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ORIGINAL ARTICLE

Effect of buffer strips along small watercourses on farmland spiders (Araneae) and ground beetles (Carabidae)

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Abstract. Buffer strips along small waterways that are adjacent to arable land are important for improving water quality and are common measures in agri-environmental schemes. To assess their contribution to arthropod species richness (alpha and gamma diversity) and differences in assemblages (beta diversity) we used pitfall traps to catch arachnids and ground beetles at 40 fields in four regions across Bavaria, Germany, during two or three one-week sampling periods in summer. A permanent vegetated buffer strip was present on 25 of the study fields, 15 were cropped to the field border adjacent to the waterway. Trapping was conducted in the riparian field border, the buffer zone (with or without an established buffer strip), the field edge about 15 m distant to the field border and in the field centre in 80 m distance. Results indicated that alpha and gamma diversity were lowest in the field centre, and the riparian field border had the highest species richness of arachnids. Alpha diversity of ground beetles and spiders was not enhanced in fields with a buffer strip and the buffer strip did not have significantly higher species richness than cropped fields at the same field position. In contrast for ground beetles a higher species richness was observed in the unbuffered field border. An indicator species analysis showed that most of this effect was due to spillover of eurytopic arable species from the neighbouring field. For ground beetle assemblages buffered riparian field borders showed a higher dissimilarity to the other sampled field positions than riparian field borders without an adjacent buffer strip. We conclude that the establishment of buffer strips altered the faunal composition within the buffered riparian field border habitat in summer. We discuss ecological consequences, such as increased beta-diversity and changes in competition, which make buffer strips an important component of the preservation of biodiversity in agricultural landscapes.

INTRODUCTION

Landscapes with intensive crop production must balance trade-offs between agricultural efficiency and ecological sustainability (Power, 2010). In these landscapes, buffer strips are a key element for protecting watercourses and ensuring high water quality (Stutter et al., 2012; Cole et al., 2020). Buffer strips can be defined as land that is subject to management restrictions (Golkowska et al., 2016). In the agricultural context this ranges from regulations on fertilization, the use of plant protection products and soil tillage to the prohibition of arable cultivation. Especially in hilly landscapes with loess soils prone to erosion, the establishment of untilled vegetation beside watercourses is essential to maintain the health of downstream aquatic ecosystems (Lind et al., 2019). Benefits to biodiversity in freshwater ecosystems are expected primarily through reduced inputs of sediments, pesticides and nutrients into waterbodies, which transport these substances far downstream from their sources. In 2018 European Environment Agency (EEA) reported that more than half of rivers failed to achieve the desired good ecological status. However, observed increases in freshwater insect abundance in the northern hemisphere may be the result of improvements in water quality (van Klink et al., 2020). The European green deal policies focus on reducing primary sources of input, highlighting measures including buffer strips, contour farming, and fallows (Bieroza et al., 2021). In the European Union the importance of riparian buffer strips is underscored by various directives and regulations aimed at promoting sustainable practices and preserving the integrity of water ecosystems. The European Water Framework Directive (WFD, 2000), a cornerstone of European water policy, emphasizes the need to achieve good ecological status in surface waters. Riparian buffer strips are integral to this strategy acting as multifunctional tools that mitigate the impact of agricultural activities on water quality. Additionally, the common agricultural policy in Europe recognizes the role of agri-environmental measures in achieving both agricultural productivity and environmental conservation. Member states are encouraged to implement buffer measures to enhance biodiversity and water quality, buffer strips align seamlessly with these objectives.

Buffer strips not only play a pivotal role in safeguarding the biodiversity of water ecosystems but also influence the field margin adjacent to the streamside vegetation. Moreover, riparian buffer strips serve as habitat for many plant and animal communities, contributing to the overall ecological richness of the landscape (Cole et al., 2020). Benefits of grassy strips and grassland remnants in the agrarian landscape on the biodiversity of arthropods are well documented (Marshall et al., 2002; Dicks et al., 2020; Massaloux et al., 2020). However, newly established grassy strips may not necessarily provide the same levels of animal biodiversity as hedges or fields (Ernoult et al., 2013). The fauna of riparian buffer strips adjacent to arable land has been investigated using methods such as pitfall traps (Stockan et al., 2014; Nelson et al., 2018), sticky cards (Nelson et al., 2018) and window traps (Gilbert et al., 2015) focusing on different indicator species groups such as Hemiptera (Gilbert et al., 2015), natural enemies (Nelson et al., 2018) and ground beetles (Stockan et al., 2014). In Scotland, the ground beetle fauna of unbuffered and fenced buffered margins adjacent to arable land or improved pasture was investigated (Stockan et al., 2014). Unbuffered sites showed a higher species richness and they concluded that riparian buffer strips do not create the quality of habitat required by truly riparian species. Building on these results, our study examined not only the riparian field border but also the established wider buffer strip and the adjacent field, reflecting the conditions of small watercourses in intensive agricultural landscapes in Bavaria. Effective options for enhancing river habitats include riverflow restoration and the establishment of woody plants (Cole et al., 2020; Popescu et al., 2021). In Bavaria grassy buffer strips have become the predominant solution, supported by recent legislation mandating a 5-meter buffer along natural water flows and funding them through agri-environmental schemes in various widths.

Species richness is just one of several indicators for evaluating habitat quality, especially when comparing habitats with varying disturbance levels, as disturbances can sometimes lead to increased species richness (e.g. Murphy & Romanuk, 2014). A more nuanced understanding can be gained by studying species compositions and their differences at field and landscape scales, analogous to beta-diversity. Jowett et al. (2019) proposed a single-species approach, highlighting that individual species responses to habitat changes are complex and not fully understood, particularly for arthropods. Ground dwelling carabid beetles and spiders were selected as well-established indicator organisms, as they offer valuable insight into the health and function of ecosystems (Holland et al., 2002; Horne, 2007; Makwela et al., 2023) and can be efficiently sampled with pitfall traps. Earlier studies have shown that ground dwelling carabid beetle and spider communities respond to habitat change from annual to perennial land use (Perner & Malt, 2003), and their sensitivity to habitat adjacency, isolation, size and connectivity has been demonstrated in various studies (Niemelä, 2001; Fischer et al., 2013). Finally, these organisms fulfill important ecological functions as top-down regulators in agricultural ecosystems. Harvestmen (Opiliones) and pseudoscorpions (Pseudoscorpiones) are rarely used as bioindicators, and little is known about their occurrence in the agricultural landscape. However, previous studies have shown partial sensitivity to microclimate, vegetation parameters and litter layer (Yamamoto et al., 2001; Litavský et al., 2024), factors that tend to be more pronounced in buffer strips than in croplands.

The main study objective was to investigate the effects of vegetated buffer strips on arthropod diversity beyond their significance for water protection as part of the Agri-Environment Schemes in Bavaria, southern Germany. To do so, we studied the effect of the buffer strips on species richness, community composition, and the occurrence of individual species of ground-dwelling beetles and arachnids in the adjacent habitat. The main aims of the study were to:

(1) examine the effect of buffer strips on biodiversity considering different field positions and different scales (alpha, beta and gamma diversity)

(2) determine differences of species communities inside the field border with and without adjacent buffer strips

and (3) identify species that exhibit different occurrence and activity densities in fields with and without buffer strips in the temporal and spatial scope of this study (referred to as "responsive species").

MATERIAL AND METHODS

Study sites, study design

The survey involved ten arable fields in each of four regions in South Germany (Fig. 1). The study regions were situated in the hilly landscape of Lower and Upper Bavaria which are especially prone to erosion and therefore have a high need for the expansion of water protection measures such as buffer strips. In 2019, the study areas were located in the Dingolfing-Landau district (river Aiterach and tributaries) and in the Passau district (river Kleeberger Bach and tributaries). In 2020, sample areas were selected in the Kelheim district (river Laaber and tributaries) and in the Dachau district (river Glonn and tributaries).

Arable fields directly adjacent to a watercourse were selected as study sites within the study regions. The distance between studied fields varied from 100 m to 8.2 km within each study region. The watercourses varied in size, ranging from small ditches with only temporary waterflow near roadways to small rivers with a width of up to 5 m. Only fields that met the following criteria within a 50 m radius around trapping locations were selected: more than 60% arable land, less than 10% forest, hedges, woody remnants, settlements, and grassland. Crops of the fields were mainly cereals (Supplement 1). There was a slightly higher share of cereal fields in the control plot without buffer strips.

On every field a set of 16 pitfall traps was established in a gradient with four zones from the watercourse to the field centre (Fig. 2). Four pitfall traps spaced 5 m apart were placed in each of the four zones: (a) top edge of the embankment adjacent to the water course (riparian field border); (b) in 5 m distance from the top edge of the embankment (buffer); (c) in 12 m distance to the

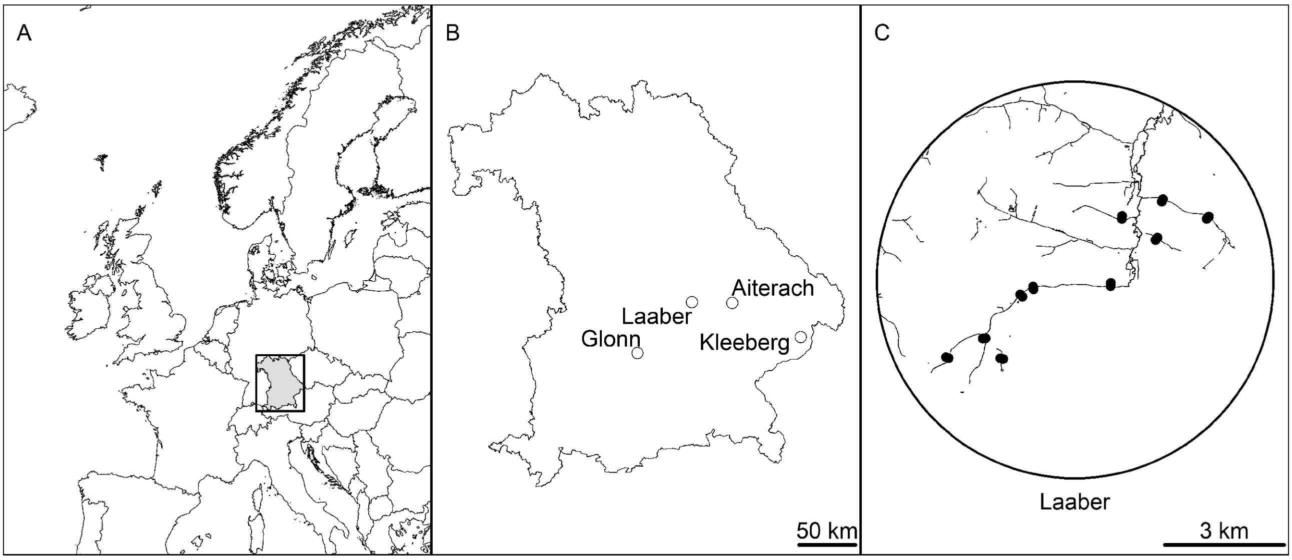

Fig. 1. Sampling locations of the survey. A – Location of Bavaria in Europe, B – Location of study regions in Bavaria, C – Location of study sites in the watershed of the river Laaber.

embankment or in 2 m distance from the buffer strip boundary (field edge); and (d) in 80 m distance from the top edge of the embankment in the field centre (field centre). As the buffer strips were about 5 to 20 m wide (mean 10 m) and the field borders behind the edge of the embankment were significantly narrower than 2 m, this resulted in very similar distributions of the pitfall traps for each field. In 15 fields no buffer strip was established in the year of observation. In 25 fields a buffer strip was present. The time since establishment of the buffer strip ranged between one and nine years, except one buffer strip being present since more than 30 years. Since a large proportion of the buffer strips was created one or two year before the survey, our study represents rather young stages of development. The sown seed mixtures were mainly grass species (mainly rye grass *Lolium perenne* L., Poaceae) and grass clover mixtures (*Trifolium* sp., Fabaceae), but also seed mixtures of flowers (three strips) and lucerne (*Medicago sativa* L., Fabaceae, one strip,) were part of the study. Mainly depending on the age and management of the buffer strip, the plant community at sampling time differed from the sown seed mixture. Notably, three strips had a high share of stinging nettle (*Urtica dioica* L., Urticaceae) and/or reed (*Phragmites australis* (Cav.) Trin. ex Steud.). The field edge position was established to investigate whether the established buffer strip affects the composition of adjacent field fauna. The field centre allowed us to check

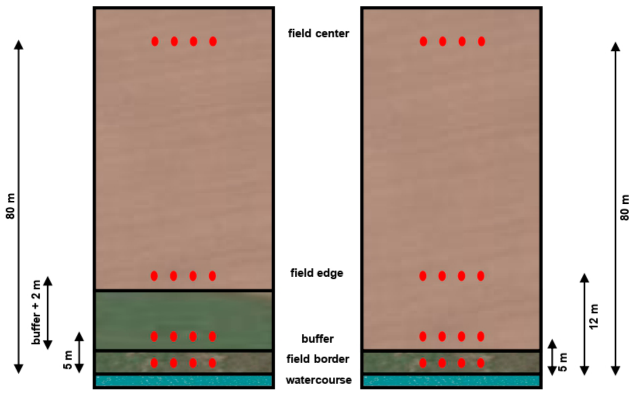

Fig. 2. Position of pitfall traps in a field with an established buffer strip (left) and a field without established buffer strip (right). Distances in relation to the top edge of the river embankment.

for field specific differences and to stabilize models for management (soil cultivation, crop, intensity) and site condition effects (exposition, soil properties).

Pitfall trapping and species identification

Pitfall traps with an opening diameter of 7.2 cm were used to study the epigeic ground beetle and arachnid fauna. Traps were filled with 0.3 l of 25% salt solution and covered by a grid with a mesh size of about 1 cm and a roof of acrylic glass about 10 cm above ground. Sampling was done in three trapping occasions of weeklong sample intervals in June, July and September in 2019 and 2020. Another week of sampling subsequent the sampling intervals served as an alternative sample. For arachnids only the first two sampling intervals (June, July) could be determined to species level. Five pitfall samples (Laaber: 2, Kleeberg: 2, Glonn: 1) had to be excluded due to losses of ground beetle material. In this case, samples from the same site and the same period as the missing samples were replaced with material from the following week for ground beetle data. Species identification was carried out by experts using the following keys: spiders (Araneae) Nentwig et al. (2023), harvestman (Opiliones) Martens (1978), and pseudoscorpions (Pseudoscorpiones) Mahnert (2004), ground beetles (Carabidae) Freude et al. (2012). All arachnids not determined to species level were excluded from analysis of assemblages. For species richness estimate, arachnids not determined to species level were considered, if no other species on a higher level of identification was present in the sample, as proposed by the method of Burmeister & Panassiti (2022).

Data analysis

The raw dataset is published in Burmeister et al. (2025). The data was pooled over the three (ground beetles) and two (arachnids) sampling periods, resulting in a sample size of 160 for both groups (4 distances in 10 sites in 4 regions). Species richness was analysed with mixed models with a Poisson error distribution (R-package lme4, v. 1.1-34; Bates et al., 2015). Field nested within study region was included as a random factor. Study region is an environment factor (time : space) because the study year was confounded with the study region. Fixed effects were the position of the traps within the field (riparian field border, buffer, field edge, field centre) and the presence of a bufferstrip on the field (yes/no). Model assumptions were checked using residual plots and the Dharma R-package (v. 0.4.6; Hartig, 2022). Overdispersion was not found for all models (R-package blemeco, v. 1.4; Korner-Nievergelt et al., 2015). Spatial autocorrelation was checked for model residuals with Moran's I (Gittleman & Kot, 1990). Marginal and conditional pseudo R^2 values were calculated to get an overall estimation of model fit (R-package piecewiseSEM, v. 2.3.0; Lefcheck, 2016). Likelihood ratio tests were conducted to verify the usability of the model (full model M_{full} vs. null model M_{null}), to check for the importance of interaction effects (M_{full} vs. no-interaction model M_{nox}) and to clarify significant contribution of the main effects to the explained variance in the model. Differences between the fixed effects including the interaction were analysed by contrasts on the marginal means (R-package emmeans, v. 1.8.7; Lenth, 2023). As the interaction effect was part of the study design, contrasts included the interaction effect. The significance level was 0.05 and tukey method was used for post hoc tests on fixed effects.

To estimate gamma diversity species accumulation and extrapolation curves were conducted with the iNEXT package (v. 3.0.0; Hsieh & Cao, 2016). In this context, γ-diversity refers to the total species richness across all fields within a treatment group. Fields were used as sampling units for each field position and for fields with buffer strips and without separately. Curves were extrapolated to 30 sampling units and treatments standardized to 15 sampling units. This allowed us to compare the expected species richness (γ-diversity) across treatments at a standardized sampling effort.

To detect differences in the species assemblages and to check if there was a reasonable effect of the buffer strip on ground beetle and arachnid species assemblages inside the riparian field border the Bray Curtis distance was calculated. For each field the dissimilarity between the riparian field border and the other field positions was calculated. The differences within treatments were tested with mixed models, with the same model structure as above, but assuming a gaussian error distribution. The comparison of assemblages between the field centre and the other field positions can be found in Supplement 2. Examining replacement and richness components in beta diversity allows for a more nuanced understanding of community turnover (Legendre, 2014). While replacement reveals the substitution of species from one site to another, richness highlights the unique species composition within each site, collectively providing insights into the dynamic processes shaping biodiversity patterns across different habitats. Beta diversity was compared between riparian field borders without and with buffer strips using beta.multi function (R-package BAT, v. 2.9.4).

The frequency of species in Germany was obtained from the German red lists for ground beetles (Schmidt et al., 2016) and arachnids (Blick et al., 2016; Muster & Blick, 2016; Muster et al., 2016). The ordinal frequency was ranked from highly abundant (1), abundant (2), moderately abundant (3), rare (4), very rare (5), extremely rare (6), the community weighted mean computed and the result log-transformed to get an indicator of the constitution of the captured fauna from rare to abundant species. Community weighted means have been shown to distinguish species assemblages along ecological gradients of land use intensity (Hanson et al., 2016). Result plots are provided in Supplement 4.

Finally, to identify which species differentiate between buffered and unbuffered sites (further referred to as responsive species) we conducted an indicator species analysis (Dufrêne & Legendre, 1997; R-package inidicspecies v.1.7.13; De Cáceres & Legendre, 2009) separately for each distance. All species with less than ten total individuals and occurring on less than five sites were removed from analysis. Monte Carlo sampling was done with 100,000 iterations. Obtained p-values were adjusted using the false detection rate (Waite & Campbell, 2006) and species with a distribution that deviated from random on a significance level of 0.05 were reported.

RESULTS

A total of 18,150 ground beetles belonging to 102 species were captured within pitfall traps during the three weeks of sampling. Arachnids accounted for 32,773 individuals and a total of 124 species during the two weeks of sampling. Species richness per sampled field for ground beetles and arachnids was on average 31 and 33, respectively.

Alpha diversity

The full model for ground beetle species richness explained significantly more variation than the null model (M_{full} vs M_{null}: $\chi^2 = 19.2$, $p = 0.008$, marginal R^2 0.08). The interaction between field position and the presence of a buffer strip was significant, as confirmed by likelihood ratio tests (M_{full} vs M_{nox} $\chi^2 = 9.0$, $p = 0.030$). The comparison of estimated marginal means over the different distances to the watercourse showed a significant difference for the riparian field border, with significantly higher ground beetle species richness in unbuffered riparian field borders compared to those bordered by a buffer strip ($z = 2.98$, $p = 0.003$, Fig. 3). The field centre of the field gradient without buffer strip had a significant lower species richness than the riparian field border ($z = 2.64$, $p = 0.041$).

For arachnid species richness the full model explained significantly more variation than the null model (M_{full} vs M_{null}: $\chi^2 = 25.5$, $p < 0.001$, conditional R^2 0.28), but interactions between field position and the presence of a buffer strip were not significant (M_{full} vs M_{nox}: $\chi^2 = 1.4$, $p = 0.71$). The most important factor for spider species richness was the distance from the riparian field border. Species richness decreased from riparian field border to the field centre. The comparison of the marginal means regarding the effect of the buffer strip for different field locations resulted in no significant differences. Even though we found significantly higher species richness of arachnids in the riparian field border compared to the field centre for fields with buffer strip ($z = 3.40$, $p = 0.004$) and those without ($z = 3.20$, $p = 0.008$) the differences amounted to a maximum of five species.

Gamma diversity

Species accumulation curves for ground beetles were similar for the buffer strip and the riparian field border in fields with buffer strip (Fig. 4A). For fields without buffer strip only the riparian field border showed notable differences compared to the other field positions (Fig. 4B). By comparing fields with and without buffer strips at 15 sampling units, riparian field borders without an adjacent buffer strip had a higher ground beetle species richness by about eight species. In contrast to unbuffered field borders, the establishment of a permanently vegetated buffer strip resulted in a higher ground beetle species richness (γ-diversity) by about 13 species. Only a slightly higher estimated species richness between the fields with buffer and those without could be observed in the field edge (two species). The rarefaction estimation for ground beetle spe-

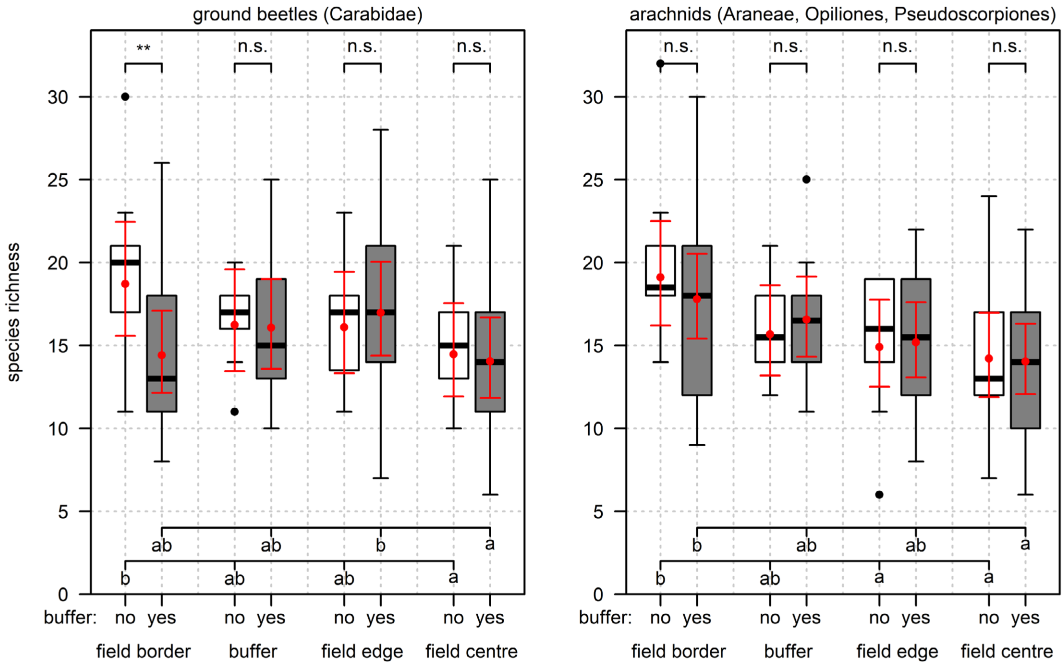

Fig. 3. Boxplots of species richness for ground beetles (left) and arachnids (right) in 25 fields with buffer strip (grey boxplots) and 15 fields without buffer strip (white boxplots). Red dots and intervals correspond to the estimated marginal means and their 95% confidence interval of the mixed model. Significance of differences was obtained for the comparison of fields with and without buffer strips (brackets to the top) and a separate comparison of location within the two groups (brackets below), ** $p < 0.01$, letters show significant differences within group levels (used significance level was 0.05).

cies richness in field centres for fields with an established buffer strip indicated a lower species richness by about seven species in comparison to the field edge position. The field centres without buffer strip were similar in ground beetle species richness but showed a steeper increase. The extrapolation showed high uncertainty and unsaturated species curves, particularly for fields without buffer strip.

The species accumulation curves for arachnids indicated distinctly higher gamma diversity of the riparian field border habitat compared to the buffer strip, which again was

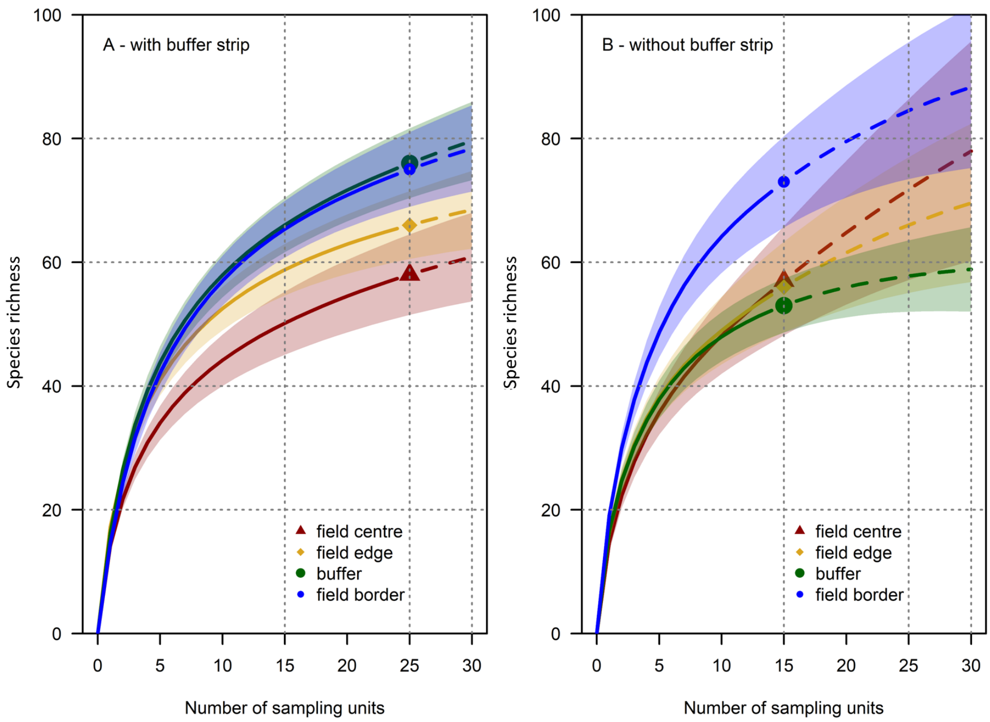

Fig. 4. Species accumulation curves for ground beetles for fields with buffer strip (A) and fields without buffer strip (B). Species richness was extrapolated to 30 sampled fields, interpolation to the same sampling effort (15 fields) is marked with a vertical line at 15 sampling sites.

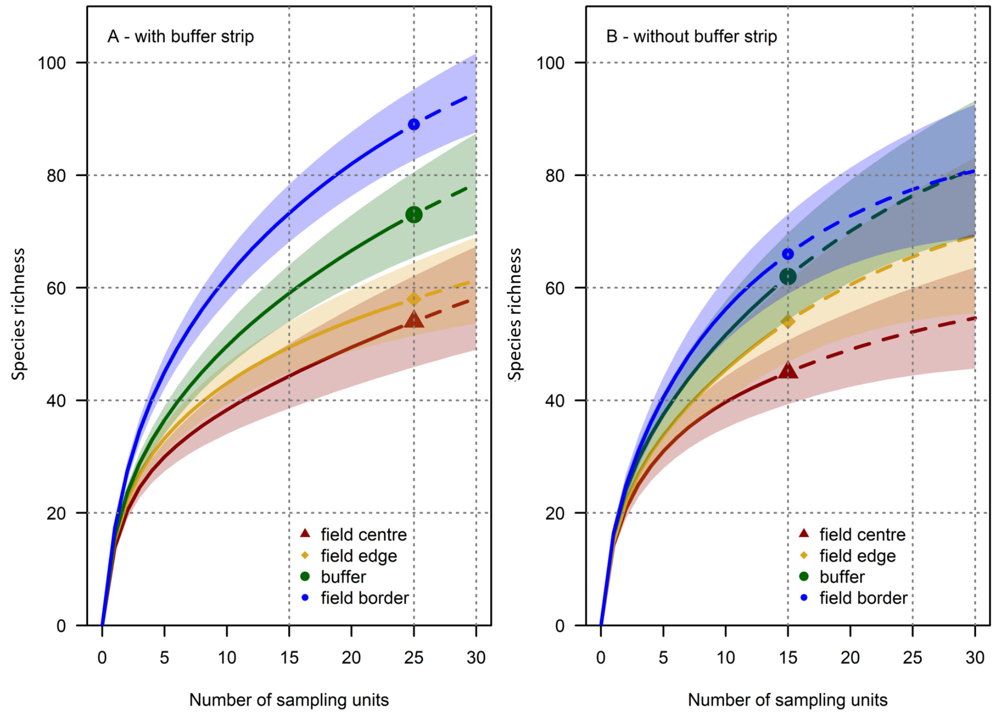

Fig. 5. Species accumulation curves for arachnids for fields with buffer strip (A) and fields without buffer strip (B). Species richness was extrapolated to 30 sampled fields, interpolation to the same sampling effort (15 fields) is marked with a vertical line at 15 sampling sites.

clearly higher than the field centre and the field edge samples in fields with an established buffer strip (Fig. 5A). Remarkably, the comparison of fields without (Fig. 5B) and with buffer strip (Fig. 5A) at 15 field sample units indicated that estimated riparian field border arachnid species richness was about seven species higher when a buffer strip

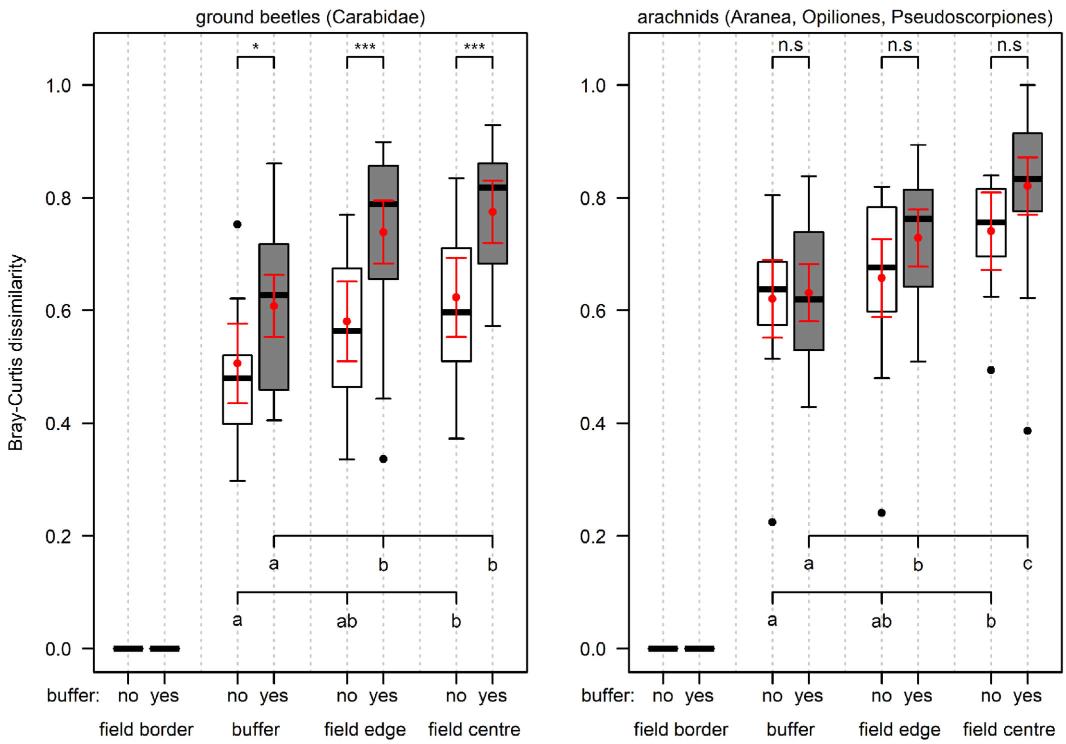

Fig. 6. Boxplots of the Bray-Curtis dissimilarity Index of riparian field borders to the different sampling locations of the gradient for ground beetle (left) and arachnid (right) assemblages in 25 fields with buffer strip (grey boxplots) and 15 fields without buffer strip (white boxplots). Red dots and intervals correspond to the estimated marginal means and their 95% confidence interval of the mixed model. Significance of differences was obtained for the comparison of fields with and without buffer strips (brackets to the top) and a separate comparison of location within the two groups (brackets below), *** p < 0.001, * p < 0.05, letters show significant differences within group levels (used significance level was 0.05).

Table 1. Average and variance of partitioned Beta diversity (species replacement, richness difference) for field borders with and without buffer strip for ground beetle and arachnids.

Taxon	Component	with buffer strip		without buffer strip	
		Average	Variance	Average	Variance
Ground beetles	Total	0.889	0.048	0.821	0.016
	Species replacement	0.526	0.028	0.458	0.009
	Richness difference	0.364	0.020	0.364	0.007
Arachnids	Total	0.846	0.033	0.819	0.019
	Species replacement	0.468	0.018	0.425	0.010
	Richness difference	0.378	0.015	0.395	0.009

was established. On the other hand, gamma diversity at the field edge position was unexpectedly about five species lower near the established buffer strip. Again, the extrapolation for the fields without buffer strip showed unsaturated species curves, so differences between field positions could not be verified.

Beta diversity

The dissimilarity (Bray Curtis) of ground beetle and arachnid communities between the riparian field border and the other positions of the traps calculated on every single field, is shown in Fig. 6. The models indicated no significant interaction effect for both species groups (ground beetles: M_{full} vs M_{null}: $\chi^2 = 48.4$, $p < 0.001$; M_{full} vs M_{nox}: $\chi^2 = 1.0$, $p = 0.59$; arachnids: M_{full} vs M_{null}: $\chi^2 = 36.0$, $p < 0.001$; M_{full} vs M_{nox}: $\chi^2 = 1.7$, $p = 0.44$). For dissimilarity of species composition, the closer to the riparian field border reference the lower was the dissimilarity index. This was found both in fields with buffer strips and in those without and for both species groups examined. Significantly higher differences in species composition were found between fields with an established buffer strip and those without when comparing the field centre ($t = –3.44$, $p < 0.001$), the field edge ($t = –3.59$, $p < 0.001$) and the buffer position ($t = –2.31$, $p = 0.023$) with the riparian field border. Even the buffer strips themselves showed more divergent assemblages to the riparian field border assemblages. The Bray-Curtis distance of arachnid assemblages showed no significant differences between fields with or without buffer strips, but a tendency to higher dissimilarity for field centre and the field edge to the field border comparing fields with and without buffer strips was found ($t = –1.88$, $p = 0.063$, Fig. 6). The dissimilarity with the field centre as reference can be found in Supplement 2. In brief, ground beetle and arachnid assemblages were more divergent from the field centre at the established buffer strips.

The mean beta diversity was higher in buffered than in unbuffered riparian field borders for both ground beetles and arachnids (Table 1). In the ground beetle communities, the beta-diversity of richness differences was nearly the same in riparian field borders with and without buffer strips and the main difference in total beta diversity was due to higher species replacement. The differences in beta diversity were less pronounced for arachnid communities, but species replacement also accounted for the larger share. A slightly higher proportion of species replacement was observed in riparian field borders with an established buffer strip. The presence of buffer strips therefore resulted in higher beta-diversity of species communities in the buffered riparian field border. The analysis of the community weighted means of ranked frequency values confirmed a lower share of common ground beetles in the presence of a buffer strip (details in Supplement 4). In addition, the absolute number of individuals classified as highly abundant and abundant in Germany was, on average, 30 fewer in buffer strips and 20 fewer in buffered riparian field borders than in the fields without buffer strip during the three-week survey.

Responsive species

The identification of responsive species, which was conducted to reveal species relevant for the dissimilarities in species composition between fields with and without buffer strips at each field position within the field, reported eleven species of ground beetles and two spider species (Table 2). Remarkably, three species showed a significant response to unbuffered field borders: *Poecilus cupreus* (Linnaeus, 1758), *Harpalus affinis* (Schrank, 1781) and *Oedothorax apicatus* (Blackwall, 1850). All are eurytopic species of arable land. We also found eleven responsive species to the buffer field position; however, responsive species at this position for cropped fields (9) outnumbered those for the grassy buffer strip (2). Species in the cropped area were

Table 2. Responsive species for each field position, obtained indicator value with significance level, indication for fields with (buffered) or without buffer strip (unbuffered), and mean activity density in the study.

Field position	Indication for:	Species	Indicator value	Mean activity density (unbuffered / buffered)
Field border	Unbuffered	*Poecilus cupreus* (ground beetle)	0.824 *	3.3 / 0.9
	Unbuffered	*Harpalus affinis* (ground beetle)	0.797 *	3.1 / 0.8
	Unbuffered	*Oedothorax apicatus* (spider)	0.840 .	10.4 / 3.3
Buffer	Unbuffered	*Trechus quadristriatus* (ground beetle)	0.861 *	23.5 / 8.2
	Unbuffered	*Bembidion quadrimaculatum* (ground beetle)	0.849 *	6.9 / 0.8
	Unbuffered	*Pterostichus melanarius* (ground beetle)	0.845 *	25.5 / 10.2
	Unbuffered	*Anchomenus dorsalis* (ground beetle)	0.790 *	7.1 / 2.0
	Unbuffered	*Loricera pilicornis* (ground beetle)	0.761 *	1.9 / 0.3
	Unbuffered	*Bembidion obtusum* (ground beetle)	0.648 *	1.1 / 0.1
	Unbuffered	*Limodromus assimilis* (ground beetle)	0.570 *	1.5 / 0.0
	Buffered	*Anisodactylus binotatus* (ground beetle)	0.774 *	0.2 / 2.9
	Buffered	*Poecilus versicolor* (ground beetle)	0.663 *	0.0 / 0.6
	Unbuffered	*Oedothorax apicatus* (spider)	0.860 .	78.9 / 20.2
	Unbuffered	*Porrhomma microphthalmum* (spider)	0.645 .	0.6 / 0.1

characteristic of arable land, whereas those identified for the buffer strip of grassland. Species responsive to the established buffer strip included a grassland species, *Poecilus versicolor* (Sturm, 1824) and a eurytopic inhabitant of densely vegetated loamy soils, *Anisodactylus binotatus* (Fabricius, 1787).

The evaluation of responsive species across the sampling positions, excluding the buffer strip position, in all 40 fields, is shown in Supplement 3. In total, we found four ground beetles and nine arachnid species with higher activity density in the field centre, five species (three ground beetles and two arachnids) with a significant response to the field edge, six ground beetle species and twelve arachnid species characteristic of the field border in our study. Five of the responsive species from the still cropped buffer strip were identified as "field centre species" [*Trechus quadristriatus* (Schrank, 1781), *Bembidion quadrimaculatum* (Linnaeus, 1760), *Bembidion obtusum* Audinet-Serville, 1821, *Oedothorax apicatus*, *Porrhomma microphthalmum* (Pickard-Cambridge, 1871)]. In addition, *Poecilus cupreus* which had higher abundance in unbuffered field borders, was also characterized as field centre species.

DISCUSSION

Field borders with and without buffer strips showed a higher gamma diversity of arachnids and ground beetles compared to arable fields, highlighting their role as biodiverse habitats in the agricultural landscape. Positive effects of field margins on spiders and ground beetles have been shown in several studies (e.g. Meek et al., 2002; Marshall et al., 2006; Öberg et al., 2007; Barberi & Moonen, 2020; Rischen et al., 2022). The contribution of riparian buffer strips to arthropod biodiversity in the agricultural landscape was not obvious from alpha diversity values (species richness) alone during the summer observation period. In contrast to expectations, species richness of ground beetles and arachnids in the field border was not enhanced by the presence of a buffer strip, and the buffer strip did not harbour a richer species assemblage than the unbuffered field at the same distance from the watercourse. Contrary to expectations, ground beetle species richness was even higher in unbuffered riparian field borders.

However, ground beetle assemblages in riparian field borders differed significantly from those in the field when a buffer strip was established. This result was particularly unexpected, as the perennial vegetation in the buffer strip was more similar to the field border than the annually cropped land. Furthermore, higher beta-diversity was observed in the buffered field borders, mainly driven by greater species replacement among the studied field borders. The activity density of ground beetle species and the community weighted means of their country wide frequency (Supplement 4) revealed fewer common species and fewer arable-land-preferring ground beetles in the buffered field border. Similarly, Stockan et al. (2014) reported higher activity density and species richness of ground beetles in unbuffered riparian margins compared to buffer strips, although their study lacked a comparison with arable field centres and buffer strip species composition.

One limitation of our study was the sampling time. As many surveys have shown, carabid beetles begin to leave their hibernation sites in early spring. Like all types of field margins, buffer strips are expected to provide important hibernation sites (e.g. Dennis & Fry, 1992; Geiger et al., 2009). As we started our study at the end of May (2020) and the beginning of June (2019), this effect could not be evaluated. A slight bias in the selection of crops – as the sample of unbuffered strips had a higher share of rape and sugar beet – did not have a relevant impact on the modelling results (tested by leaving out these crops). The specific design of the study included a high share of young recently established buffer strips. The age of the buffer strip may positively affect species richness as shown by Frank et al. (2012) for wildflower fields.

The identified responsive species for unbuffered field borders are widespread inhabitants of arable land. *Poecilus cupreus*, a spring breeding carnivore, occurs steadily on arable land of all kinds and may spend its entire life cycle within the field (Kromp & Steinberger, 1992). *Harpalus affinis* is also common but less abundant on arable fields (e.g. Kromp, 1990), and uses a wide range of seeds as food resource (e.g. Deroulers et al., 2020; Honek & Jarosik, 2000) beside zoophagous nutrition. *Harpalus affinis* is therefore one of the most abundant ground beetles in field margin habitats (Bennewicz & Barczak, 2020), which could be also shown in this study where highest catches were observed in the buffer strip, the adjacent field edge and the unbuffered field border. Clear preferences for cropped bare ground habitats can be assumed from the literature for *Bembidion quadrimaculatum* (Thiele, 1977), which is identified in our case as responsive species by the comparison of grassy buffer strips to still cropped field margins.

However, the fauna of the field border as well as of the buffer strip was mostly composed of species widespread in the agricultural landscape. Therefore, above mentioned possible effects on biodiversity have to be interpreted with care. Species, associated with wetland and riparian habitats, found only in small numbers on a limited set of field borders were (A) Carabidae: *Chlaenius nitidulus* (Schrank, 1781), *Abax carinatus* (Duftschmitd, 1812), *Panagaeus crux-major* (Linnaeus, 1758) or *Oodes helopioides* (Fabricius, 1792) and (B) Araneae: *Antistea elegans* (Blackwall, 1841), *Arctosa maculata* (Hahn, 1822), *Glyphesis servulus* (Simon, 1881), *Leptorhoptrum robustum* (Westring, 1851) or *Pocadicnemis juncea* Locket & Millidge, 1953 and (C) Opiliones: *Nemastoma dentigerum* Canestrini, 1873. This highlights the importance of the unique configuration of the riverbanks, their size and vegetation. However, these species could not be identified as responsive species, due to their sporadic occurrence only on a few surveyed fields. This is also true for some species which may be considered as beneficiaries of established buffer strips, mainly a wide range of seed eating *Amara* species – *Amara littorea* Thomson, 1857, *Amara plebeja* (Gyllenhal, 1810), *Amara bifrons* (Gyllenhal, 1810), *Amara lunicollis* Schiödte, 1837, *Amara convexior* Stephens, 1828, associated *Brachinus explodens* Duftschmid, 1812, and *Diachromus germanus* (Linnaeus, 1758).

As buffer zones/areas are intended to mitigate the impact of arable land on adjacent, less intensively managed habitats, this study demonstrates that riparian buffer strips, in addition to their main goal of reducing material input to watercourses, also limit the spill over of epigeal arthropods from arable fields. This is evidenced by the fact that species communities in field margins along water bodies with buffer strips were significantly more dissimilar to the community in the field centre than those in field margins without an established buffer strip. By identifying species that responded to the presence of a buffer strip, we confirmed that this was mainly due to the lower activity density of common arable species.

Spill-over from natural habitats to managed areas is well documented in the literature but the dispersal from cropland to natural habitats is less studied (Blitzer et al., 2012). The contact zones of different habitats have been considered particularly species-rich and valuable for biodiversity (e.g. Barberi & Moonen, 2020). On the other hand, there may be increased competition especially in crop production systems and some species may have requirements on the minimum size of undisturbed habitat. The consequences of autochthonous species moving into new habitats and competing with others are rarely documented, although effects of invasive species are known (Kenis et al., 2009). Generalist predators can increase consumer pressure on herbivores through spillover from cropland (Rand & Louda, 2006). Additionally, reproductive interference, as discussed by Hochkirch et al. (2007) and Gröning & Hochkirch (2008), can reduce the fitness of local fauna due to invading arthropods. Increased gene flow and hybridization may further affect closely related species (Larson et al., 2019).

To maintain biodiversity in the agricultural landscape, besides the diversification through smaller field sizes, flowering strips and production integrated measures, buffering of important and sensitive habitats should also be considered. Such buffering may be due to the restriction of tillage, pesticide use and fertilization, such as in the case of riparian buffer strips. Agri-Environmental Schemes should be balanced for these two aspects.

Together with the study of the flying insect fauna on riparian buffer strips in Bavaria (Birnbeck et al., 2025) on the same set of fields, we confirmed a positive effect for the insect fauna by riparian buffer strips. The current study shows that establishment of grassy strips will not simultaneously foster rare species in intensively agricultural landscapes. But one of the major strengths of measures along water bodies is the interconnection with an already existing habitat connecting system (Fermier et al., 2015). By establishing buffer strips across the country, the inevitably existing network of habitats in intensive agricultural landscapes was strengthened, increasing the area of semi-natural habitat adjacent to long existing habitats and refuges in the agricultural landscape surrounding the water bodies. In addition to the shown positive effects on local and regional diversity, we found resource populations in the vicinity for higher specialized species that may become important when considering the development of buffer strip habitats over time.

The vegetation composition of the buffer strips must be considered species-poor in most of the studied established buffer strips, as they were mainly young, not managed for biodiversity purposes, and sown with species-poor seed mixtures. Buffers established by species-rich seed mixtures or natural regeneration containing flowering species are superior to those established with a simple grass seed mixture (Meek et al., 2002; Critchley et al., 2013). But enhancing strip-shaped habitats in agricultural landscapes to promote biodiversity and the natural regulatory services provided by arthropods is still challenging (e.g. Schütz et al., 2022). Further studies should examine the impact of different riparian buffer zone management options on biodiversity.

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Supplement 1

Table S1. Main crops on the sampled fields during the study period (DG – Dingolfing-Landau, P – Passau, K – Kehlheim, D – Dachau).

Crop	Fields with buffer strip					Fields without buffer strip				
	DG	P	K	D	Total	DG	P	K	D	Total
Cereals	4	3	4	5	16	3	2	3	4	12
Maize	1	3	1	0	5	0	1	1	0	2
Legumes	1	0	0	0	1	0	1	0	0	1
Sugar beet	1	0	1	0	2	0	0	0	0	0
Oilseed rape	0	0	0	1	1	0	0	0	0	0
Total	7	6	6	6	25	3	4	4	4	15

Supplement 2

The model for Bray-Curtis dissimilarity of ground beetle and arachnid assemblages relative to the field center showed a significant better fit than the null modell, and a significant contribution of the interaction term to the explained variance (ground beetles: M_{full} vs M_{null} Chisq: 119.4 $p < 0.001$; M_{full} vs M_{nox} Chisq: 15.0 $p < 0.001$; arachnids: M_{full} vs M_{null} Chisq: 104.3 $p < 0.001$; M_{full} vs M_{nox} Chisq: 13.5 $p < 0.01$). For both studied species groups the established buffer strip resulted in a significant higher dissimilarity to the field center assemblages (Fig. S1).

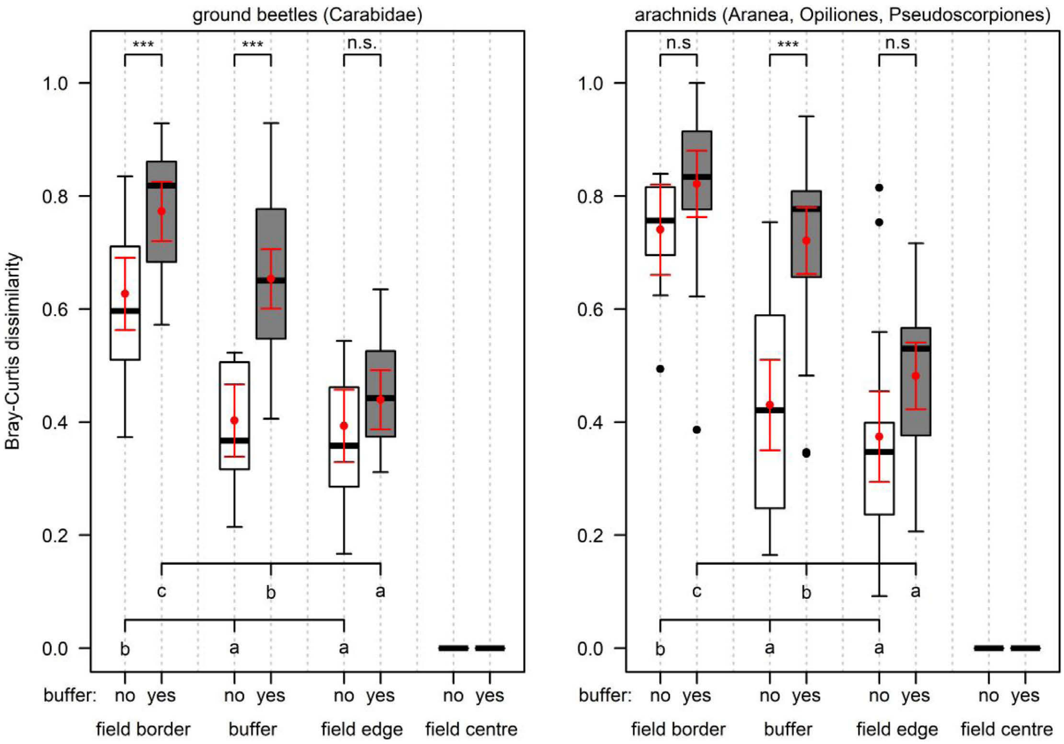

Fig. S1. Boxplots of the Bray-Curtis dissimilarity Index of field centers to the different sampling locations of the gradient for ground beetle (left) and arachnid (right) assemblages in 25 fields with buffer strip (grey boxplots) and 15 fields without buffer strip (white boxplots). Red dots and intervals correspond to the estimated marginal means and their 95% confidence interval of the mixed model. Significance of differences was obtained for the comparison of fields with and without buffer strips (brackets to the top) and a separate comparison of location within the two groups (brackets below), *** $p < 0.001$, letters show significant differences within group levels (used significance level was 0.05).

Supplement 3

Table S2. Results of indicator species analysis for field position, obtained indicator value with significance level density in the study. (*** p < 0.001, ** p < 0.01, * p < 0.05, . p < 0.1)

	Indication for field position	Species	Indicator value
Ground beetles	field centre	*Trechus quadristriatus*	0.714*
		Poecilus cupreus	0.651 *
		Bembidion quadrimaculatum	0.622 .
		Bembidion obtusum	0.586 *
	field edge	*Pterostichus melanarius*	0.657 .
		Clivina fossor	0.555 .
		Bembidion guttula	0.390 .
	field border	*Amara lunicollis*	0.693 ***
		Harpalus latus	0.691 ***
		Anisodactylus binotatus	0.609 **
		Amara convexior	0.608 ***
		Microlestes minutulus	0.575 *
		Leistus ferrugineus	0.433 *
Arachnids	field centre	*Oedothorax apicatus*	0.793 ***
		Pachygnatha degeeri	0.664 *
		Walckenaeria nudipalpis	0.626 ***
		Phalangium opilio	0.588 *
		Tenuiphantes tenuis	0.553 *
		Walckenaeria vigilax	0.523 *
		Porrhomma microphthalmum	0.466 .
		Porrhomma oblitum	0.461 *
		Araeoncus humilis	0.422 .
	field edge	*Agyneta rurestris*	0.644 .
		Trochosa ruricola	0.635 .
	field border	*Phrurolithus festivus*	0.836 ***
		Micaria micans	0.718 ***
		Pardosa prativaga	0.684 **
		Pardosa amentata	0.676 ***
		Drassyllus pusillus	0.667 ***
		Pocadicnemis juncea	0.593 ***
		Pelecopsis radicicola	0.531 ***
		Zora spinimana	0.516 ***
		Drassyllus lutetianus	0.486 .
		Xerolycosa miniata	0.455 **
		Palliduphantes pallidus	0.411 .
		Micrargus subaequalis	0.402 *

Supplement 4

The community weighted mean of ranked frequency values obtained as proxy for the "rarity"of the assemblage of ground beetles showed highest values for buffered field borders (Fig. S2), indicating a species assemblage dominated by less common species. Likelihood ratio test revealed significant contribution of fixed effects to explained variance of the whole model (M_{full} vs M_{null} Chisq: 66.3 p < 0.001) and the interaction of field position and buffer strip presence (M_{full} vs M_{nox} Chisq: 10.1 p = 0.02). Significant differences between field with and without buffer strip were obtained for the field border and the buffer strip position itself. In detail, the indicator value was mainly but not exclusively affected by higher activity density of highly abundant and abundant individuals. The number of highly abundant and abundant individuals captured was on average 30 (buffer strip) and 20 (buffered field border) fewer than in the unbuffered strip. Of the remaining less common species ten (buffer strip) and four (buffered field border) more individuals were found in the pitfall traps in the fields with buffer strip on average. Arachnid assemblages did not distinguish because 99% of the captured individuals were classified as highly abundant.

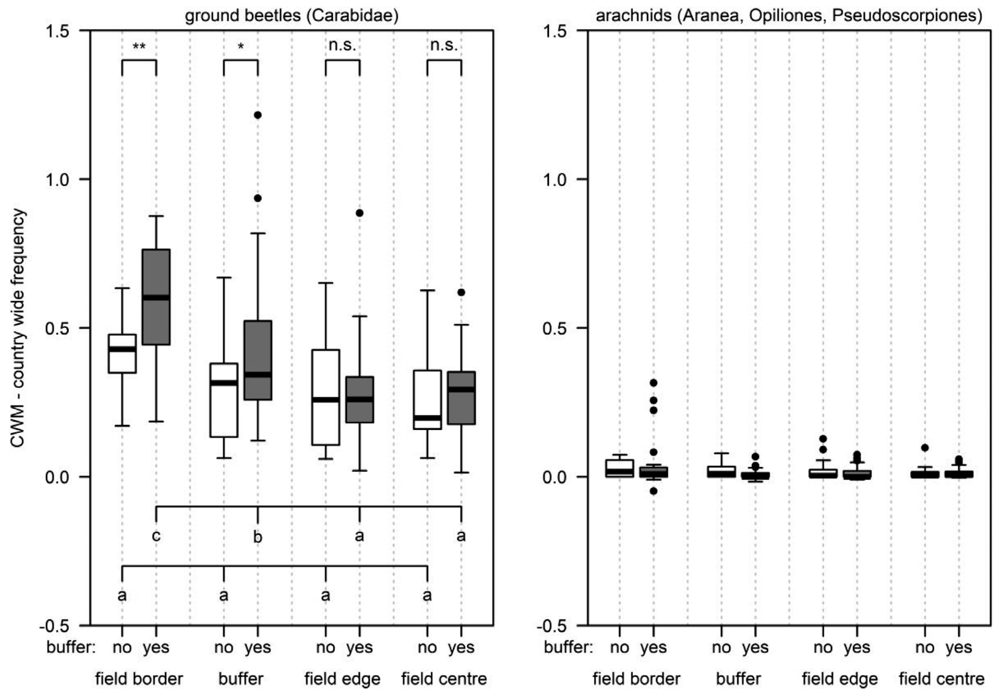

Fig. S2. Boxplots of Community weighted means (CWM) of country wide frequency values (from abundant to rare) obtained from the German red list for the different sampling locations of the gradient for ground beetle (left) and arachnid (right) assemblages in 25 fields with buffer strip (grey boxplots) and 15 fields without buffer strip (white boxplots). Estimated marginal means of the mixed model were used to obtain significant differences for the comparison of fields with and without buffer strips (brackets to the top) and separate comparison of location within the two groups (brackets below). ** p < 0.01, * p < 0.05, letters show significant differences within group levels (used significance level was 0.05).