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Length-weight relationship of *Pollicipes pollicipes* (Gmelin, 1789) on the Atlantic coast of Galicia (NW Spain). Some aspects of its biology and management.

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Abstract

This study was undertaken using data drawn from five sites along the Atlantic shoreline of Galicia (NW Spain) over a period of two years. The length-weight relationship of *Pollicipes pollicipes* (Gmelin, 1789) was estimated in order to observe the way in which individuals of this species gain weight as they increase in size. A classic allometric model was used for the purpose. As an alternative, a more general nonparametric model was also estimated, using local linear kernel smoothers. Comparison of these two models showed that use of the nonparametric model resulted in a better fit of the data. Additionally, derivatives were used for estimating a size of capture for this species. For the same purpose, we also estimated this crustacean's mean size at sexual maturation (L_{50}) and the number of broods which it spawns per annum. Individuals' weight gain, a female maturity size of 15.7 mm and *P. pollicipes*' estimated 1.73 broods per annum would tend to suggest a size of capture based on a rostro-carinal length of 21.50 mm.

Keywords: *Pollicipes pollicipes*, rostro-carinal length, size of capture, bootstrap, local linear kernel smoother

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1. Introduction

The stalked barnacle, *Pollicipes pollicipes* (Gmelin, 1789), is a strictly littoral and essentially intertidal pedunculate cirripede which lives by forming dense aggregates or clumps on exposed rocky shores and cliffs associated with a high degree of hydrodynamism (Barnes, 1996). Of the three species belonging to the genus *Pollicipes* (Newman, 1987), *P. pollicipes* is found along the Atlantic seaboard of France, Spain, Portugal, Morocco and Senegal. In addition, colonies of this species have been reported on the Mediterranean coasts of Spain, France, Morocco and Algeria (Barnes, 1996; Cruz, 2000; Darwin, 1851). In terms of commercial exploitation, the tropical Pacific species, *Pollicipes elegans* Lesson, 1830, serves a small, localized demand in Costa Rica (Bernard, 1988) and Perú (Pinilla, 1996; Ramírez et al., 2008), whilst *Pollicipes polymerus* Sowerby, 1833 is collected on the coast of Canada (Bernard, 1988; Lauzier, 1999).

In contrast, the Atlantic species, *P. pollicipes*, has been and is the most exploited of the three, with countries such as France, Spain, Portugal and Morocco harvesting this resource along their coasts (Bernard, 1988; Cruz and Araujo, 1999; Girard, 1982; Goldberg, 1984). Commercial interest in barnacles resides in their muscular peduncle, the edible part of the species, which commands high prices on the market (Goldberg, 1984). In Galicia (NW Spain), the leading barnacle producing region in Spain, the declared average annual production of *P. pollicipes* stands at approximately 400 metric tons (official figure, Galician Regional Authority/Xunta de Galicia, http://www.pescadegalicia.com). Yet, this is far below the real amount, due to the fact that a great proportion of the catch is not reported. Indeed, strong Spanish market demand has made it necessary for barnacles (*P. pollicipes* y *P. polymerus*) to be imported from France, Portugal, Morocco and Canada (Bernard, 1988; Girard, 1982; Molares, 1993).

In Spain and Portugal alike, countries with the highest harvests of *P. pollicipes*, the phenomenon of overfishing has affected this species to differing degrees (Bernard, 1988; Cardoso and Yule, 1995; Cruz, 2000; Molares and Freire, 2003).

Pedunculate cirripedes, which include species of the genus *Pollicipes*, grow in height due to an increase in peduncle length and width by lamellar accretion caused by the addition of calcium carbonate to the capitular plates (Anderson, 1994). According to Darwin (1854), environmental factors like food, temperature and quality of water may influence in the shape and size of individuals of the same species of cirripedes.

Despite the economical importance of *P. pollicipes* both in Spain and others countries, our knowledge on the biology and ecology of this species is fragmentary, and several aspects call for further research. One of these is the growth in this crustacean's weight. Accordingly, the main goal of this study was to estimate how individuals gain weight as their size increases, and thereby establish the length-weight relationship of *P. pollicipes*.

To this end, two biometric variables were selected, namely: rostro-carinal length (RC), the variable that best represents the growth of the species (Cruz, 1993, 2000); and individual weight, which enables use of this resource to be evaluated. To observe the relationship between these two variables, we used two regression models, which were then compared, the classic allometric model and a nonparametric model.

In the case of the nonparametric model, the length-weight relationship of *P. pollicipes* was estimated using local linear kernel smoothers. Such nonparametric regression models allow for a more flexible fit of real data than do the parametric regression techniques usually used. Similarly, they make it possible for the first derivative of the regression curve to be calculated, thereby enabling the different stages of growth to be defined as the species increases in size. Furthermore, calculation of this derivative could have a direct application in the management of this species, possibly in estimating a size of capture.

To establish the size of capture of any species that is subject to exploitation, a range of biological and ecological aspects must be taken into account, such as individual size at sexual maturation, growth rate, and biological cycle. Additionally, each specimen's weight gain must be assessed. In this respect, the Food and Agriculture Organization (FAO) of the United Nations states that, " The basic purpose of fish stock assessment is to provide advice on the optimum exploitation of aquatic living resources (...) and fish stock assessment may be described as the search for the exploitation level which in the long run gives the maximum yield in weight from the fishery" (Sparre and Venema, 1997). In line with this indication, we feel that the study of derivatives is extremely useful when it comes to establishing ideal size of capture. In particular, this paper proposes that the minimum size corresponds to the point (or size) where the first derivative reaches the maximum. From this point onwards, weight gain from one size to the next decreases, so that the yield obtained ceases to be profitable vis-à-vis the time during which the resource is left unexploited.

Apart from affording an optimized methodology for studying the length-weight relationship in various marine resources, this study also furnishes a possible method of estimating an ideal size of capture for this species on Galicia's Atlantic coast.

2. Materials and methods

2.1. Study area

The study was conducted on the Atlantic coast of Galicia (NW Spain). This consists of an approximately 1,000-kilometer long shoreline with extensive rocky stretches exposed to tidal surge and wave action, which are settled by the *P. pollicipes* populations targeted for study. The principal oceanographic characteristic of Galicia's Atlantic seaboard is attributable to the episodes of upwelling which occur here as result of the north Atlantic anticyclonic gyre that extends from Galicia to Cape Verde, with the increase in intensity in Galicia coinciding with the gyre's annual latitudinal shift (Fraga, 1981; Fraga et al., 1982).

Specimens were collected from five sites along an intertidal zone that is representative of the region's Atlantic coastline and corresponds to the stretches of coast where this species is harvested (Figure 1; Table 1). The study was conducted over two years, from January 2006 to December 2007, during which we sought to maintain a monthly sampling periodicity.

Site	Sampling sites	Coordinates	Sample size
1	Laxe do Mouro	41°57'N 08°53'W	3294
2	Punta Lens	42°45'N 09°07'W	3242
3	Punta de la Barca	43°06'N 09°13'W	3444
4	Punta del Boy	43°11'N 09°10'W	3145
5	Punta del Alba	43°19'N 08°31'W	3437

Table 1: Place names and coordinates of sampling sites, with their sample sizes.

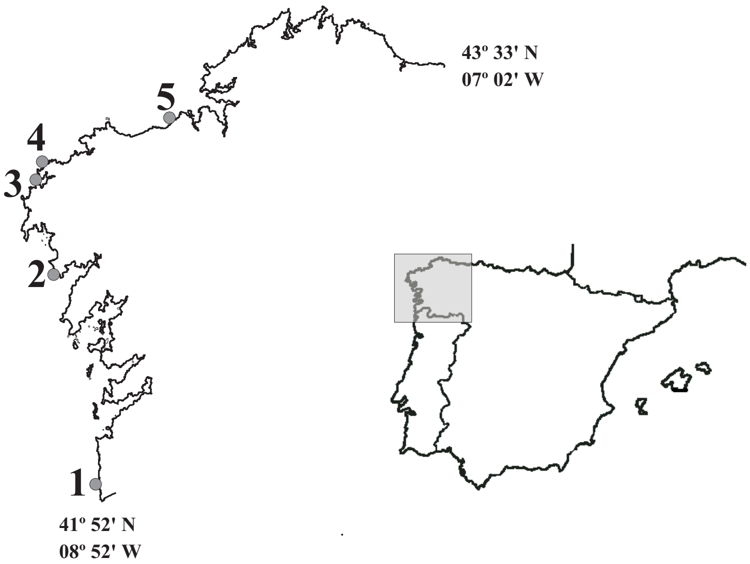

Figure 1: Sampling sites.

2.2. Methodology

The specimens of *P. pollicipes* were gathered along the lower mesolittoral zone which, together with the upper sublittoral, constitutes this species' preferred area of distribution. In each of the areas selected, three random subsamples of *P. pollicipes* were collected. The minimum number of specimens per subsample was calculated by mean stabilization (Kershaw, 1973), performed for each area and each variable used. The estimated number was 50 individuals per subsample, which were then randomly separated in the laboratory.

The following biometric variables of each specimen were measured: rostro-carinal length (RC; maximum distance across the capitulum between the ends of the rostral and carinal plates) (Figure 2); and dry weight (DW), obtained on the basis of drying individuals in a forced air oven for 24 hours at 100 ^{o}C (Montero-Torreiro and Martínez, 2003). All measurements were made using a digital caliper with a precision of 0.1 mm, and a 0.01 g precision balance. A total of 16562 specimens were measured.

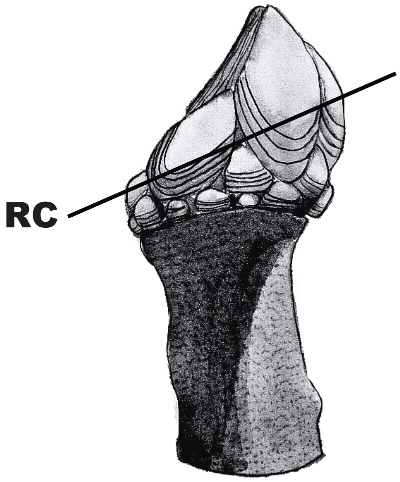

Figure 2: Sketch depicting longitudinal variable measured in *P. pollicipes*.

The relationship that defines the growth in a species' weight with respect to its length is one of the most frequent in fish biology and fisheries, and is an important element in population dynamics and stock assessment (Oniye et al., 2006). Indeed, this length-weight relationship has been studied in various marine species, using different parametric models which are easy to apply and estimate, and are all fully described in the literature (i.e. Nieto-Navarro et al., 2010; Ramón et al., 2010; Pinheiro and Fiscarelli, 2009; Ismen et al., 2007; Neves et al., 2009; Froese, 2006). One of the most widely used models of this type is the allometric model, $DW = aRC^b$, proposed by Huxley (1924), which is usually converted into its logarithmic expression,

$$logDW = log\,a + b\,logRC = a^* + b^*logRC \tag{1}$$

where a is a constant and b is the exponent of the arithmetic form of the equation and the slope of regression line in the logarithmic form. This conversion, which is quite simple, both conceptually and mathematically, facilitates the estimation of its parameters by linear regression. Once $\hat{a}^*$ and $\hat{b}^*$ have been obtained by fitting the model in (1), the parameters' original scale is commonly returned to, $\hat{a} = exp(\hat{a}^*)$ and $\hat{b} = \hat{b}^*$, and the estimated model,

$\widehat{DW} = \hat{a}RC^{\hat{b}}$, is thus obtained. In addition, the estimation of the derivative of DW is then given by $\widehat{DW}' = \hat{a}\hat{b}RC^{\hat{b}-1}$.

Despite that fact that such parametric models are frequently used, there is a problem associated with their use, i.e., in certain circumstances the assumption of a given curve on the effects of the covariates is very restrictive and is not supported by the data at hand. In this setting, nonparametric regression techniques are involved in modeling the dependence between DW and RC, though without specifying in advance the function which links the covariates to the response. Hence, to ascertain the length-weight relationship for *P. pollicipes*, this paper proposes the use of a more generalized nonparametric model of the type

$$DW = m(RC) + \sigma(RC)\varepsilon \tag{2}$$

where m is a smooth function, σ is the variance function representing heterocedasticity, and ε is the error that is assumed to be independent of the covariate RC. It should be note that in this type of model, there is not need to establish a parametric form of m.

Shown in Figure 3 are the estimated regression curves of the previous models and their derivates. As will be seen below, the regression curves of both models are monotone increasing functions, and the value of DW thus increases with the values of RC.

In the nonparametric model, however, the increase in weight per unit of RC (given by the first derivative of m) registers a maximum at a given size, that we named rc_0, beyond which this weight gain declines (or at least remains constant). This trend is not observed in the allometric model, where its first derivative rises constantly.

This could suggest the use of the nonparametric model for the estimation of the length-weight relationship of this species. Additionally, this same model could also be use for estimating of a possible minimum size of capture, which in our view should never be less than rc_0.

The procedure that enables the confidence intervals for rc_0 to be estimated and constructed is now outlined below.

Estimation

The size sought, rc_0, is given by the maximizer of $m^1(rc)$. In practice, however, neither m nor m^1 is known, so that the estimated $\widehat{rc_0}$ must be obtained on the basis of the estimates $\hat{m}$ and $\hat{m}^1$ of the true m and m^1 curves.

For the purpose of estimating the initial regression curve and its first derivate, we propose the use of the local linear kernel smoothers (Wand and Jones, 1995). Given the original sample $\{RC_i, DW_i\}_{i=1}^n$ with a sample size of $n = 16562$, the local linear kernel estimator of $m(rc)$ and its first derivative $m^1(rc)$ at a location rc are defined as $\hat{m}\,(rc) = \hat{\beta}_0(rc)$ and $\hat{m^1}\,(rc) = \hat{\beta}_1(rc)$, where $\hat{\beta} = \left(\hat{\beta}_0, \hat{\beta}_1\right)$ is the minimizer of

$$\sum_{i=1}^{n} \left(DW_i - \beta_0 - \beta_1\left(RC_i - rc\right)\right)^2 h^{-1} K\left(\frac{RC_i - rc}{h}\right),$$

$K(u) = 1/\sqrt{2\pi}\exp\left(-u^2/2\right)$ is the Gaussian kernel function, and $h > 0$ is the smoothing parameter. The non-parametric estimates obtained are known to depend heavily on the bandwidth, h, used in the kernel-based estimation. Given the difficulty of asymptotic theory, optimal bandwidth selection remains a challenging problem. Furthermore, it should be borne in mind that there is no basis to suggest that the "optimal" window for estimating m will necessarily coincide with the optimal window for estimating its first derivative m^1. As a practical solution, bandwidth h was selected automatically by minimizing the following cross-validation error criterion

$$CV = \sum_{i=1}^{n} \left(DW_i - \hat{m}^{(-i)}\left(RC_i\right)\right)^2, \tag{3}$$

where $\hat{m}^{(-i)}(RC_i)$ indicates the estimate at RC_i, leaving out the i^{th} element of the sample.

Finally, once the estimates $\hat{m}$ and $\hat{m}^1$ have been obtained, the estimate $\widehat{rc_0}$ of the true rc_0 can be defined as the maximizer of

$$\hat{m}^1(rc_1), \ldots, \hat{m}^1(rc_N)$$

with $rc_1, \ldots, rc_N$ being a grid of N equidistant points in a ranger of the RC values. In this paper, we have taken an $N = 10000$ points, so the distance between consecutive nodes is less than 0.01 mm of RC.

Confidence Intervals

In the construction of the above CIs, it is necessary to know the percentile distribution of $\widehat{rc_0}$. Nevertheless, it is well known that, within a nonparametric regression context, the asymptotic theory for determining such percentiles is not closed, and resampling methods such as bootstrap introduced by Efron (1979) (see also Efron and Tibshirani, 1993; Härdle and Mammen, 1993; Kauermann and Opsomer, 2003) can be applied instead. Bootstrap methods are statistical resampling methods for analyzing the variability of the estimator $\widehat{rc_0}$ obtained from the original sample. The steps for construction of the confidence interval for the true rc_0 are as follows:
Step 1. Obtain the estimated $\widehat{rc_0}$ from the sample data $\{(DW_i, RC_i)\}_{i=1}^n$ as explained above.
Step 2. For $b = 1$ to B (e.g. B=1000), simulate a random sample $\left\{\left(DW_i^{\bullet b}, RC_i^{\bullet b}\right)\right\}_{i=1}^n$ by randomly sampling the n items from the original data set $\{(DW_i, RC_i)\}_{i=1}^n$ with replacement (that is, each individual value (RC_i, DW_i) has a probability n^{-1} of occurring), and obtain the bootstrap estimates $\widehat{m}^{\bullet b}(rc)$, $\widehat{m}^{1\bullet b}(rc)$ and the correponding $\widehat{rc}_0^{\bullet b}$

Finally, the $100(1-\alpha)\%$ limits for the confidence interval of $m^j(rc)$ are given by

$$I = \left(\widehat{rc_0} - \widehat{rc_0}_{\,1-\alpha/2}, \widehat{rc_0} - \widehat{rc_0}_{\,\alpha/2}\right)$$

where $\widehat{rc_0}_p$ represents the percentile p of the bootstrapped estimates
$\widehat{rc}_0^{\bullet 1} - \widehat{rc}_0, \ldots, \widehat{rc}_0^{\bullet B} - \widehat{rc}_0$

In addition, this bootstrap procedure can be used to obtain pointwise confidence intervals of $m(rc)$ and $m^1(rc)$: the limits of these intervals are respectively given by

$$\left(\hat{m}(rc) - \hat{m}_{\,1-\alpha/2}(rc), \hat{m}(rc) - \hat{m}_{\,\alpha/2}(rc)\right)$$
$$\text{and}$$
$$\left(\hat{m}^1(rc) - \hat{m}^1_{1-\alpha/2}(rc), \hat{m}^1(rc) - \hat{m}^1_{\alpha/2}(rc)\right)$$

where $\hat{m}_p(rc)$ and $\hat{m}_p^1(rc)$ respectively represents the percentile p of the bootstrapped estimates $\widehat{m}^{\bullet b}(rc) - \widehat{m}(rc)$ and $\widehat{m}^{1\bullet b}(rc) - \widehat{m}^1(rc)$ for $b = 1, \ldots, B$.

2.2.1. Biological methods

The biological aspects considered in determining a possible size of capture were size at sexual maturity (L_{50} estimation, in population terms, of the point in time when individuals become mature), and the number of broods per year, which may be important in terms of reproduction.

Size at sexual maturity, or L_{50}, corresponds to the estimated length at which 50% of the individuals reach maturity. The estimation of this size in females was based on the presence of egg masses in the mantle cavity. This presence means that the individual's mature ovocytes have already fertilized (Cruz and Hawkins, 1998; Cruz, 2000). To define this size, a stereo microscope was used to examine the interior of the capitulum of each specimen taken from samples collected across the period January 2007-December 2007.

The statistical analysis was performed using a logistic model with July data (the month with the highest proportion of individuals with eggs). The percentage of individuals with egg masses in the mantle cavity was plotted against RC in each 1-mm RC class, and then fitted using a generalized additive model (GAM) (logistic family) and applying the `mgcv` library for the free statistical software environment, R (R Development Core Team, 2009).

Furthermore, the percentage of sexually mature individuals which presented with eggs in the cavity of the capitulum was used as an estimate of the brooding activity of this species (Cruz and Hawkins, 1998; Cruz and Araujo, 1999; Cruz, 2000; Lewis and Chia, 1981; Pavón, 2003).

Based solely on the samples corresponding to 2007, we then calculated the number of broods produced per individual per annum using the methodology employed by Burrows et al. (1992); Cruz and Araujo (1999); Cruz (2000); Page (1984); Pavón (2003). Accordingly, the effective time which an individual presented with eggs across the reproductive period , T_B, was calculated as

$$T_B = \sum P_{B,t} \Delta t \tag{4}$$

where $P_{B,t}$ is the proportion of sexually mature individuals in any population bearing eggs in the capitular cavity at a given moment in time t and Δt is the time interval between successive samples.

The number of broods, N_B, was thus estimated as

$$N_B = T_B / T_D \tag{5}$$

where T_D is the time needed for complete development of the embryos from oviposition to release of the *nauplius* larvae. For the purposes of our study, this period was deemed to be 25 days, in line with the estimates of Molares et al. (1994a).

3. Results

Firstly, Figure 3 despicts the regression curves of length-weight relationship estimated estimated by means of the two proposed models and their first derivatives. The grey lines refer to the allometric model and the black lines to the nonparametric model.

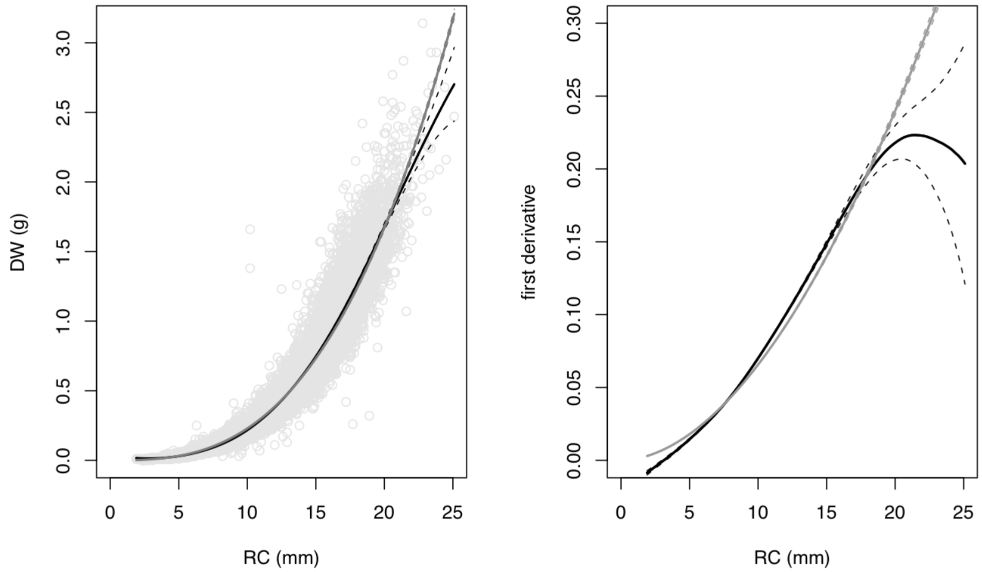

Figure 3: Regression curves and first derivatives (solid lines) with bootstrap-based 95% confidence intervals (broken lines) for dry weight and rostro-carinal length. Grey lines: allometryc model. Black lines: nonparametric regression model.

Under the allometric model, the initial regression curve shows the way in which individuals' size increased as their weight rose. The length-weight relationship was seen to be a rising function across the entire range of values. As is plain from Figure 3 (right), the first derivative of this curve is a rising monotone function.

Under the nonparametric model, the initial regression curve likewise proved to be rising and very similar to the curve estimated with the allometric model.

However, the final section of these curves seems to differ according to the model used. It would seem that, the nonparametric model detects variations in the final part of the figure, which the allometric model is not capable of discerning. If one looks at Table 2, which lists the estimated DWs with their corresponding 95 % confidence intervals, it will be seen that both models estimated similar DW values until an RC of 20.18 was reached. Thereafter, for an RC of 23.23, the allometric model yielded a DW value of 2.57 versus 2.35 estimated by the nonparametric model. Similarly, for an RC of 25.10, the DW ranged from a value of 3.21 (allometric model) to 2.70 (nonparametric model).

Focusing on the first derivative of this curve (Figure 3, right), the above described situation becomes even clearer. This derivative, rather than constantly increasing as in case of the allometric model, instead displayed a maximum at a specific size, after which it began to decrease. This is clearly visible in Table 3, where the estimated DW values are 0.20 for an RC of 18.07, 0.22 for an RC of 23.23, and 0.20 again for an RC of 25.10.

Mean Square Error ($MSE = n^{-1}\sum_{i=1}^{n}\left(DW_i - \widehat{DW}_i\right)^2$) was used to compare the fit of the two models. In addition, we used the “half-sampling” method to prevent the different degree of smoothing used by the different models from affecting said measure. Specifically, the database (16562) was split into two sub-samples, in such a way that the first of these (comprising 60 % of the data, 9937 specimens) was used for the estimation, and the second (6625 specimens) was used for an evaluation of the prediction MSE. The errors obtained with each of the models, both overall and by size intervals, are shown in Table 3.

RC	Allometric model	Nonparametric model
[0,5)	0.04	0.04
[5,10)	0.59	0.64
[10,15)	7.73	7.76
[15,20)	36.08	35.05
>20	89.48	82.63
Global	13.73	13.35

Table 3: MSE for the two proposed models, calculated both overall and by size intervals, using the ”half-sampling” method.

	Regression curve				First derivative			
	Allometric model		Nonparametric model		Allometric model		Nonparametric model	
RC	Estimates	95% CI	Estimates	95% CI	Estimates	95% CI	Estimates	95% CI
5.18	0.03	(0.03,0.03)	0.03	(0.03,0.03)	0.02	(0.02,0.02)	0.02	(0.02,0.02)
8.23	0.13	(0.13,0.13)	0.12	(0.12,0.12)	0.05	(0.05,0.05)	0.05	(0.05,0.05)
10.10	0.24	(0.23,0.24)	0.22	(0.22,0.23)	0.07	(0.07,0.07)	0.07	(0.07,0.07)
13.15	0.50	(0.50,0.50)	0.50	(0.50,0.50)	0.11	(0.11,0.11)	0.12	(0.12,0.12)
15.02	0.74	(0.73,0.74)	0.75	(0.75,0.75)	0.14	(0.14,0.14)	0.15	(0.15,0.15)
18.07	1.25	(1.24,1.26)	1.28	(1.27,1.29)	0.20	(0.20,0.20)	0.20	(0.19,0.20)
20.18	1.71	(1.70,1.73)	1.72	(1.70,1.73)	0.24	(0.24,0.25)	0.22	(0.21,0.23)
23.23	2.57	(2.55,2.59)	2.35	(2.27,2.43)	0.32	(0.31,0.32)	0.22	(0.19,0.25)
24.16	2.88	(2.85,2.90)	2.53	(2.40,2.65)	0.34	(0.34,0.35)	0.21	(0.17,0.25)
25.10	3.21	(3.18,3.24)	2.70	(2.49,2.88)	0.37	(0.36,0.37)	0.20	(0.14,0.26)

Table 2: *DW* estimates and their respective 95% confidence intervals corresponding according to the two proposed models.

For intervals constructed with low RC values, both models were competitive, with the allometric model even yielding the better fit. Nevertheless, as the size of individuals increased, it was the nonparametric model which displayed the smaller error, proving 10% better than the classic model for all lengths of over 20 mm.

Lastly, it will be seen that the MSE calculated on an overall basis was greater in the case of the allometric model. In the light of the above results, it seems that, of the two models, the nonparametric afforded the best fit.

When the study was repeated with the data being stratified by year (Figure 4), it showed the same pattern of behavior as that displayed by the overall study. Similarly, the allometric model would appear to be incapable of detecting variations in the data which the nonparametric model, in contrast, is able to record.

Based on these results, the use of the nonparametric model would seem to be a good alternative to the classic model. Figure 5, which depicts the overall study based on all the data, plots the nonparametric regression curve of weight gain vis-à-vis increases in RC, based on the former model.

It is important to underscore the fact that this curve was initially exponential, until it reached a point where the relationship between dry weight and rostro-carinal length continued with a more linear trend. The first derivative of this curve increased as individuals grew in size, until it peaked at an RC of 21.5 mm (solid vertical line).

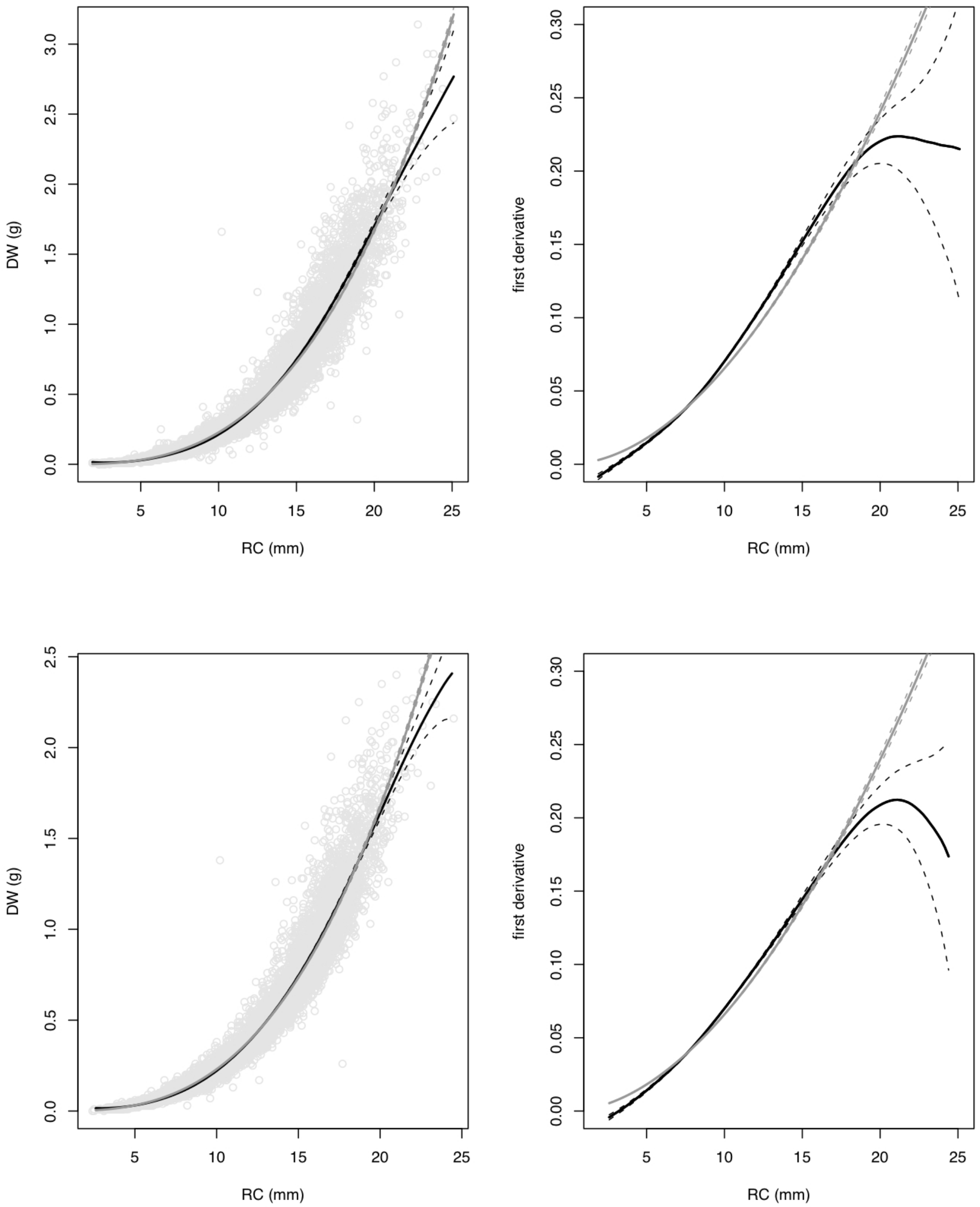

Figure 4: Regression curves and first derivatives (solid lines) with bootstrap-based 95% confidence intervals (broken lines) for dry weight and rostro-carinal length. First row: year 2006; second row: year 2007. Grey lines: allometric model. Black lines: nonparametric regression model.

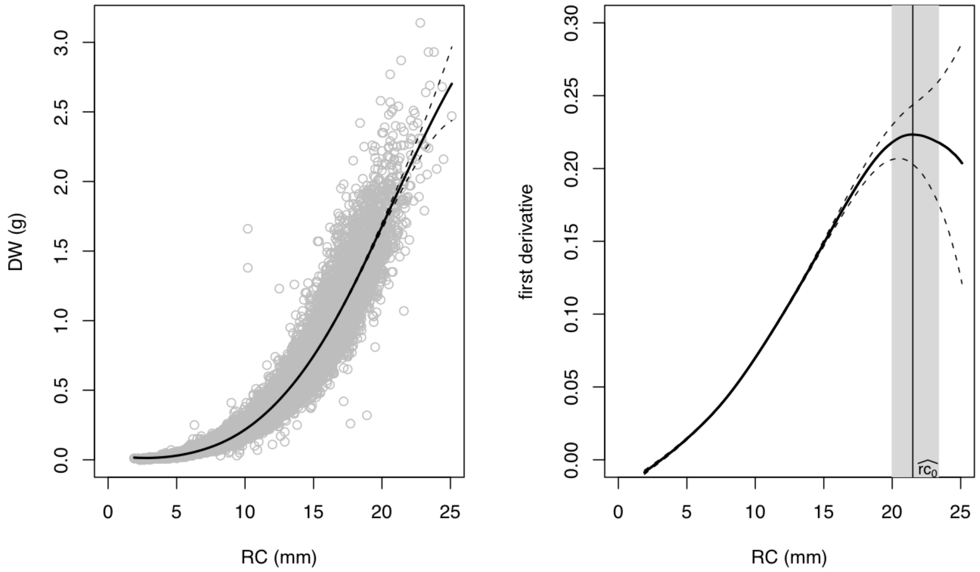

Figure 5: Regression curve and first derivative (solid lines) with bootstrap-based 95% confidence intervals (broken lines) for dry weight and rostro-carinal length (overall study). Solid vertical line: estimated rc_0. Grey area: confidence interval constructed for $\widehat{rc}_0$.

To ascertain whether this size remained constant across time and was not altered by any possible annual variability in the growth of this species, the study was repeated separately for each year, with the first and second rows of Figure 6 thus referring to 2006 and 2007, respectively. As with the overall study, in both cases the initial regression curves show the way in which smaller-sized individuals increased in weight exponentially whereas larger- sized individuals increased in weight proportionally.

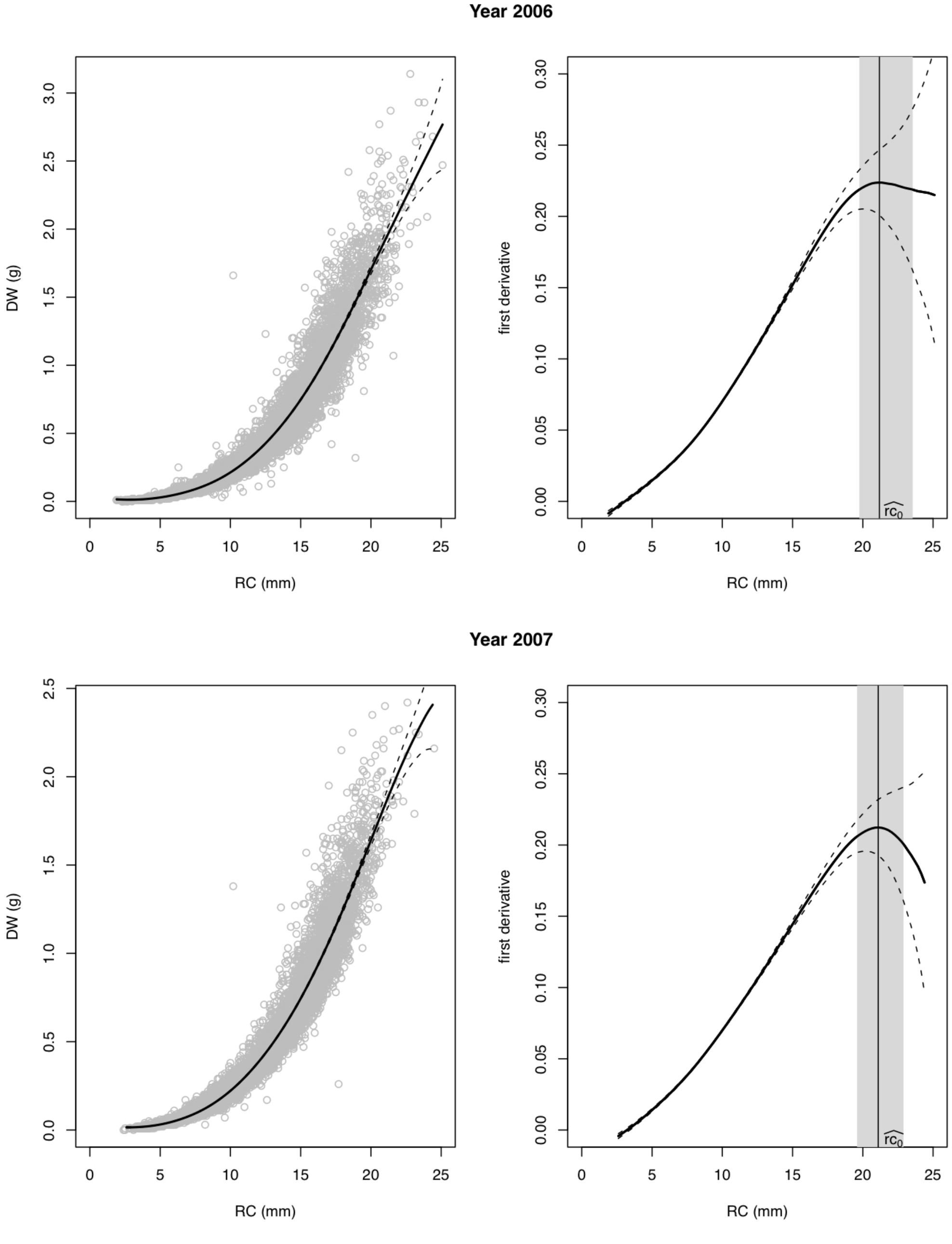

Figure 6: Regression curve and first derivative (solid lines) with bootstrap-based 95% confidence intervals (broken lines) for dry weight and rostro-carinal length. First row: year 2006; second row: year 2007. Solid vertical line: estimated rc_0. Grey area: confidence interval constructed for $\widehat{rc_0}$.

The first derivatives of these curves increased as individuals grew in size, until they peaked at an RC of 21.18 mm in 2006 and 21.10 mm in 2007 (solid vertical lines). By way of a summary, Table 4 shows the values estimated by each of the studies conducted.

Study	$\widehat{rc_0}$	95% IC
Global	21.50	(19.96,23.42)
2006	21.18	(19.75,23.56)
2007	21.10	(19.60,22.89)

Table 4: Size, $\widehat{rc_0}$, which maximazes the first derivative of the regression curves, with 95% confidence interval, for each of the studies conducted.

Insofar as biology was concerned, the size at sexual maturity (L_{50}) estimated by this study corresponded to a rostro-carinal length of 15.7 mm (Figure 7). At a population level, this size suggests the moment at which individuals reach maturity.

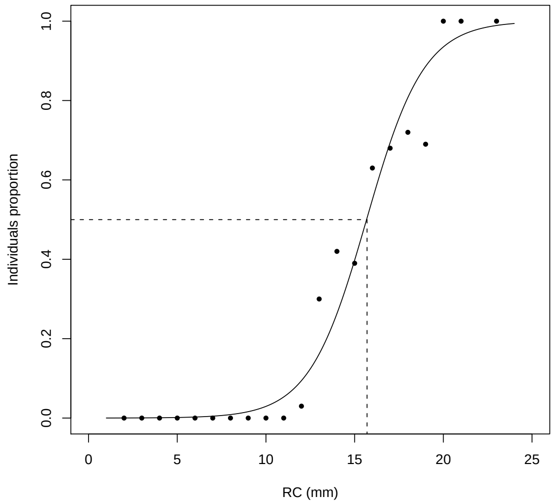

Figure 7: The L_{50} logistic curve for the proportion of mature female barnacles as a function of rostro-carinal length.

Furthermore, the mean effective time required by an individual to hatch eggs in the capitular cavity was estimated to be 43.36 ± 7.002 days. Considering that the time for completing embryonic development is 25 days (Molares et al., 1994a), the number of broods spawned was estimated at 1.73 ± 0.280 broods per annum.

4. Discussion

The length-weight relationship has been used in fishery analyses for several purposes, e.g., to convert one variable to another, to estimate the expected weight for a certain size, or to detect ontogenetic morphological changes linked to maturation of crustaceans and fishes (Pinheiro and Fransozo, 1993). Moreover, the power function, $DW = aRC^b$, fitted to the empirical points of this relationship, is used in studies on relative growth. When investigating allometric growth, researchers almost always choose the linear model for log-transformed data, which is quite simple both conceptually and mathematically, and has parameters that are easy to estimate by linear regression (Katsanevakis et al., 2007). However, it has been shown that use of the classic allometric model when not supported by the data, might lead to characteristic pitfalls, such as misinterpretation of data and loss of valuable biological information (Rabaoui et al., 2007).

Accordingly, this study describes a new approach to estimating this kind of relationship, based on the use of a nonparametric model. Results obtained from the length-weight relationship of *P. pollicipes* indicate that modeling the data nonparametrically would appear to be able to capture the effect of the values lying at either end of the distribution, whereas other more rigid models, such as the allometric model, may distort this length-weight relationship somewhat. In the examples used in this study, a large part of the information would have been lost had we arbitrarily chosen the classic allometric model. We therefore feel that weight gain vis-à-vis increase in size in this species can be more reliably explained by the nonparametric model.

Based on this model, we also sought to propose a method for estimating the size of capture of this crustacean, though we are fully aware of how complicated this might be in this particular species. To start with the initial disadvantage of not being able to ascertain or even approximate the age of individuals (a given size can correspond to very different ages), complicates such an estimation. Consequently we regard this part of the study as more of a recommendation or approximation for this type of research, which could serve to supplement the methodology used.

To estimate the size of capture of this species, this paper proposes the use of three facets, namely, specimens' respective weight gain, size at sexual maturity and number of broods per annum.

In terms of weight gain, in the case of the overall study, individuals were estimated to grow exponentially and thus ensure a high commercial yield until they reached an RC of 21.50 mm. This cut point ensures that any barnacle under this size has not yet attained its maximum yield in weight and, in accordance with FAO guidelines (Sparre and Venema, 1997), should not therefore be captured. From this threshold onwards, individual specimens' accumulated weight will continue to rise with size but the increase in weight from one size to the next will be progressively less, so that the yield obtained ceases to be profitable when seen against the time that the barnacle remains in place without being exploited.

With respect to the study broken down by year, it is surprising to observe that, despite possible annual variability in growth (e.g., barnacles sampled in 2006 attained a greater weight than did those in 2007), thanks to the method used, it could be successfully established that the size at which the maximum yield in weight of *P. pollicipes* was correctly calculated and was practically the same for both years.

Once the above methodology had been applied, different biological aspects of this crustacean, such as size at sexual maturity and number of broods spawned per annum, were studied to ascertain whether the size estimated by the model made sense and would not affect the regeneration of the species.

The estimated size of female sexual maturity is 15.7 mm RC. From this size upwards, all specimens are deemed to be adults and able to reproduce.

In this connection, a number of authors suggest that there is a degree of synchrony between the duration of development of the female gonad and that of eggs in the mantle cavity, which enables *P. pollicipes* to produce several sequential broods during the reproductive season (Cruz and Hawkins, 1998; Cruz, 2000; Molares et al., 1994b; Molares, 1993). This same synchrony has also been observed in other cirripedes (ex: *P. polymerus* (Hilgard, 1960); *Chthamalus* spp. (Burrows et al., 1992)). This claim is based on the pattern of functioning of the female gonad, which is characterized by the degeneration of the ovary after fertilization, followed by recovery (in the initial and middle stages of the reproductive season) in parallel with the development of the embryos in the capitular cavity (Cruz and Hawkins, 1998; Cruz, 2000). Accordingly, assuming that the embryonic development of this species is completed in 25 days (Molares et al., 1994a), we estimated the number of broods spawned per annum at 1.73 ± 0.280.

With regard to this latter aspect, a wide degree of variability has been observed, e.g., in Portugal, Cruz and Araujo (1999) estimated 1 to 4 broods per annum, whereas Cardoso and Yule (1995) indicated that *P. pollicipes* reproduced 1 to 3 times per annum. In Asturias, Pavón (2003) estimated a mean of 2.09 and 2.38 in the lower and middle mesolittoral levels, respectively, while in Galicia, Molares et al. (1994b) suggested that *P. pollicipes* spawned a minimum of twice a year. The differences observed may be due to the influence of various factors, such as temperature, sand bank movement (Cardoso and Yule, 1995), and individual density or size (Cruz and Araujo, 1999).

After the above three factors had been assessed, data on the *in situ* annual growth rate of this crustacean along the coast of Galicia were used to establish the ideal size of capture. The average annual growth rate for adult individuals of *P. pollicipes* (RC>9 mm) was estimated at 4.04 ± 1.294 mm rostro-carinal length (data not shown).

To sum up, based on data drawn from the model, both overall and addressing the biological aspects in particular, the ideal size of capture was estimated to be as from a rostro-carinal length of 21.50 mm upwards. Starting from a size of 15.7 mm (size of female sexual maturity) and taking, not only the growth rate (4.04 mm/annual), but also the number of broods calculated (1.73 per annum) into account, the elapse of two reproductive cycles until capture would likewise be ensured, allowing this species to produce a minimum of three broods until the designated size was reached.

Lastly, the point should perhaps be made that, in view of this crustacean's biology, characterized by its behavior of gregarious clustering with new individuals preferentially settling on the peduncle of adults, it would be advisable for a longer closed season to be set during which this species could not be exploited. Such a period should coincide with the months in which this barnacle's recruitment rate is at its maximum, a situation that occurs along the Galician coastline during November and December (data not shown).

This study provides an optimized methodology adapted to diverse marine resources which, like the species targeted here, display differentiated weight gain patterns across the various stages of their development.

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