# Assessing the suitability of the minimum capture size and protection regimes in the gooseneck barnacle shellfishery

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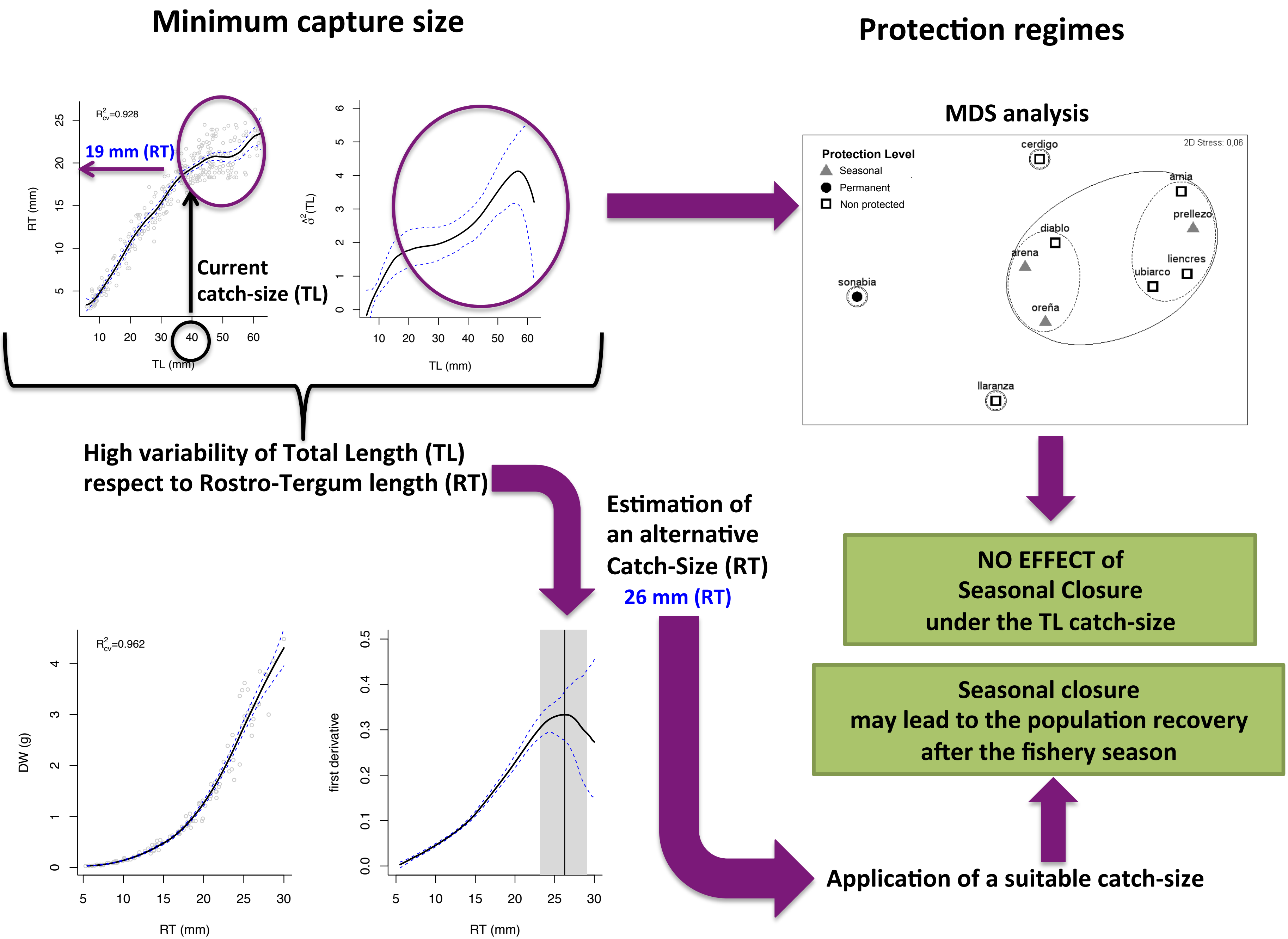
Graphical Abstract (for review)



# Assessing the suitability of the minimum capture size and protection regimes in the gooseneck barnacle shellfishery

## Abstract

The suitability of a total-length-based, minimum capture-size and different protection regimes was investigated for the gooseneck barnacle *Pollicipes pollicipes* shellfishery in N Spain. For this analysis, individuals that were collected from 10 sites under different fishery protection regimes (permanently open, seasonally closed, and permanently closed) were used. First, we applied a non-parametric regression model to explore the relationship between the capitulum Rostro-Tergum (RT) size and the Total Length (TL). Important heteroskedastic disturbances were detected for this relationship, demonstrating a high variability of TL with respect to RT. This result substantiates the unsuitability of a TL-based minimum size by means of a mathematical model. Due to these disturbances, an alternative growth-based minimum capture size of 26.3 mm RT (23 mm RC) was estimated using the first derivative of a Kernel-based non-parametric regression model for the relationship between RT and dry weight. For this purpose, data from the permanently protected area were used to avoid bias due to the fishery. Second, the size-frequency distribution similarity was computed using a MDS analysis for the studied sites to evaluate the effectiveness of the protection regimes. The results of this analysis indicated a positive effect of the permanent protection, while the effect of the seasonal closure was not detected. This result needs to be interpreted with caution because the current harvesting based on a potentially unsuitable minimum capture size may dampen the efficacy of the seasonal protection regime.

## 1. Introduction

The primary geographical distribution area of the gooseneck barnacle *Pollicipes pollicipes* ranges from the northwestern coast of France (Brittany) to the northwestern coast of Africa (Senegal) and the Mediterranean (Algeria) (Cruz and Araujo, 1999; Barnes, 1996). This species constitutes the most economically important shellfishery resource on the intertidal rocky shores of Portugal and Spain (Cunha and Weber, 2001, Sousa et al., 2013). This species is highly prized as food (> 50 Euros $Kg^{-1}$(Jacinto et al., 2010)) and heavily exploited by professional and recreational fishery. In recent years, this species has attracted increased harvesting pressure due to its high market value (Sousa et al., 2013; Stewart et al., 2014), the decline of other coastal fisheries has urged barnacle exploitation as a supplement to fishing activity (Bald and Borja, 2012), and the European economic crisis. In many regions of the Iberian Peninsula, this decline has resulted in the overexploitation of the stocks (Borja et al., 2011, Stewart et al., 2014). Likely, the current passive management model of the resource (i.e., non-take zones and legal minimal size of capture) of the northern regions of Spain (Cantabria, Basque Country) means a progressive decline of the resources (Jamieson et al., 1999; Bald and Borja, 2012).

However, the assessment of the performance of these management measures is not easy. The fishery capture data are often scarce and lack precise localization information, which leads to not very rigorous estimations of the fishery pressure upon this resource (Sousa et al., 2013). The highest abundances of *P. pollicipes* are located in the lower intertidal zone (Cruz, 2010; Pavón, 2003) of significantly energetic shores that are exposed to dominant swells, which are frequently related to high slopes and the presence of caves and crevices (Barnes, 1996; Cruz, 2000; et al., 2006: Borja et al, 2006b). Consequently, the poor capture data and the physical factors determining the distribution of the genus *Pollicipes* and explaining the difficulty of sampling (Bernard, 1988; Parada et al., 2012) contribute to the lack of large-scale population assessment studies and adequate evaluations of the performance of the management measures. As an alternative, the territorial use rights for fishing (TURF), i.e., an area-based management program that assigns a specific area to an individual, group or community, has proven to be an effective approach for the small-scale management of *P. pollicipes* fisheries in NW Spain (Molares and Freire, 2003). The TURF programs grant exclusive fishing access to these communities while giving them management responsibilities, including the development of annual management plans and the maintenance of appropriate controls of fishing mortality (Young, 2013).

Regardless of the management model, the measures that are oriented toward the achievement of a sustainable exploitation of the resources in N Spain commonly include the minimum size of capture, protected areas (e.g., seasonal or permanent closures) and individual quotas (e.g., Parada et al., 2012; Sousa et al., 2013). In recent years, to react to barnacle population decline in some regions, the establishment of a minimum capture size has received special attention from managers and researchers, particularly regarding the adequacy of the part of the barnacle that is measured. The commonly used capture size in N Spain based on the total length (TL) may be inappropriate because this measure includes both the hard part (capitulum) and the soft part (the peduncle) of the barnacle. The latter has, a priori, an importantly variable typology, with both barnacles with elongated and with smooth peduncles being able to have the same capitulum size (Parada et al., 2012). This finding may lead to heteroskedastic disturbances in the relationship between TL and the capitulum length, i.e., an important variance in TL with respect to the capitulum length as individuals grow in size. This variability in TL depends on environmental factors, such as hydrodynamic patterns, degree of immersion, availability of food and intraspecific competition (Hoffman, 1988, 1989; Page, 1986; Lewis & Chia, 1981).

Several authors have regionally determined that the rostro-tergum (RT) (Pavon, 2003) or rostrum-carina (RC) (Cruz, 1993) lengths are the best biometrical variables to explain the growth of this species. Consequently, these two measures and others also based on the capitulum have been considered more adequate for the establishment of the minimum size of capture in NW Spain and SW Portugal (Parada et al., 2012; Sousa et al., 2013). Sestelo and Roca-Pardiñas (2011) recently investigated the minimum capture size for this species using a non-parametric model that analyzes the length-weight relationship and its derivatives. This author suggested an RC length-based capture size that ensures the maximum yield in weight from the fishery. To our knowledge, no information has been published on the impact of the change in the minimum capture size from the TL-based measure to a capitulum-based measure. Despite considering the alternative minimum size based on the capitulum length, the assumed lower suitability of the TL measure compared to the RC or RT has not been properly investigated in terms of the variability of the TL with respect to the growth of the species, i.e., in terms of the heteroskedasticity in TL-RT or TL-RC relationships. However, along the northern coast of Spain (Gulf of Biscay), the minimum capture size is still based on the TL.

Regarding the effectiveness of closure regimes in enhancing population stocks, Cruz (2000) and Sousa et al. (2013) did not find significant effects on the density between areas with different types of exploitation regimes in SW Portugal. Temporal closures (from May to September) are not the most sustainable measures in N Spain because they may not permit the total recovery of the resource after the capture season (Bald et al., 2006). These authors observed that temporal closures could lead to a reduction of the captures by half compared to other measures. These authors developed a dynamic model that is capable of predicting the response of *Pollicipes pollicipes* populations to different management measures and suggested that the best management actions consisted of establishing permanently closed fishing areas that would act as important sources of larvae nourishing the exploited areas and biannual rotational temporal closures. Borja et al. (2006b) analyzed the effect of permanently protected zones in the density and biomass of gooseneck barnacle in Basque Country (N Spain). These authors found a significantly higher density of individuals and biomass in permanently unexploited zones (~8.0

Kg $m^{-2}$) compared to that in unprotected areas (~1.5 Kg $m^{-2}$). The failure of the temporal closures might be in part linked to the current minimum size in N Spain.

The extraction of *P. pollicipes* in N Spain is regulated by regional-scale management models largely based in a legal capture size of 40 mm of total length and different types of closure regimes. The purpose of this study was to investigate the effectiveness or suitability of these management measures, considering that the failure of the temporal closures may be in part associated with the potential unsuitability of the current minimum size. For this purpose, the coastline of Cantabria (Gulf of Biscay) of 215 km was selected as a case study due to (i) the fact that the management model in this region permits the analysis of three types of protection regimes (i.e., permanently open, seasonally closed, and permanently closed) and (ii) the lack of previous assessments of the efficacy of these management measures. The conditional variance of the total length with respect to the growth was analyzed (i) to properly assess the suitability of the capture size based on a measure including the soft part of the barnacle and, if unsuitable, (ii) to estimate an alternative capture size using a nonparametric regression model for the capitulum length-weight relationship. The results may confirm with a mathematical model the suitability of the capitulum length-based minimum size measures that are already implemented in other regions. The size-frequency distribution similarity between zones with different protection regimes was analyzed to evaluate their effectiveness. The results of this latter analysis were interpreted according to the differences between the original minimum capture size and the alternative size that is proposed in this study.

## 2. Material and Methods

### 2.1. Study area

The total area of study covered 215 km of coast in the Cantabria region (Figure 1). Due to the lack of proper habitat suitability data (i.e., mapping), the suitable habitat of gooseneck barnacle was identified using a compilation of information coming from cartographic data, professional shellfishers and technical personnel of the Regional Fishing Directorate. A total of 10 coastal areas of different lengths covering 60 km of coastline were considered common shellfishing zones. These areas were managed under different protection levels according to their fishery closure regime: (1) Llaranza, Ubiarco, Liencres, Arnia, Diablo and Cerdigo were opened to the fishery throughout the year; (2) Arena, Prellezo and Oreña were seasonally protected, being closed to the fishery from 1st May to 1st October; and (3) Sonabia was permanently protected and closed to the fishery throughout the year (Figure 1). A sampling site that was representative of the abundance of each fishing zone was selected based on the compiled information from shellfishermen and technical personnel. The criteria for this selection were to have similar accessibility and wave exposure for every site.

**Figure 1**

2.2. Sampling and laboratory procedures

Field surveys were carried out during the spring low tides in June 2005, except at Diablo, which was surveyed in October 2005. At each of the 10 sites, 5 intertidal transects were established along 200-300 m of coastline, except in Cerdigo and Diablo (4 transects) and in Llaranza (3 transects). At each transect, three different intertidal levels were studied: higher littoral (H), medium littoral (M) and lower littoral (L). The shallow subtidal zone was not considered because this species is mainly distributed and professionally harvested in the intertidal zone (Borja et al., 2006a). The individuals were collected by scraping the rock surface within 50 × 50-cm sampling units. In the laboratory, several biometric variables were measured: (i) Rostro-tergum length (RT) (Pavón, 2003), also known as the maximal capitulum height (MCH) by

Cruz (1993) or the capitulum length by Bernard (1988); (ii) rostro-carina length (RC) following Cruz (1993); and (iii) total length (TL) (Hoffman, 1984) (Figure 2). The dry weight (DW) was obtained by drying organisms at 60 ºC for 48 h following Cruz (1993). Encrusting and boring animals, mainly located on the capitulum plates, were removed before weighing.

**Figure 2**

2.3. Data analysis

*2.3.1. Evaluation of the total length–based minimum capture size*

The suitability of the TL for use as a minimum capture size measure was evaluated by analyzing the conditional variance $\hat{\sigma}^2$ of TL, which includes both the soft part of the peduncle and the hard part of the capitulum, with respect to the capitulum length, using the statistical software environment R (R Development Core Team, 2009). $\hat{\sigma}^2$ values that were larger than 1.5 were considered significant in terms of TL variability with respect to RT. The RT size was selected as the capitulum length measure based on a locality criterion, as it was determined by Pavon (2003) as the best biometrical variable to explain the growth of this species in the neighboring coast of Asturias (N Spain). Cruz (1993) found the RC size to be more adequate for this purpose in SW Portugal. In this study, the RC-RT relationship was also first determined to compare our and other results based on the RT size with studies based on the RC size (Figure 3).

The analysis of RT-TL relationship was conducted using a random subsample of the whole dataset, including all sites and tidal levels. A Kernel-based non-parametric regression model was used for this analysis. The model equation was of the type

$$RT = m(TL) + \sigma(TL)\,\varepsilon \qquad (1)$$

where the error variable $\varepsilon$ is independent of the covariate TL with $E(\varepsilon) = 0$ and $Var(\varepsilon) = 1$, $m(TL) = E(RT|TL)$ is the unknown regression function, and $\sigma^2(TL) = Var(RT|TL)$ is the conditional variance function representing heteroskedasticity.

The estimation of the above model is based on the use of local linear kernel smoothers (Wand and Jones, 1995). Let $\{(TL_i, RT_i)\}_{i=1}^{n}$ be an independent random sample, the kernel estimator

$$\hat{m}(tl) = \psi(tl, \{(TL_i, RT_i)\}_{i=1}^{n}, h)$$

at a location $tl$ is defined as $\hat{m}(tl) = \hat{\alpha}_0(tl)$, where $\hat{\alpha}_0(tl)$ is the first position of the vector $(\hat{\alpha}_0(tl), \hat{\alpha}_1(tl))$, which is the minimizer of

$$\sum_{i=1}^{n} \{RT_i - \alpha_0(tl) - \alpha_1(tl)(TL_i - tl)\}^2 K_h(TL_i - tl),$$

where $K_h(\cdot) = K(\cdot/h)/h$, $K(\cdot)$ denotes a kernel function (a symmetric density), and $h > 0$ is the smoothing parameter (or bandwidth). Additionally, the residual sum of square approach was used to estimate the conditional variance as

$$\hat{\sigma}^2(tl) = \psi(tl, \{(TL_i, R_i)\}_{i=1}^{n}, h_R)$$

with $R_i = (RT_i - \hat{m}(TL_i))^2$.

Finally, to determine the model's adjustment, the coefficient of determination was used, as calculated by means of cross-validation (Stone, 1977). This calculation is

$$R_{cv}^2 = 1 - \frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i^{(-i)})^2}{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}$$

where $\hat{Y}_i^{(-i)}$ indicates the estimates of $Y_i$ leaving out the *i*-th element of the sample as obtained by fitting the corresponding model and $\bar{Y} = n^{-1} \sum_{i=1}^{n} Y_i$ .

*2.3.2. Estimation of the minimum size of capture*

The conditional variance ($\hat{\sigma}^2$) analysis of TL with respect to RT showed values of $\hat{\sigma}^2$ that were larger than 1.5 beyond TL=15 mm. This result confirmed the current TL-based measure as unsuitable for setting the minimum size of capture. Consequently, an alternative catch size was estimated based on the growth-based RT length measure. Prior to this estimation, the RT size corresponding to the current minimum size of capture in Cantabria (i.e., TL=40 mm) was estimated using the regression model of the equation (1). This estimation permitted the current TL size in RT to be comparable to the alternative catch size that we estimated as follows.

For individuals that collected from the permanently protected zone of Sonabia, a minimum capture size was estimated using the methodology of Sestelo and Roca-Pardiñas (2011) by means of the RT-DW length-weight relationship. The fact that the analysis was conducted using data from a permanent protected zone ensured that results were not affected by the fishery pressure.

The following nonparametric model was applied to study the RT-DW relationship

$$DW = m^*(RT) + \sigma^*(RT)\,\varepsilon^* \quad (2)$$

where $m^*$is the unknown regression function, ${\sigma^*}^2$is the conditional variance function, and $\varepsilon^*$is the error independent of the covariate RT. The estimation of this model was obtained analogously to the model in (1).

The first derivative of $m^*$ was calculated to determine an RT-based new suitable size of capture for this species. The ideal size, named $rt_0$, was used as the maximizer of the first derivative of $m^*$. This point could be define as

$$rt_0 = arg\ \max_{rt} m^{*(1)}(rt). \qquad (3)$$

Beyond this point, the increase in weight per unit of size decreases. Thus, this size ensures that individuals thatsmaller than this size had not yet attained the maximum yield in weight. See a full description of this methodology in Sestelo and Roca-Pardiñas (2011). This RT-DW relationship was also analyzed using the classic allometric model (Huxley, 1924) only with the purpose of comparing the results of both of the models (see Figure A1 in the Appendix). Note that the first derivative of the allometric model cannot show a maximum due to its continuously increasing nature.

*2.3.3. Size frequency distributions*

Size frequency distributions with discrete size classes of 5-mm RT intervals were obtained for each site. The population class distribution was also analyzed at each tidal level for the entire dataset. For the descriptive analyses of recruitment patterns and exploitable stocks, two barnacle sizes were selected: RT<5 mm and RT>20 mm. These sizes were assumed to correspond to the previous year recruiters and to the minimum size of capture that is allowed in Cantabria, respectively. The capture size is 40 mm TL, with an approximately 20-mm RT length according to the value that was obtained in the present study (see Figure 4a).

*2.3.4. Evaluation of the protection regimes*

Using the composition of the size frequency distributions at each site as the input data, a similarity matrix was constructed to perform a multidimensional scaling analysis (MDS) (using Manhattan distances) with PRIMER 6.0 software (Primer-e Ltd, 2006). The results of the ordination analyses were used to identify similarities and differences in the population size structure among sites with different protection levels. Similar sites were then grouped using the results that were provided by a single linkage cluster analysis of the same data. The criterion to evaluate the effectiveness of the different protection levels was the following: the sites that were grouped in the same group of non-protected sites were considered to have an ineffective protection regime, while sites that were grouped in a different group to that of non-protected sites were considered to have an effective protection regime. This type of analysis was previously applied, with similar purposes, in SW Portugal by Cruz et al. (2010) and Sousa et al. (2013) for *P. pollicipes*.

## 3. Results

3.1. Evaluation of the total length–based minimum capture size

The RT-TL relationship was explained using a Kernel-based nonparametric regression model (Figure 4a). Once the model was applied, it was possible to clearly observe the nonparametric increasing trend of the estimated mean (Figure 4a) and the heteroskedastic disturbances (Figure 4b). The conditional variance $\hat{\sigma}^2$ with respect to RT significantly increases beyond a TL size of 15 mm (Mean=1.5, CI=(0.9, 1.9)) to display a maximum at TL=58 mm (Mean=4.0, CI=(1.1, 5.4)) (Figure 4b). This increase suggests that the TL-based minimum catch-size may not be as a reliable as a capitulum-length growth-based measure. The use of the TL size may lead to (i) not obtaining the maximum yield in weight from the fishery because a great percentage of individuals could correspond to harvestable sizes with an alternative capitulum-based minimum size (see Figure 4a: data with TL<40 mm and RT>19.4 mm) and (ii) harvest individuals clearly smaller than the correspondent capitulum-based minimum size (see Figure 4a: data with TL>40 mm and RT<19 mm). Note that RT=19.4 mm was obtained in section 3.2.

**Figure 4**

3.2. Minimum size of capture

Based on the nonparametric model that was used to analyze the RT-TL relationship (Figure 4a) and being cautious to interpret the result due to this model's heteroskedastic disturbances, it is possible to suggest a capture size of 19.4 mm (19.0, 19.8) in RT length corresponding to the current 40-mm TL legal capture size. This result needs to be taken with caution due to the observed variability of TL with respect to RT. Using the RC-RT relationship that was obtained in the present study, the corresponding size of the RC was 16.9 (16.8, 17.0) (Figure 3).

**Figure 5**

Alternatively and due to the significant heteroskedasticity in the RT-TL relationship, with an increase in the variance as individuals grow in size (Figure 4b), an alternative minimum capture size based on the RT-DW length-weight relationship was estimated. Thus, for individuals that were collected from the permanently protected area of Sonabia, the Kernel-based nonparametric model showed that the regression curve was an increasing function (Figure 5a) that was very similar but displayed some differences in the last part of the curve from that obtained by the allometric model (Figure A1). The first derivative of the initial curve displayed an increasing monotonous function in the first part of the curve and a maximum at a specific size, after which the curve began to decrease (Figure 5b). The size at which the maximum value was obtained for the derivative was 26.3 mm (23.2, 29.1) in RT and was considered the minimum suitable catch size. The RC-RT regression model (Figure 3) was applied to obtain a minimum suitable catch size of 23 mm (22.8, 23.2) in RC length.

### 3.3. Population size structure

Size frequency distribution plots for the 10 studied sites and for the three tidal levels are shown in Figure 6. Oreña, Llaranza, Arena and Sonabia stood out appreciably from the rest of the sites with a marked main mode at RT sizes <5 mm. Apart from the <5-mm sizes, the next mode corresponded to the 15-20-mm range in all sites, except for in Prellezo, Diablo and Cerdigo, where the main size mode corresponded to the ranges between 5 and 15 mm, even exceeding the <5 mm range. The relative percentages of individuals of exploitable sizes (>20 mm) were consistently higher at the permanently protected zone of Sonabia (19%). Arnia and Cerdigo, which were opened to the fishery, also showed important percentages of commercial-size individuals (12-15%). The average size structure plots by tidal level (Figure 6b) showed a main mode corresponding to individuals of <5 mm, especially marked at high and medium levels, and a secondary mode in the 15-20-mm range. From that size range onwards, there was a rapid decrease in the commercial sizes (>20 mm), which are mainly concentrated at the medium levels and especially at the lower tidal levels.

**Figure 6**

### 3.4. Evaluation of the protection regimes

The ordination analysis that was carried out by Multi Dimensional Scaling (MDS) using size frequency distributions showed that the permanently protected site of Sonabia clearly separated from the remainder sites (Figure 7). A Similarity Percentage analysis, SIMPER (Clarke 1993), was performed to compare the size frequency distributions between Sonabia and the rest of the sites and suggested that the main cause of these differences was the higher percentage of large sizes found in Sonabia. The Manhattan distances that were used to group the sites with similar population size structure (16 and 18) grouped 7 sites without showing any distribution pattern that was associated with seasonal closure or non-protection regimes. Cerdigo and Llaranza, both non-protected, were individually grouped apart, being located closer to the 7 grouped sites than to Sonabia.

**Figure 7**

## 4. Discussion

The results of this study suggest that the two most commonly used management measures within the commercial goose barnacle (*Pollicipes pollicipes*) fishery in N Spain, with a minimum capture size of 40 mm TL and seasonally closed areas, are not entirely suitable, at least together, for a sustainable harvesting of the resource. These results are discussed below in the context of the sustainable exploitation of this resource in the studied coast and their transferability to other coastal regions. The result regarding the suitability of temporal closures is interpreted in light of the difference between the current capture size and the alternative size that were proposed in this study. To discuss our results in comparative terms regarding previous studies, a regression model of the relationship between the capitulum RT and RC biometrical measures was formulated. This model shows that RC length was approximately 90% of the RT length (Figure 3), suggesting transforming the data when these measures are compared. The good fit of the model suggests that both of the biometrical variables could be appropriate and easily comparable.

The peduncle of the barnacle produced heteroskedasticity in the RT-TL relationship, displaying an important variance in TL with respect to the growth-based measure RT as individuals grow in size (Figure 4). This result substantiates with a mathematical model the unsuitability of the TL-based minimum capture size, which constitutes the most common reference measure for the legal minimum size of capture in N Spain, and analytically supports the capitulum measure-based (i.e., growth-based) catch size that is already adopted in several regions of the Iberian Peninsula (Parada et al., 2012; Sousa et al., 2013). Consequently, a new minimum suitable size was estimated following the methodology of Sestelo and Roca-Pardiñas (2011) and based on the RT capitulum length. The first derivative of the nonparametric model showed a suitable minimum capture size of 26.3 mm RT, which corresponds to 23 mm RC using the RT vs RC relationship (Figure 3). The size that was obtained with this methodology ensures the maximum yield in weight from the fishery. This size is clearly larger than the current catch size in N Spain (40 mm TL) considering that the parametric regression model that was obtained in the present study for the RT-TL relationship (Figure 4a) suggested a minimum size of capture of 19.4 mm RT (or 16.9 mm RC) corresponding to the current minimum size of 40 mm TL.

The results that were obtained in this study agree with the size limit that was recently proposed by Jacinto et al. (2011) in Portugal (50% of the total harvested biomass comprising individuals > 22 mm RC). Sestelo and Roca-Pardiñas (2011) recently investigated the minimum capture size for this species in NW Spain (Galicia) using the same non-parametric model as that applied in this study. Their study, based on RC, estimated a suitable minimum capture size of 21.5 mm, also ensuring that any barnacle under this size has not yet attained its maximum yield in weight. Fishing directorates in different regions of Spain and Portugal have already used the RC length to establish the minimum size of capture. For instance, in Portugal, the capture size is between 20 mm and 23 mm in RC length (Sousa et al., 2013), and in Galicia the way to measure the minimum size of capture was changed from the TL (40 mm) to the capitulum-based (CB) length

(15 mm) (Parada et al., 2012). Using the CB vs RC regression model of Parada (2013), the minimum capture size for Galicia should be 18.3 mm RC.

To a greater or lesser extent, these sizes are above the 12.5-mm RC (14.26 mm RT) sexual maturation size (Cruz, 2000) and consequently may permit the production of a minimum of 1-2 broods before the designated size is reached (Molares et al., 1994; Pavón, 2003; Sestelo and Roca-Pardiñas, 2011). However, the current minimum capture size in Cantabria (40 mm TL or 16.9 mm RC) may be less conservative in terms of the sustainability of the fishery compared to the rest of analyzed capture sizes. The important difference that was observed in the minimum size between the current capture size in N Spain or the capture size that was established in Galicia (18.3 mm RC) and that obtained in our study (23 mm RC) is explained by the highly conservative approach of Sestelo and Roca-Pardiñas (2011). This method to estimate the minimum size of capture not only ensures at least a brood before the designated size is reached but also attains, as discussed, the maximum yield in weight from the fishery. It is also worth mentioning that previous studies estimated the minimum suitable size using individuals from open fishing areas, while our analysis was conducted using data from a permanently protected zone. This analysis ensured that the minimum capture size was estimated using data that were not biased by the fishing pressure. This analysis may also contribute to the slightly larger capture size that was obtained in this study compared to that of Sestelo and Roca-Pardiñas (2011). The transferability of this result to other coastal areas to support regional or zone-based management models could be adequate for the sustainability of the resource in highly exploited areas considering that our result is the most conservative. However, for this purpose, further analysis is suggested, including more data (i.e., monthly data).

In addition to the methodology that was used and the environmental differences between study areas, the lack of a standardized measure for the RC length could also explain, in part, the differences between the above-described minimum capture sizes. The comparison between the minimum sizes of different studies was performed in terms of the RC length. For this purpose, the given size measure, CB or RT, was transformed to RC using the regression models from Parada et al. (2012: 2013) and that obtained in the present study (Figure 3), respectively. However, the RC length that was measured by Parada et al. (2012, Figure 4) and Sestelo and Roca-Pardiñas (2011, Figure 2) is slightly different from that measured in this study (Figure 2) following Cruz (1993, Figure 2). We chose to measure the RC as did Cruz (1993) because she demonstrated that it was the biometrical measure that best represented the linear growth of *P. pollicipes* and is used to establish the minimum capture size in Portugal.

The permanent protection regime had a positive effect on the population structure in terms of the abundance of large-size individuals (Figure 6). The MDS analysis demonstrated that the permanently protected site of Sonabia clearly separated from the non-protected sites group (Figure 7). This result is in agreement with those of Borja et al. (2006b), who observed that the density and biomass were 5 times higher in permanently unexploited zones than in unprotected areas in the neighboring coast of Basque Country. However, Cruz (2000) and recently Sousa et al. (2013) in a similar analysis did not find any positive significant effect on the percentage of cover or the density of large individuals in no-take areas of central and SW Portugal. Sousa et al. (2013) suggested that the absence of this effect could be observed because the restrictions of exploitation are frequently not respected. However, seasonally protected sites (from May to October) did not show any significant differences in the size frequency distribution patterns compared to those of non-protected sites, i.e., the MDS analysis mainly grouped seasonal closure sites and non-protected sites in the same group (Figure 7). Bald et al. (2006) obtained similar results in the simulations that were conducted to reproduce different closure scenarios using a system dynamic model. These authors considered that 5-7 months of temporal closures are not sufficient to permit a total recovery of the resource after the capture season and suggested an annual alternate exploitation of the fishing zones as the best management decision.

The descriptive analysis of the size frequency distributions (Figure 5) completed the understanding of the similarities between the sites as observed in the MDS analysis (Figure 6) and confirmed the absence of a positive effect as associated with temporal closures. Sonabia and Cerdigo presented the highest abundance of 20-mm-size individuals and the unique sites that present individuals greater than 25 mm. The case of Sonabia, which was clearly separated from the other sites in the MDS analysis, can be easily explained by the permanent closure of the zone, as mentioned above, while the case of Cerdigo is more probably linked to both of the low coverages that were observed in this coastal zone (Cantabria, 2005), which shows little interest for professional shell-fishermen, and the presence of a high number of deep crevices and a rock islet which are not very accessible to poachers. The analysis of size frequency distribution patterns as conducted by the tidal level showed that larger sizes are found at the lower intertidal level, which is in accordance with previous research in Portugal (Cruz, 2000: Sousa et al., 2013) and N Spain (Pavón, 2003: Borja et al., 2006b). The difficulties that are associated with fishing at the lower tidal levels (Molares and Freire, 2003) might limit the exploitation intensity, and the abundance of large-size barnacles could remain high at this tidal level. Although these results regarding the tidal levels did not contribute to the goals of this study, the observed pattern demonstrates that the population of this coastal region is behaving as do the neighboring zones under fishing pressure.

At first glance, these results suggest temporal closure as a non-suitable protection regime for assuring the protection and recovery of a population. However, the desirable effect of the temporal closures could be shaded by the fact that fishery is conducted based on a potentially unsuitable catch-size. The results should be interpreted with caution considering that they were obtained under an unsuitable TL-based capture size. The fact that an important percentage of the individuals that extracted using the TL size could be less than a suitable minimum size may lead to important changes in the size-structure of the population and consequently obscure the real effect of the protection in the MDS analysis. The population size distribution would be appreciably different under the alternative capitulum-based minimum size, and in that case, the 6-month seasonal closure could have a positive effect, leading to the recovery the population after the capture season. Nevertheless, this seasonal protection regime may not be adequate for highly overexploited populations. A longer fishery closure may be more suitable in these situations requiring a total recovery. Considering the growth rate of this species (Gutiérrez-Cobo, 2012; Cruz et al. 2000) for overexploited areas, a minimum closure period of 2.5 years may be considered, which is the time that is required for goose barnacles to achieve a commercial size in Cantabria.

## 5. Conclusions

In summary, the analysis in this paper demonstrated that the minimum capture size based on the growth-based capitulum length measure is more adequate than that based on the TL measure. We suggest a catch size of 23 mm (RC) or 26 mm (RT) in N Spain that is larger than the current catch size that is established in this coast's regions and similar to that proposed in Portugal. The establishment of this size using the first derivative of the length-weight relationship may ensure the maximum yield in weight from the fishery. A seasonal closure of 6 months may not be effective for assuring the total recovery of a highly exploited population after the fishing season, at least if it is not linked to the establishment of a more suitable catch size than the current catch size. Thus, a 6-month seasonal closure should be locally tested in the field under the new minimum size. We also propose a temporal closure of 2.5 years for highly exploited populations to completely recover. Although the analysis applied in this study may be applicable to other coastal areas, the generalizability and transferability of these results to support management decisions at a larger spatial scale are subjected to further research, including monthly data and field experiments, to test the suitability of the obtained results.

**Appendix**

**(Figure A1)**

**Acknowledgements**

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**Figure captions**

**Figure 1**. Location of sampling sites on the coast of Cantabria (N Spain). * Seasonally protected and ** permanently protected zones. Sites without label represent open fishing zones.

**Figure 2.** Longitudinal biometric variables measured in *P. pollicipes* following Cruz (1993). RT= Rostrum-Tergum length, RC= Rostrum-Carina length, TL= Total length.

**Figure 3.** Relationship between Rostrum-Tergum length (RT) and Rostrum-Carina length (RC) (n=365). Coefficient of determination ($R^2_{cv}$) calculated by means of cross-validation is presented for the regression model. Confidence intervals (dashed lines) are hardly identifiable due to the good fit of the model.

**Figure 4.** Regression curve with bootstrap-based 95% confidence intervals (dashed lines) for Total Length (TL) and Rostrum-Tergum length (RT) (n=365) (a) and the conditional variance of TL (b). $R^2_{cv}$ represents the coefficient of determination for the regression curve calculated by cross-validation.

**Figure 5.** Regression curve (a) and first derivative (b) with bootstrap-based 95% confidence intervals (dashed lines) for dry weight (DW) and Rostrum-Tergum length (RT). Solid vertical line (b) represents the estimated $rt_0$ or the size at which the derivative has the maximum value. $R^2_{cv}$ represents the coefficient of determination for the regression curve calculated by cross-validation.

**Figure 6.** Size frequency distribution plots (% of individuals) of *P. pollicipes*, (a) for each sampling site and (b) for all data at each tidal level. RT: rostro-tergum length.

**Figure 7.** MDS ordination of the studied sites showing *P. pollicipes* fishery protection levels (Circle: permanently closed fishery; Triangle: seasonally closed fishery; Square: null protection or all year open to the fishery). Manhattan distances are represented by dotted line (distance=16) and solid line (distance=18).

**Appendix figure captions**

**Figure A1.** Relationship between Rostro-Tergum length (RT) and Dry Weight (DW) (n=1200). Coefficient of determination ($R^2_{cv}$ ) calculated by means of cross-validation is presented for the regression model. Confidence intervals (dashed lines) are hardly identifiable due to the good fit of the model.

Figure 1


Bay of Biscay
France
Spain
Prellezo *
Oreña *
Ubiarco
Liencres
Arnía
Diablo
Llaranza
Arena *
Sonabia * *
Cerdigo
Cantabria
4805
4810
4815
4820
UTM Y / 1000
380
400
420
440
460
480
UTM X / 1000
0
5
10 Km

**Figure 2**

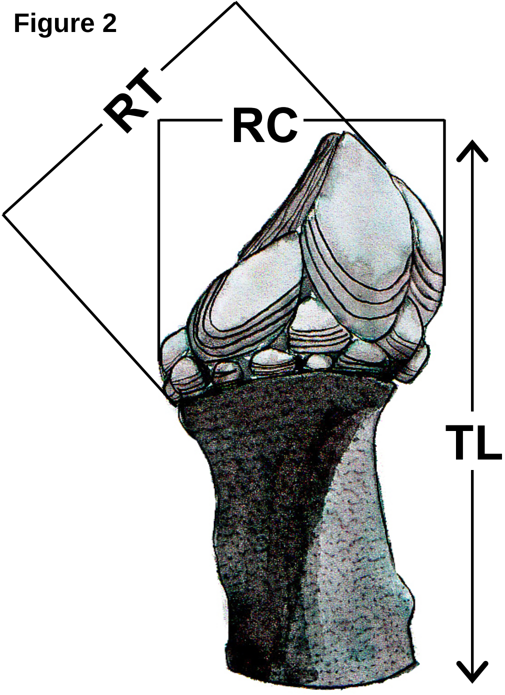
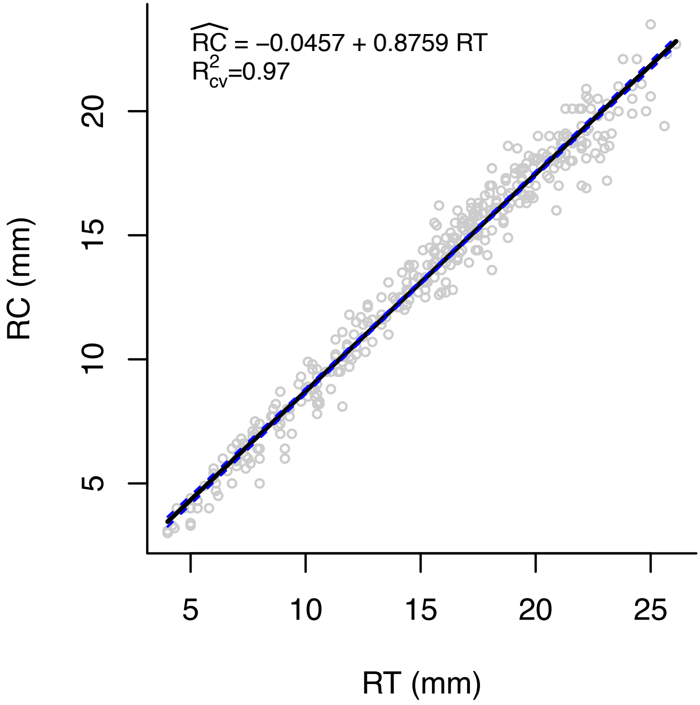
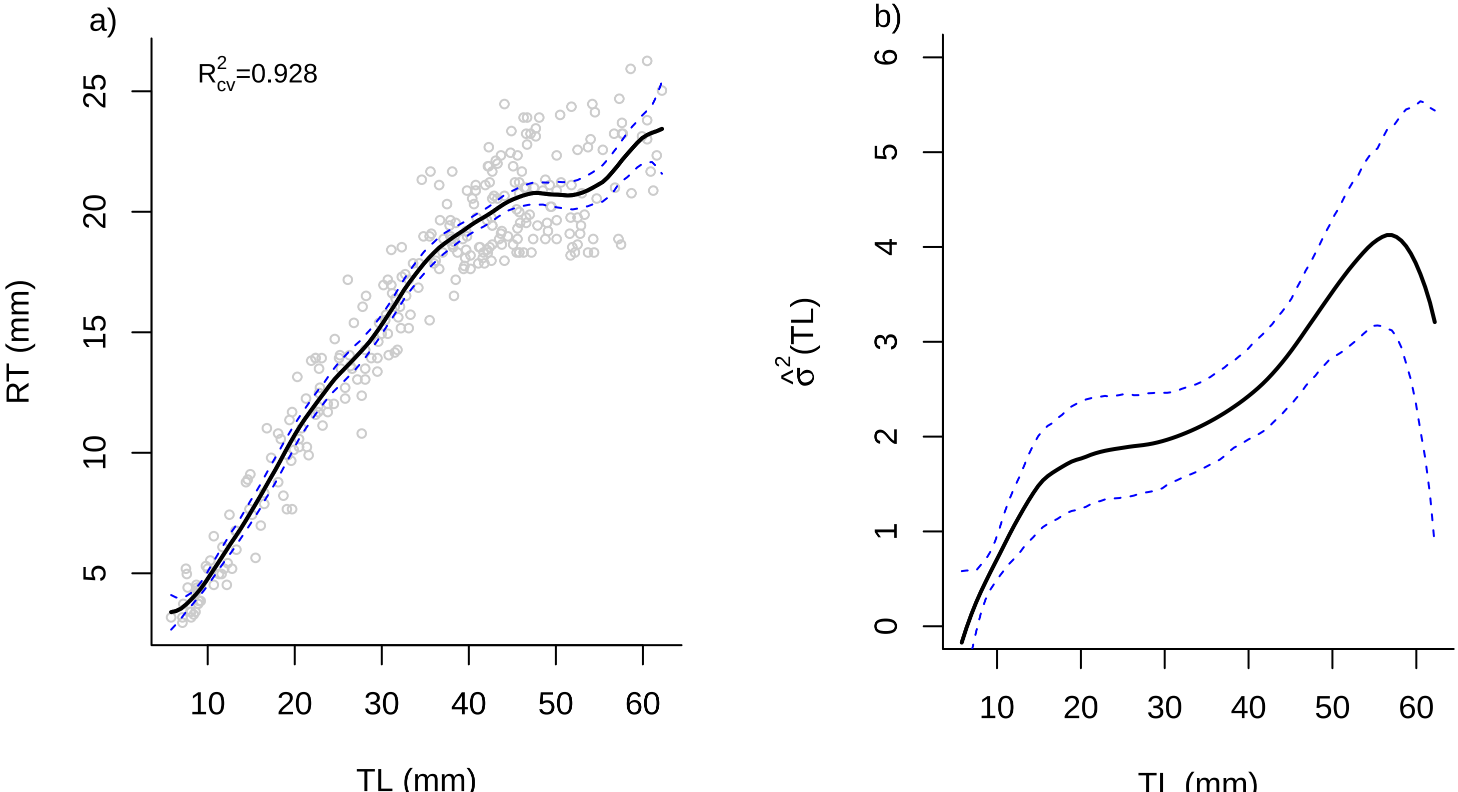


**Figure 3**



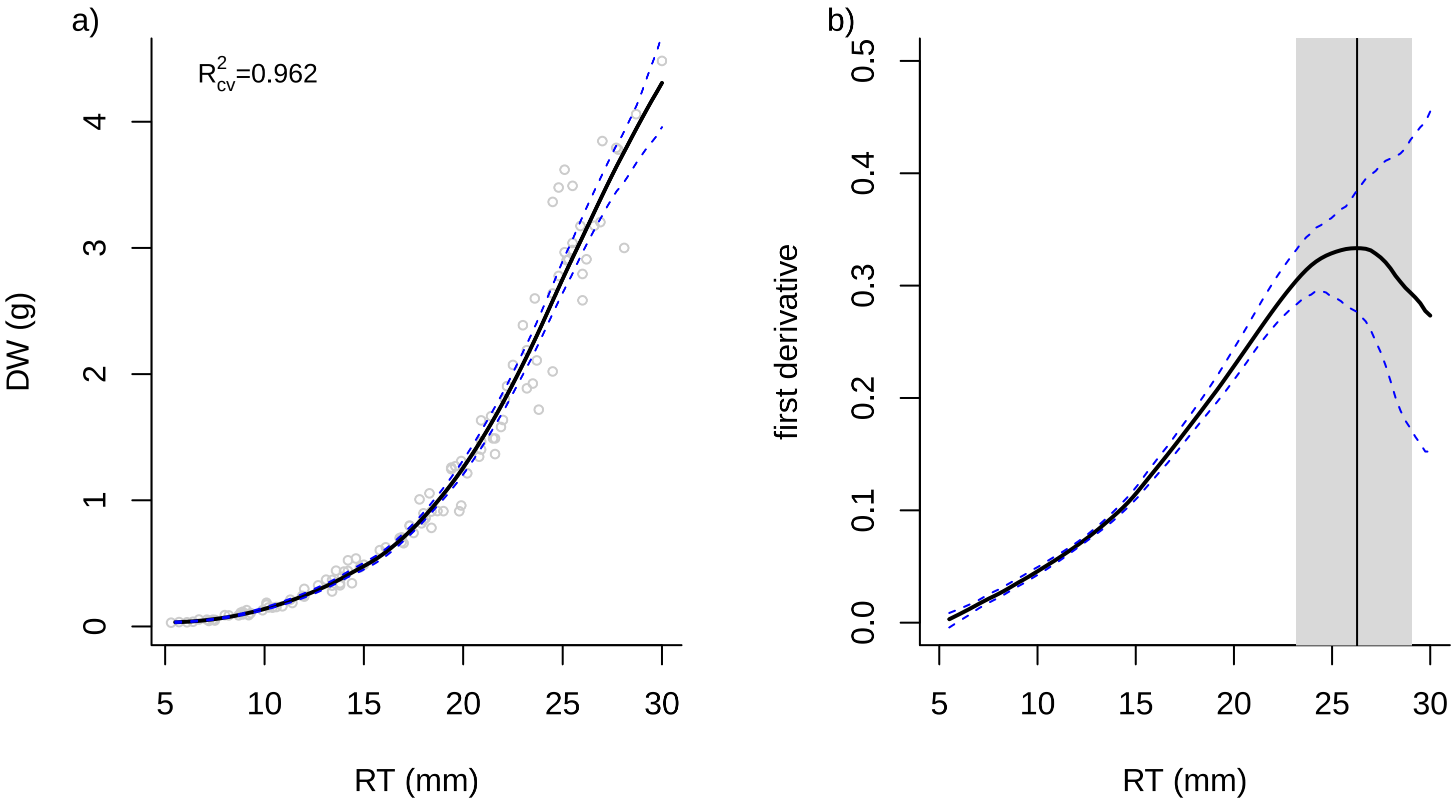
$\widehat{RC} = -0.0457 + 0.8759\ RT$
$R^2_{cv}=0.97$
RC (mm)
RT (mm)
5
10
15
20
5
10
15
20
25

**Figure 4**



a)
$R^2_{cv}$=0.928
RT (mm)
5
10
15
20
25
10
20
30
40
50
60
TL (mm)
b)
$\hat{\sigma}^2$(TL)
0
1
2
3
4
5
6
10
20
30
40
50
60
TL (mm)

**Figure 5**



a)
$R^2_{cv}$=0.962
DW (g)
0
1
2
3
4
5
10
15
20
25
30
RT (mm)
b)
first derivative
0.0
0.1
0.2
0.3
0.4
0.5
5
10
15
20
25
30
RT (mm)

Figure 6

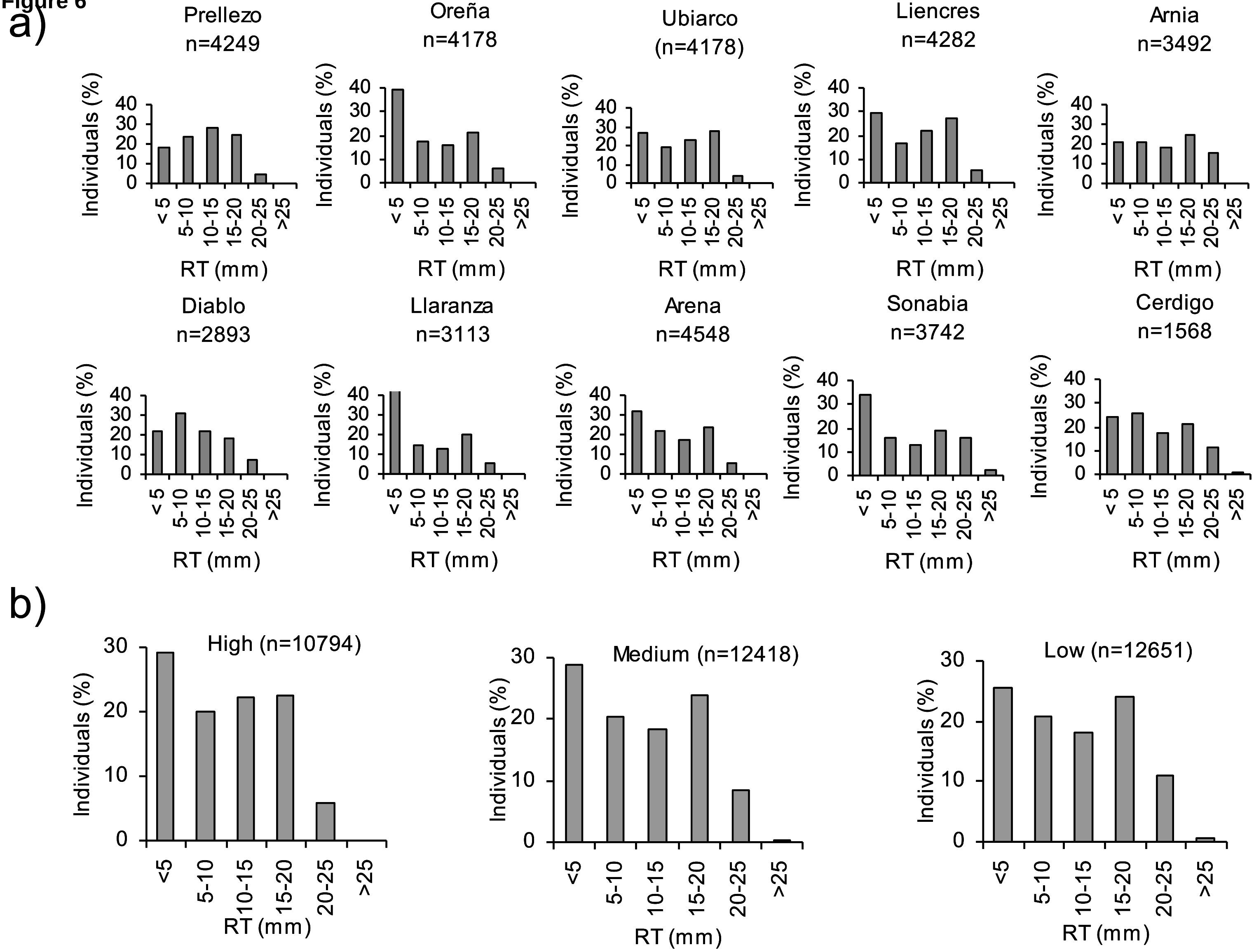
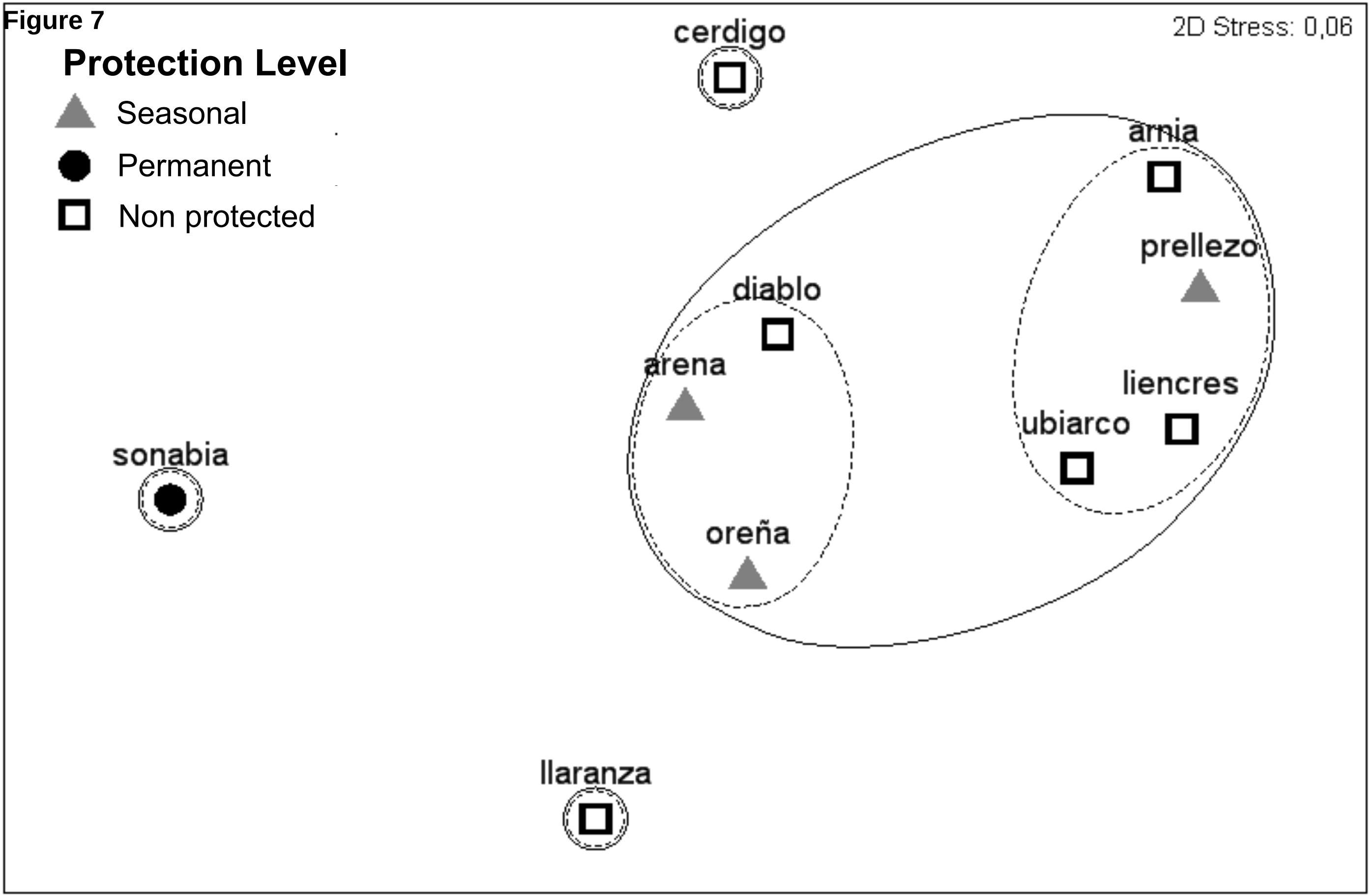
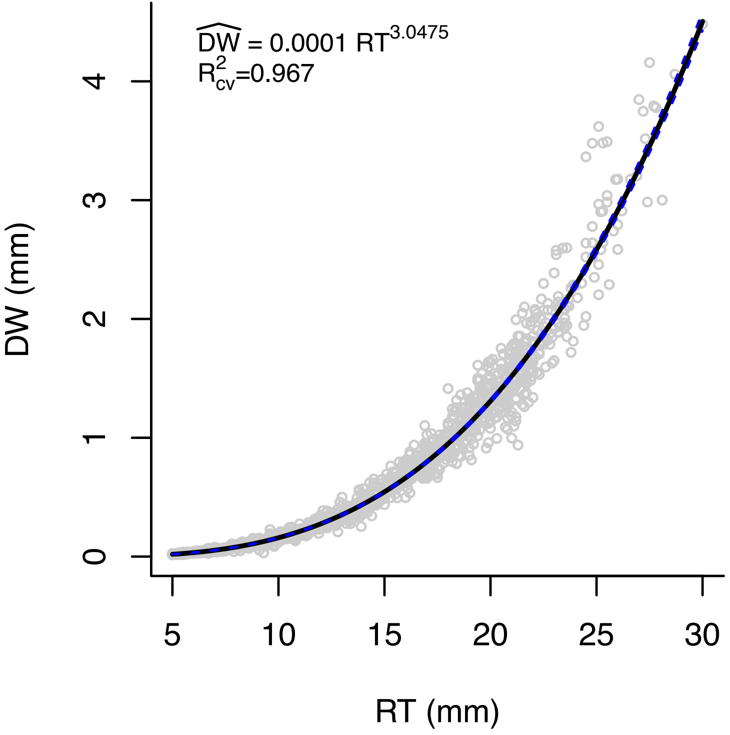

a)
Prellezo
n=4249
Oreña
n=4178
Ubiarco
(n=4178)
Liencres
n=4282
Arnia
n=3492
Diablo
n=2893
Llaranza
n=3113
Arena
n=4548
Sonabia
n=3742
Cerdigo
n=1568
Individuals (%)
RT (mm)
< 5
5-10
10-15
15-20
20-25
>25
b)
High (n=10794)
Medium (n=12418)
Low (n=12651)
Individuals (%)
RT (mm)
<5
5-10
10-15
15-20
20-25
>25

Figure 7



2D Stress: 0,06
Protection Level
Seasonal
Permanent
Non protected
cerdigo
arnia
prellezo
diablo
arena
liencres
ubiarco
sonabia
oreña
llaranza

**Figure A1**



$\widehat{DW} = 0.0001\ RT^{3.0475}$
$R^2_{cv}=0.967$
DW (mm)
0
1
2
3
4
5
10
15
20
25
30
RT (mm)