sustainability

MDPI

Article

Epigeic Carabids (Coleoptera, Carabidae) as Bioindicators in Different Variants of Scots Pine Regeneration: Implication for Forest Landscape Management

Agnieszka Kosewska [1,*], Renata Kędzior [2], Mariusz Nietupski [1] and Jakub Borkowski [3]

[1] Department of Entomology, Phytopatology and Molecular Diagnostics, University of Warmia and Mazury in Olsztyn, 10-719 Olsztyn, Poland; maniek@uwm.edu.pl
[2] Department of Ecology, Climatology and Air Protection, Faculty of Environmental Engineering and Surveying, University of Agriculture in Krakow, 31-120 Krakow, Poland; renata.kedzior@urk.edu.pl
[3] Department of Forestry and Forest Ecology, University of Warmia and Mazury in Olsztyn, 10-719 Olsztyn, Poland; jakub.borkowski@uwm.edu.pl
* Correspondence: a.kosewska@uwm.edu.pl

Abstract: Maintaining biodiversity is one of the factors determining the proper functioning of ecosystems, especially those with high human impact. Ground beetles, as bioindicators, are particularly valuable in understanding ecosystem responses and sustainability in forest and landscape management. Focusing on the regeneration of pine forests, this study aimed to describe ground beetle assemblages on Scots pine natural and artificial regeneration in northeastern Poland. This study was conducted between 2016 and 2018. Pitfall traps were set up for catching epigeic carabids on previously prepared research plots designated for natural and artificial pine regeneration. The research areas included three variants: N—natural pine regeneration, plots without soil preparation; NP—natural pine regeneration with traditional soil preparation by ploughing; and A—artificial pine regeneration with ploughing. Four plots as replicants were selected in each experimental variant, with six pitfall traps in the transects running through the centre of each study plot. In each year of the study, 11 samples were collected from each plot; overall, 33 samples per plot were collected during the three years. As a result of this study, 26,654 ground beetle individuals belonging to 89 species were caught during the three-year observation. Natural regeneration without soil preparation (N) was the most favourable in terms of the occurrence of stabilised assemblages of ground beetles. However, the remaining methods of pine regeneration, on a multi-annual scale (2016–2018), contributed to the increase in the number of ground beetles but also provided high variability in assemblage composition, diversity indices, and life-history traits. Thus, in the early stage of pine regeneration, each of the examined variants of pine regeneration can be used without fear of causing damage to carabid populations. However, further studies are required to investigate the effect of different pine regeneration types on carabid beetle assemblages over a longer period.

Keywords: forest renewal; zooindicators; species diversity; ground beetles; life traits

check for updates

Citation: Kosewska, A.; Kędzior, R.; Nietupski, M.; Borkowski, J. Epigeic Carabids (Coleoptera, Carabidae) as Bioindicators in Different Variants of Scots Pine Regeneration: Implication for Forest Landscape Management. *Sustainability* **2023**, *15*, 13322. https://doi.org/10.3390/su151813322

Academic Editor: Axel Schwerk

Received: 14 August 2023
Revised: 1 September 2023
Accepted: 5 September 2023
Published: 5 September 2023

1. Introduction

Poland's forest cover is approximately 30%, similar to that of the world and Europe [1]. Forests are an essential part of the landscape. They have many functions ranging from production and protection to tourism. The growing public interest in forests and forest management poses particular challenges for forest resource managers. Economic conditioning specifies the need for a rational economy, demonstrating the potential for cost reduction and appropriate financial, social, and environmental outcomes. Carrying out all these tasks simultaneously is a complex challenge, especially in view of the observed environmental changes. This is all the more so as tree lifespan precludes fast forest adaptation to environmental change. Forest management, with its intensive practices, such as cutting and the establishment of plantations, can be the cause of significant abiotic and biotic changes, e.g., [2–5]. However, cutting and stand regeneration are essential forest-management activities for achieving production targets. In recent years, particular attention has been paid to strengthening the importance of natural stand regeneration, which is part of the implementation of the concept of sustainability and is one of the keystones in the natural direction of silviculture [6].

The most important forest-forming species in Poland, accounting for about 60% of the forest area [1], is the Scots pine (*Pinus sylvestris* L.). It is a widespread species throughout the Eurasian region and, due to its natural plasticity, colonises a wide range of habitats [7]. Since sustainable forest management has been an important international goal [8] over the past two decades, interest in natural pine regeneration has increased [9,10]. Articles in the literature describe various aspects of natural pine regeneration, including the effect of soil preparation on pine growth and development, e.g., [11–14]. However, few studies have compared natural with artificial pine regeneration to determine the level of entomofauna biodiversity, depending on how the pine plantations are established. Monitoring changes in entomofauna is an essential part of assessing the impact of forest management on biodiversity. Ground beetles, as indicators, are suitable for this type of study due to their high abundance, diversity, and sensitivity to habitat changes [15–19]. Therefore, changes in their assemblages can be used to indicate the alterations caused by human activity [19].

This study aimed to determine the species richness, abundance, and diversity of ground beetles in naturally and artificially regenerated pine stands and the distribution of their life traits in three studied variants of pine stand regeneration (N, NP, and A). In this study, we attempted to answer the following questions: (i) what changes occur in the assemblages of the ground beetles during forest regeneration, (ii) whether different methods of forest regeneration affect the assemblages studied, and (iii) which ecological groups of Carabidae are most sensitive to different types of forest regeneration. This knowledge is fundamental, as species with specific life traits perform crucial functions in ecosystems, particularly as predators limiting populations of pests in newly established pine plantations. To answer the research questions set, the following hypotheses were followed: (i) the method of pine forest regeneration significantly affects the ground beetle assemblages. Based on the available literature, we presumed that naturally regenerated pine stands without soil preparation will be characterised by a higher abundance, species richness, and species diversity of ground beetles than naturally regenerated forests on ploughed soil or artificially regenerated stands; (ii) soil preparation leads to the appearance of a high number of macropterous generalists from open habitats and to a decreasing number of forest brachypterous specialists.

2. Materials and Methods

2.1. Study Area

This study was conducted in northeastern Poland (a map and a detailed description of the area are in our earlier paper [5]); it included three variants of pine regeneration stand (N, NP, A). Variants: N—naturally regenerated pine stand, plots without soil preparation; NP—naturally regenerated pine stand with traditional soil preparation by ploughing; A—artificial regeneration of pine stand (by planting) with traditional soil preparation (ploughing). Within each studied variant, 4 sampling plots were designed (12 plots in total). The study plots were established in fresh mixed coniferous forest habitat. The width of the clear-cuts on which the study was carried out ranged from 90 to 180 m. Each established study plot's size was approximately 0.4–0.8 ha. The study plots were selected to ensure that the parameters that characterised them were as similar as possible [5]. Therefore, the plots could be treated as replications of the analysed pine regeneration variant.

2.2. Data Collection

This study began in 2016, as, since then, following the 2014 clear-cutting, there have been simultaneously available crops from natural pine regeneration and artificial pine regeneration, established for the first time one year later than those from self-seeding. This study was conducted between 2016 and 2018. Beetles were sampled using pitfall traps containing ethylene glycol as a killing–preserving solution. Six pitfall traps, each spaced 10 m apart, were set in a transect running through the centre of each study plot. There were 72 traps each year, 24 in each study variant. Each year, the traps were set in the same locations. Trapped ground beetles were collected from April to October. In each year of the study, 11 samples were collected from each plot; in total, 33 samples per plot were collected during the three years.

2.3. Data Analysis

Ground beetles taken in pitfall traps were identified as to their species using Hůrka's [20] key and nomenclature proposed by Aleksandrowicz [21]. The beetles were analysed regarding their species composition, total abundance, species richness, diversity, dominance, and selected life-history traits. The Shannon species diversity index H′ was used to identify the diversity of carabid assemblages, and the Berger–Parker index was used to assess their dominance structure. Life traits used in the analysis were food preferences (hemizoophages and carnivores), wing development (brachypterous, dimorphic, and macropterous), and habitat specialisation (forest species, generalists, and open-area species). To specify the ecological characteristics of the Carabidae, we referred to the following sources: [15,20,21]. Nonmetric multidimensional scaling (NMDS) was performed to check the differences in species composition of ground beetle assemblages of three variants of pine forest regeneration: N—natural, NP—natural with ploughing, and A—artificial with ploughing. NMDS uses carabid presence and abundance data to depict community similarity in two-dimensional space. The spatial proximity of samples indicates a high degree of similarity of invertebrate community structure between habitats. We used ANOSIM with the Bray–Curtis dissimilarities matrix with 499 data permutations to test the significance of dissimilarity differences between pine forest regeneration types. SIMPER analysis (similarity percentage analyses) was performed to determine the relative contribution of the various species and to reveal an indicator species in each pine forest regeneration type. The NMDS, ANOSIM, and SIMPER analyses were performed using PAST software (version 4.03). General linear mixed models (GLMM) were used to test the effect of forest regeneration variants on carabid diversity indices (abundance, number of species, Shannon diversity index, and Berger–Parker dominance index) as well as life traits (food preferences, wing development, and habitat preferences) over three years of observation. The generalised linear mixed model estimates fixed and random effects and is especially useful when the dependent variables are not normally distributed. It is also useful when the dependent variable involves repeated measures since GLMMs can model autocorrelation. The analysed diversity indices and life traits of ground beetles (Coleoptera, Carabidae) were not normally distributed (Shapiro–Wilk test for normality, $p < 0.001$), and, therefore, the model was fitted to the Poisson distribution. Forest regeneration type was regarded as a fixed effect describing carabid diversity and life-trait variation. The GLMM analyses were performed using Statistica 13.0 software.

3. Results

During the three years of observations, 26,654 ground beetles representing 89 species were caught. In the total material collected, *Poecilus lepidus* (14.4%), *Harpalus rufipes* (13.6%), *Calathus erratus* (12.5%), *Amara lunicollis* (11.3%), *Harpalus rufipalpis* (10.5%), *Poecilus versicolor* (9.7%), and *Carabus arvensis* (6%) had the highest shares. The species composition of the ground beetles inhabiting the studied forest areas varied according to the type of regeneration, i.e., N—natural, NP—natural with soil ploughing, and A—artificial with soil ploughing. SIMPER analysis revealed the carabid indicator species for each variant of pine forest regeneration (Table 1).

Table 1. Simper analysis for carabid species contributing more than 1% to the dissimilarity between pine forest regeneration types: N—natural, NP—natural with soil ploughing, and A—artificial with soil ploughing.

Species/Ecological Description	Av. Dissim.	Contrib. %	Cumulative %	Forest Regeneration Type		
				Mean Abund (N)	Mean Abund (NP)	Mean Abund (A)
Poecilus lepidus/c/d/o	7.4	12.6	12.6	34.9	80.3	206.0
Calatus erratus/c/d/f	7.0	11.8	24.4	22.9	50.7	205.0
Harpalus rufipes/hz/m/o	6.8	11.6	36.0	78.8	94.9	128.0
Amara lunicollis/hz/m/o	6.4	10.8	46.8	102.0	57.1	91.2
Harpalus rufipalpis/hz/m/o	5.2	8.9	55.6	39.3	69.3	126.0
Poecilus versicolor/c/m/o	5.0	8.5	64.2	88.8	60.3	66.1
Carabus arvensis/c/b/f	4.0	6.8	70.9	76.8	21.3	28.1
Pterostichus niger/c/m/f	2.6	4.4	75.3	38.4	24.0	30.3
Pterostichus oblongopunctatus/c/m/f	2.3	3.9	79.2	39.1	19.3	6.8
Poecilus cupreus/c/m/o	2.0	3.3	82.6	30.5	17.5	21.7
Harpalus solitaris/hz/m/o	1.9	3.2	85.8	24.9	30.9	0.8
Calatus fuscipes/c/b/o	1.0	1.7	87.5	1.1	1.5	37.8
Carabus cancellatus/c/b/g	0.9	1.6	89.1	0.2	0.7	14.6
Broscus cephalotes/c/b/o	0.7	1.3	90.3	0.2	2.8	11.3
Pterostichus quadrifoveolatus/c/m/f	0.7	1.1	91.5	2.0	13.2	0.1

Ecological description: food preferences—c—carnivores, hz—hemizoophages; wing development—b—brachypterous, d—dimorphic, m—macropterous; habitat type—g—generalists, f—forest species, o—open-area species; Av. Dissim.—average dissimilarity of most representative species, Contrib %—percentage of contribution to similarity; Cumulative %—percentage of contribution to similarity; Mean abund (N)—mean abundance of carabid beetles in plots with natural forest regeneration type, Mean abund (NP)—mean abundance of carabid beetles in plots with natural forest regeneration with soil ploughing, Mean abund (A)—mean abundance of carabid beetles in plots with artificial forest regeneration type.

Species characteristic of forests regenerating naturally (N) were *Amara lunicollis*, *Poecilus versicolor*, *Carabus arvensis*, *Pterostichus niger*, *Pt. oblongopunctatus*, and *Poecilus cupreus* (Table 1). As indicators of forest habitats regenerating naturally with soil ploughing (NP), there were only two species: *Harpalus solitaris* and *Pterostichus quadrifoveolatus*, while in the artificial type of pine regeneration (A), there were *Poecilus lepidus*, *Calathus erratus*, *Harpalus rufipes*, *H. rufipalpis*, *Calathus fuscipes*, *Carabus cancellatus*, and *Broscus cephalotes* (Table 1).

The analysed variants differed significantly in the species composition of ground beetles, as confirmed by the applied non-metric multidimensional scaling (NMDS), which illustrates the similarities and differences in the species composition in the analysed study plots (Figure 1).

The ANOSIM assays confirmed significant differences between the analysed assemblages: N-NP (R = 0.2, $p = 0.04$) and N-A (R = 0.4, $p = 0.0003$). Only in the case of the NP-A variants was the ANOSIM result non-significantly different (R = 0.1, $p = 0.327$). The results of the GLMM analysis showed that, on a multi-annual scale (2016–2018), the type of pine forest regeneration had a significant impact on the total abundance of ground beetles, while the other parameters (species richness, Shannon, and Berger–Parker indices) did not show a significant effect (Table 2).

The highest total abundance of ground beetles (Coleoptera, Carabidae) was observed in areas where artificial pine regeneration with soil preparation occurred (Figure 2). Moreover, in multi-annual analyses (three years of study), we observed an increasing total abundance of carabid beetles. The highest total abundance of carabids was observed in 2018 in each variant of pine forest regeneration. Additionally, in the case of the natural pine regeneration (N), the ground beetles' total abundance was the most stable during the three years of observation. In contrast, in the NP and A variants, a large variability in this parameter was recorded (Figure 2).

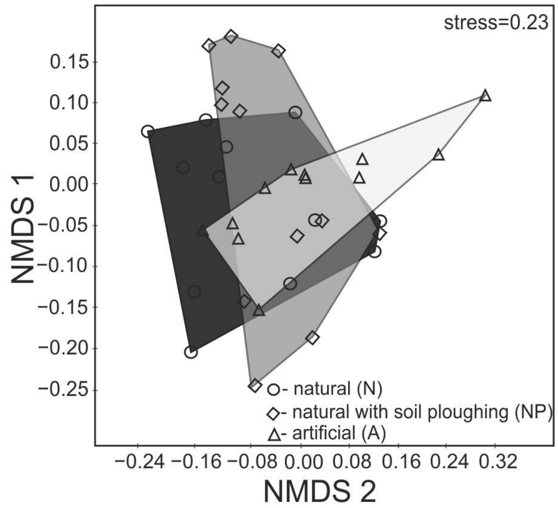

Figure 1. Non-metric multidimensional scaling (NMDS) ordination of Carabidae assemblages (based on the Bray–Curtis dissimilarity matrix) of three pine forest regeneration types: N—natural, NP—natural with soil ploughing, and A—artificial with soil ploughing.

Table 2. Results of GLMM for ground beetle (Coleoptera, Carabidae) abundance, species richness, and diversity indices, abundance of beetles of each life trait in relation to pine forest regeneration type (N—natural, NP—natural with soil ploughing, and A—artificial with soil ploughing), and year of the study (2016–2018).

		Treatment			**Year**			**Treatment × Year**		
		df	**Wald Stat.**	***p***	**df**	**Wald Stat.**	***p***	**df**	**Wald Stat.**	***p***
Diversity indices										
Total abundance		2	1063.7	<0.001	2	2930.7	<0.001	4	676.4	<0.001
Number of species			1.2	0.548		4.7	0.097		4.6	0.336
Shannon diversity			0.1	0.960		0.1	0.958		0.1	0.998
Berger–Parker index			0.0	0.988		0.2	0.892		0.1	1.000
The abundance of beetles of particular life traits										
Food preferences	Carnivores	2	688.4	<0.001	2	2454.0	<0.001	4	764.8	<0.001
	Hemizoophages		236.5	<0.001		459.7	<0.001		462.2	<0.001
Wing development	Brachypterous	2	368.6	<0.001	2	189.4	<0.001	4	224.2	<0.001
	Dimorphic		1223.8	<0.001		1727.7	<0.001		125.0	<0.001
	Macropterous		117.6	<0.001		1033.6	<0.001		313.6	<0.001
Habitat type	Generalists	2	113.1	<0.001	2	9.6	0.008	4	26.7	<0.001
	Forest		240.6	<0.001		432.9	<0.001		837.4	<0.001
	Open area		828.3	<0.001		2793.1	<0.001		271.8	<0.001
	Wetland		0.1	0.956		1.6	0.455		1.4	0.845

The pine forest regeneration type also significantly impacted the life traits of the carabid beetles, e.g., food preferences, wing development, and habitat preferences (Table 2). The highest number of carnivores (Figure 3a) was noted in variant A, where we also observed the highest variability in the abundance of carnivore species within the three study years (2016–2018). Notably, in 2018, a high increase in the abundance of carnivores was revealed. In variants N and NP, the variability of carnivores during the three years was smaller and more stable. The highest abundance and variability within 2016–2018 were observed in the case of hemizoophages (Figure 3b). The most stable abundance of hemizoophages was noted in the N variant, whereas in the NP variant, we observed an increasing abundance of this species within three years.

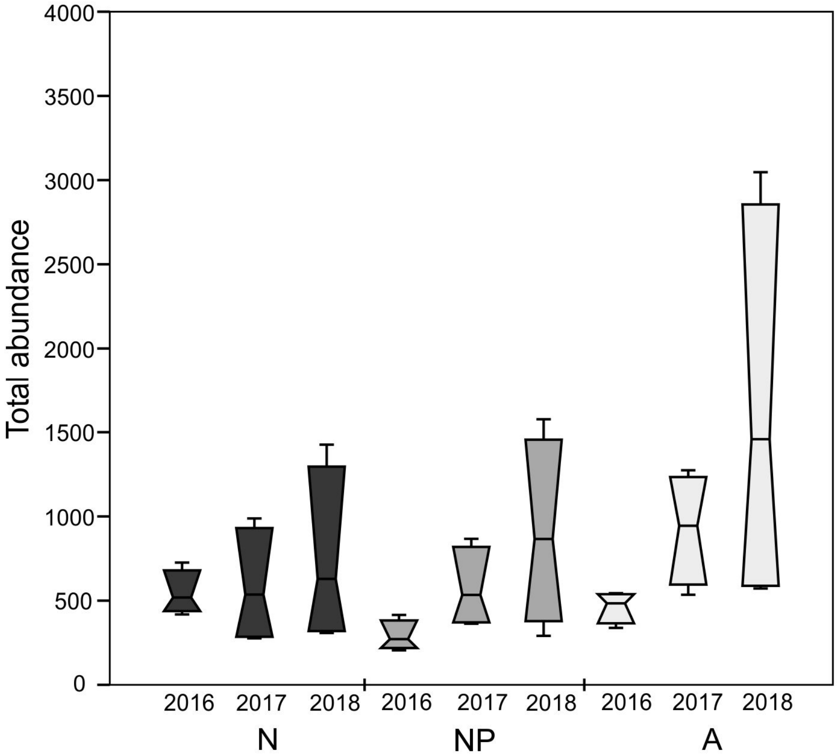

Figure 2. Distribution of median values ± SE and whisker length (1 σ) of carabid beetles' abundance in relation to three types of pine forest regeneration (N—natural, NP—natural with soil ploughing, and A—artificial with soil ploughing).

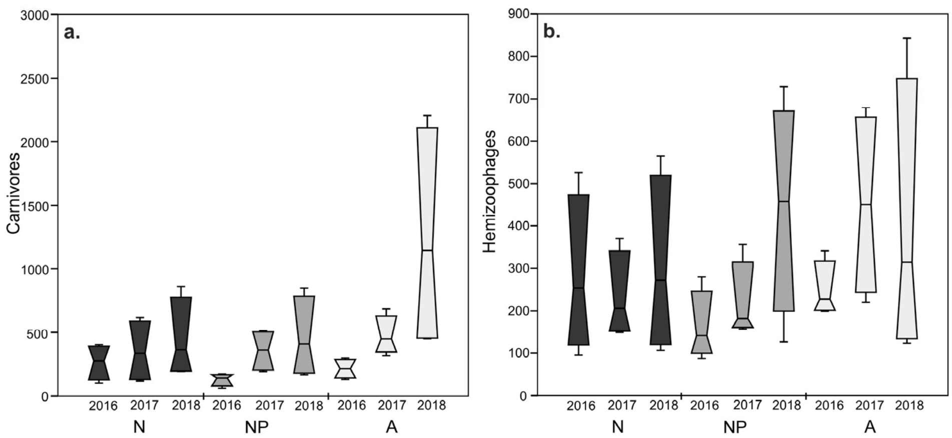

Figure 3. Distribution of median values ± SE (box) and whisker length (1 σ) of carabid beetles' food preferences: (**a**) carnivores and (**b**) hemizoophages, in relation to three types of pine forest regeneration (N—natural, NP—natural with soil ploughing, and A—artificial with soil ploughing).

Regarding wing development, a parameter which is especially important during the recolonisation of habitats, we noted that the type of pine forest regeneration and years of observation significantly impacted on the abundance of brachypterous, dimorphic, and macropterous species (Table 2). Brachypterous species were most abundant in both the natural (without ploughing) and artificial pine regeneration variants (Figure 4a). Interestingly, the abundance of brachypterous species decreased in successive years in variant N, while this life trait increased in variant A. In the case of variant NP, we observed the lowest abundance of brachypterous species. The highest share of dimorphic species was observed in variant A, especially in the third year of the study (Figure 4b). The abundance of dimorphic species in variants N and NP was similar, and both increased in subsequent years (2016–2018, Figure 4b). Species with high dispersal power were the most abundant in the N and A variants, and their abundance was similar in relation to multi-annual observation. In the case of the NP and A variants, we observed an increase in macropterous species over the three years; in the naturally regenerated forest, the abundance of macropterous species was similar within 2016–2018 (Figure 4c).

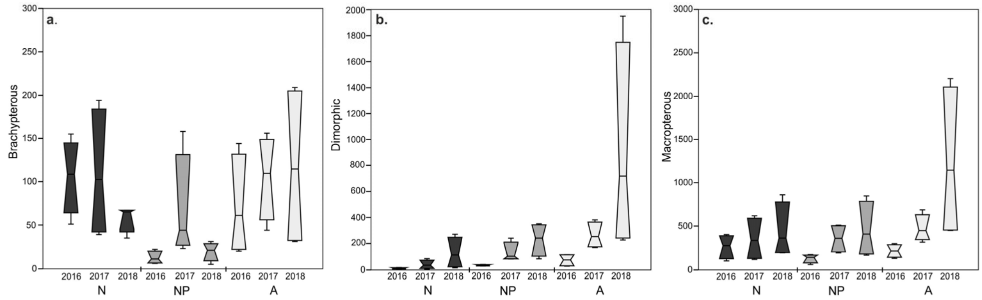

Figure 4. Distribution of median values ± SE (box) and whisker length (1 σ) of carabid beetles' wing development: (**a**) brachypterous, (**b**) dimorphic, and (**c**) macropterous, in relation to three types of pine forest regeneration (N—natural, NP—natural with soil ploughing, and A—artificial with soil ploughing).

We also analysed the habitat preferences (generalists, forest, and open-area species) of carabid beetles in relation to three pine forest regeneration types. The results revealed that this life trait significantly depends on different forest regeneration types (Table 2). Only species which preferred wetlands were not significantly different in relation to pine renewal variants (Table 2). Overall, the highest abundance of generalists was observed in the A variant, but also in this variant, the strongest decrease in generalist carabids' abundance was observed within the years 2016–2018 (Figure 5a).

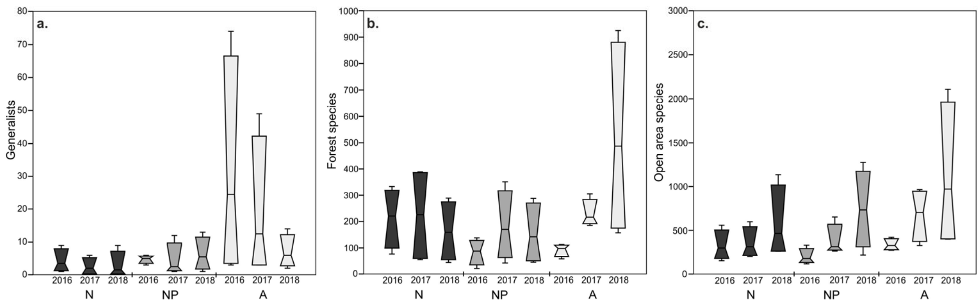

Figure 5. Distribution of median values ± SE (box) and whisker length (1 σ) of carabid beetles' habitat preferences: (**a**) generalists, (**b**) forest specialists, and (**c**) open-area species, in relation to three types of pine forest regeneration (N—natural, NP—natural with soil ploughing, and A—artificial with soil ploughing).

In the case of the N and NP variants, the abundance of generalist species was stable and at a similar level. The numbers of forest specialist carabids were similar. They were the highest in the natural (N) and artificial (A) types of pine forest regeneration. In the N variant, forest carabid abundance was the most stable within the three years of study (Figure 5b). The highest variability in this group of species was observed in the A variant, where forest specialists' abundance increased within the three years of observation. The abundance of open-area carabid species was higher in the NP and A pine regeneration variants compared to the N variant. In each type of regeneration, we observed an increase in open-area species' abundance within 2016–2018 (Figure 5c).

4. Discussion

An overarching requirement in global forest policy is promoting and protecting biodiversity. Matuszkiewicz et al. [12], as part of the framework of sustainable forest management based on flora research, point to the natural regeneration of stands of trees as a way to improve biodiversity. Based on epigeic ground beetle zooindicators, which are sensitive to changing environmental conditions, in this article, we show the position of the entomofauna in this type of practice.

The results of our study only partially support the first hypothesis, in which we predicted that the method of pine forest regeneration significantly affects the ground beetle assemblages and naturally regenerated pine stands without soil preparation, which will be characterised by a higher abundance, species richness, and diversity of ground beetles than naturally regenerated forests on ploughed soil or artificially regenerated stands. Differences in these assemblages of the ground beetles were recorded only in total abundance, while the species richness and diversity values did not differ. In our previous paper [5] describing a one-year study of Carabidae assemblages conducted two years after trees were cut down, we observed differences in the above parameters depending on the variant of pine regeneration. However, the highest values were only recorded for abundance in natural pine regeneration, where the soil was not interfered with.

Magura et al. [22] indicate that ground beetles respond to any disturbance, such as cutting down trees or ploughing, by increasing their abundance and species richness. This is somewhat similar to our study. The analysis of the total number of individuals caught shows rapid colonisation of new areas by ground beetles, such as in pine regeneration areas. This is a mechanism often observed in newly created and disturbed forest habitats. As habitat conditions diversify, the abundance of ground beetles increases. The pine regeneration plots analysed were established on cleared forests, which may have triggered the observed response of the ground beetles studied. They colonised new territory and exploited new food sources, e.g., jumping tails, which were abundant during the study and have been shown to feed on predatory arthropods [23]. In the following years of the study, ground beetles were more likely to colonise areas with artificial regeneration (A), which could host more invertebrates with the growth of pine seedlings, thus becoming a good food base. Their abundance in the surveyed regenerated areas increased with each year of the study; in 2017 and 2018, almost twice as many ground beetles were caught in this A variant compared to the other variants. This agrees with Schwerk and Szyszko's finding [24] that succession initially runs faster on planted pine forests and is connected with carabid coenoses' formation.

An important requirement for successful forest regeneration, especially in the first years of cultivation, is soil preparation [11,25,26]. The various methods of soil preparation used in forestry [13] may be more or less conducive to successful regeneration, but not necessarily to the fauna and especially to the entomofauna living on the ground, due to both the formation of a new environment (post-felling cultivation) and new threats to the seedlings (i.e., drought, parasitic fungi), also affecting the entomofauna [27–30]. Some authors [22,31] suggest omitting soil preparation with the ploughing of regenerated forest stands to preserve the original soil conditions and protect the soil-dwelling invertebrate fauna. In contrast to the results in our previous work [5], which included only the first year of study after clear-cutting, the present study showed that ground beetle abundance increased in soil-ploughing variants of pine regeneration. Considering the abundance of ground beetles in our study of pine regeneration with prepared soil, both from planting and self-seeding, it increased in each year of the study, more than tripling the values recorded in the first year. The reasons for this can be found in the early stages of succession. In the first years after the treatments (clear-cutting, ploughing), due to the uncovering of the soil and better insolation, rapid recolonisation has been observed, especially by the smaller, macropterous ground beetles.

Natural regeneration (N) without soil preparation was the most stable regarding ground beetle abundance, number of species, and Shannon diversity index values. Probably due to less human interference with the habitat, some of the Carabidae fauna characteristics of the pre-existing stand persisted there, so a faunal replacement was not so fast. SIMPER analysis identified species specific to the regeneration variants studied, indicating a high proportion of forest ground beetles such as *Carabus arvensis*, *Pterostichus niger*, and *Pterostichus oblongopunctatus* in naturally regenerated plots. Skłodowski [29], studying the influence of various types of soil preparation in cutting stands on ground beetles, also pointed out *Carabus arvensis* as a species avoiding ploughed sites. In the other regeneration variants, the soil conditions are changed significantly through ploughing, causing a change in faunal composition, hence the high abundance and often high diversity indices in subsequent years, when the easily mobile ground beetle fauna colonised new areas, taking advantage of the abundant food base, which is also in line with our second hypothesis.

To determine in more detail the impact of human activity on the assemblage of ground beetles, many authors use life-trait analysis [32–37]. Skłodowski [30] finds that the regeneration of forest assemblages of ground beetles is reflected in an increasing proportion of forest wingless zoophages. In our study, we also paid particular attention to life traits indicating habitat stabilisation and colonisation, i.e., habitat preferences, wing development, and trophic preferences.

Several studies indicate that ground beetle response to cutting is particularly noticeable during the first three years after cutting [2,18,38–40]. Early plantations with an open canopy are inhabited by small non-forest species, usually winged hemizoophages [41]. According to Magura et al. [22], the early phases after cutting are massively colonised by open-ground and generalist species, although some forest species also remain. This is somewhat similar to our results, which indicate that the regenerated areas after tree cutting had been extensively colonised by open-area species, with a tendency for their abundance to increase over the three years of the study. As mentioned earlier, forest specialists, despite the unfavourable conditions, were most often relatively abundant, preferring natural pine regeneration (N) without soil preparation, where their numbers were stable and similar in all years of the study. However, despite the loss of many microhabitats preferred by forest specialists, by ploughing the soil, they appeared in abundance in artificial regeneration plots (A) as early as the third year after the establishment of the pine plantation.

The dispersal capabilities of ground beetles are very much related to the colonisation of new areas, such as pine regeneration sites. In our study, the most numerous were macropterous ground beetles, characteristic of colonised habitats. The abundance of brachypterous ground beetles was considerably lower, and it was impossible to establish a clear pattern for their occurrence during the three years of the study. It is particularly visible in the habitats of the NP variant and may indicate a random occurrence of brachypterous species there. However, their successive increase in artificial (A) regeneration plots was observed. The presence of habitat specialists with poor dispersal ability indicates that the habitat is stable, and the patch is large enough to ensure the long-term persistence of the population or is close enough to other patches to be repopulated even by poorly dispersing species [34,42]. According to Fuller et al. [43], landscape structure is also important when considering the conservation potential of land management by a typical forestry cycle. Especially for wingless forest specialists, recolonisation after clear-cutting may be possible from stands in close proximity because of their limited dispersal ability. In sustainable forest management, it is common to leave fragments of tree stands, with approximately 5% of trees remaining on the cut forest [5]. This remnant tree-retention group provides seeds for natural regeneration and may preserve some heterogeneity and environmental conditions for forest specialists [22,44].

Predatory arthropods, which include many species of the Carabidae family, perform many important roles in forest ecosystems [45]. In the pine regeneration variants studied, carnivores accounted for most of the carabids caught, but only in natural regeneration plots (N) were their numbers stable and steadily increasing. Based on the above observations, it can be assumed that in the following years, the status of predatory ground beetles will gradually stabilise with the growth of trees in the pine regeneration.

5. Conclusions

The strongest negative effect of clear-cutting on ground beetle assemblages was observed in the first year of the study. The abundance of Carabidae in the following years of study on the analysed variants of pine stand regeneration increased. Thus, based on three years of observations, we can conclude that the forest regeneration method did not negatively affect the abundance of Carabidae.

Natural regeneration without soil preparation (N) was the most favourable in terms of the occurrence of stabilised assemblages of ground beetles. However, the remaining methods of pine regeneration, on a multi-annual scale, not only contribute to an increase in the number of ground beetles but also provide high variability in assemblage composition, diversity indices, and life traits.

Based on the findings of this study, ground beetle life traits seem to be a useful tool for estimating the direction of the early stage of pine forest regeneration, which can be useful in effective forest management. The largest number of Carabidae were observed in combination N in the first year of the study. In subsequent years, a higher number were found in combination A, which was associated with a large migration of Carabidae species related to the early phase of succession (macropterous, open areas, hemizoophagous). The number of forest species in natural forest regeneration remains at a stable, similar level. In the case of artificial regeneration, small numbers of forest species are observed in the first year, but in subsequent years, their number begins to increase significantly.

Thus, in the early stage of pine regeneration, each of the examined variants of pine regeneration can be used without fear of causing damage to populations of carabids. However, further studies are required to examine the effect of different pine regeneration types on carabid beetle assemblages over a longer period. Other limitations, i.e., costs and legal regulations, should also be taken into consideration during the planning of variants of forest stand regeneration.

Author Contributions: Conceptualisation, A.K. and R.K.; methodology, A.K.; software, R.K.; validation, A.K., R.K. and M.N.; formal analysis, A.K.; investigation, A.K. and M.N. resources, A.K.; data curation, A.K.; writing—original draft preparation, A.K., R.K., M.N. and J.B.; writing—review and editing, A.K., R.K., M.N. and J.B.; visualisation, A.K. and R.K.; supervision, A.K. and J.B.; project administration, A.K. and J.B.; funding acquisition, A.K. and J.B. All authors have read and agreed to the published version of the manuscript.

Funding: The study is part of the "Natural forest regeneration as a means of decreasing deer browsing in Warmia and Mazury" grant with funding from the General Directorate of State Forests. In frame of this research abroad internship was financially supported by the Ministry of Science and Higher Education within "Regional Initiative of Excellence" program for the years 2019–2023, Project No. 010/RID/2018/19, amount of funding 12,000,000 PLN and also by a research project of the University of Warmia and Mazury in Olsztyn, Faculty of Agriculture and Forestry, Department of Entomology Phytopathology and Molecular Diagnostics (no. 30.610.010-110). The funding bodies had no role in the study design, data collection and analysis, publication decisions, or manuscript preparation.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data relating to the species composition and abundance of ground beetles presented in this study are available on request from the corresponding author.

Acknowledgments: The authors thank unknown reviewers for valuable comments on a former draft of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. State Forests. Available online: https://www.lasy.gov.pl (accessed on 7 August 2023).
2. Szyszko, J. *Szyszko State of Carabidae (Col.) Fauna in Fresh Pine Forest and Tentative Valorisation of This Environment*; Warsaw Agricultural University Press: Warsaw, Poland, 1983.

3. Koivula, M. Boreal Carabid-Beetle (Carabidae) Assemblages Uneven-Aged and Clear-Cut Spruce Stand. *Ann. Zool. Fenn.* **2002**, *39*, 131–149.
4. Skłodowski, J. Manual Soil Preparation and Piles of Branches Can Support Ground Beetles (Coleoptera, Carabidae) Better than Four Different Mechanical Soil Treatments in a Clear-Cut Area of a Closed-Canopy Pine Forest in Northern Poland. *Scand. J. For. Res.* **2017**, *32*, 123–133. [CrossRef]
5. Kosewska, A.; Topa, E.; Nietupski, M.; Kedzior, R. Assemblages of Carabid Beetles (Col. Carabidae) and Ground-Dwelling Spiders (Araneae) in Natural and Artificial Regeneration of Pine Forests. *Community Ecol.* **2018**, *19*, 156–167. [CrossRef]
6. Masternak, K.; Głębocka, K.; Surowaniec, K.; Kowalczyk, K. Growth Traits of Natural Regeneration of Scots Pine (*Pinus sylvestris* L.) in South-Eastern Poland. *Folia For. Pol. Ser. A* **2020**, *62*, 220–226. [CrossRef]
7. Przybylski, P.; Konatowska, M.; Jastrzębowski, S.; Tereba, A.; Mohytych, V.; Tyburski, Ł.; Rutkowski, P. The Possibility of Regenerating a Pine Stand through Natural Regeneration. *Forests* **2021**, *12*, 1055. [CrossRef]
8. Pearce, J.L.; Venier, L.A. The Use of Ground Beetles (Coleoptera: Carabidae) and Spiders (Araneae) as Bioindicators of Sustainable Forest Management: A Review. *Ecol. Indic.* **2006**, *6*, 780–793. [CrossRef]
9. Lucas Borja, M.E. Climate Change and Forest Natural Regeneration in Mediterranean Mountain Areas. *For. Res. Open Access* **2014**, *3*, 1000e108. [CrossRef]
10. Moreno-Fernández, D.; Cañellas, I.; Barbeito, I.; Sánchez-González, M.; Ledo, A. Alternative Approaches to Assessing the Natural Regeneration of Scots Pine in a Mediterranean Forest. *Ann. For. Sci.* **2015**, *72*, 569–583. [CrossRef]
11. Andrzejczyk, T.; Augustyniak, G. Wpływ przygotowania gleby na wzrost sosny zwyczajnej w pierwszych latach uprawy. *Sylwan* **2007**, *8*, 3–8.
12. Matuszkiewicz, J.M.; Kowalska, A.; Kozłowska, A.; Roo-Zielińska, E.; Solon, J. Differences in Plant-Species Composition, Richness and Community Structure in Ancient and Post-Agricultural Pine Forests in Central Poland. *For. Ecol. Manag.* **2013**, *310*, 567–576. [CrossRef]
13. Korzeniewicz, R.; Wojtaszczyk, R.; Glura, J. Impact Assessment Method of Soil Preparation on Density of Scots Pine in the Poddębice Forestry District. *Acta Sci. Pol. Silvarum Colendarum Ratio Ind. Lignaria* **2016**, *15*, 247–255. [CrossRef]
14. Aleksandrowicz-Trzcińska, M.; Drozdowski, S.; Studnicki, M.; Zybura, H. Effects of Site Preparation Methods on the Establishment and Natural-Regeneration Traits of Scots Pines (*Pinus sylvestris* L.) in Northeastern Poland. *Forests* **2018**, *9*, 717. [CrossRef]
15. Thiele, H.-U. *Carabid Beetles in Their Environments*; Springer: Berlin/Heidelberg, Germany, 1977; pp. 1–353.
16. Lövei, G.L.; Sunderland, K.D. Ecology and Behavior of Ground Beetles (Coleoptera: Carabidae). *Annu. Rev. Entomol.* **1996**, *41*, 231–256. [CrossRef]
17. Rainio, J.; Niemela, J. Ground Beetles (Coleoptera: Carabidae) as Bioindicators. *Biodivers. Conserv.* **2003**, *12*, 487–506.
18. Koivula, M.J. Useful Model Organisms, Indicators, or Both? Ground Beetles (Coleoptera, Carabidae) Reflecting Environmental Conditions. *Zookeys* **2011**, *100*, 287–317. [CrossRef] [PubMed]
19. Johan Kotze, D.; Brandmayr, P.; Casale, A.; Dauffy-Richard, E.; Dekoninck, W.; Koivula, M.J.; Lövei, G.L.; Mossakowski, D.; Noordijk, J.; Paarmann, W.; et al. Forty Years of Carabid Beetle Research in Europe—From Taxonomy, Biology, Ecology and Population Studies to Bioindication, Habitat Assessment and Conservation. *Zookeys* **2011**, *100*, 55–148. [CrossRef]
20. Hurka, K. *Carabidae of the Czech and Slovak Republics*; Kabourek: Zlín, Czech Republic, 1996; pp. 1–566.
21. Skibińska, E. Aleksandrowicz O R Biegaczowate (Carabidae). In *Fauna Polski—Charakterystyka i Wykaz Gatunków*; Bogdanowicz, W., Chudzicka, E., Filipiuk, I., Skibińska, E., Eds.; Muzeum i Instytut Zoologii PAN: Warsaw, Poland, 2004; Volume I, pp. 28–42.
22. Magura, T.; Bogyó, D.; Mizser, S.; Nagy, D.D.; Tóthmérész, B. Recovery of Ground-Dwelling Assemblages during Reforestation with Native Oak Depends on the Mobility and Feeding Habits of the Species. *For. Ecol. Manag.* **2015**, *339*, 117–126. [CrossRef]
23. Hengeveld, R. Polyphagy, Oligophagy and Food Specialization in Ground Beetles (Coleoptera, Carabidae). *Neth. J. Zool.* **1979**, *30*, 564–584. [CrossRef]
24. Schwerk, A.; Szyszko, J. Successional Patterns of Carabid Fauna (Coleoptera: Carabidae) in Planted and Natural Regenerated Pine Forests Growing on Old Arable Land. *Balt. J. Coleopterol.* **2007**, *7*, 9–16.
25. Gornowicz, R.; Pilarek, Z.; Gałązka, S. Survivability of Scots Pine during the Period of 5 Years from the Cultivation Establishment in Relation to the Way of the Preparation of the Clear-Cut Surface for Regeneration. *Acta Sci. Pol. Silv. Colendar. Rat. Ind. Lignar.* **2007**, *6*, 33–39.
26. Simonsen, R. Optimal Regeneration Method-Planting vs. Natural Regeneration of Scots Pine in Northern Sweden. *Silva Fenn.* **2013**, *47*, 928. [CrossRef]
27. Bird, S.; Coulson, R.N.; Crossley, D.A. Impacts of Silvicultural Practices on Soil and Litter Arthropod Diversity in a Texas Pine Plantation. *For. Ecol. Manag.* **2000**, *131*, 65–80. [CrossRef]
28. Koivula, M.; Niemelä, J. Boreal Carabid Beetles (Coleoptera, Carabidae) in Managed Spruce Forests-a Summary of Finnish Case Studies. *Silva Fenn.* **2002**, *36*, 423–436. [CrossRef]
29. Skłodowski, J. Skłodowski Zgrupowania biegaczowatych jako zooindykatory różnych sposobów przygotowania gleby na zrębach oraz ich zagospodarowania. *Sylwan* **2010**, *154*, 625–638.
30. Skłodowski, J.J. Effects of Top-Soil Preparation and Broad-Leaved Tree Mixture on Carabid Beetles in Afforested Fallow Plots. *Restor. Ecol.* **2014**, *22*, 13–21. [CrossRef]
31. Nagy, D.D.; Magura, T.; Debnár, Z.; Horváth, R.; Tóthmérész, B. Shift of Rove Beetle Assemblages in Reforestations: Does Nativity Matter? *J. Insect. Conserv.* **2015**, *19*, 1075–1087. [CrossRef]

32. Skalski, T.; Kędzior, R.; Szwalec, A.; Mundała, P. Do Traditional Land Rehabilitation Processes Improve Habitat Quality and Function? Life-History Traits of Ground Beetles (Coleoptera, Carabidae) Say No. *Period. Biol.* **2016**, *118*, 185–194. [CrossRef]
33. Magura, T.; Tóthmérész, B.; Elek, Z. Changes in Carabid Beetle Assemblages as Norway Spruce Plantations Age. *Community Ecol.* **2006**, *7*, 1–12. [CrossRef]
34. Šerić Jelaska, L.; Durbešić, P. Comparison of the Body Size and Wing Form of Carabid Species (Coleoptera: Carabidae) between Isolated and Continuous Forest Habitats. *Ann. Soc. Entomol.* **2009**, *45*, 327–338. [CrossRef]
35. Jelaska, L.Š.; Dumbović, V.; Kučinić, M. Carabid Beetle Diversity and Mean Individual Biomass in Beech Forests of Various Ages. *Zookeys* **2011**, *100*, 393–405. [CrossRef] [PubMed]
36. Skłodowski, J. Survival of Carabids after Windthrow of Pine Forest Depends on the Presence of Broken Tree Crowns. *Scand. J. For. Res.* **2020**, *35*, 10–19. [CrossRef]
37. Kędzior, R.; Kosewska, A. Landscape Heterogeneity Determines the Diversity and Life History Traits of Ground Beetles (Coleoptera: Carabidae). *Sustainability* **2022**, *14*, 13980. [CrossRef]
38. Niemelä, J.; Koivula, M.; Kotze, D.J. The Effects of Forestry on Carabid Beetles (Coleoptera: Carabidae) in Boreal Forests. *J. Insect. Conserv.* **2007**, *11*, 5–18. [CrossRef]
39. Schwerk, A.; Szyszko, J. Model of Succession in Degraded Areas Based on Carabid Beetles (Coleoptera, Carabidae). *Zookeys* **2011**, *100*, 319–332. [CrossRef]
40. Macko, J. Impact of Clearcutting on Ground Beetles (Coleoptera: Carabidae) in a Norway Spruce Forest. *Bull. Transilv. Univ. Braşov.* **2016**, *9*, 1–8.
41. Skłodowski, J.; Bajor, P.; Trynkos, M. Carabids Benefit More from Pine Stands with Added Understory or Second Story of Broad-Leaved Trees Favored by Climate Change than from One-Storied Pine Stands. *Eur. J. For. Res.* **2018**, *137*, 745–757. [CrossRef]
42. Niemelä, J. Carabid Beetles (Coleoptera: Carabidae) and Habitat Fragmentation: A Review. *Eur. J. Entomol.* **2001**, *98*, 127–132. [CrossRef]
43. Fuller, R.J.; Oliver, T.H.; Leather, S.R. Forest Management Effects on Carabid Beetle Communities in Coniferous and Broadleaved Forests: Implications for Conservation. *Insect. Conserv. Divers.* **2008**, *1*, 242–252. [CrossRef]
44. Skłodowski, J. Responses of Ground Beetles (Coleoptera, Carabidae) to Tree Retention Groups of Various Sizes Support Leaving Them in Clear-Cut Areas. *For. Ecol. Manag.* **2021**, *493*, 119261. [CrossRef]
45. Schuldt, A.; Fahrenholz, N.; Brauns, M.; Migge-Kleian, S.; Platner, C.; Schaefer, M. Communities of Ground-Living Spiders in Deciduous Forests: Does Tree Species Diversity Matter? *Biodivers. Conserv.* **2008**, *17*, 1267–1284. [CrossRef]