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Research Article

Length-weight relationships of top predator fish caught by the sport fishing fleet off Cabo San Lucas, Baja California Sur, Mexico

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ABSTRACT. Length-weight relationships (LWRs) were estimated for Pacific blue marlin (*Makaira nigricans*), striped marlin (*Kajikia audax*), sailfish (*Istiophorus platypterus*), dolphinfish (*Coryphaena hippurus*) and yellowfin tuna (*Thunnus albacares*). These five fish species are key top predators of the pelagic ecosystem and are economically important resources in the sport fishing of Baja California Sur, Mexico. Overall, 53,359 length and weight records were analyzed for the period 1990-2015. LWRs were significant ($P < 0.05$), with b-values ranging from 2.52 to 3.13.

Keywords: length-weight relationship, top predator, isometric and allometric growth, sport fishing, Baja California Sur.

INTRODUCTION

Sport fishing is one of the main tourist attractions in Baja California Sur, Mexico. The economic income derived from this activity produces a multiplying effect in three sectors: tourism, fisheries and industry (Ditton *et al*., 1996; Klett-Traulsen *et al*., 1996; Gómez-Cabrera & Ivanova-Boncheva, 2013). This region, particularly Cabo San Lucas, has been referred to as one of the best sport fishing destinations worldwide, where the striped marlin (*Kajikia audax*) accounts for approximately 80% of the total billfish catch, with an annual mean catch rate of 0.6 fish per trip (Ortega-García *et al*., 2003). Considering all species subject to exploitation by the sport fishing fleet in this region, striped marlin represents 21.7%, Pacific blue marlin (*Makaira nigricans*) 3.4%, sailfish (*Istiophorus platypterus*) 2.6%, dolphinfish (*Coryphaena hippurus*) 46.4% and yellowfin tuna (*Thunnus albacares*) 19% (Klett-Traulsen *et al*., 1996). In Mexico, the catch of these species, with the exception of tuna, is exclusive to the sport fishing within a range of 50 nautical miles from the coastline (DOF, 2012).

Fish size, both in length and weight, provides quantitative information on fish stocks that are cornerstones for fishery research and stock assessment (Hilborn & Walters, 1992; Anderson & Neumann, 1996). Length-weight relationships (LWRs) provide information on the well-being and the somatic growth of fishes by assessing the condition factor and the allometric index, respectively (Froese, 2006).

All species mentioned above are top predators in pelagic food webs and, therefore, of potential ecological significance as keystone predators in the ecosystem context (Kitchell *et al*., 2006; Sala, 2006). In the modern understanding of aquatic ecosystems, shaped by concepts such as energy flow, food webs and trophic levels (Kemp & Boynton, 2004), LWRs may be useful to evaluate the extent to which body size explains variations among individuals in addition to foraging strategies, which contribute to our theoretical understanding of the implications of size-structured interactions for fish community dynamics (Costa, 2009; Juanes, 2016).

Also, there is a need to increase the biological information available at a regional level for these species based on a new understanding of the spatial dynamics and population structure, as well as the uncertainty about the population structure of these species in the Pacific Ocean (Diaz-Jaimes *et al*., 2006; Tripp-Valdez *et al*., 2010; Purcell & Edmands, 2011; Chang & Maunder, 2012; Schaefer *et al*., 2014; Lu *et al*., 2015; Su *et al*., 2015). This study provides the length-weight relationship (LWR) for striped marlin,

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Pacific blue marlin, sailfish, dolphinfish, and yellowfin tuna for a northern area of the Eastern Pacific Ocean (EPO). This contributes to a better spatial representation of the demographic characteristics of top predators inhabiting the Pacific basin, where the environmental spatial heterogeneity is recognized, particularly in the EPO (Fiedler & Talley, 2006; Pennington *et al*., 2006), potentially affecting process rates (*e.g.*, latitudinal variation in somatic growth rate) and, ultimately, population dynamics.

MATERIALS AND METHODS

Data were obtained from monitoring surveys conducted from 1990 to 2015 at Cabo San Lucas, Baja California Sur, by two research institutions (Centro Regional de Investigación Pesquera and Centro Interdisciplinario de Ciencias Marinas). Surveys were performed consistently over three consecutive days of each month for recording biological information. Total weight (W), length (L) and sex were recorded for each specimen sampled. The eye-fork length was measured for striped marlin, Pacific blue marlin and sailfish, and fork-length for dolphinfish and yellowfin tuna. Sex was determined based on the macroscopic observation of gonads. Since yellowfin tuna does not present external sexual dimorphism and it was not possible to dissect them because they lose their commercial value, specimens were not sexed. Total weight was measured to the nearest 0.01 kg; length, to the nearest 0.1 cm.

The length-weight relationship $W = a\ L^b$ was fit to the size attributes of fish, where W is weight (g) and L is length (cm). Parameters a and b were estimated by a nonlinear least-square regression method (Gauss-Newton algorithm). Confidence intervals for the model parameters are calculated by the confint.nls function from the MASS package as described in Venables & Ripley (2002). The degree of association between W and L was evaluated by the coefficient of determination (R^2).

To assess whether b-values were significantly different from the null hypothesis for isometric growth (H_0: $b = 3$), as well as to evaluate whether differences in b-values were statistically significant between sexes, a Student t-test was performed, using the statistic $t_s = (b-3)/S_b$, where S_b is the standard error of the slope. For these analysis, LWR was log-transformed (Sangun *et al*., 2007; Zar, 2010). All analyses were performed considering a significance level of 0.05 (α = 0.05), using the R statistical programming language (R Core Team, 2016).

RESULTS

Parameters a and b for LWRs assessed for each species analyzed in this study are shown in Table 1. All LWRs were significant ($P < 0.05$), with b-values ranging from 2.52 (sailfish males) to 3.13 (dolphinfish, pooled sexes).

For striped marlin and sailfish, females were larger than males in terms of length [($F_{(1,6331)} = 29.66$, $P < 0.05$); ($F_{(1,647)} = 36.95$, $P < 0.05$)] and weight [($F_{(1,6331)} = 58.79$, $P < 0.05$); ($F_{(1,647)} = 56.58$, $P < 0.05$)]. The opposite was found for dolphinfish, *i.e.*, males were larger than females in length ($F_{(1,30057)} = 2463$, $P < 0.05$) and weight ($F_{(1,30057)} = 3716$, $P < 0.05$). Males of Pacific blue marlin were not caught during the study period.

For sailfish, no significant differences in b-values were found between sexes ($P > 0.05$); consequently, data for both sexes were pooled for calculating LWR (Table 1). For striped marlin and dolphinfish, although significant differences were observed in b-values between sexes ($P < 0.05$), pooled values are reported, as they can be used when no information on sex is available.

Growth in yellowfin tuna (pooled sexes), pacific blue marlin (females), striped marlin (males and females) and dolphinfish (males) does not deviate from an isometric growth, as b-values were not significantly different from 3 ($P > 0.05$). Growth in sailfish (males and females) and dolphinfish (females) was negative allometric ($b < 3$).

DISCUSSION

The b-values estimated for the fish species studied here were within the expected range typical of most fish (b = 2.5-3.5) (Froese, 2006). The b-values estimated in this study for striped marlin (males and females), Pacific blue marlin (females), dolphinfish (males), and yellowfin tuna (pooled sexes) were not significantly different from 3. Thus, the weight increase in relation to length was isometric for these species.

The relationships estimated for males and females of striped marlin showed significant differences, but not for sailfish. These billfish species, as well as all others included in the family Istiophoridae, are dioecious (separate sexes) and none of them are known to display sexual dimorphism or dichromatism, but females of many species reach a larger size than males (Nakamura, 1985). Sex-specific differences in size-at-age are reported by many scientists (*e.g.*, Kopf *et al*., 2011 for striped marlin; Ramírez-Pérez *et al*., 2011 for sailfish; Shimose *et al*., 2015 for blue marlin), and

Table 1. Length-weight relationships (LWRs) of five fish species caught by the sport fishing fleet off Cabo San Lucas, Baja California Sur, Mexico. n: number of specimens, L: length, W: weight, *a*: intercept of LWR, *b*: slope of LWR, R^2: coefficient of determination, CI: confidence intervals.

Species	Sex	n	L range (cm)	W range (kg)	*a*	95% CI of *a*	*b*	95% CI of *b*	R^2
Kajikia audax	Male	3214	122 - 204*	16.06 - 81	1.96×10^{-5}	1.64×10^{-5} - 2.34×10^{-5}	2.860	2.826 - 2.894	0.91
	Female	3118	114 - 209*	14.00 - 90	114×10^{-5}	9.48×10^{-6} - 1.38×10^{-5}	2.967	2.930 - 3.004	0.90
	Pooled	6332	114 - 209*	14.00 - 90	137×10^{-5}	1.20×10^{-5} - 1.56×10^{-5}	2.930	2.905 - 2.956	0.91
Makaira nigricans	Female	2039	148 - 326*	34.00 - 454	218×10^{-5}	1.72×10^{-5} - 2.76×10^{-5}	2.896	2.852 - 2.940	0.92
Istiophorus platypterus	Male	253	133 - 196*	16.00 - 42	103×10^{-4}	6.29×10^{-5} - 1.69×10^{-4}	2.520	2.357 - 2.651	0.91
	Female	397	124 - 195*	14.00 - 44	601×10^{-5}	4.04×10^{-5} - 8.94×10^{-5}	2.563	2.486 - 2.640	0.93
	Pooled	650	124 - 196*	14.00 - 44	654×10^{-5}	4.82×10^{-5} - 8.88×10^{-5}	2.540	2.486 - 2.605	0.93
Coryphaena hippurus	Male	14319	37 - 149#	0.72 - 2	606×10^{-6}	5.73×10^{-6} - 6.42×10^{-6}	3.075	3.063 - 3.087	0.97
	Female	15739	33 - 137#	0.47 - 21	132×10^{-5}	1.22×10^{-5} - 1.38×10^{-5}	2.886	2.870 - 2.897	0.96
	Pooled	30058	33 - 149#	0.47 - 32	455×10^{-6}	4.37×10^{-6} - 4.74×10^{-6}	3.130	3.121 - 3.139	0.96
Thunnus albacares	Pooled	14280	34 - 185#	0.56 - 113	228×10^{-5}	2.22×10^{-5} - 2.34×10^{-5}	2.944	2.939 - 2.950	0.98

*Eye-fork length, #Fork length

are also reflected in the weight-length relationship. Thus, females not only grow to attain a greater length than males, but are proportionally heavier at the same length (Skillman & Yong, 1974). In FishBase (Froese & Pauly, 2016), LWR parameters *a* and *b* are shown for unsexed (pooled sexes) Pacific blue marlin. This is the first time these parameters are reported for females separately.

Sexual dimorphism is recognized in dolphinfish, with a difference in head shape between sexes (Collette, 1995), and with males attaining larger size-at-age than females (Solano-Fernández *et al*., 2015). For yellowfin tuna, there are not reports on sexual dimorphism in morphology (Collette & Nauen, 1983) or growth (Lehodey & Leroy, 1999).

The LWR parameters *a* and *b* assessed may be considered as representative for these species in the study area, since the data were collected over a period of 26 years. Accordingly, these parameters likely reflect the well-being and somatic growth of the fish species in this period, which are potentially affected by the inter-annual environmental variability of the water masses interacting in the area (Fiedler, 2002; Bograd & Lynn, 2003). In FishBase (Froese & Pauly, 2016), LWR parameters were documented from references that derived the estimations from data gathered over particular years and are available for all species analyzed in this study; however, there are no records for the Pacific blue marlin and yellowfin tuna from waters off Baja California Sur.

The new information provided here may help to elucidate if fish from this region may exhibit differences compared to other regions inhabited by these species across the Pacific basin, hence improving the understanding of a putative population structure for any of these species and their underlying spatial dynamics (Begg, 2005). There is uncertainty about the population structure of the striped marlin in the Pacific Ocean (Purcell & Edmands, 2011; Su *et al*., 2015), as well as of the sailfish in the North Pacific Ocean (Lu *et al*., 2015), and for the dolphinfish in the EPO (Diaz-Jaimes *et al*., 2006; Tripp-Valdez *et al*., 2010; Chang & Maunder, 2012). With regard to **y**ellowfin tuna, recent catch-and-release studies have indicated restricted movements, low dispersion levels, and fidelity of this species in waters surrounding our study area (Schaefer *et al*., 2014). Concerning the Pacific blue marlin, our results only for females are in agreement with previous reports about a segregation by sex for this region (Ortega-Garcia *et al*., 2006), which has been explained by sexual differences in the migration pattern related to spawning and feeding (Shimose *et al*., 2012). Differences in biological traits among groups of fish have long been used as a basis for the identification of fish stocks because of the relative ease of assessing these parameters and their dual functionality as input into fisheries stock assessment and management strategies (Begg, 2005). Thus, although information on the well-being and somatic growth of the fish species studied in waters off Baja California Sur is provided herein, the identification of each species' population structure is an interdis-ciplinary task that involves the use of various methods offering supplementary perspectives on population structure (Cadrin *et al*., 2005).

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