Carabus Population Response to Drought in Lowland Oak Hornbeam Forest

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Abstract: Forest management practices and droughts affect the assemblages of carabid species, and these are the most important factors in terms of influencing short- and long-term population changes. During 2017 and 2018, the occurrences and seasonal dynamics of five carabid species (*Carabus coriaceus*, *C. ulrichii*, *C. violaceus*, *C. nemoralis* and *C. scheidleri*) in four oak hornbeam forest stands were evaluated using the method of pitfall trapping. The climate water balance values were cumulatively calculated here as cumulative water balance in monthly steps. The cumulative water balance was used to identify the onset and duration of drought. The number of Carabus species individuals was more than three times higher in 2018 than in 2017. Spring activity was influenced by temperature. The extremely warm April in 2018 accelerated spring population dynamics; however, low night temperatures in April in 2017 slowed the spring activity of nocturnal species. Drought negatively influenced population abundance, and the effect of a drought is likely to be expressed with a two-year delay. In our investigation, a drought in 2015 started in May and lasted eight months; however, the drought was not recorded in 2016, and 2016 was evaluated as a humid year. The meteorological conditions in the year influenced seasonal activity patterns and the timings of peaks of abundance for both spring breeding and autumn breeding Carabus species.

1. Introduction

Ground dwelling invertebrates such as carabid beetles and spiders are often surveyed with respect of ecosystem changes. These invertebrates have strong potential as ecological indicators, as they are readily surveyed in sufficient numbers for meaningful conclusions to be drawn, have a stable taxonomy, and, at least in the case of ground beetles, are readily identified. They are, for example, good local scale indicators of ecosystem disturbance in forested landscapes at both the short- and long-term time scales, responding to clear-cut logging and fire differently [1].

Carabids belong to one of the most frequently used model groups for biological studies. The reasons for this are various, including the relatively stable taxonomy, species richness, occurrence in most terrestrial habitats and geographical areas, availability of simple collection methods, and known sensitivity to environmental changes [2]. The effect of clearcutting on Carabidae is well studied. Clearcutting has a definitive impact on Carabidae, depending on species, and notably in cases with the replacement of large forest species by the usually smaller eurytopic open field species in clearings [3]. Human impacts in forest ecosystems generally cause losses for some relict species and gains for ubiquitous species. Clearcutting leads to a drastic decrease in mean individual biomass. The regeneration of carabid fauna after clearcutting is a very slow process, and typical relict forest

species are absent even after several decades of forest regeneration [4]. The impact of a drought on carabid assemblage has been studied in forests damaged by a windstorm in the High Tatra Mountains, focusing on the trends of community differentiation according to the state and management of damaged sites. The revealed trends included reversible quantitative changes recorded on stands with the fallen timber in situ, the disappearance of less tolerant forest species at sites with extracted timber, and temporal invasions of xenocoenous open-landscape species at the sites with extracted timber and additionally burned sites [5].

Phenology, which is the timing of the seasonal activities of animals and plants, is perhaps the simplest process for monitoring changes in the ecology of species in response to climate change. Species responses to climate change can disrupt their interactions with others at the same or adjacent trophic level. If closely cooperating or competing species show different responses or susceptibility to change, the outcome of their interactions may change, as suggested by long term data for terrestrial and marine organisms. Therefore, rapid climate change or extreme climatic events can be expected to change the compositions of organism communities [6]. Phenological changes caused by climate change are slower at higher trophic levels (i.e., secondary consumers) than at lower trophic levels (excluding woody plants), thus higher trophic levels are particularly sensitive to the disruption of phenological connections [7]. Carabidae represent an important food role in many terrestrial ecosystems [8,9]. They are among the most important insect predators of soil fauna, especially in temperate climate regions [10].

Climate change is expected to alter average temperature and precipitation values and increase the variability of precipitation events, which may lead to even more intense and frequent floods and droughts [11], although future projections reveal regionally different occurrences of extreme events. As projected in [12], at a pan-European scale, the regions that are most prone to a rise in flood frequency are located in northern to northeastern Europe, while the southern and southeastern European regions show significant increases in the frequencies of drought. Similarly, significant regional differences have also been projected for extreme events in China and East Africa [13,14].
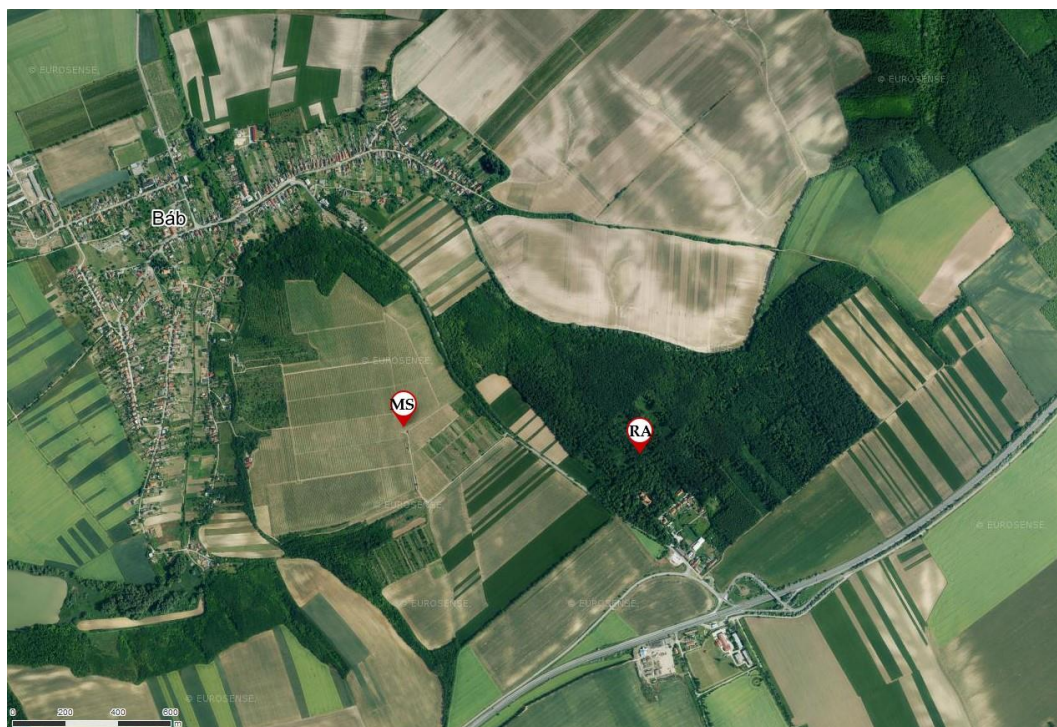
As pointed out in [15], altitude and topography are strong climate-differentiating factors. The Slovak territory has been divided by [16] into nine altitudinal vegetation stages. The vegetation stages of lower elevations, i.e., oak vegetation (stage 1), are rather arid during the vegetation period (from March to September). Altitudinal analysis of the drought climatology of the Western Carpathians in Slovakia has been carried out by [15,17], and the results point out a significant trend for aridity at the lowest altitudes, which is where the oak vegetation stage occurs. The southern part of the Slovak Republic territory is the region where agricultural landscape is prevailing, and forests are scarce there and mostly occur as isolated enclaves [18]. Apart from altitudinal vegetation stage division, the Slovak Republic territory is traditionally divided into the varying agroclimatic zones, and the climatic water balance is the basis for such regionalization [19]. This practice of regionalization is still under scientific revision with respect to climate change [20] or drought occurrence analysis [21].

The aim of our research here is to determine the impact of drought on Carabus beetles populations in lowland oak hornbeam forest occurring at the driest region of the Slovakia. The influence of different types of forest stands on the Carabus beetles populations is also studied.

2. Materials and Methods

The study was carried out at the locality of Báb (Figure 1), which is situated approximately 15 km from Nitra, Slovakia, and located in the southwest of Slovakia. The forest is a rest of former climax woodland covered lowlands and hill areas of in the Nitrianska pahorkatina region. The locality belongs to the Pannonian Bio-geographical Region. The deciduous oak hornbeam forest of 66 ha is partly preserved as a natural reserve and the rest of the forest area is managed [22]. Báb research site is a part of the national LTER (Long term ecological research) network, which is part of the organizational structure of LTER-Europe (http://www.lter-europe.net/). The site was established in 1967 under the International Biological Program (IBP) framework and research started with the IBP (1967–1970)

and UNESCO Man and Biosphere (1971–1974) projects. The research activities were carried out until 1974 [23]. After the complex and intensive ecosystem research in 1967–1974, research continued to a restricted extent with the work of individual researchers [24]. In November 2006, single line and shelterwood logging was carried out and, the area was than cleaned up from brushwood beginning 2007. After tree removal, four clear-cut stands were created at the locality.

Figure 1. The localization of the Báb research area (RA) and meteorological station (MS) where the meteorological data were derived. The coordinates for the RA are 17.886, 48.3033, with an average elevation of 190 m a.s.l. (minimum of 170 m a.s.l, maximum of 210 m a.s.l.). The coordinates for the MS are 17.87881, 48.30331, with an elevation of 207 m a.s.l. The data were obtained from the DEIMS-SDR (Dynamic Ecological Information Management System-Site and dataset registry) database [25].

For our study, four 20×20 m^2 study plots were chosen at the locality. Two plots were chosen to represent forest stands. The first, named L1, represented close-to-nature forest, i.e., where no forest intervention had been carried out since 1962. The characteristic features of the L1 stand are higher wood cover and lower herb cover caused by overshadowing. The characteristics of the second forest stand, named L2, were influenced by logging in the neighborhood. Higher illumination resulted in higher herb cover and lower cover of the shrub layer. The other two plots represented recovering forest after clearcutting 10 years prior. The plot R1 represented a recovering forest stand that had become overgrown with shrubs and young tree vegetation (*Acer campestre*, *Crataegus laevigata*, *Carpinus betulus*, *Rosa canina*, *Quercus cerris*, *Q. petrea*, etc.). The dense canopy closure of the young trees resulted in lower herb cover. A higher presence of fine woody debris was typical for the ground at the R1 study plot. The plot named R2 represented another after recovering stand after logging operations. Compared to R1, the R2 plot was characterized by the dominance of the invasive tree species *Ailanthus altissima* and the dense herb layer cover that was mostly formed by medium to tall herbs (e.g., *Mercurialis annua*, *Convallaria majalis, Urtica dioica, Ballota nigra*). The trees of *A. altissima* were approximately 2–3-year-old sprout shoots, as single-cut removal of this invasive species was performed in 2015. The localizations of the individual study plots are given in Figure A1.

Carabids were collected using the method of pitfall trapping (180 mL plastic cups buried in the soil and filled with vinegar to kill and preserve samples). Seven pitfall traps were installed at each

research plot. Four traps were located at the corners, where the remaining three traps were placed diagonally inside the plots at regular spacings. The samples were removed weekly from the beginning of April to the end of September. The species determination was based on adult beetles morphology, where the classification method of [26] was adopted.

The occasional damage of traps is common in the field. For this reason, it was not possible to use absolute numbers of trapped individuals. The numbers of individuals for each species were evaluated as the number of individuals per trap. Weekly catches, i.e., the number of individuals per trap per week, were used for seasonal activity evaluation. Weekly evaluation allowed comparison of the dynamics of carabid populations between the two years and more precise identification of the peak activity timing. With the monthly catches, number of individuals per trap per month values were calculated for the purpose of the evaluation of the impact of drought on carabid species populations.

We used the index of dominance (D_i) to compare the occurrence levels between species and the four forest stands:

$$D_i = (n_i/N) \times 100 \ (\%) \tag{1}$$

where n_i is the abundance of individual species and N is the total abundance.

The temperature and precipitation data were obtained from the automatic climatic station located in the open area next to the Báb forest (Figure 1). The meteorological conditions in the year were characterized according to the climatological normal and the period of 1961–1990 was used as normal. The monthly values of the precipitation total and the average temperature were compared to the normal values. The cumulative water balance was used for drought episode identification and the duration of the drought. Firstly, the climate water balance calculation, based on the monthly values of atmospheric precipitation and potential evapotranspiration, was derived for every month in the year. The result can be positive, representing a positive water balance in the given month, or negative, representing the water deficit. Then, the climate water balance values were cumulatively calculated as cumulative water balance in monthly steps. The criterion for identifying a drought was the occurrence of a negative cumulative value for a specific month. A polynomial fourth-order trend line described the dynamics of the drought. When the trend line cut the x-axis towards the negative values, this was considered as the onset of a drought, and vice versa, where cutting the x-axis towards positive values represented the end of a drought [20,27].

3. Results

3.1. The Occurrence of the Carabus Species

Five species of the genus *Carabus* were recorded during the two years of our research: *Carabus coriaceus*, *Carabus nemoralis*, *Carabus ulrichii*, *Carabus scheidleri*, and *Carabus violaceus*.

Carabus beetles were active during the whole period of study, i.e., from the beginning of April until the end of September. The considerable difference between the total number of caught beetles was the most obvious aspect between the two compared years, where more than triple the number of individuals were caught in 2018 than in 2017 (583 and 1789 individuals in 2017 and 2018, respectively).

The Carabid occurrence levels, evaluated as the number of individuals per trap caught through the whole research period, were not equal for the four study plots. The highest carabid occurrence was recorded at the forest stand L2, where 7.7 and 22.8 individuals per trap were caught per season in 2017 and 2018, respectively. The results for the close-to-nature forest stand (i.e., the L1 research plot) showed that Carabid occurrence there was the lowest in 2017, but the second best overall in 2018, with 3.4 and 18 individuals per trap per season, respectively. The occurrences recorded at the recovering forest stand R1 were lowest in 2018, but second best in 2017 (12.8 and 6.3 individuals caught per trap per season in 2018 and 2017, respectively). For the R2 recovering forest stand, the numbers of caught individuals per trap and season were 5.5 in 2017 and 15 in 2018.

The differences between the occurrences of the individual species were also recorded, and some specifies that related to stand preference were also recorded.

Carabus ulrichii was the most frequent species for both 2017 and 2018, with approximately 27 and 42% of collected individuals belonging to this species in 2017 and 2018, respectively (Table 1). In 2018, *C. ulrichii* dominated at all stands, and its dominance was even higher than 50% at the L2 study plot. In 2017, *C. ulrichii* dominated at the two the closest stands, which were the recovering forest plot R2 and forest plot L2 (Table 2).

Table 1. The index of dominance calculated for *Carabus* species at four different forest stands (L1 and L2 are forest plots and R1 and R2 are recovering forest plots) at the locality of Báb (southwestern Slovakia) in 2017.

Species	Index of Dominance (%)				
	Total	**L1**	**L2**	**R1**	**R2**
C. coriaceus	20.8	24.2	15.1	30.8	13.9
C. scheidleri	23.3	24.2	26.0	25.4	16.7
C. ulrichii	27.4	17.7	32.3	16.2	39.6
C. nemoralis	6.3	11.3	8.9	3.2	4.9
C. violaceus	22.1	22.6	17.7	24.3	25.0

Table 2. The index of dominance calculated for *Carabus* species at four different forest stands (L1 and L2 are forest plots and R1 and R2 are recovering forest plots) at the locality of Báb (southwestern Slovakia) in 2018.

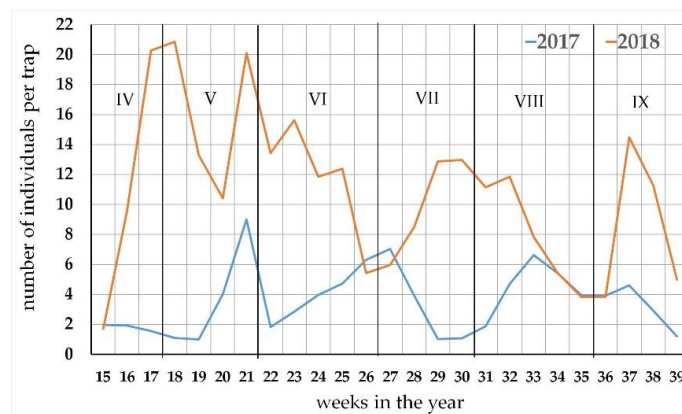| Species	Index of Dominance (%)				
	Total	**L1**	**L2**	**R1**	**R2**
C. coriaceus	22.1	14.4	11.8	30.3	21.9
C. scheidleri	23.4	34.6	15.9	26.2	29.6
C. ulrichii	41.5	25.8	53.2	34.5	37.4
C. nemoralis	7.5	23.5	15.1	4.4	2.0
C. violaceus	5.5	1.7	4.1	4.7	9.1

The species with the lowest occurrence was *Carabus nemoralis*. The dominance of this species was slightly higher in 2018 than 2017. The dominance of this species was especially low at the two recovering forest stands (Table 2). In 2018, almost 70% of the individuals of *C. nemoralis* were caught at the L1 forest stand, and more than 90% of individuals were collected at both forest stands. In 2017, the catch percentages at the forest plots were lower, but still high with values of almost 65%.

Carabus coriaceus and *Carabus scheidleri* reached dominance percentages of approximately 20% during both survey years (Tables 1 and 2). Almost 50% of *Carabus coriaceus* individuals were caught at the R1 recovering forest stand in 2017, where it was also the dominant species (Table 1); however, the dominance of this species was still high at the same study plot in 2018 (Table 2). The same number of individuals were collected at L2. Comparing the dominance of the species *Carabus scheidleri* in the two years of study and the four studied stands, there was no clear preference for a specific stand. When comparing the absolute numbers of caught individuals, slightly fewer individuals were captured at the L1 forest stand.

The species *Carabus violaceus* was the only species with lower occurrence in 2018; however, the absolute number decrease was only 31 individuals, where several-fold increases in the numbers of individuals for other species made this species the least represented in 2018 (Table 2).

3.2. The Seasonal Activity of the Carabus Species

In 2017, Carabus species activity remained low until first ten days of May (Figure 2). Then, the activity raised gradually, reaching a peak by the end of May, followed by a sudden decline in activity in the beginning of June (22nd week). The early summer activity period reached a peak in the beginning of July. After the summer stagnation, *Carabids* performed late summer–early autumn activity period with the peak of activity recorded in the middle of August.

Figure 2. The seasonal activity of Carabus species in the oak hornbeam forest at the locality of Báb (southwestern Slovakia) during 2017 and 2018.
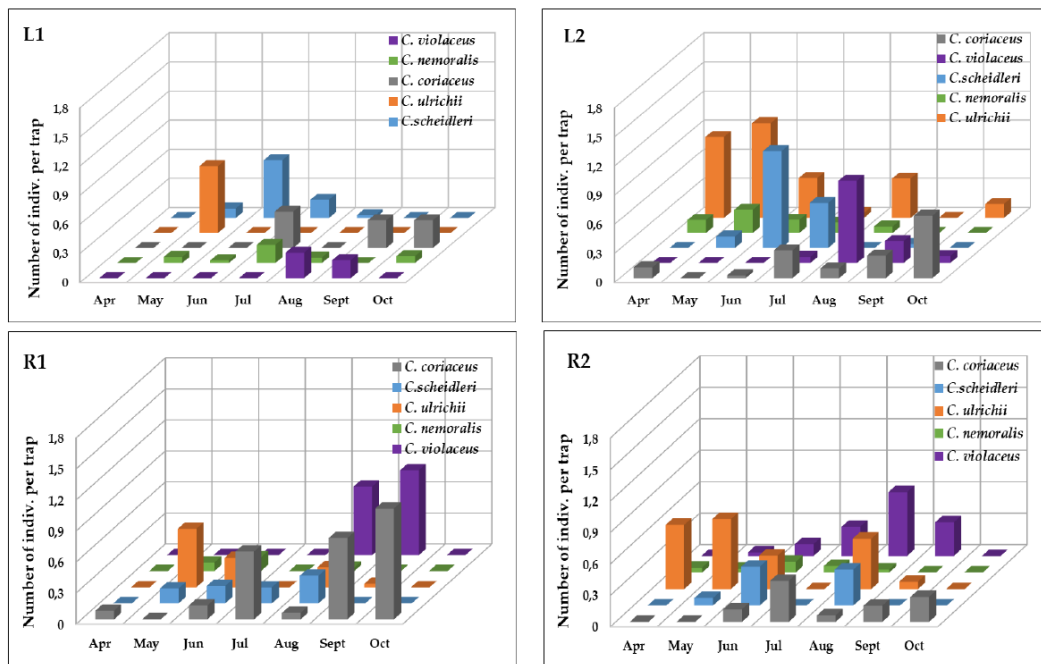
Besides the higher culmination levels, the difference in timing was another important aspect of the seasonal activity course in 2018 (Figure 2). In 2018, the beginning of Carabid activity was more dynamic when compared to the previous year. From the beginning of April, the activity rapidly increased and the spring peak of activity was recorded at the turn of April to May. After the period of decline in the middle of May, the activity raised again by the end of May and decreased in the end of June. The summer activity period culminated at the turn of July to August. The autumn period of activity culminated in the middle of September (Figure 2).

The observed activity peaks could be divided into seasonal activity for three distinct periods: (1) the spring to early summer activity period, (2) summer activity period, and (3) late summer to autumn activity period.
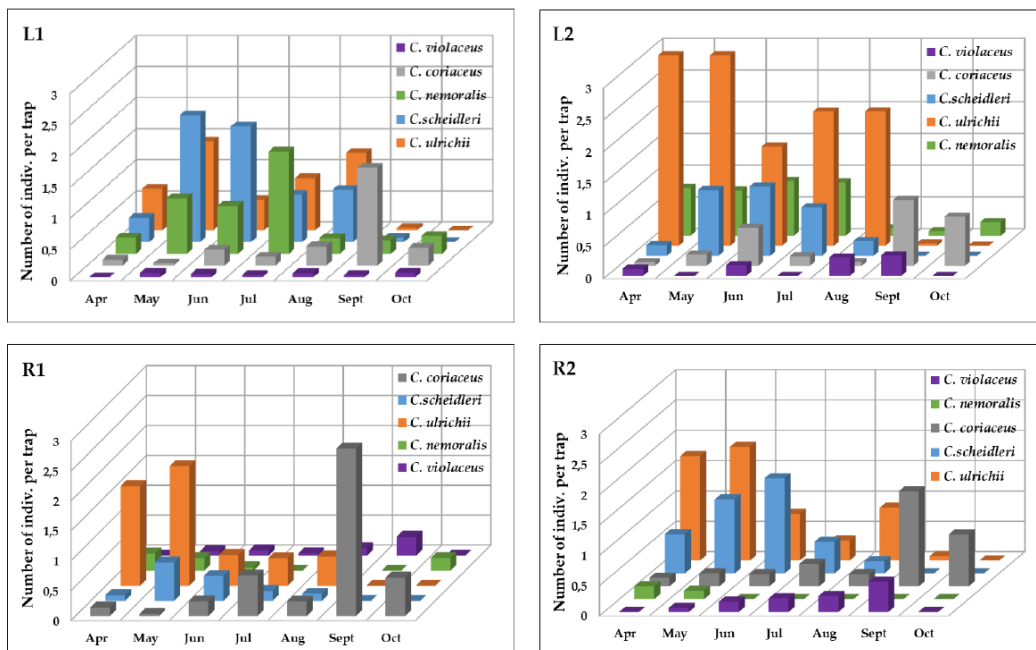
In 2017, the carabid activity through April and May was mostly influenced by the activity of *C. ulrichii* at all study plots (Figure 3). The peak of activity recorded by the end of May was almost exclusively influenced by this species. *C. scheidleri* started to activate from the second half of May, and the activity culmination at the turn of June to July was considerably influenced by this species, especially for both forest study plots (Figure 3); however, few individuals of the species *C. coriaceus* were recorded in April at L2 and R1. The species started its main activity at the end of June, where the maximum activity was recorded during the beginning of July. During the same period, the activity of *C. nemoralis* peaked at both forest stands (Figure 3). From the second half of July to the first half of August, summer activity stagnation was observed at all research plots. *C. violaceus* started to activate at the turn of July to August and considerably contributed to activity during middle to late August. The activities of *C. ulrichii* and *C. scheidleri* at the two forest recovering stands also significantly contributed to the August activity culmination. The autumn activity period was characterized by *C. coriaceus* and *C. violaceus* activity (Figure 3).

The very dynamic start of carabid activity in April in 2018 was affected by *C. ulrichii* activity. In contrast with the spring activity observed in 2017, the two other species, *C. scheidleri* and *C. nemoralis*, were active through April and May. *C. nemoralis* was especially active at the both forest stands (Figure 4). A sudden decline in activity in the middle of May was recorded for *C. ulrichii* at all study plots. The decline in activity was also recorded for other spring active species in 2018, with the exception of *C. scheidleri* activity in the close-to-nature forest stand (L1, Figure 4). Afterwards, the recovery of activity was recorded, and the culmination of the activity at the end of May was affected by the activity of *C. ulrichii* and *C. scheidleri* at the two forest stands (Figure 4, L1, L2). The June activity period in 2018 was affected by the three mentioned species, featuring gradual decreases in activity towards the end of June. Similar to 2017, *C. coriaceus* and *C. nemoralis* exhibited their typical summer activity period in July. The high activity rate in late summer (July and August) is the most obvious difference in the activity patterns between the two years (Figure 2). Two species were active through this period (*C. ulrichii* and *C. scheidleri*), in contrast with the same period in 2017, especially in terms of increased activity in the

two forest stands. The late summer to early autumn activity of *C. coriaceus* and *C. violaceus* showed the same pattern as in 2017, with much higher occurrence levels in 2018, as in 2017 in the case of *C. coriaceus*.

Figure 3. The monthly activity of five carabid species at Báb forest stands with four different study plots in 2017. Two forest stands: L1—close-to-nature forest plot; L2—managed forest plot. Two stands after logging operations 10 years ago: R1—recovering indigenous tree species plot; R2—alien *Ailanthus altissima* dominance.

Figure 4. The monthly activity of five carabid species at Báb forest stands with four different study plots in 2018. Two forest stands: L1—close-to-nature forest plot; L2—managed forest plot. Two stands after logging operations 10 years ago: R1—recovering indigenous tree species plot; R2—alien *Ailanthus altissima* dominance.

3.3. Meteorological Conditions in 2017 and 2018 for the Locality of Báb

The year of 2017 was characterized by the onset of higher air temperatures compared to the climate normal, especially during the months of February and March. The middle of the growing season was very warm in 2017 and the end of the year was normal in terms of the temperature (Table 3). Overall, 2017 was characterized as warm with an average annual air temperature of 10.3 °C. The beginning of the growing season in 2018 was characterized by a sudden transition from cold March to extremely warm April (Table 4). Until the end of the year, the temperature was above the long-term normal. During the growing season, there were up to three extremely warm months (Table 4). Overall, 2018, with an average annual air temperature of 11.5 °C, was assessed as extremely warm in terms of the deviation of the annual air temperature from the climatic normal ΔT of +1.8 °C.

In 2017, dry conditions prevailed in the first half of the year, where two extremely dry months were recorded and May fell into the growing season (Table 3). The second half of the year was slightly richer in terms of precipitation and September was evaluated as extremely wet. Overall, 2017 was extremely dry and seven of the months were evaluated as dry (either very dry or extremely dry), and the annual precipitation total was 69% compared to the normal period 1961–1990. As in the case of temperature, the beginning of the season in 2018 was characterized by a sudden transition from normal precipitation in March to an extremely dry April (Table 4). Four of the months were evaluated as wet, and, as in the previous year, September was assessed as extremely wet (Table 4). With an annual precipitation total of 540 mm, 2018 was evaluated as a year with normal precipitation.

Table 3. The comparison of monthly precipitation totals and the average monthly temperature in 2017 with the climatological normal (period 1961–1990) for the locality of Báb (southwestern Slovakia).

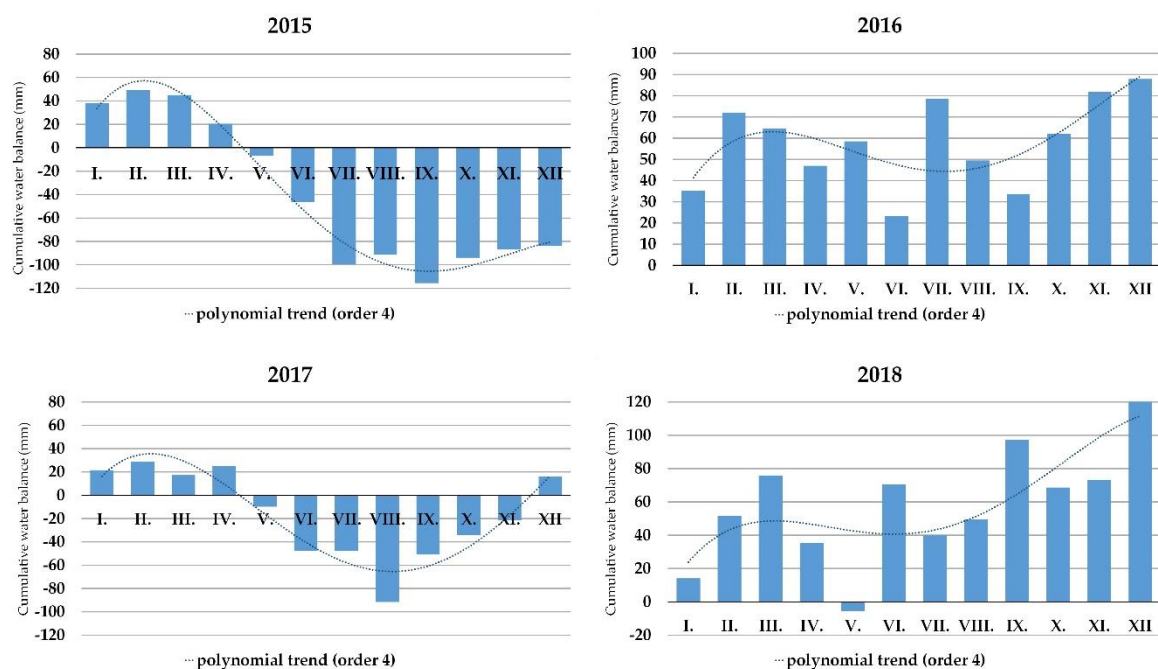| Month	Average Monthly Temperature (T, °C)		Thermal Characteristic	Monthly Precipitation (P, mm)		Precipitation Characteristics
	2017	1961–1990	ΔT (°C)	2017	1961–1990	ΔP (%)
I.	−7.1	−1.7	−5.4	Extremely cold	0	31	0	Extremely dry
II.	1.9	0.5	1.4	Warm	13.2	32	41	Very dry
III.	8.4	4.7	3.7	Extremely warm	13.8	33	42	Very dry
IV.	9.5	10.1	−0.6	Normal	36.2	43	84	Normal
V.	16.2	14.8	1.4	Warm	13.8	55	25	Extremely dry
VI.	20.8	18.3	2.5	Very warm	24.6	70	35	Very dry
VII.	21.3	19.7	1.6	Warm	63.6	64	99	Normal
VIII.	22.1	19.2	2.9	Very warm	22.6	58	39	Very dry
IX.	14.3	15.4	−1.1	Cold	83.4	37	225	Extremely wet
X.	10.5	10.1	0.4	Normal	48.4	41	118	Normal
XI.	4.4	4.9	−0.5	Normal	25.8	54	48	Very dry
XII.	0.8	0.5	0.3	Normal	40.0	43	93	Normal

Table 4. The comparison of monthly precipitation totals and the average monthly temperature in 2018 with the climatological normal (period 1961–1990) for the locality of Báb (southwestern Slovakia).

Month	Average Monthly Temperature (T, °C)		Thermal Characteristic	Monthly Precipitation (P, mm)		Precipitation Characteristics
	2018	1961–1990	ΔT (°C)	2018	1961–1990	ΔP (%)
I.	1.6	−1.7	3.3	Very warm	19	31	61	Dry
II.	−1.5	0.5	−2.0	Cold	33	32	103	Normal
III.	2.9	4.7	−1.8	Cold	33	33	100	Normal
IV.	15.2	10.1	5.1	Extremely warm	5	43	13	Extremely dry
V.	18.6	14.8	3.8	Extremely warm	15	55	27	Very dry
VI.	20.0	18.3	1.7	Warm	136	70	195	Very wet
VII.	21.6	19.7	1.9	Warm	34	64	53	Dry
VIII.	22.8	19.2	3.6	Extremely warm	78	58	134	Wet
IX.	17.0	15.4	1.6	Warm	99	37	267	Extremely wet
X.	12.9	10.1	2.8	Very warm	10	41	25	Very dry
XI.	6.5	4.9	1.6	Warm	24	54	44	Very dry
XII.	0.4	0.5	−0.1	Normal	54	43	125	Wet

3.4. The Drought Occurrence at the Locality of Báb between 2015 and 2018

Figure 5 documents the occurrence of drought episodes during the years 2015 to 2018 at the locality of Báb (southwestern Slovakia). According to the cumulative water balance, drought occurrences were recorded in 2015 and 2017. Drought lasted longer in 2015 and was more pronounced in 2017. For both 2016 and 2018, positive water balance was recorded throughout the year and there was only the occurrence of a mild drought in May in 2018 (Figure 5). Comparing the trend line trajectories and the points of x-axis cutting in 2015 and 2017, the onset of drought started earlier in 2017, i.e., by the end of April, and lasted seven months. The drought episode ended in the turn of November to December in 2017; however, the drought onset started a little later in 2015, where the drought lasted until the end of the year.

Figure 5. The cumulative water balance for the locality of Báb (southwestern Slovakia) in 2015, 2016, 2017 and 2018.

4. Discussion

In [28], changes in the occurrence of beetle families in the locality of Báb were evaluated in terms of research during the periods of 1968–1969 and 2002–2004. The results were evaluated from the point of view of changing climate parameters in the research area; however, there were no significant changes recorded for the proportions of beetle families, but some aspects of desertification were observed in the research area. The occurrence of six hygrophilous carabid species was not recorded and new thermophilous species were recorded when compared to the results of a survey thirty years ago.

The five monitored carabid species have different phenological characteristics, which has an impact on seasonal activity but also seasonal changes in carabid assemblage compositions.

In Europe and elsewhere within temperate zone, most Carabidae are single-generation [8], although adults may survive for more than one season. They can overwinter either as a larva or as an adult beetle.

Carabus coriaceus has a two-year cycle, where in Central Europe it is mostly reported to reproduce in autumn. The copulation and laying of eggs takes place from the second half of August to November, where individuals overwinter as larva of the first to second instar. The larva of the last instar require a long time to mature, so they pupate only in the following year during June to July. Newly hatched individuals appear in summer and early autumn, where after hibernation they are active in spring but

do not reproduce until autumn after aestivation [29]. The work in [30] showed females with developed eggs since the beginning of August. Before this date, the female ovaries were undeveloped. [29] shows that *Carabus nemoralis* is an active species in early spring, laying eggs from March to May. Adults remain active until about July, then start aestivation during August and September. The work in [31] states that *C. nemoralis* is a species that reproduces in spring and that its seasonal activity features two peaks. The second maximum of the activity of *C. nemoralis* occurs in October, which is outside the period of our study. The course of the second maximum is influenced by temperature, where, in warmer years, newly hatched individuals are more active in autumn [31]. This situation occurred in the autumn of 2018, where the species was active at three study plots (both forest stands and the R1 recovering forest stand, Figure 4).

　　Carabus ulrichii overwinters as an adult [30] and therefore this species showed the earliest activity in both years (Figures 3 and 4). Wintering individuals lay eggs from the second half of April to June. Newly hatched individuals appear during the second half of August, rarely from the end of July, and are active until hibernation [30]. The spring activity of this species is affected by the activity of the overwintering population and the summer activity is affected by the population of newly hatched individuals (Figures 3 and 4). *Carabus violaceus*, like *C. coriaceus*, overwinter as larvae [30] and therefore their activity peaks later in the summer months (Figures 3 and 4). *C. violaceus* lay eggs from the second half of July to early September. The third instar larvae usually overwinter, but part of the adult population also overwinters and reproduces again during the following year [30]. The peak activity of this species was recorded during July to September, and this was the activity of the reproducing population (Figures 3 and 4).

　　Carabid spring activity is also influenced by the wintering conditions. For most temperate invertebrates, the length of the day is a stimulus for the onset of hibernation, but the end of winter is already controlled by other environmental factors, often in the temperate zone of the frost [32,33]. After the diapause is terminated by a frost, the synchronization of spring development is passively achieved based on the cumulative effect of rising temperatures [34]. The warm February and extremely warm March in 2017 (Table 3) could have promoted the spring activity of carabids. In reality, beetle activity declined throughout April and the first ten days of May (Figure 2). The answer is instead found in the behavioral pattern of the studied carabid species, where the species feature nocturnal activity, with the exception of *C. ulrichii*. If we take a closer look at the night temperatures (Figure A2), after approximately the 10th of April until the end of April, the night temperatures were mostly below 5 °C, including a few nights with frost. Even during the first ten days of May, the night temperatures did not rise above 10 °C. Warm nights with a temperature above 10 °C occurred regularly since the middle of May in 2017. The only species active in April in 2017, was *C. ulrichii*, the species having both nocturnal and diurnal activity. Warmer days with a temperature above 15 °C occurred regularly from the middle of March and activated this species early in the season, especially at the L2 and R2 plots, where this species was the most abundant the previous year when compared with its occurrence at the two other stands (Figure 3).

　　Ref [35] analyzed drought occurrence in the period of 1966–2013 and identified drought trends for the Danubian lowland area. Both a significant difference and trend were observed in April, where they confirmed a significant increase ($\alpha = 0.05$) in the number of dry periods, i.e., an arid trend. The authors evaluated the significant arid trend in April as the main warning signal. Drought occurrence analysis and future projection within the region where our research locality occurs, is vital because the region is important from an agricultural production point of view. The Danubian lowland is classified as a very dry and hot region, as projected by the climate change scenario in [21]. Cumulative water balance was used for the projection of drought occurrence alongside climate change. According to the RCP 4.5 scenario for time slice 2070–2100, the onset of drought could occur from the 10th of March in the warmest regions, and balanced cumulative water balance are projected to not occur until the end of the year [27].

Humidity significantly affects the activity of the ground beetles. Carabidae are not adapted to low humidity and Central European species are strictly hydrotactic [36]. The work in [37] studied the impact of drought on ground beetle assemblages in Norway spruce forests with different management after windstorm damage. Comparison of the changes in the numbers of individuals and species as a result of drought periods showed that changes in both the numbers of species and individuals mostly occur with an approximate delay of 1–2 years after an incidence of extreme drought or rainy years. However, only five species occurrences were evaluated during our research, similar effect was observed if we take into account the climatic characteristics of the two previous years. The year of 2015 was characterized as dry, where five months were evaluated as extremely dry and three of them (April, June, and July) fall within the main growing season. Moreover, May was evaluated as very dry as well. According to the cumulative water balance, the drought started during the turn of April to May and lasted until the end of the year. In contrast with 2015, the drought did not occur throughout whole year of 2016. Three months of 2016 were evaluated as extremely wet and two of them (July and September) fall within the main growing season. Moreover, none of the months in 2016 were evaluated as extremely warm, which contributed to the positive water balance in 2016. As in the findings of [37], we can suppose, that the two-year delay effect of the meteorological conditions on carabid populations was manifested in our study as well. The cause of such a delay stems from the relationship between the predator and the prey population dynamics. The main food sources for carabids are snails, slugs, earthworms, and other soil arthropods [29], where all are hygrophilous organisms. According to an analysis of carabid gut content, the prey group most frequently detected was earthworms, followed by slugs, especially in the case of large carabids such as *Carabus* species [38]. The activity of land gastropods is restricted to humid conditions in both time and space [39]. The effect of dry conditions on the terrestrial slug species *A. biplicata* was delayed reproduction, and a drought that lasted two weeks resulted in lower fertility [40]. A drought could also affect snail mortality where during a drought that lasted 1 month, immediately after arousal from hibernation when snails had to recover from winter fasting, mortality reached up to 70% for *H. pomatia* in Germany [41]. Regarding earthworms, [42] reported that the monthly abundance of earthworms is significantly related to the amount of rainfall. Earthworms are only active if free water is available in the soil [43]. Epigeic earthworm species living at the soil surface are strongly affected by dry and hot conditions during summer, as these species dwell in and feed on the litter layer and have a limited ability to move down into deeper soil [44]. The work in [45] also revealed strong relationship between carabid and slug population dynamics. The change in the beetle population from year to year was strongly related to both the slug population numbers in the soil and the crop mass of the beetles. This indicated that the slugs influenced the nutritional status of the beetles, and hence their reproductive success. The beetle crop mass was positively correlated with growth in the beetle population, suggesting that the greater the quantity of prey consumed one year, the greater the growth in the beetle population between years. [46] revealed that the egg production of the females of *Anchomenus dorsalis* (Carabidae) was positively affected by the amount of food, influencing the number of mature eggs in female ovaries, as well as total egg production. Starved females had no mature eggs in their ovaries.

However [47] studied the effect of temperature on the activity of selected Carabidae species. It was found that in addition to temperature, humidity also has a significant effect. The study highlighted the same temperature recorded for higher activity on a moist substrate, e.g., after rain. Both the soil moisture and humidity of the air layer near the ground are extremely important factors for limiting the distribution of the ground beetles, as well as the water balance [8]. However we did not measured the humidity conditions at the individual study plots, two plots, recovering forest stand R2 and forest stand L2, were more humid than the two other study plots. The terrain at the research site gradually decreases towards the Bábsky potok stream, and the forest stand L2 plot was situated at the foot of the slope and study plot R2 was situated within the near vicinity. The slope features a northeastern orientation, and thus study plot R2 was located in the shade of the neighboring forest vegetation for almost half of the day, causing dew to remain longer there; however, this observation is only based

on subjective personal experience during field work This aspect is likely to be reflected by a higher abundance of carabids than with the two other study plots in 2017 (Figure 4).

5. Conclusions

The Carabus species populations observed in the oak-hornbeam forest considered here over two years showed large differences in terms of both the abundance and seasonal activity. The meteorological conditions during the year influenced the seasonal activity, and the temperature influenced the peak timings of Carabus species activity. Early spring activity was influenced by temperature, influencing the onset and the dynamics. Warmer spring conditions in 2018 caused a rapid onset of activity. Especially, the effect of warmer spring was observed with C. *ulrichii*, having both nocturnal and diurnal activity; however, very low night temperatures during April and the beginning of May in 2017 negatively influenced the spring activity of nocturnal species.

Drought negatively influenced the abundance of Carabus species population numbers, and this negative effect was reflected by lower populations with a two-year time delay. By analyzing the observations of other authors in terms of the effects of a drought on earthworm and mollusk populations, being the main food sources for Carabus species, we believe that the low population abundance in 2017 was influenced by the drought that lasted for eight months in 2015. In 2016, a drought was not recorded, and the populations of Carabus species in 2018 were more than three times more numerous than in 2017; however, a more detailed study, including, for example, carabid body mass evaluation, is needed to explain the mechanisms of the impact of drought on forest carabid populations at the studied locality.

The Carabus populations in the oak hornbeam forest, occupying forest enclaves in the intensively used agricultural landscape within Slovakia's driest region, are experiencing several environmental and anthropogenic pressures. The results of this study could contribute to finding appropriate management schemes for such forest ecosystems.

Appendix A

Figure A1. The forest research area in Báb with the localizations of the research plots. (R1, R2, L1, L2). The picture is a screenshot of an aerial map from the mapy.cz web application. The tool for adding the marks on the map was that used [48].

Figure A2. The night temperatures (20:00–05:00) through April and May in 2017 and 2018 at the locality of Báb (southwestern Slovakia).

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