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Weight–length relationships of four intertidal mollusc species from the northeastern Atlantic Ocean and their potential for conservation

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ABSTRACT

Weight-length relationships (WLRs) are frequently used for the development of comparative studies of life history, population dynamics, ecosystem modelling and estimation of the production and biomass of populations among regions. WLRs provide information about growth, wellbeing and fitness of a population in a marine environment. WLRs for four topshells (*Phorcus atratus, Phorcus lineatus, Phorcus mariae, Phorcus sauciatus*) caught in North-eastern Atlantic Ocean (Azores, Canaries, Cape Verde, Madeira and Mainland Portugal) were established and their relative growth was assessed. The results showed that almost all species exhibited a positive allometric growth. A comparative study on the effect of harvest in the relative growth of *P. sauciatus* in the archipelago of Madeira showed that all the populations from exploited areas exhibited a negative allometric growth in contrast to the populations from the Marine Protected Areas (MPAs) which were predominantly isometric. The present results indicate that the conservation measures established in the protected areas promoted a positive effect in the protected populations and are valuable for establishing a set of monitoring and management measures aiming at the sustainable exploitation and conservation of these species. These results are important to demonstrate the role of MPAs in the conservation of these keystone species in the north eastern Atlantic Ocean rocky shore ecosystems.

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Relative growth; topshells; MPAs; north-eastern Atlantic Ocean

Introduction

Topshells of the genus *Phorcus* Risso, 1826 inhabit one of the most extreme and dynamic environments in nature, occurring from the supratidal to the subtidal zones in the rocky sea shore ecosystems (Rafaelli and Hawkins 1999; Ramírez et al. 2005) of the north eastern Atlantic Ocean and the Mediterranean Sea (Templado and Rolán 2012). These marine gastropods are ecologically important keystone species, with a major role in the overall structure of rocky shore communities due to their ability to control algae and have been used as biological indicators in the evaluation of anthropogenic impacts on this ecosystem (Donald et al. 2012; Henriques et al. 2017).

Harvesting of keystone species such as topshells negatively affects the exploited populations by altering population structure and decreasing abundance (Sousa et al. 2019) and thus the knowledge of species and ecosystems is important to promote the implementation of management measures. Marine Protected Areas (MPAs), defined as no-take zones, are a popular measure for the conservation of harvested marine populations, since they promote the recovery of populations by removing harvesting pressure (Halpern and Warner 2002).

Weight–length relationships (WLRs) allow the estimation of the average weight at a given length of a species in a given geographic zone (Ferreira et al. 2008). These relationships are often used in the comparison of life history, population dynamics, ecology and estimation of the production and biomass of a population among regions (Anderson and Gutreuter 1983; Erzini 1994; King 1995; Santos et al. 2002). WLRs of a species may vary between habitats and regions so that accurate estimation of local parameters is important for the development of comparative studies, ecosystem modelling and for stock assessment

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management (Vaz-dos-Santos and Gris 2016). Also, the condition factor based on WLR data is widely regarded as a useful tool to quantify an animal's physical well-being (Bagenal and Tesch 1978; Rochet 2000).

The aim of this work was to study the weight–length relationship and condition factor of four species of topshells, namely *Phorcus sauciatus* (Koch, 1845), *Phorcus lineatus* (da Costa, 1778), *Phorcus atratus* (Wood, 1828) and *Phorcus mariae* Templado & Rolán, 2012, harvested in the north eastern Atlantic Ocean (Azores, Canaries, Cape Verde, Madeira and mainland Portugal). In addition, a comparative study was carried out in the archipelago of Madeira, considering the exploitation status of the populations, harvested (exploited areas) or non-harvested (MPAs) in order to verify the effectiveness of the no-take areas in the preservation of populations of *P. sauciatus*.

Material and methods

All specimens were randomly collected throughout the mid-to-lower intertidal zone of the rocky shores of mainland Portugal, and the Azores, Canaries, Cape Verde and Madeira (NE Atlantic Ocean), during low tide, without selecting for size, by the same experienced harvester, between January 2017 and May 2018 (Figure 1).

The locations were as similar as possible to each other and were selected considering the coastal settlements with analogous conditions (e.g., type of substrate, slope of the coast, rugosity). The selection of locations was as rigorous as possible and considered the same degree of wave exposure (sheltered areas) and seasonality in order to minimise local environmental effects on shell growth.

All specimens were measured (total shell length, L) using a Vernier calliper (0.1 mm) and weighed (total weight, W) on a digital balance (0.01 g).

WLRs for four species of Phorcus

The shell weight – length relationship was estimated using the equation $W = aL^b$ (Bagenal and Tesch 1978), where W is the total weight in grams, L the shell length in millimetres, a is the intercept (condition factor) and b is the slope (relative growth rate). The parameters a and b were estimated by linear regression analysis fitted by the least-squares method over log-transformed data ($\log W = \log a + b \log L$) subsequently log–log plots were used to detect and exclude outliers (Froese 2006).

The coefficient of determination r^2 was used to indicate the amount of variation explained by the linear regression (King 1995) and a Student's t-test was used to test the hypothesis of an isometric relationship (H_0: $b = 3$; H_1: $b \neq 3$, at the 5% significance level). A statistically significant difference of the b parameter from 3 implies an allometric growth either negative ($b < 3$; $P < 0.05$) or positive ($b > 3$; $P < 0.05$) and an isometric growth is assigned when b is not significantly different from 3 ($P > 0.05$) (Zar 1996).

All statistical analyses were performed using SPSS v.24.0 (IBM Corp 2016). For all tests, statistical significance was accepted when $P < 0.05$.

Comparative analysis of WLRs among MPAs and exploited areas in the archipelago of Madeira

A comparative study was conducted considering the WLRs of *P. sauciatus* according to the exploitation level, harvested (exploited areas) or non-harvested (MPAs), throughout the intertidal zone of Madeira. For this study four exploited areas along the South (two – Ribeira Brava and Santa Cruz), and North coasts (two – São Jorge and São Vicente) and four MPAs (Desertas, Porto Santo, Rocha do Navio and Selvagens) were sampled (Figure 2).

Results

A total of 13,697 topshells belonging to the species *P. atratus* (16.29 ± 1.27 mm L), *P. lineatus* (15.23 ± 3.00 mm L), *P. mariae* (16.65 ± 2.16 mm L) and *P. sauciatus* (14.78 ± 3.92 mm L) were sampled. *P. sauciatus* presented the smallest mean shell length in Madeira (13.71 ± 4.18 mm L) and the largest in Azores (21.09 ± 3.31 mm L) (Table 1). In terms of body weight, the lightest species was *P. sauciatus* (1.24 ± 1.02 g W) and the heaviest *P. atratus* (2.33 ± 0.57 g W).

WLRs for four species of Phorcus

The WLRs, related statistics and nature of growth for the four topshell species by locality are presented in Table 2. The estimated relative growth rate ranged between 2.830 for *P. sauciatus* in the archipelago of Madeira and 3.720 for the same species in Azores. The relative growth was negatively allometric for *P. sauciatus* collected in the Madeira archipelago ($t_{7339} = 26.108$, $P < 0.05$), isometric for *P. atratus* from the Selvagens ($t_{51} = 0.180$, $P < 0.05$) and positively allometric for the remaining species/localities.

Comparative analysis of WLRs among MPAs and exploited areas in the archipelago of Madeira

In exploited populations mean size (13.27 ± 4.26 mm L) was smaller than in MPAs (18.15 ± 2.83 mm L). The body weight showed the same pattern with lighter specimens present in harvested populations (0.88 ± 1.00 g W) and heavier in protected populations (2.07 ± 1.02 g W). The smallest mean shell length occurred in Ribeira Brava with 11.87 ± 4.51 mm L (exploited

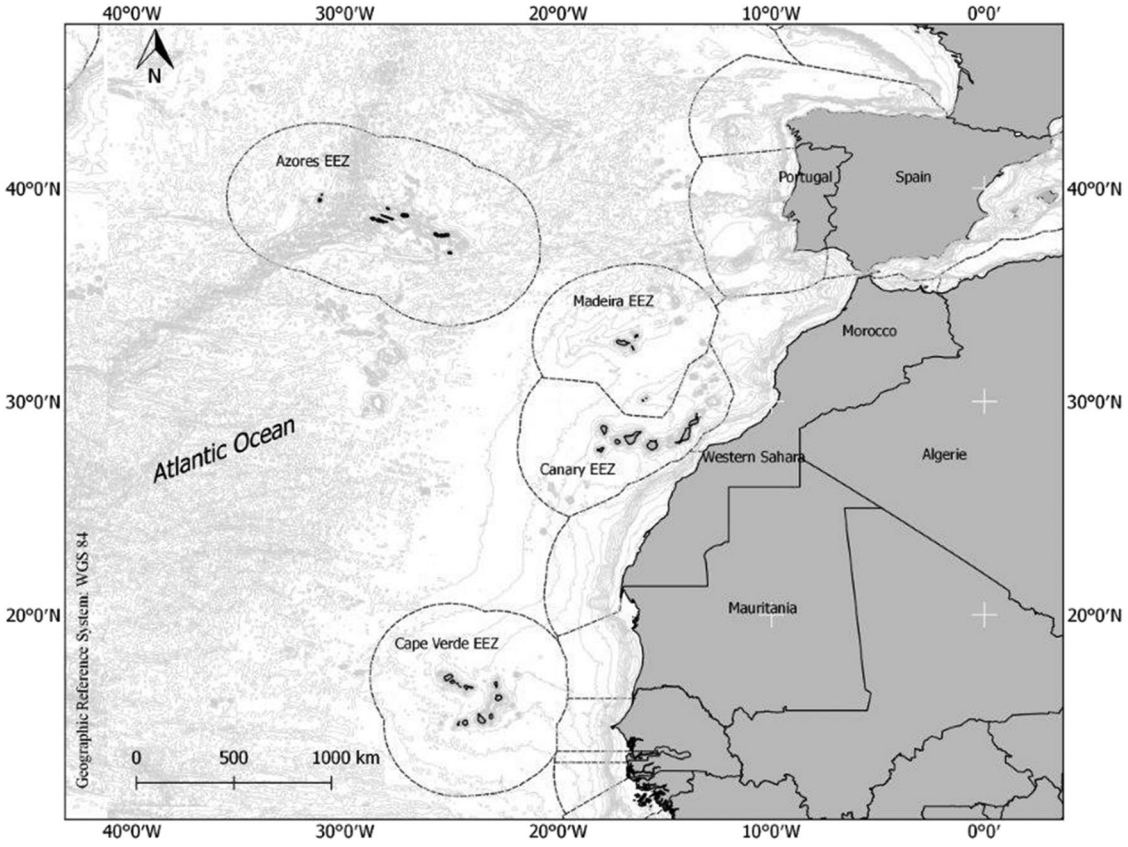

Figure 1. Sampling locations of *Phorcus* spp. populations in the north eastern Atlantic Ocean (mainland Portugal, Azores, Madeira, Canaries and Cape Verde).

area) and the largest in Rocha do Navio with 19.21 ± 3.39 mm L (MPA) (Table 3).

The WLRs, related statistics and nature of growth for *P. sauciatus* specimens by exploitation status in the archipelago of Madeira are presented in Table 4. The estimated relative growth rate ranged between 2.797 (Ribeira Brava) and 2.914 (Santa Cruz) in the exploited populations and from 2.952 (Desertas) to 3.702 (Selvagens) in MPAs.

The relative growth pattern was negatively allometric for all the populations collected in exploited areas, isometric for the populations of Desertas, Rocha do Navio and Porto Santo and positively allometric for the population of Selvagens in MPAs.

Discussion

Topshells of the genus *Phorcus* have been target of intensive research over the past decades because they are useful tools in assessing coastal habitat quality, due to their particular eco-biological features (Creese 1998; Branch and Moreno 1994; Sousa et al. 2018). The most recent phylogenetic study of this genus recognises nine species, five restricted to the northeastern Atlantic Ocean and four to the Mediterranean Sea (Donald et al. 2012).

Herein we present the WLRs for four species of *Phorcus* in the northeastern Atlantic Ocean. The WLRs are considered to provide a practical condition index that could vary temporally according to several factors as food availability, feeding rate and reproduction, however the *b* parameter usually does not vary significantly throughout the year (Bagenal and Tesch 1978). The results indicate a strong pattern of positively allometric growth for *P. lineatus* (mainland Portugal), *P. mariae* (Cape Verde) and *P. sauciatus* (Azores, Canaries and mainland Portugal) which implies a disproportionate increase in total weight in relation to the increase in individual shell length.

The correlation between shell length and total weight of *P. sauciatus* in the Madeira archipelago showed a distinct growth pattern. In this region a negatively allometric growth was obtained, this may result from the high level of harvesting pressure leading to lower population densities and to alterations in population dynamics and size structure (Riera et al. 2016; Sousa et al. 2018). This is corroborated by the study of Sousa et al. (2019) that found a similar pattern of growth, smaller mean size populations and lower proportion of reproductive individuals in this region.

The high coefficient of determination (r^2) obtained in the estimation of WLRs indicates the good predictability of the linear regression for the analysed topshells and suggests that it can be extrapolated to other geographical areas in future harvesting, with consideration of the significant size range.

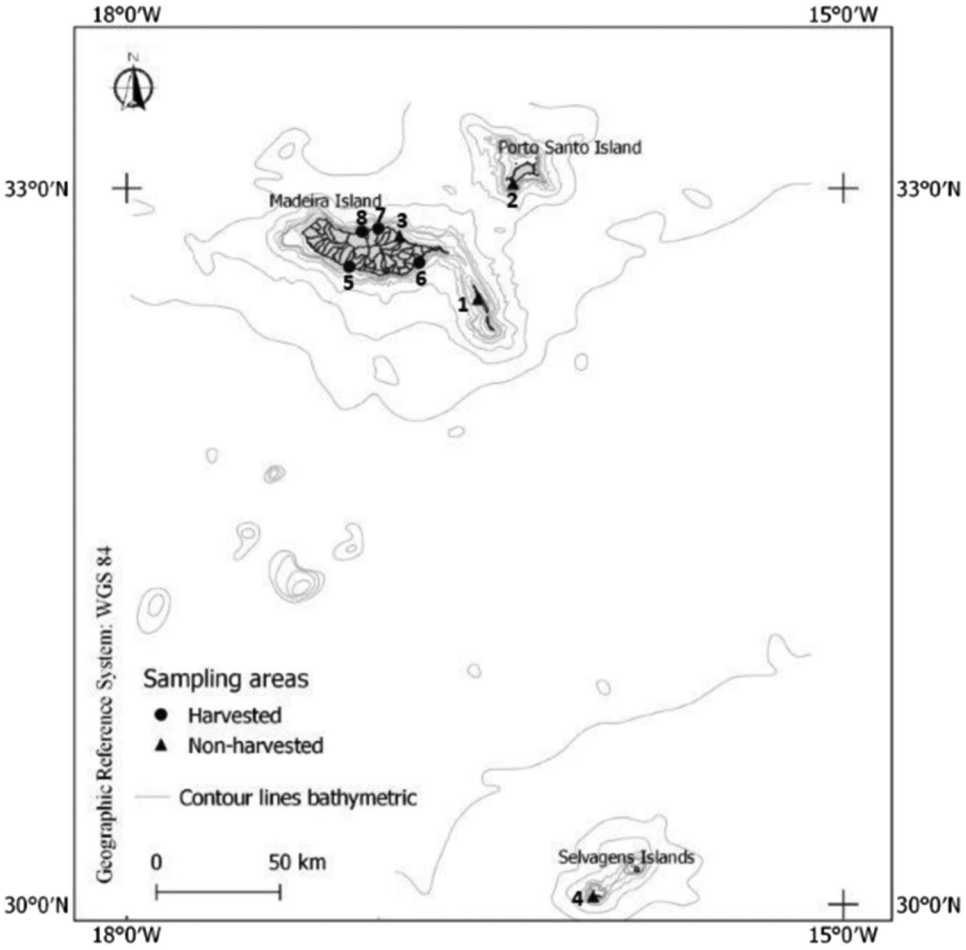

Figure 2. Sampling locations of *Phorcus sauciatus* populations in Madeira archipelago. Non-harvested areas (1 – Desertas, 2 – Porto Santo, 3 – Rocha do Navio, 4 – Selvagens) and harvested areas (5 – Ribeira Brava, 6 – Santa Cruz, 7 – São Jorge, 8 – São Vicente).

Table 1. Descriptive statistics of four topshell species from the northeastern Atlantic (n: sample size; S.D.: standard deviation; Min: minimum; Max: maximum; and CV: coefficient of variation).

			Shell length (mm)				
Species	Locality	*n*	Mean	S.D.	Min	Max	CV (%)
Phorcus atratus	Selvagens	52	16.29	1.27	13.81	19.34	7.81
Phorcus lineatus	Mainland Portugal	2848	15.23	3.00	3.89	27.71	19.70
Phorcus mariae	Cape Verde	126	16.65	2.16	8.87	21.93	12.97
Phorcus sauciatus	Azores	70	21.09	3.31	13.38	17.98	15.69
	Canaries	1322	17.72	2.60	7.73	25.39	14.66
	Madeira	7340	13.71	4.18	2.34	29.25	30.46
	Mainland Portugal	1939	15.87	2.87	4.67	25.24	18.07

Table 2. WLR parameters of four topshell species from the northeastern Atlantic (*n*: sample size, *a* and *b* = parameters of equation $W = aL^b$; S.E.: standard error; CL 95%: confidence limits; r^2: coefficient of determination, type of allometry; *t*: test values and d.f.: degrees of freedom).

			WLR parameters and statistics									
Species	Locality	*n*	*a*	SE(*a*)	95% CL(*a*)	*b*	SE(*b*)	95% CL(*b*)	r^2	allometry	*t*	d.f.
Phorcus atratus	Selvagens	52	0.039	0.171	0.028–0.055	2.974	0.141	2.691–3.258	0.90	Isometry	0.180	51
Phorcus lineatus	Mainland Portugal	2848	0.025	0.017	0.024–0.026	3.264	0.014	3.236–3.292	0.95	Positive	18.504	2847
Phorcus mariae	Cape Verde	126	0.025	0.079	0.021–0.029	3.218	0.065	3.089–3.346	0.95	Positive	3.351	125
Phorcus sauciatus	Azores	70	0.012	0.128	0.009–0.015	3.720	0.097	3.530–3.916	0.96	Positive	7.472	69
	Canaries	1322	0.022	0.027	0.021–0.023	3.257	0.021	3.215–3.298	0.95	Positive	12.018	1321
	Madeira	7340	0.036	0.007	0.035–0.036	2.830	0.007	2.817–2.842	0.96	Negative	26.108	7339
	Mainland Portugal	1939	0.029	0.024	0.027–0.030	3.060	0.020	3.022–3.099	0.93	Positive	3.052	1938

Table 3. Descriptive statistics of *Phorcus sauciatus* from MPAs and exploited areas in the archipelago of Madeira (*n*: sample size; S.D.: standard deviation; Min: minimum; Max: maximum; and CV: coefficient of variation).

			Shell length (mm)				
Exploitation status	Locality	*n*	Mean	S.D.	Min	Max	CV (%)
MPAs	Desertas	226	17.11	3.07	8.36	23.39	17.95
	Porto Santo	129	16.24	2.41	10.24	22.41	14.81
	Rocha do Navio	306	19.21	3.39	7.35	25.79	17.65
	Selvagens	270	18.74	2.39	9.60	24.73	12.77
Exploited	Ribeira Brava	1987	11.87	4.51	2.34	23.00	38.01
	Santa Cruz	835	13.50	3.99	3.89	29.25	29.61
	São Jorge	270	12.52	2.78	6.68	21.64	22.21
	São Vicente	3317	14.12	3.50	2.97	26.78	24.79

Table 4. WLR parameters of *Phorcus sauciatus* from MPAs and exploited areas in the archipelago of Madeira (*n*: sample size, *a* and *b* = parameters of equation $W = aL^b$; S.E.: standard error; CL 95%: confidence limits; r^2: coefficient of determination, type of allometry; *t*: test values and d.f.: degrees of freedom).

			WLR parameters and statistics									
Exploitation status	Locality	*n*	*a*	SE(*a*)	95% CL(*a*)	*b*	SE(*b*)	95% CL(*b*)	r^2	allometry	*t*	d.f.
MPAs	Desertas	226	0.033	0.047	0.030–0.037	2.952	0.038	2.876–3.027	0.96	Isometry	1.272	225
	Porto Santo	129	0.024	0.082	0.021–0.029	3.174	0.068	3.039–3.308	0.95	Isometry	2.553	128
	Rocha do Navio	306	0.026	0.033	0.024–0.028	3.077	0.026	3.026–3.129	0.98	Isometry	1.951	305
	Selvagens	270	0.013	0.074	0.011–0.014	3.702	0.058	3.588–3.816	0.94	Positive	12.134	269
Exploited	Ribeira Brava	1987	0.037	0.012	0.036–0.038	2.797	0.011	2.775–2.819	0.97	Negative	17.823	1986
	Santa Cruz	835	0.032	0.029	0.030–0.034	2.914	0.026	2.865–2.965	0.94	Negative	3.327	834
	São Jorge	270	0.034	0.046	0.031–0.037	2.894	0.042	2.811–2.977	0.95	Negative	1.969	269
	São Vicente	3317	0.013	0.037	0.036–0.038	2.801	0.011	2.779–2.823	0.95	Negative	17.982	3316

The value of the *b* parameter obtained for the four studied species analysed is within the range of values usually obtained which lies between 2.5 and 3.5 (Bagenal and Tesch 1978; Froese 2006), indicating normal growth dimensions and/or the well-being of the studied population (Carlander 1969; Bagenal and Tesch 1978; King 1995). The results for *P. sauciatus* in the Azores archipelago need to be taken with caution since the *b* value obtained ($b > 3.5$) may be due to samples with narrow size ranges (Carlander 1977).

Topshell harvesting is a traditional activity in the Madeira archipelago, dating back to the early years of colonisation (Silva and Menezes 1921). *P. sauciatus* seems to be moderately exploited in this region, but harvesting is unregulated except for MPAs where harvesting is interdicted and as such, management measures are urgently needed to promote a sustainable exploitation at medium and long-term (Sousa et al. 2018).

The effects of protection from MPAs on the populations of *P. sauciatus* were not only restricted to an increase in mean size but also resulted in a more balanced growth. Isometric (Desertas, Rocha do Navio and Porto Santo) and positively allometric growth (Selvagens) indicates an improvement of the ecosystem and population health for this topshell in the MPAs. Porto Santo, Rocha do Navio and Desertas were more balanced areas with an increase in length and weight at approximately the same rate. In contrast, the exploited areas had populations with negatively allometric growth indicating differential growth between length and weight. In this case, there is a higher investment in individual shell growth in relation to the increase in total weight.

The results highlight the importance of MPAs in the preservation of *P. sauciatus* populations in Madeira archipelago, as well as the need for implementation of management measures aiming at the sustainable exploitation and conservation of these species in the medium and long-term.

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