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Ground-dwelling arthropods as biodiversity indicators in maize agroecosystems of Northern Italy

Francesco Lami [a,*], Giovanni Burgio [a], Serena Magagnoli [a], Daniele Sommaggio [a], Roland Horváth [b,c], Dávid D. Nagy [d], Antonio Masetti [a]

[a] DISTAL-Department of Agricultural and Food Sciences, University of Bologna, 40127 Bologna, Italy
[b] Department of Ecology, University of Debrecen, H-4032 Debrecen, Hungary
[c] ELKH-DE Anthropocene Ecology Research Group, University of Debrecen, Debrecen, Hungary
[d] MTA-DE Biodiversity and Ecosystem Services Research Group, Debrecen, Hungary

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ABSTRACT

Reliable monitoring of arthropod diversity in a given agroecosystem is essential for the conservation of the related ecosystem services, such as biological control. The often daunting complexity of arthropod collection and identification, however, highlights the need for surrogate taxa that can be easily sampled and be representative of a number of other taxa in term of diversity, general community features and specific composition.

In this study, we used pitfall traps to sample three ground-dwelling arthropod taxa important as biocontrol agents (ground beetles, rove beetles and spiders) in 9 conventionally managed maize agroecosystems of Northern Italy over the course of two years, with the goal of characterizing their assemblages and evaluating their reciprocal potential as indicators of activity density, species richness, community turnover and species co-occurrence.

Although dominated by few generalist species, sampled arthropod communities were relatively species-rich, and included the first Italian record of the spider *Zelotes metellus* (Roewer) (Araneae: Gnaphosidae). Ground beetles as a group were confirmed as promising indicators for the species richness and community composition turnover of rove beetles and spiders. Additionally, several abundant arthropod species acted as indicators of the species richness of their respective groups, and the ground beetle *Pterostichus macer* (Marsham) also worked as an indicator of overall rove beetle activity density. While the co-occurrence of individual arthropod species was limited for the studied taxa, a few species such as the ground beetle *Parophonus maculicornis* (Duftschmid) did show promise as species-specific bioindicators. Our results could be useful in improving the monitoring and management of these important natural enemies in maize-growing regions.

1. Introduction

Accurately monitoring and mapping biodiversity is essential for planning conservation actions (Niemelä, 2000). This becomes especially important in agroecosystems, as biodiversity is linked with several ecosystem services crucial for agriculture itself (Altieri, 1999; Mace et al., 2012; Swinton et al., 2007). Therefore, agricultural practices need to be carefully planned in order to minimize the negative impacts on beneficial organisms (Garbach et al., 2014; Moonen and Bàrberi, 2008).

As one of the most abundant and diversified group of terrestrial animals (Santos et al., 2021), arthropods are in fact responsible for the provision of a wide array of important ecosystem services, ranging from pollination to nutrient cycling acceleration (Dangles and Casas, 2019; Kremen et al., 1993; Losey and Vaughan, 2006). The biological control of harmful organisms through the conservation and enhancement of predatory and parasitoid arthropod communities (conservation biological control) has gained impetus in the last few decades as a promising, environmentally friendly way of protecting crops (Begg et al., 2017; Fiedler et al., 2008). Ground-dwelling arthropods such as ground beetles (Coleoptera: Carabidae) are included among the most important natural enemies of pests and weeds (Kromp, 1999; Lami et al., 2020; Lövei and Sunderland, 1996). Other groups such as rove beetles (Coleoptera Staphylinidae) and ground-dwelling spiders (Araneae), comparatively less studied, have been attracting much interest in recent years owing to

* Corresponding author.
E-mail address: francesco.lami2@unibo.it (F. Lami).

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an increasing body of evidence highlighting their biological control potential (Albertini et al., 2018; Betz et al., 2018; Michalko et al., 2019b, 2019a). Ground beetles and ground-dwelling arthropods in general are also studied for their potential as bioindicators of environmental impacts caused by agricultural practices and other human activities (Hågvar and Klanderud, 2009; Magagnoli et al., 2021; Pearce and Venier, 2006; Rainio and Niemelä, 2003).

The conservation of biodiversity, including the diversity of arthropods, is greatly improved when based on up-to-date biodiversity inventories that can be used as a reference to detect changes and compare biotic communities (Balmford and Gaston, 1999; Stephenson and Stengel, 2020), underlining the importance of faunistic surveys (Ejsmont-Karabin, 2019). The unparalleled diversity of arthropods coupled with their complex and ever-shifting taxonomy informed by advances in systematics, however, represents an enormous challenge when undertaking such efforts (Lovell et al., 2007; Samways, 2015). These difficulties are exacerbated by the currently dwindling numbers of expert taxonomists able to identify arthropod taxa to the species level (Ebach et al., 2011; Hopkins and Freckleton, 2002). As a consequence, an increasing number of studies highlights the need for the identification of surrogate taxa that can be used as indicators of the overall biodiversity in a given area or, more realistically, of the biodiversity of a number of other important taxa, or as indicators of ecosystem services (Birkhofer et al., 2018; Harry et al., 2019; Lovell et al., 2007). This line of research has led, until now, to mixed successes (Heino, 2010), with sometimes contradictory results regarding the potential value of certain taxa as surrogates (Lewandowski et al., 2010). Vascular plants, for instance, are frequently proposed as biodiversity indicators of various arthropod groups, but while significant correlations are often reported with phytophagous and plant-associated taxa (Bucher et al., 2019; Larrieu et al., 2019), relations with groups such as ground-dwelling taxa are less consistent (Harry et al., 2019; Schoeman et al., 2020; Uboni et al., 2019). Recent studies indicated that the habitat context can greatly affect the potential of a given taxon as a biodiversity indicator (Corcos et al., 2021; Yong et al., 2020). This suggests that each habitat type might require different indicators, implying that research should prioritize the most abundant and ecologically important natural and agricultural habitats in a given area.

Ideally, a good biodiversity indicator group should be relatively easy to collect and identify, and of course its diversity should co-vary with that of other taxa (Mandelik et al., 2010; Oberprieler et al., 2020; Westgate et al., 2017). The usefulness of a certain diversity index in bioindication, from simple abundance or species richness to more complex metrics based on community composition, is never universal, and different indices might be suitable for different taxa or habitat contexts (Corcos et al., 2021; Gao et al., 2015). The choice of a certain index might also depend on the conservation goals (Duelli and Obrist, 2003; McQuatters-Gollop et al., 2019). If the aim is to preserve a high level of biodiversity in general, then indices that provide general information on bioindicator and target communities, such as species richness or evenness (Magurran, 1988), are adequate. However, different species in a same taxon might play different ecological role (Cane and Payne, 1993; Harvey et al., 2008); thus, if the aim is to gather data useful for preserving specific ecological functions, indices based on functional diversity and ecological traits (Teresa and Casatti, 2017) or on community composition, turnover and species identity (Carvalho et al., 2013; Veech, 2013) might be more suitable. Different species or taxa are more likely to co-occur (and thus act as biodiversity indicators) if they depend on each other, for instance through mutualism, parasitism or predation (Aubier and Elias, 2020; Bell et al., 2010), or if they share the same environmental requirements without strongly competing for important resources (Araújo et al., 2011; Sfenthourakis et al., 2006). In case of strong competition or very different environmental requirements, on the other hand, two species or taxa will tend not to occur simultaneously (Gotelli and McCabe, 2002).

The main aims of our study were to i) improve baseline knowledge on biodiversity by characterizing arthropod assemblages and ii) evaluate the potential of three important groups of ground-dwelling predatory arthropods (ground beetles, rove beetles and spiders) as biodiversity indicators of each other in maize agroecosystems of Northern Italy. Conventionally-managed maize (*Zea mays* L.) was chosen as it is one of the most widespread and ecologically important crops in the study area (6th Census of Agricultural Holdings – ISTAT, Istituto Nazionale di Statistica). Given the impacts on biodiversity associated with maize cropping (Chmelíková and Wolfrum, 2019; Norris et al., 2016) and the projected widespread positive changes that would derive from large-scale application of sound agroecological principles to it (Triquet et al., 2022; von Redwitz et al., 2019), it is particularly important to draw a clear picture of beneficial arthropod diversity and protect it in such agroecosystems. Based on methodologies from recent relevant literature (Corcos et al., 2021; Griffith et al., 2016; Zara et al., 2021), the potential of biodiversity indicators of the studied groups was assessed in terms of i) general community features (activity density and species richness) ii) community turnover, iii) specific species relations to community features and iv) species co-occurrence.

2. Materials and methods

2.1. Sampling sites

The sampling was carried out in the spring and summer months of 2013 and 2014 in the Bologna province in Northern Italy. The study area is dominated by arable crops, with a mean annual temperature of 14 °C and mean annual precipitation of approximately 800 mm. We sampled a total of 9 sites (maize fields) in an area of roughly 70 km^2. In order to adapt to the local crop rotations, 4 of the sites were sampled only in 2013, 4 only in 2014 and one in both years (Table A.1). For the sake of bioindicator potential analyses, the two sampling years at the same site were considered as two separate sites (10 total sites). Distance between fields sampled in the same year ranged between 0.4 km and 15.5 km.

As the landscape context (Lami et al., 2021) and the nature of field margins (Maas et al., 2021; Marshall and Moonen, 2002) can deeply influence arthropod communities, we characterized landscape features in a 1000 m radius around each field using ArcGIS Desktop v10.8.2 and a 2011 CORINE Land Cover map (Büttner et al., 2002) of the Bologna province publicly available at the website of Regione Emilia-Romagna (https://geoportale.regione.emilia-romagna.it/). In general, landscapes around fields were dominated by farmland, with little, if any, natural habitats (Table A.2). Field margins were represented by spontaneous grassy strips in all cases.

Agronomic practices (and especially soil management for ground-dwelling arthropods) are other important factors that can impact arthropod communities (Gallé et al., 2020; Gayer et al., 2019; Lami et al., 2020; Rusch et al., 2016). In our case, all fields were managed conventionally and were similar in terms of tillage (conventional tillage), cover crop usage (no cover crops) and crop that preceded maize (wheat). Additional details about soil insecticides, herbicides and fertilization are reported in Table A.2.

2.2. Arthropod sampling and identification

Ground-dwelling arthropods were collected using pitfall traps (Brown and Matthews, 2016). Each trap consisted of 2 plastic cups (600 ml, 10 cm in diameter) flushed with soil surface, placed at 1 m from each other and connected with a 10 cm high plastic barrier used to intercept arthropods and direct them towards the collection cups. A plastic cover was placed above the cups to protect them from rain. During activation, traps contained about 200 ml of 40% propylene glycol per cup.

The number of traps in each sampled field was proportional to the size of the field, ranging from 10 to 20 traps and maintaining a density of roughly 1 trap per 0.05 ha, as field size ranged from 0.5 to 1 ha. Traps were placed 10 m from each other, either in single or multiple rows depending on the size and shape of the field. In two cases, two neighboring maize fields were sampled together and considered as a single site given their small size and that they were managed in the exact same way (Table A.1–A.2).

The sampling timing was partially dictated by the protocol of the funding project (see Acknowledgements), and it took place monthly from tasseling to harvest, which resulted in 4 sampling rounds (from June to September) in 2013 and 5 sampling rounds (from May to September) in 2014, with each sampling round lasting 7–9 consecutive days. The total number of sampling days per site is reported in Table A.1. The temporal window of our sampling encompassed the expected peak activity periods of both spring/early summer and late summer/early autumn of many ground-dwelling arthropod groups in Italian agroecosystems (Lami et al., 2021; Lövei and Sunderland, 1996; Nardi et al., 2019; Rossi et al., 2019).

The collected ground beetles, rove beetles and spiders were counted and identified to species level using morphological characters. A reason to focus on these three groups was their previously mentioned and widely reported potential as biological control agents and bioindicators. Moreover, they were among the most abundant groups collected during the study, and experts were available for their identification. Specifically, authors carried out the identification process using relevant literature (Assing and Schülke, 2012; Freude et al., 1974; Netwig et al., 2023; Pesarini and Monzini, 2011, 2010; Trautner and Geigenmueller, 1987). In the case of rove beetles, 8 specimens (2.1% of the total) could not be identified to species level and were assigned to 7 morphospecies.

2.3. Data analysis

2.3.1. General community features, diversity and species turnover

We calculated the overall activity density and species richness of ground beetles, rove beetles and spiders in each site, with activity density being the average number of captures of a single trap station per day. Pearson correlations between groups were computed for both metrics. Analyses were carried out in R v3.6.2 (R Core Team, 2016).

In order to evaluate cross-taxon congruence in community composition spatial turnover (Corcos et al., 2021), we first calculated Jaccard's dissimilarity index (Carvalho et al., 2013) based on species presence/absence for each taxon. We then used a Mantel test (Mantel, 1967) with 9999 randomized permutations to evaluate pairwise correlations between the dissimilarity matrices of the different arthropod groups.

We pooled all the traps for each maize field rather than analyzing the data divided by trap, as our aim was to test the correlation between community features and the cooccurrence of species within habitats, and because the distance between traps within a field was vastly inferior to the average dispersal abilities of ground-dwelling macroarthropods (Bertrand et al., 2016; Schmidt et al., 2008). The individual traps within a field were thus highly unlikely to represent independent communities or micro-habitat patches.

2.3.2. Species-level bioindication and co-occurrence

The potential of individual species as bioindicators of entire community features was tested using the activity density of the species as an indication parameter. We focused on the most abundant species as they were the most likely to occur in a high number of sites with varying levels of activity density, also meaning that they would likely be easier to sample and provide useful data in future real world applications. Specifically, we selected species with at least 100 sampled individuals. As no rove beetle species occurred with more than 100 individuals, to include representatives of this family we decided to select rove beetle species that were sampled with at least 50 individuals and found in more than half of the sites. We then calculated Pearson correlations between the activity density of each species and the activity density and species richness of each group.

Second, we wanted to test specific species co-occurrence. As the analysis is based on presence-absence data rather than abundance, we included a higher number of species, but we nonetheless removed very rare species (<10 total individuals) from the dataset, as estimation of co-occurrence and other ecological characters for rare species is problematic (Barlow et al., 2010; Plowman et al., 2020). We used Veech's pairwise method (Veech, 2013) to identify species pairs which showed significant positive co-occurrence (i.e. the two species tended to occur simultaneously in the studied sites) or negative co-occurrence (i.e. the two species tended to avoid each other). Co-occurrence analysis was performed using the "cooccur" v1.3 package (Griffith et al., 2016) in R v3.6.2. As the number of negative co-occurrences was very low (13 species pairs, 0.9% of the total), we focused on the more abundant positive co-occurrences (65 species pairs, 4.5% of the total). Our response variable was thus binary (1 in the case of positive significant co-occurrence or 0 in the other cases). We therefore fitted two logit regression models: one testing the proportion of positive species co-occurrences over the entire dataset (using taxon as an explanatory variable), and the other testing the proportion of positive co-occurrences in each possible taxon pairing (Ground beetle – Ground beetle, Rove beetle – Rove beetle, Spider – Spider, Ground beetle – Rove beetle, Ground beetle – Spider, Rove beetle – Spider). We then conducted a *post-hoc* analysis by calculating pairwise comparisons with a Tukey adjustment with the "emmeans" v1.4.4 package (Lenth, 2018).

3. Results

3.1. General community features and faunistic notes

We collected a total of 3447 ground beetles (Table A.3), 386 rove beetles (Table A.4) and 2210 spiders (Table A.5) belonging to 45, 43 and 91 species respectively. Spiders were representative of 21 families. Most species were infrequent, with only 17 ground beetle species, 10 rove beetle species and 28 spider species being represented by at least 10 individuals.

The dominant ground beetle species was *Harpalus rufipes* (De Geer) with 1951 individuals (56.6% of the collected ground beetles). The most abundant rove beetle was *Dinaraea angustula* (Gyllenhal) with 89 individuals (23.1% of the collected rove beetle). Finally, the most abundant spider family was Titanoecidae, and the dominant spider species was its representative *Nurscia albomaculata* (Lucas) with 781 individuals (35.3% of the collected spiders). An interesting faunistic note is represented by the first Italian record of the spider *Zelotes metellus* (Roewer) (Araneae: Gnaphosidae), which was found in 8 out of 9 studied fields with a total of 41 individuals.

3.2. Bioindicator potential

We did not detect any significant relationships between the activity densities of the studied groups. Conversely, we found significant positive correlations among the species richness of all arthropod groups (Table 1). Pairwise correlations in community turnover among all groups were also positive and significant (Table 1).

The most abundant species, which were tested for their potential as indicators of group-level features, included the ground beetles *H. rufipes*, *Pterostichus macer* (Marsham) and *Pterostichus melas* (Creutzer), the spiders *N. albomaculata*, *Pardosa cribrata* Simon and *Pardosa agrestis*

Table 1
Pearson correlations (for activity density and species richness) and Mantel correlations (for community turnover) between the studied arthropod groups.

	Activity density		Species richness		Community turnover	
Pair type	r_p	*p*	r_p	*p*	r_m	*p*
Carabidae - Staphylinidae	0.51	0.132	0.78	0.008	0.39	0.013
Carabidae - Araneae	−0.14	0.703	0.71	0.023	0.29	0.041
Araneae - Staphylinidae	0.29	0.423	0.71	0.020	0.31	0.032

(Westring) and the rove beetle *D. angustula*. The activity densities of the tested ground and rove beetle species always had significant positive correlations with the overall activity density and species richness of their respective groups (Table 2). Moreover, the ground beetle *P. macer* was positively correlated with rove beetle activity density, while the rove beetle *D. angustula* was positively correlated with both activity density and species richness of ground beetles. The only significant correlations for spiders were between *N. albomaculata* and overall spider activity density, and between *P. cribrata* and overall spider species richness.

Considering the whole arthropod dataset, rove beetle species showed a significantly higher proportion of positive co-occurrences with other species in the 3 groups (Fig. 1a). When dividing the dataset by arthropod taxon pairing, the proportionally highest number of co-occurrences was among rove beetle species, and the lowest was among ground beetle and spider species, or between different spider species, with the proportion of co-occurrences between ground and rove beetle species at an intermediate level (Fig. 1b).

The species showing the highest number of co-occurrences across the entire dataset were the rove beetles *Anotylus sculpturatus* (Gravenhorst) and *Tachyporus hypnorum* (Fabricius) (Table A.4) and the spider *Trachyzelotes huberti* Platnick & Murphy with 13 co-occurrences each (24.1% of the dataset) (Table A.5). *Anotylus sculpturatus* and *T. hypnorum* also had the highest proportion of co-occurrences with ground beetle species (5 species for each, 29.4% of the ground beetle dataset) and with spider species (5 species each, 17.9% of the spider dataset). On the other hand, the ground beetle *Parophonus maculicornis* (Duftschmid) and the spider *Robertus arundineti* (O. Pickard-Cambridge) had the highest proportion of co-occurrences with rove beetle species (6 species each, 60% of the rove beetle dataset).

4. Discussion

4.1. Community features and faunistic notes

Our data shed some light on the ground beetle, rove beetle and spider fauna of Italian maize agroecosystems, highlighting the local presence of several species considered important or potentially important as biocontrol agents (Carbonne et al., 2020; Klimaszewski et al., 2018; Kuusk and Ekbom, 2010; Renkema et al., 2012). In spite of their lower abundance (6 and 9 fold lower than spiders and ground beetles, respectively), rove beetles too were recorded with a comparatively high number of species, a pattern that had been found before in agricultural landscapes (Corcos et al., 2021). Assemblages of all arthropod groups (and especially ground beetles, the most abundant) were dominated by a

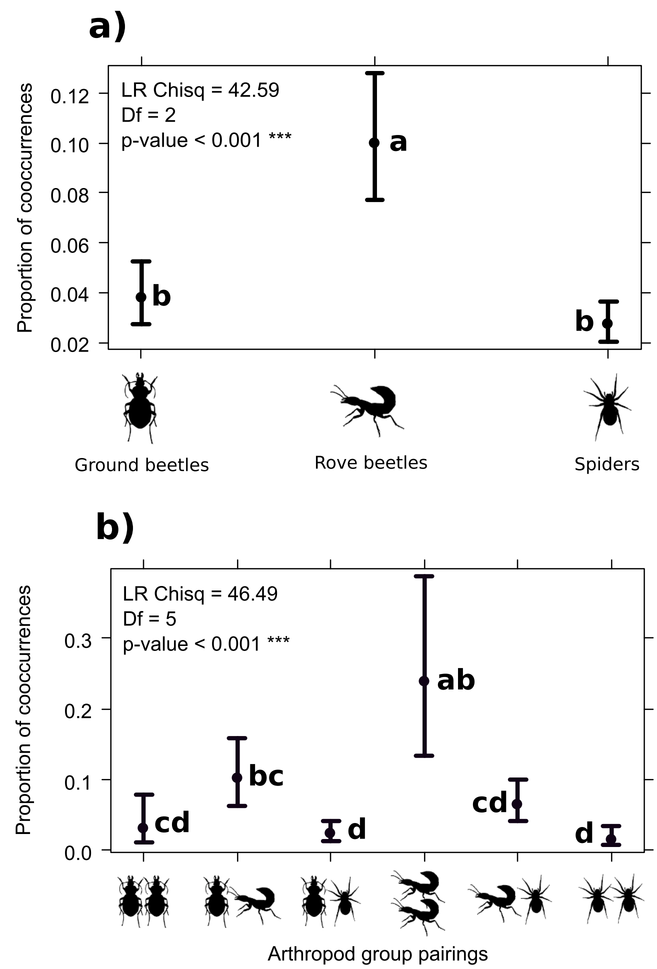

Fig. 1. (a) Effect of arthropod group on the proportion of positive species co-occurrences of each group over the entire dataset. (b) Effect of arthropod group pairing on the proportion of positive species co-occurrences in the pairing. The results of the relative logit regression models, complete with p-values, are reported on the plots. Different letters indicate statistically significant differences ($p < 0.05$) according to the pairwise comparison test with Tukey adjustment ($p < 0.05$).

Table 2
Pearson correlations between the activity density (AD) of the most abundant arthropod species and the activity density and species richness of the 3 arthropod groups.

		Carabidae AD		Staphylinidae AD		Araneae AD	
Group	Species	r_p	*p*	r_p	*p*	r_p	*p*
Carabidae	*Harpalus rufipes* (Duftschmid)	0.98	<0.001	0.39	0.254	−0.23	0.515
	Pterostichus macer (Marsham)	0.89	<0.001	0.64	0.048	0.12	0.748
	Pterostichus melas (Creutzer)	0.97	<0.001	0.39	0.254	−0.29	0.413
Staphylinidae	*Dinarea angustula* (Gyllenhal)	0.69	0.026	0.83	0.003	0.12	0.749
Araneae	*Nurscia albomaculata* (Lucas)	−0.54	0.110	−0.15	0.686	0.74	0.015
	Pardosa cribrata Simon	0.34	0.332	0.36	0.305	0.15	0.674
	Pardosa agrestis (Westring)	0.39	0.258	0.57	0.085	0.05	0.882
		Carabidae richness		Staphylinidae richness		Araneae richness	
Group	Species	r_p	*p*	r_p	*p*	r_p	*p*
Carabidae	*Harpalus rufipes* (Duftschmid)	0.73	0.017	0.42	0.230	0.57	0.086
	Pterostichus macer (Marsham)	0.81	0.005	0.54	0.104	0.57	0.085
	Pterostichus melas (Creutzer)	0.71	0.021	0.46	0.178	0.57	0.083
Staphylinidae	*Dinarea angustula* (Gyllenhal)	0.75	0.013	0.67	0.034	0.49	0.155
Araneae	*Nurscia albomaculata* (Lucas)	−0.28	0.434	−0.23	0.526	−0.16	0.650
	Pardosa cribrata Simon	0.33	0.348	0.45	0.193	0.73	0.016
	Pardosa agrestis (Westring)	0.33	0.354	0.59	0.076	0.61	0.063

limited number of agrobiont species adaptable to heavily intensified agricultural contexts.

The prevalent ground beetle *H. rufipes*, in particular, is often very common in agroecosystems (Labruyere et al., 2016), were it has been reported as an important omnivorous natural enemy of both weeds and pest insects (Carbonne et al., 2020; Monzó et al., 2011). Roughly two thirds of the remaining ground beetle individuals belonged to the second and third most abundant species of the study, the opportunist predators *P. macer* and *P. melas* (Giglio et al., 2021; Nourmohammadpour-amiri et al., 2022), which are both habitat generalists and common in agricultural landscapes (Corcos et al., 2021; Lövei et al., 2006; Vician et al., 2015). The dominant rove beetle species *D. angustula* is also a common agrobiont (Balog et al., 2009). Assemblages dominated by such species are frequently found in disturbed agricultural ecosystems (Lami et al., 2021; Shearin et al., 2008).

Nonetheless, several less common and more specialized species were sampled as well; for instance, a single individual of the ground beetle *Calosoma sycophanta* (L.) was collected. This was an unusual finding given the specialization of this species for forest habitats (Burgess, 1911), which are extremely scarce in our study areas and completely lacking in the landscape surrounding the field (CAS2) in which the species was found (Table A.2). We even recorded in most sites the presence of the spider *Z. metellus*, which was previously known from Greece, Iran, Israel, Russia and recently France (Mazzia et al., 2018), and which had never been reported in Italy – a reminder of the fact that our knowledge of the fauna of even these supposedly familiar and simplified agroecosystems is often lacking. Baseline faunistic datasets such as these are decisive for the organization of conservation efforts and for monitoring the long term effects of anthropogenic impacts (Ejsmont-Karabin, 2019; Girardello et al., 2018; Valdecasas and Camacho, 2003) including climate change and agricultural practices such as tillage, pesticide use and genetically modified plant cultivation (Arpaia et al., 2018; Lami et al., 2016; Lener et al., 2013).

4.2. Community-level bioindication potential

Before discussing bioindication potential, it is worth mentioning that the relatively limited spatial and temporal extent of the sampling might represent a drawback. Even though the conditions of the studied sites are very common in maize agroecosystems of Northern Italy, thus improving the likelihood that the conclusions of our study could find application in a wider area, confident extrapolation of general patterns (even if just at the regional scale) should definitely be based on additional research in similar environmental contexts. That being said, some interesting considerations can be made about our results.

Regarding community-level bioindication, activity density showed little potential as a biodiversity indication parameter in the studied area and habitat type, as correlations between groups were never significant. Species richness and community turnover, however, showed significant co-variation among all three groups. The correlations involving species richness were particularly strong, with r values always higher than 0.7 – a value that has been often proposed as a threshold to identify truly informative biodiversity indicators (Harry et al., 2019; Heino, 2010; Lovell et al., 2007). Such strong correlations are rarely found in real world scenarios (Burrascano et al., 2018; Larrieu et al., 2019; Oberprieler et al., 2020), a fact that is often attributed to the confounding effects of different environmental and habitat factors (Filgueiras et al., 2019; Schalkwyk et al., 2019). Our findings, therefore, support the appropriateness of focusing on a specific habitat type, and the fact that monitoring biodiversity through surrogate taxa might be more feasible in maize agroecosystems than in other contexts.

In addition to that, ground beetles are taxonomically well-known, and usually easier to identify than the other two studied groups (Kotze et al., 2011). Given their importance as biocontrol agents of pest invertebrates and weeds (Honek et al., 2003; Lövei and Sunderland, 1996) and their use as environmental indicators (Piano et al., 2020; Pizzolotto et al., 2018; Rainio and Niemelä, 2003) there is great interest in ground beetle conservation. For the above reasons, ground beetles have been widely studied, and a relatively high number of experts are available for their identification (Kotze et al., 2011; Magura and Lövei, 2021; Niemelä, 1995). Ground beetles thus have all the necessary features to be considered potentially useful bioindicators of the species richness and community turnover of rove beetle and spider communities in maize agroecosystems of Northern Italy. Future research will have to assess the validity of our findings for other geographical areas, as cross-taxon congruence involving ground beetles has been mostly investigated in relation to different organisms such as plants or in a variety of habitat types, not focusing specifically on maize (Oberprieler et al., 2020; Uboni et al., 2019; Zara et al., 2021). Nonetheless, some existing sources concerning general bioindication potential in maize seem to draw an encouraging picture (Albajes et al., 2013; Lee and Albajes, 2016).

4.3. Abundant species as bioindicators of community features

While tested for the sake of completeness, the fact that the activity density of the most abundant species was often linked with the activity density of their respective groups is hardly surprising and scarcely informative. Skewed species-abundance distributions, in which one or few species are disproportionally influential on community size and function because of their numerical dominance, are very common in nature (McGill et al., 2007; Winfree et al., 2015). Notwithstanding, the case of the two species that have significant correlations with different groups (the ground beetle *P. macer* with rove beetles, and the rove beetle *D. angustula* with ground beetles) is potentially important for bioindication. *Pterostichus macer* seems particularly promising, being a significantly larger ground beetle (Klimaszewski et al., 2013; Magura et al., 2006), and thus comparatively easier to confidently identify, and being more common than *D. angustula*, at least in our study. *Pterostichus macer* might thus be a useful, easily sampled indicator that simplifies the estimation of rove beetle abundance and activity, making up for the lack of significant correlation between overall ground beetle activity density and rove beetle activity density.

Perhaps even more interesting are the cases of species whose activity density is significantly correlated with the species richness of their respective groups. In literature it is often reported that increasing arthropod community abundance, while usually disproportionately driven by common species, is also linked with higher species richness (Hallmann et al., 2021; McArt et al., 2012). This might be explained by the more-individuals hypothesis (Gaston, 2000), which postulates that habitats with a higher availability of resources can support a higher number of individuals of each species (including dominant ones), which in turn contributes at least partially to a higher species richness, as larger populations have a lower chance of extinction (Storch et al., 2018). The practical consequence is that the activity density of *H. rufipes*, *P. macer* and *P. melas* could be used as an indicator for overall ground beetle species richness in maize agroecosystems of Northern Italy, just as the activity density of *D. angustula* and *P. cribrata* (alongside ground beetle richness) could be used as indicators of rove beetle and spider richness respectively. This could potentially greatly reduce the taxonomic burden of monitoring the diversity of these groups. It is also worth noting that *D. angustula* activity density could be an indicator of ground beetle richness, although for the reasons discussed above it would be likely more convenient to use one of the more abundant and easily identifiable ground beetle species, rather than this rarer and more difficult to identify rove beetle.

4.4. Species co-occurrence

The situation is more complex when examining species-specific bioindication (co-occurrence). Available literature reports varying levels of positive ("true") co-occurrence and avoidance among ground-dwelling arthropod species, once again often indicating environmental features as key drivers of these patterns (Fernandes et al., 2020; Tsafack et al., 2021; Ulrich et al., 2010), as the availability of space, food and other resources, as well as the level of disturbance, heavily influences the strength of interspecific competition. The very limited number of negative co-occurrences (i. e. species avoidances) suggested that strong competition or strong differences in general habitat requirements are extremely rare among the species in the studied context. Positive co-occurrences were more common, but they still represented a minority of the dataset. Agricultural landscapes, and maize agroecosystems in particular, are highly disturbed and environmentally homogeneous (Chmelíková and Wolfrum, 2019; Ponisio et al., 2016), so the low proportion of positive and negative relations is coherent with literature highlighting disturbance as a factor disrupting segregated arthropod communities (Pitzalis et al., 2010; Ulrich et al., 2010), and habitat homogeneity as a factor disrupting both segregation and co-occurrence (Tsafack et al., 2021). More heterogeneous landscapes with a high proportion of semi-natural habitats and margins might have yielded different results and thus influenced the implications for bioindication, given the importance that these elements have as habitat resources for arthropods (Bertrand et al., 2016; Maas et al., 2021; Marshall and Moonen, 2002). In our case, the highest proportion of positive co-occurrences were found between rove beetle species and other arthropod species (especially other rove beetles), with spiders showing the lowest proportion of co-occurrences with other species and ground beetles not faring much better than spiders in that regard. The most common rove beetle species in the studied habitats are thus likely to share the same environmental needs with each other in a much stronger fashion than either spiders or ground beetles.

It follows that most ground beetle species will be scarcely useful as bioindicators of other predatory arthropod species in the studied context, with some exceptions. Among these promising species-specific bioindicator candidates we can mention *P. maculicornis* – especially as a rove beetle bioindicator, given its co-occurrence with a sizeable portion of the most common rove beetle species of the studied sites. A possible limitation that can be mentioned in the case of this species is the fact that, at least in our study, it was a scarce species (11 individuals), meaning that detecting its presence in an area might require an intensive sampling effort. Many rove beetles, such as *A. sculpturatus* and *T. hypnorum*, and even some spiders, such as *T. huberti* and *R. arundineti*, also showed potential as species-specific biodiversity indicators for one or more arthropod groups because of their relatively high proportion of co-occurrences with other species – with *A. sculpturatus* also having the advantage of being relatively abundant (74 individuals) when compared with the other species. However, it must be considered that the taxonomy and identification of rove beetles and spiders is often complex (Bohac, 1999; Pearce and Venier, 2006) and this might limit the usefulness of these species in biodiversity indication. It is thus advisable, while further investigating the potential of these promising species, to also continue the search for other surrogate taxa that can act as species-specific bioindicators for ground-dwelling predatory arthropods of maize.

5. Conclusions

In this study, we characterized the ground-dwelling predatory arthropod fauna in maize agroecosystems of Northern Italy, focusing on three groups potentially very important for biological control – ground beetles, rove beetles and spiders. Positive correlations were found among the species richness and community turnover of all arthropod groups, whereas activity density correlations were non-significant. In particular, we identified ground beetles as useful bioindicators for the species richness and community turnover of the other two groups. Additionally, several abundant arthropod species worked as bioindicators of the species richness of their respective groups, and the ground beetle *P. macer* also worked as a bioindicator of overall rove beetle activity density. We also showed that the potential for species-specific bioindication was in general limited in the three studied groups, highlighting the need to search for other potential surrogate taxa to fill this gap. Nonetheless, we did find some species showing promise in this sense, such as the ground beetle *P. maculicornis* as a rove beetle bioindicator, which might deserve further evaluation.

The results of this work could improve the monitoring and management of these important natural enemies in maize-rich regions, speeding up biodiversity assessments and thus facilitating the understanding of the relation between biodiversity and environmental/agricultural factors (Dudley and Alexander, 2017), or between biodiversity and ecosystem services provision (Duncan et al., 2015). Another important application of these biodiversity indicators would be facilitating the identification of biodiversity-rich cropland that should be maintained in its current state and of biodiversity-poor cropland to be restored (Barral et al., 2015). Finally, our study provides baseline faunistic datasets that could prove useful as a reference to detect and evaluate the effects of climate change, land use change and agricultural practices on soil biodiversity.

CRediT authorship contribution statement

Francesco Lami: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Giovanni Burgio:** Supervision, Funding acquisition, Writing – review & editing. **Serena Magagnoli:** Investigation, Writing – review & editing. **Daniele Sommaggio:** Investigation, Writing – review & editing. **Roland Horváth:** Investigation, Writing – review & editing. **Dávid D. Nagy:** Investigation, Writing – review & editing. **Antonio Masetti:** Conceptualization, Investigation, Data curation, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Giovanni Burgio reports financial support was provided by European Commission Seventh Framework Programme for Research and Technological Development.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.110352.

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