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An application to the American lobster (Homarus americanus) fishery of Long Island Sound

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RESEARCH PAPER

Estimating weight–length relationships without individual weight data: an application to the American lobster (*Homarus americanus*) fishery of Long Island Sound

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Abstract The estimation of weight–length relationship of fish species requires having data on individual weight and length. However, individual weight data are often not available because they are too expensive or not feasible to gather and the relationship cannot be explicitly estimated. Yet, in this paper I develop a simple methodology that allows me to estimate a weight–length relationship when only aggregate weight data are available. To show its usefulness, the methodology is applied to the American lobster (*Homarus americanus*) population of Long Island Sound. Results indicate the existence of isometric growth for American lobsters in this geographical location: $W = 0.000924L^{2.9619}$. The estimated relationship is used to predict individual weight of lobsters which are then used to construct biomass indexes for three size classes of lobsters for the time period 1987–2006. This analysis suggests that is not necessary to invest efforts in collecting individual weight data to be able to construct meaningful indicators of fish population.

Keywords Fish growth · Weight–length relationship · Biomass index · American lobster

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Introduction

The knowledge of the weight–length relationship (WLR) for fish species is important for a variety of reasons. For instance, it allows to convert growth in length equations to growth in weight, calculate biomass of a population, or to compare the morphology between species or the same species across different geographical regions (see the introduction of Santos et al. 2002).

WLR's are also useful to estimate indexes of stock biomass such as weight per given area, as opposed to abundance indexes, expressing density per given area. Such indexes can be constructed for different size classes (or size cohorts) that can be used to investigate the dynamics of a size-structured population.

The estimation of a WLR requires having data on the individual weight and length of the fish species that is investigated. However, individual weight data are often not available because not collected. Surveys are usually very expensive and the cost depends on the quality and detail of the data that are collected. Also, measuring individual weight accurately is more challenging and time consuming than measuring length and so it commonly leads to higher measurement errors (Anderson and Neumann 1996, pp. 452–453). Thus, it is often more convenient to measure weight in aggregate.

In this paper I develop a methodology that allows me to estimate a weight–length relationship with a certain degree of confidence without having individual weight data. In fact, a WLR can be estimated having weight only collected at the aggregate level. With this, the weight of individuals can be predicted and used to calculate biomass indexes for different size classes or other meaningful indicators of the biomass of a fish population.

Methodology

In general, a weight–length relationship is expressed by the formula

$$W = a\,L^b \qquad (1)$$

where W and L are respectively the weight and length of the individual of a fish species, a is defined as the condition factor, and b is the allometric factor which defines the shape of the curvature of the relationship (Quinn and Deriso 1999, pp. 129–131). When $b = 3$ the WLR indicates that the relative growth of both variables is identical, i.e. isometric growth, while $b < 3$ and $b > 3$ reflect negative and positive allometry, respectively (Anderson and Neumann 1996, p. 454).

This relationship is generally estimated using individual data on weight and length of the species. When individual weight data are not available the problem can be overcome by taking parameters of a WLR, for the same species, that are found in the literature and using them with the available individual length data to obtain a prediction for the individual weight. However, this approach could be misleading because such parameters would be specific to the area where data were collected. The habitat for the species under study is likely to present different characteristics, such as environmental conditions (e.g., temperature). Therefore the "true" weight–length relationship may be rather different and therefore it should be re-estimated (Froese 2006).

Yet, an alternative and simple procedure is available. Let the equation

$$W_j = a\,L_j^b \qquad (2)$$

be the WLR for the j-th individual of a (fish) species such that W_j indicates the unobserved individual weight, with $j = 1, \ldots, J$. Since the parameters a and b are constant across individuals of the same population (e.g., French McCay et al. 2003), it can be noticed that by summing both sides over all individuals yields the following relationship:

$$W = a \sum_{j=1}^{J} L_j^b \qquad (3)$$

where $W = \sum_{j=1}^{J} W$ is the aggregate weight. This indicates that when individual weight data are unavailable a WLR can still be estimated using only aggregate weight and individual length data.

The next section shows how Eq. 3 is empirically estimated using data on the American lobster population of Long Island Sound.

An application: the american lobster fishery of long island sound (CT/NY)

The American lobster (*Homarus americanus*) is distributed along the entire northwestern Atlantic ocean and adjacent inshore waters from Maine through North Carolina and it is managed by Atlantic States Marine Fisheries Commission (ASMFC). The American lobster fishery is a valuable and traditional industry for Long Island Sound (LIS). Lobsters were first harvested in the early 1800's, but only in the two last decades has expanded across the length of the inshore area (Dyer and Allee 2002).

Estimates for the American lobster weight–length relationship can be found in the scientific literature (e.g., French McCay et al. 2003; Steinback et al. 2008). French McCay et al. use data from individual weight and carapace length of lobsters collected by research trawls in Rhode Island estimating the weight–length relationship to be $W = 0.001143L^{2.934}$ for the whole lobster population. Steinback et al. use instead individual weight and carapace length data for different cohorts and sex. They report the parameter a equal to 0.000149 for males and 0.000834 for females, and the parameter b equal to 3.347 for males and 2.972 for females.

Furthermore, in the 2006 ASMFC Stock Assessment Report it is assumed a WLR to be $W = 0.001167\,L^{2.919}$ for all the management areas: southern New England, Gulf of Maine, Georges Bank (ASMFC 2006). However, this is a very large and heterogeneous area and the LIS lobster population may well present different characteristics from the other populations along the rest of the northeastern coast. Furthermore, it has been shown that most lobsters remain resident in the Sound and do not travel extensive distances Howell et al. (2005). Thus, American lobster population of LIS can be considered as a separate population.

Data

Since 1984, the Connecticut Department of Environmental Protection (CTDEP) gathers information on the abundance and distribution of finfish and invertebrates via a stratified random trawl survey (Long Island Sound Trawl Survey, or LISTS) with the goal to calculate indexes of abundance for forty common species in the Sound.

The survey is conducted twice a year, Spring (April–June) and Fall (September–October), by randomly sampling across twelve strata defined by substrate type and depth interval. The data are collected for each sample (or tow)[1] and include the aggregate number and weight of individuals as well as the carapace length at 0.1 mm interval of each individual lobster, along with sex and other biological and environmental information. Details of the survey designs can be found in a study by CTDEP (2006, pp. 69–71).

The dataset provided by CTDEP reports measurements taken in the time period 1987–2006 for each sampled site; data for 2046 sites are available. Notice that aggregate weight started being collected only from 1992. The average aggregate weight for period 1992–2006 was 32.59 kg tow^{-1}, while the average individual carapace length was 64.7 mm. Figure 1 shows the distribution of individual length in the available dataset.

It is interesting to see how the aggregate weight predicted using the results by French McCay et al. (2003) relates to the aggregate weight reported in the LISTS dataset. Predicted individual weight is obtained by plugging the individual lengths from the LISTS data in the WLR they estimated. Then, aggregating the individual weight and comparing this to the aggregate weight reported in LISTS dataset it can be noticed that the aggregate predicted weight and the weight collected by LISTS are very highly correlated. Specifically, pooling the data for all the strata I found a correlation of 0.981, while the weighted (by the number of observations) average using data for each stratum I find a correlation of 0.986. This indicates that aggregate weight is related to individual length, hence this gives a reassuring indication that Eq. 3 can be used to estimate the weight–length relationship for Long Island Sound.

[1] A sample consists of a site surveyed (trawled) on a specific date.

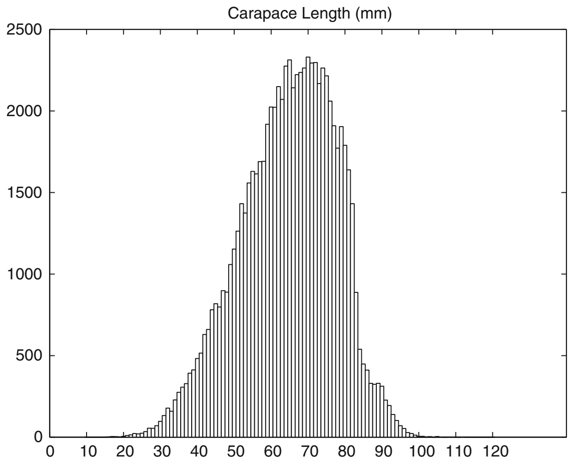

Fig. 1 Sample distribution for carapace length

Estimation and results

Using LISTS data on aggregate weight and individual length of lobsters at each sample the following relationship is estimated:

$$W_s = a \sum_{j=1}^{J} L_{j,s}^{b} + u_s. \tag{4}$$

The variable W_s indicates the total biomass collected in sample s, while $L_{j,s}$ is carapace length of lobster j measured at the same sample; u_s is an additive error assumed to be distributed with zero mean and variance σ_u^2.

Equation 4 is estimated using nonlinear least squares pooling the data for all strata together. Given the data, the sum of squares of the error terms is minimized with respect to the parameters a and b, where the error terms are $u_s = W_s - a \sum_{j=1}^{J} L_{j,s}^{b}$. Since the specification is nonlinear, the minimization process involves using numerical optimization. This is done by employing the routine *lsqnonlin* with the Gauss–Newton algorithm in Matlab. Notice that since the parameters are assumed to be constant across

Table 1 Estimation results of the WLR for American lobster population of LIS

	Coeff	T-stat	CI 95%
a	0.000924	7.5383	[0.000683; 0.001164]
b	2.9619	94.786	[2.9006; 3.0231]
R^2	0.988		
N. obs	2046		
H_0: $\widehat{b} = 3$,	H_1: $\widehat{b} \neq 3$;	t-stat $= -1.219$,	$\alpha_{10\%} = -1.697$

strata, the same relationship applies to lobsters for all sites across the whole Sound.

The model fits the data well and both coefficients are significant at 1% level. Estimates (Table 1) appear to be similar to those found in the literature (French McCay et al. 2003; Steinback et al. 2008). However, unlike others, this methodology does not use individual weight data. The point estimate for the allometric factor is $\widehat{b} = 2.962$, suggesting negative allometric growth. This seems to be compatible with what reported in the 2006 ASMFC Stock Assessment report (ASMFC 2006, p. 277). However, the coefficient is statistically not different from 3 (bottom of Table 1).[2] This indicates that there is strong statistical evidence that the WLR reflects isometric growth, meaning that for the American lobster population of Long Island Sound the relative growth of weight and length is perfectly identical.[3] The same result is also found for the American lobster population of Rhode Island (French McCay et al. 2003). Figure 2 shows the estimated weight–length relationship for LIS population.

Derivation of the biomass index

This procedure is useful to disentangle the individual weight of the lobsters collected with LIS trawling survey. Having individual weight data allows me to calculate biomass indexes for different size classes for the lobster population. Being able to observe different stages is important for the management of a natural resource that exhibits differences in the phases of their development. This is especially significant when the effects of adverse events on stages that are not usually observed can be experienced for several years, with implications on the abundance of commercially exploited species.[4]

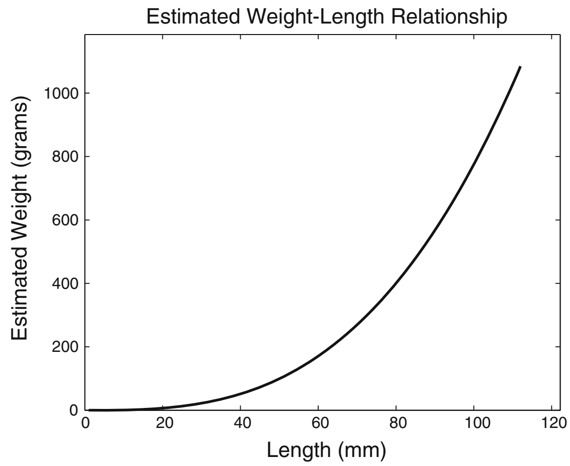

Fig. 2 Predicted weight–length relationship

It is assumed that lobster population is composed of three main classes: pre-recruit, recruit, and legal (Giannini and Howell 2007, p. 6). These three classes are defined such that, after one year, individuals of one class enter the next class and eventually become legal size lobsters.[5] The smallest class is composed by the *pre-recruits*, young lobsters that will become sexually mature in one year. Then, lobsters that are sexually mature, although smaller than the minimum legal size, are defined as *recruits* which constitute the second class. Lastly, lobsters above minimum legal size are defined as *legals* because they can be legally landed.

As reported in the 2006 ASMFC Stock Assessment Report (ASMFC 2006, age 313), the average annual molt increment for lobsters in LIS is about 11 mm. Therefore, I assume that each size class is composed of lobsters of measurements within a range of 11 mm, where the range of each class varies

[2] A two-side t-test fails to reject the hypothesis that $\widehat{b}$ is statistically different from 3.

[3] As remarked in Santos et al. (2002), weight–length relationships are not constant over time. Hence, when the data span over long period of time like in this application, estimates should be regarded as mean annual values.

[4] For example, the decline of landings of American lobsters in Rhode Island was preceded by a reduction in the abundance of pre-recruit lobsters, a smaller size class (Wale et al. 2009). This effect would be missed by observing only one growth stage or the aggregate population.

[5] According to ASMFC (2006, p. 33) “recruits are lobsters that are not legal size at the time of the survey but are expected to molt and grow to legal size during the next year.”

Table 2 Changes in minimum size restrictions (source: Howell et al. (2005), Giannini and Howell (2007))

Class	Year	Size
Pre-recruit	1984–1988	Less than 71 mm
	1989	Less than 72 mm
	1990-	Less than 73 mm
Legal	1984–1988	Greater than 80.9 mm
	1989	Greater than 81.7 mm
	1990–2003	Greater than 82.5 mm
	2004–Aug 2005	Greater than 82.6 mm
	Sep 2005–Jun 2006	Greater than 83.3 mm
	Jul 2006-	Greater than 84.1 mm

according to the changing of the minimum size policy. The minimum size restrictions for LIS lobster fishery are presented in Table 2.[6]

Biomass indexes for the three classes are obtained as follows. The estimated relationship 4 is used to predict individual weight for lobsters sampled in Long Island Sound. Then, individual weight is aggregated by size class where each class is defined according to the definition of the minimum length policy. Finally, the index is calculated as the geometric mean for the weight of lobsters caught in each survey tow.[7]

These indexes provide seasonal measures of the density of lobster stock expressed in biomass, i.e. kilograms per tow. They reflect the estimated average lobster biomass for Long Island Sound, by class size, for the time period 1987–2006 for both fall and spring season (Table 3).

For each class size, after an initial decline the predicted Fall index (Fig. 3) shows an increasing trend until the peak of 1997. After that, average biomass (almost) steadily declined until reaching a minimum in 2006. The index for Spring (Fig. 4) presents a slightly different dynamics, alternating direction until reaching a maximum in 1998. Subsequently, as for the Fall index, average biomass declined the minimum of 2006.[8]

Table 3 Estimated biomass index for each size class: legal, recruit, pre-recruit (kg/tow)

Year	Legal		Recruit		Pre-recruit	
	Fall	Spring	Fall	Spring	Fall	Spring
1987	0.688	0.495	1.141	0.559	0.777	0.456
1988	0.502	0.362	0.728	0.395	0.525	0.273
1989	0.422	0.518	0.757	0.774	0.630	0.485
1990	0.777	0.526	1.159	1.024	1.001	0.837
1991	0.543	0.889	1.419	1.343	1.513	0.991
1992	0.839	0.499	1.381	1.327	1.489	1.150
1993	0.577	0.260	1.594	0.928	1.513	0.941
1994	0.866	0.197	1.467	0.697	1.534	0.631
1995	0.699	0.729	1.350	1.589	1.355	1.161
1996	0.668	0.560	1.488	1.150	1.482	1.024
1997	1.500	0.735	3.160	1.458	2.797	1.278
1998	0.695	1.113	1.920	2.792	1.695	2.285
1999	0.601	0.892	2.086	2.579	1.624	1.843
2000	0.438	0.660	1.335	1.730	1.156	1.389
2001	0.224	0.661	1.148	1.490	0.827	1.272
2002	0.078	0.622	0.544	1.203	0.487	0.947
2003	0.083	0.205	0.663	0.643	0.573	0.621
2004	0.155	0.198	0.663	0.463	0.618	0.443
2005	0.092	0.161	0.353	0.449	0.364	0.436
2006	0.011	0.150	0.308	0.364	0.261	0.315

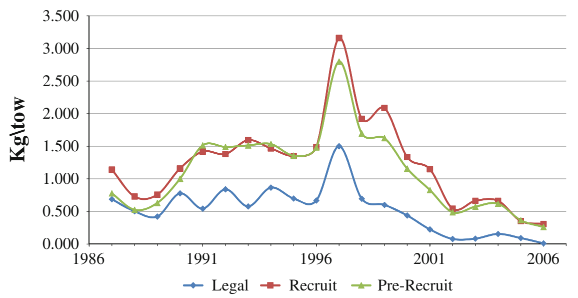

Fig. 3 Predicted biomass index by class, Fall

[6] There is also a maximum legal size policy. This makes sure that extremely large lobster are left in the water so that they can just reproduce. However, in LIS lobsters do not live long enough to grow beyond the maximum size. At September 2009 the maximum carapace length set for Long Island Sound is 133.35 mm.

[7] To calculate the geometric mean, the weight per tow are logged to normalize the highly skewed catch. Means are computed on the log scale and then re-transformed to the geometric mean. The same procedure is used by CTDEP to calculate the mean number per tow and weight per tow for the common fish and invertebrate species (CTDEP 2006, pp. 71–72). As done by the CTDEP, the weight per tow is first logged (natural log), then means are computed on the log scale and finally re-transformed to get the geometric mean.

[8] The reasons for the collapse that followed 1999 have been investigated by researchers in both natural (see Pearce and Balcom 2005, for a review) and social science (Baggio 2011), and so such discussion is omitted.

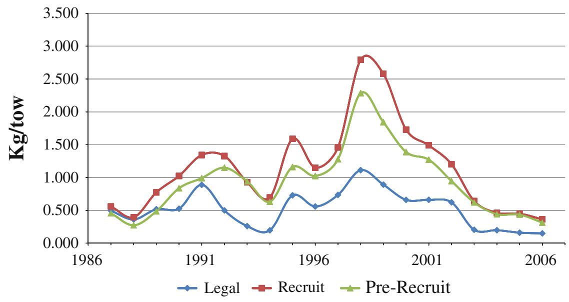

Fig. 4 Predicted biomass index by class, Spring

Comparing these biomass indexes with the indexes of abundance reported in Giannini and Howell (2007, figures 16–17) shows similar dynamics. Also, the minimum and the maximum of the series roughly coincide. This seems to suggest that the average weight of lobster in each class is constant throughout the time period.

Concluding remarks

This paper presented a methodology that can be used to estimate a weight–length relationship without having individual weight data. Since weighting fish under field conditions can be particularly challenging (Anderson and Neumann 1996, pp. 452–453) and expensive, this analysis provides a useful and comforting indication to agencies interested in estimating this type of biological relationships.

The procedure is applied to the American lobster population of Long Island Sound. The WLR estimated for this specific population is comparable to those estimated for other geographical locations. However, I found statistical evidence that the WLR for American lobster of LIS reflects isometric growth.

The estimated WLR is used to predict individual weight which is used to construct biomass indexes for three size classes of lobsters. These indexes could be used to monitor the relative biomass of lobsters at different stages of growth, or used in an empirical analysis of the lobster population dynamics. But it could be further used to analyze the condition factors expressing the well-being of fish such as the Fulton factor and the relative condition factor, and the relative weight.

The contribution of the present analysis is therefore twofold. First, it indicates that is not necessary to invest efforts in collecting individual weight data to be able to construct meaningful indicators of fish population. Then, it represents a contribution to the available WLR for the American lobster of Long Island Sound which previously has not been estimated.

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