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3 **Mitochondrial phylogenomics and genome rearrangements in the**  
4 **barklice (Insecta: Psocodea)**

5

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16

17 **ABSTRACT**

18

19 The mitochondrial genome arrangement in the insect order Psocodea (booklice, barklice, and  
20 parasitic lice) is extremely variable. Genome organization ranges from the rearrangement of a  
21 few tRNAs and protein coding genes, through extensive tRNA and protein coding gene  
22 rearrangements, to subdivision into multiple mini-chromosomes. Evolution of the extremely  
23 modified mitochondrial genome in parasitic lice (Phthiraptera) has been the subject of several  
24 studies, but limited information is available regarding the mitochondrial genome organization  
25 of the more plesiomorphic, free-living Psocodea (formerly known as the "Psocoptera"). In  
26 particular, the ancestral state of the psocodean mitochondrial genome arrangement and the  
27 evolutionary pathway to the rearranged conditions are still unknown. In this study, we  
28 addressed mitochondrial evolutionary questions within the Psocodea by using mitochondrial  
29 genome sequences obtained from a wide range of Psocoptera, covering all three suborders.  
30 We identified seven types of mitochondrial genome arrangements in Psocoptera, including  
31 the first example in Psocodea of retention of the ancestral pancrustacean condition in  
32 *Prionoglaris* (Prionoglarididae). Two methods (condition-based parsimony reconstruction  
33 and **common-interval genome distances**) were applied to estimate the ancestral  
34 mitochondrial arrangement in Psocodea, and both provided concordant results. Specifically,  
35 the common ancestor of Psocodea retained the ancestral pancrustacean condition, and most of  
36 the gene arrangement types have originated independently from this ancestral condition. We  
37 also utilized the genomic data for phylogenetic estimation. The tree estimated from the  
38 mitochondrial genomic data was well resolved, strongly supported, and in agreement with  
39 previously estimated phylogenies. It also provided the first robust support for the family  
40 Prionoglarididae, as its monophyly was uncertain in previous morphological and molecular  
41 studies.

42

43 **Keywords:** mitochondrial genome, gene rearrangements, Psocodea, Psocoptera,  
44 Prionoglarididae, phylogeny

45

## 46 **1. Introduction**

47        During the last couple of decades, sequences of the mitochondrial genome from  
48 hundreds of insect species have been obtained. These sequences have been used  
49 for phylogenetic analyses at both deep and shallow levels, as well as for analyses of  
50 mitochondrial genome organization (Cameron, 2014a, 2014b). As the sequences of  
51 more and more insect mitochondrial genomes have been obtained, it has become  
52 clear that, although gene arrangement is quite stable throughout many insects (the  
53 ancestral Pancrustacean condition is by far the most common mitochondrial genome  
54 arrangement observed), rearrangements of a few transfer RNA genes (tRNAs) are  
55 also quite common (Cameron, 2014a). In contrast, more extensive gene  
56 rearrangements, particularly those involving protein-coding genes (PCGs) or  
57 ribosomal RNA genes (rRNAs), are rather rare events and are common in only a few  
58 insect orders (Embioptera: Kômoto et al., 2012; Thysanoptera: Shao and Barker,  
59 2003; Psocodea: Shao et al., 2001a; Hymenoptera: Mao et al., 2015). Extensive gene  
60 rearrangements, however, also occur in a number of highly derived members of  
61 orders in which most other taxa lack major rearrangements (e.g. Cecidomyiidae,  
62 Diptera: Beckenbach, 2012; Iberobaeniidae, Coleoptera: Andujar, 2017;  
63 Enicocephalidae, Hemiptera: Li et al., 2012; Aleyrodidae, Hemiptera: Thao et al.  
64 2004).

65        Among insects, the highest variation in mitochondrial gene arrangement occurs  
66 in the order Psocodea (booklice, barklice, and parasitic lice, formerly known as two  
67 independent orders, "Psocoptera" and Phthiraptera: Yoshizawa and Johnson, 2006).  
68 The mitochondrial variation observed in Psocodea ranges from the rearrangement of  
69 a few tRNAs and two PCGs in the suborder Psocomorpha (Shao et al., 2001b;  
70 Cameron, 2014a; Li et al., 2013), through extensive tRNA and PCG rearrangements  
71 in the suborder Trogiomorpha (Shao et al., 2003), the family Liposcelididae (Shi et al.,  
72 2016), and Phthiraptera (e.g., Shao et al., 2001a), to extreme subdivision into multiple  
73 mini-chromosomes in some Liposcelididae (Chen et al., 2014) and Phthiraptera  
74 (Shao et al., 2009, 2015; Cameron et al., 2011). Evolution of the extremely modified  
75 mitochondrial genome in Phthiraptera has been the subject of several studies (e.g.,  
76 Shao et al., 2001a, 2009, 2015; Cameron et al., 2011). However, other than the  
77 family Liposcelididae (the sister-group of the parasitic lice, with many reduced traits

78 similar to parasitic lice; Yoshizawa and Lienhard, 2010), limited information is  
79 available for the more plesiomorphic, free-living Psocodea (formerly the  
80 "Psocoptera"). Therefore, the ancestral condition of the psocodean mitochondrial  
81 genome arrangement is still unknown. In addition, extensive mitochondrial  
82 rearrangements are also known from thrips (Thysanoptera) (Shao and Barker, 2003;  
83 Yan et al., 2014; Dickey et al., 2015; Liu et al., 2017), an order classified with  
84 Psocodea as part of the superorder Paraneoptera (Yoshizawa and Lienhard, 2016).  
85 Additional mitochondrial genomic information from free-living Psocodea is thus  
86 crucial to inferring both the ancestral mitochondrial genome organization of Psocodea  
87 and for understanding supra-ordinal level evolution of the mitochondrial genome.

88 Additional mitochondrial genome data from Psocodea will also contribute to our  
89 phylogenetic understanding of the order. Although the higher-level phylogenetic  
90 relationships within Psocodea have been the subject of several studies (e.g.,  
91 Yoshizawa et al., 2006; Yoshizawa and Johnson, 2010, 2014), unresolved problems  
92 still remain. One of these concerns the monophyly of the Prionoglarididae (suborder  
93 Trogiomorpha). Because the family is known to retain many plesiomorphic features  
94 (Lienhard, 1998; Yoshizawa et al., 2006), its monophyly is highly controversial.  
95 Although one previous molecular phylogenetic analysis (Yoshizawa et al., 2006: fig.  
96 2) provided support for the monophyly of Prionoglarididae, analyses with more  
97 extensive taxon or gene samplings (Yoshizawa et al., 2006: fig. 3; Yoshizawa and  
98 Johnson, 2014) suggested the family may be paraphyletic. As mentioned above, this  
99 family retains the most plesiomorphic morphology among the extant Psocodea, and  
100 so resolving the status of Prionoglarididae has great impact on how we interpret  
101 ancestral states and the evolution of the Psocodea.

102 In this study, we address both phylogenetic and mitochondrial evolutionary  
103 questions within the Psocodea by using the mitochondrial genome sequences  
104 obtained from a wide range of free-living Psocodea. The selected taxa cover all three  
105 suborders of the "Psocoptera". In particular, three genera representing both  
106 subfamilies of the Prionoglarididae were sampled to test the monophyly of this family  
107 and also to examine the origin of the extensive gene rearrangements previously  
108 recorded in members of the suborder Trogiomorpha. Two methods of the ancestral  
109 state estimation, condition-based coding with parsimony reconstruction and common-

110 interval genome distances (implemented in the TreeREx software: Bernt et al., 2007,  
111 2008), are compared to test the effectiveness of these methods for ancestral state  
112 reconstruction.

113

## 114 **2. Materials and Methods**

### 115 *2.1. Samples*

116 Ten species (Table 1) were sequenced representing all three of the free-living  
117 suborders of Psocodea, including eight different families. In addition, sequences of  
118 Lepidopsocidae sp. (Shao et al., 2003), *Stenocaecilius quercus* (= *Caecilius quercus*:  
119 Shao et al., 2001b), *Psococerastis albimaculata*, and *Longivalvus hyalospilus* (Li et  
120 al., 2013) were obtained from GenBank. Mitochondrial genomes have also been  
121 previously sequenced for parasitic lice (Phthiraptera) and booklice (Liposcelididae).  
122 However, sequences from both groups were excluded from the present study due to  
123 their extremely high rates of mitochondrial genome rearrangement and fragmentation  
124 (Cameron et al., 2011; Chen et al., 2014; Shao et al., 2017), which obscure genome  
125 evolution events within free-living Psocodea. Two outgroup sequences, *Abidama*  
126 *producta* (Cercopidae, Hemiptera: an order classified to Paraneoptera together with  
127 Psocodea) and *Dysmicohermes ingens* (Corydalidae, Megaloptera: an order of  
128 Holometabola, the sister taxon of Paraneoptera), were also obtained from GenBank.

129

### 130 *2.2. Sequencing and assembling*

131 DNA was extracted using a Qiagen QIAamp DNA Micro Kit or DNeasy Blood  
132 and Tissue Kit. DNA of *Dorypteryx*, *Prionoglaris*, and *Neotroglia* was sheared using a  
133 Covaris M220 instrument to approximately 400 bp and sequence libraries were  
134 prepared using a Kapa Library Preparation kit. Libraries were pooled with two other  
135 taxa and sequenced together in a single lane with 160 bp paired-end reads on an  
136 Illumina HiSeq 2500. Raw reads are deposited in NCBI SRA (SRR5308267,  
137 SRR5308282, SRR5308278). To obtain mitochondrial genome sequences from  
138 these libraries we generated contigs using a combination of aTRAM (Allen et al.,  
139 2015) and MITObim (Hahn et al. 2013). First, aTRAM was used to assemble five  
140 protein-coding mitochondrial genes (*cox1*, *cox2*, *cob*, *nad2*, and *nad5*) for each genus  
141 using amino acid sequences as targets for these assemblies. In all cases, aTRAM

142 was run for a single iteration on 10% of the paired-end libraries, and contigs were  
143 assembled in aTRAM using ABySS (Simpson et al. 2009). Second, MITObim was  
144 used to extend the contigs assembled with aTRAM by using each contig as a starting  
145 reference for that species. Additionally, partial previously generated Sanger  
146 sequences of *rrnS* were used as starting references for all three genera, and Sanger  
147 sequences of *rrnL* as starting references for *Dorypteryx* and *Prionoglaris*. MITObim  
148 was then run for each starting reference a maximum of 100 iterations, using either  
149 10% (*Dorypteryx* and *Prionoglaris*) or 20% (*Neotroglia*) fractions of the paired-end  
150 libraries. To obtain *trnI* and *trnM* sequences for *Neotroglia*, we used aTRAM with  
151 sequences of these tRNAs from the *Prionoglaris* and *Speleketor* genomes in this  
152 study. A small region not recovered by aTRAM and MITObim (part of *nad4* and *nad4l*  
153 of *Prionoglaris*) was amplified by PCR and sequenced by Beckman CEQ2000 Sanger  
154 sequencer (Yoshizawa & Johnson, 2003).

155 The complete mitochondrial genomes of *Speleketor*, *Stimulopalpus*,  
156 *Archipsocus*, *Lachesilla* and *Amphigerontia*, and partial mitochondrial genomes for  
157 *Echmepteryx* and *Trogium*, were amplified by long PCR and sequenced by primer  
158 walking (Cameron 2014b). Long PCRs were performed with Elongase (Invitrogen), Sanger  
159 sequenced with the ABI Big Dye ver3 chemistry and run on an ABI 3770 automated  
160 sequencer. Amplification primers are listed in Supplementary Table S1. Long PCR and  
161 sequencing conditions match those used in Cameron et al. (2011).

162

### 163 2.3. Annotations

164 The MITOS server (Bernt et al., 2013) was used for initial annotation. However,  
165 the MITOS server often could not correctly identify the start and stop codons, so  
166 these were manually annotated by aligning the sequences with the annotated  
167 mitochondrial genome data of the other Psocodea downloaded from GenBank  
168 (Cameron 2014b).

169

### 170 2.4. Alignment

171 Protein coding genes (PCGs) were aligned based on translated amino-acids  
172 using Muscle (Edgar, 2004) implemented in MEGA 7 (Kumar et al., 2016). Ribosomal  
173 RNAs (rRNA) were aligned using MAFFT 6.5 (Kato and Standley, 2013) with the Q-

174 INS-i option, in which secondary structure information of RNA is considered.  
175 Apparent misalignments were corrected manually. Transfer RNAs (tRNAs) were  
176 manually aligned based on secondary structure models estimated in MITOS. Poorly  
177 aligned regions (such as hyper variable regions of RNAs near the start and stop  
178 codons of PCGs) were excluded from the analyses.

179

## 180 2.5. Data set

181 We prepared the following six data sets: (1) ALL = all protein coding and RNA  
182 genes; (2) ex.3rd = all protein coding genes (third codon position excluded) and RNA  
183 genes; (3) PCG = all protein coding genes; (4) PCG12 = all protein coding genes  
184 (third codon position excluded); (5) RNA = all RNA genes; (6) AA = amino-acid  
185 sequences of the PCG dataset. For each data set, two taxon sets were prepared: (1)  
186 all taxa and (2) excluding taxa with missing data (*Stenocaecilius*, *Echmepteryx*, and  
187 *Trogium*).

188 For detecting potential biases affecting the accuracy of phylogenetic estimation  
189 using mitochondrial genome data (Sheffield et al., 2009), AT content and P-distances  
190 were calculated by using MacClade 4 (Maddison and Maddison, 2000) and PAUP\*  
191 4.0a152 (Swofford, 2002), respectively. AT content was calculated for each PCG  
192 gene, combined tRNAs, each rRNA, and codon positions (PCG1, 2, 3). A chi-square  
193 test of base homogeneity was performed using PAUP\*.

194

## 195 2.6. Model selection

196 The best substitution models and partition schemes for the maximum likelihood  
197 (ML) and Bayesian analyses were estimated using PartitionFinder 2.1.1 (Lanfear et  
198 al., 2017), with the greedy algorithm. Taxa with missing data were excluded for model  
199 estimation to avoid the potential negative effects caused by missing data. The  
200 following partitions were predefined for the PartitionFinder analyses: codon positions  
201 for each PCGs (13 genes x 3 codons = 39 partitions), tRNAs (22 partitions), and  
202 rRNAs (2 partitions)

203

## 204 2.7. Tree Search

205 We estimated a maximum likelihood tree using IQ-Tree 1.4.3 (Nguyen et al.,



206 2015), with 1000 replicates of ultrafast likelihood bootstrap (Minh et al., 2013) to  
207 obtain bootstrap branch support values. Bayesian analyses were performed using  
208 MrBayes (Ronquist and Huelsenbeck, 2003). We performed two runs each with four  
209 chains for 500 000 generations, and trees were sampled every 100 generations. The  
210 first 50% of sampled trees was excluded as burn-in, and a 50% majority consensus  
211 tree was computed to estimate posterior probabilities. To evaluate the potential  
212 impact of substitution rate and compositional biases on phylogeny estimation, we  
213 also performed tree searches using PhyloBayes 4.1 (Lartillot et al., 2009) under a  
214 heterogeneous (CAT+GTR) model. We ran two independent tree searches for 10,000  
215 cycles. However, for the PCG12 data, the two runs did not converge by 10,000 cycles  
216 (maxdiff > 0.3), so we ran 20,000 cycles for this data set. The first 50% of sampled  
217 trees were excluded as burn-in, and trees were sampled every 10 cycles. A majority  
218 consensus tree was computed from the two combined runs.

219

## 220 2.8. Character Coding and Ancestral State Estimation

221 Each genome was compared to the inferred ancestral insect mitochondrial  
222 genome (present in both outgroup taxa) to examine pairs of adjacent genes or gene-  
223 boundaries. Novel gene boundaries, those not observed in the ancestral insect  
224 mitochondrial genome, were coded as binary characters (either present or absent).  
225 Genome rearrangements result in new gene-pairs from both the insertion of a  
226 gene/gene-block at a novel location and from its deletion from the ancestral location.  
227 Both of these types of events were coded separately (Fig. 1: insertions labelled with  
228 numbers, deletions labelled with letters). For example, in *Speleketor* the translocation  
229 of *trnC* results in both *trnC-trnQ*, a novel boundary formed by an insertion, whereas  
230 *trnW-trnY* is also a novel boundary but was formed by the deletion of *trnC* from its  
231 ancestral location, the *trnW-trnC-trnY* condition. This condition-based data matrix  
232 was optimized parsimoniously on the best phylogenomic tree obtained from the ALL  
233 dataset (see above) using MacClade.

234 We also reconstructed the gene rearrangement history by using TreeREx 1.85  
235 (Bradt et al., 2008). TreeREx reconstructs genomic evolution based on common  
236 intervals (blocks of genes shared between taxa in a clade) and a defined phylogeny,  
237 allowing the inference of tandem-duplicate-random-loss events (TDRL after Boore,

238 2000), simple transpositions, inversions and inversion-transpositions (the latter three  
239 models can also be coded in the condition-based matrix described above). However,  
240 there are limitations to TreeREx, particularly that gene-duplications are not allowed,  
241 even though these are comparatively common in rearranged mitochondrial genomes  
242 and are an inferred mid-point in the TDRL model (after tandem duplication but prior to  
243 random loss). Duplicated genes were identified in two of the taxa sequenced in this  
244 study, two control regions (CR) are present in *Neotrogla* and *Speleketor*. Therefore,  
245 for these, only the CR at a novel position (indicated by asterisk in Fig. 1) was coded.

246

### 247 **3. Results**

#### 248 *3.1. Sequencing, Annotation, and Data Evaluation*

249 Eight new, complete/nearly complete (missing only a portion of control region)  
250 mitochondrial genomes were sequenced representing five additional psocodean  
251 families and each of the three free-living suborders: Trogiomorpha (Prionoglarididae:  
252 *Prionoglaris stygia* 15,684+ bp at 67x mean coverage, *Neotrogla* sp. 16894+ bp at  
253 81x mean coverage, *Speleketor irwini* 16,849bp at 66x mean coverage,  
254 Psyllipsocidae: *Dorypteryx domestica* 18,512+ bp at 320x mean coverage),  
255 Troctomorpha (Amphientomidae: *Stimulopalpus japonicus* 14,904bp) , and  
256 Psocomorpha (Archipsocidae: *Archipsocus nomas* 15,349bp, Lachesillidae:  
257 *Lachesilla anna* 16,236bp Psocidae: *Amphigerontia montivaga* 15,566+ bp).  
258 Additionally, partial mitochondrial genomes were sequenced for two additional  
259 families of Trogiomorpha, Trogiidae (*Trogium pulsatorium*) and Lepidopsocidae  
260 (*Echmepteryx hageni*), to confirm genome rearrangements previously reported in the  
261 latter family (Shao et al., 2003) (Supplementary Table S2).

262 These genomes were sequenced by a mix of methods including long-PCR  
263 followed by primer walking (Cameron, 2014b), direct NGS sequencing of extracted  
264 DNA (also known as genome skimming, Linard et al., 2015), and a combination of  
265 both methods. The control region (CR) of *Stimulopalpus* could not be amplified by  
266 long-PCR and a combination of PCR and NGS derived sequences allowed the  
267 sequences of genes flanking the CR to be determined for this species. The *trnI-trnM*  
268 genes of *Neotrogla* were assembled separately from the other mitochondrial genes  
269 using NGS approaches, and the two contigs could not be connected into a single

270 sequence. Therefore, the possibility that they are on separate mini-chromosomes or  
271 that they represent pseudogenes cannot be excluded. However, phylogenetic  
272 analyses of the *trnI* and *trnM* genes alone placed those from *Neotrogla* in the  
273 expected position, consistent with them being the functional copy of these genes in  
274 this species. In addition, homologous repeat units (38–42 or 66–73 bp/repeat,  
275 Supplementary Fig. S1) were identified at the 3' end of the *trnI-trnM* contig and the 5'  
276 end of the *trnQ...rrnS* contig. Therefore, it is very likely that these contigs are  
277 connected via this repeat region. No homologous sequence was detected between  
278 the 3' end of *rrnS* and the 5' end of *trnI*, except that both are AT rich. Repeat units of  
279 this size present known assembly problems for Illumina HiSeq reads, and it seems  
280 more likely that these regions failed to assemble rather than the two assembled  
281 contigs represent separate mini-chromosomes. Repeat units were also identified in  
282 the control regions of several other sequenced species including *Speleketor* (two  
283 repeat classes 20 x 30bp, 3 x 44bp respectively), *Stimulopalpus* (3x 108bp),  
284 *Lachesilla* (7x 121bp), and *Amphigerontia* (5x 149bp) (Supplementary Table S2),  
285 although none of these species failed to assemble into a single contig. Sequence  
286 level homology between repeat units in different taxa was not identified.

287

### 288 3.2. Genome Rearrangements

289 A total of seven genome arrangement types (1–6 and 6') were detected in free-  
290 living Psocodea, four of them (1–3, 5) for the first time (Fig. 1). Type 1, identified in  
291 *Prionoglaris* (Prionoglarididae) was identical to the ancestral Pancrustacean  
292 condition. Both *Neotrogla* (type 2) and *Speleketor* (type 3) possess unique tRNA  
293 rearrangements, but they share a novel rearrangement of *trnM* to between duplicated  
294 control regions. All species of non-prionoglarid trogiomorphs possess a complicated  
295 rearrangement involving 7 tRNAs and *cox2* (type 4), first identified in Lepidopsocidae  
296 (Shao et al., 2001ab), but now identified by our study as also occurring in Trogiidae  
297 and Psyllipsocidae. The rearranged tRNA block in non-prionoglarid trogiomorphs  
298 includes a novel boundary, *trnI-trnM* (Character 1: Fig. 1), that is also observed in  
299 *Neotrogla*. *Stimulopalpus* (type 5) also closely resembles the ancestral  
300 pancrustacean mitochondrial genome, with one tRNA inverted (*trnI*) and one tRNA  
301 transposed (*trnM/trnQ*). All species of Psocomorpha share a complicated

302 rearrangement of the genes *nad3*, *nad5*, and associated tRNAs (type 6). In addition,  
303 *Stenocaecilius* (type 6') likely has a secondary tRNA transposition (*trnE-trnS1*,  
304 character 17), but is otherwise the same as other psocomorphans. However, the  
305 tRNAs rearrangements between CR and *nad2* identified in other psocomorphans  
306 have not been sequenced for *Stenocaecilius*.

307 In addition to gene rearrangements, a couple of long non-coding regions were  
308 identified in *Neotroglia*: 97 bp between CR repeat units and *trnQ*, 96 bp between *trnQ*  
309 and *nad2*, and 255 bp between *nad4L* and *trnT*. The former two non-coding regions  
310 correspond to the prior positions of *trnI* and *trnM*, respectively, in the ancestral  
311 Pancrustacean mitochondrial genome, and may represent 'junk' DNA regions left  
312 over from the rearrangement event which resulted in the transposition of these genes.  
313 Evidence for this interpretation lies in the identification of a characteristic hair-pin  
314 structure similar to the anticodon arm of *trnI* within the 97 bp non-coding region  
315 between CR repeats and *trnQ* (Supplementary Fig. S2).

316

### 317 3.3. Mito-phylogenomics (Fig. 2)

318 The aligned DNA data matrix consisted of 15 360 bp in total length (11 436 bp  
319 for PCG and 3 294 for RNA: Supplementary Data S1), of which 1 077 bp of PCG and  
320 684 bp of RNA data were excluded from the analyses because of highly unreliable  
321 alignment. Within the PCG data (after excluding unaligned sites), 7 023 sites were  
322 variable, of which 1 281 sites were phylogenetically informative. Within the RNA data,  
323 1 545 sites were variable, of which 467 sites were phylogenetically informative. Within  
324 the aligned AA data, 2 261 of 3 453 total sites were variable, of which 510 sites were  
325 phylogenetically informative.

326 Plots of P-distance showed that homoplasies caused by multiple substitutions  
327 were not problematic for phylogenetic estimation, except for the 3rd codon position  
328 where the slope of plots seemed to plateau (Supplementary Fig. S3). Although  
329 significant codon heterogeneity was detected by chi-square test in all data sets ( $p =$   
330 0.000), comparisons of base composition suggested that there seemed no directional  
331 base composition biases causing artificial phylogenetic affinities (Fig. 2;  
332 Supplementary Table 3). Comparing datasets including versus excluding third codon  
333 positions and RNA genes, and using multiple inference methods, allowed us to

334 further test if these factors resulted in artefactual relationships or nodal support.

335 Trees estimated from six data sets, each with two taxon sets  
336 (including/excluding taxa with missing data), were all concordant. Only one exception  
337 was the placement of *Stenocaecilius* (the taxon with a large amount of missing data:  
338 Fig. 1): it was placed as sister to *Lachesilla* with high support values in almost all  
339 datasets, but was placed at the base of Psocomorpha by RNA data with very low  
340 support values (<50% bootstrap [BS] and posterior probability [PP]). *Stenocaecilius*  
341 lacked large amounts of data, including two rRNAs that occupied the largest  
342 proportion of the RNA dataset. Although support values for the placement of taxa with  
343 missing data were relatively low (66–97% BS and 77–100% PP: *Echmepteryx*,  
344 *Trogium*, and *Stenocaecilius* [except for the placement by RNA dataset discussed  
345 above]), almost all other branches were supported with very high support values  
346 (>99% BP and 100% PP). Therefore, there were almost no detectable differences  
347 caused by different data/taxon sets and analytical methods. The only exception  
348 concerned the monophyly of Prionoglarididae: the family was consistently recovered  
349 as a monophyletic group (Fig. 2), but its support values were significantly lower than  
350 other branches (Table 2), although there were no missing data in three prionoglaridid  
351 taxa. The support values were high in combined PCG+RNA or in separated RNA  
352 analyses (over 80% BS and 100% PP) (Table 2). In contrast, when the PCG and  
353 amino-acid data were analyzed separately, monophyly of Prionoglarididae generally  
354 received lower support values (Table 2). Increasing the size of the data set generally  
355 increased support for this clade, as was evident by comparing the results from RNA  
356 or PCG to All. Exclusion of the highly homoplasious 3rd codon position did not  
357 change the results significantly (ex.3rd and PCG12 datasets: Table 2).

358 Monophyly of the suborder Trogiomorpha was robustly supported. The  
359 trogiomorphs excluding Prionoglarididae formed a clade (*Echmepteryx*–*Dorypteryx*  
360 clade), in which *Dorypteryx* placed to the sister of the rest (= infraorder Atropetae).  
361 The support values for the relationships among taxa within this clade were relatively  
362 low, most probably due to large amount of missing data in *Trogium* and *Echmepteryx*.  
363 *Stimulopalpus* was placed sister to Psocomorpha with high support values.  
364 *Stimulopalpus* was the only representative sampled here from the suborder  
365 Troctomorpha, so the monophyly of this suborder could not be tested. Monophyly of

366 the suborder Psocomorpha was robustly supported, with *Archipsocus*  
367 (Archipsocetae: Archipsocidae) sister to the rest of psocomorphans with high support  
368 values. *Stenocaecilius* (Caeciliusetae: Caeciliusidae) and *Lachesilla*  
369 (Homilopsocidea: Lachesillidae) formed a clade with high support values. The  
370 remaining three samples all belong to the Psocidae, and its monophyly was robust.

371

### 372 3.4. Estimation of the History of Rearrangements

373 A total of 28 characters (17 insertion and 11 deletion characters) were coded  
374 (Supplementary Data S2) from the observed mitochondrial genome arrangements  
375 (Fig. 1). Novel tRNA rearrangements observed between the CR and *cox1* in  
376 Psocomorpha were treated as missing data for *Stenocaecilius* (Fig. 1).

377 The most parsimonious reconstruction of the condition-based data matrix on the  
378 ML phylogenomic tree (Fig. 2) is shown in Fig. 3. The insertions (Character 1–17)  
379 contained very little homoplasy (CI = 0.94, RI = 0.98). Translocation of *trnM* was  
380 identified as a synapomorphy of *Neotroglia* and *Speleketor*. Both the *Echmepteryx*–  
381 *Dorypteryx* clade and the Psocomorpha were characterized by unique gene  
382 rearrangements, including a series of non-homoplasious characters (11 and 6  
383 respectively). The pattern seen in *Stenocaecilius* (type 6') could be derived by a  
384 single tRNA transposition from the psocomorphan type (type 6). The derived gene  
385 boundary, *trnI-trnM*, was identified in both *Neotroglia* and the *Echmepteryx*–  
386 *Dorypteryx* clade (Character 1), but they were inferred to have independent origins. In  
387 comparison, the deletions (Characters A–K) were more homoplasious (CI = 0.79, RI  
388 = 0.92). Furthermore, although deletion of *trnM* from its ancestral position (Character  
389 B) was identified in almost all taxa except for *Prionoglaris* and was reconstructed to  
390 have occurred in the common ancestor of Psocodea, this interpretation is unlikely  
391 (see Discussion).

392 Reconstructing the pattern of genome rearrangements using the ALL dataset  
393 topology (Fig. 2) in TreeREx recovered the following events between the ancestral  
394 pancrustacean mitochondrial genome (including arrangement type 1 *Prionoglaris*)  
395 and the 6 derived conditions identified above (Figs 1 and 4):

396 A) a small TDRL involving a 4 gene block (CR to *trnM*) resulting in both the  
397 duplication of the CR, and the relative rearrangement of *trnQ* and *trnM* (TDRL I),



- 398 in the common ancestor of *Neotroglia* and *Speleketor* (Arrangement types 2 and  
399 3);
- 400 B) three rearrangement events including an inversion of *trnI*, transposition of *trnQ*,  
401 and a TDRL of an 7 gene block (*trnI* to *trnC*) (TDRL II) in the branch leading to  
402 *Speleketor* (Arrangement type 3);
- 403 C) an enormous TDRL involving duplication of almost the entire mt genome (33 of 37  
404 genes) and 14 separate block deletions ranging in size from 1 to 9 genes (65 –  
405 5200bp deletions) (TDRL III) in the ancestors of the *Echmepteryx–Dorypteryx*  
406 clade (Arrangement type 4) ;
- 407 D) a single translocation of *trnM* in the common ancestor of Psocomorpha and  
408 Troctomorpha (*Stimulopalpus*) (Arrangement types 5 and 6)
- 409 E) a single inversion (*trnI*) in *Stimulopalpus* (Arrangement type 5);
- 410 F) two moderate sized TDRLs (TDRL IV 8 genes, TDRL V 4 genes) in the ancestors  
411 of the Psocomorpha (Arrangement types 6 and 6');  
412 G) transposition of *trnE* in *Stenocaecilius* (Arrangement type 6').

413

414 In addition, there are two possible optimizations for the derived position of *trnM* in  
415 the clade *Stimulopalpus*+Psocomorpha (depicted by dotted line in Fig. 4). The  
416 transposition of *trnM* could have occurred in the ancestor of this clade or it could have  
417 transposed independently in *Stimulopapulus* and as part of the TDRL V event. The  
418 number of inferred random losses in TDRL V are the same (4) whether *trnM* was in  
419 the insect ancestral genome position or a derived position (*trnI-trnM-trnQ*) prior to this  
420 duplication.

421

## 422 **4. Discussion**

### 423 *4.1. Mito-phylogenomics*

424 The tree estimated from the mitochondrial genomic data agreed completely with  
425 those estimated previously from nuclear and mitochondrial Sanger gene sequencing  
426 (Fig. 2: Yoshizawa et al., 2006; Yoshizawa and Johnson, 2010, 2014). Most branches  
427 received 100% bootstrap support and posterior probability, except for branches that  
428 included taxa with missing data. Tree and support value differences from different  
429 data sets were also minimal. In some previous studies, the usefulness of

430 mitochondrial genomic data for estimating deep insect phylogeny has been  
431 questioned (e.g., Cameron et al., 2004 for interordinal relationships). However, for the  
432 case of our study of the free-living Psocodea (excluding Liposcelididae), the  
433 mitochondrial genome data seems to contain consistent signal for resolving deep  
434 phylogenetic relationships between and within suborders.

435 The only uncertainty and potential conflict with previous studies concerns the  
436 monophyly of Prionoglarididae. In a previous analysis, Prionoglaridae was recovered  
437 as a monophyletic group (Yoshizawa et al., 2006: fig. 2). However, most of the signal  
438 supporting its monophyly was from the nuclear *Histone 3* gene, in which the 3rd  
439 codon position shows extremely biased base composition (over 60% AT) for  
440 Prionoglarididae species compared to other trogiomorphans (20–34% AT in most  
441 cases: Yoshizawa and Johnson, 2010). Therefore, the monophyly of the family  
442 recovered in this prior analysis might be an artifact caused by the similarity of base  
443 composition. Subsequent analyses with denser taxon and/or gene sampling did not  
444 provide support for monophyly of Prionoglarididae (Yoshizawa et al., 2006: fig. 3;  
445 Yoshizawa and Johnson, 2014).

446 In the present analyses, the Prionoglarididae was consistently recovered as a  
447 monophyletic group (Fig. 2; Table 2). No obvious directional biases in substitution  
448 rate and base composition were identified in the present dataset (Fig. S3, Table S2).  
449 Although different datasets provided somewhat variable support values for this clade,  
450 they are consistently high. In addition, combining different datasets (e.g., PCG and  
451 RNA) provided increased support values (Table 2). Therefore, the mitochondrial data,  
452 including the highly variable 3rd codon position, seem to contain consistent signal  
453 supporting the monophyly of Prionoglarididae. Alternatively, although monophyly was  
454 also supported, support values for Prionoglarididae from the AA data were generally  
455 low (Table 2). This pattern of reduced nodal support for the same/highly similar  
456 topologies from mitochondrial AA datasets versus nucleotide coding of the same  
457 genes has been observed in other insect groups including Polyneoptera (Cameron et  
458 al. 2006), Orthoptera (Fenn et al. 2008), and Hymenoptera (Dowton et al. 2009a) and  
459 therefore is not surprising at the finer taxonomic scales considered in this study.

460

#### 461 4.2. Mitochondrial gene rearrangements



462 Seven types of mitochondrial genome arrangement were identified in the free-  
463 living Psocodea studied here (the extensively rearranged and modified mitochondrial  
464 genomes of Liposcelididae and Phthiraptera were excluded) (1–6 and 6' in Fig. 1). Of  
465 them, the condition identified in *Stenocaecilius* (type 6') can be simply formed from  
466 the condition identified in all other Psocomorpha (type 6) by a single rRNA  
467 transposition (*trnE*), and thus is regarded here as its sub-category (Fig. 1). Although  
468 mitochondrial gene rearrangements are recognized as rare-genomic change events  
469 (Boore et al., 1998; Rokas and Holland, 2000) and widely held to not result in  
470 homoplasious convergences, a couple of homoplasies were also evident between  
471 closely related members of Psocodea. In the following, we evaluate their gene  
472 rearrangement history by comparing the results from two different analytical  
473 strategies.

474

#### 475 4.2.1. Condition-based coding

476 The condition-based coding method here proposed can handle transpositions,  
477 inversions, and inverse-transpositions but cannot recognize more complicated TDRL  
478 events as it breaks them up into multiple observed novel gene-boundaries. Character  
479 coding and ancestral state reconstruction can be done without any specific  
480 mechanistic assumptions as to how genomes rearrange (e.g. the long-running  
481 discussion as to whether mitochondrial recombination occurs in animals or not: Mortiz  
482 et al. 1987; Downton & Campbell 2001; Kraytsberg et al. 2004; Ma & O'Farrell, 2015),  
483 which can be an advantage of this method. However, if different assumptions about  
484 the cause of rearrangements are applied, two alternative character-coding strategies  
485 are possible, potentially allowing a test of those assumptions. If deletion and insertion  
486 are recognized as simultaneous or a single event (e.g., as would be the case for  
487 recombination within a single mitochondrial genome molecule), then either only  
488 insertion or only deletion events should be coded. The consequences of such an  
489 approach can be seen in Fig. 3, where the insertion and deletion events are  
490 separately coded and the utility of each signal type can be clearly assessed. If  
491 insertion and deletion are recognized as different evolutionary events (e.g.,  
492 recombination between-molecules, which first causes an insertion, then a deletion  
493 follows; or as is proposed by the TDRL model), then both insertion and deletion

494 events may be coded. For example, the present analyses recovered possible  
495 remnants of the *trnI* and *trnM* genes in their ancestral position flanking *trnQ* in  
496 *Neotrogla* (Supplementary Fig. S2). This strongly suggests that the rearrangements  
497 in *Neotrogla* were not caused by within-molecule recombination, but rather that the  
498 insertions and deletions occurred as different evolutionary events.

499         However, the present results showed that inclusion of deletion characters for the  
500 ancestral state estimation is highly problematic, even if between-molecules  
501 recombination is an assumed mechanism of rearrangement. First, deletion events are  
502 more homoplasious, as has been demonstrated in other insect groups (e.g.  
503 Hymenoptera: Dowton et al., 2009b). If gene deletion is random with respect to the  
504 newly inserted and original copies, then a half of all deletion events should have  
505 occurred in the copy located at the original position. Aside from possibly a stretch of  
506 non-coding DNA, deletions of newly inserted genes will not leave any evidence of  
507 gene transposition, whereas deletions at the original location will always leave  
508 evidence of gene transposition in the form of a novel gene boundary between the  
509 genes flanking the deleted one. In addition, while there are 36 possible positions for  
510 gene insertions, we observe that some genes rearrange considerably more frequently  
511 than others, and thus deletions will cluster on these more mobile genes. For instance  
512 within the present set of taxa, *trnM* is rearranged in 5 of the 6 genome arrangement  
513 types, resulting in 5 instances of the deletion character state B. These heightened  
514 rates of transposition by particular tRNAs have been observed in other taxa giving  
515 rise to recognition of rearrangement hotspots (e.g. Dowton and Austin, 1999; Dowton  
516 et al., 2003) which are also recognized as sites of convergent rearrangements  
517 (Dowton et al., 2009b). Therefore, it is obvious that deletion events at the ancestral  
518 location are far more frequently observed than convergent insertion events and thus  
519 are more homoplasious.

520         Second and more importantly, homoplasies of deletion characters sometimes  
521 can cause very unlikely ancestral state reconstructions. Under both the between-  
522 molecules recombination and TDRL scenarios, an insertion event must precede the  
523 deletion event. However, for example, as seen in Fig. 3, deletion of *trnM* from  
524 between *trnQ* and *nad2* (Character B) is most parsimoniously interpreted to have  
525 occurred in the common ancestor of the Psocodea, which was followed by insertions

526 of *trnM* at multiple different positions in different psocodean lineages: Characters 2, 8,  
527 12 and 15, and reinsertion at its ancestral position in *Prionoglaris* (i.e. reversal of  
528 Character B). Therefore, for the most highly supported mitochondrial genome  
529 rearrangement models (i.e. between-molecules recombination, TDRL), insertion-only  
530 coding provides more accurate ancestral state estimation. If one needs to count the  
531 number of actual evolutionary events in the genomic history of a given group, then  
532 this can be accomplished by simply doubling the number of insertion events, because  
533 deletion events inevitably occurred following the corresponding insertion events.

534 The mitochondrial genome arrangement of *Prionoglaris* retains the ancestral  
535 pancrustacean condition (Fig. 1). Focusing only on the insertion events (i.e.,  
536 excluding Characters A–K in Fig. 3), four of the five recorded types of novel genome  
537 arrangement (2–6 in Fig. 1) were identified as originated independently from the  
538 ancestral pancrustacean mitochondrial genome. The majority (10 of 17) of insertion  
539 characters are thus autapomorphies. Character 1 (*trnI-trnM*) was homoplasious: it is  
540 shared by *Neotroglia* and the *Dorypteryx–Echmepteryx* clade, but their independent  
541 origins are quite obvious from the radically different genomic location of the *trnI-trnM*  
542 gene pair in these taxa (middle of the CR versus poly-tRNA block between *cox3* and  
543 *cox2*, respectively). Only one character (Character 2: *trnM*-CR) was interpreted as a  
544 synapomorphic change that groups taxa of different gene arrangement types (2 and 3  
545 in Fig. 1), suggesting multiple rounds of gene rearrangement through time, rather  
546 than direct rearrangement from the ancestral pancrustacean mitochondrial genome  
547 to the arrangement type seen in these extant genera. Character 2 also supports the  
548 close relationship between *Neotroglia* and *Speleketor* (currently grouped in the  
549 subfamily Speleketorinae: Lienhard, 2010). Finally, four synapomorphic insertions are  
550 identified in the common ancestor of the Psocomorpha (type 6), with only one  
551 psocomorphan lineage (*Stenocaecilius*, type 6') having a subsequent rearrangement  
552 (Character 17). The type 6' condition was also confirmed recently in a species of  
553 *Stenopsocidae* (*Stenopsocus immaculatus*: Liu et al., 2017), a member of the  
554 infraorder Caeciliusetae to which *Stenocaecilius* (Caeciliusidae) is also classified.  
555 Therefore, translocation of *trnE* may represent an autapomorphy of the infraorder.  
556 The mitochondrial genome of the common ancestor of Psocodea is thus estimated to  
557 have retained the pancrustacean ancestral condition. It is also evident from this result

558 that the extensive rearrangements observed in Psocodea and Thysanoptera have  
559 thus occurred independently.

560

#### 561 4.2.2. TreeREx analyses

562 TreeREx software considers tandem-duplication-random-loss (TDRL) as well as  
563 transpositions, inversions, and inverted-transpositions (termed 'reverse-  
564 transpositions' in the software, however this is less precise and can be misinterpreted  
565 as transpositions back to an ancestral gene position, i.e. a character reversal in the  
566 cladistics sense). Estimation of TDRL events is much harder to recover without the  
567 aid of software like CREx or TreeREx (Bernt et al., 2007, 2008). TDRL events cannot  
568 be coded using the condition-based coding method. Because of this difference, the  
569 rearrangement histories estimated from the condition-based coding and TreeREx  
570 analyses are quite different. However, by both estimations, each type of genome  
571 arrangement identified in the free-living Psocodea originated via unique history. The  
572 mitochondrial genome arrangement of the common ancestor of Psocodea was  
573 estimated to retain the ancestral pancrustacean condition also by TreeREx. By using  
574 the condition-based matrix, a single transposition event (Character 2: *trnM*) was  
575 identified as synapomorphic between *Speleketor* and *Neotrogla*, and TreeREx also  
576 recovered a shared TDRL event between them. TreeREx identified that, from the  
577 ancestral condition of *Neotrogla* and *Speleketor* (type 2), the condition of *Speleketor*  
578 (type 3) was established by one inversion (*trnI*), one transposition (*trnQ*), and one  
579 TDRL (TDRL II: Fig. 1) (see Results). However, the arrangement of *Speleketor* can  
580 also be achieved by transposition of *trnC* and inverted-transposition of *trnI* only,  
581 without any TDRL event. The former less parsimonious output may potentially be  
582 caused by incomplete input data: i.e., duplicated CR in *Speleketor* and *Neotrogla* not  
583 coded (Supplementary Data S3).

584 In contrast, while the condition-based analysis did not recover any shared  
585 rearrangement event between *Stimulopalpus* and Psocomorpha, TreeREx recovered  
586 a transposition of *trnM* as a shared event. However, there is also an equally  
587 parsimonious scenario: occurrence of transposition of *trnM* in *Stimulopalpus*, while  
588 TDRL V from the ancestral insect genome arrangement (Fig. 1) in Psocomorpha can  
589 also explain the final arrangement types with exactly the same numbers of

590 transposition (1), tandem duplication (1) and independent loss (4) events.

591

#### 592 4.2.3. Conclusion

593 Both methods (character-based coding and TreeREx) provided similar  
594 conclusions for the ancestral states of the mitochondrial genome arrangement (Figs  
595 3–4). The effectiveness of these methods cannot be compared directly (e.g.  
596 comparing identified number of events by a parsimony criterion) because the different  
597 methods use different assumptions for the mechanism of mitochondrial gene  
598 rearrangements. Nevertheless, as mentioned above, incorporation of deletion  
599 characters into the condition-based matrix involves higher risk of inferring incorrect  
600 historical reconstructions and thus should be avoided regardless of the assumed  
601 evolutionary mechanisms. The character-based coding method is straightforward,  
602 and the constructed matrix can be used directly for ancestral state reconstruction,  
603 which provided quite reasonable conclusions in the present case. Each character in  
604 the matrix can be considered as an evolutionary event so that the data matrix  
605 constructed by the condition-based coding can also be used for phylogenetic  
606 estimation. A drawback of the condition-based coding is that it cannot handle TDRL  
607 events.

608 In contrast, TreeREx considers TDRL as well and estimates the rearrangement  
609 history directly from the gene order data, without specific character coding. The  
610 present analyses, however, recovered some potential flaws of the present TreeREx  
611 algorithm. First, TreeREx does not allow the existence of duplicated gene in the input  
612 data. Possibly because of this, an apparently less-parsimonious interpretation was  
613 obtained for the rearrangement history of *Speleketor*. In addition, TreeREx only  
614 outputs a single result, even if there are equally parsimonious possibilities (TreeREx  
615 output ACCTAN-type reconstruction, although DELTRAN-type reconstruction is  
616 also possible for the transposition of *trnM* in *Stimulopalpus* and Psocomorpha: Fig. 4).  
617 Such possibilities must be manually examined based on the phylogenetic  
618 relationships and TreeREx output.

619 Plausibility of different mechanistic assumptions should also be evaluated, not  
620 only by parsimony criterion, but also by detailed mitochondrial genome analyses, with  
621 dense taxon sampling and strong phylogenetic backbone. Previous evidence has

622 favored the TDRL model (Dowton et al., 2009; Beckenbach, 2011) but, in the present  
623 case, the inversion of *trnI* cannot be explained by TDRL. Alternatively, the presence  
624 of a potential *trnI* remnant in *Neotroglia* cannot be explained by within-molecule  
625 recombination. The between-molecule recombination model can explain both, but  
626 this does not overwhelmingly favor that model because each rearrangement event  
627 might have been caused by different mechanisms. The present study showed that  
628 more highly rearranged mitochondrial genomes can still be quite consistent within  
629 higher taxa (i.e., *Echmepteryx–Dorypteryx* clade which includes all trogiomorphs  
630 except Prionoglarididae, and Psocomorpha from which all major clades were  
631 sampled). Therefore, their intermediate genome arrangements cannot be recovered  
632 from the extant species. In contrast, variation was identified within the family  
633 Prionoglarididae. Only three representatives of Prionoglarididae were included in the  
634 present analyses, and there are more genera not analyzed here (e.g., *Sensitibilla* and  
635 *Afrotroglia* considered close to *Neotroglia*, and *Siamoglaris* and *Speleopsocus*  
636 considered close to *Prionoglaris*) each of which includes multiple species (except for  
637 the monotypic *Speleopsocus*). In addition, only a single species (*Stimulopalpus*) was  
638 analyzed from the primitive members of the suborder Troctomorpha (i.e., excluding  
639 highly derived Liposcelididae), although there are seven more families in this group.  
640 Analyses of these taxa may provide further clues to evaluate mitochondrial  
641 rearrangement history and mechanisms in the Psocodea.

642

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644

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823

824 **Captions**

825 Fig. 1. Seven types of the mitochondrial gene arrangements detected from  
826 "Psocoptera". Numbers indicate novel gene boundary possibly caused by  
827 insertion events, whereas alphabets indicate possible deletion events  
828 (condition-based coding: see Fig. 3). Red dotted lines under genome map  
829 indicate tandem-duplication-random-loss events (TDRL) identified by TreeREx  
830 analysis (see Fig. 4).

831 Fig. 2. Mitochondrial phylogeny of the "Psocoptera" estimated from ALL dataset.  
832 Numbers associated with branches indicate bootstrap/posterior probability  
833 values estimated from this data set. Support values for Prionoglarididae  
834 estimated from other datasets are provided in Table 2.

835 Fig. 3. Most parsimonious reconstruction of the condition-based coding data of the  
836 mitochondrial gene arrangements. Numbers (gain condition, filled square or  
837 triangle) and alphabets (loss condition, open square or triangle) on branches  
838 corresponds those scored in Fig.1. Square indicates non-homoplasious  
839 condition whereas triangle indicates homoplasious condition. Numbers  
840 associated to taxa corresponds the gene arrangement types in Fig. 1.

841 Fig. 4. Gene rearrangement history as estimated by TreeREx software. See Result  
842 section for detailed rearrangement events. Equally parsimonious  
843 interpretations are indicated by gray dotted line. A–E correspond to  
844 evolutionary events discussed in the text. Abbreviations: Inv.–inversion; TD–  
845 tandem duplication; Trans–transposition.

846

847 Table 1. List of taxa analyzed in this study, with GenBank accession numbers

848 Table 2. Support values for Prionoglarididae estimated from different gene and taxon  
849 sets with different analytical methods.

850

851 **Supplements**

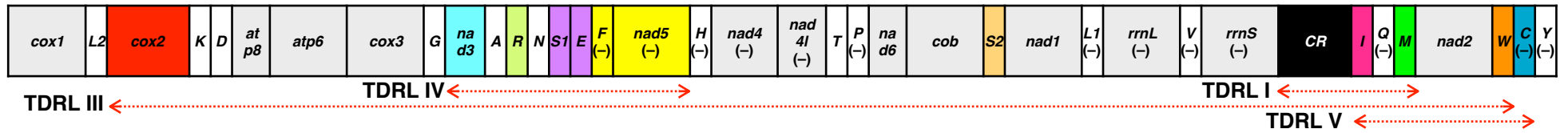
852 Data S1. Nexus file of aligned mitochondrial data.

853 Data S2. Nexus file of the condition-base coding data of gene arrangements.

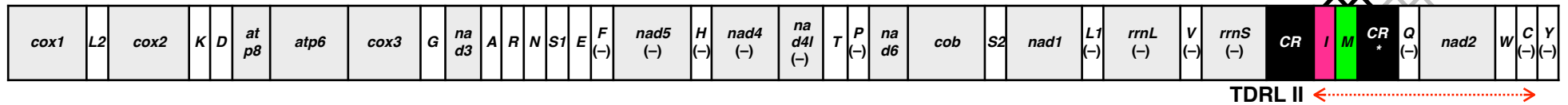
854 Data S3. Input data for the TreeREx analysis. Taxa showing the identical genome  
855 arrangement were treated as a single terminal taxon.

856 Table S1. Primers used for long PCR.  
857 Table S2. Gene annotations.  
858 Table S3. AT-content of each gene/taxon.  
859 Fig. S1. Repeat units between *trnM* and *-trnQ* of *Neotroglia*.  
860 Fig. S2. Hairpin structure between *trnI* anticodon arm and potential *trnI* ruminant  
861 detected in *Neotroglia*.  
862 Fig. S3. Plots of p-distance calculated from different data sets (taxa with missing data  
863 excluded)

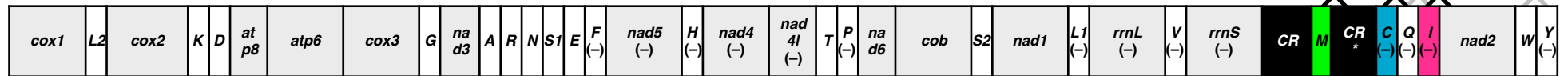
(1) *Prionoglaris* = Ancestral Condition of Pancrustacea



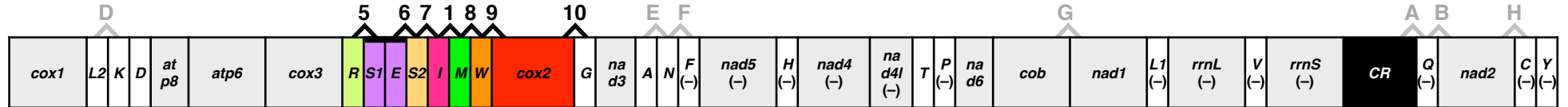
(2) *Neotroglia*



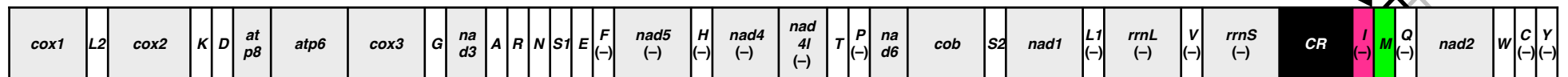
(3) *Speleketor*



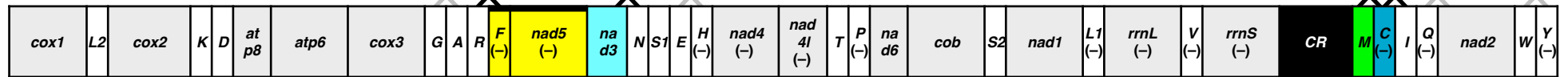
(4) *Trogiomorpha* ex. *Prionoglarididae*



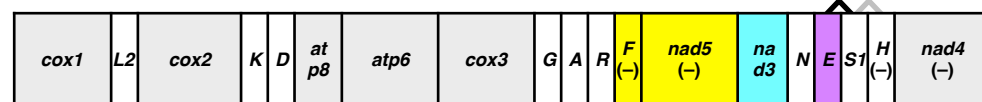
(5) *Stimulopalpus*

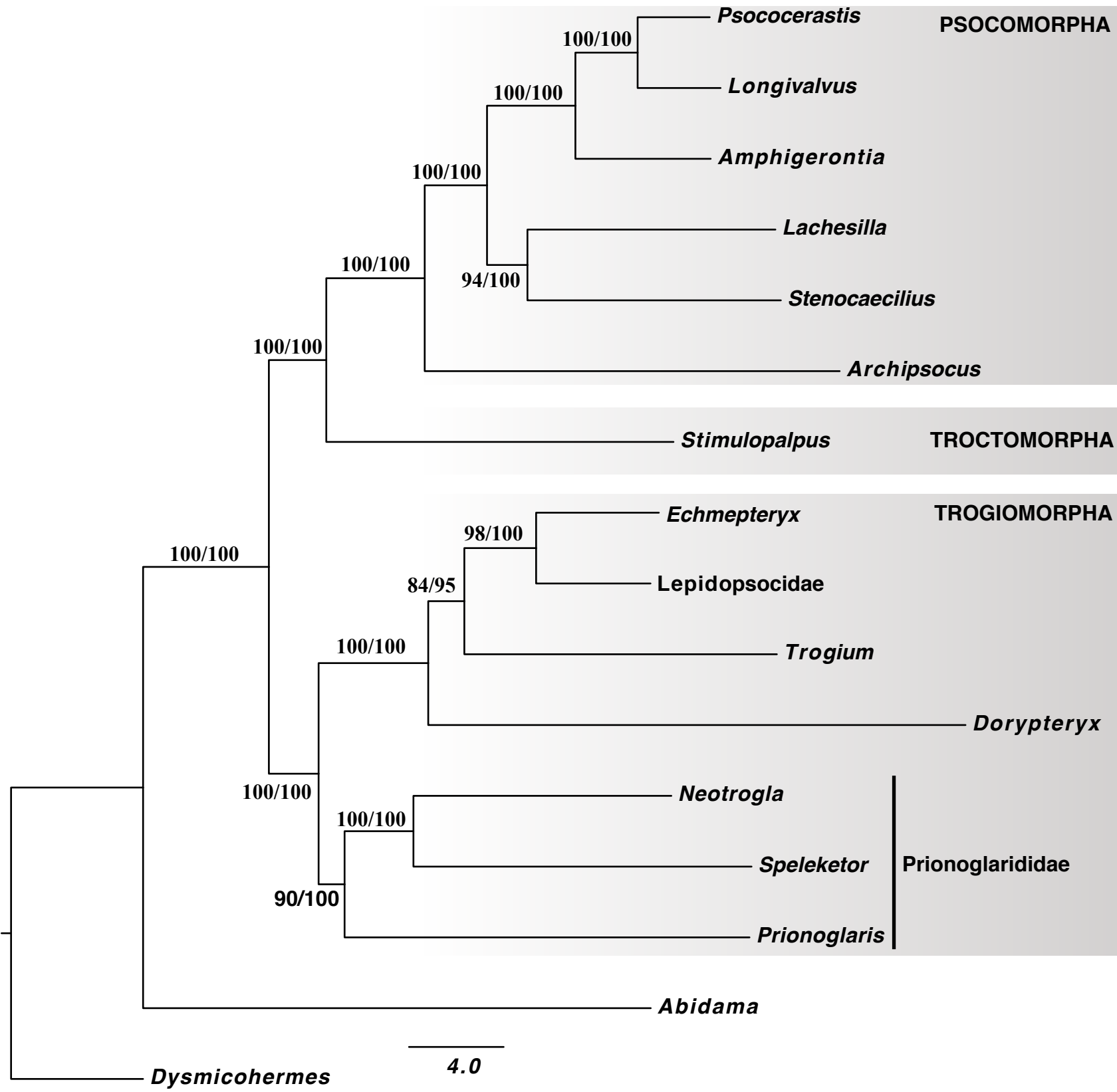


(6) *Psocomorpha* ex. *Stenocacilius*

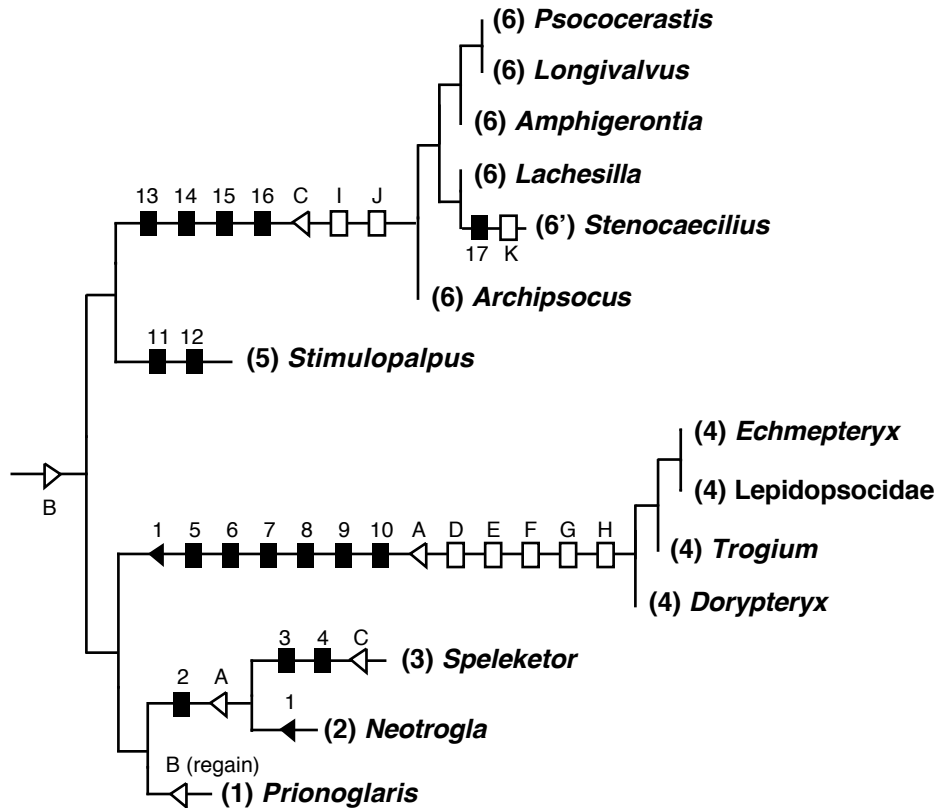


(6') *Stenocacilius*









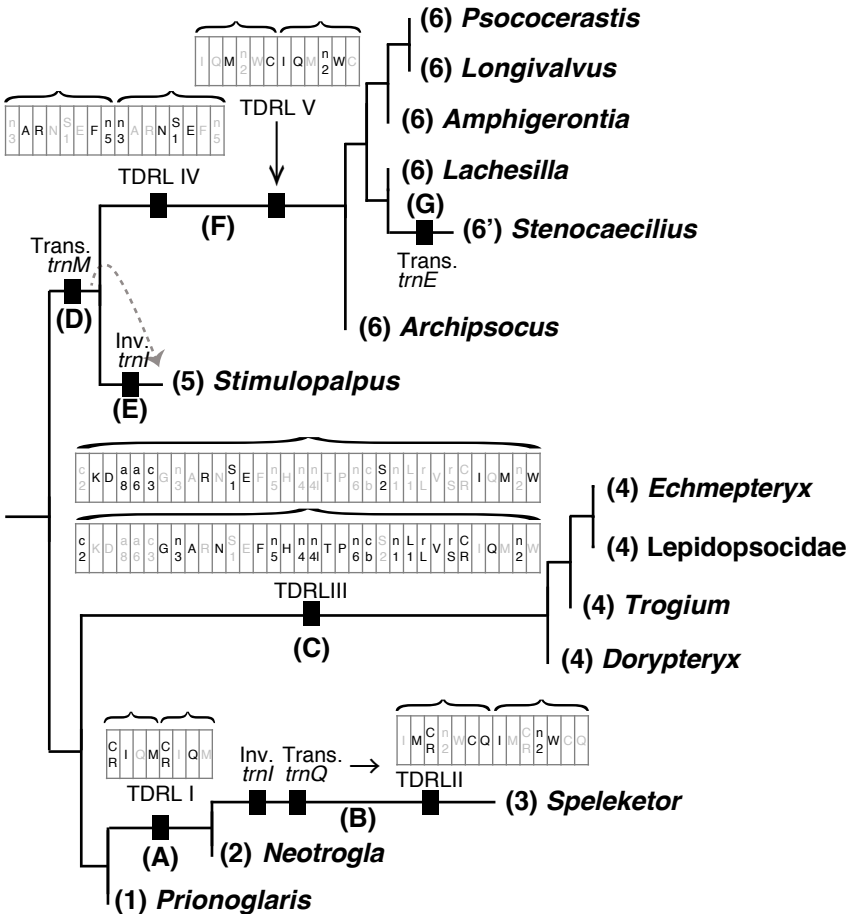


Table 1. List of taxa analyzed in this study, with GenBank accession numbers

Order	Suborder	Family	Genus	Species	Locality	GenBank #
Psocodea	Trogiomorpha	Prionoglarididae	<i>Prionoglaris</i>	<i>stygia</i>	Luxembourg	given upon acceptance
			<i>Neotrogl</i>	sp.	Brazil: Minas Gerais	given upon acceptance
			<i>Speleketor</i>	<i>irwini</i>	USA: California	given upon acceptance
		Psyllipsocidae	<i>Dorypteryx</i>	<i>domestica</i>	Switzerland: Geneva	given upon acceptance
		Trogiidae	<i>Trogium</i>	<i>pulsatorium</i>	United Kingdom: Sussex	given upon acceptance
		Lepidopsocidae	<i>Genus</i>	sp.	GenBank	NC004816
			<i>Echmepteryx</i>	<i>hageni</i>	USA: Illinois	given upon acceptance
	Troctomorpha	Amphientomidae	<i>Stimulopalpus</i>	<i>japonicus</i>	USA: Illinois	given upon acceptance
	Psocomorpha	Archipsocidae	<i>Archipsocus</i>	<i>nomas</i>	USA: Florida	given upon acceptance
		Caeciliusidae	<i>Stenocaecilius</i>	<i>quercus</i>	GenBank	AH010776.3
		Lachesillidae	<i>Lachesilla</i>	<i>anna</i>	USA: Illinois	given upon acceptance
		Psocidae	<i>Amphigerontia</i>	<i>montivaga</i>	USA: Arizona	given upon acceptance
			<i>Psococerastis</i>	<i>albimaculata</i>	GenBank	JQ910989
			<i>Longivalvus</i>	<i>hyalospilus</i>	GenBank	JQ910986
Hemiptera	Auchenorrhyncha	Cercopidae	<i>Abidama</i>	<i>producta</i>	GenBank	GQ337955
Megaloptera	–	Corydalidae	<i>Dysmicohermes</i>	<i>ingens</i>	GenBank	KJ806318

taxon\data set	All	ex.3rd	RNA	PCG	PCG12	AA
MrBayes_Full	100	100	100	99.4	98.1	98.8
exMissing	100	100	100	99.6	98.7	100
IQtree_Full	90	93	88	72	70	56
exMissing	90	91	81	75	75	70
PhyloBayes_Full	99	99	99	86	80	62

-1 CR-*trnI-trnM*-GRAATDAAGCAGGAATAA-TA---T  
 -2 AAAGGGGMATADTATTAKGAATGAAGCAGGAMTAA-YA---T  
 -3 AAAGGGGCATARTATTAGGAATGAAGCAGGAATAA-T-----  
 -4 -----GGCATAGTATTAGRAATGAAGCAGGAMTAACTAATAT  
 -5 AAAGGGGAATATTAYTATGAATGAAGCAGGAMTAA-TGRCAT

6 AAAGGGGCATAGTATTAGGAATGAAGCAGGAATAA-TA---T  
 5 AAAGGGGCATAGTATTAGGAATGAAGCAGGAATAACTAATAT  
 4 AAAGGGGAATATTATTATGAATGAAGCAGGACTAA-TA-CAT  
 3 AAAGGGGCATAGTATTAGGAATGAAGCAGGAATAA-TA---T  
 2 AARGGGGCATARTATTAGGAATGAAGCAGGAATAA-TA---T  
 1 AAAGGGGCATAGTATTAGGAATGAAGCAGGACTA-CTA-TAT

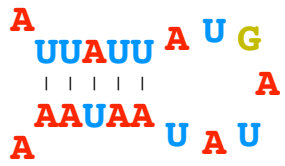
- [97 bp of non-coding region  
 not homologous to the repeat units] -*trnQ*.

repeat8: L-unit (\* and #: repeats within L-unit)

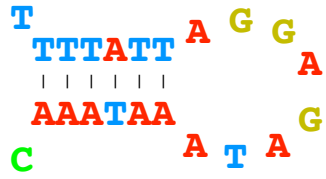
\*\*\*\*\*##### \*\*\*\*\* #####

AAAGGGGCATAGTATGAAGCAGGAATAATGGCATAGTATTAGGAATGAAGCAGGAATAACTAATAT  
 AAAGG-----GGCATAGTATTAGGAATGAAGCAGGAATAACTAATAT

repeat5: S-unit



anticodon arm of *tRNA*



potential remnant of *tRNA*

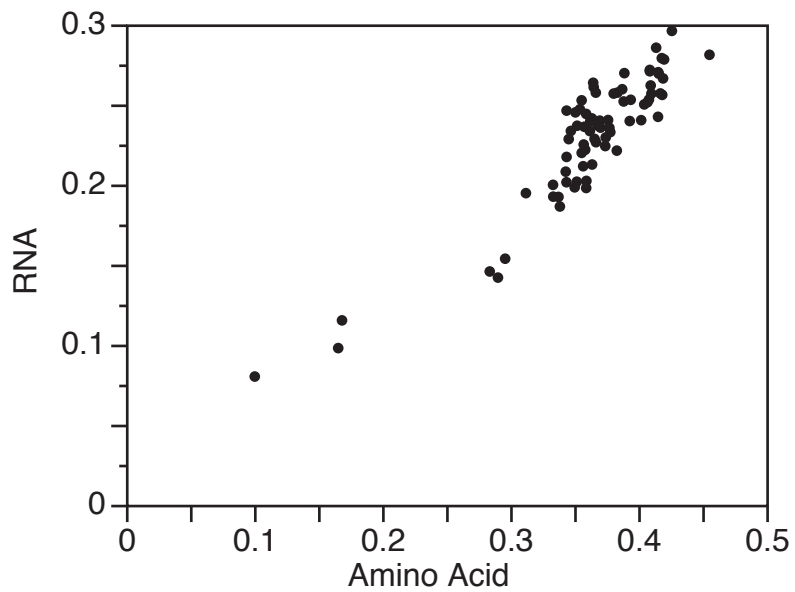
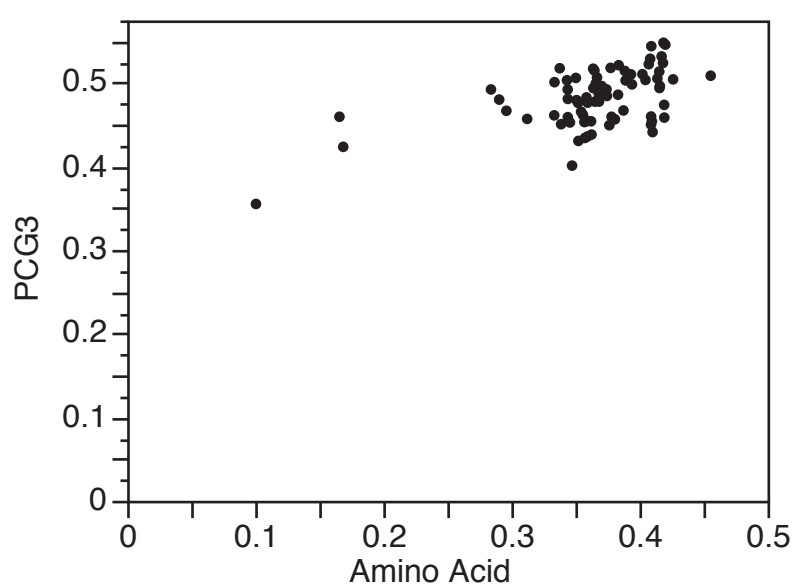
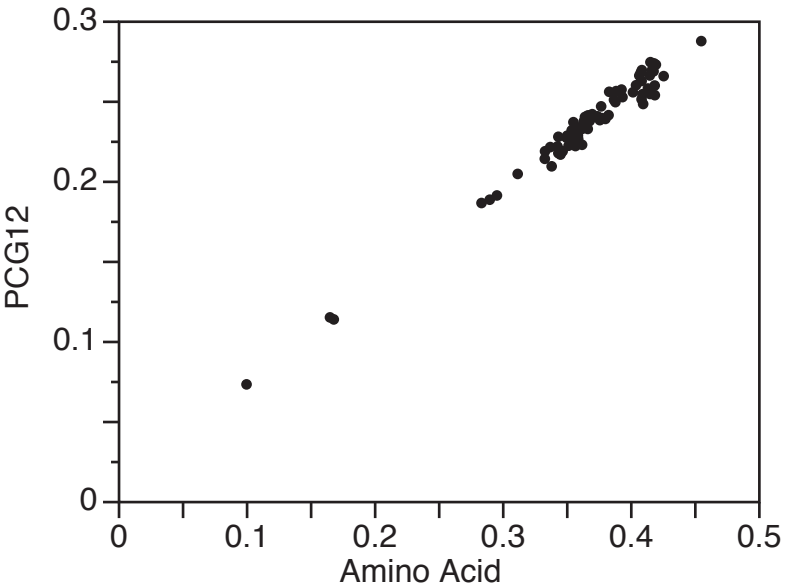


Table S1a. Long PCR Primers, sequence and location, for *Stimulopalpus japonicus*.

Region	Primer Pair (F & R)	Sequence (5' →3')
Long PCRs		
<i>trnM</i> → <i>cox1</i>	PSOC4 <sup>1</sup>	AAG CTW WTG GGY TCA TAC CYC
	STJA35 <sup>2</sup>	TTA ATC CCT GTA GGG ATA GC
<i>cox1</i> → <i>cox3</i>	C1-J-1718 <sup>3</sup>	GGA GGA TTT GGA AAT TGA TTA GTT CC
	C3-N-5460 <sup>3</sup>	TCA ACA AAG TGT CAG TAT CA
<i>cox3</i> → <i>nad4</i>	STJA2 <sup>5</sup>	TCA AGG ATT TGA ATA TTG AGA AGC
	STJA3 <sup>5</sup>	TCA GCC TGA GCG AAT TCA GGC TGG
<i>nad4</i> → <i>cytB</i>	N4-J-8944 <sup>3</sup>	GGA GCT TCA ACA TGA GCT TT
	cobR <sup>4</sup>	GCA TAA GCA AAT AAA AAA TAT CAT TC
<i>cytB</i> → <i>rrnL</i>	STJA6 <sup>2</sup>	ATT GAT AAA ATC CCA TTC CAT CC
	STJA7 <sup>2</sup>	TTT AAT AAG GGA CGA GAA GAC CC
<i>rrnL</i> → <i>rrnS</i>	16SB <sup>5</sup>	CTC CGG TTT GAA CTC AGA TCA
	SR-N-14594 <sup>6</sup>	AAA CTA GGA TTA GAT ACC C

<sup>1</sup> Primers designed from consensus sequences, for general amplification of Psocoptera

<sup>2</sup> Primers specifically designed for sequencing this genome

<sup>3</sup> Primers taken from Simon *et al.* (1994)

<sup>4</sup> Primers taken from Whiting (2002)

<sup>5</sup> Primers taken from Bybee *et al.* (2004)

<sup>6</sup> Primer taken from Skerratt *et al.* (2002)



Table S1b. Long PCR Primers, sequence and location, for *Amphigerontia montivaga*.

Region	Primer Pair (F & R)	Sequence (5' →3')
Long PCRs		
<i>cox1</i> → <i>cox3</i>	C1-J-1718 <sup>3</sup>	GGA GGA TTT GGA AAT TGA TTA GTT CC
	C3-N-5460 <sup>3</sup>	TCA ACA AAG TGT CAG TAT CA
<i>cox3</i> → <i>rrnL</i>	AMMO4 <sup>2</sup>	TGC CGA TTC AAT TTA TGG ATC GTC G
	AMMO5 <sup>2</sup>	TTA AAA GAC GAG AAG ACC CTA TAG
<i>rrnL</i> → <i>rrnS</i>	16SB <sup>5</sup>	CTC CGG TTT GAA CTC AGA TCA
	SR-N-14594 <sup>6</sup>	AAA CTA GGA TTA GAT ACC C
<i>rrnS</i> → <i>cox1</i>	AMMO8 <sup>2</sup>	TAG AAA GAG AAT GAC GGG CAA TAT G
	AMMO1 <sup>2</sup>	ATC AAC TGA TGC TCC TGT ATG TCC

<sup>1</sup> Primers designed from consensus sequences, for general amplification of Psocoptera

<sup>2</sup> Primers specifically designed for sequencing this genome

<sup>3</sup> Primers taken from Simon *et al.* (1994)

<sup>4</sup> Primers taken from Whiting (2002)

<sup>5</sup> Primers taken from Bybee *et al.* (2004)

<sup>6</sup> Primer taken from Skerratt *et al.* (2002)

Table S1c. Long PCR Primers, sequence and location, for *Lachesilla anna*.

Region	Primer Pair (F & R)	Sequence (5' →3')
Long PCRs		
<i>cox2</i> → <i>nad4</i>	FLeu <sup>4</sup>	TCT AAT ATG GCA GAT TAG TGC
	LAAN1 <sup>5</sup>	TTG TTT AAA AGA GTA GGT TCC TCC
<i>nad4</i> → <i>cytB</i>	N4-J-8944 <sup>3</sup>	GGA GCT TCA ACA TGA GCT TT
	cobR <sup>4</sup>	GCA TAA GCA AAT AAA AAA TAT CAT TC
<i>cytB</i> → <i>rrnL</i>	LAAN4 <sup>2</sup>	TTG ATA AAG CCT CTT TTC ATC CC
	LAAN5 <sup>2</sup>	TTA AAA GAC GAG AAG ACC CTA TAG
<i>rrnL</i> → <i>rrnS</i>	16SB <sup>5</sup>	CTC CGG TTT GAA CTC AGA TCA
	SR-N-14594 <sup>6</sup>	AAA CTA GGA TTA GAT ACC C
<i>rrnS</i> → <i>cox2</i>	LAAN8 <sup>2</sup>	AGA GAA TGA CGG GCA ATA TGT GC
	LAAN11 <sup>2</sup>	ACA AAA TAC GGA GGG AAG GTA GGG C

<sup>1</sup> Primers designed from consensus sequences, for general amplification of Psocoptera

<sup>2</sup> Primers specifically designed for sequencing this genome

<sup>3</sup> Primers taken from Simon *et al.* (1994)

<sup>4</sup> Primers taken from Whiting (2002)

<sup>5</sup> Primers taken from Bybee *et al.* (2004)

<sup>6</sup> Primer taken from Skerratt *et al.* (2002)

Table S1d. Long PCR Primers, sequence and location, for *Archipsocus nomas*.

Region	Primer Pair (F & R)	Sequence (5' →3')
Long PCRs		
<i>trnM</i> → <i>cox1</i>	ARNO7 <sup>2</sup>	ACG TTT TTT TCA ATT TTA CCC CGG
	RLys <sup>4</sup>	GAG ACC AGT ACT TGC TTT CAG TCA TC
<i>cox2</i> → <i>nad4</i>	ARNO11 <sup>2</sup>	TGC CCT TAC TGT CAA AAC TAT TGG TC
	ARNO19 <sup>2</sup>	AAC CTA AAG GGT TGG AAG AAC CTG
<i>nad4</i> → <i>rrnL</i>	N4-J-8944 <sup>3</sup>	GGA GCT TCA ACA TGA GCT TT
	ARNO3 <sup>4</sup>	TTT ATG GCG AAT TTA ATT GGG GTG
<i>rrnL</i> → <i>rrnS</i>	16SB <sup>5</sup>	CTC CGG TTT GAA CTC AGA TCA
	SR-N-14594 <sup>6</sup>	AAA CTA GGA TTA GAT ACC C
<i>rrnS</i> → <i>trnM</i>	ARNO4 <sup>2</sup>	ATA TTG CCA GTA AGA TAA TCG TGG
	TM-N-193 <sup>3</sup>	TGG GGT ATG AAC CCA GTA GC

<sup>1</sup> Primers designed from consensus sequences, for general amplification of Psocoptera

<sup>2</sup> Primers specifically designed for sequencing this genome

<sup>3</sup> Primers taken from Simon *et al.* (1994)

<sup>4</sup> Primers taken from Whiting (2002)

<sup>5</sup> Primers taken from Bybee *et al.* (2004)

<sup>6</sup> Primer taken from Skerratt *et al.* (2002)

Table S1e. Long PCR Primers, sequence and location, for *Speleketor irwini*.

Region	Primer Pair (F & R)	Sequence (5' →3')
Long PCRs		
<i>trnM</i> → <i>cox1</i>	TM-J-206 <sup>3</sup>	TGG GGT ATG AAC CCA GTA GC
	SPIR1 <sup>2</sup>	AAG GAG GAT AGA CTG TTC ATC CTG
<i>cox1</i> → <i>cox3</i>	C1-J-1718 <sup>3</sup>	GGA GGA TTT GGA AAT TGA TTA GTT CC
	C3-N-5460 <sup>3</sup>	TCA ACA AAG TGT CAG TAT CA
<i>cox3</i> → <i>rrnL</i>	SPIR4 <sup>2</sup>	ACT ATT ACA TGA GCT CAC CAT GCA C
	SPIR5 <sup>2</sup>	TTT ACA TGG AAA GGG TAT TGA AGG
<i>rrnL</i> → <i>rrnS</i>	16SB <sup>5</sup>	CTC CGG TTT GAA CTC AGA TCA
	SR-N-14594 <sup>6</sup>	AAA CTA GGA TTA GAT ACC C
<i>rrnS</i> → <i>trnM</i>	SPIR6 <sup>2</sup>	TAT AGT CTG CAC CTT GAC CTG AC
	TM-N-193 <sup>3</sup>	TGG GGT ATG AAC CCA GTA GC

<sup>1</sup> Primers designed from consensus sequences, for general amplification of Psocoptera

<sup>2</sup> Primers specifically designed for sequencing this genome

<sup>3</sup> Primers taken from Simon *et al.* (1994)

<sup>4</sup> Primers taken from Whiting (2002)

<sup>5</sup> Primers taken from Bybee *et al.* (2004)

<sup>6</sup> Primer taken from Skerratt *et al.* (2002)

Table S1f. Long PCR Primers, sequence and location, for *Echmepteryx hageni* and *Trogium pulsatorium*.

Region	Primer Pair (F & R)	Sequence (5' →3')
Long PCRs		
<i>cox3</i> → <i>nad4</i>	PSOC1 <sup>1</sup>	TTG AAG CNG CWG CHT GRT AYT GAC
	PSOC2 <sup>1</sup>	AAR GCT CAT GTK GAR GCW CC

<sup>1</sup> Primers designed from consensus sequences, for general amplification of Psocoptera