

Article

Attractiveness of Different Artificial Light Sources to Aquatic and Semiaquatic Beetles (Coleoptera) and Its Implications for Sampling and Conservation

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Abstract

Aquatic and semiaquatic beetles are important components of wetland ecosystems serving as bioindicators, predators, and vital prey resources. Numerous studies examined how their dispersal flights are influenced by biotic and abiotic factors, but the wavelength-specific attraction of different artificial light sources remains understudied. This study evaluated the attractiveness of three portable light traps equipped with different light sources emitting light with different wavelength ranges: a compact light tube, an LED light source, and a UV lamp. A total of 6568 individuals representing 54 species were captured. Total nightly abundance correlated positively with mean nocturnal temperature. Light source type significantly affected both species richness and abundance, with the broad-spectrum compact light tube outperforming the other tested light sources both in abundance and species richness. For Dytiscidae and Hydrophilidae, the compact light tube was significantly more attractive only than the blue LED source, while its attractiveness did not differ significantly from that of the UV lamp, demonstrating family-level differences in attraction. The light source-dependent attraction remained stable across phenological periods. Our findings suggest that while broad-spectrum lights improve the efficiency of faunistic surveys and support conservation-oriented monitoring of aquatic beetle assemblages, their integration into public lighting networks near vulnerable wetlands must be strictly avoided to prevent severe ecological trapping.

Keywords: aquatic macroinvertebrates; Coleoptera; phototaxis; wavelength; artificial light sources; Dytiscidae



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1. Introduction

Freshwater ecosystems are among the most threatened environments worldwide, and their biodiversity is declining more rapidly than that of terrestrial and marine ecosystems. Effective biodiversity monitoring has become essential for conservation planning, ecological assessment, and the evaluation of environmental change [1]. Reliable biodiversity assessment requires standardized sampling methods capable of accurately reflecting species richness, community composition, and temporal shifts in freshwater assemblages.

Aquatic and semiaquatic beetles (Coleoptera) constitute phylogenetically and morphologically diverse components of these habitats [2]. Globally, approximately 9000 of the 350,000 known beetle species are considered aquatic [3], with around 360 species occurring in Hungary alongside an additional 120 semiaquatic species [3]. These taxa fulfill diverse ecological roles, acting as predators, herbivores, and detritivores while simultaneously serving as vital prey for higher trophic levels [4]. Given their sensitivity to habitat degradation and changes in water quality, aquatic and semiaquatic beetles are widely recognized as effective bioindicators [2,4]. Thus, applying efficient monitoring techniques of the taxa is essential for assessing the ecological status of freshwater habitats [2].

While active sampling methods (e.g., aquatic netting, car-netting, and mud coring) are widely used [3,5], passive methods like light trapping are considered among the most efficient for collecting these taxa in large numbers [3,5]. Most aquatic and semiaquatic beetles are capable of flight and exhibit positive phototaxis [3,6,7], combined with the ability to sense horizontally polarized light to locate new water bodies during dispersal [8–16]. Dispersal flights, which are driven by reproductive needs, seasonal changes, or habitat degradation (e.g., decreasing water levels), occur almost throughout the year [15,17]. Thus, adult beetles moving above the water surface are highly responsive to optical cues, making light trapping an efficient tool for standardized biodiversity monitoring [3,18,19].

However, the increasing expansion of anthropogenic infrastructure poses a severe threat to these populations [13,20,21]. Artificial light sources and polarized light-reflecting surfaces (e.g., asphalt roads, dark vehicles, solar panels) act as ecological traps [16,22–25]. They disrupt nocturnal flight activity and induce disorientation, causing insects to misidentify these artificial surfaces as open water, resulting in significant mortality due to exhaustion, desiccation, or collision impact [3,5,9,13,16,24–28]. Understanding the mechanisms governing attraction to artificial light is therefore important not only for optimizing biodiversity monitoring but also for mitigating one of the most widespread anthropogenic stressors affecting aquatic and semiaquatic beetles.

While the effect of polarizing properties of artificial surfaces for insects are well-documented [10,12,14–16] the role of specific spectral characteristics in the attractiveness of artificial light sources remains underinvestigated. It is established that aquatic macroinvertebrates generally show an affinity for shorter wavelengths, particularly near-ultraviolet (UV) light [29–33]. Although data are available regarding the wavelength sensitivity of the photoreceptors of several aquatic beetle species [34,35], considerably less information is available regarding how different artificial light wavelengths attract aquatic and semiaquatic beetles specifically.

Investigating the wavelength sensitivity of these assemblages is crucial for both freshwater biodiversity monitoring and conservation. Identifying light sources and wavelength ranges that exert the least attraction could contribute to know light pollution-induced mortality near wetlands. While determining the most attractive wavelength ranges enables the development of using taxon-specific sampling methods, improving the efficiency of faunistic surveys and biodiversity monitoring.

Therefore, the primary objective of this study was to evaluate the response of aquatic and semiaquatic beetle assemblages to different artificial light sources (emitting varying

wavelength ranges) in a wetland habitat. Furthermore, we aimed to examine differences in species composition between summer and spring sampling periods and how seasonal variations influence trap efficiency. Based on previous findings regarding aquatic insects, we formulated three main hypotheses: (1) the light source type significantly influences both the abundance and species richness of attracted beetles, with broader wavelength emission spectra expected to yield higher capture rates; (2) different taxonomic and ecological groups (aquatic vs. semiaquatic beetles and families) exhibit variations in their attraction to light sources and specific wavelength ranges; and (3) while species composition differs between sampling seasons due to phenological shifts, these seasonal differences do not alter the relative capture efficiency of the tested light sources.

2. Materials and Methods

2.1. Study Area

Field investigation was carried out in a heterogeneous wetland complex located in the northern part of the Laskóvölgy Reservoir near Egerszalók, Hungary (47°53'55.7" N, 20°19'20.1" E). The study area is characterized by a mosaic of shallow wetlands, providing suitable conditions for comparing the sampling efficiency of different light sources. The wetland is situated within a relatively shallow, wind-protected valley, reducing the influence of nighttime wind on the flight activity of insects and the performance of light traps.

Although the reservoir supports numerous fish species, fish were not detected at the study site during five years of previous observations. In contrast, several amphibian species, including *Hyla arborea* (Linnaeus, 1758), *Lissotriton vulgaris* (Linnaeus, 1758), and *Pelophylax* spp., were regularly observed. These amphibians may prey on larvae of these beetles as well as adults of smaller species, whereas larger beetles (>1–2 cm) are less likely to constitute a major component of their diet. The relatively low local predation pressure was among the factors supporting the selection of the study site.

2.2. Trap Design and Light Source Spectrometry

Sampling was made using three portable light traps with identical dimensions. To evaluate wavelength-specific attraction, the traps were equipped with standard, commercially available, low-intensity light sources that are widely used in portable light traps: a compact light tube, a blue LED strip, and a near-ultraviolet (BL UV) fluorescent tube (Figures 1 and 2).

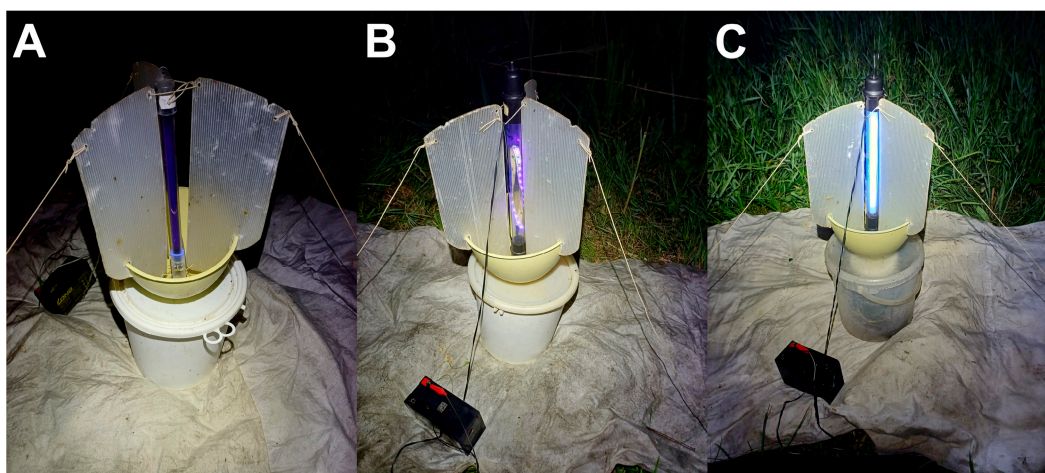


Figure 1. The three light source types used in our traps in the field experiments. (A): UV light tube (UV), (B): LED light source (LED), (C): compact light tube (CLT).

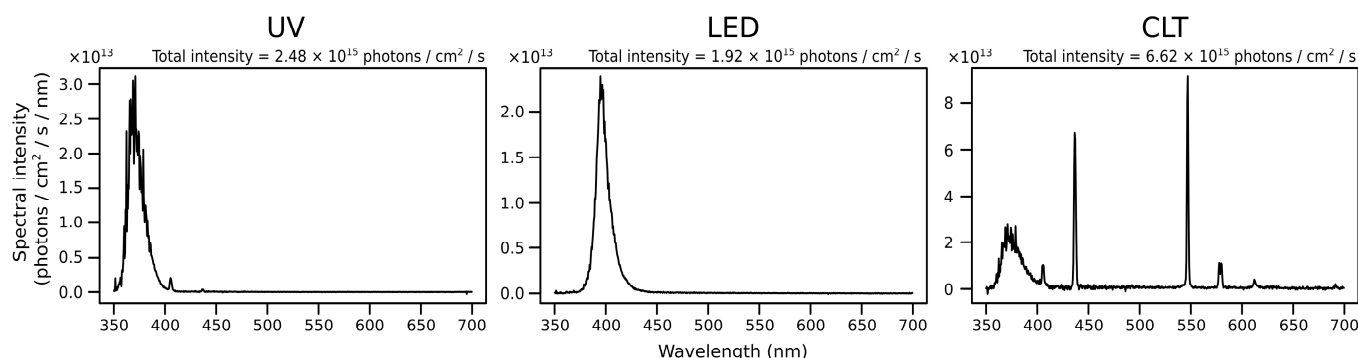


Figure 2. Emission spectrum of the three light source types used in our traps in the field experiments. CLT: compact light tube; LED: LED light source; UV: UV light tube.

The emission spectra of each light source type were measured under standardized conditions at a distance of 5 cm using a radiometrically calibrated Ocean Optics STS-VIS spectrometer (Ocean Optics, Largo, FL, USA). The compact light tube (CLT) produced a wide emission spectrum with several intensity peaks, including the near-UV, blue, and yellow spectral regions. The blue LED emitted a narrow spectral peak restricted to the blue wavelength range, whereas the BL UV fluorescent tube produced a broader emission peak concentrated within the near-ultraviolet region. The compact light tube had a higher total light intensity than the narrow-peak LED and UV lamps, while its intensity in the UV and blue spectral ranges was nearly identical to that of the latter two light sources. Thus, the CLT produced a similar level of UV and blue radiation, while additionally emitting photons at longer wavelengths. The tested light tubes were selected to represent commonly used light sources emitting in different wavelength ranges and were evaluated under conditions reflecting practical field monitoring.

The traps were powered by 12 V lead acid batteries. Captured insects were collected in a 1 L inner bucket containing a cotton-plugged glass vial filled with chloroform (CHCl_3) to ensure rapid killing and preservation of specimens. A 1 m $\times$ 1 m white reflective sheet was placed beneath each trap to facilitate the collection of individuals that landed below the trap without entering the collecting container.

2.3. Sampling Design and Data Collection

Sampling was carried out during the two main dispersal periods of aquatic beetles: summer (23–29 July 2024) and spring (25 April–31 May 2025). An additional autumn sampling period (September–October 2024) was initially included; however, persistent cold and rainy weather resulted in extremely low flight activity and insufficient sample sizes. Thus, these data were excluded from further analyses. The final dataset consisted of 14 sampling nights.

Light traps were placed along the wetland margin at a distance of 50 m from each other to maximize the capture of dispersing beetles. Traps were operated from 30 min after sunset for four consecutive hours. To minimize potential spatial bias associated with microhabitat characteristics, the three light sources were systematically rotated among sampling positions on each sampling night.

Traps were checked at 30 min intervals. Individuals that landed on the reflective sheet instead of entering the trap were collected using an insect aspirator and added to the corresponding trap sample. This procedure ensured that specimens attracted to the light source but failing to enter the collecting container were also included in the catch. Thus, the sampling protocol accounted for both individuals entering the trap and those landing on the reflective sheet, providing a more complete estimate of attraction to each source.

Air temperature and relative humidity were also recorded at 30 min intervals using a digital thermohygrometer.

2.4. Specimen Processing and Identification

Collected material was stored frozen until laboratory processing. Beetles were preserved in 70% ethanol and identified to the lowest possible taxonomic level (species or species pair) using the identification keys of Csabai [3], Csabai et al. [5], Hájek [36,37], Lókkös [38], Skalický and Ezer [39], and Litovkin et al. [40].

The classification of beetles as aquatic or semiaquatic was based on the scheme proposed by Csabai [3]. Aquatic beetles were defined as taxa strongly associated with aquatic habitats during both larval and adult stages and spending a substantial proportion of their life cycle in water (e.g., Dytiscidae, Hydrophilidae). Semiaquatic beetles were defined as taxa for which water is essential during a particular developmental stage, primarily the larval stage, whereas adults are not dependent on aquatic habitats or return to them only occasionally, for example, for reproduction (e.g., Heteroceridae, Dryopidae).

2.5. Statistical Analysis

All statistical analyses were made in R program environment [41]. Generalized linear mixed models (GLMMs) were used to evaluate the effects of light source, sampling season, and their interaction on the overall number of individuals and species, the number of aquatic and semiaquatic beetles, as well as the number of beetles from the dominant families (families with a number of beetles exceeding 1% of the overall number of individuals) using the *glmmTMB* package [42]. As environmental conditions (e.g., weather and lunar phase) can vary significantly even within the same sampling season, sampling days were included as a random factor in the models. Prior to model fitting, the most appropriate probability distributions of data were determined by the *car* [43] and *MASS* [44] packages. Based on these tests, all dependent variables were modelled using a negative binomial distribution [45].

Composition of beetle assemblages in spring and summer were analyzed by non-metric multidimensional scaling ordination (NMDS) using the Hellinger index of dissimilarity [46] with the *vegan* package [47]. The difference between the group centroids (light source type: CLT, LED, UV; season: spring, summer) in the ordination plot was tested by the *envfit* function with 999 permutations in the *vegan* package [47]. The associations between species abundance and the two NMDS axes were assessed using Spearman rank correlation analyses. For each species, Spearman's correlation coefficients were calculated between its abundance across samples and the corresponding NMDS1 and NMDS2 scores.

The relationship between mean nocturnal air temperature and total nightly abundance was evaluated using an exponential regression model. Data from 23 July 2024 were excluded from this analysis because rainfall stopped sampling approximately 90 min before the planned end of the trapping period.

3. Results

3.1. General Catch Overview

A total of 6568 individuals belonging to 54 species and nine families were collected during the sampling periods. Semiaquatic beetles slightly outnumbered aquatic species, representing 54% and 46% of the collected specimens respectively. Almost half of the captured individuals belonged to the family Heteroceridae (3551). Among the remaining families, Hydrophilidae (1726), Helophoridae (961) and Dytiscidae (289) were also abundant. All other families exhibited low abundance, collectively representing less than 5% of the total material. The assemblage was highly dominated by *Heterocerus fenestra-*

tus (Thunberg, 1784) (Heteroceridae), which accounted for nearly half of the total catch (3249 individuals). *Anacaena limbata* (Fabricius, 1792) (Hydrophilidae) was the second-most abundant species, represented by 1328 individuals. Detailed species abundances and their distribution among the different light sources are summarized in Table 1.

Table 1. List of the collected species by family and their distribution across the different light source types. CLT: compact light tube; LED: LED light source; UV: UV light tube. Cat. is referring to the categorization of species as aquatic (A) or semiaquatic (SA) based on the scheme proposed by Csabai [3].

Family	Species	Cat.	CLT	UV	LED
Dryopidae	<i>Dryops auriculatus</i> (Geoffroy, 1785)	SA	1	0	0
Dytiscidae	<i>Graptodytes pictus</i> (Fabricius, 1787)	A	0	0	1
	<i>Hydaticus grammicus</i> (Germar, 1827)	A	2	0	1
	<i>Hydroglyphus geminus</i> (Fabricius, 1792)	A	96	34	129
	<i>Hydroporus angustatus</i> Sturm, 1835	A	8	1	3
	<i>Hydroporus palustris</i> (Linnaeus, 1761)	A	1	0	2
	<i>Hygrotus impressopunctatus</i> (Schaller, 1783)	A	0	0	2
	<i>Hygrotus inaequalis</i> (Fabricius, 1777)	A	1	1	0
	<i>Laccophilus minutus</i> (Linnaeus, 1758)	A	1	3	0
	<i>Rhantus frontalis</i> (Marsham, 1802)	A	1	0	0
	<i>Rhantus suturalis</i> (MacLeay, 1825)	A	1	0	1
Haliplidae	<i>Haliplus heydeni</i> Wehncke, 1875	A	0	1	0
	<i>Haliplus lineatocollis</i> (Marsham, 1802)	A	0	0	1
Helophoridae	<i>Helophorus aquaticus</i> (Linnaeus, 1758)	A	2	0	0
	<i>/aequalis</i> Thomson, 1868				
	<i>Helophorus brevipalpis</i> Bedel, 1881	A	431	5	54
	<i>Helophorus dorsalis</i> (Marsham, 1802)	A	5	0	1
	<i>Helophorus griseus</i> (Herbst, 1793)	A	31	3	8
	<i>Helophorus minutus</i> (Fabricius, 1775)	A	41	5	18
	<i>/paraminutus</i> Angus, 1986				
	<i>Helophorus montenegrinus</i> Kuwert, 1885	A	309	6	42
Heteroceridae	<i>Heterocerus fenestratus</i> (Thunberg, 1784)	SA	1097	797	1355
	<i>Heterocerus fuscus</i> Kiesenwetter, 1843	SA	99	69	126
	<i>Heterocerus obsoletus</i> Curtis, 1828	SA	3	1	4
Hydraenidae	<i>Hydraena paganettii</i> Ganglbauer, 1901	A	6	0	2
	<i>Limnebius atomus</i> (Duftschmid, 1805)	A	2	0	0
	<i>Ochthebius bernhardi</i> Jäch & Delgado, 2008	A	0	0	2
	<i>Ochthebius minimus</i> (Fabricius, 1792)	A	12	0	3
	<i>Ochthebius pusillus</i> Stephens, 1835	A	4	0	2
Hydrochidae	<i>Hydrochus flavipennis</i> Küster, 1852	A	0	2	1
Hydrophilidae	<i>Anacaena limbata</i> (Fabricius, 1792)	A	750	268	310
	<i>Anacaena lutescens</i> (Stephens, 1829)	A	14	3	6
	<i>Berosus frontifoveatus</i> Kuwert, 1888	A	18	34	63
	<i>Berosus luridus</i> (Linnaeus, 1760)	A	0	1	0
	<i>Berosus signaticollis</i> (Charpentier, 1825)	A	1	0	2
	<i>Berosus spinosus</i> Steven, 1808	A	0	6	0
	<i>Cercyon convexiusculus</i> Stephens, 1829	A	4	1	0
	<i>Cercyon laminatus</i> Sharp, 1873	SA	17	2	14
	<i>Cercyon marinus</i> Thomson, 1853	A	2	0	3
	<i>Cercyon unipunctatus</i> (Linnaeus, 1758)	SA	2	2	3
	<i>Cymbiodyta marginella</i> (Fabricius, 1792)	A	13	3	10

Table 1. Cont.

Family	Species	Cat.	CLT	UV	LED
	<i>Enochrus affinis</i> (Thunberg, 1794)	A	3	0	2
	<i>Enochrus bicolor</i> (Fabricius, 1792)	A	3	5	8
	<i>Enochrus fuscipennis</i> (Thomson, 1884)	A	2	1	1
	<i>Enochrus melanocephalus</i> (Olivier, 1793)	A	4	0	2
	<i>Enochrus quadripunctatus</i> (Herbst, 1797)	A	11	3	3
	<i>Enochrus testaceus</i> (Fabricius, 1801)	A	2	2	0
	<i>Helochaeres lividus</i> (Forster, 1771)	A	8	0	6
	<i>Helochaeres obscurus</i> (Müller, 1776)	A	1	2	0
	<i>Hydrobius fuscipes</i> (Linnaeus, 1758)	A	29	9	36
	<i>Hydrobius rothenbergii</i> Gerhardt, 1872	A	8	1	6
	<i>Hydrochara caraboides</i> (Linnaeus, 1758)	A	3	0	1
	<i>Hydrophilus piceus</i> (Linnaeus, 1758)	A	0	0	1
	<i>Laccobius striatulus</i> (Fabricius, 1801)	A	2	0	1
	<i>Limnoxenus niger</i> Gmelin, 1790	A	5	2	1
Scirtidae	<i>Contacyphon laevipennis</i> (Tournier, 1868)	SA	1	0	1

3.2. Wavelength-Specific Attraction and Trap Efficiency

Light source type had a statistically significant effect on all dependent variables (Table 2). The compact light tube (CLT) attracted significantly more individuals and species than both the LED and UV light sources (Table 2, Figure 3). Similarly, significantly more aquatic and semiaquatic beetles were attracted by the CLT light source compared to the LED and UV ones (Table 2). At the family level, CLT light source attracted significantly more beetles from the Helophoridae and the Heteroceridae family than the LED or UV light sources (Table 2). Beetles from the Dytiscidae and the Hydrophilidae family were also significantly more abundant in the CLT trap compared to the LED and UV traps, though the number of beetles in the CLT trap did not differ significantly compared to the UV one (Table 2).

Table 2. Summary of generalized linear mixed models on the number of individuals and species, the number of aquatic and semiaquatic beetles, and the number of beetles from the dominant family collected by different light source types in spring and summer. Significant values ($p < 0.05$) are in bold.

Dependent Variable	Explanatory Variable	Estimate $\pm$ SE	z Value	p
Number of individuals				
	Light source [LED]	-0.727 ± 0.226	-3.215	0.001
	Light source [UV]	-0.598 ± 0.217	-2.759	0.006
	Season [summer]	0.343 ± 0.370	0.927	0.354
	Light source [LED] $\times$ Season [summer]	0.250 ± 0.285	0.878	0.380
	Light source [UV] $\times$ Season [summer]	0.337 ± 0.271	1.243	0.214
Number of species				
	Light source [LED]	-0.727 ± 0.226	-3.215	0.001
	Light source [UV]	-0.598 ± 0.217	-2.759	0.006
	Season [summer]	0.343 ± 0.370	0.927	0.354
	Light source [LED] $\times$ Season [summer]	0.250 ± 0.285	0.878	0.380
	Light source [UV] $\times$ Season [summer]	0.337 ± 0.271	1.243	0.214

Table 2. Cont.

Dependent Variable	Explanatory Variable	Estimate $\pm$ SE	z Value	p
Number of aquatic beetles				
	Light source [LED]	-2.015 ± 0.428	-4.709	<0.001
	Light source [UV]	-1.358 ± 0.366	-3.713	0.001
	Season [summer]	1.420 ± 0.816	1.740	0.082
	Light source [LED] $\times$ Season [summer]	0.860 ± 0.532	1.617	0.106
	Light source [UV] $\times$ Season [summer]	0.780 ± 0.476	1.638	0.101
Number of semiaquatic beetles				
	Light source [LED]	-0.873 ± 0.341	-2.562	0.010
	Light source [UV]	-0.634 ± 0.322	-1.971	0.049
	Season [summer]	1.449 ± 0.752	1.927	0.054
	Light source [LED] $\times$ Season [summer]	0.621 ± 0.438	1.419	0.156
	Light source [UV] $\times$ Season [summer]	0.725 ± 0.422	1.718	0.086
Number of beetles from Dytiscidae family				
	Light source [LED]	-1.676 ± 0.702	-2.387	0.017
	Light source [UV]	-0.829 ± 0.527	-1.574	0.116
	Season [summer]	1.594 ± 0.762	2.092	0.037
	Light source [LED] $\times$ Season [summer]	0.390 ± 0.797	0.489	0.625
	Light source [UV] $\times$ Season [summer]	0.598 ± 0.606	0.988	0.323
Number of beetles from Helophoridae family				
	Light source [LED]	-3.751 ± 0.232	16.156	<0.001
	Light source [UV]	-1.908 ± 0.098	19.508	<0.001
	Season [summer]	-2.718 ± 1.153	-2.358	0.018
	Light source [LED] $\times$ Season [summer]	-24.520 ± 435.900	0.000	0.100
	Light source [UV] $\times$ Season [summer]	0.704 ± 0.666	1.058	0.290
Number of beetles from Heteroceridae family				
	Light source [LED]	-0.859 ± 0.341	-2.520	0.012
	Light source [UV]	-0.633 ± 0.323	-1.962	<0.050
	Season [summer]	1.460 ± 0.751	1.943	0.052
	Light source [LED] $\times$ Season [summer]	0.607 ± 0.438	1.387	0.166
	Light source [UV] $\times$ Season [summer]	0.724 ± 0.423	1.711	0.087
Number of beetles from Hydrophilidae family				
	Light source [LED]	-1.271 ± 0.483	-2.629	0.009
	Light source [UV]	-0.713 ± 0.424	-1.683	0.092
	Season [summer]	3.220 ± 0.778	4.139	<0.001
	Light source [LED] $\times$ Season [summer]	0.250 ± 0.542	0.461	0.645
	Light source [UV] $\times$ Season [summer]	0.143 ± 0.485	0.295	0.768

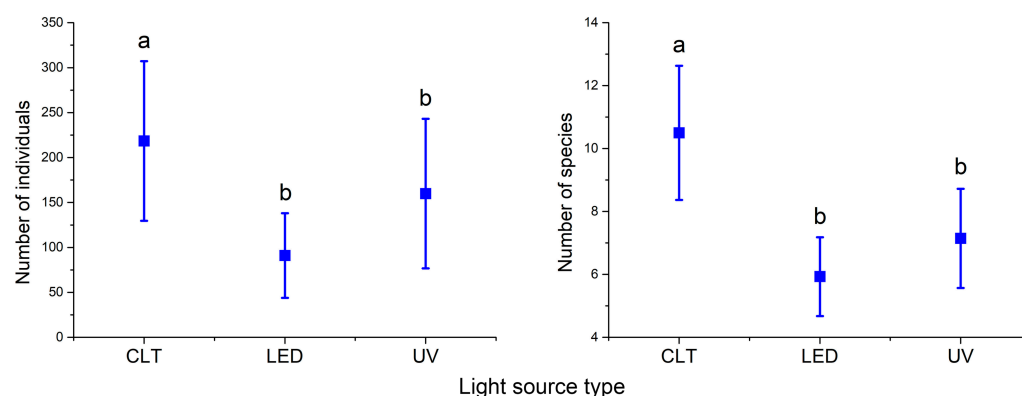


Figure 3. Mean number of individuals (N) and species (S) ($\pm$ SE) of beetles collected by the different light sources. Different letters above the means indicate significant differences (LSD test). CLT: compact light tube; LED: LED light source; UV: UV light tube.

Among the studied explanatory variables, sampling season had significant effect only at the family level, as beetles from the Dytiscidae and the Hydrophilidae family were more abundant in summer than spring, while individuals from the Helophoridae family showed the opposite pattern, they were significantly more numerous in spring than summer (Table 2). The interaction between light source type and season showed no significant influence on either dependent variable (Table 2).

3.3. Seasonal Assemblage Dynamics

The NMDS ordination (Figure 4) showed a clear separation in species composition among sampling periods. Difference in centroids in the ordination plot were not significant for light source type ($R^2 = 0.066$, $p = 0.259$); however, the centroids of the spring and summer samples were significantly different ($R^2 = 0.347$, $p = 0.001$; Figure 4).

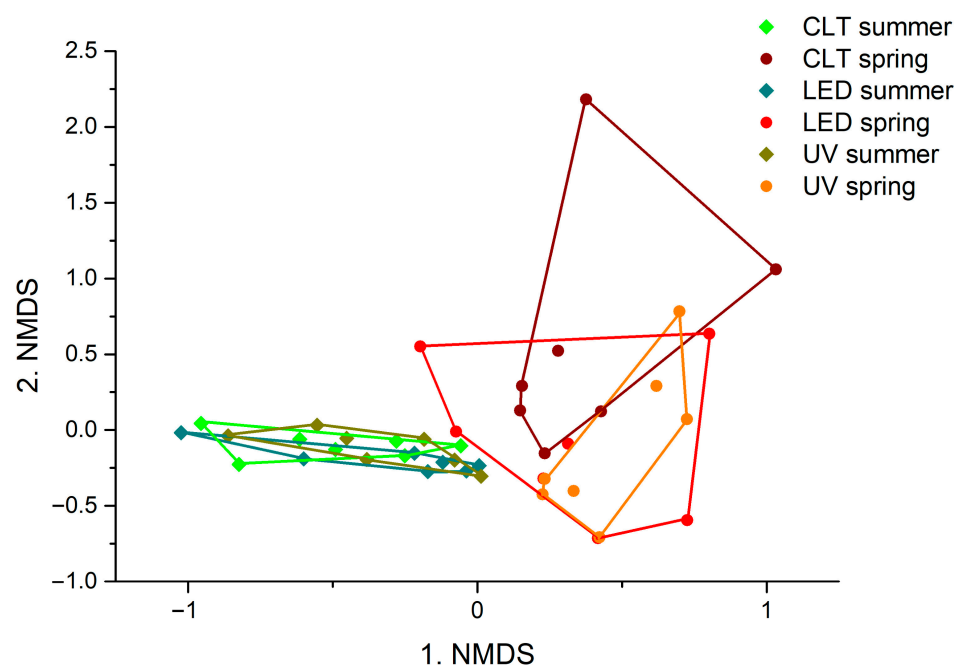


Figure 4. Non-metric multidimensional scaling (NMDS) ordination of aquatic beetle assemblages from the different sampling periods based on Hellinger distance. CLT: compact light tube; LED: LED light source; UV: UV light tube. Final stress value: 13.849.

Three species were strongly associated with the NMDS ordination axes (Table 3). *Anacaena limbata* (Hydrophilidae) showed a strong negative correlation with NMDS axis 1 ($r = -0.808$, $p < 0.001$), but was not associated with NMDS axis 2 ($r = 0.004$, $p = 0.978$). *Helophorus griseus* (Helophoridae) was positively correlated with both NMDS axis 1 ($r = 0.534$, $p < 0.001$) and axis 2 ($r = 0.612$, $p < 0.001$). Similarly, *Helophorus minutus/paraminutus* was positively correlated with both NMDS axis 1 ($r = 0.371$, $p = 0.015$) and axis 2 ($r = 0.676$, $p < 0.001$). Overall, *A. limbata* was primarily associated with the negative end of NMDS axis 1 (summer samples), whereas both *Helophorus* species were associated with the positive regions of the ordination, particularly along NMDS axis 2 (spring samples).

Table 3. Spearman rank correlation and its significance between species abundance across samples and the corresponding NMDS axis scores. Note that only associations with a correlation coefficient greater than 0.5 are listed. Asterisks indicate significant (*: $p < 0.05$, ***: $p < 0.001$), while “ns” not significant correlations.

Species	NMDS Axis 1	NMDS Axis 2
<i>Anacaena limbata</i>	−0.808 ***	0.004 ^{ns}
<i>Helophorus griseus</i>	0.534 ***	0.612 ***
<i>Helophorus minutus/paraminutus</i>	0.371 *	0.676 ***

3.4. Influence of Environmental Factors

Abiotic environmental factors significantly influenced flight activity. A positive relationship was observed between mean nocturnal air temperature and the total nightly abundance collected by the traps (Figure 5). The fitted exponential regression model (equation: $y = A1 \times \exp(x/t1) + y0$) indicated a significant correlation between the mean nocturnal temperature and abundance ($p < 0.001$; $R^2 = 0.830$, Table 4). Relative humidity, however, showed a negative but non-significant relationship with total abundance.

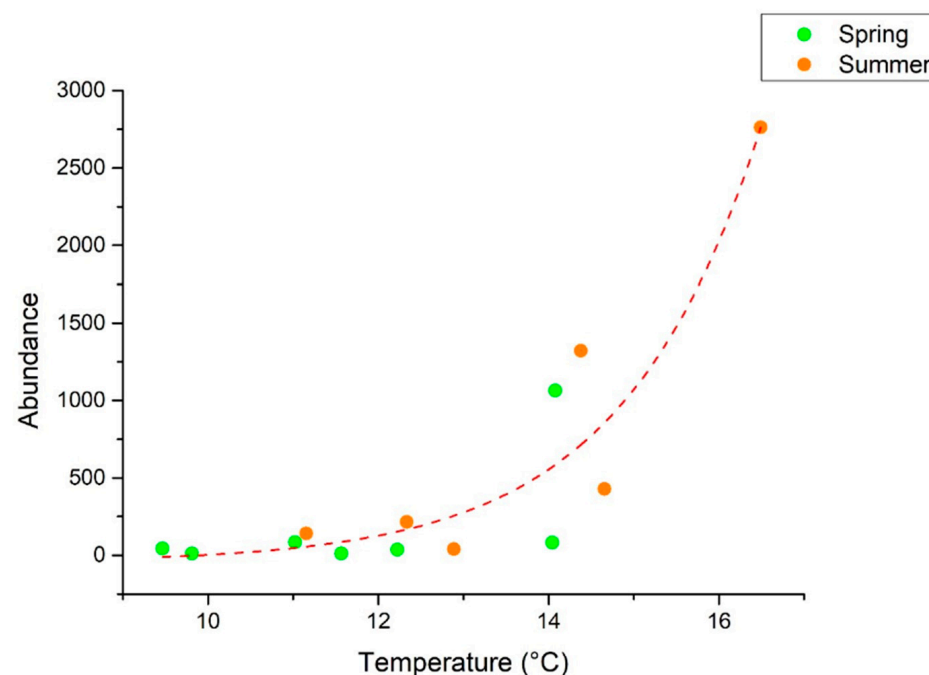


Figure 5. Positive exponential relationship between total nightly abundance and temperature. The dashed line indicates the fitted exponential regression curve.

Table 4. Parameters of the fitted exponential regression model (equation: $y = A1 \times \exp(x/t1) + y0$) between the mean nocturnal air temperature and the total nightly abundance collected by the traps.

Parameter	Value	Standard Error
y0	−47.109	194.876
A1	0.104	0.296
t1	1.616	0.448
k	0.619	0.172

4. Discussion

4.1. Assemblage Composition and Environmental Drivers

The sampling yielded a diverse assemblage comprising both widespread generalists and habitat-associated beetle species. The Dytiscidae and Hydrophilidae were the most species-rich families represented in the collected samples. This finding was not unexpected, as these two families are among the most species-rich aquatic beetle families both regionally and globally, and they are known to dominate in a wide range of aquatic habitats [3,5]. As expected based on prior surveys in Hungary, *Heterocerus fenestratus* strongly dominated the catches. The relatively high abundance of *Helophorus dorsalis* indicates that the traps also sampled local microhabitats effectively. Given its known preference for forest puddles [5], these individuals likely originated from adjacent woodlands.

Regarding abiotic factors, total abundance correlated positively with mean nocturnal temperature, reflecting the well-documented increase in insect flight activity during warmer nights. These results are consistent with previously reported findings [48–50]. The weak, non-significant negative trend observed for relative humidity is likely a secondary effect of its inverse relationship with temperature, rather than a direct driver of flight behavior.

4.2. Wavelength-Specific Attraction

Supporting our first hypothesis, the type of light source significantly influenced both species richness and abundance. Numerous studies have demonstrated that aquatic macroinvertebrates show strong phototaxis toward short-wavelength light, especially near-UV [29,30,34,35]. In our study, the compact light tube, emitting near-UV, blue, and yellow ranges, yielded higher capture rates than lamps emitting only UV or blue light despite having similar peak intensities within the respective spectral regions. This aligns with recent literature suggesting that combining UV and blue with yellow or green wavelengths often attracts more aquatic insects than narrow-band monochromatic sources [31,33].

Group and taxon-specific responses mostly supported our second hypothesis. Significant differences among light sources were detected for both investigated beetle groups. For aquatic and semiaquatic beetles, the compact light tube attracted significantly more individuals than the other two light sources. At the family level, significant differences among light sources were detected for Dytiscidae, Hydrophilidae, Helophoridae, and Heteroceridae. In Helophoridae and Heteroceridae, the compact light tube attracted significantly more individuals than either of the other two light sources. Although these taxa occupy different ecological niches [2,3,5], their dependence on aquatic habitats may impose similar selective pressures on mechanisms involved in locating suitable water bodies [3,5,51]. Thus, they may exhibit partially overlapping visual responses to the used light sources. This interpretation is consistent with previous evidence that insects inhabiting similar environments can exhibit similar visual adaptations to environmental cues [51].

In Dytiscidae and Hydrophilidae, the compact light tube resulted in significantly higher abundance than the LED light source, whereas no significant difference was detected between the compact light tube and the UV light source. This pattern may indicate that the near-UV wavelengths contribute strongly to the attraction of these families, while

the additional spectral components emitted by the compact light tube do not result in significantly higher attraction than the near-UV peak alone. However, targeted experiments are needed to test this interpretation.

No significant differences among light sources were detected for the remaining families. This may have resulted from the relatively low number of individuals collected from these families, which may have limited the statistical power to detect differences.

4.3. Phenological Shifts and Seasonal Efficiency

Species composition shifted clearly between spring and summer, confirming our third hypothesis. The abundances of two *Helophorus* species (Helophoridae) and *Anacaena limbata* (Hydrophilidae) varied significantly between seasons. Notably, these seasonal shifts did not alter light source preferences, indicating that wavelength-dependent attraction is a stable trait across phenological periods.

The spring peak in Helophoridae catches corresponds well with their utilization of temporary habitats, like ephemeral puddles, which typically dry out by summer [52,53]. Conversely, the summer peak observed in Hydrophilidae is in agreement with previous studies showing that the peak flight activity of several hydrophilid beetle species occurs during the summer months [6,54].

5. Conclusions

Our results indicate that the spectral composition of artificial light is a key driver of attraction in aquatic and semiaquatic beetles. Among the tested commercially available, light sources, the broad-spectrum compact light tube, emitting wavelengths in near-UV, blue, and yellow regions, consistently attracted a higher relative abundance and species richness than the narrower-spectrum UV and LED light sources under field conditions. The observed differences among taxa indicate that aquatic/semiaquatic beetle taxa do not respond uniformly to the spectral characteristics of artificial light. Thus, spectral properties must be carefully selected when designing light-trapping protocols for freshwater monitoring. Optimizing emission spectra can directly improve sampling efficiency and the taxonomic representativeness of surveys. Based on our findings, light sources emitting near-UV, blue and yellow light attract the investigated groups better than lamps emitting only UV or blue light at similar peak intensities. These mixed light sources are recommended for faunistic surveys and ecological assessments. In contrast, for artificial public lighting applications, the use of light sources emitting these wavelength ranges should be avoided.

Our findings provide a valuable basis for future field trials using standardized monochromatic LED light sources emitting within the spectral range of the most effective light source identified in this study. Testing these wavelengths individually across a wider range of freshwater habitats could help identify more precisely the specific spectral regions responsible for aquatic and semiaquatic beetle attraction. Such studies would further improve our understanding of wavelength-dependent phototaxis and facilitate the development of standardized, evidence-based monitoring protocols while simultaneously informing environmentally responsible lighting strategies near freshwater habitats.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w18182225/s1>, Table S1: Occurrence data of the caught species by light source type, sampling date, category, and family; Table S2: Climate data recorded during the sampling nights.

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