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1 **A phylogenetic framework to investigate the microsporidian communities through**
2 **metabarcoding and its application to lake ecosystems**

3

4 ***Running title: Microsporidian diversity in freshwater lakes***

5

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13

14 **ORIGINALITY-SIGNIFICANCE STATEMENT**

15 We introduce here a methodology which enables the study of environmental Microsporidia diversity (a
16 phylogenetically diverse phylum of unicellular parasites), through metabarcoding.

17 We provide a comprehensive reference database which positions microsporidian SSU rRNA gene
18 sequences within a coherent ranked phylogenetic framework. Using the developed methodology on
19 lacustrine samples, we highlighted a considerable diversity, with many unknown genera and families.

20

21 **SUMMARY**

22 Microsporidia are obligate intracellular eukaryotic parasites known to parasitize many species of the
23 animal kingdom as well as some protists. However, their diversity is underestimated, in part as a
24 consequence of the failure of “universal” primers to detect them in metabarcoding studies. Besides, due
25 to the inconsistency between taxonomy and phylogenetic data, available databases may assign
26 incorrectly sequences obtained with high-throughput sequencing. In this work, we developed a
27 comprehensive reference database which positions microsporidian SSU rRNA gene sequences within a
28 coherent ranked phylogenetic framework. We used this phylogenetic framework to study the
29 microsporidian diversity in lacustrine ecosystems, focusing on < 150 µm planktonic size fractions. Our
30 analysis shows a high diversity of Microsporidia, with the identification of 1531 OTUs distributed
31 within 7 clades, of which 76% were affiliated to clade IV2 and 20% to clade I (nomenclature presented
32 hereby). About a quarter of the obtained sequences shared less than 85% identity to the closest known
33 species, which might represent undescribed genera or families infecting small hosts. Variations in the
34 abundance of Microsporidia were recorded between the two lakes sampled and across the sampling
35 period, which might be explained by spatio-temporal variations of their potential hosts such as
36 microeukaryotes and metazooplankton.

37 INTRODUCTION

38 For long underestimated, the diversity of parasites and their central role in the functioning of ecosystems
39 are nowadays recognized (Lafferty et al., 2006; Dobson et al., 2008; Lafferty et al., 2008). For example,
40 it is estimated that about 40% of species, all ecosystems combined, are parasites (Dobson et al., 2008)
41 and that more than 75% of the trophic links include parasites (Lafferty et al., 2006). However, these
42 parasites only represent 5% of the described species (Costello, 2016) and further studies are needed to
43 reveal the extent of their diversity and to clarify their role in ecosystems. The advent of molecular
44 approaches, in particular metabarcoding, has revealed a considerable diversity of microeukaryotes (<200
45 µm) in different types of ecosystems, including parasite groups which can represent up to 50% of the
46 total diversity (Cleary and Durbin, 2016; Lepère et al., 2016; Mahé et al., 2017). In lacustrine ecosystems
47 these studies highlighted the presence of several group of putative parasites, such as chytrids (Fungi),
48 Apicomplexa and Perkinsea (Alveolates) (Debroas et al., 2017). Some groups of parasites, however, are
49 largely absent from these studies (see Bass et al., 2015 for review). This is the case of Microsporidia,
50 which are obligate unicellular intracellular parasites related to Fungi (Vavra and Lukes, 2013). Because
51 of their rapid evolution and significant reduction of their genomes (Keeling and Fast, 2002), they are
52 genetically divergent from other eukaryotes, making the primers conventionally targeting the conserved
53 regions of the rRNA 18S gene ineffective (Marande et al., 2009; Hadziavdic et al., 2014; Hugerth et al.,
54 2014). Some studies attempted to characterize the diversity of this phylum using Microsporidia-specific
55 primers, mainly in particular hosts such as daphnids, amphipods or mosquitoes (Weigl et al., 2012;
56 Quiles et al., 2019; Trzebny et al., 2020) but more rarely in environmental samples (Ardila-Garcia et al.,
57 2013; Williams et al., 2018).

58 Based on ultrastructural, ecological (*e.g.* host species, habitat, transmission route) and tissue tropism
59 criteria, more than 1300 Microsporidia species have been described so far (Vossbrinck et al., 2014),
60 most infecting one or several closely related hosts. This may nevertheless represent only a minor fraction
61 of their real diversity, as the number of microsporidian species is estimated to approach the number of
62 all animal species (Keeling and Fast, 2002; Larsen et al., 2017). Microsporidia are found in all
63 ecosystems, and particularly in aquatic ecosystems which harbour about 50% of the described genera
64 (Stentiford et al., 2013a). Vertebrates, crustaceans and insects alone account for nearly 80% of known

65 microsporidian hosts (Stentiford et al., 2013a; Weiss and Becnel, 2014; Stentiford et al., 2016). Such
66 proportion however is likely due to biases towards the search of infectious agents in hosts of sanitary
67 (human, disease vector insects such as mosquitoes), veterinarian (domestic and farm animals),
68 agronomic (auxiliary insects and pests) or ecological importance (daphnids, amphipods). As a result,
69 the global diversity of Microsporidia is largely unknown, particularly in small sized hosts, such as
70 protists which represent only 10 of the 7366 microsporidian SSU sequences listed in the databases
71 (NCBI consultation 18/11/2020 with the key words ‘small subunit ribosomal’+ microsporidia).

72 In this work we used a targeted metabarcoding approach to specifically study the microsporidian
73 diversity in lake ecosystems, focusing on planktonic fractions containing small sized hosts. High-
74 throughput sequencing classically produces thousands of sequences, which need to be assigned
75 taxonomically in order to perform comparisons between samples. Such assignments are based on
76 databases that link sequences to taxonomy. We first checked the consistency between available
77 databases and phylogenetic data, and found that they are either weakly detailed or contain several errors.
78 We thus built a comprehensive reference database which positions microsporidian SSU rRNA gene
79 sequences within a coherent ranked phylogenetic framework covering the microsporidian diversity.
80 Moreover, we addressed the question of OTU (Operational Taxonomic Unit) definition in
81 Microsporidia. Indeed, sequences of taxonomic marker genes with high similarity scores are classically
82 clustered into OTUs, themselves considered as proxies for species. We therefore determined the
83 clustering threshold that maximizes the recovery of distinct species and/or genera for microsporidian
84 SSU sequences. Using this framework, we highlighted a considerable uncovered microsporidian
85 diversity in our samples, and evidenced spatio-temporal variations in the abundance of many
86 Microsporidia species.

87

88

89 MATERIALS AND METHODS

90 *Microsporidia database*

91 An exhaustive search of all Microsporidia species for which a SSU sequence is available was conducted
92 (last update: march 2020), using hundreds of publications and the NCBI database (nucleotides and WGS
93 sequences). We focused on the canonical Microsporidia, characterized by a specific invasion apparatus
94 known as the polar tube, an extreme genome compaction, a lack of true mitochondria, and a rRNA
95 operon of prokaryote-like size and structure (Wadi and Reinke, 2020). We also included sequences from
96 Chytridiopsida and Metchnikovellida, considered as unusual Microsporidia as they lack some of the
97 typical features of Microsporidia (Mikhailov et al., 2016; Corsaro et al., 2019). When several sequences
98 were found for a species, we kept the longest or the most consensual one. We found 337 microsporidian
99 species with a SSU sequence. We then selected the species for which the full length of the SSU rRNA
100 gene was available (at least 90% of the V1-V9 region, 265 sequences, Supplementary Information 1).
101 Their taxonomic assignments were searched in public databases (NCBI, SILVA, PR², PHYMYCO-DB)
102 and compared with several microsporidian phylogenies (Vossbrinck and Debrunner-Vossbrinck, 2005;
103 Smith, 2009; Vossbrinck et al., 2014; Corsaro et al., 2019) and a recent taxonomic review
104 (Wijayawardene et al., 2018).

105 As none of the public databases was satisfying (see results), we built an extensive phylogeny of
106 Microsporidia, based on their full-length SSU gene sequences. These sequences, as well as 6 outgroup
107 sequences (from *Rozella allomycis*, *Paramicrosporidium* sp., *Nucleophaga* sp. and *Mitosporidium*
108 *daphnia*), were aligned using the online version of MAFFT (ver. 7; Computational Biology Research
109 Consortium [<http://mafft.cbrc.jp/alignment/server/index.html>]; Katoh et al., 2005) with the E-INS-i
110 multiple alignment method, leaving gappy regions, a gap opening penalty of 1.0 and gap extension
111 penalty extension of 0.0. The alignment was checked using MEGA 7 (Kumar et al., 2016) and both ends
112 were trimmed. The resultant alignment was analysed by Maximum Likelihood (ML) and Neighbor
113 joining (NJ) using MEGA 7.0 (Kumar et al., 2016). A General Time-Reversible (GTR) model of
114 evolution with gamma-distributed rate heterogeneity (G) and a proportion of invariable sites (I) (GTR

115 + G + I) was used to create the ML tree, with 500 bootstrap replications and partial deletion (85%). The
116 NJ tree was obtained using the Kimura-2-parameter model with a gamma distribution of 4, partial
117 deletion (85%) and 1000 bootstraps. Metadata (habitat and hosts) were reported on the ML tree using
118 iTOL (Letunic and Bork, 2016). Similar phylogenetic analyses were done using the region of the SSU
119 gene which was chose for the metabarcoding analysis described below (V1-V3, corresponding to the
120 first three variables regions of the SSU gene). These trees were used to define three phylogenetic ranks
121 inside the Microsporidia phylum: clade, group and genus. This classification (see results and discussion
122 section) was subsequently used to assign the Operational Taxonomic Units (OTUs) obtained from
123 environmental samples.

124

125 ***OTU definition***

126 We tested different clustering thresholds on selected SSU sequences (species with a clear genus
127 affiliation, and for which the full length of the SSU gene was available, 255 sequences) in order to
128 determine which one could maximize the recovery of distinct genera and species. Full-length and V1-
129 V3 sequences were aligned with the Needleman-alignment algorithm and a distance matrix was obtained
130 with the pairwise.seqs command in Mothur (Schloss et al., 2009). Then, the average neighbor algorithm
131 was used with clustering thresholds ranging from 100% (unique sequences) to 90% in steps of 1%. The
132 number of obtained OTUs was then compared to the number of species (255) and genera (104) in the
133 dataset (% recovery).

134

135 ***Study sites and sampling procedure***

136 The study was conducted in two lakes (Massif Central, France). Lake Pavin (45°55' N and 2°54' E) is an
137 oligo-mesotrophic lake with an area of 0.44 km² and a maximum depth of 92 m, at an altitude of 1197
138 m above sea level. It is a meromictic lake characterized by the presence of two permanent stratified
139 layers. Lake Aydat (45°39' 50" N, 2° 59' 04" E) is a dimictic and eutrophic lake with a maximum depth

140 of 15 m, situated at an altitude of 825 m. In April, May and June 2016, water samples were collected in
141 the euphotic zone of both lakes at a permanent station located at the deepest zone of the water column.
142 6-10 L of water were filtered successively through 150 μm , 50 μm , and 10 μm pore-size filters in order
143 to concentrate Microsporidia spores (<10 μm fraction) and planktonic species susceptible to host
144 Microsporidia (10-50 and 50-150 μm fractions). The microbial biomass of each size-fraction was
145 collected on 0.8 μm pore-size (pressure, <10 kPa) polycarbonate filters (Millipore, Molsheim, France)
146 and stored at -80°C until further analysis.

147

148 ***Nucleic acids extraction, amplification and sequencing***

149 Filters were covered with the extraction buffer (50 mM glucose, 10 mM EDTA, 25 mM Tris). 0.1g of
150 0.1 mm glass beads were added and samples were homogenized in a bead beater (3 pulses for 30s at 30
151 Hz). Tubes were then centrifuged during 1 min at 600 g. EDTA pH8 and a lysozyme solution (final
152 concentrations 0.1 M and 1.5 mg.ml⁻¹ respectively) were added to the supernatant and incubated at 37°C
153 for 30 min. Then sodium dodecyl sulfate (1.8%, final), proteinase K (100 $\mu\text{g.ml}^{-1}$, final) and RNaseA
154 (50 $\mu\text{g.ml}^{-1}$, final) were added, and samples were incubated at 37°C for at least 60 min. A
155 cetyltrimethylammonium bromide (CTAB) solution (final concentration 1% in a 0.7 M NaCl solution)
156 was added, and samples were incubated at 65°C for 10 min. Nucleic acids were extracted with phenol-
157 chloroform-isoamyl alcohol (25:24:1); the aqueous phase containing nucleic acids was kept and purified
158 by adding chloroform-isoamyl alcohol (24:1). After isopropanol (0.6 vol) addition, the nucleic acids
159 were precipitated at -20°C for 12 h. After centrifugation, the DNA pellet was ethanol rinsed and
160 resuspended in 20 μL of water.

161 Amplification of the V1-V3 region of the Microsporidia small subunit rDNA was performed using the
162 universal microsporidian V1F (CACCAGGTTGATTCTGCCTGAC) and 530R
163 (CCGCGGCTGCTGGCAC) primers set (Baker et al., 1994; Weiss et al., 1994) modified by adding
164 barcodes. Each PCR was performed in a total volume of 30 μL containing 3 μL of 10 \times NH₄ reaction
165 buffer, 1.2 μL of 50 mM MgCl₂, 0.15 μL of EurobioTaqII (Eurobio, Les Ulis, France, 5 U/ μL), 0.6 μL

166 of 10 mM each dNTP, 0.3 μ L of 50 mg/mL BSA and 1.2 μ L of each 5 μ M primer. The amplification
167 conditions consisted of initial denaturation at 94 $^{\circ}$ C for 5 min followed by 35 cycles for 1 min at 94 $^{\circ}$ C,
168 1 min 10 s at 61 $^{\circ}$ C and 1min at 72 $^{\circ}$ C, and a final elongation of 7 min at 72 $^{\circ}$ C.

169 The PCR products were run on a 1.2 % agarose gel electrophoresis. The amplicons were purified and
170 concentrated using the MinElute gel extraction kit (Qiagen®, Courtaboeuf, France), and quantified
171 using the Agilent 2200 TapeStation system and the D1000 ScreenTape kit (Agilent Technologies, Les
172 Ulis, France). Finally, the purified amplicons for each sample were pooled at equimolar concentrations
173 and sent to GATC Biotech (Konstanz, Germany) for library preparation and paired-end (2x300 bp)
174 sequencing on a MiSeq Illumina instrument (San Diego, CA).

175

176 ***Amplicons analysis & phylogenetic affiliation***

177 The MiSEQ data were assembled with the VSEARCH tool (Rognes et al., 2016). These sequences were
178 then subjected to four cleaning procedures: (i) no undefined bases (Ns), (ii) a minimum sequence length
179 of 300 bp, (iii) no sequencing error in the forward and reverse primers and (iv) no chimeras (Edgar et
180 al., 2011). After this cleaning step and demultiplexing process, the remaining DNA sequences were
181 clustered at 99%. The representative OTUs were then affiliated by similarity and phylogeny using a
182 custom curated reference database (Freshwater-database: [https://github.com/panammeb/Freshwater-](https://github.com/panammeb/Freshwater-database)
183 [database](https://github.com/panammeb/Freshwater-database)). This database contains eukaryote references extracted from the SSURef SILVA database
184 (Pruesse et al., 2007), typical freshwater lineages identified in previous studies (e.g. Debroas et al.,
185 2015), and 528 sequences from the 265 microsporidian species (107 genera) we analysed in the
186 microsporidian phylogenetic tree (full length SSU sequences). After a comparison of the OTUs with the
187 Freshwater-database by a similarity approach (VSEARCH tool), trees of OTUs with their closest
188 reference sequences were built in FastTree (Price et al., 2010) (see the detailed pipeline in Debroas et
189 al., 2017). Taxonomic assignment was conducted according to two methods: nearest neighbour (NN)
190 and last common ancestor (LCA) affiliations. This process was implemented in the pipeline PANAM
191 (Phylogenetic Analysis of Next-generation Amplicons; <https://github.com/panammeb/>) and is described

192 in more detail in Taib et al., 2013. Affiliations to groups and genera were considered as valid when
193 identity scores were $\geq 85\%$ and $\geq 94.5\%$, respectively (empirical thresholds based on comparisons
194 between affiliations and phylogenetic analyses, not shown).

195 Since the clustering threshold we used (99%) may generate OTUs resulting from sequencing errors, we
196 only kept for the final analysis OTUs representing more than 0.05% of the total reads in at least one
197 sample. Two samples were removed from the analysis since they contained less than 20 000 reads. Data
198 were finally normalized using rarefaction with the phyloseq package on R (R Development Core Team,
199 2011; McMurdie and Holmes, 2013).

200

201 *Diversity indices*

202 Community richness and diversity indices (Richness observed, Chao1, Shannon and Simpson) were
203 calculated using vegan package on R (R Development Core Team, 2011; Oksanen et al., 2017). Non-
204 metric multidimensional scaling (NMDS) ordinations, based on a Bray-Curtis dissimilarity matrix (Bray
205 and Curtis, 1957; Paliy and Shankar, 2016), were performed to depict the difference in Microsporidia
206 community compositions among the samples using the R vegan package (R Development Core Team,
207 2011; Oksanen et al., 2017).

208

209 *Phylogenetic analysis of OTUs*

210 All OTUs obtained in this analysis were assigned at least to a clade, but 24% of them were not assigned
211 to a group. We therefore performed phylogenetic analyses (for each clade) on OTUs not assigned to a
212 group in order to determine whether new groups could be highlighted. Besides, only 48% of the OTUs
213 were assigned to a genus. We checked the accuracy of affiliations to genera and highlighted potential
214 new genera through phylogenetic analyses in each identified group. We focused our analyses on
215 abundant OTUs ($>1\%$ of reads in at least one sample, 95 OTUs), as they represent between 53 and 92%
216 of the total reads in each sample. We included in these analyses several sequences from undescribed

217 microsporidian species (found through BLAST search and/or bibliographic review), in addition to
218 species from our database. After alignment using the MAFFT algorithm (Katoh et al., 2005), ML trees
219 were obtained using a General Time-Reversible (GTR) model of evolution with gamma-distributed rate
220 heterogeneity (G) and a proportion of invariable sites (I) (GTR + G + I), with 200 bootstrap replications
221 and partial deletion (85%), using MEGA 7 (Kumar et al., 2016). Relative abundances were plotted on
222 these trees using iTOL (Letunic and Bork, 2016).

223

224 **RESULTS AND DISCUSSION**

225 *OTU definition for Microsporidia*

226 Metabarcoding analyses usually produce thousands of sequences, which are then clustered into OTUs
227 to produce ‘species equivalents’ (Eren et al., 2011; Alberdi et al., 2018). For eukaryotic SSU sequences,
228 a similarity threshold of 95% (Caron et al., 2009; Debroas et al., 2015) or alternatively 97% (Cleary and
229 Durbin, 2016; Bista et al., 2017) is usually employed. However, an incorrect clustering threshold could
230 cause oversplitting or undersplitting of sequences into species equivalents, resulting in either inflated or
231 underestimated species counts (Alberdi et al., 2018). We therefore addressed this issue by applying
232 different clustering thresholds on the full-length and V1-V3 sequences of the Microsporidia species we
233 selected. Such analysis indicated that an important proportion of microsporidian species has highly
234 similar SSU sequences (about 13% of species clustered together with a 99% clustering threshold) or
235 even identical sequences (0.4% (full-length) and 2.7% (V1-V3) of species clustered together with a
236 100% clustering threshold) (Supplementary Information 2). None of the clustering thresholds may in
237 this way generate OTUs that could be identified with high accuracy at the species level, thus highlighting
238 the limits of this gene marker for species discrimination. Besides, thresholds for species delineation may
239 vary according to the lineages, since some species belonging to the same genera have sometimes less
240 than 90% identity (Zheng et al 2016), while some share more than of 99.5% identity in other genera
241 (Tokarev et al., 2020). For the later genera, combination of different molecular markers is then
242 sometimes required to improve phylogenetic resolution (Bacela-Spychalska et al 2018; Tokarev et al

243 2020). As 100% of genera could nevertheless be distinguished using a 99% threshold on V1-V3
244 sequences, we chose to keep this threshold and only consider affiliations to genera as valid in further
245 analyses.

246

247 ***Available databases are not reliable for microsporidian classification***

248 OTUs assignment to phylogenetic clades requires the use of a reliable reference database, in which
249 species are classified into several taxonomic ranks. As assignment lies on the comparison between OTUs
250 and reference sequences, the efficiency of OTU classification depends on the degree to which taxonomic
251 classification of reference sequences fits their evolutionary relationships. However, it is largely
252 recognized that taxonomic designation of Microsporidia, based primarily on morphological characters,
253 is inconsistent with phylogenetic analyses (Vossbrinck and Debrunner-Vossbrinck, 2005; Stentiford et
254 al., 2013b; Tokarev et al., 2020). We thus primarily checked whether taxonomic information contained
255 in various public databases was consistent with microsporidian phylogenetic data, focusing on the
256 species for which the full length of the SSU gene was available (265 sequences). We found that
257 taxonomic data found in GenBank (Federhen, 2012) are largely in disagreement with the phylogenetic
258 clusters identified in the literature (Vossbrinck and Debrunner-Vossbrinck, 2005; Smith, 2009;
259 Vossbrinck et al., 2014; Corsaro et al., 2019; Supplementary Information 1). In SILVA (Quast et al.,
260 2013), many of these microsporidian species are lacking (12%, Supplementary Information 1) or when
261 present, often assigned incorrectly to phyla which are not Microsporidia (21%, Supplementary
262 Information 1). Besides, SILVA, as well as PR² (a database dedicated to protists; Guillou et al., 2013),
263 do not include any taxonomic rank between phyla and genera (see Supplementary Information 1).
264 PHYMYCO-DB (Mahé et al., 2012), a database dedicated to Fungi, does not contain microsporidian
265 sequences. The existing databases being inappropriate, another one based on the phylogeny rather than
266 on morphological characters, was thus required. Although the microsporidian taxonomy should
267 probably be revised (as discussed in Vossbrinck and Debrunner-Vossbrinck, 2005 and Stentiford et al.,

268 2013b), our objective was simply here to provide a practical classification of microsporidian species
269 which could be used to analyse metabarcoding data.

270

271 *Extensive phylogeny of Microsporidia*

272 We built a phylogenetic tree which is twice more exhaustive than the previously published reference
273 trees (Vossbrinck and Debrunner-Vossbrinck, 2005; Vossbrinck et al., 2014). NJ and ML phylogenetic
274 trees obtained on the full-length sequences placed canonical Microsporidia in a monophyletic group,
275 with Metchnikovellids and Chytridiopsidae at the basal position of the microsporidian phylogenetic tree
276 (Figure 1). A total of 10 clades were identified (9 for canonical Microsporidia numbered with Latin
277 names, and one for Metchnikovellidae), all being supported by high bootstrap values (>85%).

278 Former reference trees identified five major clades in canonical Microsporidia (Vossbrinck and
279 Debrunner-Vossbrinck, 2005; Vossbrinck et al., 2014). It should however be noted that clade numbering
280 between these two reference publications differs, as “clade 5” in Vossbrinck et al., 2014 corresponds to
281 “clade III” in Vossbrinck and Debrunner-Vossbrinck, 2005, and vice-versa. As a result, clade numbering
282 for Microsporidia is currently confusing, since some publications follow the former and others the later
283 (including in recent publications, see Zhang et al., 2016 or Quiles et al., 2019 for example). We chose
284 here to keep the oldest clade numbering, as in proportion more publications refer to it.

285 Among the ten clades we highlighted, four of them (clades I, III, IV and V) were largely in agreement
286 with the ones formerly described (Vossbrinck and Debrunner-Vossbrinck, 2005; Smith 2009;
287 Vossbrinck et al., 2014; Corsaro et al., 2019, see comparison in Supplementary Information 4). The
288 biggest clade (clade IV, thus considered as a “super-clade”, 86 species) was here subdivided into 2
289 clades (IV1 and IV2). Such division was supported by high bootstrap values, a clear genetic divergence,
290 and literature data (Vossbrinck and Debrunner-Vossbrinck, 2005; Vossbrinck et al., 2014; Trzebný et
291 al., 2020). However, we found only a weak overlap for the clade II, which species composition already
292 differed markedly between the former reference phylogenies (Supplementary Information 4). As we
293 included several new species in the current phylogenies, it appears that former clade II could be split

294 into three different clades (here II, VIII and IX). Eventually, we introduce two distinct novel clades (VI
295 and VII), containing species which were either unclassified (Vossbrinck and Debrunner-Vossbrinck,
296 2005; Smith, 2009) or included in clade 5 (Vossbrinck et al., 2014) probably due to long branch
297 attraction.

298 Within these clades, we furthermore identified 22 ‘groups’ of species, also supported by high bootstrap
299 values ($\geq 95\%$) and previous phylogenetic studies (Figure 1). We named these groups according to the
300 names given in these studies when available, or according to a representative genus (i.e. *genera name –*
301 *like* group) for the others. Again, a strong discrepancy between these phylogenetic data and taxonomy
302 provided in NCBI was found (Supplementary Information 5). However, our data were mostly in
303 agreement with the microsporidian taxonomy, since most of the phylogenetic ‘groups’ we identified
304 corresponded to families reviewed in Wijayawardene et al., 2018 (Supplementary Information 6). Other
305 groups included species classified in various families (such as the ‘Aquatic group’ (Vossbrinck et al.,
306 2004), which contains representatives of the Caudosporidae, Gurleyidae and Agglomeratidae families
307 (Wijayawardene et al., 2018)), or species not assigned yet to any family (such as representatives of the
308 Orthosomella-like or Nematocida-like groups). All these groups were recovered in the phylogeny based
309 on the V1-V3 region, highlighting the relevance of this region (Supplementary Information 7).

310 Some trends in terms of habitats and to a lesser extent of hosts are characterizing these clades or groups
311 (Figure 1). Clades I, VI, VII, VIII, as well as Neopereziiidae (clade V) mostly contain species infecting
312 freshwater hosts, such as Crustacea, aquatic Diptera or Bryozoa, while clades II, IV1, IX and
313 Tubulinosematidoidea (clade V) contain mostly species infecting terrestrial hosts. Clade III contain
314 aquatic (freshwater and marine) species. One group within clade IV2 however, contains microsporidian
315 species infecting very different hosts (ciliates, insects, crustacean, human) found in diverse habitats
316 (terrestrial, freshwater, brackish). We named this group ‘Arlequin group’ to reflect this variability.
317 Clades and groups highlighted by this phylogenetic analysis and literature review were thereafter used
318 to classify OTUs in our metabarcoding analysis. Sequences included in the phylogeny, as well as other
319 full-length SSU sequences of the same species (total of 528 sequences), were included in a database
320 used to study eukaryotic communities in freshwater environments (Debroas et al., 2017).

321

322 *Application of the proposed methodology to study the lacustrine microsporidian diversity*

323 So far, only two studies attempted to characterize the diversity of Microsporidia in environmental
324 samples, focusing mostly on terrestrial and marine habitats (Ardila-Garcia et al., 2013; Williams et al.,
325 2018). Both studies highlighted new diversity across all areas of the microsporidian tree. However, due
326 to the low number of sequences obtained in these studies (25 and 745 respectively, with a maximum of
327 20 OTUs per sample), comparisons of microsporidian communities between habitats were either not
328 done or could only uncover a general variability between samples. In this study, we use our expertise
329 database combined with the use of specific primers to characterize the diversity of Microsporidia in two
330 lake ecosystems (planktonic samples) as well as its spatio-temporal variations through metabarcoding.

331

332 *Diversity*

333 After quality filtering and clustering at 99%, 1 135 287 reads were obtained, and 91% of them were
334 assigned to Microsporidia. After removal of the two samples which contained < 20 000 reads (Pavin,
335 April, fraction 50-150 µm and Pavin, June, fraction 10-50µm) and normalisation, 323 904 reads were
336 assigned to the microsporidian classification we defined above. This analysis revealed a considerable
337 diversity, since 1531 OTUs were obtained in total. However, the Microsporidia community was
338 dominated by few highly abundant OTUs, since 95 “abundant” OTUs (>1% in at least one sample)
339 covered more than 75% of the total reads. These results highlight, together with those of Ardila-Garcia
340 et al., 2013 and Williams et al., 2018, the necessity to sample more environments in order to reveal the
341 extent of the environmental microsporidian diversity.

342 All OTUs obtained in this study belonged to the canonical Microsporidia, and were distributed within 7
343 clades (over the 10 clades identified for Microsporidia). The microsporidian community was clearly
344 dominated by clades IV2 and I, which represent respectively 76% and 20% of the OTUs (Figure 2). The

345 remaining OTUs were classified into clades IV1 (<2%), V (<1.5%), II (<0.2%), VIII (<0.2%) and IX
346 (<0.2%).

347 Nine groups (over the 21 belonging to the canonical Microsporidia) were represented. Three of them
348 accounted for more than 74% of the OTUs: Aquatic outgroup (clade I, 19%), Arlequin and
349 *Orthosomella*-like groups (clade IV2, 45% and 10% respectively) (Figure 2). 47% of OTUs were
350 assigned to a genus, of which *Crispospora*, *Pseudoberwaldia* and *Conglomerata* were the most
351 represented (35%, 5% and 4%, respectively). Phylogenetic analyses confirmed these affiliations (Figure
352 3 and Supplementary Information 8), which supports the accuracy of the developed methodology. As
353 expected, most of these genera are known to infect hosts having at least one aquatic stage across their
354 full development (crustaceans: daphnids or cyclops, insects: chironomids, Figure 2).

355 Besides the identified genera, many OTUs were not assigned to a genus (53%) nor sometimes even to a
356 group (23%). OTUs not assigned to any genus within the Arlequin group (Figure 3), Aquatic outgroup
357 (Supplementary Information 8) and *Orthosomella*-like group (Supplementary Information 9) were often
358 related to undescribed Microsporidia found in freshwater hosts, such as amphipods, cladocerans,
359 copepods (crustacean), caddisflies, mayflies and mosquitoes (insects). OTUs not assigned to any group
360 mostly belonged to clade IV2 (21%), and few to clades IV1 and V (1% each) (Figure 2). Phylogenetic
361 analysis of these OTUs confirmed that they do not belong to any of the groups we formerly identified
362 (clade IV2: Figure 4; clades IV1 and V: Supplementary Information 10-11). Their closest relatives were
363 often Microsporidia amplified from environmental samples (Ardila-Garcia et al., 2013; Williams et al.,
364 2018) or from amphipods sampled in the lake Baikal (Ironside and Wilkinson, 2018). In clade IV2, they
365 notably form 5 new groups (Van9, BFAS6, Van10, BPAR5 and Van8 groups, Figure 4), each having
366 less than 85% similarity with groups identified in this clade through phylogenetic analysis of known
367 species (Supplementary Information 12). These results suggest that for freshwater habitats, a large
368 proportion of genera and/or families remains to be described. As our analysis focused on small sized
369 fractions (< 150 μm), this novel diversity may correspond at least partly to not yet described
370 microsporidian species infecting small hosts. Some studies report infections of ciliates and rotifers by
371 Microsporidia in freshwater environments (Fokin et al., 2008; Wolska and Mazurkiewicz-Zapalowicz,

372 2013; Stentiford et al., 2013a; Yakovleva et al., 2020), but only two sequences from ciliates, and none
373 from rotifers are currently available in the databases. Further sampling efforts aiming to identify host-
374 microsporidian interactions in these small size organisms will be necessary in order to confirm this
375 hypothesis.

376

377 *Spatio-temporal variations*

378 α -diversity of microsporidian community varied among the different samples (Supplementary
379 Information 13). When focusing on community richness (Richness observed, Chao1 index, number of
380 OTUs), the two lakes seem to present an opposite pattern, as richness increased from April to June in
381 lake Aydat while it decreased in Lake Pavin. Similar patterns were observed for Shannon and Simpson
382 indexes (Supplementary Information 13 B).

383 While no trend for the different size fractions was detected, variations in the relative abundances of
384 some taxa were observed between sampling sites, and to a lesser extent across time (in lake Aydat
385 notably), as suggested by the non-metric multidimensional scaling (Figure 5A). For example, while
386 OTUs identified as *Crispospora* (IV2-Arlequin group), *Conglomerata* and *Pseudoberwaldia* (I-Aquatic
387 outgroup) sp. are very abundant in lake Aydat (up to 91, 17 and 5%, respectively, shown in black, light-
388 blue and deep blue in Figure 5B), their relative abundances were in comparison low in lake Pavin
389 (maximum 11, 0.2 and 0.3%, respectively, except in one sample where they reached 19, 2 and 3%).
390 OTUs belonging to clade IV1 from unknown group(s) had similar pattern, reaching up to 13% in Aydat,
391 and being nearly absent in Pavin (<0.4%) (striped green on Figure 5B). These trends were also observed
392 at the OTU level, some being clearly more abundant in one lake than in the other (Figure 3 and
393 Supplementary Information 8 and 10). At the opposite, lake Pavin was clearly dominated by
394 Microsporidia belonging to unknown group(s) in the clade IV2 or to unknown genera in the Aquatic
395 outgroup (clade I) (striped orange and dotted blue respectively on Figure 5B). Phylogenetic analysis of
396 these unassigned OTUs within clade IV2 revealed that they belong to 3 *de novo* groups (Van 9, BFAS6
397 and Van8) (Figure 4). In particular, a cluster of closely related OTUs in group Van8 was far more

398 abundant in lake Pavin (some OTU reaching up to 54% of the total reads) than in lake Aydat (<1.3%)
399 (Figure 4). Similarly, phylogenetic analysis of abundant OTUs belonging to the Aquatic outgroup
400 revealed that several OTUs clustering with *Octosporea muscadomesticae* and unknown Microsporidia
401 found in freshwater hosts were far more abundant in lake Pavin (up to 21%) than in lake Aydat (<0.5%)
402 (Supplementary Information 8).

403 Relative abundances of some taxa can also significantly vary across the sampling period (Figure 5B).
404 For example, abundances of *Pseudoberwaldia* sp. (Aquatic outgroup, clade I) increased over time in
405 lake Aydat (deep blue in Figure 5B, Supplementary Information 8), as did Microsporidia in the Van8
406 group (clade IV2) in lake Pavin, which clearly dominates in June (>84% of the reads) (Figure 4).
407 Besides, Microsporidia belonging to the *Orthosomella* group were much more abundant in April
408 compared to May and June (dotted green in Figure 5B, Supplementary Information 9). Although these
409 general trends can be observed at the group or genus level, striking differences can also be observed at
410 the OTU level: in OTUs assigned to the genus *Crispospora* for example, OTU3989 and OTU7498 were
411 more abundant in April (up to 85 and 29%), while OTU19444 was more abundant in May (up to 45%),
412 and OTU24464 in June (up to 21%), suggesting these OTUs might belong to different species (Figure
413 3 and Supplementary Information 14A). As genetic distances between these OTUs can be lower than
414 2% (Supplementary Information 14B), such data support the relevance of a clustering threshold fixed at
415 99%.

416 These spatio-temporal variations might be related to the abundance of the hosts present in these lakes at
417 the time of sampling, as Microsporidia have generally a narrow host specificity. Indeed, these two lakes
418 differ in their zooplankton species compositions (Lair, 1978; Devaux, 1980; Lair, 1990; Quiblier-
419 Lloberas et al., 1996), which could themselves be influenced by differences in the nutrients content,
420 altitude and mixing type recorded in these two lakes (Lepère et al., 2010). Considerable temporal
421 variations in the abundances of these species have also been recorded, which could in part explain the
422 temporal variations observed in some Microsporidia lineages. For example, increases of the Cladoceran
423 population are repeatedly recorded in lake Aydat in spring, which could explain the increase of
424 Agglomeratidae (*Pseudoberwaldia* and *Conglomerata* species) across our sampling period (Lair, 1990).

425 Monitoring the presence and abundances of both the microsporidian and other eukaryotic species across
426 a significant period of time could help, for example through co-occurrence network analyses, to
427 highlight potential new host-microsporidian interactions. This could be of particular interest for the
428 Van8 group, which clearly dominates in lake Pavin, and which hosts are totally unknown. This group,
429 as well as the other dominant lineages (*Crispospora* sp. and Agglomeratidae species) might play a
430 significant role in the regulation of hosts populations, that further work may help to determine.

431

432 *Conclusion*

433 In this work, we propose a methodology which aims at studying the microsporidian diversity through
434 metabarcoding. We notably provide a robust database, based on an extensive phylogenetic and
435 bibliographic analysis, which classify microsporidian species in a coherent framework. Using this
436 database, we explored the microsporidian diversity in lacustrine samples through a metabarcoding
437 approach, and highlighted a substantial amount of Microsporidia phylogenetically distant from any
438 described microsporidian species, which might represent undescribed genera and families. Further
439 studies, including larger datasets (in terms of geography and/or ecology) will help to reveal the extent
440 of Microsporidia diversity, which is obviously far from being fully uncovered. Besides, further analyses
441 will be necessary to determine which hosts these Microsporidia are able to infect, a necessary step to
442 understand the role of these parasites in the ecosystem functioning.

443

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451

452 **CONFLICT OF INTEREST**

453 The authors declare they have no competing interests

454

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- 624

625 **FIGURE LEGENDS**

626

627 **Figure 1: Microsporidian phylogenetic tree based on full length SSU rDNA of 265 microsporidian**
628 **species and six outgroup taxa (1127 positions).** Values above branches indicate the ML and Neighbour
629 Joining bootstrap supports (the same topology has been obtained, at least at the clade and group levels).
630 Bootstraps below the group level are not shown to lighten the figure. Nine clades (highlighted with
631 background colours, and Latin numbers I to IX) are identified for canonical Microsporidia and one for
632 unusual Microsporidia (Metchnikovellidae). Correspondence between different clade numbering
633 systems is provided for the four major clades recovered in all phylogenetic analyses (Latin numbers:
634 this study and Vossbrinck and Debrunner-Vossbrinck, 2005; Arabic numbers: Vossbrinck et al., 2014).
635 Within these clades, 1 to 5 groups are identified (highlighted with branches and species names colours),
636 for a total of 22 groups. References to other studies that support these groups are provided, and listed in
637 Bibliography for Supplementary Information. Colour strips indicate hosts (different colours can be given
638 for a single species when different hosts are known) and habitat (different colours can be given for a
639 single species when different habitats are known). Tree annotated using the interactive Tree of Life
640 (iTOL) server (Letunic & Bork, 2016). The alignment used to build the phylogenetic tree is provided in
641 Supplementary Information 3.

642

643 **Figure 2: Krona chart representing the affiliation of the 1531 OTUs found in the analysis.** Inner
644 circles represent clades, and deeper taxonomic ranks (groups and genera) are presented in outer circles.
645 Group names are given in capital letters, and genera names in italic. For identified genera, habitats are
646 shown with coloured squares and host species are given in brackets. Seven clades are represented,
647 although most OTUs fall in clades I and IV2. A large proportion of OTUs are unidentified at the group
648 (stripe patterns) or genus (dot patterns) level. Among OTUs identified at the genera level, most are
649 assigned to genera known to parasitize freshwater hosts.

650

651 **Figure 3: Maximum Likelihood phylogeny of abundant OTUs (>1% of reads in at least one**
652 **sample) affiliated to the Arlequin group (clade IV2) with other sequences belonging to this group.**
653 Numbers next to branches indicate the ML bootstrap support (200 replicates). Node supports <70 are
654 not shown. Outgroup species are representative species of other groups belonging to clade IV2 (details
655 in Supplementary Information 15). Affiliation of each OTU following the bioinformatics analysis is
656 given in grey text. Described species are given in bold-italic, and sequences from undescribed species
657 in normal text. Hosts are given in brackets. C: Crustacea; I: Insecta. Relative abundances of each OTU
658 across samples are reported with a heatmap.

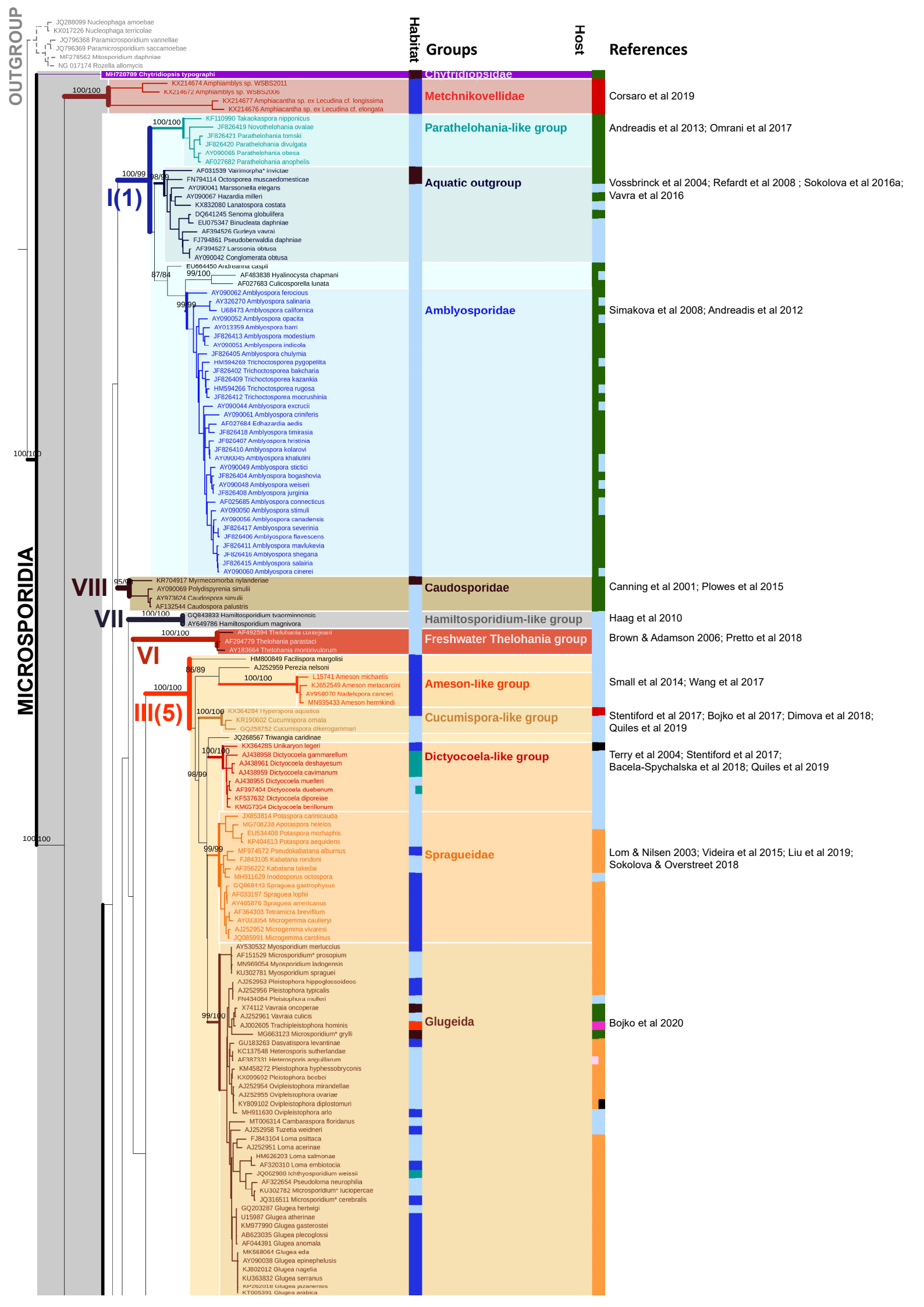
659

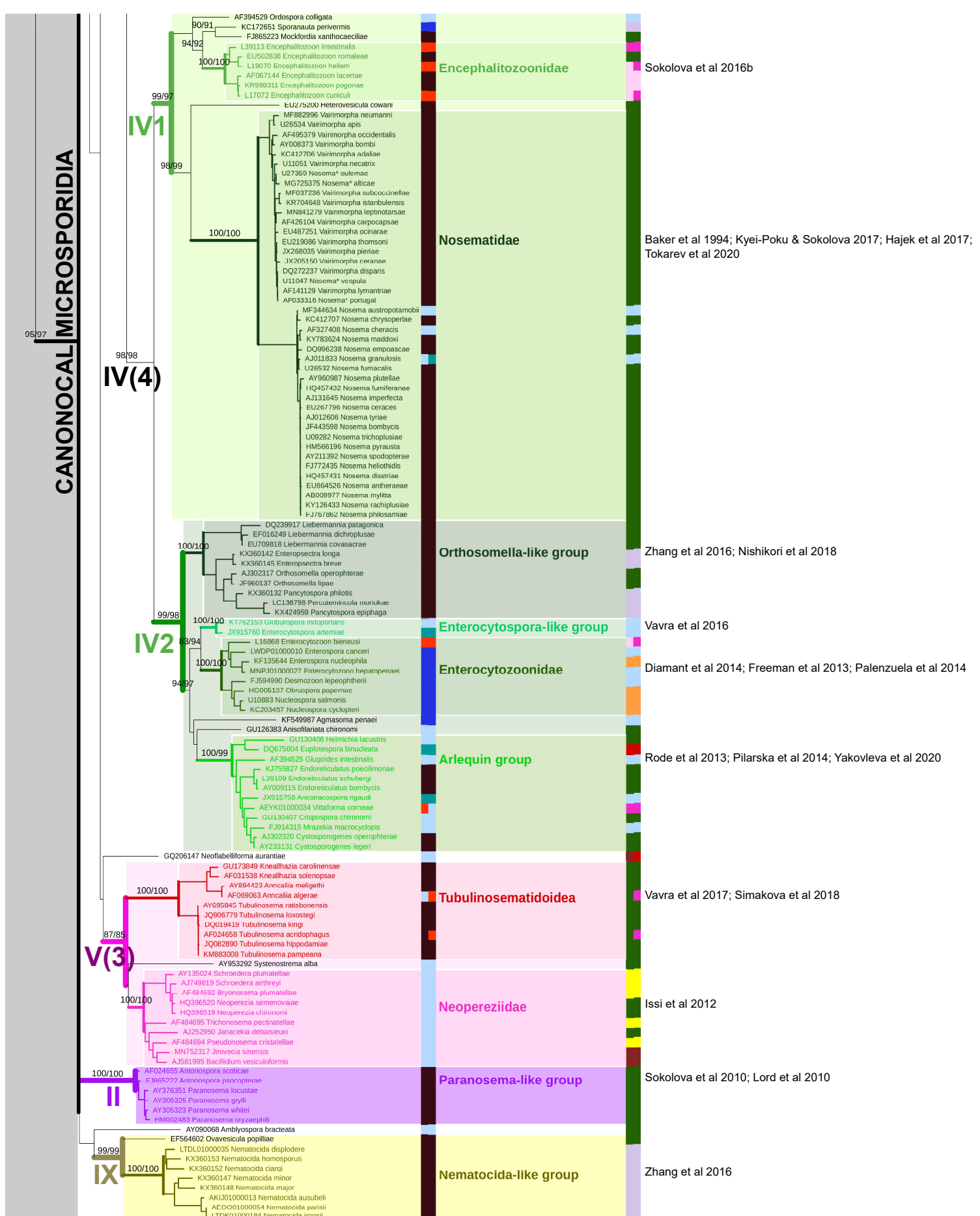
660 **Figure 4: Maximum Likelihood phylogeny of abundant OTUs (>1% of reads in at last one sample)**
661 **not assigned to any group, within clade IV2, with other sequences belonging to this clade.** Numbers
662 next to branches indicate the ML bootstrap support (200 replicates). Node supports <70 are not shown.
663 Outgroup species are representative species of clade IV1 (details in Supplementary Information 15).
664 Affiliation of each OTU following the bioinformatics analysis is given in grey text. Described species
665 are given in bold-italic, and sequences from undescribed species in normal text. Hosts are given in
666 brackets. C: Crustacea; I: Insecta. Relative abundances of each OTU across samples are reported with a
667 heatmap.

668

669 **Figure 5: A. Non-metric multidimensional scaling (NMDS) ordination of the microsporidian OTU**
670 **relative abundances across samples based on Bray–Curtis distances** (stress: 0.09). Ellipses in the
671 plots denote 95% confidence intervals, points that are not overlapped by the two ellipses are considered
672 significantly different. **B. Relative abundance of identified microsporidian taxa across samples.**

673





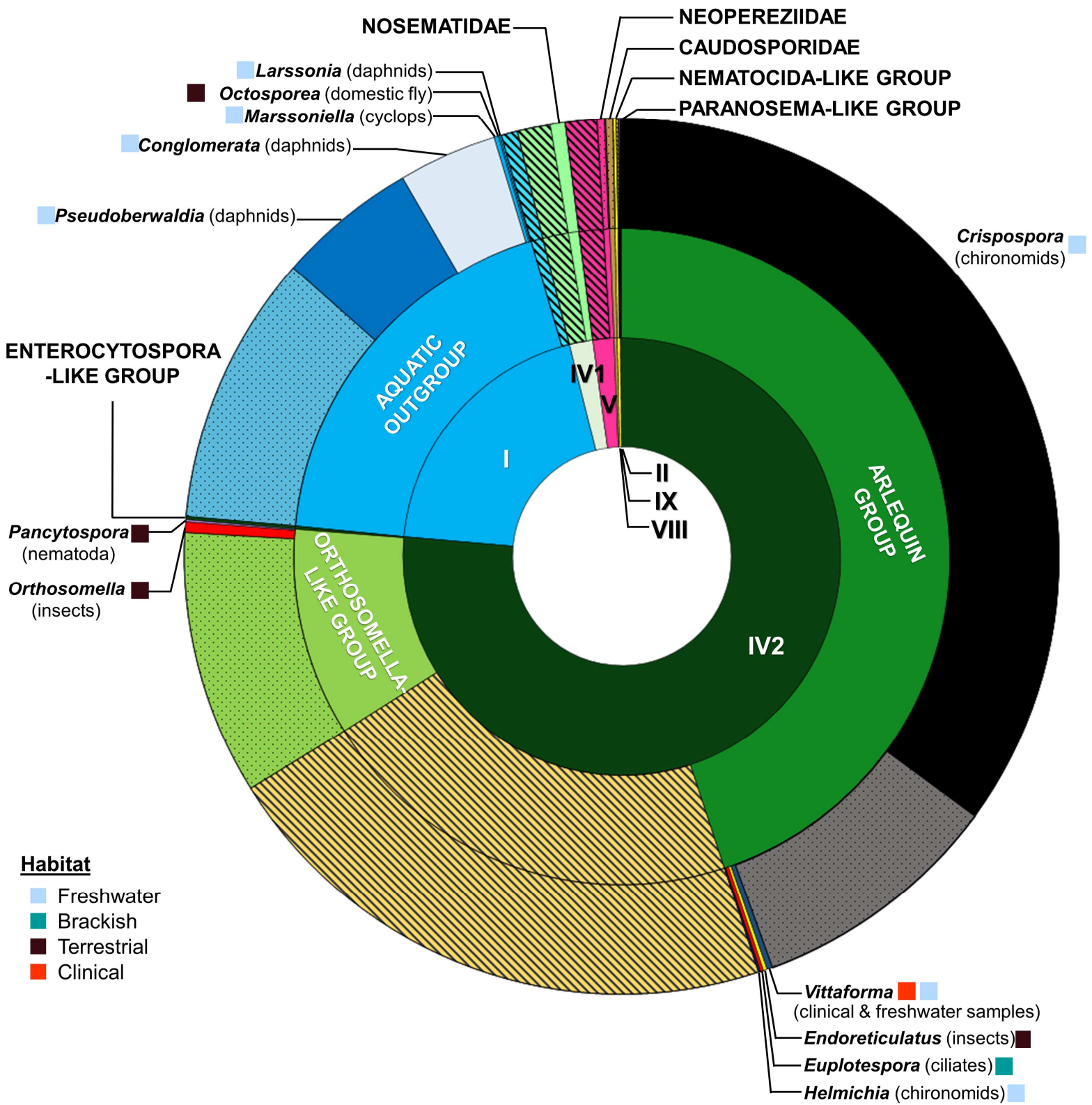
Tree scale: 0.1

Habitat

- Freshwater
- Brackish or saltern
- Marine
- Terrestrial
- Clinical

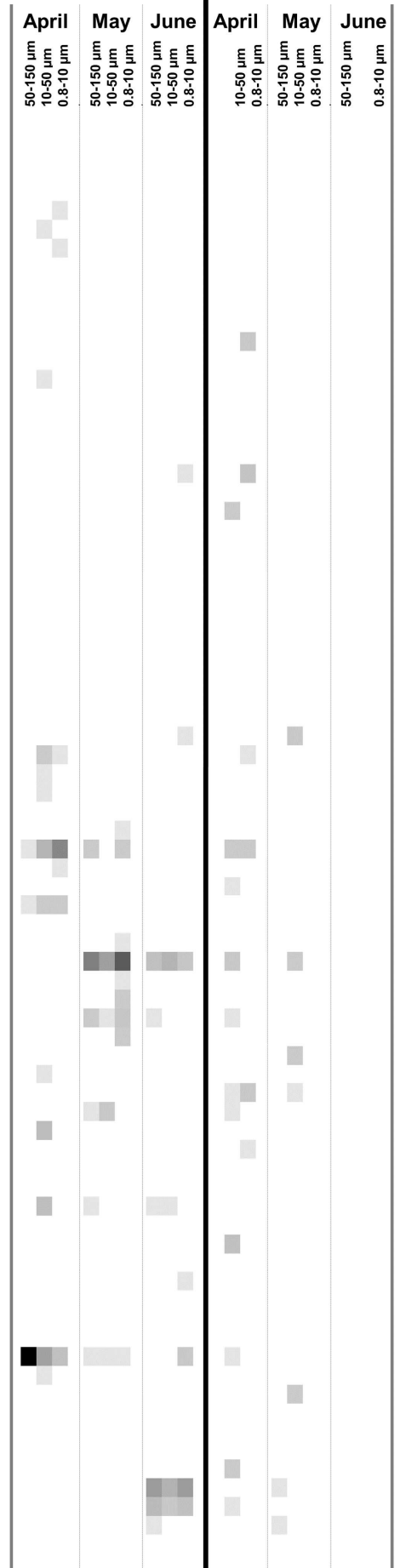
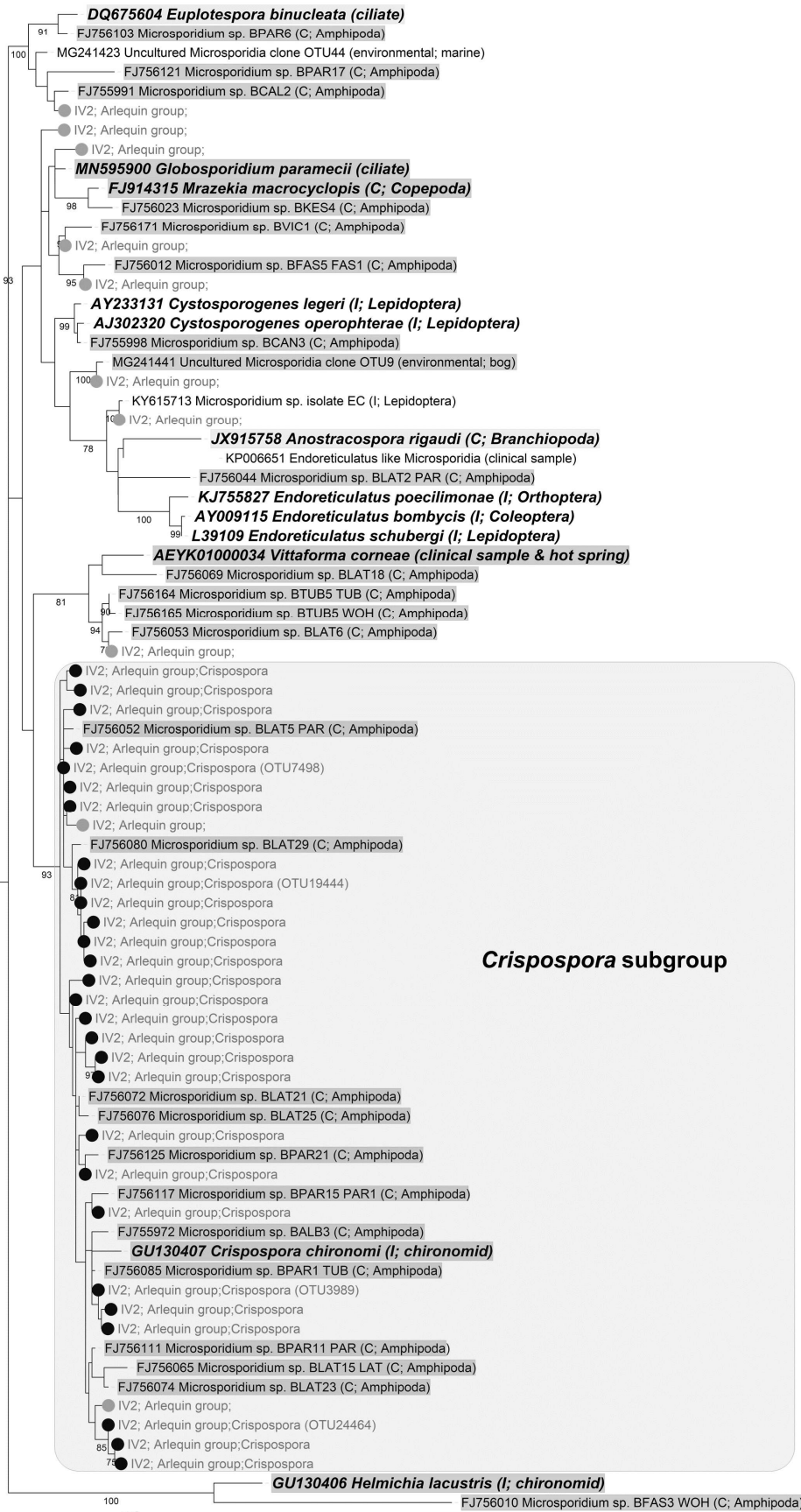
Hosts

- Crustacea
- Insects
- Fishes
- *Homo sapiens*
- Other vertebrates
- Annelida
- Bryozoa
- Trematoda
- Nematoda
- Unicellular hosts



Aydat

Pavin



Abundances (%)

0 8 16 24 32 40 48 56 64 72 >80



