Biodiversity of benthic macroinvertebrates in three Alpine lakes of Piedmont (Northwest Italy)

Alessia Merialdi 1,
Marino Prearo 1,
Alessandra Maganza 1,
Camilla Mossotto 1,
Giuseppe Esposito 1,
Bruno Aimone 2,
Barbara Rizzioli 2,
Elena Bozzetta 1,
Paolo Pastorino 1,
Alice Gabetti 1, *

1, Istituto Zooprofilattico Sperimentale del Piemonte, Liguria e Valle d'Aosta, Via Bologna 148, 10154 Torino, Italy
2, Ente di Gestione delle Aree Protette delle Alpi Cozie, Via Fransuà Fontan 1, Salbertrand, Italy
* Corresponding author: alice.gabetti@izsplv.it

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Abstract: Alpine lakes are lentic ecosystems located above 1500 m a.s.l., characterized by particularly harsh environmental conditions and generally oligotrophic waters due to low organic matter input.
Whitin these systems, which have relatively simple biotic communities, benthic macroinvertebrates play an essential role in organic matter processing and constitute a food source for higher trophic levels. They are widely used as indicators of environmental change and anthropogenic pressure.
This study provides a checklist of benthic macroinvertebrates from three alpine lakes (Nero Lake, Clot-Foiron Lake and Fontanafredda Lake) located within Special Area of Conservation (SAC) IT1110058 "Cima Fournier – Lago Nero" (Habitats Directive 92/43/EEC), Italy.
Each lake was sampled once during the summers of 2024 and 2025 using a standardized Surber net. Samples were preserved in ethanol, sorted under a stereomicroscope, and organisms were identified to the lowest possible taxonomic level.
The observed communities are aligned with those reported for other alpine lakes, characterized by the dominance of Chironomidae and Oligochaeta. Nero and Fontanafredda Lakes exhibit higher taxonomic richness than Clot-Foiron Lake, indicating a wider variety of littoral microhabitats. These findings contribute to improving knowledge of biodiversity in high-altitude lake ecosystems.

Keywords: alpine lakes; benthic macroinvertebrates; biodiversity; high-altitude ecosystems.

1. Introduction

Alpine lakes, also known as "high-altitude lakes", are lentic ecosystems located above the tree line, typically at elevations exceeding 1500 m a.s.l. (Catalán et al., 2009, Sommaruga, 2001). They are characterized by particularly harsh environmental conditions, such as low temperatures, limited nutrient availability, oligotrophic status, and prolonged periods of snow or ice cover. During the winter, photosynthetic activity is virtually absent, and lakes remain isolated in a predominantly heterotrophic state until the spring thaw, when a sudden increase in ultraviolet radiation occurs (Pechlaner, 1966; Pechlaner et al., 1973; Ventelä et al., 1997). These abrupt environmental shifts result in unstable summer dynamics within lake ecosystems (Knapp et al., 2001a, Knapp et al., 2001b; Robinson & Oertli, 2009; Winder et al., 2003).
The morphology of alpine lakes is strongly influenced by the glacial origin of their basins, hydrological processes and catchment characteristics. These factors significantly impact the main chemical, physical, and biological parameters of lake waters (Marchetto et al., 1994, Marchetto et al., 1995; Tiberti et al., 2019).
Aquatic vegetation in these environments is generally sparse, and organic matter inputs originate mainly from the surrounding terrestrial vegetation. Consequently, alpine lakes are typically oligotrophic, characterized by low concentrations of phosphorus and nitrogen (Čiamporová-Zat'ovičova et al., 2010). Therefore, biotic communities tend to be relatively simple, consisting of organisms that are highly adapted to extreme conditions and largely confined to littoral zones.
In this context, benthic macroinvertebrates represent a key component of the biodiversity of lakes. The term "benthic macroinvertebrates" refers to aquatic organisms with a body size of 1 mm or more at larval or adult stage. They include mainly insects, oligochaetes, crustaceans, hirudineans, and mollusks, as well as platyhelminthes, poriferans, cnidarians, and bryozoans (Ghetti & Bonazzi, 1981). The life cycle of these organisms may take place entirely within an aquatic environment, or solely during their larval stages. They also play a crucial role in processing organic matter, occupying a range of functional feeding groups, including herbivores, detritivores, and predators. Due to these characteristics, benthic macroinvertebrates are widely used both as indicators of environmental change and as tools for assessing the impacts of anthropogenic pressures on aquatic ecosystems (Fjellheimet all, 2000; Hodkinson & Jackson, 2005).
In alpine lakes, macroinvertebrate communities are generally dominated by chironomids and oligochaetes (Boggero & Lencioni, 2006; Kownacki et al., 2006). They occupy a

wide range of habitats, from fine sediments to submerged surfaces (Dumnicka, 1994; Lencioni et al., 2011; Verdonschot, 2001). Alongside these dominant groups, other taxa such as trichopterans, aquatic coleopterans, odonates, megalopterans, gastropods, and bivalves are present, although generally in lower abundance and diversity. Their distribution is strongly influenced by the physicochemical characteristics of the water and by the composition of substrate (Boggero & Lencioni, 2006; Gabetti et al., 2024). Alpine lakes are particularly sensitive ecosystems, where even minor environmental changes can substantially affect chemical and biological processes. For this reason, despite their remote and seemingly isolated location, they are now widely recognized as valuable systems for monitoring the effects of ongoing climate change (Pastorino et al., 2024). Within this context, documenting local biodiversity through faunistic checklists is an important way to improve our understanding of these environments and provides a valuable reference for future studies. The present study aims to provide a checklist of benthic macroinvertebrates recorded in three alpine lakes included in the Special Area of Conservation (SIC) IT1110058 “Cima Fournier – Lago Nero”, established under the Habitats Directive (92/43/EEC). Each lake was sampled only once during the summer season, either in 2024 or in 2025.

2. Materials and Methods

2.1 Study Area

Three alpine lakes (Nero Lake, Clot-Foiron Lake and Fontanafredda Lake) located in the upper Val Susa (Cesana Torinese, Turin, NW Italy) were sampled. These lakes are included within the Special Area of Conservation (SIC) IT1110058 “Cima Fournier – Lago Nero”.

This Natura 2000 site is characterized by typical glacial morphology, with gently sloping hillsides formed from outcrops of limestone schist. The hydrographic network is mainly fed by springs and snowmelt. Larch-Swiss stone pine woodlands dominate the forest vegetation, though more than half of the area is covered by grasslands used for cattle grazing (Sindaco et al., 2008).

Nero Lake

Nero Lake is located at an altitude of 2020 m, with a surface area of approximately 1.65 ha and a shoreline length of 718 m. The southern margin of the lake borders a relatively extensive wetland area, while smaller wetlands occur intermittently along the shoreline and host plant species of conservation interest. The northern sector of the basin is characterized by extensive stands of *Potamogeton nodosus* and, to a lesser extent, *P. alpinus* (Selvaggi, 2022).
The lake shores are generally steep and show significant signs of disturbance, particularly along the eastern side, due to trampling by livestock and tourists. These conditions limit the growth of emergent vegetation to a narrow strip dominated by *Carex vesicaria* and *C. elata*, often associated with *Menyanthes trifoliata* (IPLA, 2001).
Five littoral sampling stations were identified along the lake perimeter. These stations were selected by surveying the entire shoreline and placing sampling points at water depths ranging from 25 to 60 cm, based on the presence of different microhabitats and the occurrence of inflows or outflows (Dumnicka et al., 2015), as well as site accessibility. The location and main characteristics of each station are reported in Table 1 and shown in Figure 1.

Table 1. Description of the sampling stations in Nero Lake.

Station	Latitude	Longitude	Description
1	44°54’06”N	6°47’40”E	Northern shoreline station, characterized by a predominance of gravel substrate and a lower amount of organic detritus compared to the other sites. Water depth ~25 cm.
2	44°54’06”N	6°47’39”E	North-western shoreline station, close to an inflow from the “Fattoria Lago Nero” and “Grange Servierettes” alpine pastures. The substrate is mainly silty, with stands of *Menyanthes trifoliata*. Water depth ~35 cm.
3	44°54’04”N	6°47’40”E	Western shoreline station located at the apex of an alluvial fan. The substrate is dominated by organic detritus and *Carex vesicaria*. Water depth ~45 cm.
4	44°54’01”N	6°47’42”E	South-eastern shoreline station near a wetland area. The substrate is predominantly silty, and aquatic vegetation is dominated by *Carex vesicaria*. Water depth ~60 cm.
5	44°54’05”N	6°47’43”E	North-western shoreline station. The substrate is silty with submerged vegetation; the riparian vegetation mainly consists of *Carex vesicaria*, *Potamogeton* sp. and *Menyanthes trifoliata*. Water depth ~40 cm.

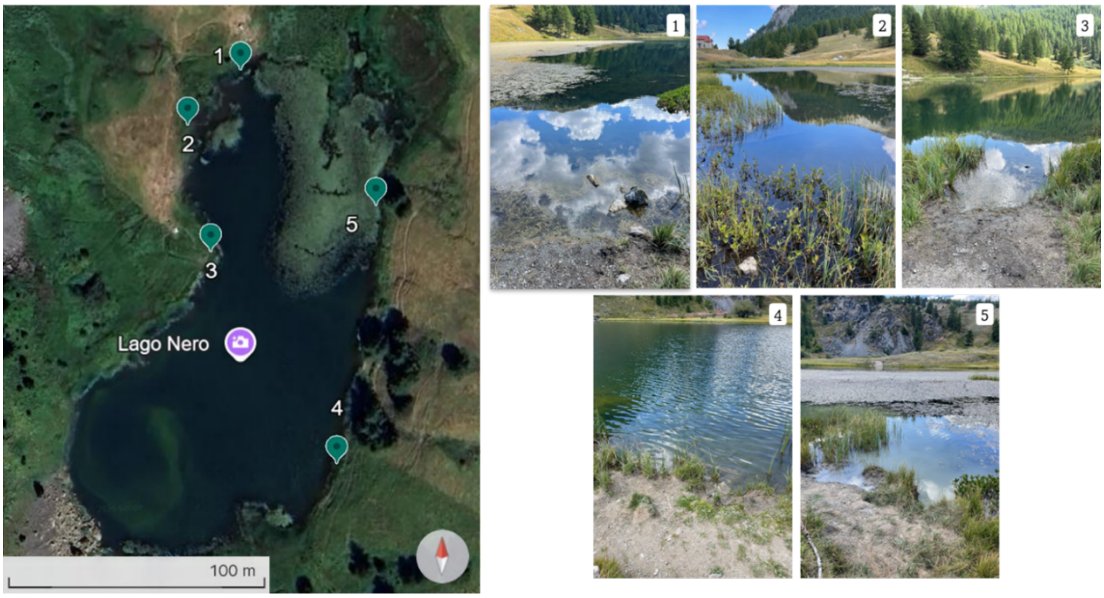

Figure 1. Sampling stations (1–5) at Nero Lake

Clot-Foiron Lake

Clot Foiron Lake lies at 2134 m a.s.l. and is located within an area characterized by numerous peatlands which were formed as a result of deep-seated gravitational slope deformations connected to the Nero Lake basin (ISPRA, 2025).
The lake shores are generally homogeneous and widely colonized by riparian vegetation, while the lake bottom mainly consists of fine, silty, muddy sediments. However, exceptions occur in some sectors of the basin, where the vegetation cover is more discontinuous and the substrate includes coarser elements such as gravel and boulders.
Five littoral sampling stations were identified along the lake perimeter and distributed across different shore sectors. Station selection considered the presence of distinct microhabitats, inflows or outflows, and site accessibility. Overall, the stations showed low variability in terms of substrate and riparian vegetation characteristics, except for site 4, where vegetation cover was sparser and the substrate included gravel and boulders.
The locations and main environmental features of the stations are reported in Table 2 and Figure 2.

Table 2. Description of the sampling stations in Clot-Foiron Lake.

Station	Latitude	Longitude	Description
1	44°54'50.4"N	6°47'08.0"E	South-western shoreline station near a small inflow. Soft, predominantly silty substrate; riparian vegetation with *Carex* spp. Water depth ~50 cm, very weak current.
2	44°54'51.3"N	6°47'10.7"E	Southern shoreline station with soft, silty and unstable substrate. Water depth ~60 cm; shores colonized by *Carex* spp.
3	44°54'52.3"N	6°47'11.5"E	Eastern shoreline station near a small outflow. The area includes small inlets and emergent grassy patches; soft silty substrate. Presence of *Menyanthes* sp. and *Carex* spp. along the shores. Water depth ~30 cm.
4	44°54'53.8"N	6°47'10.3"E	Northern shoreline station with submerged logs, macrolithal and microlithal elements, and woody debris. Water depth ~40 cm; riparian vegetation dominated by *Carex* spp.
5	44°54'53.1"N	6°47'08.0"E	North-western shoreline station at the edge of a wetland area. Predominantly silty substrate, water depth ~40 cm; presence of *Menyanthes* sp. along the shores.

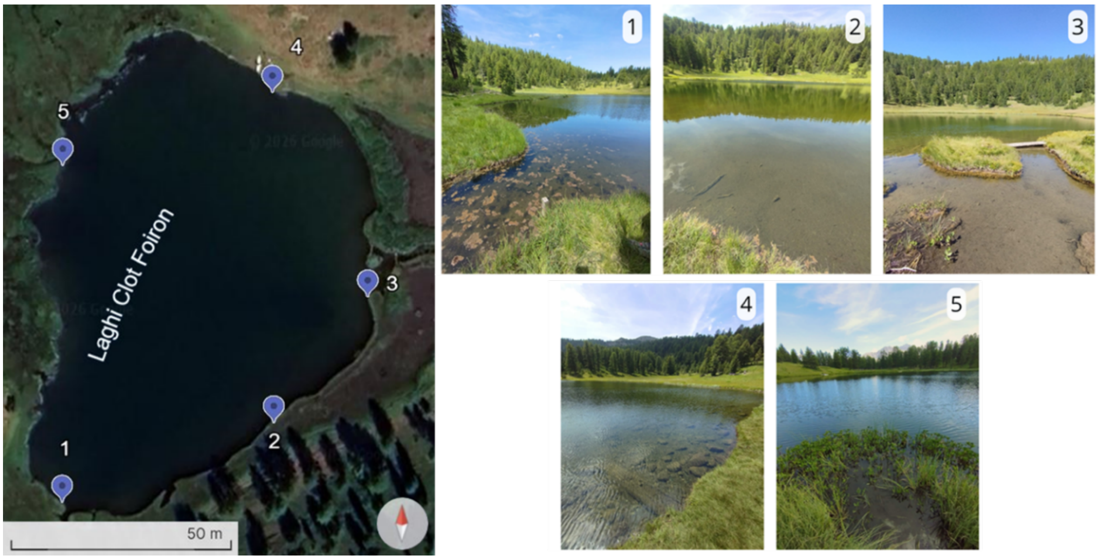

Figure 2. Sampling station (1–5) at Clot-Foiron Lake

Fontanafredda Lake

Fontanafredda Lake is located at 2167 m a.s.l. (Regione Piemonte, 2025). The area's geomorphological features promote the development of wetlands, peat bogs and oligo-mesotrophic waters, supporting a flora of high conservation value, including the rare *Swertia perennis* (Ente di Gestione delle Aree Protette delle Alpi Cozie, 2024).

Detailed information on macrobenthic sampling sites is reported in Table 3 and Figure 3. The selected sampling sites share homogeneous environmental characteristics. The shores are widely colonized by riparian vegetation, and the substrate is predominantly soft and fine-grained, lacking gravel or rocky elements. At sites 1, 2, 4 and 5, dense stands of *Potamogeton* spp. dominate the water surface, and sampling was carried out near *Menyanthes* spp. patches.
Due to the high homogeneity of the lake perimeter, microhabitat availability is limited, resulting in low environmental heterogeneity among the sampling sites.

Table 3. Description of the sampling stations in Fontanafredda Lake.

Station	Latitude	Longitude	Site description
1	44°53'44.6"N	6°46'57.5"E	South-eastern shoreline station. Soft, very fine silty–muddy substrate; shores widely colonized by riparian vegetation. Water depth ~30 cm; dense aquatic vegetation.
2	44°53'46.6"N	6°46'57.9"E	Northern shoreline station along a gently sloping shore. Soft, fine, predominantly silty substrate; uniform riparian vegetation. Presence of submerged *Potamogeton* spp. and *Menyanthes* spp. Water depth ~35 cm.
3	44°53'46.4"N	6°46'55.9"E	North-western shoreline station. Soft, very fine substrate without coarse elements; water surface lacking the dense vegetation cover typical of other stations. Water depth ~45 cm.
4	44°53'45.5"N	6°46'54.3"E	Western shoreline station. Soft, fine silty–muddy substrate; shores densely colonized by riparian vegetation. Widespread submerged *Potamogeton* spp. Water depth ~35 cm.
5	44°53'41.8"N	6°46'53.0"E	South-western shoreline station. Soft, very fine substrate without gravel or rocks; abundant riparian vegetation. Water depth ~50 cm.

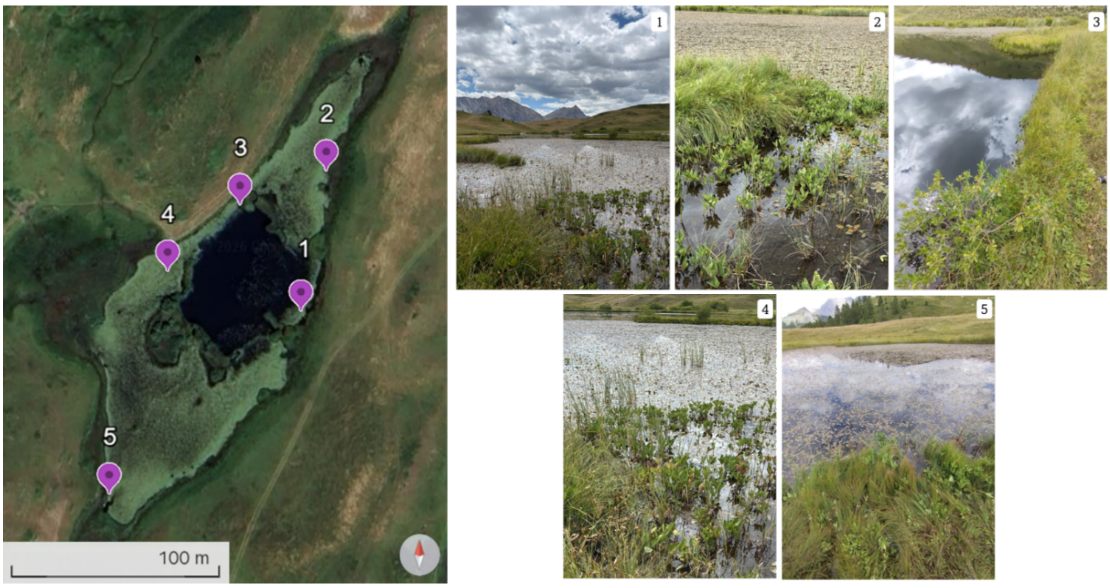

Figure 3. Sampling station in Fontanafredda Lake

2.2 Macrobenthic invertebrate sampling

Littoral sampling was carried out using the methodology outlined by Boggero et al. (2006) and Fjellheim et al. (2000). A Surber net (SCUBLA S.r.l., Remanzacco, Italy) with a mesh size of 250 µm and a frame opening of 32 × 32 cm was used (Boggero et al., 2006; Fjellheim et al., 2000; Frost et al., 1971; Maiolini et al., 2006). The steel frame delimited a sampling area of 0.1 m^2, enabling for quantitative substrate sampling.
Sampling was conducted by stirring up the sediment within the designated area, thereby generating a water flow to facilitate the entry of organisms into the net. To standardize sampling effort, each sample was collected over a 2-minute period (Boggero & Lencioni, 2006). At each station, three replicate samples were collected, covering all available microhabitats.
All samples were sieved using a 250 µm mesh to reduce sample volume and remove fine detritus. Replicates were preserved immediately in 70% ethanol and subsequently processed in the laboratory. Samples were sorted under a stereomicroscope (Stereomicroscope Binocular Zoom 0.8×–8×, LED illumination, Eurotek, Orma) to separate macroinvertebrates from residual detritus. Organisms were counted and identified to species level, where possible, using standard taxonomic keys (Campaioli et al., 1994; Campaioli et al., 1999; Tachet et al., 2000).

2.3 Data analysis

For each sampling site, benthic macroinvertebrate density (number of specimens per square meter, ind m^{-2}) was calculated for each identified taxon. In addition, total individual counts were reported for higher taxonomic categories.
All calculations and graphical representations were performed using Microsoft Excel software.

3. Results

3.1 Nero Lake

A total of 1905 organisms were identified through sampling. Identification to the lowest possible taxonomic level is reported in Table 4. Figure 4 shows the number of specimens in each taxonomic group at the different stations.

Table 4. Number of specimens sampled at different stations in Nero Lake.

TAXONOMIC GROUPS		SAMPLING STATIONS				
		1	2	3	4	5
Ephemeroptera	*Baetis* sp.	2	0	0	1	4
Megaloptera	*Sialis* sp.	2	11	1	10	33
Coleoptera	Dytiscidae (larvae)	1	0	7	4	3
Odonata	Unidentifiable	5	0	1	2	0
	Lestidae	0	0	0	1	0
	Coenagrionidae	3	0	6	1	4
Diptera	Dixidae	0	0	1	0	0
	Tabanidae	0	0	0	1	0
	Empididae	0	0	2	1	0
Diptera f. Chironomidae	Chironominae tr. Chironomini	4	9	106	58	85
	Chironominae tr. Tanytarsini	11	5	12	18	100
	Tanypodinae	25	29	45	33	106
	Orthocladiinae	65	9	12	7	49
	Corynoneurinae *Corynoneura* sp.	13	11	49	22	39
	Pupae	4	1	4	9	11
Diptera f. Ceratopogonidae	Sf. Ceratopogoninae	1	0	1	2	1
Crustacea	*Gammarus* sp.	5	11	23	27	18
Gastropoda	*Valvata piscinalis*	147	14	70	247	69
Bivalvia	*Pisidium* sp.	19	0	0	3	56
Oligochaeta	Unidentifiable	22	32	20	15	14
Hirudinea	Unidentifiable	3	1	14	2	4
Heteroptera	Gerridae	0	0	0	1	0
	Plea sp.(ninfae)	0	0	4	0	0
Trichoptera	Unidentifiable	0	0	0	1	0
TOTAL SPECIMENS PER SITE		**332**	**133**	**378**	**466**	**596**
TOTAL SPECIMENS SAMPLED				**1905**		

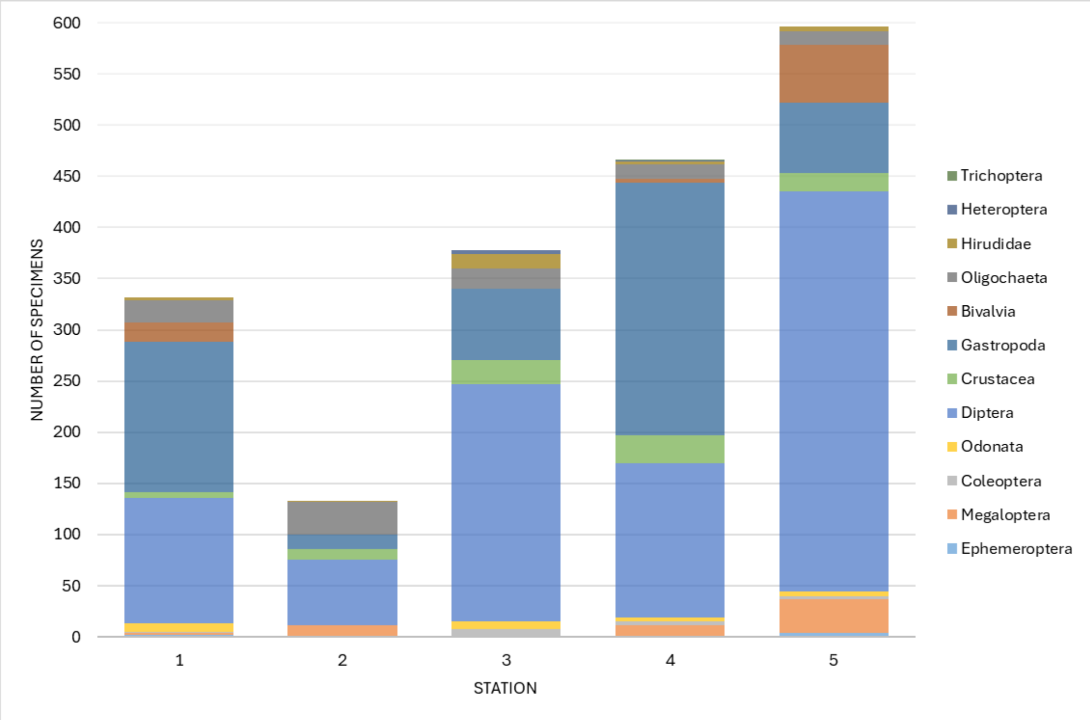

Figure 4. Number of sampled specimens per station in Nero Lake

Densities of macroinvertebrates (ind. m^{-2}) varied among the sampling stations, ranging from 1106.7 ind. m^{-2} at Station 1, 443.3 ind. m^{-2} at Station 2, 1260 ind. m^{-2} at Station 3, 1553.3 ind. m^{-2} at Station 4 and 1986.7 ind. m^{-2} at Station 5, which showed the highest abundance of macroinvertebrates.

The most abundant taxonomic group was Hexapoda (3563.3 ind. m^{-2}), followed by Mollusca (2083.3 ind. m^{-2}). Within Mollusca, the gastropod *Valvata piscinalis* was the most prevalent species, while the most abundant family within Hexapoda was Chironomidae (Diptera), with an overall density of 3170 ind. m^{-2}. Chironomidae were distributed among the subfamilies Chironominae (tribes Chironomini and Tanytarsini), Orthocladiinae, Tanypodinae, and Corynoneurinae. Pupae were also present.

The densities of the different taxa and chironomids are shown respectively in Figure 5 and Figure 6.

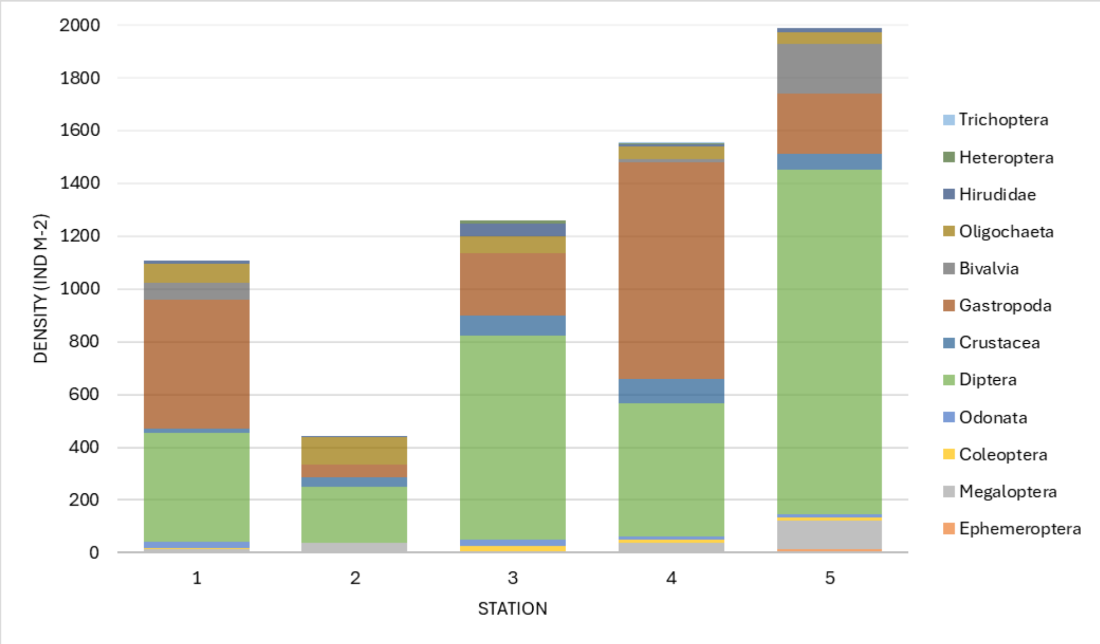

Figure 5. Density of each taxon identified in Nero Lake

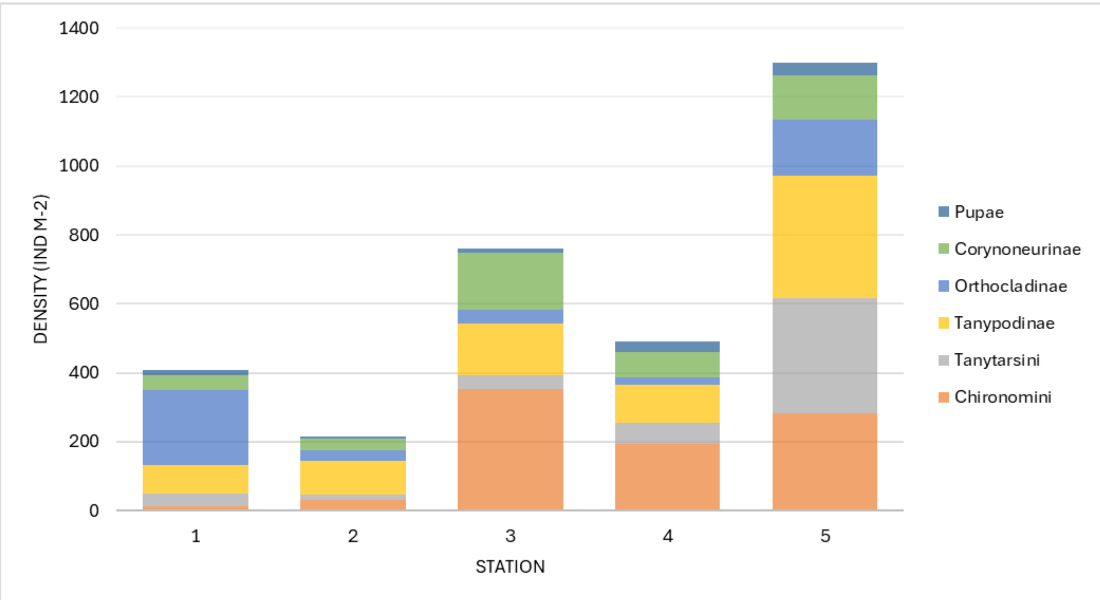

Figure 6. Diptera Chironomidae: density of the main identified taxa in Nero Lake

3.2 Clot-Foiron Lake

A total of 725 specimens were identified through sampling (Table 5). Overall, the macrobenthic community was characterized by low abundance and low taxonomic diversity.

Table 5. Relative abundances of taxa identified in Clot-Foiron Lake.

TAXONOMIC GROUPS		SAMPLING STATIONS				
		1	**2**	**3**	**4**	**5**
Odonata	Aeshnidae	0	0	1	0	0
Diptera f. Chironomidae	Chironominae tr. Chironomini	0	39	0	12	13
	Chironominae tr. Tanytarsini	20	112	52	146	63
	Prodiamesinae	3	1	0	0	0
	Tanypodinae	2	5	0	5	1
	Orthocladiinae	14	19	8	51	12
	Corynoneurinae C*orynoneura* sp.	1	0	7	6	43
	Pupae	0	4	0	5	3
Diptera f. Ceratopogonidae	Ceratopogoninae	2	1	4	7	12
Megaloptera	*Sialis* sp.	0	0	0	2	2
Oligochaeta	Unidentifiable	2	3	3	8	29
Heteroptera	Unidentifiable	1	0	0	0	0
Trichoptera	*Phryganeidae* (pupae)	0	0	0	0	1
TOTAL SPECIMENS PER SITE		**45**	**184**	**75**	**245**	**179**
TOTAL SPECIMENS SAMPLED				**728**		

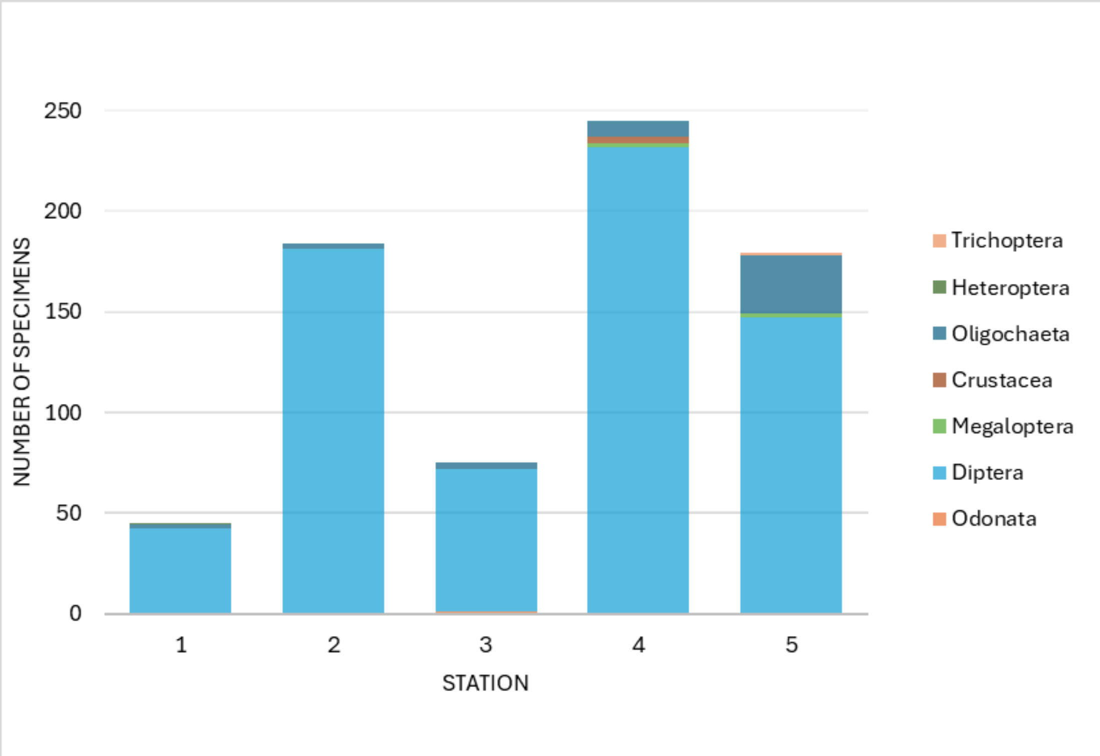

Figure 7. Number of specimens per station in Clot-Foiron Lake

There was marked variation in individual densities among the sampling stations, ranging from 150 ind. m^{-2} at Station 1, 613.3 ind. m^{-2} at Station 2, 250 ind. m^{-2} at Station 3, 816.7 ind. m^{-2} at Station 4 and 596.7 ind. m^{-2} at Station 5. The highest abundance was observed at Station 4.

Hexapods were the dominant taxon (2266.7 ind. m^{-2}), followed by Oligochaeta (150 ind. m^{-2}). Crustaceans were present at lower densities, whereas molluscs were absent. Whitin the order Hexapoda, the most prevalent family was the Chironomidae (Diptera), with a total density of 2156.7 ind. m^{-2}, distributed among the subfamilies Chironominae (tribes Chironomini and Tanytarsini), Orthocladiinae, Tanypodinae, Corynoneurinae, and Prodiamesinae.

Densities of the different taxa and the Chironomidae family are shown in Figure 8 and Figure 9.

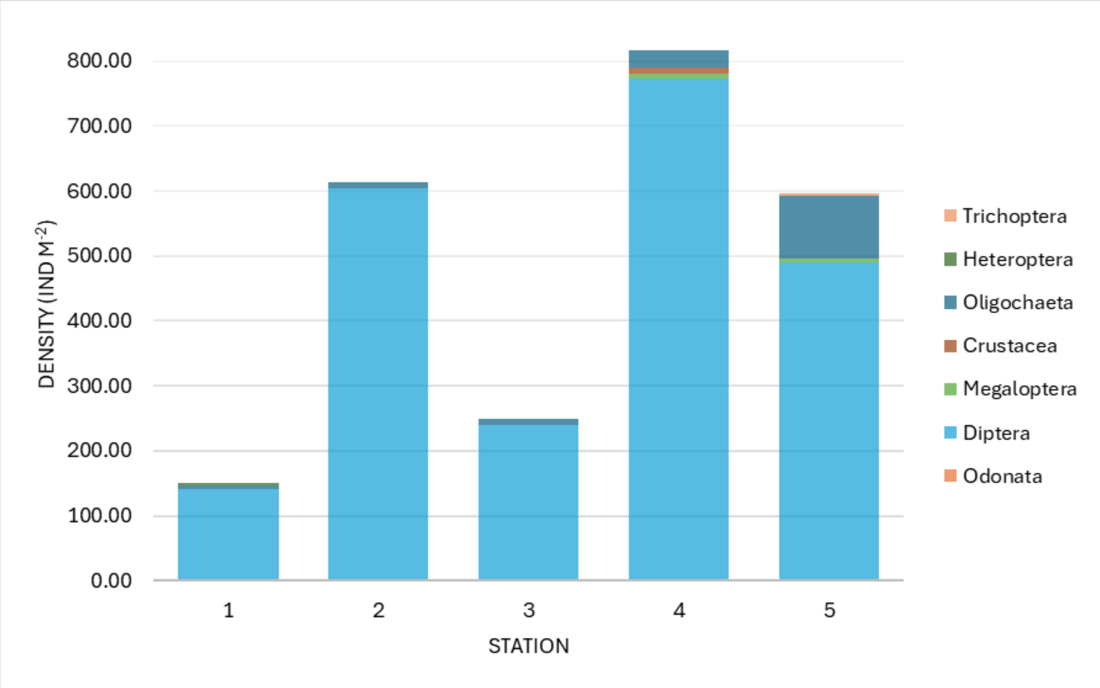

Figure 8. Density of each taxon identified at different stations in Clot-Foiron Lake

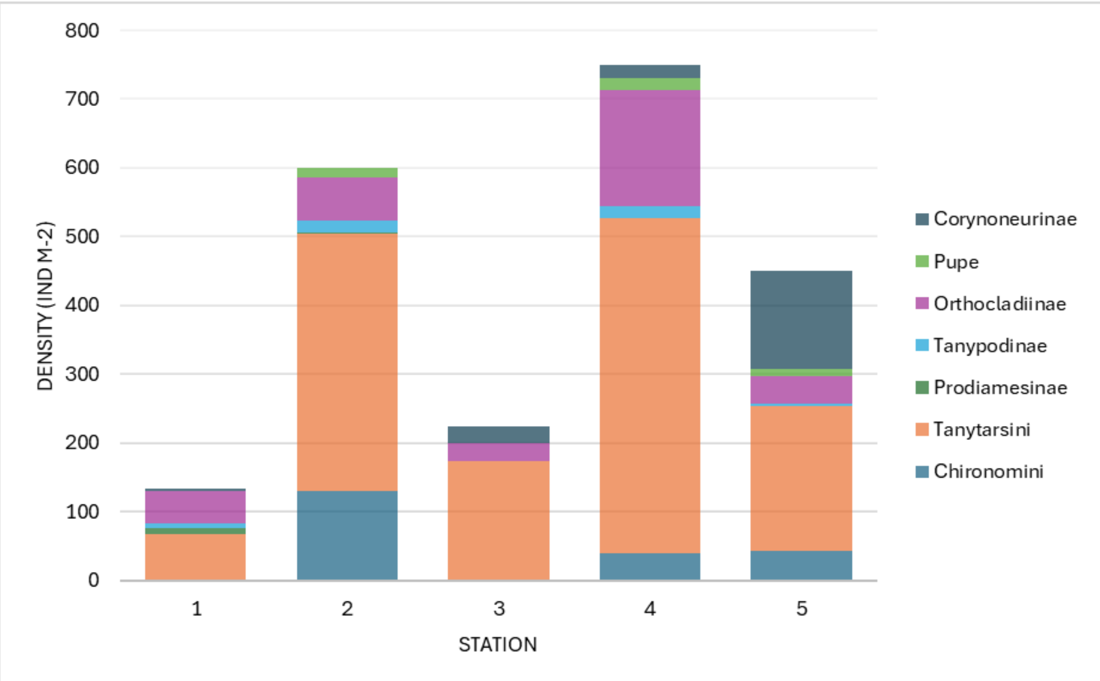

Figure 9. Diptera Chironomidae: density of the main identified taxa in Clot-Foiron Lake

3.3 Fontanafredda Lake

A total of 985 organisms were identified through sampling. Table 6 shows the identified taxonomic groups, Figure 10 shows the number of specimens in each group at the different stations.

Table 6. Relative abundances of taxa identified in Fontanafredda Lake.

TAXONOMIC GROUPS		**SAMPLING STATIONS**				
		1	**2**	**3**	**4**	**5**
Ephemeroptera	*Baetis* sp.	0	0	1	0	0
Heteroptera	Notonectidae (ninfa)	0	0	0	0	1
	Mesovelia sp.	0	0	0	0	2
	Hebrus sp. (ninfa)	0	0	0	0	2
	Gerris sp. (ninfa)	0	0	0	0	1
	Corixidae (ninfa)	0	0	1	0	0
Coleoptera	Haliplidae (larva)	1	0	0	1	0
	Helodidae (larva)	0	2	0	0	1
	Dytiscidae (larva)	0	0	12	13	6
	Hygrobiidae	4	3	0	4	0
Odonata	unidentifiable	2	2	16	8	1
	Libellulidae	1	7	0	3	1
	Lestidae	0	0	4	14	6
	Aeshnidae	0	0	2	8	1
Diptera	Chaoboridae	0	0	10	30	27
	Empididae	0	0	1	0	0
	Dixidae	0	0	6	3	14
Diptera f. Chironomidae	Chironominae tr. Chironomini	36	7	47	11	36
	Chironominae tr. Tanytarsini	22	6	18	5	11
	Tanypodinae	64	59	89	88	56
	Orthocladiinae	4	0	0	0	2
	Corynoneurinae *Corynoneura* sp.	1	2	5	4	4
	Pupae	1	3	5	0	2
Diptera f. Ceratopogonidae	Ceratopogoninae	1	3	6	1	1
Megaloptera	*Sialis* sp.	0	0	0	0	0

Table 6. Continued.

TAXONOMIC GROUPS		SAMPLING STATIONS				
		1	2	3	4	5
Gasteropoda	*Valvata* sp.	0	0	7	0	0
Bivalvia	*Pisidium* sp.	1	0	15	25	16
Oligochaeta	unidentifiable	0	7	37	28	25
Hirudinea	unidentifiable	0	0	0	1	1
TOTAL SPECIMENS PER SITE		**138**	**101**	**282**	**247**	**217**
TOTAL SPECIMENS SAMPLED				**985**		

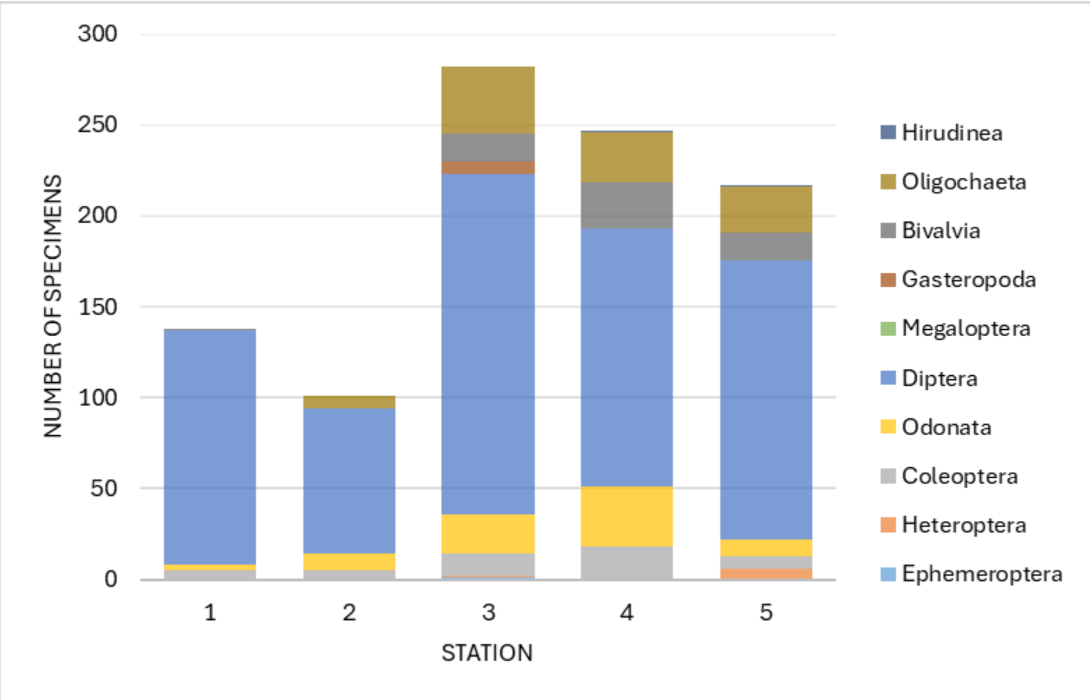

Figure 10. Number of specimens per station in Fontanafredda Lake

Density of specimens varied among the sampling stations: 460.0 ind. m^{-2} at Station 1, 335.7 ind. m^{-2} ad Station 2, 940.0 at Station 3, 823.3 at Station 4 and 723.3 ind. m^{-2} ad Station 5. The highest abundance was observed at Station 3.

The most abundant taxon was Hexapoda (2740.0 ind. m^{-2}), followed by Oligochaeta (323.3 ind. m^{-2}); Mollusca and Hirudinea occurred at lower densities.

Within the order Hexapoda, the family Chironomidae (Diptera) was the most prevalent, with an overall density of 1960 ind. m^{-2}. The chironomid community composition was relatively similar among the stations, with Tanypodinae predominating (186.7–296.7 ind. m^{-2}), followed by Chironomini, Tanytarsini, Corynoneurinae, and pupae. Orthocladiinae were only recorded at Station 1 and 5. The densities of the different taxa are shown in Figure 11 and density of chironomids are shown in Figure 12.

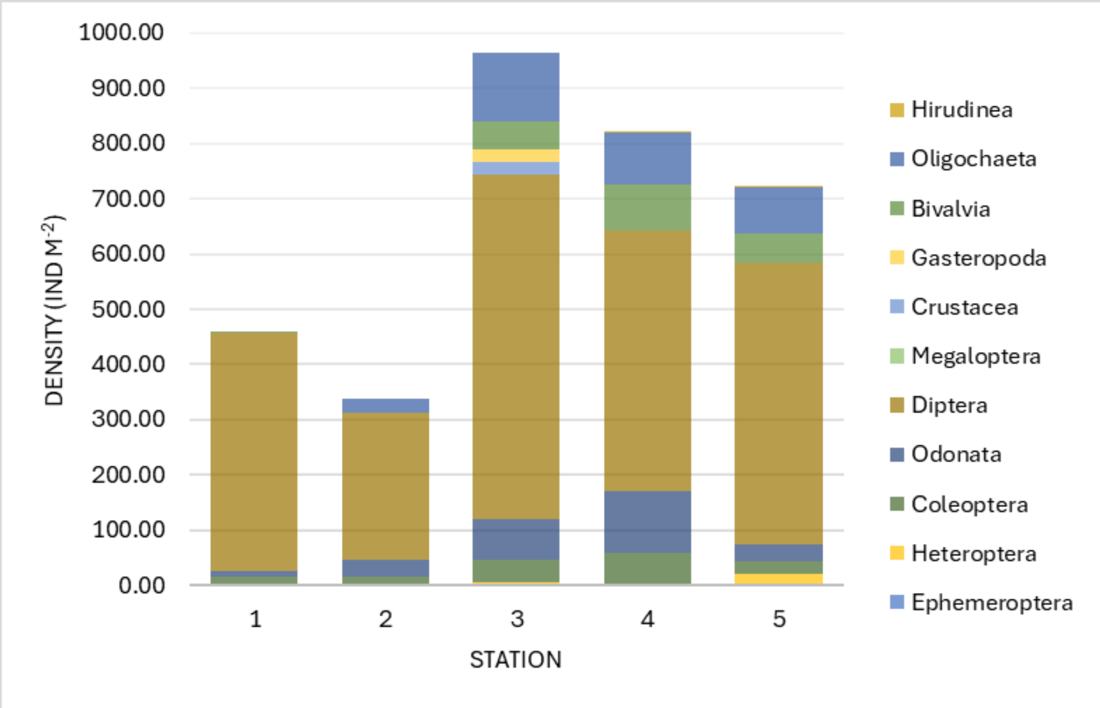

Figure 11. Density of each taxon identified at different stations in Fontanafredda Lake

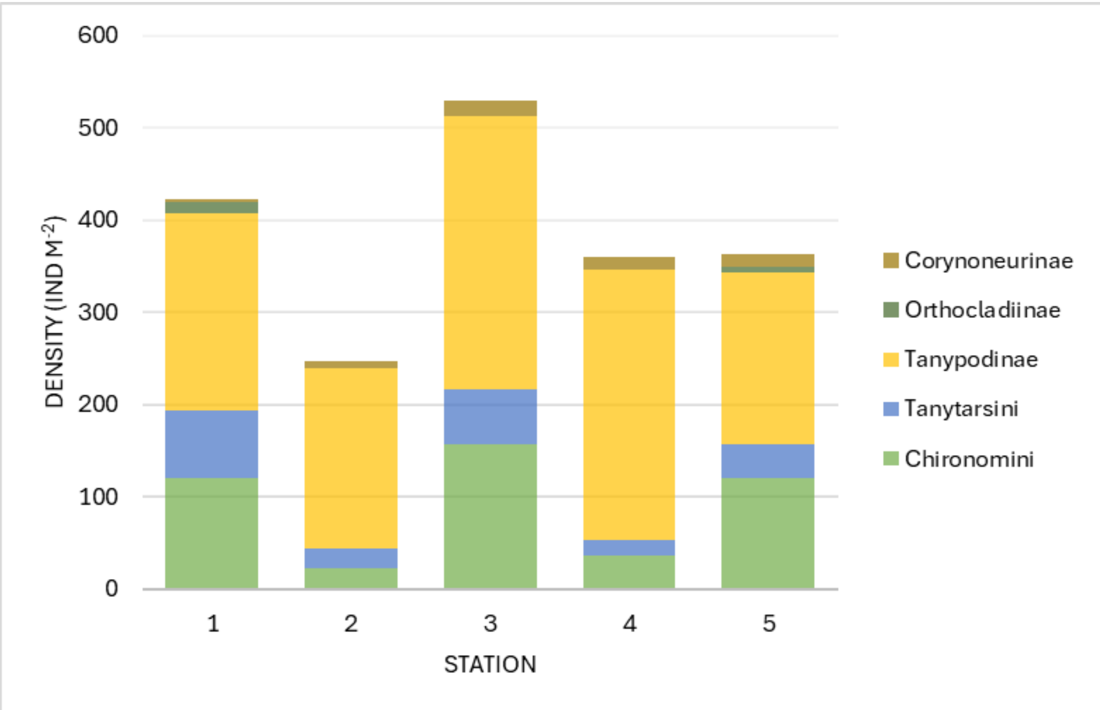

Figure 12. Diptera Chironomidae: density of the main identified taxa in Fontanafredda Lake

4. Discussion

The taxonomic richness recorded in each of the three lakes studied is consistent with the values reported for other high-altitude alpine lakes (Bertoli et al., 2023; Čiamporová-Zaťovičova et al., 2010; Free et al., 2009; Tiberti et al., 2010). As expected for lakes located above 1500 m a.s.l. and subject to harsh climatic conditions, the macrobenthic communities exhibited a relatively simple structure characterized by a limited number of taxa and dominated by organisms capable of colonizing fine substrates and structurally simple habitats.

As in previous studies conducted in similar alpine environments (Bartels et al., 2021; Boggero et al., 2005; Füreder et al., 2006), chironomids and oligochaetes represented the predominant groups in all lakes. The main exception was Nero Lake, where mollusks were particularly abundant, exceeding oligochaetes in terms of density. Within this group, *Valvata piscinalis* was the most abundant species. This taxon's high density may be related to the availability of soft substrates and the presence of aquatic macrophytes observed at several sampling stations (Antoine et al., 2004).

Although chironomids dominated all three lakes, differences were observed in the relative abundance of the main subfamilies. Nero and Fontanafredda Lakes were characterized primarily by Chironomini and Tanypodinae, the latter of which was particularly abundant in Fontanafredda lake. In contrast, Clot-Foiron Lake was dominated by Tanytarsini and Orthocladiinae. All these groups are typical components of alpine lake communities. However, the observed differences in dominance patterns may reflect variations in the local environmental conditions of the lakes under investigation. In the absence of physicochemical data, these interpretations remain provisional.

In line with their known affinity for lentic or weakly stagnant waters with fine, silty substrates (Verdonschot, 2001) oligochaetes were the second most abundant group in Clot-Foiron and Fontanafredda Lakes. Although they did not rank second in Nero Lake, oligochaetes were nonetheless present at relatively high densities.

Crustaceans were only found in Nero Lake, where they were mainly represented by amphipods of the genus *Gammarus*, which were found in relatively high numbers. Identifying them to the species level based solely on morphological traits is challenging. While *Gammarus lacustris* is a common inhabitant of small alpine lakes, a newer species endemic to the Alps, *Gammarus alpinus*, was described in 2017 (Alther et al., 2017). Genetic analyses are necessary to determine whether Nero Lake hosts one or both of these species, as *G. alpinus* is known to be particularly sensitive to the specific stressors

present in this lake, such as climate change, eutrophication, and the introduction of alien fish species.
Other insect taxa, including Odonata, Trichoptera, Coleoptera, Ephemeroptera, Heteroptera and Megaloptera, were generally recorded at low densities and exhibited an irregular distribution across the sampling stations. At Fontanafredda Lake, higher densities of Odonata and Coleoptera were recorded at certain locations, which may be due to the presence of more structured microhabitats associated with submerged macrophytes, such as *Potamogeton* and *Menyanthes* spp. In contrast, the sporadic occurrence of Ephemeroptera and Trichoptera across all lakes suggests that suitable conditions for these taxa are locally restricted.
Overall, differences in abundance and community composition were observed between sampling stations within each lake. Without physicochemical measurements, it is impossible to assess the role of water chemistry or temperature in shaping these patterns directly. However, field observations suggest that spatial variability within lakes is primarily associated with the physical characteristics of the habitat, such as the composition of the substrate, the presence of coarse elements or submerged woody debris, and the presence of aquatic or riparian vegetation.

5. Conclusions

This study provides a checklist of the littoral microbenthic communities of three high-altitude lakes, thereby contributing to our current understanding of the biodiversity of these sensitive ecosystems. The macrobenthic assemblages recorded in the lakes are generally consistent with those found in other alpine lacustrine environments. They are dominated by widespread and tolerant taxa such as Oligochaeta and Chironomidae and characterized by limited taxonomic differentiation among lakes (Bartels et al., 2021; Bertoli et al., 2023; Boggero & Lencioni, 2006; Tiberti et al., 2010). Differences in taxonomic richness and organism abundance among the study sites suggest that local habitat characteristics play an important role in structuring littoral microbenthic communities. In particular, the higher richness and abundance observed in Nero and Fontanafredda Lakes compared to Clot-Foiron Lake may reflect a greater availability and diversity of littoral microhabitats in the former two systems. Whereas the relative homogeneity of sampling sites in Clot-Foiron Lake appears to be associated with a simpler community structure. These findings highlight the importance of macroenvironmental features such as substrate composition and vegetation cover in shaping littoral microbenthic assemblages. It should be noted that sampling was conducted exclusively during the summer period; therefore, the results represent a temporal snapshot of the faunal composition and may not fully capture seasonal variability in these high-altitude ecosystems. Further investigations conducted at finer spatial and temporal scales are recommended to achieve a more comprehensive understanding of macrobenthic assemblages and their potential changes over time, whether driven by natural dynamics or anthropogenic pressures.

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