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1 **Genomic signatures of clonality in the deep water kelp *Laminaria***
2 ***rodriguezii***

3 **Genomic signatures of clonality**

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26 **ABSTRACT**

27 **Partial clonality, mode of reproduction, heterozygote excess, population genomics, kelp**

28 The development of population genomic approaches in non-model species allows for renewed
29 studies of the impact of reproductive systems and genetic drift on population diversity. Here,
30 we investigate the genomic signatures of partial clonality in the deep water kelp *Laminaria*
31 *rodriguezii*, known to reproduce by both sexual and asexual means. We compared these
32 results with the species *Laminaria digitata*, a closely related species that differs by different
33 traits, in particular its reproductive mode (no clonal reproduction). We analysed genome-wide
34 variation with dd-RAD sequencing using 4077 SNPs in *L. rodriguezii* and 7364 SNPs in *L.*
35 *digitata*. As predicted for partially clonal populations, we show that the distribution of F_{IS}
36 within populations of *L. rodriguezii* is shifted toward negative values, with a high number of
37 loci showing heterozygote excess. This finding is the opposite of what we observed within
38 sexual populations of *L. digitata*, characterized by a generalized deficit in heterozygotes.
39 Furthermore, we observed distinct distributions of F_{IS} among populations of *L. rodriguezii*,
40 which is congruent with the predictions of theoretical models for different levels of clonality
41 and genetic drift. These findings highlight that the empirical distribution of F_{IS} is a promising
42 feature for the genomic study of asexuality in natural populations. Our results also show that
43 the populations of *L. rodriguezii* analysed here are genetically differentiated and probably
44 isolated. Our study provides a conceptual framework to investigate partial clonality on the
45 basis of RAD-sequencing SNPs. These results could be obtained without any reference
46 genome, and are therefore of interest for various non-model species.

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51 INTRODUCTION

52 Partial clonality, defined as a mode of reproduction where species reproduce both sexually
53 and asexually, occurs in a wide variety of organisms across the tree of life, and is particularly
54 widespread in fungi, plants, rotifers, cladocerans and insects (Halkett et al., 2005). Clonal
55 reproduction can occur through different mechanisms such as fragmentation, vegetative
56 reproduction, mitotic parthenogenesis, or some forms of meiotic parthenogenesis (De Meeûs
57 et al., 2007; Jaron et al., 2020). Partial clonality has attracted considerable attention among
58 evolutionary biologists due to the potential effects of asexuality on the evolutionary trajectory
59 of species since reproductive modes have a major impact on the level of genome-wide genetic
60 diversity and its distribution within and among populations (Halkett et al., 2005; Duminil et
61 al., 2007). Moreover, reproductive modes profoundly affect other biological traits that play
62 important roles in colonization processes and the spread of populations, such as population
63 growth and dispersal (Kettenring & Mock, 2012; González de León et al., 2016), and in
64 buffering and resilience after catastrophic events (Becheler et al., 2020).

65 Theoretical models predict that when clonality predominates, it will increase heterozygosity
66 (Marshall & Weir, 1979; Balloux et al., 2003; De Meeûs et al., 2006), which may ultimately lead
67 to higher levels of observed heterozygosity (H_o) than those expected (H_e) under panmixia. This
68 deviation has been observed empirically through negative values of fixation index F_{IS} , reported
69 in various partially clonal populations (in animals Adjeroud et al., 2014; Halkett et al., 2005;
70 angiosperms Alberto et al., 2002; Alberto et al., 2005; Arnaud-Haond et al., 2007, and red and
71 brown macroalgae Guillemin et al., 2008; Ardehed et al., 2015; Coleman & Wernberg, 2018,
72 Pardo et al., 2019). Without sex, alleles do not segregate independently, which implies that
73 heterozygosity can be preserved rather than reduced over generations (Judson & Normark,
74 1996). Increasing clonal reproduction can increase effective population size at the allelic scale
75 but it decreases the genotypic effective population size: as a consequence asexual populations
76 can maintain higher allele diversity but lower genotype diversity compared to sexual ones
77 (Balloux et al., 2003). Asexual reproduction also leads to specific patterns of the distribution
78 of F_{IS} over the genome, characterized by a high occurrence of extreme, mainly negative, values
79 (Stoeckel & Masson, 2014; Reichel et al., 2016). These last theoretical studies reported, among
80 other points, that high rates of asexuality increased the variance of the distribution of F_{IS}
81 compared to that obtained from fully sexual populations (Stoeckel & Masson, 2014) but also

82 as compared to fully clonal populations (De Meeûs et al. 2006). Some variation in F_{IS} among
83 loci can also indicate the occurrence of rare recombination events as in the automictic
84 parthenogenetic species *Artemia parthenogenetica* (Nougué et al., 2015). In addition, if
85 asexuality is stable over generations, the accumulation of mutations in different alleles can
86 increase sequence differences among alleles, which corresponds to the "Meselson effect"
87 (Birky 1996; Judson & Normark, 1996; Balloux et al., 2003; De Meeûs et al., 2007). This effect
88 has been empirically demonstrated in ancient asexual *Timema* stick-insects (Schwander et al.,
89 2011) and in the human pathogen *Trypanosoma brucei gambiense* (Koffi et al., 2009; Weir et
90 al., 2016) and *Candida albicans* (Nébavi et al., 2006). Conversely the long term persistence
91 without sex of Bdelloid rotifers, referred as asexual scandals, has been challenged by the
92 suggestion of non-canonical sex (Schwander, 2016).

93 In this paper, we investigated how population genomic studies of partially clonal species allow
94 analysis of both the rate of clonality and its consequences for the distribution of F_{IS} . With the
95 development of thousands of Single Nucleotide Polymorphism (SNP), we will test whether the
96 observed empirical distribution of F_{IS} follows the aforementioned predicted variations in F_{IS}
97 among loci. The development of reduced representation sequencing methods (see for review
98 Davey et al., 2011) now allows such investigations in non-model species. These approaches
99 are also useful to more precisely delineate clonal lineages, where microsatellite loci have
100 failed to detect any genetic variation, as in the case of the selfing species *Sargassum muticum*
101 in the introduction range (Le Cam et al., 2019). Among the diversity of reduced representation
102 sequencing methods, Restriction Site Associated DNA sequencing (RAD sequencing; Baird et
103 al., 2008) is useful to efficiently develop enough SNPs to study the genomic distribution of
104 population genetic statistics.

105 We used the kelp *Laminaria rodriguezii* as a model species for the study of partial clonality.
106 *Laminaria rodriguezii* is a deep water kelp endemic to the Mediterranean Sea, mainly reported
107 from depths below 70 m, rarely found in shallower waters on seamounts or in upwelling
108 systems (Ballesteros, 2006), and with a maximum depth recorded at 260 m in the Adriatic Sea
109 (Ercegović, 1960). The rare populations of this species are exposed to various levels of
110 disturbances, such as direct destruction by fishing gear and a decline in water transparency,
111 which has led to *L. rodriguezii* being classified as endangered (Zuljevic et al., 2016). Besides
112 sexual reproduction, *L. rodriguezii* can reproduce asexually by stoloniferous or rhizoidal
113 growth. This mode of asexual reproduction involves somatic cells and should lead to clonal

114 lineages. Vegetative reproduction is only known in two *Laminaria* species: *L. rodriguezii* (Huvé,
115 1955) and the northeast Pacific *L. sinclairii* (Demes & Graham, 2011). *Laminaria rodriguezii*
116 can also reproduce sexually with a haplo-diplobiontic life cycle involving the alternation of
117 microscopic dioicous unisexual haploid gametophytes with large diploid sporophytes typically
118 found in kelps (Bringloe et al., 2020). Even if we do not know the importance of self
119 incompatibility in this species, self fertilisation (i.e. fertilisation between male and female
120 gametophytes originating from a single sporophyte parent), was reported to be possible
121 experimentally in most studied species of Laminariales (see the recent review of Goecke et
122 al., 2020). *Laminaria rodriguezii* then presents a mixed reproductive system, for which the
123 genetic consequences have not been studied. This deep water species is also characterized by
124 small and highly fragmented populations (Araújo et al., 2016). Therefore, the populations of
125 *L. rodriguezii* should be impacted by a reduction in genetic polymorphism through drift, a
126 reduction that can be counterbalanced by the aforementioned effects of asexual reproduction
127 on allele diversity (Balloux et al., 2003).

128 We specifically studied here whether the levels of asexual reproduction have discernable
129 effects on the empirical genomic distribution of diversity and F_{IS} among loci. We included
130 populations of the fully sexual congeneric species, *L. digitata*, with different levels of
131 microsatellite genetic diversity (Liesner et al., 2020) to take into account the consequence of
132 the mode reproduction with the confounding effect of variation in the strength of genetic drift
133 in our interpretations. *Laminaria digitata* is analysed only for comparative purposes, and we
134 did not develop the study of the genetic structure of this species in this article. We also
135 interpret our results in the light of previous theoretical studies, especially considering the full
136 distribution of F_{IS} among loci (Stoeckel & Masson, 2014). Among other factors, we tested
137 whether the clonal rates in populations of *L. rodriguezii* lead to a shift toward highly negative
138 F_{IS} values among loci, as expected for the highest levels of clonality (Stoeckel & Masson, 2014).
139 We used a large set of SNPs in order to access the most complete distribution of F_{IS} values over
140 populations of genomes. We also evaluated the robustness of our results by considering
141 different cutoffs in the filtering of SNPs. The implications of the inferred genetic diversity and
142 genetic structure for the management and conservation of this rare deep water kelp *L.*
143 *rodriguezii* are discussed.

144

145 MATERIAL AND METHODS

146 Sampling, DNA extraction

147 Individuals of *L. rodriguezii* were sampled from four sites in the Mediterranean, three in
148 Eastern Provence (Banc Magaud_1, Banc Magaud_2, Cap Camarat) and one in Southern
149 Corsica (Bonifacio), between 65 to 76 meters depth (Figure 1). Sampling was done by scuba
150 divers between June and August 2018. Sampling for DNA collection was performed by
151 collecting a small piece of tissue from the blade of sporophytes. More precisely, a total of 47
152 samples were collected from sporophytes not connected to each other by a stolon, and with
153 a minimum distance of two meters between sampled blades. This strategy aimed to promote
154 the sampling of distinct genets. For one of the two Banc du Magaud sites, namely Banc
155 Magaud_2, we used a different sampling design: the spatial distance between the sampled
156 sporophytes was recorded along a regular transect of 20 meters to study the spatial genetic
157 structure inside the population. Regarding *L. digitata*, we used samples from five northeastern
158 Atlantic populations of *L. digitata* collected in 2018 (Table S1, Supporting Information).
159 Genomic DNA was extracted using the Nucleospin® 96 plant kit (Macherey-Nagel, Düren,
160 Germany), according to the manufacturer's protocol.

161 ddRAD-sequencing

162 Two double-digest RAD-sequencing libraries (ddRAD-seq) with 47 individuals of *L. rodriguezii*
163 and 125 individuals of *L. digitata* were prepared according to Peterson et al., (2012). To
164 minimize bias in library preparation, all DNA samples were randomized across libraries, and
165 two and five replicates of *L. rodriguezii* and *L. digitata*, respectively, were included. DNA
166 concentrations were estimated with PicoGreen (Invitrogen, Carlsbad, CA, USA), and 100 ng of
167 genomic DNA was double digested using PstI and HhaI (NEB) for 12 hours at 37°C. The
168 purification of digested DNA was conducted by the NucleoMag NGS clean-up and size select
169 kit (Macherey-Nagel, Düren, Germany) according to the manufacturer's protocol. When these
170 steps were completed, the ligation of sequencing adapters to restriction digested DNA was
171 performed as follows: P1 adapters (overhang PstI), including unique barcodes (6-12 bp) and
172 P2 universal adaptor (overhang HhaI) were ligated to DNA using 0.5 µl (400 U/µL) of T4 DNA
173 ligase (NEB), 6 µl of 10X T4 ligase buffer (NEB) and incubated for 12 hours at room

174 temperature. Before PCR amplification, an additional purification step was done with the
175 NucleoMag NGS clean-up and size select kit. Amplification by PCR was restricted to 15 cycles
176 and performed with the Q5 hot Start High-Fidelity DNA polymerase kit (NEB). Then, samples
177 were multiplexed, and automated size selected for a range between 400 and 900 bp using a
178 Pippin Prep (Sage Science, Beverly, MA, USA). Finally, the libraries were sequenced with the
179 paired-end method (2×150 bp) on an Illumina Hiseq 4000 platform (G enome Qu ebec
180 Innovation Centre, McGill Univ., Montreal, Canada).

181 **Genotyping and SNP filtering**

182 Raw quality reads were checked using FastQC v0.11.7 (Andrews, 2010) and trimmed to 137
183 bp after the removal of adapters sequencing by Trimmomatic (Bolger et al., 2014). Then,
184 paired-reads were demultiplexed by both index and barcode using Stacks's process_radtags
185 (Catchen et al., 2011). Thanks to the phylogenetic proximity between *L. rodriguezii* and *L.*
186 *digitata* (Žuljevi c et al., 2016), we were able to use the draft genome of *L. digitata*
187 (unpublished data, Mark Cock) to align our reads with the BWA-mem algorithm in BWA
188 v0.7.17 (Li & Durbin, 2009). Aligned reads were then assembled into loci and finally, we called
189 single nucleotide polymorphisms (SNPs) with the Stacks v2.4 pipeline (Rochette et al., 2019).
190 Aligned reads of mapping quality below 30 (which means a probability of incorrect alignment
191 below 0.001) were excluded to minimize errors resulting from the erroneous assembly of
192 paralogous loci as a single locus. To avoid a strong linkage between SNPs, we kept only the
193 first SNP of each RAD locus. Further filtering was performed on the basis of minor allele
194 frequency, missing data rates for both individuals (i.e the percentage of missing genotypes per
195 individual) and loci (the percentage of non-genotyped individuals per locus), using VCFtools
196 v0.1.17 (Danecek et al., 2011) (Table 1). We aimed to identify the signatures of clonality from
197 putatively neutral loci. To this end, we excluded outlier loci identified as involved under
198 divergent selection with *pcadapt* v3.5 (Luu et al., 2017). *Pcadapt* starts by analysing population
199 structure with a PCA. Then candidate outliers are identified as those which are excessively
200 correlated with population structure (Luu et al., 2017). The outlier identified with *pcadapt*
201 should then correspond to inflated signals of genetic differentiation.

202 **The impact of SNP filtering on population genetic summary statistics**

203 RAD-seq is subject to different sources of genotyping errors (Mastretta-Yanes et al., 2015) that
204 may generate spurious inferences in surveys of genetic variation. However, the noise of
205 artifactual SNPs can be efficiently overcome by applying a rigorous filtering strategy of raw
206 RAD-seq datasets (e.g. McKinney et al., 2017; O'Leary et al., 2018) and measuring its effects
207 on population genetic summary statistics (Shafer et al., 2017). Care was taken in this study to
208 minimize the impact of artifactual SNPs on the true biological signal of the datasets (see
209 Supporting Information "Materials S1"). To achieve this, we studied the impact of different
210 filtering cutoffs on several parameters of genetic diversity and departure from panmixia: i) the
211 mean F_{IS} and standard deviation (SD) among loci, ii) the overall F_{ST} and SD among loci, iii) the
212 SNP error rate, defined as the proportion of SNP mismatches between replicate pairs
213 (Mastretta-Yanes et al., 2015). We have specifically explored the effect of the maximum rate
214 of missing data allowed per SNP (max-missing), the minor allele frequency (MAF), and the
215 mean read depth per locus across all individuals (meanDP), or by considering only loci for
216 which genotypes were strictly identical between replicates. Further details are given in
217 Supporting Information "Materials S1".

218 **Clonality in *Laminaria rodriguezii***

219 Because of somatic mutations and sequencing errors, we do not expect to get two strictly
220 identical genotypes over thousands of loci even if they belong to the same clonal lineage.
221 Consequently, we considered that genotypes with very low divergence corresponded to the
222 same clonal lineage. We chose the maximum distance between replicates ($d = 0.022$ for *L.*
223 *rodriguezii*, $d = 0.020$ for *L. digitata*, see Results) as a threshold to identify repeated genotypes.
224 Distances were computed as the ratio of the number of allelic differences between two
225 individuals (the Hamming distance, implemented in the function *diss.dist* of the Poppr v2.8.2
226 R package). Samples of *L. rodriguezii* separated by a distance lower than the aforementioned
227 threshold were clustered into clonal lineages (referred here as MLLs Multi-Locus Lineages, see
228 Arnaud-Haond et al., 2007) using the UPGMA clustering algorithm (implemented in Poppr
229 v2.8.2 R packages: Kamvar et al., 2014; Kamvar et al., 2015). The matrix of genetic distances
230 was additionally used for the construction of a network with the neighbor-net method
231 implemented in SplitsTree, which was used to visualize genetic proximity of samples from the
232 same clonal lineages, and also the differences among populations (Huson, 1998). We

233 computed the genotypic richness (R) index within populations (Dorken & Eckert, 2001), as
234 follows: $R = \frac{G-1}{N-1}$, where G is the number of distinct genotypes detected in the population and
235 N the total number of individuals sampled. We thus considered each cluster of clonal
236 individuals as a single genotype to calculate G. The distribution of clonal membership was
237 analysed with the Pareto β index as described in Arnaud-Haond et al. (2007) using the Poppr
238 v2.8.2 R package. Finally, the average values of genetic diversity and population differentiation
239 of *L. rodriguezii* were estimated in two complementary ways: firstly, including all genotyped
240 individuals, secondly by keeping only one representative of each clonal lineage.

241 **Genetic diversity**

242 The within-population genetic diversity was assessed with the datasets of *L. rodriguezii* and *L.*
243 *digitata*, after the removal of potentially selected loci. Given that the percentage of
244 polymorphic loci (%P) may be affected by the variations in sample sizes, we used a random
245 sampling approach implemented in a custom bash script (available at
246 <https://github.com/rebecca-cj/revegetation>). The percentage of polymorphic loci was
247 calculated from 100 random resamplings (with replacement between samples) for each
248 sample size at the population level. In addition, estimates of observed heterozygosity (H_o),
249 expected heterozygosity (H_e), and F_{IS} (Weir & Cockerham, 1984) were calculated with the
250 GENEPOP v1.0.5 R package (Rousset, 2008). The same data sets were also analyzed with the
251 HierFstat R package (Goudet, 2005) to compute the distribution of F_{IS} values across loci. We
252 used a two-sample Kolmogorov-Smirnov (KS) test to test for differences in the distribution of
253 F_{IS} between populations. We used the KS D statistic as the maximum distance between
254 cumulative distributions to assess the magnitude of these differences. The P-value of the D
255 statistic was computed using a bootstrapping method (10^6 bootstraps), with the Matching
256 v4.9.7 R package (Sekhon, 2008). The distributions were divided into ten discrete classes of F_{IS}
257 for which the frequency of occurrence in populations was shown as histograms. The Global
258 Hardy-Weinberg test [Score (U) test] (Rousset & Raymond, 1995), implemented in GENEPOP,
259 was used to test departure from panmixia across all loci for the different populations. The test
260 was performed twice: firstly by considering the alternative hypothesis of heterozygote excess
261 and secondly by considering heterozygote deficiency. The P-value of each test was
262 approximated by Markov chain (MCMC) algorithm with the following settings;

263 dememorization: 10 000, batch: 100, iterations per batch: 10 000. Then, a multisample score
264 test (Rousset & Raymond, 1995) was performed to obtain a global P-value per population.
265 Finally, the two-sided P-value of the Global Hardy-Weinberg test [Score (U) test] was obtained
266 by computing the following formula: $P_{min} + (1 - P_{max})$ where P_{min} and P_{max} are the smaller
267 and the higher probabilities of unilateral tests, respectively (De Meeûs, 2012). Linkage
268 disequilibrium (LD) among loci was analyzed with the standardized index of multilocus
269 association $\overline{r_d}$ (Agapow & Burt, 2001) in Poppr v2.8.2. The $\overline{r_d}$ index is a summary statistic of
270 linkage disequilibrium based on the variance of pairwise distances among individuals (see
271 details in Agapow & Burt, 2001). This index is particularly useful for datasets with a high
272 number of loci for which pairwise approaches are difficult to apply. To avoid the consequences
273 of a Wahlund effect, we computed the $\overline{r_d}$ index separately for each sampling site. Genotypes
274 were permuted 1000 times among individuals inside populations to test for linkage
275 disequilibrium.

276 **Population differentiation in *Laminaria rodriguezii***

277 The overall level of genetic differentiation (overall F_{ST}) was estimated in Genepop v4.2.2. We
278 performed a G-based test of genotypic differentiation across loci (Goudet et al., 1996) with
279 the same software. The P-value for each locus was computed using the Markov chain method
280 with default parameters (500000 iterations). The significance of the test was evaluated by the
281 method of the harmonic mean P-values (HMP) (Wilson, 2019), implemented in the
282 `harmonicmeanp` v3 R package. The test compares P_R , the HMP of a set of P-values R , to α_L ,
283 the significance threshold for a false positive rate weighted by ω_R , the total number of
284 individual P-values (see Table 1 in Wilson, 2019). The HMP P-value is significant when $P_R \leq$
285 $\alpha_L \omega_R$. We used a false positive rate of 0.05 and an equal weight for each P-value, considered
286 as similar to Bonferroni correction.

287 **RESULTS**

288 **Sequencing and SNPs filtering**

289 Approximately 1.2 billion (1 154 828 457) raw reads were produced from 49 samples of *L.*
290 *rodriguezii* (i.e. 47 individuals and two replicates) and 130 samples of *L. digitata* (i.e. 125

291 individuals and five replicates). After quality filtering and read trimming, an average of 2.7
292 million (± 1.5 million SE) and 2.3 million (± 2.1 million SE) high-quality reads per individual were
293 retained for *L. rodriguezii* and *L. digitata*, respectively. The percentage of reads mapped to the
294 *L. digitata* genome, ranged from an average of 85.4% (min: 53.9%; max: 92.2%) for *L.*
295 *rodriguezii*, to 94.2% (min: 67.9%; max: 97.6%) for *L. digitata*. The initial filtering of loci, which
296 retained those shared by a high proportion of individuals, resulted in catalogs of 44 716 loci
297 and 60 942 loci for *L. rodriguezii* and *L. digitata*, respectively. At this stage, the number of SNPs
298 was more than eight times higher for *L. digitata* than for *L. rodriguezii* (Table 1). Additional
299 quality filtering steps followed by outlier exclusion resulted in the selection of 4077 putatively
300 neutral SNPs among 43 individuals of *L. rodriguezii* and 7364 putatively neutral SNPs among
301 116 individuals of *L. digitata* (Table 1). Specifically, 289 SNPs (6.62%) and 174 SNPs (2.31%)
302 were identified as outliers for *L. rodriguezii* and *L. digitata*, respectively. The rate of missing
303 data was slightly higher in *L. digitata* (i.e. 3.36%) than in *L. rodriguezii* (i.e. 2.24%). The mean
304 SNP error rate across replicates was estimated to be 1.06% in *L. digitata* and 3.89% in *L.*
305 *rodriguezii* datasets.

306 **Clonal structure of *Laminaria rodriguezii***

307 In *L. rodriguezii*, the distribution of pairwise genetic distances was discontinuous with a gap
308 from the threshold $d = 0.022$ to the lowest distance reported above this threshold ($d = 0.042$)
309 (Figure 2A). This threshold corresponded to the maximum distance observed among
310 replicates. The use of this threshold allowed us to identify four different clonal lineages with
311 several members: namely MLL-A, MLL-B, MLL-C and MLL-D, composed of three, three, seven,
312 two samples respectively (see the network, Figure 3). By selecting only one sample for each
313 clonal lineage, we finally retained 32 different samples in our data analyses from the 43
314 samples initially present in the whole dataset. At Bonifacio (Southern Corsica), we reported a
315 relatively strong occurrence of clonal lineages ($R = 0.20$), with the dominance of a few large
316 clones ($\beta = 0.56$), which contrasted with the low occurrence of clonal lineages ($R = 0.90$) of
317 small size ($\beta = 2.66$) in Eastern Provence (Table S2, Supporting Information). For instance, the
318 maximum clonal size reported was seven at Bonifacio against three in Eastern Provence. The
319 analysis of the spatial genetic structure along the transect at Banc Magaud_2 (Figure S1,
320 Supporting Information) revealed that: i) individuals belonging to the same clonal lineage
321 were relatively close to one another (less than one meter) and ii) the genetic distance between

322 individuals increased with spatial distance (Mantel test, $R = 0.40$, $p < 0.001$). For the other
323 sites, the sampling protocol (with a minimum spacing of two meters), did not allow a similar
324 investigation of the spatial genetic structure. Contrary to *L. rodriguezii*, no pairwise distance
325 among distinct individuals of *L. digitata* was below the distance threshold defined by
326 replicates (Figure 2B), indicating that there was no cluster of genotypes grouped in clonal
327 lineages. The lowest divergence among individuals in *L. digitata* was around $d = 0.035$, and
328 corresponded to intra-population differences within the Helgoland population.

329 Besides the detection of clonal lineages, we observed in *L. rodriguezii* three individuals, with
330 distinct long branches in the phylogenetic networks (indicated as outliers in Figure 3). These
331 three outlier individuals shared a common characteristic: the highest proportion of
332 heterozygous genotypes among loci per individual, with an average of 33% against 16% in
333 other individuals (Figure S2, Supporting Information). These outlier individuals also had the
334 highest percentage of private alleles among all individuals (average percentage of private
335 alleles at the individual level (Pr) = 20.3% for outlier individuals and $Pr = 1.0\%$ among the other
336 40 genotyped individuals, see Figure S2, Supporting Information). By definition, these private
337 alleles were different among the three individuals.

338 **Genetic diversity**

339 *Laminaria rodriguezii* and *Laminaria digitata* displayed similar expected heterozygosity (H_e),
340 with an average H_e within populations of 0.14 and 0.15, respectively (Table 2). The proportion
341 of polymorphic loci (P) within populations (estimated with the minimum sampling size $n = 10$
342 and 100 random resamples) was higher in *L. rodriguezii* (average $P = 54.42\%$) than in *L. digitata*
343 (average $P = 39.39\%$) (see Table 2, Figure S3, Supporting Information). We observed a
344 departure from panmixia in both species, with an excess of heterozygotes in *L. rodriguezii*, and
345 a deficit of heterozygotes in *L. digitata* (see Table 3 for *L. rodriguezii* and Table S1, Supporting
346 Information for *L. digitata*). The heterozygotes excess was statistically significant (Score [U]
347 test, $P < 0.001$) within populations for *L. rodriguezii*, except for Banc Magaud_1. The
348 heterozygotes deficit was significant (Score [U] test, $P < 0.001$) within populations of *L.*
349 *digitata*.

350 The distributions of F_{IS} were significantly different for all intra and inter-specific comparisons
351 of *L. rodriguezii* and *L. digitata* populations (KS tests, $p < 0.001$, D statistic: 0.07-0.53). At the
352 intraspecific level, the most striking difference in the distributions of F_{IS} (KS tests, D statistic:

353 0.26-0.27) was detected for *L. rodriguezii* between Eastern Provence (Banc Magaud_1,
354 Banc_Magaud_2 and Cap Camarat) and Bonifacio (Figure 4A). The distributions of F_{IS} in
355 Eastern Provence were moderately skewed to negative values with a long tail to positive
356 values (skewness = 0.69; kurtosis = 4.07). The distribution of F_{IS} in Bonifacio was highly skewed
357 toward negative values (skewness = -0.95; kurtosis = 3.14) and showed a much higher
358 proportion of extreme negative values as above to -0.8 (13.6%) in comparison to those
359 measured in Eastern Provence (average, 0.6%). Similarly, the variance in F_{IS} among loci was
360 higher at Bonifacio (var = 0.13) than in Eastern Provence (var = 0.08, 0.07 and 0.06 for Banc
361 Magaud_1, Banc Magaud_2, and Cap Camarat, respectively).

362 In contrast to these results, F_{IS} values were mainly positive in *L. digitata*, whatever the
363 population considered even if the distribution mode of F_{IS} is always observed between -0.1
364 and 0 (Figure 4B). Extreme negative F_{IS} (above -0.8) and even moderate to high negative values
365 (those between -0.5 and -0.3) were almost absent in *L. digitata* with frequencies of 0.03% and
366 0.06%, respectively. The distribution mode of F_{IS} was observed for slightly negative values
367 between -0.1 and 0 whatever the population considered (Figure 4B). The asymmetry of the
368 distributions, as revealed by the positive skewness (skewness = 0.98; kurtosis = 3.32) is
369 indicative of a long tail toward high and extreme positive values (0.5 to 1). This class of
370 extreme positive F_{IS} corresponded to 28% of all loci in Helgoland. At the intra-specific level,
371 the second major difference in the shape of the distribution of F_{IS} was reported between
372 Helgoland and all other populations of *L. digitata* (KS tests, D statistic 0.11-0.23).

373 The average multilocus estimates of F_{IS} within populations ranged from 0.12 to 0.43 for *L.*
374 *digitata* (Table S1, Supporting Information) whereas mean values were mainly negative within
375 populations in *L. rodriguezii*, with a range from -0.47 in Bonifacio to -0.02 at Banc Magaud_1
376 (Table 3A). After applying the correction for repeated genotypes, the average multilocus
377 estimates of F_{IS} increased to a range from $F_{IS} = -0.26$ at Bonifacio to $F_{IS} = -0.01$ at Banc
378 Magaud_2 (Table 3B). After the correction for repeated genotypes, the heterozygosity excess
379 only remained significant at Bonifacio (Score [U] test, $P < 0.001$).

380 The distribution of the index of multilocus association $\overline{r_d}$ (Figure 5) was nearly identical
381 whatever the number of SNPs subsampled (i.e. 1000; 2000 and 3000 random SNPs). The mean
382 $\overline{r_d}$ was statistically significant ($p < 0.001$) within all populations of both species. For *L.*
383 *rodriguezii*, the $\overline{r_d}$ index reached high levels within all populations (mean $\overline{r_d} = 0.08$ to 0.27),
384 except at Banc Magaud_1 (mean $\overline{r_d} = 0.01$) for which there was no repeated sampling of a

385 clonal lineage (Table 3). The values of $\overline{r_d}$ decreased slightly by keeping only one representative
386 of each clonal lineage (Table 3, Figure 5). For *L. digitata*, the mean $\overline{r_d}$ ranged between 0.01 to
387 0.03 within all populations (Table S1, Figure 5), except for Helgoland that displayed a
388 remarkably high level of linkage disequilibrium similar to values observed in *L. rodriguezii*
389 (mean $\overline{r_d} = 0.20$).

390 **Population differentiation in *Laminaria rodriguezii***

391 *Laminaria rodriguezii* exhibited high levels of population structure with a global F_{ST} of 0.28
392 when considering all individuals ($n = 43$). After applying the clone correction (i.e. one sample
393 per clonal lineage), the estimate of genetic differentiation decreased (global $F_{ST} = 0.18$). After
394 correcting for multiple testing, genotypic differentiation among populations of *L. rodriguezii*
395 was significant (HMP significance threshold, $\alpha_L \omega_R = 0.032$; HMP P-value, $P_R = 0$), with and
396 without the clone correction.

397 **Negative F_{IS} and high F_{ST} in *L. rodriguezii* over SNP filtering methods**

398 For *L. rodriguezii*, the mean F_{IS} and overall F_{ST} varied between the reference dataset and the
399 filtered datasets (Table 4). However, the mean F_{IS} was always negative, with high variance
400 among loci, whatever the levels of stringency. In the same way, the overall F_{ST} stayed high and
401 it was never below 0.27. The maximum rate of missing data allowed per SNP (max-missing)
402 had a very limited effect on mean F_{IS} and overall F_{ST} , which ranged from -0.06 to -0.07 and
403 from 0.27 to 0.30, respectively. The highest variance was associated with MAF cutoff as the
404 filter excluded the lowest polymorphic loci, and subsequently increased the level of genetic
405 variation in the dataset. Therefore, we choose to keep the MAF cutoff at 2% so as not to inflate
406 the levels of genetic variation in *L. rodriguezii*. The SNP error rate decreased from 5.22% in the
407 reference dataset to 2.74% in the dataset which was filtered by excluding loci with low
408 coverage (i.e. meanDP > 15X). Genotyping errors were probably non-randomly distributed and
409 occurred mostly in loci with low coverage, so we excluded them by applying meanDP > 15X.

410

411

412 **DISCUSSION**

413 We used RAD-sequencing to analyze the genome-wide diversity of the rare *Laminaria*
414 *rodriguezii*. We found that intra-individual genomic diversity is a powerful tool to identify
415 clonal lineages. We also proposed that the observed F_{IS} distribution and linkage disequilibrium
416 at the genome scale can be compared with theoretical models to search for a discernable
417 signal of clonality, even in this partially clonal reproducing species. Finally, we will discuss here
418 the findings of high heterozygosity within some individuals that raise questions about the
419 mechanisms allowing the persistence of such genomic features.

420 **RAD-seq as a powerful tool for detection of clonal lineages**

421 The identification of clonal lineages in natural populations was addressed by assessing the
422 probability that identical or slightly distinct genotypes belong to the same clonal lineage. That
423 can be achieved through the development of standardized methods allowing for investigation
424 of the influence of somatic mutations and scoring errors (Arnaud-Haond et al., 2007).
425 However, while this methodological framework is particularly robust for a small number of
426 loci, RAD-seq and the amount of data generated by Next Generation Sequencing (NGS) brings
427 new challenges. The main concern is that increasing the number of loci is equivalent to
428 increasing the number of missing data and genotyping errors that can subsequently affect the
429 detection of clonal lineages. This is especially the case for reduced representation sequencing
430 (e.g. RAD-seq) sensitive to missing data and genotyping error, thus necessitating appropriate
431 filtering strategy (e.g. Mastretta-Yanes et al., 2015; Shafer et al., 2017; Andrews et al., 2018;
432 Boscari et al., 2019). How then can we find an adequate distance threshold for collapsing
433 slightly distinct genotypes into clonal lineages? For that purpose, we can define a threshold
434 using the pairwise genetic distances, a threshold below which genotypes are assumed to
435 belong to the same clonal lineage. Some studies have fixed a cut-off based on the gap in
436 pairwise genetic distances (e.g. Shrestha et al., 2014), while others have defined an arbitrary
437 95% genotype similarity threshold (e.g. Locatelli & Drew, 2019). Nevertheless, such
438 approaches can be inaccurate, particularly when different sources of noise (i.e. genotyping
439 error, missing data, somatic mutation) can accentuate differences between clonal genotypes
440 above the detection threshold. This also depends on the genetic diversity of the populations:

441 clonal lineages are more easily identified in populations where the diversity among sexually
442 produced individuals is high, i.e. in partially clonal species. In this study, we proposed defining
443 a threshold on the basis of the pairwise genetic distance across replicates. While this approach
444 seems to be useful in evaluating the genetic distance expected as a result of genotyping errors
445 and somatic mutations, it has rarely been reported, except in *Leptopsammia pruvoti* (Boscari
446 et al., 2019). For this organism genotyped with 1386 SNPs (with the 2b-RAD protocol), slightly
447 distinct genotypes below a distance threshold set at $d = 0.043$ were collapsed into clonal
448 lineages. For *L. rodriguezii*, this cut-off was lower ($d = 0.022$), even if of a similar order as in *L.*
449 *pruvoti*. This difference highlights the importance of not considering a common threshold but
450 rather of adjusting it using genotype mismatch across replicates. Note that using the same
451 method on both species, the threshold was very similar between *L. rodriguezii* and *L. digitata*.

452 **The genomic patterns of clonality**

453 Our results show how the distribution of F_{IS} among loci can be used to study species and
454 populations with various signals of clonality including partial clonality. Signatures of clonality
455 in natural populations are usually inferred from repeated genotypes, along with mean
456 negative values of F_{IS} , and linkage disequilibrium across loci (Balloux et al., 2003; Halkett et al.,
457 2005). Nevertheless, recent studies reported that one of these signatures, genotypic richness,
458 had poor relevance for measuring the relative importance of sexual versus clonal reproduction
459 (Arnaud-Haond et al., 2020), even using relatively large sample sizes (from 100 to 500
460 individuals) (Stoeckel et al., 2019). This is because the estimates of genotypic richness are
461 strongly dependent on sampling strategy and density, basically decreasing with increasing
462 sampling effort (Arnaud-Haond et al., 2007; Gorospe et al., 2015; Becheler et al., 2017). In our
463 study, by looking at the F_{IS} distribution in the genome, we propose a new analysis which seems
464 useful to detect partial clonal reproduction. Our approach confirmed the prediction that inter-
465 locus variance of F_{IS} (rather than an average value) increased as clonal rates increased (Balloux
466 et al., 2003; Halkett et al., 2005; Stoeckel & Masson 2014; Reichel et al., 2016; Stoeckel et al.,
467 2019). We also reported (1) contrasted distribution of F_{IS} between species, with F_{IS} shifted
468 towards negative values in the partially clonal species *L. rodriguezii*, and towards positive
469 values in the fully sexually reproducing species *L. digitata*; (2) striking differences in
470 distributions of F_{IS} among populations of *L. rodriguezii*, with higher inter-locus variance in F_{IS}

471 at Bonifacio (Corsica) than in the three localities of Eastern Provence. Remarkably, the
472 empirical distributions of F_{IS} in Eastern Provence matched well with the simulation results of
473 Stoeckel & Masson (2014) which predicted that most F_{IS} values are concentrated between -
474 0.3 and 0.1 below intermediate levels of clonality.

475 Genetic drift is another possible explanation for negative F_{IS} values. In a finite population with
476 random mating, genetic drift due to sampling effect indeed tends to create a slightly negative
477 mean F_{IS} , but the effect is small, of order $1 / (2N)$ where N is the size of the population (see
478 Figures 3 and 4 in Stoeckel & Masson, 2014). For the fully sexual dioicous species *L. digitata*,
479 this drift effect could explain why the distribution mode of F_{IS} is between -0.1 and 0 whatever
480 the population considered. However, the probability of highly negative values increases when
481 genetic drift is combined with intermediate rates of clonality (Stoeckel & Masson, 2014).
482 Nevertheless, Stoeckel & Masson (2014) showed that values below -0.3 remain rare if the
483 clonality rate is below 0.9. This is indeed what is observed for all *L. rodriguezii* populations,
484 suggesting that their clonality rates are intermediate, except at Bonifacio, the Corsican
485 population for which we observed the highest proportion of F_{IS} below -0.3 and even below -
486 0.8. In addition, the estimates of genotypic richness (R), Pareto (β), and linkage disequilibrium
487 ($\overline{r_d}$) emphasized the degree of distinction between the Eastern Provence and Bonifacio
488 populations, thus strengthening our hypothesis of a higher level of clonality in Corsica than in
489 Eastern Provence. A more in-depth investigation of the combined effects of drift and clonal
490 reproduction on the distribution of F_{IS} would be useful in this context. Parameters other than
491 reproductive mode differ between the two species compared here, such as the levels of
492 genetic drift, the investigated geographical range, and potentially their demographic history.

493 The population of Helgoland for the fully sexually reproducing species, *L. digitata*, reached a
494 high level of linkage disequilibrium comparable to the Bonifacio population of *L. rodriguezii*
495 for which the signature of clonality was clearly discernible. Nevertheless, Helgoland had a
496 distribution of F_{IS} markedly different from *L. rodriguezii*, with a majority of positive values.
497 Helgoland is a rocky island surrounded by several hundreds of kilometers of sandy seafloor.
498 This population shows the highest levels of positive F_{IS} , the lowest values of pairwise genetic
499 distances between individuals, and the highest value of linkage genetic disequilibrium
500 observed for *L. digitata*. This is most probably explained by the effect of low effective size and
501 maybe of a bottleneck. This population also showed the lowest level of genetic diversity
502 observed for *L. digitata* when genotyped with the microsatellite locus in the study of Liesner

503 et al. (2020). There is a lack of case studies to conclude more precisely on the role of drift and
504 of demographic history in the distribution of inter locus F_{IS} variance. However, the theoretical
505 results of Stoeckel & Masson (2014) and Stoeckel et al. (2019) agree well with our
506 experimental results. This paves the way toward a better assessment of the importance of
507 clonality through genomic studies, but it remains the case that the estimation of clonality rates
508 is still only possible using temporal sampling (Ali et al., 2016; Becheler et al., 2017).

509 **Extreme levels of individual genomic heterozygosity**

510 We reported an intriguing signal of genome-wide heterozygosity in three of the 43 individuals
511 in *L. rodriguezii*. These outlier individuals were characterized by an exceptionally high
512 proportion of heterozygous genotypes compared to other individuals. Given the relatively low
513 sample sizes, we do not really know how these individuals depart from the population
514 distribution in individual heterozygosity, but we can discuss several hypotheses regarding
515 their origin. High heterozygosity at particular loci can correspond to paralogs assembled in the
516 same RAD locus depending on assembly parameters (Verdu et al., 2016; Mckinney et al., 2017;
517 Nadukkalam Ravindran et al., 2018). However, for the following reasons, we would argue that
518 polymorphisms detected within these outlier individuals do not correspond to artefactual loci:
519 firstly, sequencing reads were mapped to the reference genome of a closely related species,
520 followed by stringent filter criteria, including for maximum heterozygosity. Secondly, paired-
521 end sequencing protocols provide additional information on correct read placement since
522 RAD loci are retained when both reads are properly mapped (according to the insert length
523 between forward and reverse reads). Thirdly, if paralogs were responsible for high levels of
524 heterozygosity, we would not expect to observe this in only three individuals. On the other
525 hand, recent studies have revealed that both cross-contamination among samples and
526 environmental contamination, especially during library preparation and/or sequencing, can
527 lead to artifactual results, with the sequencing of loci of different origins in the same sample
528 (Laurin-Lemay et al., 2012; Ballenghien et al., 2017). Here, the three outlier individuals were
529 also characterised by the highest proportion of private alleles at the individual level, and they
530 were not grouped on the network. Such private alleles can then not be explained by cross-
531 contamination among samples of the same species. Rather they could be explained by the
532 accumulation of mutations along with clonal reproduction, thus increasing the divergence
533 among loci in the same individuals, a potential signal of the Meselson effect (Birky, 1996;

534 Welsh & Meselson, 2000; De Meeûs et al., 2007). These outlier individuals could then belong
535 to a relatively ancient asexual lineage. However, we lack temporal sampling to get more
536 precise estimates of the rates of clonal reproduction, and therefore, the hypothesis of
537 clonality to explain these outlier individuals remains highly speculative. A high frequency of
538 heterozygous loci could also be observed following hybridization among well differentiated
539 genetic lineages. Hybridization has indeed been proposed as the main driver of high
540 heterozygosity in parthenogenetic animals (Jaron et al., 2020). Here, the hybrid hypothesis
541 should involve several hybridizations from three different sources to explain the observed
542 pattern of private alleles, as well as the genetic distance among the three outliers. It would
543 therefore be interesting to analyze the genomic diversity of other *L. rodriguezii* populations in
544 the Mediterranean in order to go further on this topic. Nevertheless, the populations of *L.*
545 *rodriguezii* are scarce, and there are no other congeneric species in this area.

546 **Implications for conservation**

547 Our results emphasise that *L. rodriguezii* is spatially structured into genetically distinct
548 populations. At Banc Magaud_2 we also evidenced a significant spatial genetic structure:
549 regarding the low occurrence of clonality in this population, this structure is better explained
550 by reduced dispersal through haploid spores. Although high levels of population genetic
551 structure are not uncommon in kelps (e.g. Billot et al., 2003; Coleman et al., 2009; Durrant et
552 al., 2018), our results contrast with the lack of genetic differentiation among populations of *L.*
553 *digitata* spatially distant by up to 10 km (Billot et al., 2003; Robuchon et al., 2014). In this
554 respect, the spatial scale of dispersal of *L. rodriguezii* is presumably smaller than that reported
555 in other species of the genus *Laminaria* (Santelices, 1991). The patchy distribution and small
556 population sizes of *L. rodriguezii* can probably explain this pattern of high and local genetic
557 differentiation through strong local genetic drift and limited gene flow among populations.
558 The identification of such a local genetic structure has important implications for management
559 and conservation. The high genetic drift and limited gene flow can explain the lower genetic
560 diversity expected in *L. rodriguezii* compared to *L. digitata*, a species with a wider geographical
561 distribution, exhibiting semi-continuous and dense populations (see Hamrick & Godt, 1990;
562 Frankham, 1996; Levy et al., 2016). Furthermore, the range of *L. rodriguezii* has been
563 drastically reduced during the last half-century, especially in the Adriatic Sea, where the
564 species has suffered losses of 85% from its historical range (Žuljević et al., 2016). However, the

565 observed heterozygosity and the percentage of polymorphic loci were higher in *L. rodriguezii*
566 when compared to *L. digitata*. This can be explained by the conservation of heterozygous
567 genotypes with low recombination rates (Judson & Normark, 1996; Balloux et al., 2003; see
568 Meloni et al., 2013 for an empirical example), as genetic drift under clonal reproduction acts
569 on genotype frequencies rather than allele frequencies (Stoeckel & Masson, 2014; Reichel et
570 al., 2016). Further studies would be necessary to test with genomic data whether the current
571 fragmented range and small populations of *L. rodriguezii* correspond to a demographic
572 reduction from a larger ancestral population. The extensive cartography and monitoring of
573 the biocenoses down to 100 m along French coasts do point to the rarity of this species. The
574 conservation of these last isolated populations should become a high priority for stakeholders.

575 **Conclusion**

576 Our study shows that despite limitations on the detection of clonal lineages, SNPs derived
577 from RAD sequencing are interesting markers for population genomic studies of partially
578 clonal species. The interaction between demographic history and reproductive mode shaped
579 the distribution of F_{IS} and linkage disequilibrium in *L. rodriguezii*. Interestingly, even if our loci
580 were mapped to a reference genome for assembly, we did not use the physical location of loci
581 in our analyses, which indicates that similar approaches could be envisioned with *de novo*
582 assembly. In order to decipher the respective impact of demography and reproduction in our
583 results, one next step could be to use summary statistics linked with these distributions (such
584 as higher moments) for evolutionary inferences, using for example Approximate Bayesian
585 Computation (Csilléry et al., 2010).

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919 **DATA ACCESSIBILITY**

920 Individual high-quality reads (dd-RADseq) that support the findings of this study are openly
921 available in a Dryad Digital Repository (doi:10.5061/dryad.hmgqnk9dq). The home-made
922 scripts used to generate the distribution of F_{IS} values into classes, the histograms of pairwise
923 genetic distances, and the graphs representing the percentage of polymorphic loci are
924 available in the public repository: <https://github.com/LauricReynes>

925 **AUTHOR CONTRIBUTION**

926 Thierry Thibaut and Didier Aurelle devised the project and were responsible for the main
927 conceptual ideas. Florian Holon performed the sampling of *Laminaria rodriguezii*. Aurélie
928 Blanfuné contributed to sample preparation. Stéphane Mauger and Lauric Reynes performed
929 the RAD-sequencing experiment and analyzed sequencing reads. Corinne Cruaud and Arnaud
930 Couloux provided the draft genome of *Laminaria digitata*. Lauric Reynes performed research,
931 analyzed data, and wrote the manuscript in close collaboration with Didier Aurelle and
932 Myriam Valero. All authors provided critical feedback and helped to shape the research,
933 analysis, and manuscript.

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942 **TABLES AND FIGURES**

943 **Table captions**

944 **Table 1.** Quality filters used to build the final RAD-seq datasets of *Laminaria rodriguezii* and
945 *Laminaria digitata*. For each filtering step, the number of SNP passing the filter (SNPs count),
946 as well as the mean missing data rate per individual (missingness) and the mean sequencing
947 depth per individual (coverage) are reported. Loci were initially built in both species from the
948 draft genome of *L. digitata* using the Stacks v.2.4 bioinformatics pipeline. The threshold of
949 missing genotypes per individual < 30% has deleted four and nine individuals in *L. rodriguezii*
950 and *L. digitata* datasets respectively. See Methods for details.

951 **Table 2.** Comparison of population genetic summary statistics (mean and range of values) in
952 *Laminaria rodriguezii* and *Laminaria digitata*. %P, average percentage of polymorphic loci
953 within populations rarified at $n = 10$ by random resampling (see methods for details), H_o ,
954 observed heterozygosity, H_e , expected heterozygosity, F_{IS} , fixation index.

955 **Table 3.** Genetic variation within populations of *Laminaria rodriguezii* (A) before and (B) after
956 applying the clonal correction. Clonal correction consists of keeping only one representative
957 of clonal lineages. N, number of individuals successfully genotyped, H_o , observed
958 heterozygosity, H_e , expected heterozygosity, F_{IS} , fixation index, $\overline{r_d}$, average multilocus linkage
959 disequilibrium. F_{IS} and $\overline{r_d}$ values highlighted in bold indicate significant heterozygote excess
960 within populations ($P\text{-val} < 0.001$) and significant linkage disequilibrium ($P\text{-val} < 0.001$),
961 respectively.

962 **Table 4.** The effect of SNP filtering cutoffs on the mean (\pm SD) F_{IS} over loci, overall (\pm SD) F_{ST}
963 over loci and the SNP error rate in *Laminaria rodriguezii*. As thresholds, we considered the
964 maximum rate of missing data allowed per SNP (max-missing), the Minor Allele Frequency
965 (MAF), the mean read depth per locus across all individuals (meanDP). For each cutoff value
966 we reported the number of SNP passing the filter (SNPs count), the mean missing data rate
967 per individual (missingness), and the mean read depth per individual (coverage). We
968 considered an additional set of SNPs (matching genotypes) for which replicates have exactly
969 the same multi-locus genotypes (SNP error rate = 0).

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978 **Figure captions**

979 **Figure 1.** Sampling map of *Laminaria rodriguezii* in Eastern Provence and Southern Corsica,
980 reporting the depth in meters of sampling sites and the number of individuals sampled per
981 site (N).

982 **Figure 2.** Frequency of pairwise genetic distances between individuals of (A) *Laminaria*
983 *rodriguezii* and (B) *Laminaria digitata*. Intra-population (Intra-pop), inter-population
984 (Inter-pop), within Helgoland (Intra-Hel) and replicates (Replicates) comparisons are colored
985 according to the legend. The frequency of pairwise genetic distances across replicates was
986 multiplied by 40 to create an optimum bin size. The vertical dotted line shows the distance
987 threshold ($d = 0.022$) as reported as the maximum value of replicate pairs.

988 **Figure 3.** Phylogenetic networks of *Laminaria rodriguezii* represented with the neighbor-net
989 method. Each dot represents an individual, Individuals belonging to the same clone (MLLs,
990 Multi-Locus Lineages) are colored according to the legend. Individuals characterized by the
991 highest proportion of heterozygous genotypes and private alleles are indicated as outliers.

992 **Figure 4.** Distributions of the fixation index F_{IS} among loci within populations of (A) *Laminaria*
993 *rodriguezii* and (B) *Laminaria digitata* computed across 4 077 and 7364 putatively neutral
994 SNPs, respectively. The F_{IS} values were distributed into 10 discrete classes and the number of
995 occurrences for each class is indicated on top of histogram bars. The variance of F_{IS} among loci
996 (Var) is indicated in brackets next to population labels.

997 **Figure 5.** Distributions of the standardized index of multilocus association \bar{r}_d within
998 populations of *Laminaria rodriguezii* before (highlighted in red) and after (highlighted in
999 green) clonal correction (cc). Comparison of the index value was done with five populations
1000 of *Laminaria digitata* (highlighted in blue). The \bar{r}_d values were estimated using 10 000
1001 iterations by random subsampling of 1000; 2000 and 3000 SNPs. The abbreviations used for
1002 populations are those reported in Table 3 for *L. rodriguezii* and Table S1 for *L. digitata*.

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1011 **Table 1**

	%P			H _o			H _e			F _{IS}		
<i>L. rodriguezii</i>												
Average	54.42			0.16			0.14			-0.14		
Range	40.96	-	72.14	0.11	-	0.19	0.11	-	0.18	-0.47	-	-0.02
<i>L. digitata</i>												
Average	39.39			0.11			0.15			0.26		
Range	21.44	-	54.89	0.09	-	0.14	0.12	-	0.19	0.12	-	0.43

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1016 **Table 2**

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Filtering thresholds	<i>Laminaria rodriguezii</i>			<i>Laminaria digitata</i>		
	SNP counts	missingness	coverage	SNP counts	missingness	coverage
Locus genotyped > 75% of the samples > 75% of the populations SNP kept observed heterozygosity < 80%	70 026	13.97 %	11.29	609 699	12.26 %	14.11
Linkage disequilibrium single SNP per locus	27 769	13.18 %	11.88	58 830	13.45 %	14.36
Minor Allele Frequency (MAF) MAF > 2%	16 865	13.51 %	12.18	21 090	15.01 %	14.43
Missingness per individual < 30% per SNP < 20%	13 235	4.46 %	13.91	15 150	4.73 %	17.24
Coverage mean read depth > 15 X mean read depth < 100 X	4 366	2.27 %	22.17	7 538	3.40 %	21.63
Outliers detection putatively neutral	4 077	2.29 %	22.04	7364	3.39 %	21.64

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Table 3

(A)						
Population	Label	N	H_o	H_e	F_{IS}	\bar{r}_d
Banc Magaud_1	BM_1	10	0.18	0.17	-0.02	0.01
Banc Magaud_2	BM_2	11	0.19	0.18	-0.04	0.08
Cap Camarat	CAM	11	0.11	0.11	-0.05	0.10
Bonifacio	BON	11	0.16	0.11	-0.47	0.27
(B)						
Population	Label	N	H_o	H_e	F_{IS}	\bar{r}_d
Banc Magaud_1	BM_1	10	0.18	0.17	-0.02	0.01
Banc Magaud_2	BM_2	9	0.19	0.19	-0.01	0.05
Cap Camarat	CAM	10	0.11	0.11	-0.02	0.10
Bonifacio	BON	3	0.20	0.16	-0.26	0.20

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Table 4

Quality filter	cutoff	SNPs count	missingness (%)	coverage	mean (\pm SD) F_{IS}	overall (\pm SD) F_{ST}	SNP error rate (%)
Reference dataset		21 357	4.11	13.00	-0.07(0.20)	0.27(0.18)	5.22
max-missing (%)	< 15	21 114	3.97	13.08	-0.07(0.20)	0.27(0.18)	5.17
	< 10	19 468	3.33	13.52	-0.07(0.20)	0.27(0.18)	4.94
	< 5	14 480	1.95	14.88	-0.07(0.19)	0.28(0.18)	4.30
	0	5 479	0.00	18.12	-0.06(0.18)	0.30(0.19)	2.90
MAF (%)	> 2	12 735	4.28	13.31	-0.08(0.26)	0.30(0.22)	7.07
	> 5	5 094	4.54	16.18	-0.12(0.34)	0.37(0.26)	4.92
	> 10	3 428	4.56	17.29	-0.14(0.37)	0.42(0.26)	3.86
meanDP (X)	> 5	19 245	3.59	13.71	-0.08(0.20)	0.28(0.18)	4.88
	> 10	11 773	2.52	17.41	-0.11(0.22)	0.31(0.21)	3.92
	> 15	6 163	1.90	21.85	-0.13(0.23)	0.33(0.22)	2.74
max-missing cutoff for fixed MAF (2%) and meanDP (>15)	< 20	3 911	2.14	21.83	-0.15(0.29)	0.34(0.25)	3.71
	< 10	3 850	1.99	21.81	-0.14(0.28)	0.35(0.25)	3.70
	< 5	3 464	1.41	21.90	-0.12(0.28)	0.35(0.25)	3.53
	0	1 813	0.00	22.71	-0.10(0.27)	0.37(0.26)	2.68
matching genotypes		3 638	2.14	22.07	-0.15(0.29)	0.35(0.25)	0.00

FRANCE

ITALY

SPAIN

Mediterranean Sea

5 km

Eastern
Provence

Cap Camarat
(N=12); -65 to -73m

Banc Magaud_1
(N=12); -76m

Banc Magaud_2
(N=11); -71m

South of
Corsica

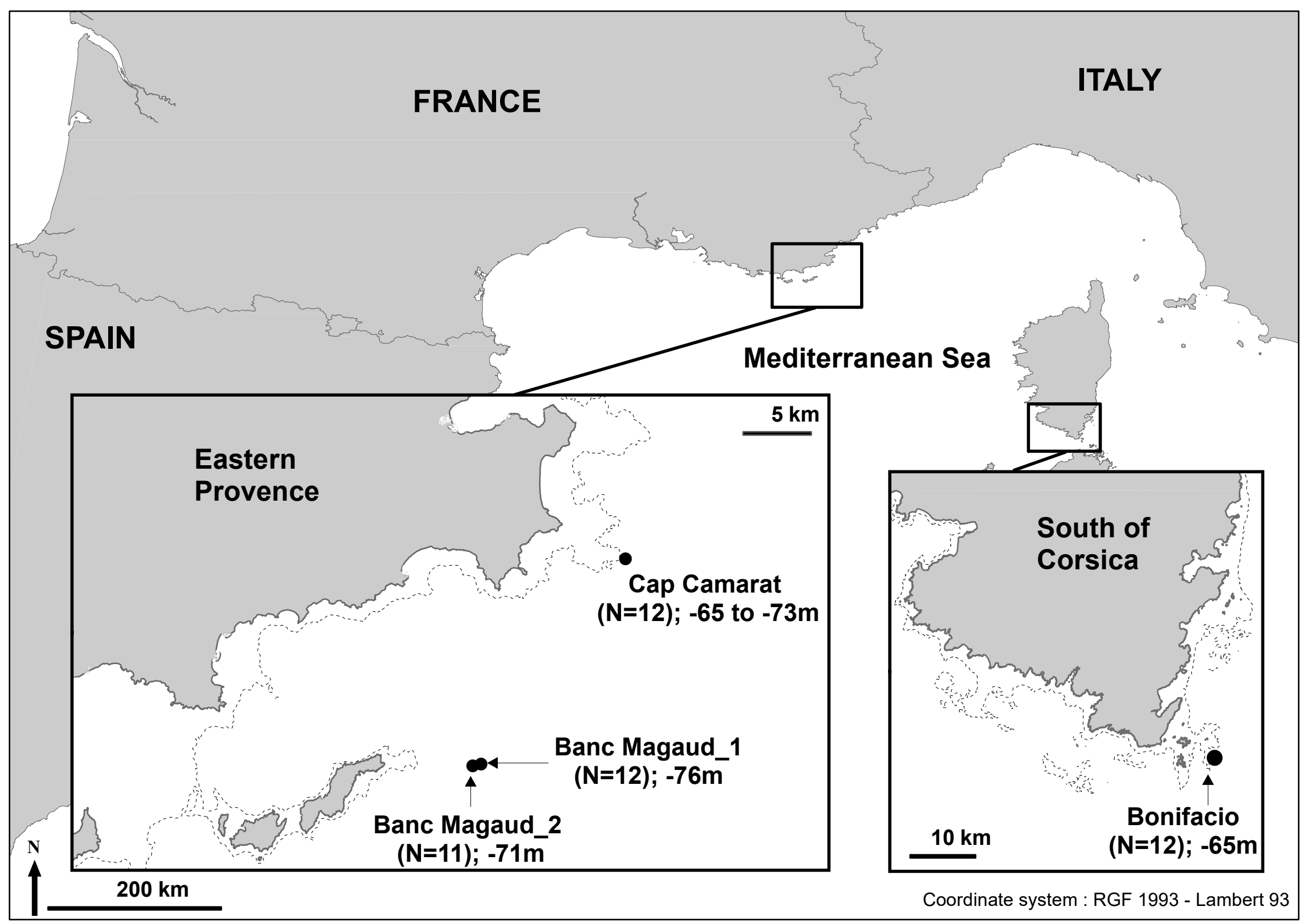
Bonifacio
(N=12); -65m

10 km

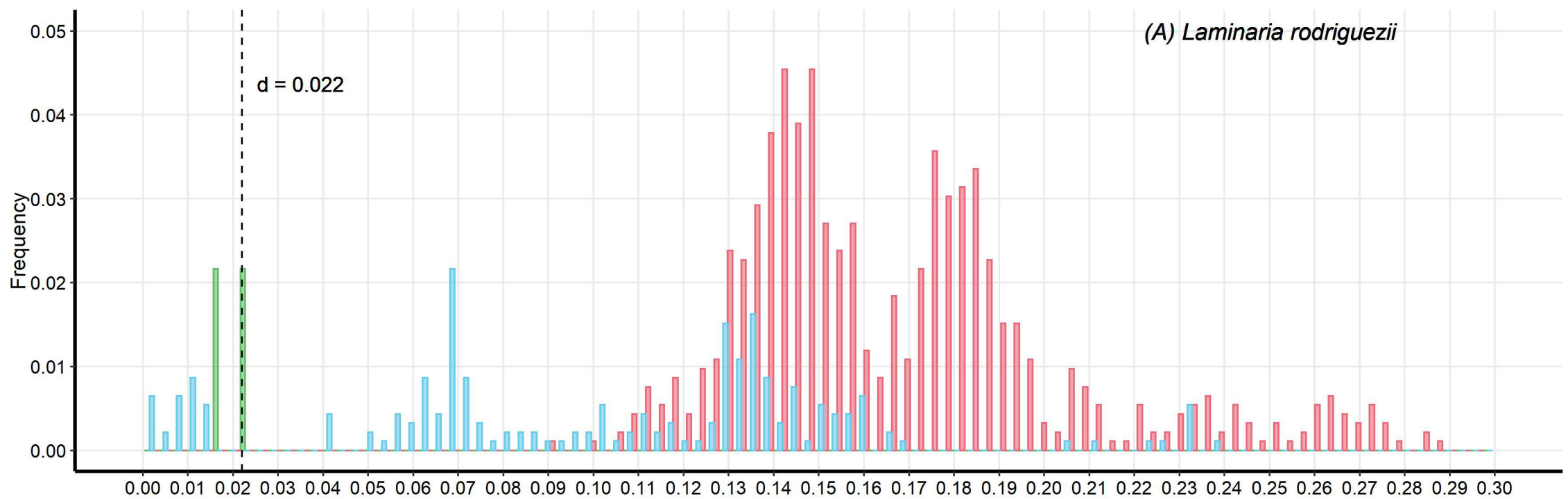
200 km

N

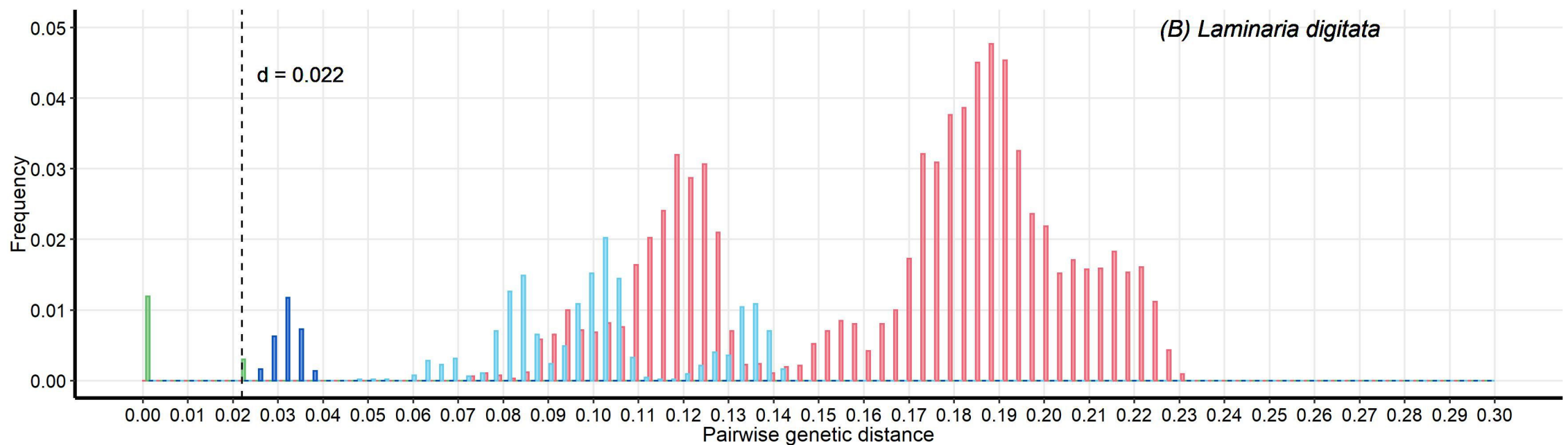
Coordinate system : RGF 1993 - Lambert 93



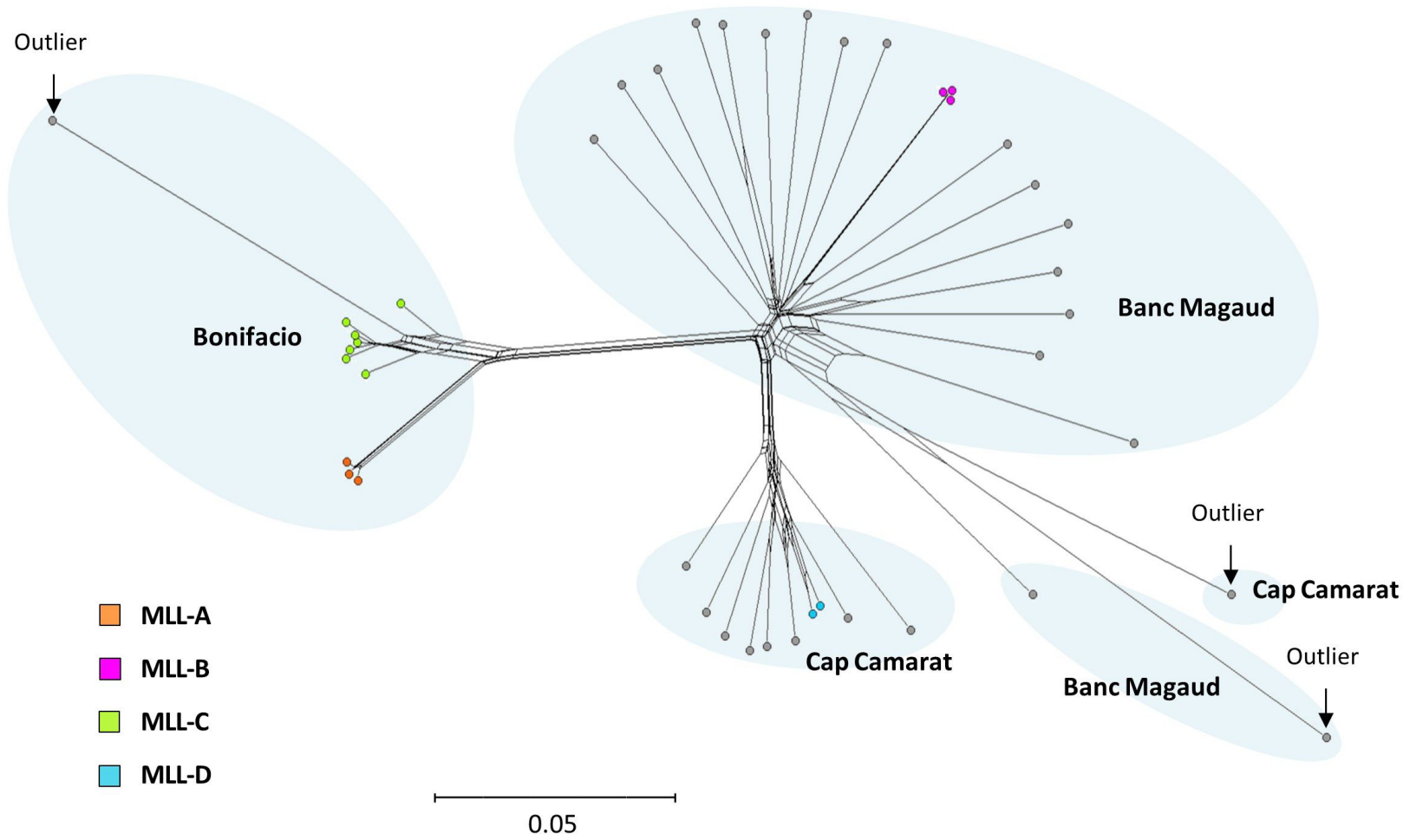
(A) *Laminaria rodriguezii*

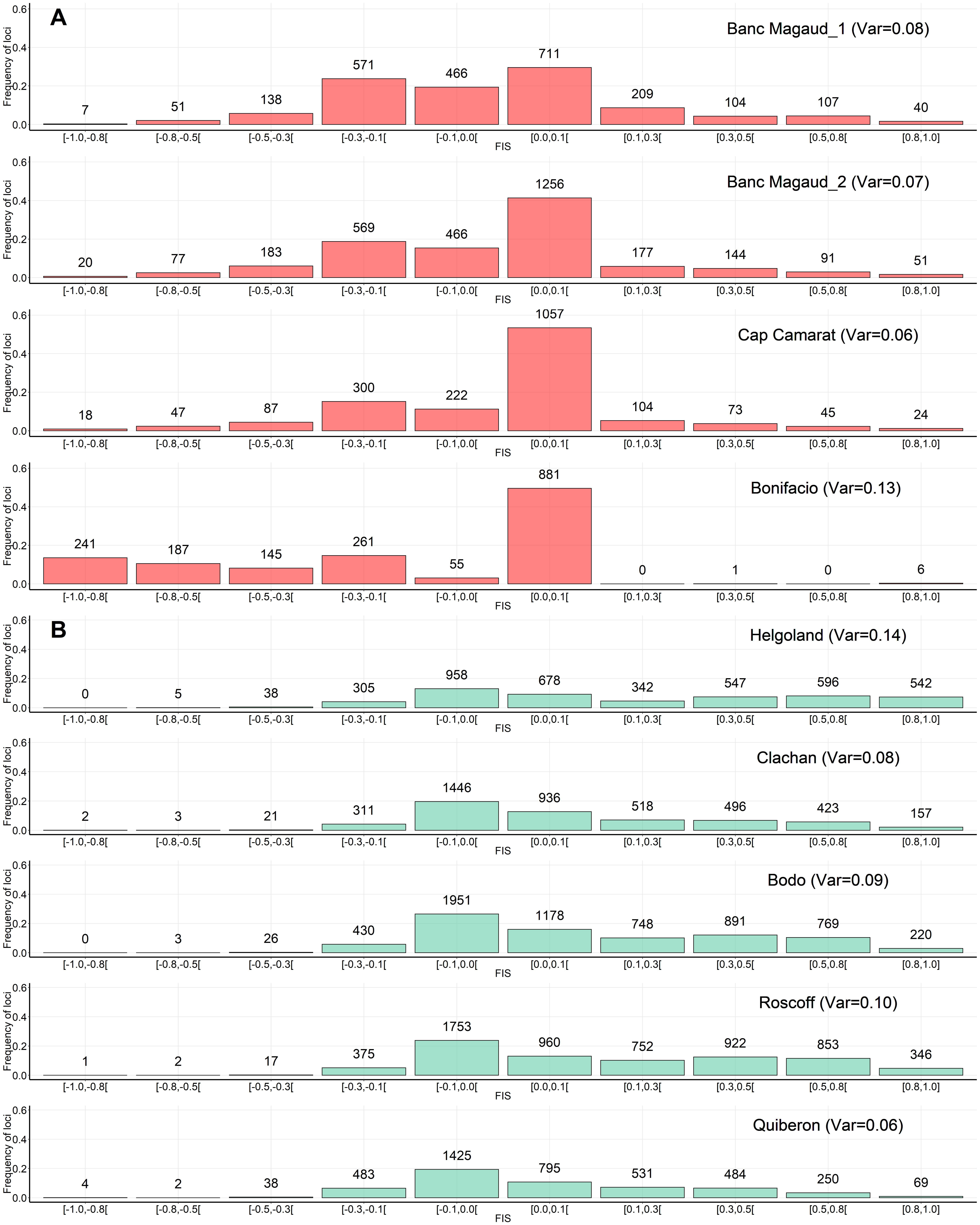


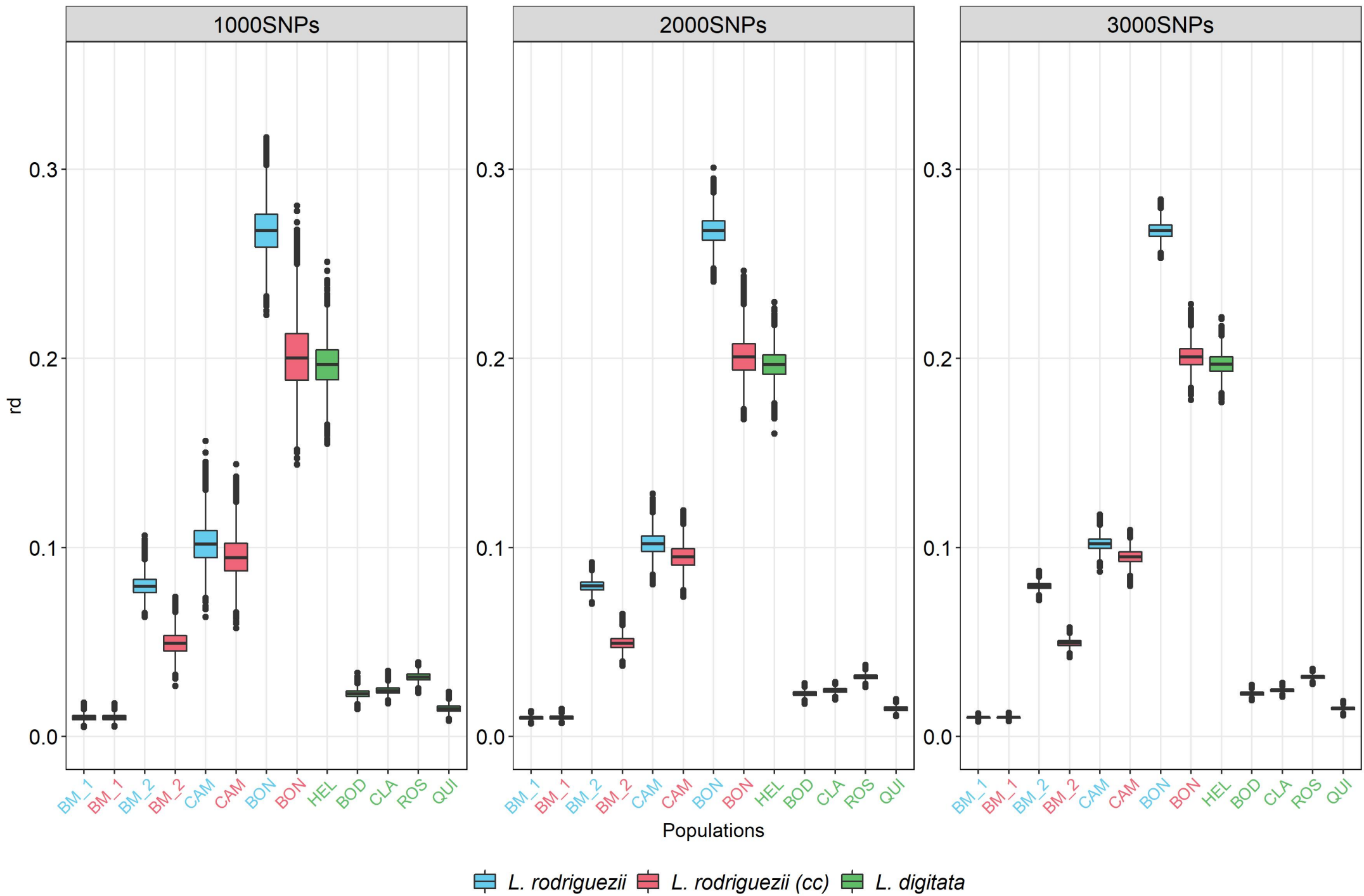
(B) *Laminaria digitata*



Intra_Hel Intra_pop Inter_pop Replicates







Supplemental Information for:

Genomic signatures of clonality in the deep water kelp *Laminaria rodriguezii*

Lauric Reynes, Thierry Thibaut, Stéphane Mauger, Aurélie Blanfuné, Florian Holon, Corinne Cruaud, Arnaud Couloux, Myriam Valero, Didier Aurelle

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Supplementary materials

Table S1. Genetic variation within populations of <i>Laminaria digitata</i> . N, number of individuals successfully genotyped, Ho, observed heterozygosity, He, expected heterozygosity, FIS, average fixation index, $\overline{r_d}$, average multilocus linkage disequilibrium. FIS and $\overline{r_d}$ values highlighted in bold indicate significant heterozygote deficit within populations (P-val < 0.001) and significant linkage disequilibrium (P-val < 0.001), respectively.	Page S3
Table S2. Genotypic richness (R) and Pareto (β) indexes estimated for populations of <i>Laminaria rodriguezii</i> . No β value is reported at Banc Magaud_1 due to the absence of clonal lineages.	Page S4
Figure S1. Spatial analyses at Banc Magaud_2. (A) the pairwise genetic distances were those previously used to assess clonal identity and (B) the spatial distance matrix (m)	Page S5

<p>was generated from the positions of individuals within the transect. Mantel tests between spatial and genetic distances were significant ($R = 0.40$, $P < 0.001$) after 10 000 permutations. LRBM2P12, LRBM2P13, and LRBM2P14 belong to the same clone, while LRBM2P2 is one of the outliers highlighted in the study. (C) The linear regression between genetic and spatial distances by including (red) or excluding (blue) pairwise comparisons with the outlier.</p>	
<p>Figure S2. Genomic patterns of the three outliers as comparison to other individuals of <i>Laminaria rodriguezii</i>. (A) Percentage of private alleles per individual and (B) percentage of heterozygosity per individual.</p>	<p>Page S6</p>
<p>Figure S3. Average percentage of polymorphic loci (%P) within populations of (A) <i>Laminaria rodriguezii</i> and (B) <i>Laminaria digitata</i> obtained using a random sampling approach implemented in a custom bash script (available at https://github.com/rebecca-cj/revegetation). The percentage of polymorphic loci was calculated for each sample size from 100 random resamples. Standard error from the mean from replicates is represented as error bars.</p>	<p>Page S7</p>
<p>Materials S1</p>	<p>Pages S8-9</p>

Table S1

Population	Label	Lat.	Long.	N	H_o	H_e	F_{IS}	$\overline{r_d}$
Bodo	BOD	67.2765	14.5747	23	0.14	0.18	0.23	0.02
Clachan	CLA	56.3171	-5.5832	25	0.09	0.12	0.22	0.02
Helgoland	HEL	54.1779	7.8926	20	0.09	0.15	0.43	0.20
Quiberon	QUI	48.7275	4.0079	23	0.11	0.13	0.12	0.01
Roscoff	ROS	47.4700	-3.0914	25	0.13	0.19	0.28	0.03

Table S2

Population	β	R
Banc Magaud_1	NA	1.00
Banc Magaud_2	2.00	0.80
Cap Camarat	3.32	0.90
Bonifacio	0.56	0.20

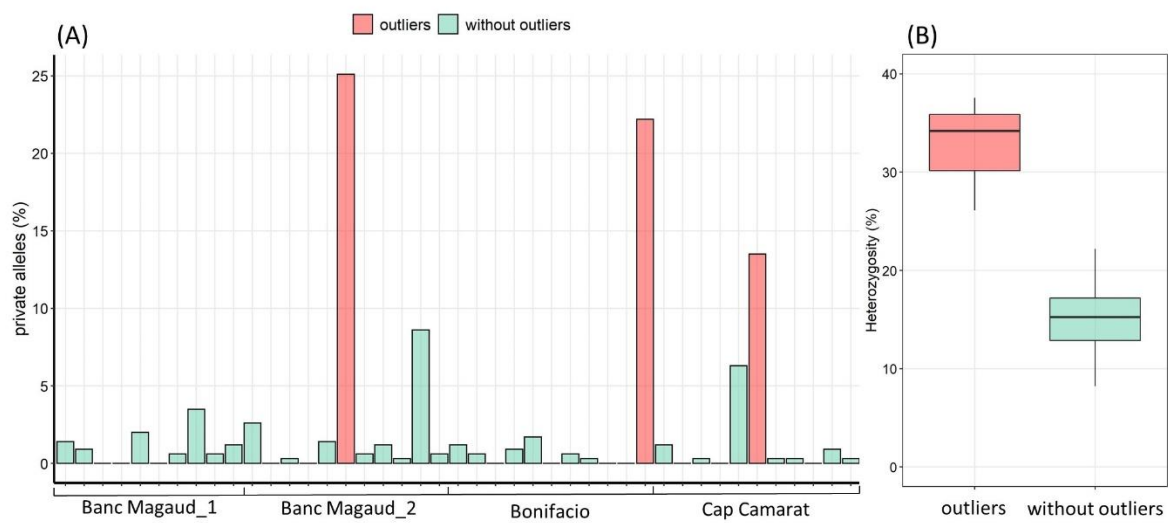
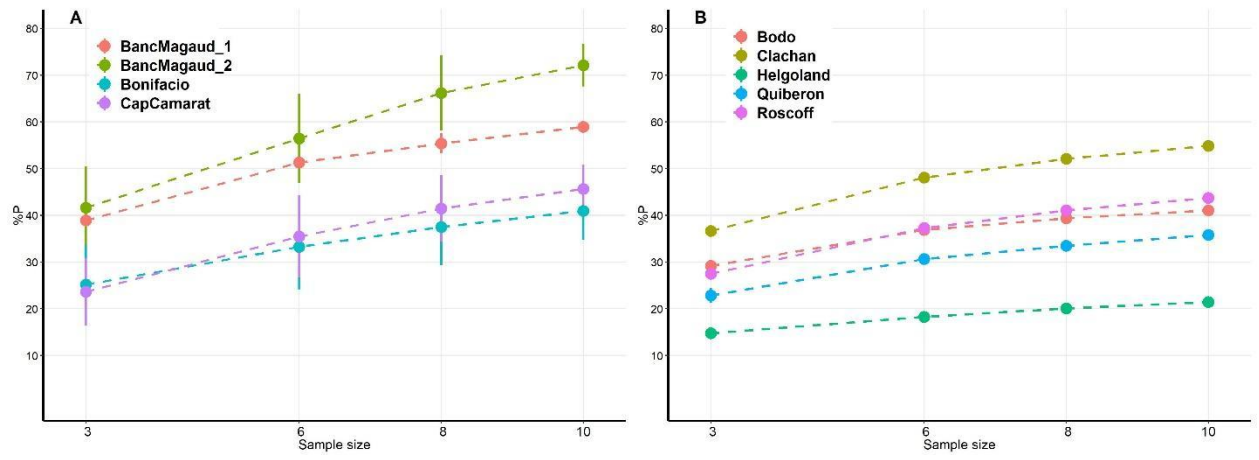


Figure S3



Materials S1

To address the effect of SNP filtering we started from the output of the catalog of 867 513 loci of *L. rodriguezii*, in which 283 864 SNPs were initially reported using the Stacks v2.4 bioinformatics pipeline (Rochette et al., 2019). Then, we selected a subset of informative SNPs by requiring a locus to be present at a frequency of greater than 80% at each of the four study sites. Additionally, we excluded SNPs with more than 80% heterozygosity and selected the first SNP of each RAD locus. As reported in the present study, we eliminated four individuals (with from 35% to 63% of missing genotypes) for which RAD-sequencing has been unsuccessful. At the end of this step, 21 357 informative SNPs were genotyped among the 43 individuals of the present study, thus constituting the reference dataset for the following analyses. We applied many filtering cutoffs (see Table 4) to the reference dataset, using VCFtools v0.1.17 (Danecek et al., 2011), thus producing 15 VCF files. Using the same software, we computed the number of SNP passing the filter (SNPs count), the mean missing data rate per individual (missingness), and the mean read depth per individual (coverage) for each dataset. Finally, we computed both F_{IS} and F_{ST} values (Weir & Cockerham, 1984) using the HierFstat R package (Goudet, 2005) and the mean SNP error rate between replicates with the R function developed by Mastretta-Yanes et al., (2015). We also considered a dataset including SNPs for which genotypes are strictly identical between replicates (matching genotypes) to consider the effect of potentially problematic SNPs on population genetic summary statistics. The results of these analyses are presented in the main manuscript (see Table 4).

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