

1 **Long telomeres are associated with clonality in wild populations**
2 **of the fissiparous starfish *Coscinasterias tenuispina***

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6 **Alex Garcia-Cisneros^{*,a}, Rocío Pérez-Portela^b, Bethanie Carney Almroth^c,**
7 **Sofie Degerman^d, Creu Palacín^a, and Helen Nilsson Sköld^e**

8 ^aDept. Animal Biology (Invertebrates), University of Barcelona, and Biodiversity Research Institute (IRBIO),
9 643 Diagonal Avenue, 08028 Barcelona, Spain.

10 ^bCenter for Advanced Studies of Blanes (CEAB-CSIC), Acceso a la Cala Sant Francesc 14, Blanes, 17300
11 Girona, Spain.

12 ^cDept. Biological and Environmental Sciences, University of Gothenburg, Sweden.

13 ^dDepartment of Medical Biosciences, Umeå University, SE-90185 Umeå, Sweden.

14 ^eSven Lovén Centre for Marine Sciences - Kristineberg, University of Gothenburg, Kristineberg 566, SE – 451
15 78 Fiskebäckskil, Sweden.

16 ^{*}Corresponding author: alexgarcia.cis@gmail.com.

17

18 **Abstract**

19 Telomeres usually shorten during an organism's lifespan and have thus been used as an aging and health marker.
20 When telomeres become sufficiently short, senescence is induced. The most common method of restoring
21 telomere length is via telomerase reverse transcriptase activity, highly expressed during embryogenesis.
22 However, although asexual reproduction from adult tissues plays an important role in the life cycles of certain
23 species, its effect on the aging and fitness of wild populations, as well as its implications for the long-term
24 survival of populations with limited genetic variation, is largely unknown. Here we compare relative telomere
25 length of fifty-eight individuals from four populations of the asexually-reproducing starfish *Coscinasterias*
26 *tenuispina*. Additionally, 12 individuals were used to compare telomere lengths in regenerating and non-
27 regenerating arms, in two different tissues (tube feet and pyloric caecum). The level of clonality was assessed by
28 genotyping the populations based on twelve specific microsatellite loci and relative telomere length was
29 measured via qPCR. The results revealed significantly longer telomeres in Mediterranean populations than
30 Atlantic ones as demonstrated by the Kruskal-Wallis test ($K = 24.17$, significant value: $p\text{-value} < 0.001$), with the
31 former also characterized by higher levels of clonality derived from asexual reproduction. Telomeres were
32 furthermore significantly longer in regenerating arms than in non-regenerating arms within individuals (pyloric
33 caecum tissue: Mann-Whitney test, $V = 299$, $p\text{-value} < 10^{-6}$; and tube feet tissue Student's-t = 2.28, $p\text{-value} =$
34 0.029). Our study suggests that one of the mechanisms responsible for the long-term somatic maintenance and
35 persistence of clonal populations is telomere elongation.

36

37 **Keywords:** Aging, Asexual Reproduction, Clonal, Microsatellites, Population Genetics, Regeneration

38 **Introduction**

39 Although aging is observed in most organisms, there is a large degree of variation in the rate at which it occurs,
40 at both the species and individual level. Telomere length has frequently been used as an aging marker because
41 telomere caps normally become shorter during an organism's lifetime, primarily during DNA replication but also
42 in association with other factors such as stress (von Zglinicki, 2002; Epel *et al.*, 2004; Kotschal *et al.*, 2007).
43 Critically short telomeres trigger a signal prompting the cell to permanently stop dividing, which leads to the
44 induction of cellular senescence (Herbig *et al.*, 2006). Furthermore, long telomeres have been found to correlate
45 with good health and higher life expectancies in several species, thereby also serving as an indicator of somatic
46 fitness, which represents the boundary of aging diseases (Bize *et al.*, 2009; Horn *et al.*, 2010; Barrett *et al.*,
47 2013).

48 During fission or fragmentation in asexual organisms, two or more separate individuals are formed, resulting in
49 clonal offspring with genotypes identical to the parent and to each other. In wild asexual populations and after
50 recurrent fissions, it is difficult to determine the age of an individual by morphological means, not only for the
51 potential clone itself but also the original parental half. In these cases, genetic analyses can reveal the level of
52 clonality within a population as well as the extent of a clone, thus providing information regarding its age and
53 longevity (Ally *et al.*, 2010). Indeed, extremely large and long-lived clonally propagating populations exist, such
54 as some sea grass species, with clones that are estimated to be 1,000 yr (Reusch *et al.*, 1999) or more (Arnaud-
55 Haond *et al.*, 2012). In the case of a terrestrial tree, the age of some clones have been estimated as old as 10,000
56 yr (Ally *et al.*, 2010) and in cold waters, clonal individuals of the coral *Lophelia pertusa* are estimated to be
57 4,500-6,000 yr (Dahl *et al.*, 2012). These estimations obtained for several plants and animal groups may in some
58 way indicate the existence of mechanism to largely delay, or even resist, aging in particular clones although the
59 evolutionary significance of these long-term resistance has not been clarify yet.

60 In sexually-reproducing species, telomere length is restored during embryogenesis by the reverse transcriptase
61 telomerase (Schaetzlein *et al.*, 2004). However, little is known about aging in asexual organisms that propagate
62 via fission or budding; many questions remain unanswered as to whether they are able to fully maintain and/or
63 restore their telomeres to persist over time or whether they undergo somatic aging (Sköld and Obst, 2011). In a
64 study using laboratory cultures of two invertebrate species, upregulation of telomerase has been shown to at least
65 partly restore telomeres in the clones of a flatworm (Tan *et al.*, 2012). Telomerase is also upregulated during

66 budding in the colonial ascidian *Botryllus schlosseri* (Laird and Weissman, 2004). On the other hand,
67 experiments involving another colonial ascidian, *Diplosoma listerianum*, found that telomerase activity declined,
68 telomeres shortened and the growth rate slowed after prolonged asexual duplication, indicative of long-term
69 senescence in the studied clones (Sköld and Obst *et al.*, 2011). There is however very limited information
70 available regarding the effect of prolonged periods of asexual duplication on telomere length and aging in wild
71 populations. Whether molecular aging occurs and how it could potentially be delayed in wild clones is still
72 unknown.

73 Most asteroids have the ability to regenerate their body parts after autotomy or injuries, and about 26 species can
74 reproduce asexually via fission (Emson and Wilkie, 1980). All four known species of the cosmopolitan genus
75 *Coscinasterias*, commonly found in shallow waters, can reproduce both sexually and asexually via fission (Alves
76 *et al.*, 2001; Lawrence 2013, among other references). When individuals of *Coscinasterias* reproduce sexually,
77 they release planktotrophic larvae that remain in the water column for several weeks, with a high potential to
78 colonize new habitats via dispersal (Karako *et al.*, 2002). The species *Coscinasterias tenuispina* (Lamarck, 1816),
79 widely distributed throughout the Atlantic Ocean and Mediterranean Sea, presents in some cases populations
80 either consisting of individuals of only one gender (usually males) or with an unbalanced proportion of males
81 and females (Alves *et al.*, 2002, authors' unpublished data). The absence of one gender in some populations of
82 this species, as well dominance of a few genotypes - according to allozyme analyses (Ventura *et al.*, 2004) -
83 suggests that maintenance of these populations takes place solely via asexual reproduction.

84 The aim of the present study was to assess the effect of asexual reproduction on relative telomere length in wild
85 populations of the starfish *C. tenuispina*, and its implication for the long-term survival of populations with
86 limited genetic variation. For this purpose, telomere length and its relationship with different levels of genetic
87 diversity related to asexuality were assessed using populations from two Mediterranean and two Atlantic sites.
88 Additionally, we explored the potential existence of mechanisms for telomere length control in somatic tissues
89 by comparing regenerating and non-regenerating arms within a set of individuals.

90

91 **Material and Methods**

92 *Sampling*

93 Starfish of the species *C. tenuispina* (Supplementary material FS. 1) were collected from four different European
94 sites (Fig. 1A), two in the Atlantic basin and two in the Mediterranean basin, with between 13 and 17 individuals
95 collected per locality. The two Mediterranean sites, Llançà (Costa Brava, Northwestern Mediterranean) and
96 Taormina (east of Sicily, Central Mediterranean), hereafter referred to as LLA and TAO, respectively, were
97 sampled in autumn 2011. Both Atlantic sites, Bocacangrejo and Abades (BOCA and ABA, separated by 33 km),
98 were located near Tenerife (Canary Islands) and were sampled in the spring (June) of 2012 (Table 1). These four
99 sampling locations were selected based on the abundance of the studied species and on the varying prevalence of
100 individuals undergoing fission. The starfish were sampled at between 0 and 20 m depth by snorkeling or
101 SCUBA-diving. Immediately after their removal from the sea, the animals were photographed on a millimeter-
102 scaled table in order to determine body size. Tube feet, used for the starfish locomotion and substrate attachment,
103 from the middle part of the longest arms of each individual were also collected (Fig. 1B) and preserved in either
104 RNAlater (Invitrogen, www.invitrogen.com) for telomere length analysis or absolute ethanol for microsatellite
105 genotyping. The animals were then released back into the sea. All tissue samples were stored at -20° C once in
106 the laboratory prior to analysis. Body size was assessed as the longest diameter across the starfish using the
107 ImageJ software program.

108 Additionally, both tube feet and pyloric caeca tissue (stomach extensions for processing and storage organ) were
109 collected from the middle part of the longest (non-regenerating) and shortest (regenerating arm; when the length
110 of this arm was less than a 50 % of the longest arm) arms of 12 asymmetric specimens sampled at site LLA (Fig.
111 1B, Supplementary material FS. 1). Pyloric caeca tissue was considered in the present analysis because it is a
112 distinct tissue that has further been shown to be involved in arm regeneration (Hernroth *et al.*, 2010). Although
113 gonads may be also considered for the telomere length analysis, they cannot be used in this study because more
114 than 50 % of the individuals of the species lack gonads, even during the reproductive season (Crozier 1920).

115

116 *Genetic analyses using microsatellites*

117 Twelve microsatellite markers (m.ten1, m.ten6, m.ten13, m.ten14, m.ten19, m.ten24, m.ten25, m.ten27, m.ten30,
118 m.ten31, m.ten32, m.ten40) specifically designed for *C. tenuispina* (Garcia-Cisneros *et al.*, 2013) were employed
119 for population genetic analyses (Table 1). Extractions and amplifications were performed using a REExtract-
120 N-Amp Tissue PCR Kit (Sigma-Aldrich, www. sigmaaldrich.com). For PCR reactions we added 4 µl of PCR

121 Ready Mix, 4 pmol of each primer, between 10 ng and 50 ng of DNA, and ultrapure water for molecular use to a
122 final reaction volume of 10 μ l. Forward primers for each locus were labeled with a fluorescent dye as described
123 in Garcia-Cisneros et al. (2013). Amplifications were performed on an S1000TM Thermal Cycler Dual 48/48
124 Reaction Module (BioRad Laboratories, [HYPERLINK "http://www.bio-rad.com/"](http://www.bio-rad.com/)www.bio- [HYPERLINK](http://www.bio-rad.com/)
125 ["http://www.bio-rad.com/"](http://www.bio-rad.com/)rad.com), with an initial step of 1 min denaturation at 96 °C followed by 35 cycles of
126 96 °C for 1 min, 49 °C for 30 seconds and 72 °C for 20 seconds, and a final step at 72 °C for 3 min.
127 Amplification products were analyzed on an ABI Prism 3730xl Genetic Analyzer (Applied Biosystems/Life
128 Technologies, www.lifetechnologies.com) by the Scientific-Technical Services of the University of Barcelona.
129 Allele size was estimated relative to an internal size standard 70-400 ROX (Bioventures Inc.,
130 www.bioventures.com) using the software program Peak-Scanner-96 (Applied Biosystems). The prevalence of
131 identical genotypes, considered as potential clones, within and between populations was tested using GenoDive
132 (Meirmans and Van Tienderen, 2004) and MLGsim (Stenberg *et al.*, 2003). Both approaches were applied to
133 count the number of individuals with identical Multi Locus Genotypes (MLGs) and to calculate the likelihood of
134 observing identical MLGs in a population due to sexual events (P_{sex}). MLGsim calculations of the P_{sex} , and their
135 significance values, were based on 1,000 random simulations. MLGsim set a critical value for MLGs due to
136 sexual events at a minimum of 0.040. Values obtained for MLGs of *C. tenuispina* were significantly lower than
137 the critical value of 0.040 (see Table 1) pointing to clonal reproduction as the origin of identical MLGs. Genetic
138 diversity was measured by calculating allelic richness, including all individuals from the populations even if they
139 were considered the same clone, genotype diversity (synonym of clonal diversity) after rarefaction for each
140 population, heterozygosity expected and observed and the inbreeding coefficient (F_{is}) using the Hierfstat and
141 Vegan packages (Dixon, 2003; Goudet, 2005) in the software program R v. 3.0.0.

142 In order to assess genetic differentiation between populations, we calculated values of the D estimator (Jost,
143 2008), a statistic to measure differences in genetic structure between populations based on the allele frequencies,
144 using the R package DEMETics (Gerlach *et al.*, 2010). The significance of these D values was evaluated by
145 performing 10,000 permutations including all the individuals from the populations (Gerlach *et al.*, 2010).

146

147 *Telomere measurements*

148 The relative telomere lengths in either tube feet or pyloric caeca tissue were measured for each specimen via a
149 qPCR method (Farzaneh-far *et al.*, 2008), and modified and optimized in our laboratory (Gothenburg, Sweden).
150 Telomere length assessment via qPCR has already been validated (Grabowski *et al.*, 2005; O’Callaghan *et al.*,
151 2008). However, although qPCR telomere measurements are normalized based on single copy genes in humans
152 and other model species, the lack of genomic data for non-model species such as *C. tenuispina* hinders the
153 identification of nuclear genes without paralogs for normalization. For this reason, telomeric DNA
154 measurements in the present study were performed relative to the total quantity of DNA in the samples.

155 Genomic DNA was extracted using the DNeasy Blood and Tissue kit (Qiagen, www.qiagen.com) according to
156 the manufacturer's instructions, and DNA concentrations assessed with a NanoDrop (Thermo Scientific,
157 www.thermoscientific.com) in triplicate to obtain an accurate value of DNA quantity. Absorbance ratios
158 measuring DNA purity at 260/280 averaged approximately 1.9 ± 0.1 , with the 260/230 absorbance ratio also
159 indicating acceptable sample purity (1.8 ± 0.2). Small differences in absorbance ratios were not correlated with
160 final telomere length (260/280: $R^2 = 0.006$, $p = 0.96$; 260/230: $R^2 = 0.001$, $p = 0.99$).

161 The amount of DNA to be added in the qPCR reaction was estimated from a standard curve obtained via a
162 dilution series of a mixed sample DNA pool (10 – 0.0001 ng). The reaction efficiency calculated from the
163 standard curve was $E = 104.1\%$, $R^2 = 0.997$. For the sample qPCR reaction, all DNA samples were adjusted to
164 the same concentration, and 0.5 ng of DNA was added for each PCR mix; this produced a concentration value
165 falling well within the linear range of the mixed sample standard curve.

166 Telomere analyses examining a broad range of species have indicated that the TTAGGG sequence is conserved
167 among deuterostomes (Gomes *et al.*, 2010); the primers used for the qPCR reaction in *C. tenuispina* were
168 therefore those described for humans in Farzaneh-far *et al.* (2008):

169 (forward) 5' CGGTTTGTGGGTTTGGGTTTGGGTTTGGGTTTGGGTT 3', and

170 (reverse) 5' GGCTTGCCTTACCCTTACCCTTACCCTTACCCTTACCCT 3'.

171 Concentrations used for the forward and reverse primers were 100 nM and 200 nM, respectively. A 10 μ l KAPA
172 SYBR FAST qPCR Kit (Kapa Biosystems, www.kapabiosystems.com) was employed as a Mastermix, with 3 μ l
173 of water added for a final PCR volume of 20 μ l following the protocol described by Carney Almroth *et al.*
174 (2012). Telomeres were amplified in triplicate for each sample to ensure accurate measurements using the
175 following qPCR protocol cycle: 3 min at 95 °C followed by 25 cycles of 15 sec at 95 °C and 1 min at 56 °C. The
176 final step comprised 81 cycles of temperature increase from 55 °C to 95 °C in order to generate a melt curve,

177 indicating the presence of a single product. Relative telomere length is represented as a Cycle Threshold Value
178 (Ct Value), which is inversely proportional to telomere amount; longer telomeres thus produce an earlier
179 detectable signal than shorter telomeres. All measurements were analyzed in seven PCR plates, with the mixed
180 sample DNA dilution series included on each plate as an internal standard; Ct values for these differed by less
181 than 1.5 % between plates and were adjusted for.

182 Telomere length verification was performed in an independent laboratory (Umeå, Sweden) using a similar
183 protocol for telomere length qPCR (Cawthon 2002). DNA from 11 samples were send to Umeå and DNA
184 concentration were re-measured by the Nanodrop instrument (Thermo scientific). Each qPCR reaction contained:
185 17.5 ng DNA (diluted in TE/E.coli buffer), 0.1 μ M forward primer, 0.9 μ M reverse primer, 1X PCR Buffer 2,
186 1.7 mM MgCl₂, 2.5 mM DTT, 0.2 mM dNTP, 150 nM ROX, 0.2X SYBR and 0.625 U AmpliTaq Gold (Applied
187 Biosystems).

188 Telomere primer sequence (5'-3') Forward: CGGTTTGTTTGGGTTTGGGTTTGGGTTTGGGTTTGGGTT,
189 Reverse: GGCTTGCCTTACCCTTACCCTTACCCTTACCCTTACCCT. Each sample was analyzed two
190 separate times in triplicates on the ABI7900HT instrument (Applied Biosystems).

191

192 *Statistical analyses*

193 To compare body size between specimens from different populations, a non-parametric Mann-Whitney test was
194 performed since the data did not match our prior expectation of homoscedascity (Bartlett test = 35.97, and
195 signification value, p-value < 10⁻⁷). As body size data also did not match normality (Shapiro-Wilk test; W =
196 0.93, p-value = 0.0048), a Spearman correlation was used to test if telomere lengths were correlated to body size.
197 A mixed model analysis of variance, with telomere length (expressed as the Ct value) as a dependent variable,
198 was performed using "basin" (Atlantic and Mediterranean basins) as a fixed factor, and "population" and
199 "MLGs" as random factors. A non-significant effect was found for the MLGs (p-value > 0.98) and was therefore
200 not considered for further analyses (see Supplementary material FS. 3). Since our data did not match normality
201 (Shapiro-Wilk test; W = 0.96, p-value < 0.01), a Kruskal-Wallis test of the telomere length was performed
202 between the different sites, and a Mann-Whitney test between basins. Spearman correlation was used to test the
203 relationship between genetic diversity and mean telomere length.

204 Potential differences in telomere length between regenerating and non-regenerating arms within individuals were
205 tested using a mixed model involving the logarithmic transformation of Ct values, “tissue type” as a factor, and
206 interaction with “regeneration”. Moreover, we separately tested the effects of regeneration for both tissue types
207 via a paired-data student’s t-test for tube feet, and a paired Mann-Whitney test for pyloric caeca telomere length
208 since the data did not match normality (non-normal distribution; Shapiro-Wilk test; $W = 0.8482$, $p\text{-value} =$
209 0.002).

210 All statistical analyses of telomere length and box plots were performed in R v. 3.0.0.

211

212 **Results**

213 *Genetic diversity and genetic distance between localities*

214 The low and significant values (p-values) of the P_{sex} (Table 2) indicated that the identical genotypes observed
215 among individuals are a consequence of clonal propagation in this species. The studied populations of *C.*
216 *tenuispina* presented different levels of allelic richness and clonality as defined by identical genotypes (Table 1).
217 Populations from the Atlantic Ocean were genetically more diverse than those from the Mediterranean Sea,
218 presenting twelve out of the thirteen single multilocus genotypes (MLGs) found in the whole study area.
219 Furthermore, excess of heterozygotes were found in all populations except Taormina. The D estimator, used to
220 assess differences in genetic structure between populations, revealed significant genetic differences among all
221 four populations here analyzed (Table 3). Large and significant differences were recorded between the two
222 Mediterranean populations, with the latter characterized by a higher prevalence of genetic clones compared to
223 the Atlantic populations. Indeed, only one multilocus genotype was detected at Llançà (Table 1).

224

225 *Differences in telomere length and body size between and within populations*

226 Telomeres were significantly longer in the Mediterranean than in the Atlantic starfish populations as shown by
227 the Kruskal-Wallis test ($K = 24.17$, significant value: $p\text{-value} < 0.001$) (Figs. 2A, 2B). When the four
228 populations were analyzed separately, significantly longer telomeres were again observed in the two

229 Mediterranean populations (Kruskal-Wallis test; $K = 37.03$, $p\text{-value} < 0.001$), with individuals from Llançà
230 presenting the longest telomeres (Fig. 2B). Telomere length measurements were double-checked and verified by
231 an independent laboratory (Umeå, Sweden), and the result showed a strong correlation between the
232 measurements between both independent sets of analyses (value of the correlation for the regression: $R^2=0.88$),
233 (Supplementary material FS 2).

234 Genotype diversity (also expressed as clonal diversity) in this species depends on the relative ratio of fission
235 (asexual reproduction) versus sexual reproduction. Here, populations with lower genotype diversity, and
236 therefore higher fission rates had longer telomeres at the population level, as demonstrated by a significant
237 correlation (Pearson correlation: $R = 0.99$, $p\text{-value} < 0.007$). In Figure 3, it is presented the high correlation
238 between mean of genotype diversity per population and the Ct value (which is inversely proportional to telomere
239 length).

240 Populations analyzed showed differences in the mean body size of the starfish, demonstrated by a significant
241 value of the Mann-Whitney test ($W = 740$, $p\text{-value} < 10^{-7}$), with considerably larger specimens observed in the
242 Atlantic populations (mean body size = $6.36 \pm SD 3.8$ cm) than in those from the Mediterranean Sea (mean body
243 size = $2.81 \pm SD 1.1$ cm). However, telomere length did not depend on the starfish body size, as demonstrated by
244 the absence of correlation between these two variables (Correlation value: $\rho = 0.065$, $p\text{-value} = 0.63$, non-
245 significant) (Supplementary material FS. 3).

246

247 *Telomere length in relation to arm regeneration*

248 Our results showed that telomere length was significantly longer in regenerating (short) arms than in non-
249 regenerating (long) arms (Fig.1B, SF. 1), as demonstrate by the significance of the different tests applied ($F =$
250 52.26 , $p\text{-value} < 0.001$), for both tissue types analyzed, tube feet (Student's-t = 2.28 , $p\text{-value} = 0.029$) and
251 pyloric caecum tissue (Mann-Whitney, $V = 299$, $p\text{-value} < 10^{-6}$) (Fig. 4). Pyloric caecum telomeres were always
252 longer in regenerating arms in all individuals, while eight out of twelve specimens displayed longer telomere
253 lengths in regenerating arm tube feet. .

254

255 **Discussion**

256 Life expectancy in clonal lineages remains unclear due the lack of understanding of different phenomena that
257 would influence on its time survival. Firstly, we do not know the real consequences of the accumulation of
258 somatic mutations and their deleterious effects on the individual and their clonal offspring. Secondly, we ignore
259 the real effect in wild populations of the lack of genetic diversity for adaptive potential, and finally the
260 mechanisms to avoid senescence. The first two difficulties are usually overcome when the species are able to
261 maintain sex, even at low rates or sporadic events, by combining genomes and eliminating phenotypic
262 expression of deleterious mutations when recessive. Here, in this study, we shed some light on the third problem,
263 evidencing telomere elongation during asexual reproduction of the starfish *Coscinasterias tenuispina*.

264 Our work represents the first study to explore the potential implications of asexual reproduction on relative
265 telomere length in wild populations of a clonal starfish. To date, most ecological studies examining telomere
266 length and/or telomerase activity have focused on obligate sexually-reproducing species or clonal organisms
267 maintained in laboratory cultures (see examples in Klapper *et al.*, 1998; Ojimi and Hidaka, 2010; Horn *et al.*,
268 2010; Sköld and Obst, 2011; Carney Almroth *et al.*, 2012; Tan *et al.*, 2012), and no previous study based on
269 telomeres and aging has been conducted on wild clonal populations of any species.

270 Longer telomeres were recorded in the Mediterranean populations of the starfish *C. tenuispina*, while these
271 specimens also significantly smaller in size. Although shorter telomeres were observed in the Atlantic
272 populations characterized by a larger mean body size, our results did not detect any correlation between the two
273 variables. This finding is consistent with the lack of age-related telomere shortening demonstrated for other
274 marine species, including sea urchins and lobsters, and may be attributed to high phenotypic plasticity in body
275 size and/or to continuous telomerase activity throughout their life-span (Klapper *et al.*, 1998; Ebert *et al.*, 2008).
276 Nevertheless, telomere length is regarded as an indicator of health and somatic fitness, and its variation observed
277 in our populations may be influenced by both inherited and/or environmental components (Epel *et al.*, 2004).
278 Thus, populations of *C. tenuispina* comprising only one clone may be healthily maintained, including those in
279 Llançà, which were also characterized by the longest telomeres.

280 The longer telomeres found in regenerating compared to longer non-regenerating arms are indicative of telomere
281 elongation and the preservation of chromosome ends in somatic tissue over the asexual cycle. These results may

282 explain the positive correlation between telomere length and level of clonality. Asexual reproduction via fission
283 has been proposed as more prevalent in small specimens of *Coscinasterias* (Emson and Wilkie, 1980), which is
284 also consistent with our results and observations. It is therefore possible that the key to retain long telomeres in
285 these starfish is to frequently undergo fission. On the other hand, fission may be influenced by the environment,
286 either directly, e.g. by different temperature regimes between the Mediterranean and Atlantic basins here
287 analyzed, or indirectly, e.g. by growth limitation and therefore it could be more prevalent in such situations
288 (Haramoto *et al.* 2007). Therefore, in *C. tenuispina*, longer telomeres and greater somatic fitness may be
289 triggered by unstable environmental conditions in wild populations.

290 Elongation of telomeres in populations of *C. tenuispina* may be one of the mechanisms related to the absence of
291 senescence and genetic defects associated to prolonged periods of asexual propagation. Studies investigating
292 terrestrial species have demonstrated that both telomere length and telomere erosion are predictors of survival
293 and somatic fitness (Bize *et al.*, 2009; Horn *et al.*, 2010), with the combination of long telomeres and telomere
294 elongation in regenerating tissues potentially providing these clonal starfish a high probability of survival.
295 Although the results of a previous study examining a colonial ascidian suggest that passing through a sexual
296 reproductive phase is required in order to avoid senescence after prolonged periods of asexual budding (Sköld *et*
297 *al.*, 2011), it is not known how generally this finding can be applied to other species. Despite the fact that
298 asexual reproduction facilitates clonal dispersion and renewal, it depends on mitotic divisions, which may
299 increase the accumulation of somatic mutations, the Muller ratchet phenomena. Different studies with asexual
300 species already revealed accumulation of somatic mutations on non-synonymous position in clonal lineages
301 compared to their non-clonal sibling species (Paland and Lynch 2006; Barraclough *et al.*, 2007). Unfortunately,
302 the negative effects of deleterious mutations in wild populations of clonal species have never been fully
303 investigated or proved, and these effects have been only supposed, but asexual lineages persist over short
304 evolutionary periods (Schwander and Crespi 2009). However, older clones of aspen species has been found to
305 exhibit a significant reduction in reproductive performance associated with male sexual fitness decline,
306 suggesting that at least some long-lived clonal organisms may be vulnerable to senescence over long periods of
307 time (Ally *et al.*, 2008). A hypothesis to explain the excess of heterozygosity found in the studied populations of
308 *C. tenuispina* may be a positive selection of heterozygotes to keep genetic diversity, besides having greater
309 individual adaptability by high phenotype plasticity (Hörandl, 2009; Goudie *et al.*, 2012). Nevertheless, our
310 current results cannot actually test this hypothesis, and the heterozygotes excess found in all populations may be

311 results from other stochastic processes that have not been controlled in this study. In other organisms as plants
312 that maintain asexual lineages has been observed that polyploidy and hybridization commonly generate
313 heterozygotes. In other species as fur seals, inbreeding is avoided by an active selection from females for non-
314 relative males or heterozygotes (Hoffman *et al.*, 2007). However, we do not have evidences of any of these
315 processes, and positive selection of heterozygotes is the only hypothesis that can be presented here, but further
316 studies on this particular point may shed light on it.

317 Although the molecular mechanisms responsible for telomere elongation and its preservation in *C. tenuispina*
318 remain unknown, studies examining other asexual and sexual organisms indicate a pivotal role for telomerase in
319 the telomere length regulation of somatic cell lineages. In *Asterias rubens*, a sexually reproducing starfish,
320 telomerase activity is high throughout the animal irrespectively of mitotic activity and there was no difference in
321 telomerase activity nor telomere length between regenerating and non-regenerating arms (Hernroth *et al.*, 2010),
322 but clonal starfishes may have higher telomerase activities after fission as other asexual species. In flatworms,
323 maintenance of somatic telomere length seems to be an adaptation of asexual but not sexual strains, and is based
324 on different levels of telomerase activity (Tan *et al.*, 2012). Furthermore, in the colonial ascidian *Botryllus*
325 *schlosseri*, telomerase activity is up-regulated in early bud rudiments, and declines during zooid development
326 (Laird and Weissman, 2004). Differences in the relative abundance of somatic versus stem cells might also
327 determine variation in telomere length (Ojimi and Hidaka, 2010), but we cannot either discard recombination
328 between homologous telomeres as a means to elongate telomeres (Liu *et al.*, 2007). Even in plants, telomere
329 restoration is only present in meristomatic and reproductive tissues, with exceptions in long-lived species
330 (Flanary and Kletetschka, 2005; Watson and Riha, 2010; among other references), while in some algae it has
331 been described telomerase activity during all life cycles, but large differences in telomerase activity have been
332 found across algae groups (Fulnecková *et al.*, 2013; Ševčíková *et al.*, 2013). Further comparison of telomerase
333 and stem cells in relation to regeneration in the analyzed populations of *C. tenuispina* would thus be of future
334 interest.

335 The results presented here reveal the need for further research exploring the ecological and evolutionary
336 significance of asexual reproduction and telomere elongation in clonal lineages. Future empirical studies
337 measuring the success of Atlantic and Mediterranean populations should consider additional variables such as
338 sexual reproductive success, as well as an evaluation of whether genetic diversity is fundamental to the

339 maintenance of clonal populations, concepts that have been only theoretical explored for few authors as
340 Weissman *et al.* (2009) and Marriage and Orive (2012). Those theoretical models for asexual species have
341 evaluated and proposed that clones with large population sizes exhibit high successful levels (Weissman *et al.*,
342 2009; Marriage and Orive, 2012). Nevertheless, further analysis regarding possible somatic deleterious
343 mutations, as well as health and population size monitoring, is essential in order to understand the life
344 expectancy of clonal populations.

345

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354

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- 462

464 **Tables**

465 **Table 1.** Geographical coordinates and genetic information of the sampled *Coscinasterias tenuispina*
 466 populations. Data presented include: Sample size (n), Number of different Multi Locus Genotypes (MLGs),
 467 Clonal MLGs (found in more than one individual) and Single MLGs (found in only one individual), as well as
 468 Allelic richness after rarefaction to 13, Clonal richness (R), Genotype diversity measured after rarefaction,
 469 observed and expected heterozygosity (Ho/He) and inbreeding coefficient (F_{is}).

<i>Population</i>	<i>Code</i>	<i>Coordinates</i>	<i>n</i>	<i>MLG</i>	<i>Clonal MLG</i>	<i>Single MLG</i>	<i>Allelic richness r[13]</i>	<i>R (Clonal richness)</i>	<i>Genotype diversity r[13]</i>	<i>Ho/He</i>	<i>F_{is}</i>
<i>Llança, Costa Brava</i>	<i>LLA</i>	<i>42°23' N, 3°09' E</i>	<i>17</i>	<i>1</i>	<i>1</i>	<i>0</i>	<i>1.33</i>	<i>0.00</i>	<i>1.00 (±0.0)</i>	<i>0.33/0.17</i>	<i>-1</i>
<i>Taormina, Sicily</i>	<i>TAO</i>	<i>37°51' N, 15°18' E</i>	<i>15</i>	<i>4</i>	<i>3</i>	<i>1</i>	<i>1.75</i>	<i>0.21</i>	<i>3.80 (±0.4)</i>	<i>0.24/0.27</i>	<i>0.11</i>
<i>Bocacangrejo, Tenerife</i>	<i>BOCA</i>	<i>28°24' N, 16°19' W</i>	<i>13</i>	<i>8</i>	<i>2</i>	<i>6</i>	<i>2.06</i>	<i>0.58</i>	<i>7.54 (±0.5)</i>	<i>0.53/0.27</i>	<i>-0.29</i>
<i>Abades, Tenerife</i>	<i>ABA</i>	<i>28°08' N, 16°26' W</i>	<i>13</i>	<i>7</i>	<i>1</i>	<i>6</i>	<i>2.14</i>	<i>0.50</i>	<i>6.54 (±0.5)</i>	<i>0.43/0.25</i>	<i>-0.22</i>
<i>TOTAL</i>			<i>58</i>	<i>20</i>	<i>7</i>	<i>13</i>		<i>0.33</i>			

470 **Table 2.** Different Multi Locus Genotypes (MLGs) found in more than one individual in the four localities.
 471 Llançà (LLA), Taormina (TAO), Boca Cangrejo (BOCA), and Abades (ABA). Data presented include the
 472 number of individuals sharing the same MLG (n), the probability of obtaining the same MLG from different
 473 sexual events (P_{sex}), and the associated p-value of P_{sex} . * Significant when p-values < 0.01.

<i>Clonal MLG</i>	<i>Locality</i>	<i>n</i>	<i>P_{sex}</i>	<i>p-value</i>
<i>MLG 1</i>	<i>LLA</i>	<i>17</i>	<i>< 10⁻¹⁴</i>	<i>0.000*</i>
<i>MLG 2</i>	<i>TAO</i>	<i>5</i>	<i>0.000</i>	<i>0.000*</i>
<i>MLG 4</i>	<i>TAO</i>	<i>3</i>	<i>< 10⁻⁸</i>	<i>0.007*</i>
<i>MLG 8</i>	<i>TAO</i>	<i>6</i>	<i>< 10⁻¹⁵</i>	<i>0.000*</i>
<i>MLG 9</i>	<i>BOCA</i>	<i>2</i>	<i>< 10⁻¹⁰</i>	<i>0.000*</i>
<i>MLG 11</i>	<i>BOCA</i>	<i>5</i>	<i>0.000</i>	<i>0.000*</i>
<i>MLG 12</i>	<i>ABA</i>	<i>7</i>	<i>< 10⁻¹⁴</i>	<i>0.000*</i>

474

475 **Table 3.** Values of the D genetic differentiation estimator between populations of *Coscinasterias tenuispina*.
476 Llançà (LLA), Taormina (TAO), Boca Cangrejo (BOCA), and Abades (ABA). * Indicates significant p-values <
477 0.01.

	<i>TAO</i>	<i>LLA</i>	<i>BOCA</i>
<i>LLA</i>	0.167*		
<i>BOCA</i>	0.159*	0.233*	
<i>ABA</i>	0.143*	0.148*	0.138*

478 **Figure legends**

479 **Figure 1.** Map of sampling locations, including those in Mediterranean Sea and Northeastern Atlantic Ocean.

480 Circles highlight the three sampling areas. Two different populations were sampled in Tenerife.

481 **Figure 2.** Box plots of telomere qPCR Ct values obtained from tube feet for the *Coscinasterias tenuispina*

482 populations from different seas and localities: A) Ct values of grouped Atlantic and Mediterranean populations,

483 and B) Ct values of each separate locality. Llança (LLA), Taormina (TAO), Abades (ABA), and Bocacangrejo

484 (BOCA). Lower Ct values indicate longer telomeres. Boxes are represented by the first and third quartile, the

485 dark line is the median, and dots are outliers.

486 **Figure 3.** Correlation between relative telomere length in tube feet (telomere qPCR Ct Value) and genotype

487 diversity for the four *Coscinasterias tenuispina* populations analyzed. Horizontal and vertical bars represent the

488 standard error for genotype diversity and relative telomere length, respectively. The relative telomere length was

489 represented as the mean value per locality.

490 **Figure 4.** Box plot of *Coscinasterias tenuispina* telomere qPCR Ct values in regenerating and non-regenerating

491 arms for two different tissues from individuals of Llança: pyloric caecum (Pyl) and tube feet (TF). Pyloric

492 caecum from non-regenerating arms (Pyl NR); Pyloric caecum from regenerating arms (Pyl R); Tube feet from

493 non-regenerating arms (TF NR); Tube feet from regenerating arms (TF R). Boxes are represented by the first and

494 third quartile, the dark line is the median, and dots are outliers.

495 **FS 1.** Picture of the aboral side of a *Coscinasterias tenuispina* individual (black and white image). The

496 individual had three longer non-regenerating arms, and five shorter regenerating arms.

497 **FS 2.** Telomere length PCR verification. Eleven samples were sent to an independent laboratory in Umeå,

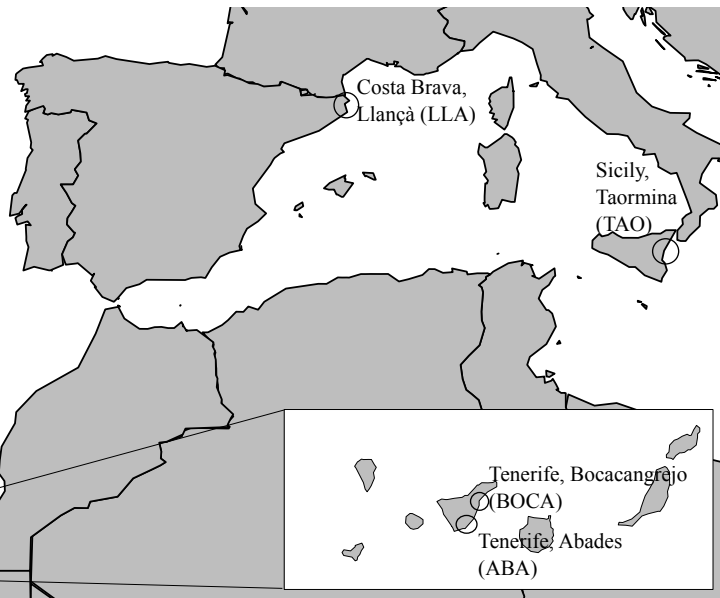
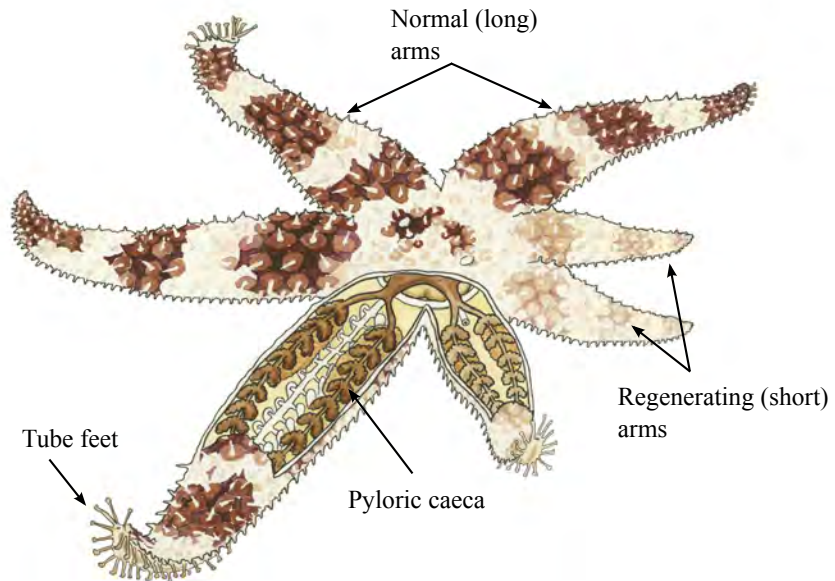
498 Sweden, and reanalyzed for telomere length. The samples telomere Ct-values were compared between

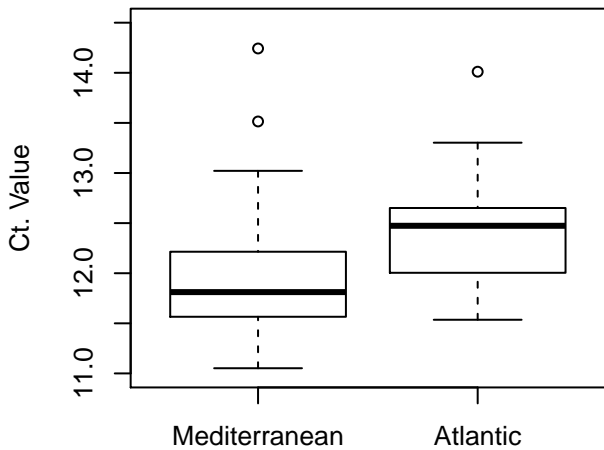
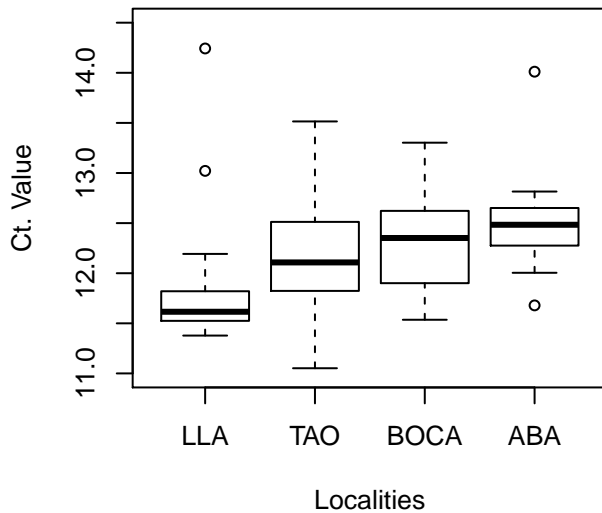
499 Gothenburg and Umeå laboratories.

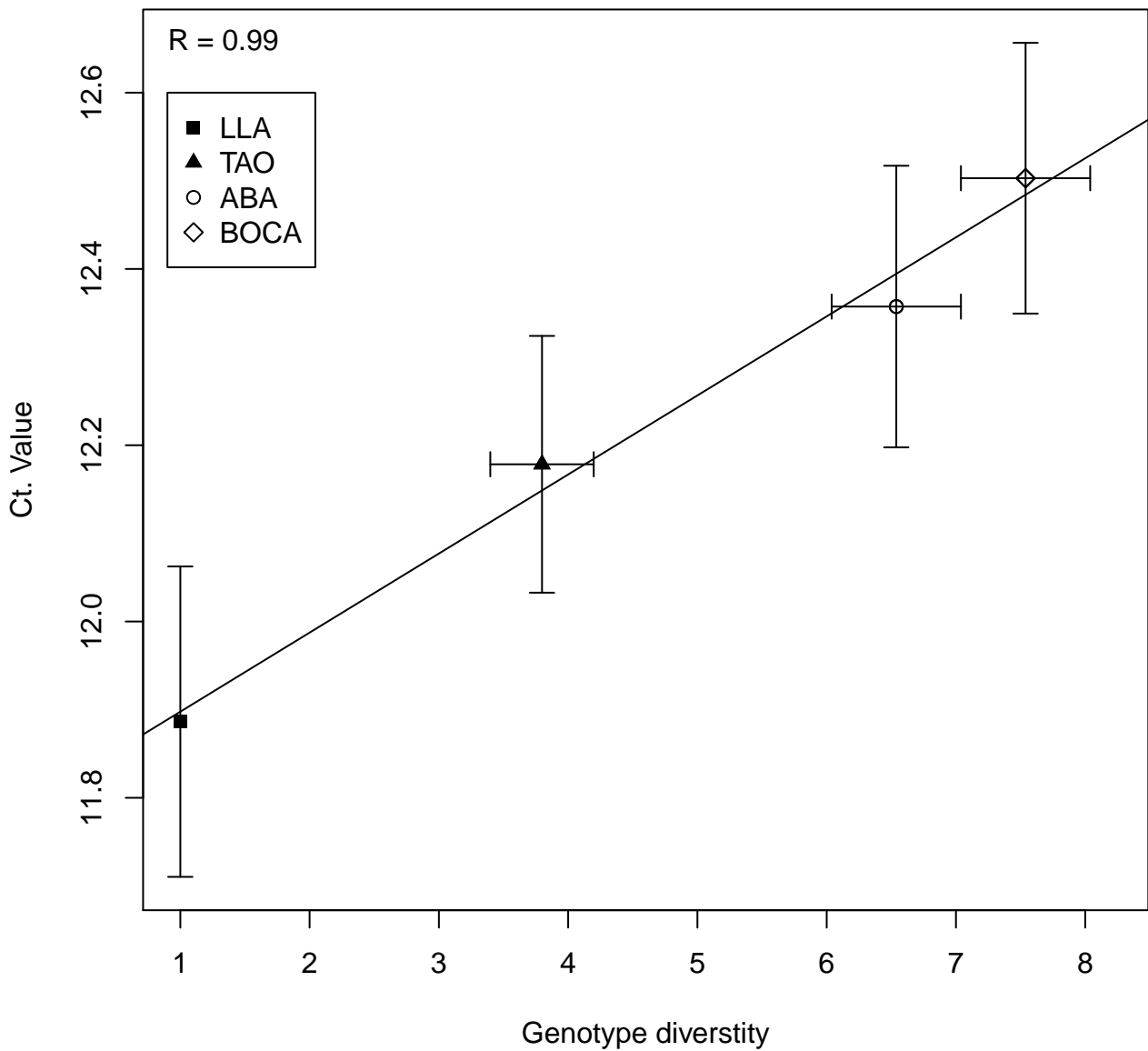
500 **FS3.** Dot plot representing the mean of Ct. value at the y-axis, and the longest arm length at the x-axis. Full

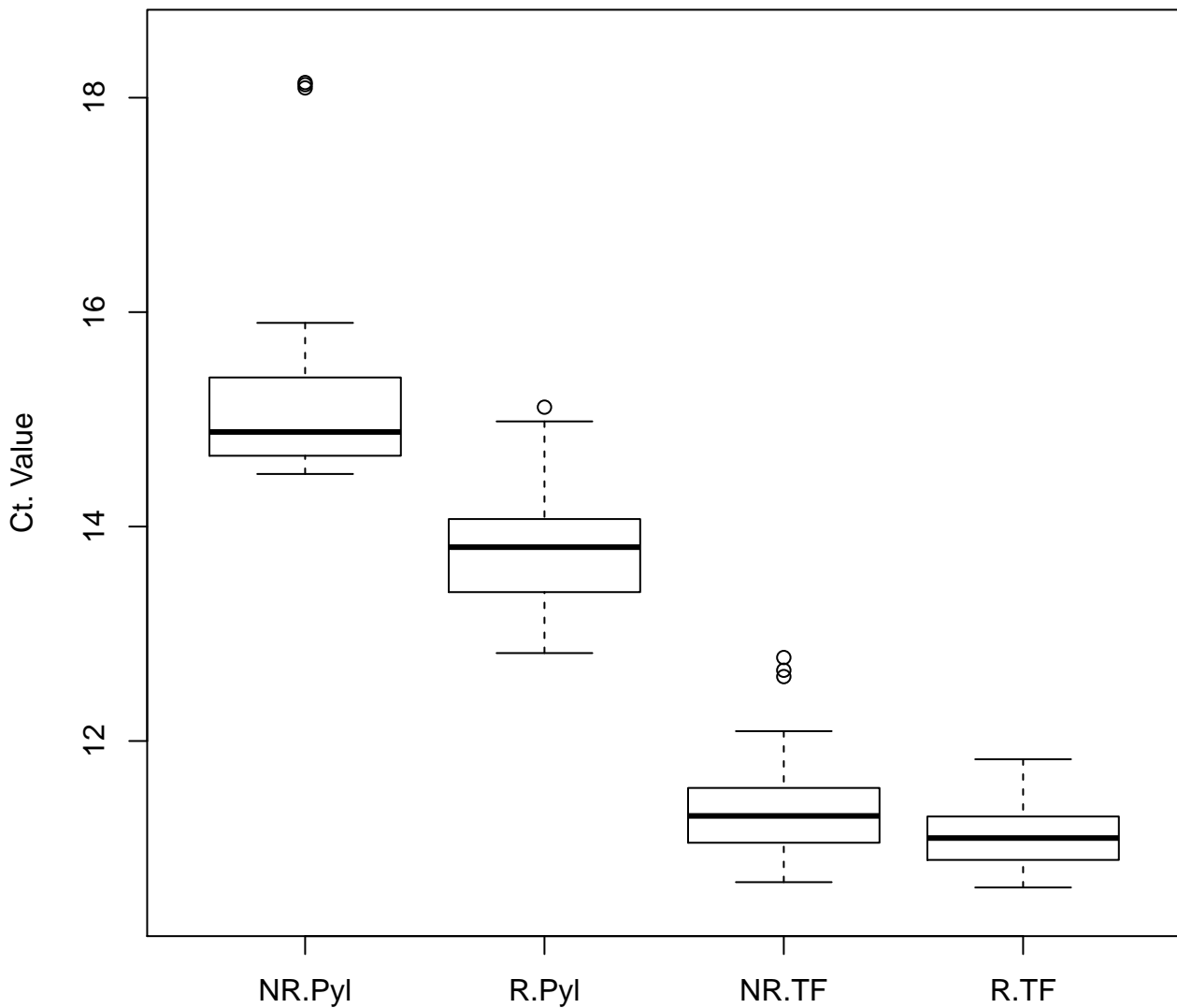
501 filled dots represent Mediterranean individuals while white dots represent individuals from the Atlantic side.

502 Vertical bars represent the standard deviation from the three replicate analyses per each individual.

A**B**

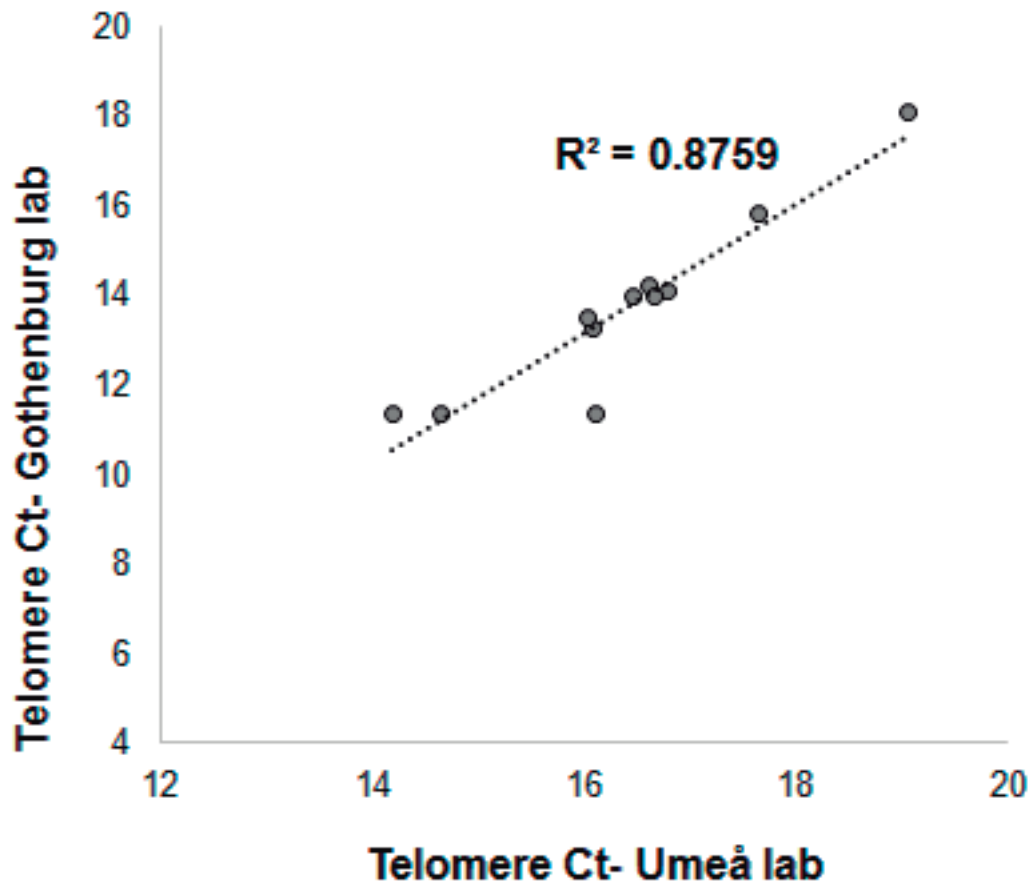
A)**B)**



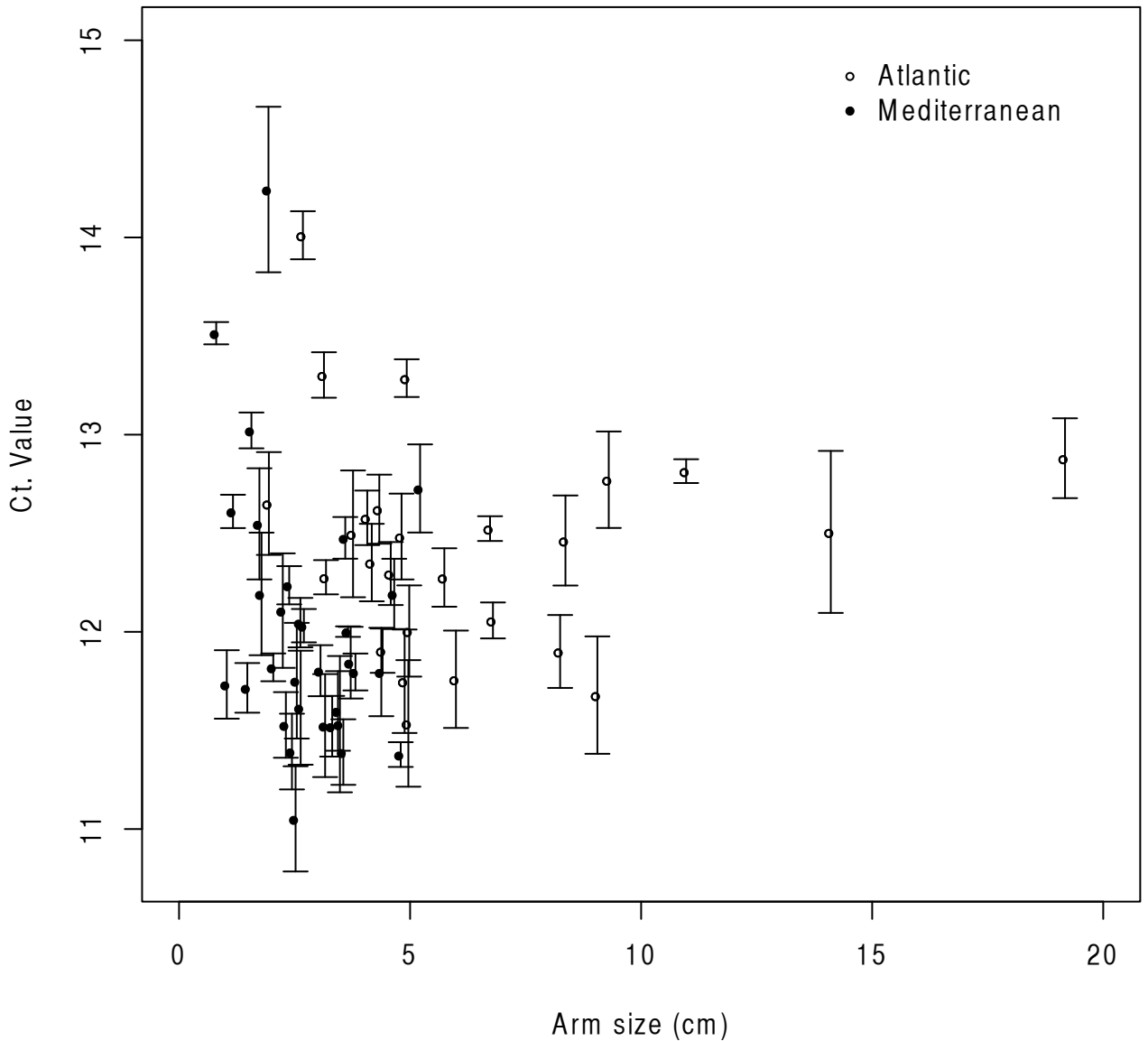




FS1. Picture of the aboral side of a *Cosciansterias tenuispina* individual (black and white image). The individual had three longer non-regenerating arms, and five shorter regenerating arms.



FS2. Telomere length PCR verification. Eleven samples were sent to an independent laboratory in Umeå, Sweden, and reanalyzed for telomere length. The samples telomere Ct-values were compared between Gothenburg and Umeå laboratories.



SF 3. Dot plot representing the mean Ct. value, at the y-axis, and the longest arm length, at the x-axis. Full filled dots represent Mediterranean individuals while white dots individuals from the Atlantic. Vertical bars represent the standard deviation from the three replicas analysis per each individual.