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The Influence of Plant Protection on Carabids (Coleoptera, Carabidae) in Potato Crops Cultivated in a Four-Year Rotation

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Abstract: Ground beetles (Coleoptera, Carabidae) are common predators found in agricultural ecosystems. They feed on crop pests and help reduce pest population. Additionally, they are used as bioindicators to determine the impact of human activities on entomofauna and habitat conditions. The aim of this study was to investigate the ground beetles that inhabit chemically protected (CP) and non-chemically protected (NCP) potato crops and to assess the impact of pesticide use on these beneficial insects. This study was conducted in Poland, on potato fields where ground beetles were caught during four-year crop rotation cycles in 2004, 2008, 2012, and 2016. Two fields with potato crops were chosen: one without chemical protection and the other with chemical protection. Soil traps were used to catch insects, resulting in 7095 individuals of Carabidae, belonging to 41 species, caught throughout the study. The abundance and species richness of ground beetles fluctuated depending on the year of the study and the type of crop protection. Results showed that pesticide use in potato crops decreased ground beetle abundance while species richness remained unaffected. Furthermore, the use of chemical plant protection (CP) induced changes in some life traits of the carabids, leading to a decrease in the abundance of hemizoophages and autumn-breeding carabids. The abundance of the other ecological groups of Carabidae was also year-dependent.

Keywords: ground beetles; plant protection; integrated agricultural production; life traits

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1. Introduction

Agriculture is constantly changing and progressing, and a fundamental factor shaping the direction and effectiveness of these changes is biodiversity [1,2]. However, the unquestionable productive success of industrial agriculture (which began in the 18th century), directed solely at economic purposes, has pushed the limits of reproduction and the sustainability of the natural environment [3]. Consequently, the prospect of the growing demand for food due to demographic growth and increasing environmental and climate problems is one of the most critical challenges of the 21st century [4–6]. Global anthropopressure is an inevitable consequence of the development of civilization. However, the strength and extent of this challenge can be corrected by making the right decisions, taking into account both economic and environmental welfare aspects [7]. The need to transform conventional agriculture towards sustainable agriculture has become a priority objective of the European Union's agricultural policy. Restrictive reduction in pesticide use, a strategic element in determining crop yields, necessitates the search for alternative methods in agricultural production [4,5,8]. Among the pro-ecological farming practices that increase crop production potential is crop rotation [9,10]. A planned crop rotation system that varies year to year creates a diverse soil with balanced nutrient cycling and good structure. In addition, a properly implemented crop rotation can eliminate or reduce the appearance of diseases, pests, and weeds without the use of mineral fertilisers and pesticides. This ensures high yields and the resilience of agricultural ecosystems [9].

It is important to carefully select the crops that will follow each other to ensure successful crop rotation. This decision significantly affects the outcome of the rotation [8,11]. The potato is an essential component of global food security [12–15]. Due to its versatile use, the potato is one of the most important food crops in the world, cultivated in 150 countries (over 20 million hectares) [12,16]. In recent years, the cultivation of potatoes in Europe has become less profitable due to climate change and high storage costs. As a result, the acreage dedicated to potato cultivation has decreased. However, the potato can nevertheless be an important alternative to agricultural landscapes impoverished by cereal monocultures, as its cultivation leaves weed-free soil, rich in nutrients. This makes potato cultivation a good forecrop for following crops and is the basis for a rational crop rotation [15–17].

Changes in the natural environment are assessed by analyzing the responses of living organisms [18,19]. A model group used to understand the functioning and direction of ongoing changes in agricultural ecosystems is ground beetles (Coleoptera, Carabidae). These insects are both predators of crop pests and effective bioindicators [20–24].

This study aimed to evaluate the impact of pesticide use on the ground beetle assemblages in potato crops grown under a four-year crop rotation system.

The following hypotheses were tested: (i) ground beetle abundance and species richness are lower in chemically protected fields due to increased habitat disturbance and reduced food availability, and (ii) the use of chemical plant protection reduces the abundance of larger carnivores, which require more prey and are more sensitive to disturbance; macropterous species, which tend to colonize disturbed habitats; and autumn-breeding species, whose larvae are exposed longer to chemically treated soils.

2. Materials and Methods

2.1. Study Area

This study was carried out at the Agricultural Experimental Station in Winna Góra, near Środa Wielkopolska, (52°12′32.0″ N 17°26′16.0″ E), western Poland. The experimental fields consisting of four-year crop rotations (potato, spring barley, yellow lupin, and winter wheat) have been in use since the 1960s. This study comprised a block of control fields where no chemical plant protection preparations were applied and a second block where a plant protection programme was implemented according to conventional or integrated agricultural production guidelines. Crops were grown under a ploughing system. In fields without chemical protection (NCP), mechanical weeding was used instead of herbicides. The same fertilization method was used in both blocks. The surface area of each field was 0.5 ha. The soils in the experiment were similar and belonged to the good wheat complex (class IIIa and IIIb) in the Polish soil taxonomy system [25].

2.2. Data Collection

This study was carried out on potato fields grown in a four-year rotation in 2004, 2008, 2012, and 2016. Two fields with potato crops were selected: without chemical protection (NCP—no chemical protection) and with chemical protection (CP—chemical protection).

The studied fields were separated from others by isolation strips sown with phacelia or clover. During the four years chosen for our study, the field under chemical protection was treated with insecticides, herbicides, and fungicides, as specified in Table S1. Ground beetles were collected between May and September using soil traps made from plastic cups, 10 cm in diameter and 15 cm deep, filled with ethylene glycol. These traps were emptied every two weeks. Two transects with ten traps were established in each field. The details of the study are shown in Figure S1.

2.3. Data Analysis

The species composition, abundance, and richness of ground beetles were assessed. Because of the different requirements, the ground beetles were divided into groups based on the following traits: feeding strategy and body size, and the type of breeding and dispersion capability. These life traits are considered the best for describing ground beetle assemblages in field crops. Due to their essential role as the predators of plant pests, the ground beetles were divided in terms of food preference and body size. The following groups were distinguished: phytophages (feeding on plant food), hemizoophages (generalists, feeding on both plants and animals), large carnivores (body length over 12 mm), medium carnivores (5- 12 mm), and small carnivores (body length less than 5 mm). The categorization into large, medium, and small carnivores was performed according to Aleksandrowicz [26], based on the average body length of each species given by Hůrka [27]. Additionally, the ground beetles were classified as autumn breeders, which reproduce in autumn and hibernate as larvae, or spring breeders, which hibernate as adults and reproduce in spring [28]. The presence of ground beetles of different breeding types is also a reflection of field conditions [22]. The ability to disperse, especially in distorted habitats, is another crucial aspect in the study of ground beetles [29]. Using Hůrka's [27] description, the following groups were distinguished among the ground beetles: macropterous, with fully developed wings; brachypterous, with reduced second pair wings; and dimorphic, whose second pair wings can be developed or reduced.

The Shapiro–Wilk test was used to analyze the distribution of the data. Considering the data distribution, we used a generalized linear model (GLM) with a Poisson distribution to analyze differences in the mean species richness and abundance of assemblages, factoring in plant protection and the study year. A non-metric multidimensional scaling (NMDS) analysis was used to visualize and evaluate the patterns of dissimilarity within the ground beetle assemblages in the years of study in the different types of plant protection based on their species composition. NMDS was calculated in PAST 4.17 software [30] on a Bray–Curtis similarity matrix. The significance of the differences between the analyzed assemblages in the NMDS method was carried out using the ANOSIM non-parametric statistical test [31]. An investigation of correlations between the ground beetles and the following environmental variables: the type of protection (with or without chemical plant protection), chemical treatments applied (herbicides, insecticides, and fungicides), and the years of study, was completed using redundancy analysis (RDA) [32]. The Monte Carlo permutation test was conducted with 499 permutations, where $p < 0.05$ was considered statistically significant.

The temperature and distribution of rain precipitation in the years of the study were also analyzed. ANOVA analysis of variance did not demonstrate statistically significant differences in the temperature or rainfall between the years examined.

All analyses were carried out using untransformed data. Statistical calculations and their graphic presentation were performed using the Statistica 13.3, PAST 4.17, and Canoco 4.5 software programs.

3. Results

During the four years of study, 7095 ground beetles representing 41 species were caught (Table 1). More specifically, 3127 specimens representing 38 species were captured in the fields with chemical plant protection (CP), while 3968 individuals belonging to 39 species were captured in fields without chemical plant protection (NCP). The species composition of the ground beetles in both field types was similar (Table 1). In the total material collected, *Harpalus rufipes* (46.4%) and *Calathus ambiguus* (11.4%) had the highest contribution.

Table 1. List of the Carabid species and their feeding preferences (Hz—hemizoophages, Sc—small carnivores, Mc—medium carnivores, Lc—large carnivores, Ph—phytophages), breeding types (Ab—autumn breeding, Sb—spring breeding), dispersion capability (Dpt—dimorphics, Mpt—macropterous, Bpt—brachypterous), and total abundance and species richness in the analyzed study fields (CP—chemically protected, NCP—non-chemically protected) in the years of study (2004, 2008, 2012, 2016).

Species	Abbr.	Ecological	CP				NCP			
		Description	2004	2008	2012	2016	2004	2008	2012	2016
Acupalpus meridianus (Linnaeus, 1767)	Acu_mer	Hz/Sb/Mpt	1	0	0	0	0	0	0	0
Amara aenea (Degeer, 1774)	A_aen	Ph/Sb/Mpt	1	0	0	4	0	0	1	1
Amara bifrons (Gyllenhal, 1810)	A_bif	Hz/Ab/Mpt	0	1	17	0	0	3	6	0
Amara convexior Stephens, 1828	A_conv	Hz/Sb/Mpt	0	0	0	0	0	0	2	0
Amara plebeja (Gyllenhal, 1810)	A_ple	Ph/Sb/Mpt	1	0	0	5	0	0	0	3
Amara similata (Gyllenhal, 1810)	A_sim	Ph/Sb/Mpt	0	0	2	2	1	0	0	6
Anchomenus dorsalis (Pontoppidan, 1763)	Anc_dor	Mc/Sb/Mpt	0	1	18	6	0	0	10	8
Badister bullatus (Schrank, 1798)	Ba_bul	Sc/Sb/Mpt	0	0	0	0	0	0	1	0
Bembidion femoratum Sturm, 1825	Be_fem	Sc/Sb/Mpt	8	7	44	3	2	4	11	11
Bembidion lampros (Herbst, 1784)	Be_lam	Sc/Sb/Mpt	40	33	7	24	34	17	13	38
Bembidion properans (Stephens, 1828)	Be_pro	Sc/Sb/Mpt	40	34	19	45	30	36	15	65
Bembidion quadrimaculatum (Linnaeus, 1761)	Be_quma	Sc/Sb/Mpt	59	26	96	51	37	12	67	71
Bembidion tetracolum Say, 1823	Be_tet	Sc/Sb/Mpt	24	34	39	8	13	16	8	18
Broscus cephalotes (Linnaeus, 1758)	Br_cep	Lc/Ab/Mpt	0	2	0	0	3	0	1	0
Calathus ambiguus (Paykull, 1790)	Cal_amb	Mc/Ab/Mpt	12	206	72	33	7	384	34	63
Calathus cinctus Motschulsky, 1850	Cal_cin	Mc/Ab/Dpt	0	25	4	2	0	55	5	0
Calathus erratus (Sahlberg, 1827)	Cal_err	Mc/Ab/Dpt	2	2	2	0	2	1	0	3
Calathus fuscipes (Goeze, 1777)	Cal_fus	Mc/Ab/Dpt	1	25	22	39	2	34	16	34
Calathus halensis (Schaller, 1783)	Cal_hal	Lc/Ab/Mpt	2	2	18	5	1	6	24	6
Calathus melanocephalus (Linnaeus, 1758)	Cal_mel	Mc/Ab/Dpt	0	18	13	8	0	36	11	11
Calosoma auropunctatum (Herbst, 1784)	Calo_aur	Lc/Sb/Mpt	0	0	0	0	0	1	2	0
Carabus cancellatus Illiger, 1798	C_canc	Lc/Sb/Bpt	1	0	1	0	0	0	1	0
Cicindela hybrida Linnaeus, 1758	Ci_hyb	Mc/Sb/Mpt	1	2	0	0	1	0	0	1
Clivina fossor (Linnaeus, 1758)	Cli_fos	Mc/Sb/Dpt	0	1	0	0	3	1	0	4
Curtonotus aulicus (Panzer, 1797)	Cur_aul	Hz/Ab/Mpt	0	0	1	0	0	3	10	1
Harpalus affinis (Schrank, 1781)	Har_aff	Hz/Sb/Mpt	14	11	24	18	22	40	16	17
Harpalus autumnalis (Duftschmid, 1812)	Har_aut	Hz/Sb/Mpt	0	0	1	0	0	2	1	0
Harpalus distinguendus (Duftschmid, 1812)	Har_dist	Hz/Sb/Mpt	0	0	0	1	0	0	0	0
Harpalus griseus (Duftschmid, 1812)	Har_gri	Hz/Ab/Mpt	0	18	8	0	0	34	16	0
Harpalus rubripes (Duftschmid, 1812)	Har_rub	Hz/Sb/Mpt	0	0	0	1	0	3	0	0
Harpalus rufipes (De Geer, 1774)	Har_ruf	Hz/Ab/Mpt	97	515	319	288	51	971	496	557
Harpalus smaragdinus (Duftschmid, 1812)	Har_smar	Hz/Sb/Mpt	2	2	1	2	0	4	0	2
Harpalus tardus (Panzer, 1797)	Har_tar	Hz/Sb/Mpt	0	4	2	1	1	7	1	0
Loricera pilicornis (Fabricius, 1775)	Lor_pil	Mc/Sb/Mpt	0	0	1	0	0	0	1	0
Microlestes minutulus (Goeze, 1777)	Mic_min	Sc/Sb/Dpt	31	9	14	19	12	1	10	5
Poecilus cupreus (Linnaeus, 1758)	Poe_ cup	Mc/Sb/Mpt	118	39	77	16	18	10	58	16
Poecilus lepidus (Leske, 1785)	Poe_lep	Mc/Sb/Dpt	4	4	2	3	12	0	20	1
Poecilus versicolor (Sturm, 1824)	Poe_vers	Mc/Sb/Mpt	4	3	2	0	1	0	0	0
Pterostichus melanarius (Illiger, 1798)	Pt_mel	Lc/Ab/Dpt	13	73	44	32	14	82	28	50
Trechus quadristriatus (Schrank, 1781)	Tr_quad	Sc/Ab/Dpt	3	43	5	2	4	45	4	3
Zabrus tenebrioides (Goeze, 1777)	Zab_ten	Hz/Ab/Mpt	0	15	0	0	0	5	0	0
Number of individuals			479	1155	875	618	271	1813	889	995
			3127				3968			
Number of species			23	28	29	25	22	27	30	25
			38				39			

Significant differences between the analyzed study variants in the research years were observed with respect to the abundance of ground beetles (Table 2). A significantly higher number of ground beetles was determined in the NCP fields (Figure 1). Regarding the number of species, no significant differences were observed between fields with different protection variants. The factor indicating the differences in the number of collected species was the year of the study (Table 2, Figure 1).

Table 2. Generalized linear model (GLM, Wald statistics) for changes in total abundance, species richness, and life trait distribution in relation to the year of study and type of plant protection.

Carabids Assemblage Parameters	Wald Statistic Results and Level of Significance (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, ns—not significant)		
	Treatment	Year	Treatment × Year
Number of individuals	11.54 ***	1215.19 ***	188.24 ***
Number of species	0.51 ns	41.51 ***	13.81 **
Feeding strategy			
Hemizoophages	42.46 ***	832.81 ***	51.81 ***
Small carnivores	21.00 ***	3.29 ns	40.62 ***
Medium carnivores	7.99 ***	535.85 ***	97.10 ***
Large carnivores	1.42 ns	77.37 ***	3.63 ns
Breeding type			
Autumn breeders	29.54 ***	1594.45 ***	67.88 ***
Spring breeders	32.96 ***	50.57 ***	48.36 ***
Dispersion capability			
Macropterous	15.63 ***	985.73 ***	187.63 ***
Dimorphic	1.29 ns	235.99 ***	12.97 **

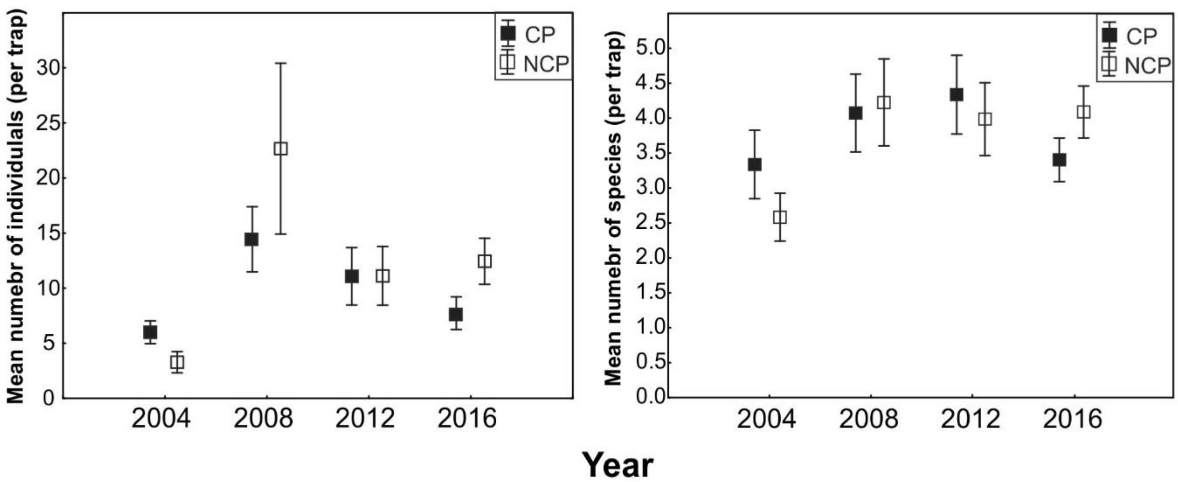

Figure 1. Mean abundance and species richness of ground beetles (Coleoptera, Carabidae) depending on plant protection type (CP—chemically protected, NCP—non-chemically protected) in years of study.

ANOSIM analysis revealed no significant differences in the ground beetle assemblages in the protected (CP) and unprotected (NCP) fields in only two of the years studied (2012, 2016) (Table 3). The non-metric multidimensional scaling (NMDS) analysis for individual objects also showed differences in the analyzed ground beetle assemblages (ANOSIM R = 0.64; $p < 0.001$) connected not only with the application of pesticides in the experimental fields but also with the research year (Figure 2). The assemblages of the ground beetles caught in 2004 in chemically protected (CP) and unprotected (NCP) fields differed significantly from those in other years.

Table 3. R statistics of ANOSIM analysis comparing ground beetle variation between plant protection type (CP—chemically protected, NCP—non-chemically protected) in years of study (2004, 2008, 2012, and 2016), * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, ns—not significant; significance after Bonferroni correction.

		CP			
		2004	**2008**	**2012**	**2016**
NCP	2004	0.56 **	0.99 **	0.94 **	0.77 **
	2008	0.99 **	0.36 ns	0.76 ***	0.81 **
	2012	0.87 **	0.42 **	0.25 ns	0.31 ns
	2016	0.95 **	0.42 **	0.54 **	0.27 ns

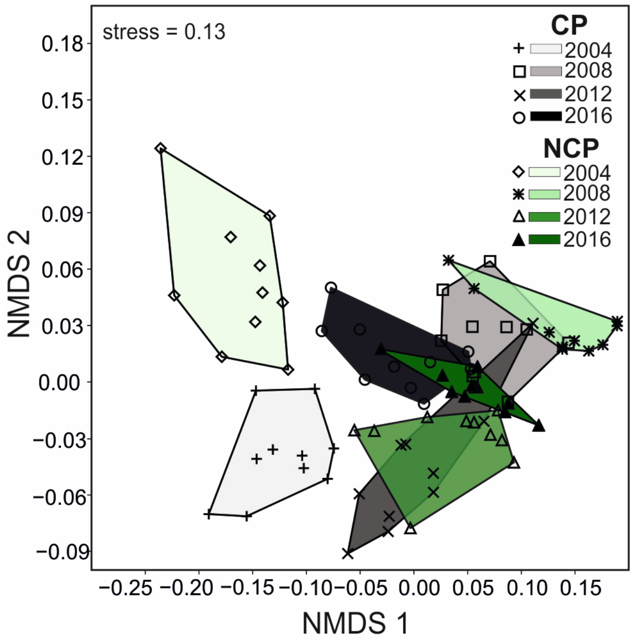

Figure 2. DA diagram of non-metric multidimensional scaling (NMDS) performed on the Bray–Curtis similarity matrix of ground beetles in the years of study with different types of plant protection (CP—chemically protected in the shades of grey, NCP—non-chemically protected in the shades of green).

The redundancy analysis (RDA) demonstrated relationships between the ground beetle species and environmental variables such as the form of plant protection; the application of insecticides, fungicides, herbicides; and the study year (Figure 3). The first and the second ordination axes described 96.6% of the variation. The first axis (92.1% of the variation) was correlated with the fungicide application. The Monte Carlo permutation test showed that fungicides (F-ratio = 12.14, $p = 0.002$) and herbicides (F-ratio = 3.67, $p = 0.05$) had the highest effects on the carabids community. Also, some carabid species demonstrated the strongest correlation with the tested axis: *Microlestes minutulus*, *Carabus cancellatus*, *Harpalus smaragdinus*, *Amara bifrons*, *Clivina fossor*, *Calathus melanocephalus*, *Harpalus tardus*, and *Harpalus rufipes* (Figure 3). Fields without chemical protection (NCP) were associated with a large number of ground beetle species, mainly with large and medium carnivores. The application of herbicides and insecticides in chemically protected (CP) fields was correlated with the occurrence of *Poecilus cupreus* and some species classified as small carnivores.

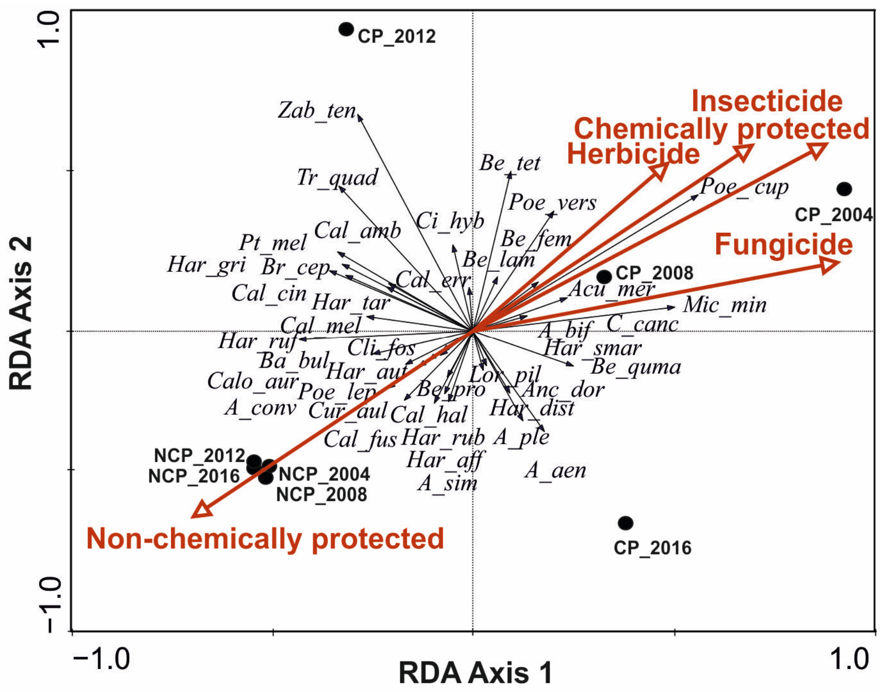

Figure 3. RDA analysis demonstrating the relationships between the analyzed environmental variables: the type of plant protection (CP—chemically protected, NCP—non-chemically protected); the use of insecticides, herbicides, fungicides; the year of study; and the species of Carabidae (abbreviations are listed in Table 1).

Analysis of the effect of chemical protection on the carabid feeding strategy indicated that the application of pesticides significantly affected the abundance of hemizoophages and medium and small carnivores (Table 2). A decrease in the number of hemizoophages was found in chemically protected fields (CP). In the case of carnivores, increases and decreases in their abundance differed between years. Small carnivores in 2004 were more numerous in NCP fields, while in subsequent years, they were more numerous in CP fields. The mean abundance of medium carnivores was higher in CP fields in most of the years studied (Figure 4). Due to their small number, phytophages were excluded from the above analysis. Our results indicated that chemical protection had a significant effect on the breeding strategy of ground beetles. The number of autumn breeders was significantly higher in the field not treated with pesticides (NCP). In contrast, in chemically protected fields (CP), spring breeders were more abundant (Figure 4). In terms of the dispersal ability, no unambiguous effect of the use of chemical crop protection on this group of beetles was observed. Brachypterous species were very scarce and, therefore, excluded from the analysis. The plant protection technology did not have a significant effect on the abundance of dipterous carabids but did influence the number of macropterous carabids (Table 2). The year of study was an important determinant of the differences in the abundance of both dimorphic and macropterous carabids. Macropterous carabids were more abundant in chemically protected (CP) fields during the first two years of the study, whereas in the subsequent years, their numbers were higher in fields without chemical protection. In contrast, the pattern for dimorphic species was the opposite (Figure 4).

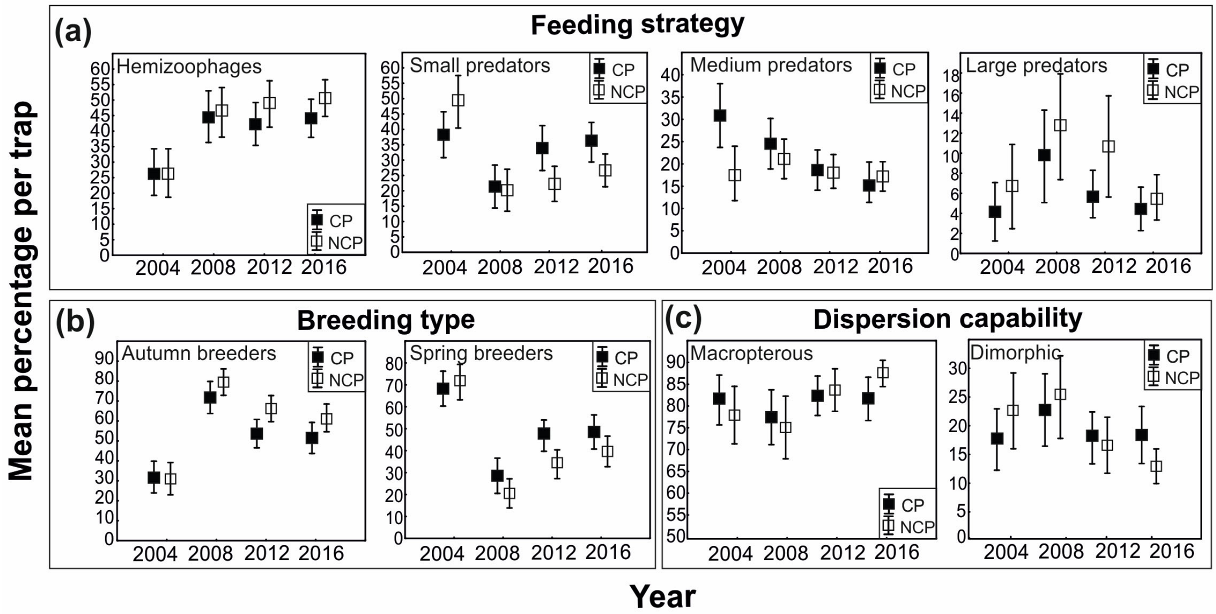

Figure 4. Percentages of statistically significant ecological groups of carabids: (**a**) feeding strategy (hemizoophages, large carnivores, medium carnivores, small carnivores), (**b**) breeding type (autumn and spring breeders), and (**c**) dispersion capability (macropterous and dimorphic species), depending on plant protection type (CP—chemically protected, NCP—non-chemically protected) in years of study (mean ± SE).

4. Discussion

Organic potato plantations are prone to the massive incidences of pests, causing economic losses and yield deterioration [33,34]. Rempelos et al. [35], analyzing the metadata, indicated a decrease in the yields in organic crops of up to 20–25%. To prevent crop loss, various agricultural practices, including crop rotation and vegetation management to enhance natural pest enemies, are used, with chemical control as a last resort [36]. The use of chemical plant protection products still remains a controversial topic [37] due to their impact on beneficial entomofauna also present in fields, e.g., [38–42]. Nonetheless, the implementation of integrated pest management (IPM) and advancements in plant protection products, characterized by increased selectivity and faster degradation rates, seem to be mitigating the extent of this harmful progress.

Our studies carried out on the effects of pesticides on ground beetles provide important information on the abundance, species richness, and structure of the assemblages of these insects. Analysis of the species composition of ground beetles in both field types showed considerable similarity. Despite this, the RDA diagram indicated that the majority of ground beetle species avoided fields in which chemical plant protection was used. The results revealed that ground beetles were more abundant in potato fields without chemical plant protection (NCP). However, in terms of the species richness, the method of plant protection was not significant. These results were in line with studies indicating that agricultural practices, such as pesticide use, can affect the abundance and structure of ground beetle assemblages [43]. However, the results obtained were inconclusive. Although the experimental treatments did not have a statistically significant effect on species richness, other parameters of the ground beetle assemblages, such as abundance or ecological traits, showed clear differences between chemically protected and unprotected fields. Our results partially supported the hypothesis that chemical protection affects ground beetle assemblages. However, they also suggested that commonly used parameters, such as species richness and abundance, may not fully reflect the scale of ecological change. Most similar to these obtained results were from the studies of Dritschilo and Wanner [44], who recorded a much higher abundance of Carabidae in organic fields with a comparable level of diversity. Clark et al. [45] also reported higher Carabidae abundance in organic fields. In addition to higher abundance, higher species richness was observed in organic fields [46]. On the other hand, Rondon et al. [47] did not confirm the above results entirely, pointing to a higher abundance of ground beetles in conventional potato crops. A small effect of insecticide on Carabidae was also reported by Kalushkov et al. [48]. In view of such different data on the abundance and species richness of ground beetles in fields where pesticides were applied and in organic fields, we also followed the data in the various years of potato cultivation in a four-year rotation. The data obtained, which varied greatly over the years of the study, also did not provide a clear answer on how the use of pesticides in potato cultivation affected the ground beetle assemblages. The ANOSIM analysis showed no significant differences in the ground beetle assemblages in potato fields with chemical plant protection (CP) and without chemical plant protection (NCP) in 2012 and 2016. However, NMDS and RDA analysis revealed significant differences in the ground beetle assemblages. Fields where chemical protection (NCP) was not applied correlated positively with the occurrence of mainly large and medium-sized carnivores. These species are generally more sensitive to pesticide use due to their predatory lifestyle and greater exposure to contaminated prey [42], which most likely explained their limited occurrence in fields under chemical protection. The use of herbicides and insecticides in chemically protected (CP) fields correlated mainly with the presence of *Poecilus cupreus*, a field-specific species with a high tolerance to disturbance including chemical ones. Sowa et al. [49] suggested that exposure to pesticides leads to the selection of more resistant individuals, resulting in their dominance in fields where pesticides are applied. Differences in the studied ground beetle assemblages were related not only to pesticide application but also to the year of the study. According to Holland and Luff [24], this variability may have been due to differences in climatic and agronomic conditions from one year to the next. In our study, no significant differences in the average temperatures and precipitation were noted across the years. However, the use of different pesticides in each year of the study may have affected the carabid fauna. As reported by Pearsons and Tooker [50] some active compounds may have different effects on carabids.

Lundgren and Mc Cravy [51] pointed out that agricultural practices can directly or indirectly impact ground beetle assemblages. Crucial information can be gathered by examining certain aspects of their life traits. The use of chemical protection has had a significant impact on the feeding strategy of ground beetles. The vast majority of ground beetles are active predators feeding on molluscs and other invertebrates, and they may also be omnivorous or partially herbivorous, e.g., [39,52–54]. In the studies conducted, the abundance of hemizoophages decreased in potato fields with chemical plant protection (CP), which may be due to the direct effect of pesticides on their populations. In contrast, the abundance of medium carnivores was higher in CP fields in most years of the study. According to Sądej and Nietupski [55], ground beetles can feed on insects, such as aphids, that fall from leaves during rainstorms or as a result of chemical treatments. The increased availability of dead prey, in particular, may attract predatory insects that do not exclusively hunt live animals but also feed on freshly dead prey. These results were consistent with the second hypothesis we established and suggested that different groups of ground beetles respond differently to pesticide use, which may affect the structure of the agrocenosis ecosystem [39]. Theis study also showed that the abundance of autumn-breeding species was higher in NCP fields, while spring breeders dominated CP fields. This pattern may indicate that NCP fields provided more stable habitats, allowing autumn breeders to develop their larvae successfully. In contrast, CP fields, subjected to pesticide applications may be less suitable for these species, favouring spring breeders with shorter development cycles [24]. Additionally, the abundance of macropterous ground beetles was higher in CP fields during the first two years of the study, and later increased in NCP fields. Meijer [29] stated that macropterous carabids are the first to colonize new habitats. Once a habitat is colonized, individuals with reduced wings begin to appear in the population, which partially aligned with our observations. These results suggested that pesticides may influence the dispersal abilities and life-history strategies of ground beetles, potentially by selecting for species with greater dispersion capability in more disturbed environments [23].

5. Conclusions

These results showed that the use of pesticides in potato crops did not significantly affect the species richness of carabids, but led to changes in the structure of their assemblages and a decrease in the abundance of some ecological groups, such as hemizoophages and autumn breeders. This could disrupt natural pest control mechanisms and the ecological balance of agroecosystems.

For the sustainable management of agroecosystems, it is important not only to monitor the species diversity of ground beetles but also to analyze their functional groups, as these provide insights into trophic relationships and overall ecosystem health. Conducting long-term ecological monitoring will allow us to better understand interannual variability and the effects of pesticide use on epigeic fauna.

Based on these results, it is recommended to integrate ecological knowledge into agricultural practice by, among others, reducing chemical plant protection, using crop rotation, and increasing habitat diversity to protect beneficial entomofauna and maintain ecological balance.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app15126572/s1, Figure S1. Diagram of the distribution of traps for trapping carabids in a field experiment conducted on chemically protected (CP) and non-chemically protected (NCP) potato plantations. Table S1. Characterization of the potato crops in the consecutive years alongside the specification of pesticides used in chemically protected (CP) fields.

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Abbreviations

The following abbreviations are used in this manuscript:

CP	Chemically protected field
NCP	Non-chemically protected field

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