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Taxonomic composition of zoopsammon in fresh and brackish waters of Estonia, a Baltic province ecoregion of Europe

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Abstract. Zoopsammon communities, i.e. fauna dwelling in the interstitial sandy habitat at the water's edge, are largely understudied. The aim of the present study was to provide an overview of the taxonomic structure of zoopsammon in Estonian waters. The study is based on samples collected from four lakes across Estonia and from three sandy beaches on the Estonian coast of the Gulf of Finland, Baltic Sea, in 2008–2014. Animals from 12 phyla were found, of which the majority of rotifers and testate amoebae were identified to species level. A total of 156 taxa were determined, including 84 rotifer species and 39 testate amoebae species. In addition to the 46 new taxa for the Estonian fauna already registered in our previous works, the present study reports further 11 new rotifer, 19 testate amoebae, and 6 nematode taxa. The psammic communities in lake beaches had higher species richness than in coastal beaches, and the communities were more similar in coastal beaches than in lake beaches. The mesotrophic Lake Saadjärv had the highest taxon richness with 80 taxa from 10 phyla. Similarly, the number of testate amoebae species was higher in lake beaches than in coastal beaches. The number of taxa, especially the number of rotifer species, was lower in sampling sites with an elevated trophic state and/or human population density. The number of testate amoebae species was the highest in the hypertrophic Lake Verevi. As compared to testate amoebae, rotifer communities had a higher taxonomic richness at landscape scale characterized by variable communities both in time and space.

Key words: psammon, meiofauna, rotifers, testate amoebae, Baltic Sea, lake beach, Estonia.

INTRODUCTION

Zoopsammon is a diverse group of organisms living in the interstitial spaces between sand grains at the shoreline. The term *psammon* is nowadays mainly used to characterize freshwater sandy beach habitats, although it was originally defined as 'a transitional zone between aquatic and soil habitats' (Schmid-Araya, 1998), and is also applicable to brackish and marine beach habitats, where the intertidal zone can be considered as psammon habitat if the sediment consists of sand and is regularly exposed (e.g. Tzschaschel, 1983; Golemansky, 1998; De

Smet and Chernyshev, 2006; Alekperov et al., 2007). However, in the marine literature psammic comunities are more often referred to as meiofauna.

Psammon communities have received very little attention compared to lower littoral and sublittoral meiobenthos, and psammon has been rarely treated as a single entity. Despite its unstable and very fluctuating environment, the arenal zone hosts a large variety of species (Pejler, 1995; Golemansky, 1998; Gheskiere et al., 2005). Protists, nematodes, rotifers, small crustaceans, tardigrades, gastrotrichs, turbellarians, oligochaetes, and insect larvae are regularly found from psammon habitats (Thane-Fenchel, 1968; Whitman and Clark, 1984; Schmid-Araya, 1998, Kotwicki et al., 2005a, 2005b). From psammic taxa, rotifers have received relatively much attention in freshwater habitats (e.g. Pejler, 1995; Bielańska-Grajner, 2001; Segers and Chittapun, 2001). In marine beach habitats, nematodes tend to be the most thoroughly researched psammic taxa (e.g. Gheskiere et al., 2004, 2005; Liu et al., 2008; Maria et al., 2012, 2013).

From the Baltic Sea area some information is available on psammic ciliates (Czapik and Fyda, 1992), testate amoebae (Golemansky, 1998), rotifers (Thane-Fenchel, 1968; Sørensen, 2001), and nematodes (Gheskiere et al., 2005). In Europe, freshwater zoopsammon has received more attention in Poland (e.g. Bielańska-Grajner, 2001; Ejsmont-Karabin, 2003; Nesteruk, 2007; Kalinowska, 2008, 2013; Bielańska-Grajner and Poznańska, 2010).

At the Estonian water bodies, the coastal zone was sampled already in the 19th century. In these studies, some beach invertebrates were recorded (Eichwald, 1849, 1852; Levander, 1894). However, it is not known where exactly the samples were taken (water or sediment, at waterline/beach or deeper water). First true reports on the interstitial fauna, i.e. zoopsammon, of sandy beach in Estonia date from the 1980s. In these sampling campaigns, Golemansky (1983) investigated psammic testate amoebae from the Estonian coast of the Gulf of Finland, and Kutikova and Haberman (1986) determined the taxonomic composition of rotifers from the arenal zone of Lake Võrtsjärv. Recently, some information has been provided about the taxonomic composition and density of zoopsammon communities, their temporal and spatial distribution, and relation with various environmental variables in some Estonian coastal beaches (Lokko et al., 2014) and in two lakes (Lokko et al., 2013; Lokko and Virro, 2014).

The aim of this study is to provide an overview and sum up the current knowledge on the taxonomic structure of zoopsammon in Estonian waters. This summarized information serves as a basis of the current status of psammic communities both in freshwater and marine habitats and potentially allows assessing the current status and conservation value of Estonian interstitial beach habitats.

MATERIALS AND METHODS

The present study is based on two previous studies (Lokko et al., 2013, 2014) and an additional sampling campaign carried out in 2011–2014. Samples were taken from three sandy beaches along the Estonian coast of the Gulf of Finland, Baltic Sea, and from four lakes across Estonia (Fig. 1). The coastal sampling sites were located at Keibu Bay near Nõva village (Nõva Beach, the westernmost sampling site), at Pirita Beach within Tallinn City, and at a popular beach of Narva Bay adjacent to a small town of Narva-Jõesuu (the easternmost site). The Gulf of Finland has a strong horizontal salinity gradient: the surface salinity varies from 0 in its eastern end to 7 ppt in the western areas (Pitkänen et al., 2008). Also nutrients input and trophic state increase from west to east, and the gulf is considered one of the most eutrophicated basins in the Baltic Sea area (HELCOM, 2003; Pitkänen et al., 2007).

The sampling sites from lakes were located at the eastern coast of Lake Võrtsjärv, at two beaches of Lake Saadjärv, at Lake Verevi, and at Lake Männiku. Võrtsjärv is the second largest lake in Estonia (surface area 27 000 ha). It is a shallow (max depth 6 m, average 2.8 m) eutrophic lake with a short water residence time (Timm, 1973; Tuvikene et al., 2004). Saadjärv is smaller (surface area 707.6–723.2 ha), but much deeper (max depth 25 m, average 8 m) (Mäemets, 1977; http://register.keskkonnainfo.ee/envreg/main?reg_kood=VEE2065300&mount=view, accessed 29.06.2014). Saadjärv has the lowest trophic status of the studied lakes. The mesotrophic Saadjärv is characterized by slow water exchange rates, high water transparency, high hardness, and alkaline water (Ott, 2007). The smallest of the studied lakes is Verevi, which is located in

Fig. 1. Study area and the location of the sampling stations. Blue dots represent sampled coastal beaches and red dots beaches of the studied lakes.

a small town of Elva and is very popular among swimmers. It is a hypertrophic and relatively deep (max 11 m, average 3.6 m, surface area 12.6 ha) lake with a low water exchange rate (Loopmann, 1984; Ott et al., 2005). The fourth of the studied lakes, Männiku, is located at the edge of Tallinn City. It is a moderately deep (max depth 9 m, average 5 m, surface area 118.7 ha) eutrophic lake of anthropogenic origin (Tamre, 2006; http://register.keskkonnainfo.ee/envreg/main#HTTPb8aODzH81I2Zv8PJCBXuHAhsXWViIR, accessed 29.06.2014) with steep slopes. It belongs to a complex of several lakes/water bodies within a sand quarry, which was established in the early 20th century. The main characteristics of the studied beaches, coordinates, and sampling times are presented in Table 1.

In each sampling site, samples of psammon were collected along transects across the waterline (up to 50 cm from the waterline in both directions). The samples were collected with sharp-edged corers with diameters of 2.9 and 4.75 cm down to a depth of 3–5 cm in the sand. The samples were transferred to a plastic container and rinsed three times with carbonated drinking water. After each rinse the supernatant was poured off into a plastic bottle and fixed with Lugol's solution. Then the samples were condensed to 100 mL by sedimentation for at least four days and siphoning off excess water. From each sample, five 2-mL subsamples were taken wherein all organisms were counted in a Bogorov chamber under a microscope. For the identification, specimens were slide-mounted in glycerol and determined to the lowest possible taxon. Illoricate rotifers were identified by their trophi, which were dissolved out using the household disinfectant Domestos®, which contains sodium hypochlorite ($NaClO < 5\%$). At each sampling time various environmental parameters such as sand grain size, vegetation coverage, sand organic content, pH, temperature, and salinity were estimated. The details of measuring and estimating environmental parameters are described in Lokko et al. (2013, 2014).

The nomenclature of higher taxonomic units is based on the classifications in Halanych (2004), the Catalogue of Life (Roskov et al., 2014), and the World Register of Marine Species (WoRMS Editorial Board, 2014), and those of rotifers on Melone et al. (1998) and Sørensen and Giribet (2006). The classification of protists is based on Mazei and Tsyganov (2006) and Cavalier-Smith (2010). The nomenclature of rotifer species follows Jersabek et al. (2012). For testaceans, Mazei and Tsyganov (2006) was used. In other cases, the Catalogue of Life (Roskov et al., 2014) was consulted.

The Sørensen index (Krebs, 1989) was used to evaluate similarity between zoopsammic communities of the sampling sites. In order to identify clusters of stations that are statistically dissimilar, a similarity profile (SIMPROF) test was used (Clarke et al., 2008) in the R environment and package clustsig (R Core Team, 2014; Whitaker and Christman, 2014).

Table 1. Sampling site coordinates, sampling time, and general environmental characteristics in the sampling sites. Variable mean (continuous variables) or most common value (categorical variables); minimum and maximum value or variable range is shown in brackets

	Võrtsjärv	Saadjärv	Verevi	Männiku	Nõva	Pirita	Narva-Jõesuu
Sampling site coordinates	58°13′45″N; 26°07′17″E	58°31′59″N; 26°38′46″E and 58°31′41″N; 26°41′45″E	58°13′44″N; 26°24′21″E	59°21′35″N, 24°42′59″E	59°13′45″N, 23°42′8″E	59°28′11″N, 24°49′38″E	59°27′8″N, 28°1′18″E
Sampling time	Mar–Nov 2008; May–Oct 2011, Apr 2012	Apr–Oct 2008; May–Oct 2011, Apr 2012	May–Oct 2011, Apr 2012	May 2014	May–Oct 2011, Apr 2012	May–Oct 2011, Apr 2012	May–Oct 2011, Apr 2012
Sand type	Fine (fine–coarse)	Medium (medium–coarse)	Medium (fine–medium)	Medium–coarse	Medium (medium–coarse)	Medium (fine–coarse)	Fine (fine–medium)
Vegetation cover	15% (0–50%)	11% (0–60%)	19% (2–40%)	0%	0% (0–12%)	0%	0% (0–100%)
pH (littoral/ interstitial)	7.73 (6.77–9.5)	7.84 (6.92–9.4)	7.48 (6.63–7.98)	7.99 littoral	8.19 (6.68–9.11) interstitial	7.86 (7.67–8.34) interstitial	8.18 (7.57–8.7) interstitial
Porewater conductivity, mS	0.579 (0.446–0.775)	0.626 (0.399–0.942)	0.629 (0.513–0.711)	NA	11.05 (9.09–12.43)	11.19 (7.19–12.80)	5.46 (0.72–9.09)
Porewater salinity, ppt	NA	NA	NA	NA	5.41 (4–6.2)	5.46 (3–6.6)	2.4 (0–4)
Sand temperature, °C	19.9 (8.7–30.2)	16.6 (5.1–28.3)	20.1 (7.7–32)	15.8	15.67 (6.2–23.2)	15.16 (6–22.6)	14.99 (5.2–23.6)
Sand organic content	1.06 (0.22–7.39)	0.72 (0.33–3.18)	0.85 (0.22–4.77)	NA	0.53 (0.07–4.09)	0.59 (0.06–2.87)	0.48 (0.04–2.43)

NA – not analysed.

RESULTS AND DISCUSSION

A total of 156 non-overlapping taxa belonging to 12 phyla were found in the Estonian psammon communities, 69 taxa occurring in the Gulf of Finland and 123 taxa in lakes (Table 2). In our preceding studies (Lokko et al., 2013, 2014), 46 new zoopsammon taxa for the Estonian fauna were registered, including 25 rotifers, 17 testate amoebae, 1 cercozoan, 1 clitellate, 1 tardigrade, and 1 harpacticoid. The present study further adds new records of 11 rotifer, 19 amoebozoan, and 6 nematode taxa for Estonia (Table 2). Of all the taxa found, 90 occurred only in lake beaches and 39 in beaches of the Baltic Sea. The number of taxa per sample was higher in lake beaches than in coastal areas. Areal taxonomic richness was related to sample taxonomic richness in coastal areas but not in the lake ecosystems (Fig. 2). The most common taxa were nematodes, rotifers, ciliates, testate amoebae, and harpacticoids. Individuals from these taxa were found from all studied beaches. No oligochaetes were found from the beach of Lake Verevi. The most taxon-rich season was summer, whereas diversity peaked later in lake (in August) than in coastal beaches (June or July).

Table 2. Zoopsammon taxa from beaches of lakes Võrtsjärv, Saadjärv (two sites), Verevi, and Männiku, and coastal beaches Nõva, Pirita, and Narva-Jõesuu. Summarized information from previous studies (Lokko et al., 2013, 2014) and recent supplementary material. Asterisked (*) taxa are new records for Estonia

Taxon	Võrtsjärv	Saadjärv	Verevi	Männiku	Nõva	Pirita	Narva-Jõesuu
Phylum Amoebozoa							
Class Lobosea							
Order Arcellinida							
Arcella sp.					x	x	
Arcella artocrea Leidy, 1876*			x				
Arcella catinus Penard, 1890*			x				
Arcella crenulata Deflandre, 1928*	x		x				
Arcella discoides Ehrenberg, 1843	x	x	x				
Arcella hemisphaerica Perty, 1852		x			x	x	
Centropyxis aerophila Deflandre, 1929	x	x	x		x		x
Centropyxis aculeata (Ehrenberg, 1838)	x	x	x	x			
Centropyxis cassis (Wallich, 1864)	x	x					
Centropyxis constricta (Ehrenberg, 1841)	x	x	x				
Centropyxis discoides Penard, 1902					x		

Continued overleaf

Table 2. *Continued*

Taxon	Võrtsjärv	Saadjärv	Verevi	Männiku	Nõva	Pirita	Narva-Jõesuu
Centropyxis delicatula Penard, 1902*	x	x	x				
Centropyxis ecornis (Ehrenberg, 1841)*	x		x				
Centropyxis hirsuta Deflandre, 1929*			x				
Centropyxis cf. *laevigata* Penard, 1890*			x				
Centropyxis orbicularis Deflandre, 1929*			x	x			
Centropyxis platystoma Penard, 1890	x	x					
Cyclopyxis spp.					x	x	x
Cyclopyxis arcelloides (Penard, 1902)	x	x					
Cyclopyxis eurystoma Deflandre, 1929*			x				
Cyclopyxis kahli (Deflandre, 1929)*	x		x				
Difflugia amphora (Leidy, 1874) Penard, 1902							x
Difflugia bidens Penard, 1902		x					
Difflugia brevicolla Cash et Hopkinson, 1909*		x					
Difflugia elegans Penard, 1890	x		x		x		
Difflugia globulosa (Dujardin, 1837) Penard, 1902*			x				
Difflugia gramen Penard, 1902	x	x					
Difflugia lacustris (Penard, 1899)					x	x	x
Difflugia lithophila (Penard, 1902) Gauthier-Lièvre et Thomas, 1958	x		x				
Difflugia lobostoma Leidy 1879	x		x				
Difflugia penardi Hopkinson, 1909	x	x	x		x		
Difflugia cf. *pulex* Penard, 1902*			x				
Difflugia urceolata Carter, 1864		x			x		x
Lesquereusia modesta Rhumbler, 1895*	x						
Netzelia tuberculata (Wallich, 1864)*	x		x				
Phryganella acropodia (Hertwig et Lesser, 1874) Hopkinson, 1909*			x		x		
cf. *Trigonopyxis* sp.*			x				
Zivkovicia cf. *spectabilis* (Penard, 1902)*					x		
Phylum Ciliophora							
Ciliophora indet.	x	x	x	x	x	x	x

Table 2. *Continued*

Taxon	Võrtsjärv	Saadjärv	Verevi	Männiku	Nõva	Pirita	Narva-Jõesuu
Phylum Cercozoa							
Class Imbricatea							
Cyphoderia ampulla (Ehrenberg, 1840) Leidy, 1879	x			x	x		x
Psammonobiotus communis Golemansky, 1967					x		
Phylum Foraminifera							
Class Monothalamea							
cf. *Allogromia* sp.*					x		
Phylum Platyhelminthes							
Class Rhabditophora							
Rhabditophora indet.	x	x		x	x	x	x
Phylum Gastrotricha							
Chaetonotidae gen. et spp. indet.		x			x	x	x
Chaetonotus sp.				x			
Phylum Rotifera							
Class Bdelloidea							
Bdelloidea gen. et spp. indet.	x	x	x		x	x	x
Philodina roseola Ehrenberg, 1832*			x				
Class Monogononta							
Cephalodella catellina (Müller, 1786)		x					
Cephalodella elegans Myers, 1924	x						
Cephalodella forficula (Ehrenberg, 1838)	x	x					
Cephalodella gibba (Ehrenberg, 1830)	x	x					
Cephalodella gracilis (Ehrenberg, 1830)		x					
Cephalodella intuta Myers, 1924	x	x					
Cephalodella labiosa Wulfert, 1940*		x					
Cephalodella limosa Wulfert, 1937		x					
Cephalodella megalocephala (Glascott, 1893)	x	x					
Cephalodella tenuiseta (Burn, 1890)	x	x					
Cephalodella spp.	x						x
Colurella adriatica Ehrenberg, 1831		x		x	x		

Continued overleaf

Table 2. *Continued*

Taxon	Võrtsjärv	Saadjärv	Verevi	Männiku	Nõva	Pirita	Narva-Jõesuu
Colurella colurus (Ehrenberg, 1830)	x	x			x	x	
Colurella dicentra (Gosse, 1887)	x				x		
Colurella geophila Donner, 1951					x		
Colurella hindenburgi Steinecke, 1916					x		x
Colurella marinovi Althaus, 1957					x		x
Dicranophorus capucinus Harring et Myers, 1928	x	x					
Dicranophorus hercules Wiszniewski, 1932	x	x					
Dicranophorus leptodon Wiszniewski, 1934*	x						
Dicranophorus semnus Harring et Myers, 1928*	x						
Dicranophorus sigmoides Wulfert, 1950		x					
Elosa spinifera Wiszniewski, 1932				x			
Elosa worrallii Lord, 1891*				x			
Encentrum belluinum Harring et Myers, 1928					x	x	x
Encentrum boreale Harring et Myers, 1928					x	x	x
Encentrum limicola Otto, 1936					x		
Encentrum marinum (Dujardin, 1841)					x	x	x
Encentrum matthesi Remane, 1949					x		x
Encentrum rousseleti (Lie-Pettersen, 1905)	x						
Encentrum uncinatum (Milne, 1886)	x						
Euchlanis dilatata Ehrenberg, 1832		x					
Gastropus stylifer Imhof, 1891		x		x			
Keratella cochlearis (Gosse, 1851)		x	x	x		x	x
Keratella cruciformis (Thompson, 1892)					x		
Keratella hiemalis Carlin, 1943	x	x					
Keratella quadrata (Müller, 1786)					x	x	
Lecane bulla (Gosse, 1851)		x					
Lecane closterocerca (Schmarda, 1859)	x	x	x	x			
Lecane doryssa Harring, 1914*			x				
Lecane flexilis (Gosse, 1886)	x	x	x				
Lecane galeata (Bryce, 1892)	x	x					
Lecane hamata (Stokes, 1896)		x	x				

Table 2. *Continued*

Taxon	Võrtsjärv	Saadjärv	Verevi	Männiku	Nõva	Pirita	Narva-Jõesuu
Lecane luna (Müller, 1776)		x	x		x		
Lecane nana (Murray, 1913)							x
Lecane perpusilla (Hauer, 1929)		x					
Lecane psammophila (Wiszniewski, 1932)	x	x					x
Lecane punctata (Murray, 1913)	x	x					
Lecane pusilla Harring, 1914			x		x		
Lecane scutata (Harring et Myers, 1926)*	x	x		x			
Lecane stenroosi (Meissner, 1908)			x				
Lecane subulata (Harring et Myers, 1926)		x		x			
Lepadella ovalis (Müller, 1786)	x	x					
Lepadella patella (Müller, 1773)	x	x	x	x			
Lindia torulosa Dujardin, 1841			x		x		x
Monommata sp.*			x				
Mytilina mucronata (Müller, 1773)		x					
Notholca squamula (Müller, 1786)	x	x			x		
Notommata cyrtopus Gosse, 1886		x					
Notommata cf. *doneta* Harring et Myers, 1924						x	
Notommata stitista Myers, 1937	x						
Pleurata vernalis (Wulfert, 1935)*				x			
Polyarthra dolichoptera Idelson, 1925	x						
Polyarthra luminosa Kutikova, 1962				x			
Polyarthra remata Skorikov, 1896				x			
Proales globulifera (Hauer, 1921)					x	x	x
Proales halophila Remane, 1929					x	x	x
Proales reinhardti (Ehrenberg, 1834)					x	x	x
Proales theodora (Gosse, 1887)					x	x	x
Proales spp.	x					x	
Proalinopsis caudatus (Collins, 1872)						x	x
Synchaeta cecilia Rousselet, 1902					x		x
Synchaeta tremula (Müller, 1786)							x
Trichocerca dixonnuttalli (Jennings, 1903)	x	x			x	x	x
Trichocerca intermedia (Stenroos, 1898)	x	x					
Trichocerca obtusidens (Olofsson, 1918)		x					
Trichocerca rousseleti (Voigt, 1902)		x					

Continued overleaf

Table 2. *Continued*

Taxon	Võrtsjärv	Saadjärv	Verevi	Männiku	Nõva	Pirita	Narva-Jõesuu
Trichocerca similis (Wierzejski, 1893)		x			x		x
Trichocerca tenuidens (Hauer, 1931)*		x					
Trichocerca tenuior (Gosse, 1886)	x	x			x		x
Trichotria pocillum (Müller, 1776)		x					
Trichotria truncata (Whitelegge, 1889)							x
Wierzejskiella sabulosa (Wiszniewski, 1932)	x						x
Wierzejskiella velox (Wiszniewski, 1932)	x	x					
Wigrella depressa Wiszniewski, 1932*	x	x					
Phylum Annelida							
Class Polychaeta							
Hediste diversicolor (Müller, 1776)					x		
Polychaeta juv.					x		x
Class Clitellata							
Clitellata indet.	x			x			
Chaetogaster diastrophus (Gruithuisen, 1828)		x					
Chaetogaster setosus (Svetlov, 1925)		x					
Chaetogaster sp.		x					
Lumbricillus lineatus (Müller, 1774)					x		
Marionina sp.					x	x	x
Nais elinguis Müller, 1774					x		x
Paranais litoralis (Müller, 1780)						x	
Tubificidae juv.		x					
Phylum Mollusca							
Class Bivalvia							
Bivalvia juv.		x					
Phylum Nematoda							
Nematoda indet.	x	x	x	x	x	x	x
Class Adenophorea							
Leptolaimidae indet.	x						
Prochromadora sp.*					x		
Microlaimus sp.					x		
Enoplida indet.		x					

Table 2. *Continued*

Taxon	Võrtsjärv	Saadjärv	Verevi	Männiku	Nõva	Pirita	Narva-Jõesuu
Enoplolaimus sp.*						x	
Amphimonhystera sp.*						x	
Linhystera sp.*					x	x	x
Retrotheristus sp.*					x		
Valvaelaimus sp.*					x		
Phylum Tardigrada							
Class Eutardigrada							
Milnesium sp.	x	x		x			
Class Heterotardigrada							
Oreella sp.					x		x
Phylum Arthropoda							
Subphylum Chelicerata							
Class Arachnida							
Arachnida indet.	x	x			x		
Subphylum Tetraconata							
Class Maxillopoda							
Harpacticoida gen. et spp. indet.	x	x		x	x	x	x
Harpacticus uniremis Krøyer, 1842		x			x		
Parastenocaris brevipes Kessler, 1913		x		x	x		
Mesocyclops leukarti (Claus, 1857)		x					
Cyclopidae juv.	x	x					
Nauplii indet.			x	x	x	x	x
Class Branchiopoda							
Alona sp.			x				
Chydorus sphaericus (Müller, 1776)	x	x					
Peracantha truncata (Müller, 1785)		x					
Class Ostracoda							
Ostracoda indet.		x	x	x		x	
Class Insecta							
Ephemeroptera indet.		x					
Diptera juv.	x	x	x		x	x	x
Number of taxa: 156	65	81	42	25	61	32	42

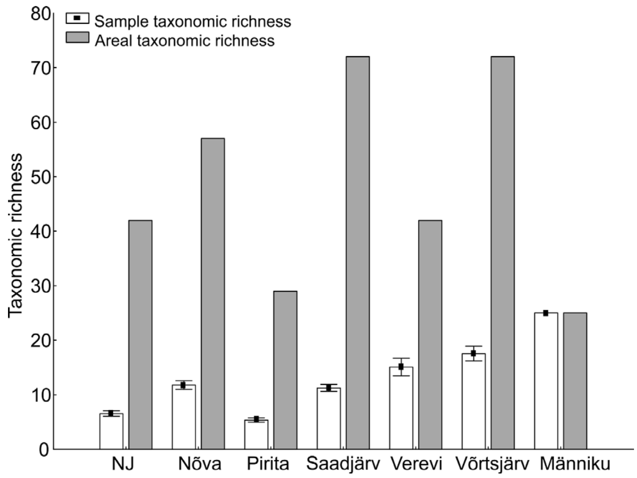

Fig. 2. Sample taxonomic richness (±SE) in the studied beaches in 2011–2012 and in Lake Männiku (represented by a single sample). NJ – Narva-Jõesuu.

Rotifers are one of the main groups of zoopsammon. As compared to other psammic taxa, rotifers have received much more attention (e.g. Bielańska-Grajner, 2001, 2005; Ejsmont-Karabin, 2001, 2003, 2005; Thane-Fenchel, 1968), at least in freshwater habitats. This gives a possibility of comparing communities among different water bodies and making assumptions about the ecological status and overall taxonomic richness of a water body. Rotifers are ideal for analysing relationships between habitat and community as this group of invertebrates are very diverse, giving often the highest number of species to local diversity, and cosmopolitan to a large extent (Pejler, 1995; Segers, 2008). In our material, the majority of rotifer species belong to the families Dicranophoridae (18% of the 84 identified species), Notommatidae (18%), and Lecanidae (18%). The most diverse genus was *Lecane* (15 species), followed by *Cephalodella* (10) and *Encentrum* (7). Domination of these families and genera is typical of psammic communities (Schmid-Araya, 1998). According to the present information on global distribution of rotifers (Segers, 2007; Jersabek and Leitner, 2013), of the rotifer species recorded in the psammon of the studied water bodies, 48 (58%) are cosmopolitan and other 22 (27%) have a wide distribution covering both Palaearctic and Nearctic, several of these are also known from some other biogeographic regions. Eleven (13%) species are restricted to Palaearctic. The occurrence of *Encentrum belluinum* in the samples from the Estonian coast of the Gulf of Finland and *Notommata stitista* in Lake Võrtsjärv is of interest. These two species are presently reported only from the Nearctic region. Probably *N. stitista* is a rare species, as it has not been found since its discovery (Nogrady et al., 1995). Our findings indicate a potential Holarctic distribution of these two species. *Cephalodella intuta*, *C. tenuiseta*, *Lecane doryssa*, *Notommata doneta*, and *Pleurata vernalis* are also regarded as rather rare (Nogrady et al., 1995; Segers, 1995). The presence of *L. doryssa* and *L. punctata* is noteworthy for their known cosmotropical–cosmosubtropical distribution (Segers, 1995). The range of these warm-stenotherms appears to be wide, reaching the temperate zone where they can find suitable conditions during summer months. A peculiar female specimen of *Monommata* sp. was encountered in a sample from Lake Verevi. The rotifer has toes of equal length like *Monommata aequalis* (Ehrenberg, 1830), but differs from it having a smaller body and uniformly wide blade-like toes, which to our knowledge are dissimilar from the previously described *Monommata* taxa. However, further study based on sufficient material is needed for a formal description of a possible new taxon.

Testate amoebae are another key component of psammon, although much less information is available about this highly diverse group. Unfortunately, we currently lack the taxonomic competence of free-living nematodes in Estonia. Therefore nematodes have received very little attention in freshwater psammon and it is not possible to make any interregional comparisons.

In the studied lakes the number of taxa decreased with increasing trophic state. The zoopsammon of the mesotrophic Lake Saadjärv had the highest taxonomic diversity among the studied beaches with a total of 81 taxa from 10 phyla. Altogether, 65 taxa were found from the eutrophic Lake Võrtsjärv. The zoopsammon of the hypertrophic Lake Verevi consisted only of 42 taxa. However, this pattern applied only to the overall number of taxa and the number of rotifer taxa. The number of testate amoebae species had a reversed pattern. Nevertheless, as the total number of samples varied from lake to lake, it may not reflect the true relationship between diversity and trophic state of the lake. Moreover, dominant ciliates, nematodes, and bdelloids were generally not identified to lower taxa, which may further bias the overall pattern of diversity. However, a similar relationship between the number of rotifer species and trophic state was found in a study carried out in Poland, where more rotifer species were found in lakes with a lower trophic status (Bielańska-Grajner, 2005). In another study in the same ecoregion the species richness was notably lower in hypertrophic lakes (Ejsmont-Karabin, 2003).

Taxonomic richness per sample was the highest in Lake Männiku, probably due to good environmental conditions for a large number of taxa at the time of sampling. Based on the sampling campaign carried out in 2011–2012, the highest average number of taxa per sample was recorded in Lake Võrtsjärv and lowest in Lake Saadjärv (Fig. 2). In 2008 the average number of taxa per sample in Lake Saadjärv was somewhat higher, yet lower than in the hypertrophic Lake Verevi in 2011–2012. While Saadjärv has a lower trophic status than the other studied lakes it is possible that the habitat can support a lower number of taxa in a small patch at a given time and the overall high number of taxa in the lake was provided by the high patchiness and complex seasonal dynamics.

In coastal areas the sample taxonomic richness was lower than in lake beaches. It followed the same pattern as sea-scape taxonomic richness, indicating that compared to lakes beach habitats in coastal areas were more homogeneous in space and time.

Our study also suggested a similar pattern between the trophic state and the number of psammic taxa in coastal beaches with the number of taxa decreasing with increasing anthropogenic impact. The lowest taxonomic richness (32 taxa, including 15 rotifer and 4 testate amoebae taxa) was recorded from Pirita Beach, which is located within Tallinn City adjacent to a yacht harbour and is a very popular beach. However, differently from lakes the number of testate amoebae taxa was likewise lower in coastal beaches with a higher anthropogenic impact.

Only 25 taxa were found from Lake Männiku. As this lake was represented by only one sample, the true biodiversity can be probably much higher. Moreover, the lake was sampled in May, which was not a season of high psammic taxonomic richness in any of the other studied lakes. Yet this sample represented the highest zoopsammon abundance recorded in Estonia (279 ind cm^{-3}) so far.

The overall zoopsammon abundance was generally much higher in lake beaches than in coastal beaches. The maximum psammic abundance reached 203 ind cm^{-3} in Lake Võrtsjärv and 92.3 ind cm^{-3} in Lake Saadjärv (Lokko et al., 2013), whereas for coastal beaches the respective value was only 46.6 ind cm^{-3}.

A total of 13 taxa of testate amoebae were recorded from the psammon of the Gulf of Finland in this study. Previously, Golemansky (1983) sampled beach sand from the Estonian coast of the Gulf of Finland and found 23 species of testate amoebae. Interestingly, the only overlapping taxa were *Cyphoderia ampulla*, *Psammonobiotus communis*, and *Cyclopyxis* sp. This is possibly caused by different sampling and analysing techniques and a wider habitat range (up to 16 m landwards from the waterline) compared to our study. Freshwater beaches had more testate amoebae species than coastal beaches. The testate amoebae community of Lake Verevi with 23 testate amoebae taxa seemed to have an especially high taxonomic richness.

The psammic rotifer community of the Gulf of Finland was represented by 35 taxa. This is similar to the numbers recorded from interstitial habitats in Scandinavia where Thane-Fenchel (1968) found 28 interstitial rotifer species from Askö Harbor. In Nõva Beach with similar salinities we recorded 26 rotifer taxa. The number of rotifer species found in the psammon from lakes Võrtsjärv and Saadjärv resembles the numbers previously recorded from some Polish lakes with a similar trophic level; moreover, quite a few species overlapped in the two countries (Radwan and Bielańska-Grajner, 2001; Ejsmont-Karabin, 2005).

The coefficients of Sørensen similarity between the studied areas are presented in Table 3. Lake Männiku was not included in comparisons as it was represented by only one sample. According to the Sørensen similarity coefficient, the zoopsammon communities of coastal sampling sites were much more similar with one another than zoopsammon at different lakes, and rotifer communities differed much more from beach to beach than testate amoebae communities. SIMPROF analysis showed that all sampling sites had significantly different psammic communities. Nevertheless, the coastal sampling sites clustered together, showing that their communities were more similar to each other than those of lakes (Figs 3 and 4).

Table 3. Sørensen similarity coefficient between the studied areas

	All taxa	Only rotifer taxa	Only testate amoebae taxa
Võrtsjärv vs Saadjärv	0.566	0.590	0.606
Võrtsjärv vs Verevi	0.374	0.170	0.619
Saadjärv vs Verevi	0.279	0.246	0.324
Võrtsjärv vs Nõva	0.238	0.200	0.194
Võrtsjärv vs Pirita	0.186	0.163	0.000
Võrtsjärv vs Narva-Jõesuu	0.243	0.207	0.083
Saadjärv vs Nõva	0.298	0.229	0.308
Saadjärv vs Pirita	0.214	0.136	0.111
Saadjärv vs Narva-Jõesuu	0.230	0.176	0.211
Verevi vs Nõva	0.233	0.205	0.229
Verevi vs Pirita	0.189	0.143	0.000
Verevi vs Narva-Jõesuu	0.190	0.162	0.071
Nõva vs Pirita	0.516	0.537	0.500
Nõva vs Narva-Jõesuu	0.641	0.640	0.471
Pirita vs Narva-Jõesuu	0.595	0.564	0.444

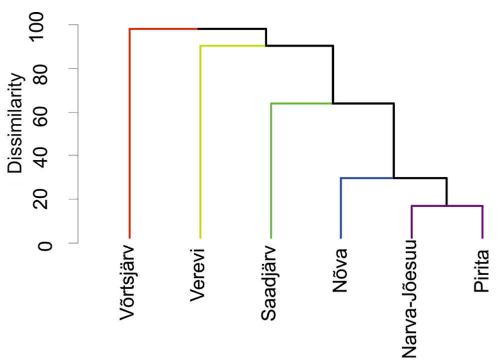

Fig. 3. A dendrogram of the Similarity Profile Analysis based on the total average number of species showing statistical differences among sites in terms of psammic communities. Different colours denote statistically different clusters. NJ – Narva-Jõesuu.

Although this study compiled different data sets with different spatial and temporal extent, we were able to discover some generic psammic patterns in the Estonian fresh- and brackish-water bodies. In general, the abundance and richness of psammic taxa were higher in lake than in coastal beaches. Besides, variability between samples of psammon communities was higher in lake than in coastal beaches. Psammon taxonomic richness was higher in beaches with a lower trophic state and/or anthropogenic impact. However, such relationship appeared only at a wide spatial scale pooling a large number of samples. The sample taxonomic richness followed regional taxonomic richness only in coastal areas. This also suggests that the communities of psammon vary more in space and time in lake beaches than in coastal beaches.

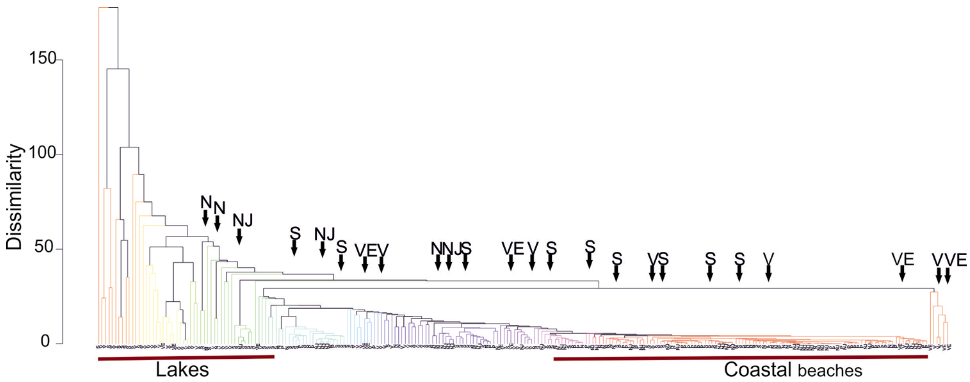

Fig. 4. A dendrogram of the Similarity Profile Analysis showing statistical differences among samples in terms of psammic communities. Different colours denote statistically different clusters. Areas marked with a red line and the text ‘Lakes’ or ‘Coastal beaches’ denote areas in the dendrogram dominated by samples from lake beaches or from coastal beaches, respectively. Coastal beaches: N – Nõva Beach, NJ – Narva-Jõesuu Beach, P – Pirita Beach; lake beaches: V – Võrtsjärv, VE – Verevi, S – Saadjärv.

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