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1 **MICROSATELLITE DEVELOPMENT IN RHODOPHYTA**
2 **USING HIGH-THROUGHPUT SEQUENCE DATA**

3

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11

12 Shotgun genome sequencing is rapidly emerging as the method of choice for the identification
13 of microsatellite loci in nonmodel organisms. However, to the best of our knowledge, this
14 approach has not been applied to marine algae so far. Herein, we report the results of using the
15 454 next-generation sequencing (NGS) platform to randomly sample 36.0 and 40.9 Mbp
16 (139,786 and 139,795 reads, respectively) of the genome of two red algae from the northwest
17 Iberian Peninsula [*Grateloupia lanceola* (J. Agardh) J. Agardh and a still undescribed new
18 member of the family Cruoriaceae]. Using data mining tools, we identified 4,766 and 5,174
19 perfect microsatellite loci in 4,344 and 4,504 sequences / contigs from *G. lanceola* and the
20 Cruoriaceae, respectively. After conservative removal of potentially problematic loci
21 (redundant sequences, mobile elements), primer design was possible for 1,371 and 1,366 loci,
22 respectively. A survey of the literature indicates that microsatellite density in our Rhodophyta
23 is at the low end of the values reported for other organisms investigated with the same
24 technology (land plants and animals). A limited number of loci were successfully tested for
25 PCR amplification and polymorphism finding that they may be suitable for population genetic

26 studies. This study demonstrates that random genome sequencing is a rapid, effective
27 alternative to develop useful microsatellite loci in previously unstudied red algae.

28

29 **Key index words:** 454 sequencing; conservation genetics; expressed sequence tags;
30 microsatellite development; primer design; Rhodophyta; seaweed

31 **Abbreviations:** bp, base pairs; ESTs, expressed sequence tags; GS-FLX, Genome Sequencer
32 FLX; Mbp, mega base pairs; MIDs, multiplex identifiers; NGS, next-generation sequencing;
33 PAL, potentially amplifiable loci; TE, Tris-EDTA

34

35 Population genetics studies are an important tool for developing effective management
36 strategies for endangered species (Frankham et al. 2004). However, obtaining appropriate
37 molecular markers—a prerequisite for such studies—often becomes a limiting step. This is the
38 case for microsatellites. Although they are often considered the marker of choice for population
39 genetics analysis due to their high levels of polymorphism and codominant nature, their de novo
40 development is a costly and time-consuming endeavor (Zane et al. 2002). These difficulties
41 have acted in many cases as a deterrent for the utilization of these markers, particularly in poorly
42 studied taxonomic groups (Squirrell et al. 2003).

43 The recent accessibility to NGS technologies is revolutionizing life sciences in several research
44 fields (reviewed in Hudson 2008). Even though NGS is typically cited as a fast and cheap route
45 to assemble genomes or transcriptomes, it also provides avenues to many broader purposes,
46 including marker development (Thomson et al. 2010). In particular, high-throughput
47 sequence data from the Roche 454 platform offer the potential for a rapid identification of
48 microsatellite loci on nonmodel organisms, and several examples of this have been published
49 already (Abdelkrim et al. 2009, Allentoft et al. 2009, Santana et al. 2009, Castoe et al. 2010,
50 Csencsics et al. 2010). Briefly, the Genome Sequencer FLX System (GS-FLX) powered by 454
51 sequencing (454 Life Sciences, Branford, CT, USA) enables a random and extensive survey of

52 the genome providing thousands of short reads (average length of 400 bp using GS-FLX
53 Titanium Series Reagents). This huge data set of reads is then screened with simple
54 bioinformatic tools to detect microsatellite motifs and to design PCR primers. Thus, this
55 approach eliminates the prolonged, expensive, and laborious steps of constructing genomic
56 libraries, including cloning, hybridization to detect positive clones, plasmid isolation, and
57 Sanger sequencing. Herein, we report the results obtained by applying this approach to two
58 Rhodophyta of conservation concern in Galicia (northwest Iberian Peninsula): *G. lanceola* and
59 a still undescribed new member of the Cruoriaceae. Compared to other taxa, seaweeds have not
60 been traditionally included in the debate about endangered species. However, there is a growing
61 recognition that many seaweeds are restricted in their
62 distribution and may thus be vulnerable to stochastic environmental and anthropogenic events
63 (Brodie et al. 2009). The two species studied herein are candidates for inclusion in the regional
64 catalog of endangered species (Xunta de Galicia 2007). In Galicia, *G. lanceola* occurs in only
65 a few (<30) enclaves mostly concentrated in 30 km of coastline (Peez-Cirera et al. 1989,
66 Ba' rbara and Cremades 2004). Besides their regional rarity, these populations possess
67 biogeographic value derived from their marginality and isolation (Eckert et al. 2008) (Galician
68 populations are located > 1,000 km north of the species' main range in the Atlantic coast of
69 Africa). The conservation status of the second species also deserves attention. Its Galician
70 populations were traditionally identified as *Furcellaria lumbricalis* (Huds.) J. V. Lamour., a
71 common inhabitant of northern latitudes with a southern limit of distribution in the Iberian
72 Peninsula (Pe' rez-Cirera 1975, Granja et al. 1993). However, some anatomical peculiarities
73 led us to produce DNA sequence data to determine its taxonomic identity. Surprisingly, both
74 plastid (*rbcl*) and nuclear (*rDNA* LSU) gene sequences have revealed that the plant found in
75 Galicia is a still undescribed erect member of the Cruoriaceae family (unpublished results). Its
76 limited presence in Galicia (it is known only from 12 enclaves, Barbara et al. 2006) renders this
77 new species an interesting case to investigate its population structure and, eventually, to

78 determine its suitability for inclusion in the regional catalog of seaweeds of conservation
79 concern. Previous experience with conventional protocols for microsatellite isolation suggests
80 that seaweeds may display comparably low genomic frequencies of microsatellites (Wattier and
81 Maggs 2001, Andreakis et al. 2007). Since we were particularly interested in discovering
82 whether or not the use of NGS technology will still support this conventional wisdom, our
83 results with the 454 technology are compared to those for other taxa obtained using comparable
84 high-throughput approaches.

85

86 **MATERIALS AND METHODS**

87

88 DNA extraction and pyrosequencing. For each species, a single specimen was used as the sole
89 source of tissue/DNA. Prior to DNA extraction, samples were frozen in liquid nitrogen and
90 homogenized using a mechanical tissue disrupter (Mini-Bead- beater 1; Bio Spec Products Inc.,
91 Bartlesville, OK, USA) and steel beads. Total DNA was then extracted with the Wizard
92 Magnetic 96 DNA Plant System (Promega Corp., Madison, WI, USA) following
93 manufacturer's recommendations. To achieve the required amount of DNA, multiple DNA
94 isolations from each specimen were pooled, lyophilized, resuspended in Tris- EDTA (TE)
95 buffer, and purified with QIAquick PCR Purification kit (Qiagen Sciences Inc., Germantown,
96 MD, USA).

97 A total of 2–5 lg of DNA from each species was used to prepare their respective GS-FLX
98 Titanium general libraries (454 Life Sciences) following manufacturer's protocols and quality
99 control steps. Briefly, genomic DNA was fragmented by nebulization, small DNA fragments
100 (<350 bp) were removed, short adaptors were ligated to the ends of each fragment, and, finally,
101 only those fragments with adaptors in both 5' and 3' ends were retained. Each DNA sample
102 was appropriately tagged using two different multiplex identifiers (MIDs) to enable pooling for
103 simultaneous sequencing. DNA library fragments were then captured onto beads and clonally

104 ampli- fied within individual emulsion droplets (emPCR). Finally, amplified fragments from
105 both species were evenly mixed and sequenced on ¼ PicoTiterPlate regions using the Titanium
106 GS-FLX chemistry (454 Life Sciences). Libraries preparation, amplification, and sequencing
107 were carried out at the external facilities Centre de Recerca en Agrigenomica (Barcelona,
108 Spain).

109 Data preprocessing and microsatellite discovery. Each read was automatically assigned to its
110 correct library by GS-FLX software (454 Life Sciences) based on sample-specific MID
111 sequence. In an initial attempt to remove redundancy, sequence reads from each species were
112 analyzed using 454 GS De Novo Assembler v2.3 (454 Life Sciences) with default parameters.
113 The assembled contigs and remaining singletons resulting from this analysis were clustered
114 into a single fasta format file and used as input for the software QDD, a collection of freely
115 available modules (ActivePerl, BLAST, CLUSTALw2 and Primer3) that proceeds in three
116 successive stages (Meglec et al. 2010). Firstly, it selects sequences that are longer than a user-
117 defined limit and have perfect microsatellites with a minimum number of repeats. Secondly,
118 QDD automatically detects and removes redundancy as well as groups of sequences that
119 potentially are part of a repetitive region of the genome and, consequently, might be problematic
120 for microsatellite amplification (although QDD is not designed to describe mobile elements,
121 this is a conservative method that eliminates many of these sequences). Finally, the software
122 selects sequences that contain a target microsatellite and a flanking region free from
123 nanosatellites and designs PCR primers to amplify these repeats when flanking regions enable
124 it. All QDD parameters, including the parameters of the module Primer3, were set to default
125 values.

126 Data analysis. Tab-delimited files generated from QDD steps 1 (identified loci) and 3
127 (potentially amplifiable loci, PAL) were converted to spread-sheet files for use in Microsoft
128 Office Excel 2003 (Microsoft Corporation, Redmond, WA, USA). Microsatellite frequency for
129 each species was expressed as total number of identified microsatellites per mega base pair

130 (Mbp), and subsequent data analysis included sorting according to microsatellite category (i.e.,
131 di-, tri-, tetra-, penta-, and hexanucleotides), specific motifs and number of tandemly repeated
132 units. Reverse-complement repeat motifs and translated or shifted motifs were grouped together
133 so that there were four unique dinucleotide repeats and 10, 33, 102, and 350 unique tri-, tetra-
134 -, penta-, and hexanucleotide repeats, respectively (Jin et al. 1994). To provide some comparison
135 with other Rhodophyta, microsatellite frequency / attributes were also investigated using
136 exactly the same procedure in seven species with >1,000 expressed sequence tag (EST)
137 sequences available in the public database EST-GenBank: *Porphyra yezoensis*, *Furcellaria*
138 *lumbricalis*, *Eucheuma denticulatum*, *Gracilaria changii*, *Porphyra haitanensis*, *Chondrus*
139 *crispus*, and *Griffithsia okiensis*. Portions of this data set were screened for micro- satellite
140 motifs by other authors (e.g., EST data for the two *Porphyra*; Liu et al. 2005, Sun et al. 2006,
141 Wang et al. 2007, Xie et al. 2009), but they were reanalyzed here under common search criteria
142 to facilitate comparison.

143 **Microsatellite testing.** A subset of the PAL for each species was tested for amplification (18
144 and 23 PAL for the *Cruoriaceae* and *G. lanceola*, respectively). To increase the chance of
145 targeting polymorphic loci, we selected PAL with the highest number of repetitions. Markers
146 producing clear electropherogram patterns were assessed for polymorphism using a number
147 of individuals from various populations in the Iberian Peninsula (32 specimens from four
148 populations in the case of the *Cruoriaceae*; 26–30 specimens from three populations in *G.*
149 *lanceola*). DNA extractions were performed as described above, and PCR reactions (10 μ L)
150 contained 10 ng of DNA, 200 nM of each primer (Life Technologies Corp., Carlsbad, CA,
151 USA), 150 μ M of dNTPs (Fermentas Inc., Geln Burnie, MA, USA), 1.5 mM of MgCl₂ (Promega
152 Corp.), 1 \times PCR Buffer (Promega Corp.), and 0.35 U Taq DNA polymerase (Promega Corp.).
153 Amplifications were carried out separately for each locus on PTC-200 Thermo Cycler (GMI
154 Inc., Ramsey, MI, USA) with initial denaturing at 94 C for 5 min, followed by 30 cycles of 94
155 C for 30 s, 57 C–60 C for 30 s, and 72 C for 30 s with a final extension of 72 C for 10 min.

156 DNA fragments were separated on an ABI 3730 Genetic Analyzer (Life Technologies Corp.)
157 with GeneScan 600 LIZ as size standard (Life Technologies Corp.). Finally, electropherograms
158 were analyzed with the software GeneMapper v4.0 (Life Technologies Corp.), and diversity
159 estimates (number of alleles per locus, NA; observed heterozygosity, Ho; expected
160 heterozygosity, He) were calculated with GenALEX 6 software (Peakall and Smouse 2006).

161

162

163 **RESULTS**

164

165 Undescribed Cruoriaceae species. A total of 139,795 reads and 40,896,217 bp were obtained
166 from the 454 shotgun library for the Cruoriaceae (mean read length 293 bp). When sequence
167 reads were assembled using 454 GS De Novo Assembler v 2.3 with default parameters, the new
168 data set consisted in 4,329 contigs plus 51,622 singletons. A total of 5,174 microsatellite loci
169 (di-, tri-, tetra-, penta-, and hexanucleotides) with ≥ 4 repeats were identified in 4,504 of these
170 sequences amounting to a yield of 0.037 microsatellites per initial read and 126.5 microsatellites
171 per mega base pairs (Mbp). Most loci contained di- and trinucleotide repeats (4,309 and 699,
172 respectively), followed far behind by hexa- (65), tetra- (64), and pentanucleotides (37) (Table
173 1). After a conservative removal of redundancy and potentially problematic sequences (e.g.,
174 those located in repetitive regions of the genome), PCR primers design was possible in 1,366
175 loci (26% of the loci identified). Again, these potentially PAL were dominated by di- and
176 trinucleotide repeats (1,178 and 168 loci, respectively), while larger motifs lagged well behind
177 (≤ 8 loci in each repeat category). A detailed description of these results including a unique
178 accession for each PAL, GenBank accession number, repeat monomer sequence, number of
179 perfect tandemly repeated units, and forward / reverse primer sequences is provided in
180 Appendix S1 (see the supplementary material).

181 The relative numbers of perfect tandemly repeated units were fairly similar across the various
182 microsatellite categories (Table 1). In all five categories, there were many short repeats and
183 fewer long repeats although the relative abundance of loci with the lowest number of repeated
184 units (four) decreased with microsatellite complexity (from >70% for di- and tri- nucleotides to
185 <55% for larger motifs). Differences were even more pronounced in PAL where most loci
186 (>95%) only contained four to five repeat units. Since di- and trinucleotides were 97% of all
187 identified microsatellite loci and 99% of all PAL, differences in the relative abundance of
188 specific motifs were only investigated in these two categories (Fig. 1). For the dinucleotide
189 repeats, three of the four possible motifs were evenly represented and accounted 88% of the
190 identified loci, while AT was less frequent (12%). Among the trinucleotides, one of the 10
191 possible motifs (CCG) was clearly overrepresented and nearly doubled the frequency expected
192 simply by chance; the other nine motifs showed comparable frequencies except for two motifs
193 (ACT and AGT) with frequencies <5%. In general, the same pattern was applicable to PAL
194 data. Twelve of the 18 PAL tested for amplification (Table 1) yielded a product of the expected
195 size. Reliable scoring of allele sizes (one to two clear peaks, no multiband pattern) was possible
196 for seven of them, and they were used for subsequent polymorphism assessment. Among these
197 seven loci, five were polymorphic and heterozygous in at least one individual (Table S1 in the
198 supplementary material) with three to four (mean 3.4) alleles per locus. The observed and
199 expected heterozygosities ranged from 0.031 to 0.969 (mean 0.569) and from 0.254 to 0.656
200 (mean 0.515), respectively. The five polymorphic loci produced 28 distinct multilocus
201 genotypes in 32 individuals (88%). *Grateloupia lanceola*. The 454 shotgun library for *G.*
202 *lanceola* provided a number of reads very close to those obtained for the *Cruoriaceae* (139,786
203 reads) but a slightly lower number of base pairs (36,013,235 bp, mean length read 258 bp). The
204 preliminary assembling with the 454 GS De Novo Assembler v 2.3 resulted in 2,526 contigs
205 plus 67,005 singletons. A total of 4,766 microsatellite loci (di-, tri-, tetra-, penta-, and
206 hexanucleotides) with ≥ 4 repeats were identified in 4,344 of these sequences amounting to a

207 yield of 0.034 microsatellites per initial read or 132.3 microsatellites per Mbp (Table 1). As in
208 the other species, most loci contained di- and trinucleotide repeats (3,959 and 686, respectively)
209 followed far behind by tetra- (59), hexa- (33), and pentanucleotides (29). After removing
210 redundancy in its widest sense, the proportion of loci for which PCR primers design was
211 possible was again very similar to that obtained for the other red alga (1,371 loci, 29% of the
212 identified loci). Likewise, PAL were dominated by di- and tri- nucleotide repeats (1,176 and
213 165, respectively), while more complex motifs lagged well behind (14 loci). A detailed
214 description of these results including a unique accession of each PAL, GenBank accession
215 number, repeat monomer sequence, number of perfect tandemly repeated units, and forward/
216 reverse primers sequences is provided in Appendix S2 (see the supplementary material).

217 As already observed in the Cruoriaceae, the relative abundance of perfect tandemly repeated
218 units was fairly similar across microsatellite categories (Table 1) with abundant short repeats
219 and fewer long repeats. However, the relative abundance of loci with the lowest number of
220 repeated units (four) decreased with microsatellite complexity (86, 75, 69, 62, and 60% for di-
221 , tri-, tetra-, penta-, and hexanucleotides, respectively). The higher relative abundance of loci
222 with a small number of repeated units was even more marked in PAL as >95% loci only
223 contained four to five repeats.

224 Both di- and trinucleotide loci revealed notable changes in the relative abundance of specific
225 motifs and, more interestingly, substantial differences with the other species (Fig. 1). For the
226 dinucleotide repeats, one of the four possible motifs (AG) accounted for 50% of the identified
227 loci, while AC showed a frequency similar to that expected by chance (31%) and the other two
228 motifs (AT and CG) were <15%. Among the trinucleotides, one of the 10 possible motifs
229 (AAG) doubled the frequency expected by chance; the other nine motifs exhibited comparable
230 frequencies (10%) except for AGC and CCG with frequencies <7%. PAL showed the same
231 general pattern of motif frequencies.

232 A large proportion of the PAL tested for this spe- cies showed good, size-expected amplification
233 prod- ucts (20 of 23 tested PAL, 87%) and easily scorable profiles (19 of 23 tested PAL, 83%)
234 (Table 1). Twelve of these loci were monomorphic, and the seven remaining ones were
235 polymorphic; however, six were heterozygous in at least one individual, while the last one was
236 homozygous across all sam- ples. The mean number of different alleles per locus was lower
237 than in the Cruoriaceae (2.4 vs. 3.4, two to four alleles per locus), and the observed and expected
238 heterozygosities ranged from 0 to 0.933 (mean 0.196) and from 0.034 to 0.531 (mean 0.204),
239 respectively (Table S1). Likewise, the seven loci produced 13 distinct multilocus genotypes in
240 30 individuals (43%). The low levels of polymorphism detected in *G. lanceola* are consistent
241 with the low genetic diversity found in this species using AFLP markers (unpublished results).
242 Microsatellite frequency / attributes in other Rhodophyta. A total of 60,444 public EST
243 sequences (27 Mbp) from the other seven red algae were screened for perfect tandemly repeats
244 units with QDD using the same criteria applied to our shotgun sequencing data (Table S2 in the
245 supplementary material). Micro- satellite frequency oscillated from 261.8 counts \pm Mbp)¹ in
246 *E. denticulatum* to 860.89 counts \pm Mbp)¹ in *G. changii*. As in our Cruoriaceae and *G.*
247 *lanceola*, most of the microsatellite loci (>95%) contained di- and trinucleotide repeats. Relative
248 abundances of perfect tandemly repeated units were also similar to our results with genome
249 sequencing data. More than 65% of the detected loci contained just four repeats, while the
250 percentage of microsatellites with >10 repeats was <1% in three species (*E. denticula-*
251 *tum*, *F. lumbricalis*, and *G. changii*), ranged 1%–5% in *C. crispus* and *G. okiensis*, and was >5% in the
252 two *Porphyra*. The relative abundance of specific motifs also showed considerable variation.
253 AG was the most abundant dinucleotide motif in three species (*E. denticulatum*, *P. haitanensis*,
254 and *G. changii*; 34.4%–44.9%), AC dominated in *F. lumbricalis* (49.2%) as well as in *G.*
255 *okiensis* (39.4%), and CG was the most common motif in *C. crispus* (44.4%) and *P. yezoensis*
256 (48.2%). Among the trinucleotides, CCG prevailed in all species except *F. lumbricalis*, but its
257 relative abundance was variable.

258

259 **DISCUSSION**

260

261 Population genetics studies are still comparatively scarce in seaweeds (Valero et al. 2001) and
262 have mostly focused on a limited number of genera / species (Andreakis et al. 2007). This
263 shortage of intraspecific studies has been attributed, at least in part, to a lack of appropriate
264 molecular markers. In particular, the detection of useful microsatellite loci has been
265 challenging, and it has been suggested that their genomic frequency in this group might be low
266 (Olsen et al. 2002, Andreakis et al. 2007). Our relatively extensive and random survey of the
267 genome of two Rhodophyta should allow some test- ing of this conventional wisdom.

268 Microsatellite frequency is known to vary to a con- siderable extent among eukaryotes. Even
269 when complete genomes are screened for microsatellite occurrence with consistent procedures,
270 among-taxa differences can be as high as three orders of magni- tude (Sharma et al. 2007). A
271 review of the literature reveals that microsatellite frequency is likewise variable in taxa
272 investigated with a genome sequencing approach comparable to ours (Table S3 in the sup-
273plementary material). Estimates for a number of plants and animals range from 11.7
274 microsatellite counts per Mbp to 544.0 counts \pm Mbp)¹ (mean 148.4 counts \pm Mbp)¹). In this
275 context, our results may seem comparable to those obtained for various animals and higher than
276 the estimates reported for some plants. However, our review also shows that search parameters
277 vary between studies, and, consequently, caution must be exercised in doing this comparison.
278 In particular, the minimum number of repeats for microsatellite detection can be especially
279 influential. Most studies used cutoff values slightly larger than ours, especially for the smaller
280 motifs that often constitute a major fraction of the detected loci. When our estimates were
281 recalculated for a higher cutoff (five for every category), the new microsatellite frequencies
282 (21.9 and 28.8 counts \pm Mbp)¹) placed our two red algae in the lower end of the values reported
283 in the literature (Table S3).

284 As our study is the first case where 454 shotgun genome sequencing was used to detect
285 microsatellite motifs in algae, it is difficult to assess to what extent our estimates may be
286 relevant for other taxa. However, it is worth mentioning that our two taxa yielded very similar
287 microsatellite frequencies despite the fact that they belong to different orders and show obvious
288 differences in other microsatellite attributes. Thus, the genome of the Cruoriaceae was
289 particularly enriched in CG motifs, while *G. lanceola* was dominated by AG motifs. This
290 variation is consistent with the great differences in di- and trinucleotide motifs reported in
291 other photosynthetic organisms (Von Stackelberg et al. 2006). It also suggests that
292 microsatellite attributes are species specific rather than group specific, an observation with
293 obvious implications for the enrichment protocols often used for isolating microsatellite loci
294 (Zane et al. 2002) as inappropriate a priori choices about repeat size and motif sequence may
295 lower the efficacy of obtaining useful microsatellite loci.

296 In contrast with the absence of random genomic sequencing data for Rhodophyta, the growing
297 body of publicly available DNA sequences—including vast collections of ESTs—can be used
298 to explore the density/attributes of repeat motifs in the genome of other red algae. Our analyses
299 of EST data for seven species of Rhodophyta (covering four orders and six families) reveal that
300 microsatellite density is 2- to 7-fold higher in EST sequences than in our 454 sequencing data,
301 suggesting that EST collections may be a more effective source for microsatellite mining. As
302 in our random sequencing, EST-derived loci were dominated (>95%) by di- and trinucleotide
303 repeats (Table S2); also, dinucleotides were three to five times more abundant than trinucleo-
304 tides in all taxa except the two Porphyra. This prevalence of dimer repeats is in agreement
305 with the higher density of dinucleotides found in nine of the 25 photosynthetic organisms
306 investigated by Von Stackelberg et al. (2006), and contrasts with the notion that EST-derived
307 microsatellites may be prone to trinucleotides (Varshney et al. 2002, Rota et al. 2005, Wang et
308 al. 2006). However, the particulars of our search criteria may have had some influence on our

309 estimates, and alternative estimates for the two *Porphyra* can be found in the literature (Liu et
310 al. 2005, Sun et al. 2006, Wang et al. 2007, Xie et al. 2009).

311 A survey of service providers indicates that many companies guarantee the development of 10
312 poly-morphic microsatellite loci in 1–3 months with a cost of \$5,000–10,000 (Abdelkrim et al.
313 2009). Using shotgun sequencing, we were able to develop 12 polymorphic microsatellite loci
314 in a similar period of time with a final cost of €7,000. Polymorphism (as number of alleles) in
315 our loci was comparable to values reported for other red algae (Guillemin et al. 2005, Andreakis
316 et al. 2007). In this regard, previous analysis with dominant AFLPs markers has revealed very
317 low levels of genetic diversity in one of the species included in this study (*G. lanceola*; I.
318 Maneiro, L. Couceiro, I. Ba'rbara, J. Cremades, J. M. Ruiz, and R. Barreiro, unpublished),
319 and the slightly lower number of alleles found for this species, as well as the high proportion
320 of monomorphic loci (12 / 19), seems consistent with these previous results. Therefore, our
321 approach shows a time- and cost-effectiveness comparable to those of traditional methods of
322 microsatellite development. However, the genome sequencing approach still offers a number
323 of alternatives that may enhance its effectiveness. Using microsatellite-enriched DNA before
324 pyrosequencing, Santana et al. (2009) reported that 25%–97% of their initial reads contained
325 microsatellite motifs (estimates vary depending on the species and enrichment protocol used),
326 values that clearly surpass the <10% found in our two red algae. Likewise, our microsatellite
327 search was restricted to perfect motifs, but there is some evidence that complex repeated core
328 motifs (i.e., multiple or interrupted repeats) dominate in other red algae (Wattier et al. 1997,
329 Luo et al. 1999, Guillemin et al. 2005, Andreakis et al. 2007). The possibility that complex
330 patterns may be more abundant in red algae surely warrants further investigation and suggests
331 that the development of polymorphic loci from NGS data could benefit from less stringent
332 screening criteria. Although interrupted repeats are expected to have lower mutation rates
333 compared to pure ones (Buschiazzo and Gemmell 2006), empirical data from red algae reveal

334 that many useful microsatellite loci have complex patterns (Wattier et al. 1997, Luo et al. 1999,
335 Guillemin et al. 2005, Andreakis et al. 2007).

336 Microsatellite detection with genome sequencing data has other additional benefits. The access
337 to a large volume of sequences allows the detection of putative mobile elements by spotting
338 sequence simi- larity groups (Meglecz et al. 2010). Using the package QDD (Meglecz et al.
339 2010), we removed 25.8%–26.2% of the sequences with potential loci, possibly saving time
340 and money in primer design and laboratory testing for useless loci since PCR amplification can
341 be seriously affected by microsatel- lite and mobile element associations. On the other hand,
342 genome sequencing produces a large number of novel genomic resources that may be useful
343 for both related and unrelated research such as gene content, gene functions, or even the
344 association of PAL with coding regions (Sharma et al. 2007, Tang- phatsornruang et al. 2009).
345 In summary, we have reported the cost- and labor-effective development of microsatellite
346 markers in two red algae using shotgun sequencing data (454 technology). To our knowledge,
347 this is the first time that random genome sequencing is used for microsatellite identification in
348 seaweeds. Our results suggest that microsatellite density in our two red algae is below the levels
349 reported for other taxa studied with shotgun technology. However, and despite the use of a
350 stringent filtering procedure to avoid redundancy, we still obtained a substantial number of
351 PAL. A limited number of these PAL were successfully tested for PCR amplification and
352 polymorphism finding that they may be suitable for population genetic studies. Shotgun
353 sequencing appears as an efficient alternative for the fast devel- opment of microsatellite loci
354 in difficult and/or poorly studied red algae species.

355

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360

361 **References**

362 Abdelkrim, J., Robertson, B., Stanton, J. A. & Gemmell, N. 2009. Fast, cost-effective
363 development of species-specific microsatellite markers by genomic sequencing. *BioTechniques*
364 46:185–92.

365 Allentoft, M., Schuster, S. C., Holdaway, R., Hale, M., McLay, E., Oskam, C., Gilbert, M. T.,
366 Spencer, P., Willerslev, E. & Bunce, M. 2009. Identification of microsatellites from an extinct
367 moa species using high-throughput (454) sequence data. *BioTechniques* 46:195–200.

368 Andreakis, N., Kooistra, W. & Procaccini, G. 2007. Microsatellite markers in an invasive strain
369 of *Asparagopsis taxiformis* (Bon- nemaisoniales, Rhodophyta): insights in ploidy level and sex-
370 ual reproduction. *Gene* 406:144–51.

371 Barbara, I. & Cremades, J. 2004. *Grateloupia lanceola* versus *Grateloupia turuturu*
372 (*Gigartinales*, Rhodophyta): en la Península Iberica. *An. Jard. Bot. Madr.* 61:103–18.

373 Barbara, I., Diaz, P., Cremades, J., Pen˜ a, V., Lopez-Rodriguez, C., Bercibar, E. & Santos, R.
374 2006. Catalogo gallego de especies amenazadas y lista roja de las algas bentonicas marinas de
375 Galicia. *Algas* 35:9–19.

376 Brodie, J., Andersen, R. A., Kawachi, M. & Millar, A. J. K. 2009. Endangered algal species
377 and how to protect them. *Phycologia* 48:423–38.

378 Buschiazzo, E. & Gemmell, N. J. 2006. The rise, fall and renaissance of microsatellites in
379 eukaryotic genomes. *Bioessays* 28:1040–50.

380 Castoe, T. A., Poole, A. W., Gu, W., de Koning, A. P. J., Daza, J. M., Smith, E. N. & Pollock,
381 D. D. 2010. Rapid identification of thousands of copperhead snake (*Agkistrodon contortrix*)
382 micro- satellite loci from modest amounts of 454 shotgun genome sequence. *Mol. Ecol. Resour.*
383 10:341–7.

384 Csencsics, D., Brodbeck, S. & Holderegger, R. 2010. Cost-effective, species-specific
385 microsatellite development for the endangered dwarf bulrush (*Typha minima*) using next-
386 generation sequencing technology. *J. Hered.* 101:789–93.

387 Eckert, C. G., Samis, E. & Loughheed, C. 2008. Genetic variation across species' geographical
388 ranges: the central-marginal hypothesis and beyond. *Mol. Ecol.* 17:1170–88.

389 Frankham, R., Ballou, J. D. & Briscoe, D. A. 2004. *A Primer of Conservation Genetics*.
390 Cambridge University Press, Cambridge, UK, 220 pp.

391 Granja, A., Cremades, J. & Ba'rbara, I. 1993. Contribucio' n al co- nocimiento de la flora bento'
392 nica marina del noroeste de la Pen'insula Ibe' rica I. Primeros datos sobre el cara'cter flor'istico
393 del litoral de Lugo (Galicia). *Nova Acta Cient. Compostelana (Biol.)* 4:15–23.

394 Guillemain, M. L., Destombe, C., Faugeron, S., Correa, A. & Valero, M. 2005. Development of
395 microsatellites DNA markers in the cultivated seaweed, *Gracilaria chilensis* (Gracilariales,
396 Rhodo- phyta). *Mol. Ecol. Notes* 5:155–7.

397 Hudson, M. E. 2008. Sequencing breakthroughs for genomic ecology and evolutionary biology.
398 *Mol. Ecol. Resour.* 8:3–17. Jin, L., Zhong, Y. & Chakraborty, R. 1994. The exact numbers of
399 possible microsatellite motifs. *Am. J. Hum. Genet.* 55:582.

400 Liu, B. Q., Zeng, Q. G., Luo, Q. J., Wang, Y. J. & Li, S. H. 2005. Isolation of microsatellite
401 loci from dbEST of algae *Porphyra yezoensis* and primer amplification of interspecies transfer.
402 *Oceanol. Limnol. Sin.* 36:248–54.

403 Luo, H., Moerchen, M., Engel, C. R., Destombe, C., Epplen, J. T., Epplen, C., Saumitou-
404 Laprade, P. & Valero, M. 1999. Charac- terization of microsatellite markers in the red alga
405 *Gracilaria gracilis*. *Mol. Ecol.* 8:685–702.

406 Meglec, E., Costedoat, C., Dubut, V., Gilles, A., Malausa, T., Pech, N. & Martin, J. F. 2010.
407 QDD: a user-friendly program to select microsatellite markers and design primers from large
408 sequencing projects. *Bioinformatics* 26:403–4.

409 Olsen, J. L., Sadowski, G., Stam, W. T., Veldsink, J. H. & Jones, K. 2002. Characterization of
410 microsatellite loci in the marine seaweed *Ascophyllum nodosum* (Phaeophyceae; Fucales).
411 *Mol. Ecol. Notes* 2:33–4.

412 Peakall, R. & Smouse, P. E. 2006. GENALEX 6: genetic analysis in Excel. Population genetics
413 software for teaching and research. *Mol. Ecol. Notes* 6:288–95.

414 Pe´ rez-Cirera, J. L. 1975. Notas sobre la vegetacio´ n ficolo´ gica bento´ nica de la R´ ia de
415 Cedeira (NO. de Espan˜ a). *An. Inst. Bot. A. J. Cavanilles* 32:161–71. Pe´ rez-Cirera, J. L.,
416 Cremades, J. & Ba´ rbara, I. 1989. *Grateloupia lanceola* (Cryptonemiales, Rhodophyta) en las
417 costas de la Pen´ insula Ibe´ rica: estudio morfolo´ gico y anato´ mico. *Lazaroa* 11:123–34.

418 Rota, L. M., Kantety, R. V., Yu, J. K. & Sorrells, M. E. 2005. Non- random distribution and
419 frequencies of genomic and EST- derived microsatellite markers in rice, wheat, and barley.
420 *BMC Genomics* 6:23–34.

421 Santana, Q., Coetzee, M., Steenkamp, E., Mlonyeni, O., Hammond, G., Wingfield, M. &
422 Wingfield, B. 2009. Microsatellite discovery by deep sequencing of enriched genomic libraries.
423 *BioTech- niques* 46:217–23.

424 Sharma, P. C., Grover, A. & Kahl, G. 2007. Mining microsatellites in eukaryotic genomes.
425 *Trends Biotechnol.* 25:490–8.

426 Squirrell, J., Hollingsworth, P. M., Woodhead, M., Russell, J., Lowe, A. J., Gibby, M. &
427 Powell, W. 2003. How much effort is re- quired to isolate nuclear microsatellites from plants?
428 *Mol. Ecol.* 12:1339–48.

429 Sun, J., Liu, T., Guo, B., Jin, D., Weng, M., Feng, Y., Xu, P., Duan, D. & Wang, B. 2006.
430 Development of SSR primers from EST sequences and their application in germplasm
431 identification of *Porphyra* lines (Rhodophyta). *Eur. J. Phycol.* 41:329–36.

432 Tangphatsornruang, S., Somta, P., Uthaipaisanwong, P., Chanpra- sert, J., Sangsrakru, D.,
433 Seehalak, W., Sommanas, W., Tra- goonrung, S. & Srinives, P. 2009. Characterization of

434 microsatellites and gene contents from genome shotgun sequences of mungbean (*Vigna radiata*
435 (L.) Wilczek). *BMC Plant Biol.* 9:137.

436 Thomson, R. C., Wang, I. J. & Johnson, J. R. 2010. Genome-enabled development of DNA
437 markers for ecology, evolution and conservation. *Mol. Ecol.* 19:2184–95.

438 Valero, M., Engel, C. R., Billot, C., Kloareg, B. & Destombe, C. 2001. Concepts and issues of
439 population genetics in seaweeds. *Cah. Biol. Mar.* 42:53–62.

440 Varshney, R. K., Thiel, T., Stein, N., Langridge, P. & Graner, A. 2002. In silico analysis on
441 frequency and distribution of microsatellites in ESTs of some cereal species. *Cell Mol. Biol.*
442 *Lett.* 7:537–46.

443 Von Stackelberg, M., Rensing, S. A. & Reski, R. 2006. Identification of genic moss SSR
444 markers and a comparative analysis of twenty-four algal and plant gene indices reveal
445 species-specific rather than group-specific characteristics of microsatellites. *BMC Plant Biol.*
446 6:9.

447 Wang, C. B., Guo, W. Z., Cai, C. P. & Zhang, T. Z. 2006. Characterization, development and
448 exploitation of EST-derived microsatellites in *Gossypium raimondii* Ulbrich. *Chin. Sci. Bull.*
449 51:557–61.

450 Wang, M. Q., Hu, J. J., Zhuang, Y. Y., Zhang, L., Liu, W. & Mao, Y. X. 2007. In silico
451 screening for microsatellite markers from expressed sequence tags of *Porphyra yezoensis*
452 (Bangiales, Rhodophyta). *J. Ocean Univ. China (Oceanic Coast. Sea Res.)* 6:161–6.

453 Wattier, R., Dallas, J. F., Destombe, C., Saumitou-Laprade, P. & Valero, M. 1997. Single
454 locus microsatellites in Gracilariales (Rhodophyta): high levels of genetic variability within
455 *Gracilaria gracilis* and conservation in related species. *J. Phycol.* 33:868–80.

456 Wattier, R. & Maggs, C. A. 2001. Intraspecific variation in seaweeds: the application of new
457 tools and approaches. *Adv. Bot. Res.* 35:171–212.

458 Xie, C. T., Chen, C. S., Ji, D. & Xu, Y. 2009. Characterization, development and exploitation
 459 of EST-derived microsatellites in *Porphyra haitanensis* Chang et Zheng (Bangiales,
 460 Rhodophyta). *J. Appl. Phycol.* 21:367–74.

461 Xunta de Galicia 2007. Decreto 88/2007 do 19 de abril polo que se regula o Cata'logo
 462 galego de especies ameazadas. Available at:
 463 <http://www.xunta.es/Doc/Dog2007.nsf/FichaContenido/12742?OpenDocument> (last accessed
 464 29 August 2011).

465 Zane, L., Bargelloni, L. & Patarnello, T. 2002. Strategies for microsatellite isolation: a
 466 review. *Mol. Ecol.* 11:1–16.

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TABLE 1. Counts of loci for each combination of microsatellite category (di-, tri-, tetra-, penta-, and hexanucleotides) and number of perfect tandemly repeat units in each species. Within each cell, values are given for identified/potentially amplifiable microsatellite loci.

	Cruoriaceae species					<i>Grateloupia lanceola</i>				
	di-	tri-	tetra-	penta-	hexa-	di-	tri-	tetra-	penta-	hexa-
4	3,409/1,019	515/131	27/5	20/4*	25/4	3,385/1,052	513/124	41/8	18/3	20/7
5	536/118	85/18	11/1*	5/0	9/3*	385/92	107/31	11/5*	8/1	6/3*
6	134/21	38/8	3/1*	4/0	4/0	77/16	35/5	3/0	0/1	4/0
7	69/5	12/6*	7/0	0/0	0/0	30/7	4/0	2/1*	3/0	0/0
8	37/7	14/2*	4/1*	1/0	2/0	11/4*	6/2*	1/0	0/0	2/1*
9	23/5*	9/0	2/0	2/0	4/0	15/2*	5/2*	0/0	0/0	0/0
≥10	73/3*	21/3*	8/0	3/0	17/0	54/3*	16/1*	1/0	0/0	1/0
≥25	17/0	3/0	1/0	2/0	4/1*	2/0	0/0	0/0	0/0	0/0
≥50	11/0	2/0	1/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
Total	4,309/1,178	699/168	64/8	37/4	65/8	3,959/1,176	686/165	59/14	29/5	33/11

*, Denotes categories of potentially amplifiable loci that were tested for amplification and polymorphism.

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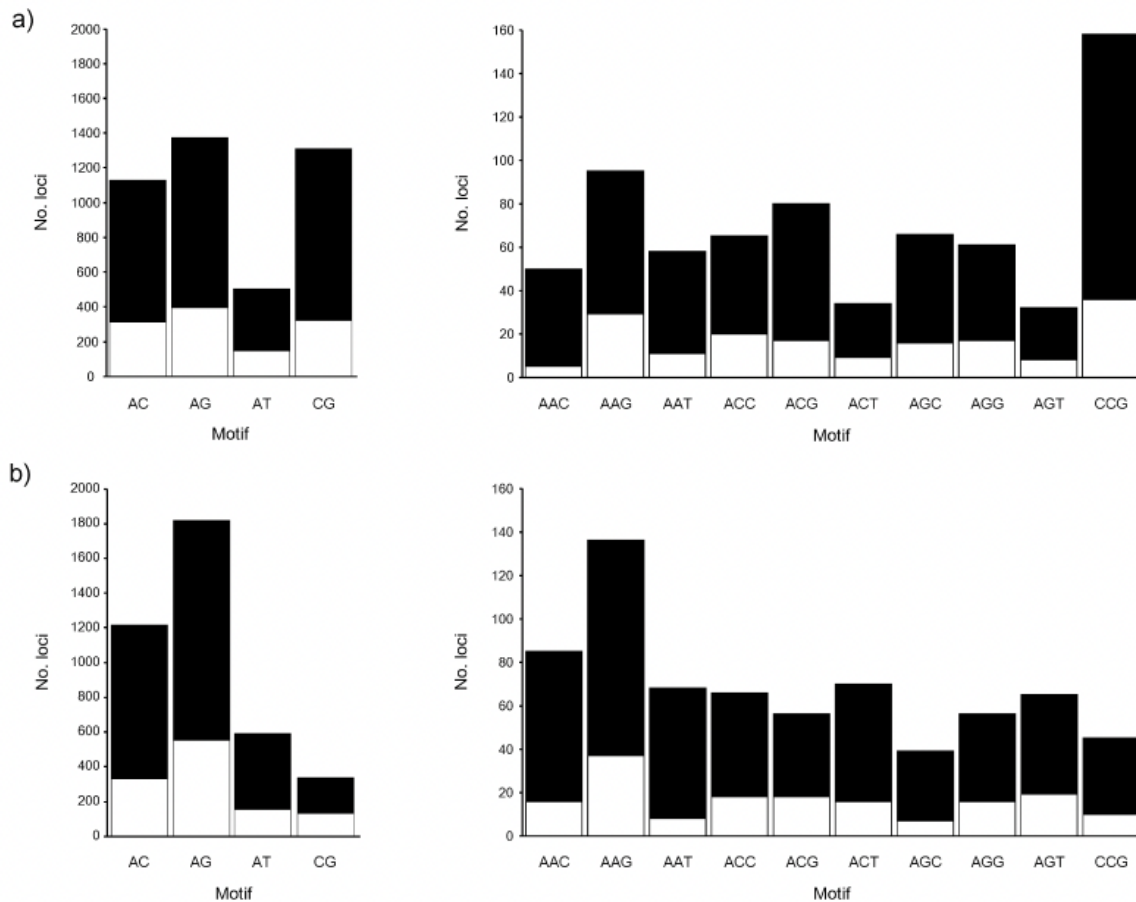


FIG. 1. Motif frequency in di- and trinucleotide repeats. Number of identified microsatellite loci (black) and subset for which PCR primers could be designed (potentially amplifiable loci, PAL; white) for different repeat sequence motifs in (a) undescribed Cruoriaceae and (b) *Grateloupia lanceola*.

470

Supplementary Material

The following supplementary material is available for this article:

Appendix S1. Details of Cruoriaceae PAL (GenBank accession, number of perfect tandemly repeated units, repeat monomer sequence) and designed primers (forward and reverse sequences, melting temperatures).

Appendix S2. Details of *Grateloupia lanceola* PAL (GenBank accession, number of perfect tandemly repeated units, repeat monomer sequence) and designed primers (forward and reverse sequences, melting temperatures).

Table S1. Characteristics of five and seven polymorphic microsatellite loci in the undescribed Cruoriaceae and *Grateloupia lanceola*, respectively (attributes/primer sequences for monomorphic loci are available from authors upon request). N : sample size; N_A : number of alleles; H_o : observed heterozygosity; H_e : expected heterozygosity.

Table S2. Frequency/attributes of EST-derived microsatellites for seven Rhodophyta species.

Table S3. Microsatellite frequencies (microsatellite counts per Mbp) reported for genome sequencing approaches in this (as shaded data) and other studies.

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