Length Specific Probabilities of Screen Entrainment of Larval Fishes Based on Head Capsule Measurements

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Introduction

The state policy on the use of ocean and estuarine waters for power plant cooling requires power plants in California that utilize once-through cooling (OTC) to evaluate and significantly reduce, as achievable, losses of larval fishes and other planktonic organisms due to entrainment. One of the options under consideration at existing facilities is the use of fine mesh screening systems that either use active 'collect-and-transfer' designs that collect the small organisms from the intake screens and return them live to the source water body, or passive designs, such as wedgewire screens (WWS) that utilize ambient currents to move organisms off and away from the screens. Critical to the implementation of any fish protection technology is the need for additional information that can be used in evaluating the feasibility and/or physical performance of the screens; including a first order approximation of the potential reductions in entrainment for the most abundant organisms subject to entrainment.

Tenera (2011) provided nonlinear regression parameter estimates to describe the size of the head capsule (head depth [height] and width) in relation to the overall length of larval fishes that were present near the intakes of eight power plants in central and southern California (**Table 1**). These estimates were based on measurements of notochord length and head capsule of individuals of the various taxa. In theory, individuals with head capsules larger than the screen mesh size would be excluded from entrainment, even if the approach vector was perpendicular (head-on) to the screen. The species-specific dimensions for those larvae that are known to occur in the source waters adjacent to facilities utilizing OTC were made by re-measuring a small subset of larval fishes collected during larval entrainment studies at the eight plants.

Table 1. Location and collection period of larval fish samples.

Power Plant	Owner (present)	Intake Latitude	Intake Longitude	Sample Period
Moss Landing	Dynegy Inc.	36° 48.292' N	121° 47.130' W	1999–2000
Diablo Canyon	Pacific Gas and Electric Company	35° 12.456' N	120° 51.407' W	1996–1999
Scattergood	LADWP	33° 54.985' N	118° 26.106' W	2006–2007
El Segundo	El Segundo Power, LLC	33° 54.433' N	118° 26.031' W	2006–2007
Redondo	AES Southland, LLC	33° 50.409' N	118° 23.718' W	2006–2007
Haynes	LADWP	33° 45.121' N	118° 06.556' W	2006–2007
Harbor	LADWP	33° 45.932' N	118° 15.790' W	2006–2007
South Bay	Dynegy Inc.	32° 36.869' N	117° 05.942' W	2001–2003

The mathematical relationships between overall notochord length of the larvae and the parameters of head capsule width and depth presented in Tenera (2011) were used in this report to estimate the length specific probabilities of entrainment for some of the taxa of larval fishes that have been collected in high abundance during studies at coastal power plants in California (Table 1). The probabilities were based on slot openings of 0.75 mm, 1 mm, 2 mm, 3 mm, 4 mm, and 6 mm, which have been proposed for wedgewire screens, although the results could also be used in determining the theoretical performance of screens with more conventional screen mesh.

Methods

The mathematical relationships in Tenera (2011) were based on allometric regressions where head capsule dimension is a power function of notochord length (NL). This type of regression model (equation) is used to describe proportional changes in body shape with growth (e.g. Fuiman 1983, Gisbert et al. 2002 and Pena and Dumas 2009). Regression models of the relationship between larval length and head capsule dimensions were developed for the 15 taxa shown in **Table 2**. The number of specimens included per taxa ranged from a high of 282 for anchovies to a low of 20 for Pacific barracuda. Although the numbers measured were roughly proportional to the relative abundances of the target taxa in the selected entrainment samples, the range of lengths shown in **Table 2** does not necessarily correspond to the complete size range collected during the studies. All of the taxa were first analyzed with a single model using all of the measured individuals. However, kelpfishes (*Gibbonsia* spp.), anchovies (Engraulidae), and silversides (Atherinopsidae) showed a discontinuity in the growth relationship at lengths that corresponded approximately to the larval transformation phase or slightly smaller in the case of anchovies, when the larvae start developing into a juvenile and might begin to take on some adult characteristics (Moser 1996). Separate regression models were used for the two different stages of larval development for these three taxa. For example, separate models were developed for silverside larvae smaller than 15 mm (0.59 in.) notochord length (NL), and those larger than that size, which approximately corresponds to the length of transformation.

Screen entrainment probabilities were calculated for six slot widths (0.75 mm, 1 mm, 2 mm, 3 mm, 4 mm and 6 mm) using estimates of the variability around the allometric regressions. The variability corresponding to the allometric regression estimates were calculated by using the standard errors of the two parameters of the regression (**Table 3**). To estimate the effects of this variation on head capsule dimensions, 10,000 estimates of head width and depth for each millimeter size of notochord length from a minimum up to a maximum length of 25 mm (0.98 in.) were generated using the estimated standard errors for each regression parameter and assuming that the errors are normally distributed.

For each slot size a length specific probability of entrainment was calculated for both head widths and depth. The probability of entrainment for each notochord length was determined as the larger value of either the head width entrainment probability or the head depth probability.

Table 2. Summary statistics (mean, maximum, minimum and median dimensions) and standard deviations describing the sample composition of each taxon used in the analysis.

		Length (mm)					Head Depth (mm)					Head Width (mm)				
Common Name	N	Mean	Max	Min	Median	Std. Dev.	Mean	Max	Min	Median	Std. Dev.	Mean	Max	Min	Median	Std. Dev.
kelpfishes	75	10.40	25.91	3.46	10.22	4.93	1.18	4.36	0.47	1.03	0.68	1.09	3.23	0.45	0.98	0.51
sculpins	84	5.77	11.05	2.48	5.33	2.20	1.13	2.78	0.41	0.94	0.58	1.04	2.95	0.43	0.87	0.57
flatfishes	51	4.07	7.51	1.54	4.00	1.52	0.85	2.83	0.18	0.65	0.61	0.51	1.33	0.17	0.49	0.26
monkeyface prickleback	55	10.41	17.65	4.86	10.40	3.12	1.09	2.01	0.65	1.06	0.32	0.97	1.64	0.50	0.93	0.28
combtooth blennies	42	2.54	4.31	1.87	2.25	0.66	0.49	1.10	0.35	0.44	0.14	0.42	0.89	0.32	0.39	0.12
clingfishes	37	4.59	6.76	2.87	4.42	1.09	0.81	1.49	0.51	0.72	0.24	0.82	1.55	0.51	0.70	0.27
anchovies	282	14.10	31.01	1.51	14.23	8.20	1.15	3.49	0.15	0.95	0.82	1.16	3.10	0.19	1.13	0.67
croakers	167	5.18	14.87	1.23	4.18	3.59	1.29	4.31	0.15	0.89	1.03	0.94	3.21	0.20	0.73	0.69
gobies	204	7.88	22.14	1.90	6.46	4.98	1.04	3.44	0.31	0.78	0.69	0.92	3.90	0.25	0.71	0.63
silversides	221	12.28	31.07	3.63	11.01	5.77	1.54	4.37	0.34	1.14	0.95	1.42	3.70	0.35	1.15	0.71
Pacific barracuda	20	2.61	4.22	1.66	2.70	0.62	0.52	1.07	0.24	0.50	0.23	0.42	0.58	0.26	0.41	0.10
rockfishes	25	4.16	6.57	2.71	4.01	0.77	0.69	1.23	0.52	0.68	0.14	0.52	1.02	0.33	0.46	0.15
cabezon	33	5.30	6.40	3.58	5.16	0.85	0.79	1.15	0.55	0.80	0.16	0.70	0.95	0.51	0.73	0.14
sea basses	34	2.34	9.47	1.23	1.77	2.01	0.44	2.29	0.19	0.27	0.54	0.40	1.83	0.20	0.28	0.39
pricklebacks	48	10.08	16.39	5.83	9.55	2.99	1.02	1.85	0.58	0.98	0.24	0.99	1.59	0.62	1.00	0.20

The probabilities were calculated over a size range that approximately corresponded to the range of the lengths of larvae that would be potentially entrainable. The minimum lengths for the taxa were based on the smallest larvae observed from the studies (**Table 1)**. The maximum was set at either 20 or 25 mm depending on the fish taxon. Fishes larger than 20–25 mm generally have characteristics (eg. presence of head and opercular spines) that would likely bias entrainment probabilities based only on larval head capsule measurements. Fishes at this size also have swimming abilities that allow them to avoid entrainment, especially at reduced intake velocities that could be used at plants retrofitting with fine mesh or wedgewire screens.

Results and Conclusions

The statistics and parameters resulting from the allometric regressions are shown in **Table 3**, and dispersion plots of the data for each taxon are shown in the attached figures that also appeared in Tenera (2011). The results for kelpfishes (Appendix Figure 1), anchovies (Appendix Figure 8), and silversides (Appendix Figure 13) showed discontinuities in the relationship that corresponded approximately to the larval transformation phase for kelpfishes and silversides (Moser 1996). Moser (1996) gives transformation sizes of 15 mm (0.59 in.) for silversides and 21 mm (0.83 in.) for kelpfishes. Anchovies (Engraulids) appear to have a growth inflection at about 19 mm (0.75 in.) which is less than the reported northern anchovy transformation size (Moser 1996). Separate calculations for both growth phases (smaller and larger sized groups) were calculated for those taxa and are shown in Appendix figures that follow each taxon's initial figure showing all the lengths. The same approach was used by Gisbert et al. (2002) and Pena and Dumas (2009) in their analyses of allometric growth patterns in California halibut and spotted sand bass larvae, respectively. Their allometric equations of body length to head depth for these two species are also presented in **Table 3**.

Parameters of allometric regressions and their standard errors that described head capsule dimensions as a function of notochord length were used to predict the proportion of 15 larval taxa that could be susceptible to entrainment through specific slot sizes of fine mesh screens. **Tables 4** to **23** show the estimated length specific entrainment probabilities for the larval taxa as a function of slot dimension. Tables of entrainment probabilities for larval kelpfishes less than 21 mm, anchovies less than and greater than 19 mm, and silversides less than and greater than 15 mm follow the tables that present the result based on all the length data for those taxa. It should be noted that the results from the two models for the different size groups of anchovies and silversides are dissimilar at the inflection or transformation lengths due to the different allometric regressions for these taxa.

The probabilities in **Tables 4** to **23** can be used to assess the effects on population mortality when using a particular screen dimension for reducing the entrainment of larvae. Two simple assumptions to calculate the reduction of mortality are 1) linear growth over time and 2) constant exponential natural mortality. The assumption of linear growth indicates that size is proportional to age. As a result, a larval population progresses through consecutive length classes as it follows an exponential decrease in numbers over time due to natural mortality. Under these assumptions, each length (or age) would result in an identical number of adult equivalents or fishes at an age where they are not subject to entrainment. Following these two assumptions, a first approximation of the reduction for each screen mesh dimension can be made by summing the length specific entrainment probabilities, and dividing by the number of probability estimates. The subtraction of this value from one determines the reduction of population mortality based on the particular mesh dimension. Using the tabulated probabilities, and omitting the size-specific estimates for kelpfishes, anchovies, and silversides the mortality reductions to the population by taxa can be estimated (**Table 24**). The population level mortality reductions shown in **Table 24** would apply to the total population where the larvae are at a length of 20 or 25 mm size and no longer vulnerable to entrainment. The average reduction in mortality would need to be adjusted for the composition and size structure of the fish larvae for a specific location and sample year, but otherwise provides an estimate of population level mortality identical to an adult equivalent model using constant growth and survival rates.

The results indicate that larger mesh or slot openings will result in very little reduction in population-level mortality, especially for fishes that are entrained in large numbers in southern California such as anchovies, croakers, and gobies.

Table 3. Allometric regression parameter statistics ($y = ax^b$) and standard errors describing the sample composition of each taxon used in the analysis, where x = notochord length (mm). Parameters for California halibut and spotted sand bass from Gisbert et al. (2002) and Pena and Dumas (2009), respectively. All stages (sizes) were used unless noted.

	Y Variable: Head Depth (Height)				Stage	Y Variable: Head Width			
Taxon	a	SE(a)	b	SE(b)		a	SE(a)	b	SE(b)
kelpfishes	0.0541	0.0079	1.2856	0.0533	all	0.0998	0.0091	1.0137	0.0344
	0.1175	0.0132	0.9680	0.0441	≤ 21 mm	0.1492	0.0103	0.8436	0.0274
sculpins	0.1237	0.0178	1.2479	0.0713		0.0877	0.0158	1.3810	0.0881
flatfishes	0.0502	0.0146	1.9182	0.1669		0.0824	0.0125	1.2811	0.0912
monkeyface prickleback	0.1422	0.0214	0.8724	0.0610		0.1199	0.0156	0.8927	0.0529
combtooth blennies	0.1833	0.0160	1.0427	0.0814		0.1777	0.0166	0.9231	0.0884
clingfishes	0.1475	0.0266	1.1139	0.1105		0.1281	0.0293	1.2111	0.1398
anchovies	0.0215	0.0023	1.4524	0.0342	all	0.0776	0.0046	1.0167	0.0195
	0.0964	0.0062	0.8739	0.0247	≤ 19 mm	0.1202	0.0054	0.8461	0.0173
	0.0104	0.0035	1.6831	0.1037	≥ 19 mm	0.0216	0.0054	1.4184	0.0784
croakers	0.2094	0.0129	1.0979	0.0276		0.1894	0.0148	0.9783	0.0356
gobies	0.1100	0.0073	1.0735	0.0258		0.0890	0.0068	1.1123	0.0297
silversides	0.0588	0.0035	1.2880	0.0206	all	0.1006	0.0038	1.0531	0.0135
	0.0908	0.0060	1.0730	0.0280	≤ 15 mm	0.1328	0.0073	0.9219	0.0236
	0.1400	0.0220	1.0089	0.0520	≥ 15 mm	0.1394	0.0171	0.9490	0.0406
Pacific barracuda	0.1216	0.0347	1.5004	0.2581		0.2057	0.0330	0.7505	0.1545
rockfishes	0.1867	0.0359	0.9164	0.1298		0.0936	0.0271	1.1971	0.1929
cabezon	0.1615	0.0417	0.9504	0.1511		0.1085	0.0231	1.1183	0.1240
sea basses	0.1468	0.0094	1.2305	0.0317		0.1516	0.0054	1.0968	0.0184
pricklebacks	0.2809	0.0561	0.5623	0.0839		0.3506	0.0599	0.4534	0.0723
California halibut	0.1310		1.2300		preflexion				
	0.0990		1.5200		postflexion				
spotted sand bass	0.1100		1.4570		preflexion				
	0.3700		0.8180		postflexion				

Table 4. Probabilities of screen entrainment of kelpfish larvae based on head capsule allometric regressions on notochord lengths to 25 mm.

Notochord	Screen Slot Dimension (mm)					
Length (mm)	0.75	1	2	3	4	6
2	1	1	1	1	1	1
3	1	1	1	1	1	1
4	1	1	1	1	1	1
5	1	1	1	1	1	1
6	0.9785	1	1	1	1	1
7	0.7781	0.9991	1	1	1	1
8	0.4144	0.9614	1	1	1	1
9	0.1584	0.7541	1	1	1	1
10	0.0499	0.4207	1	1	1	1
11	0.0158	0.2112	1	1	1	1
12	0.0046	0.0889	0.9999	1	1	1
13	0.0014	0.0369	0.9995	1	1	1
14	0.0004	0.0144	0.9945	1	1	1
15	0	0.0059	0.9772	1	1	1
16	0	0.0022	0.9309	1	1	1
17	0	0.0006	0.8369	0.9999	1	1
18	0	0.0002	0.7064	0.9999	1	1
19	0	0	0.5438	0.9993	1	1
20	0	0	0.4057	0.9968	1	1
21	0	0	0.2738	0.9899	1	1
22	0	0	0.1748	0.9769	0.9999	1
23	0	0	0.1052	0.9513	0.9999	1
24	0	0	0.0619	0.9071	0.9997	1
25	0	0	0.0367	0.8458	0.9988	1

Table 5. Probabilities of screen entrainment of kelpfish larvae based on head capsule allometric regressions on notochord lengths less than or equal to 21 mm.

Notochord	Screen Slot Dimension (mm)					
Length (mm)	0.75	1	2	3	4	6
2	1	1	1	1	1	1
3	1	1	1	1	1	1
4	1	1	1	1	1	1
5	0.9994	1	1	1	1	1
6	0.8963	1	1	1	1	1
7	0.4259	0.9989	1	1	1	1
8	0.1481	0.9563	1	1	1	1
9	0.0421	0.7127	1	1	1	1
10	0.0103	0.3444	1	1	1	1
11	0.0017	0.1330	1	1	1	1
12	0.0005	0.0548	1	1	1	1
13	0.0001	0.0223	1	1	1	1
14	0	0.0080	0.9999	1	1	1
15	0	0.0026	0.9989	1	1	1
16	0	0.0009	0.9947	1	1	1
17	0	0.0004	0.9779	1	1	1
18	0	0.0001	0.9364	1	1	1
19	0	0.0001	0.8585	1	1	1
20	0	0	0.7472	1	1	1
21	0	0	0.6104	1	1	1

Table 6. Probabilities of screen entrainment of sculpin larvae based on head capsule allometric regressions on notochord lengths to 25 mm.

Notochord	Screen Slot Dimension (mm)					
Length (mm)	0.75	1	2	3	4	6
2	1	1	1	1	1	1
3	0.9998	1	1	1	1	1
4	0.8709	0.9959	1	1	1	1
5	0.3744	0.8353	1	1	1	1
6	0.0981	0.4337	0.9990	1	1	1
7	0.0256	0.1609	0.9713	1	1	1
8	0.0068	0.0563	0.8535	0.9988	1	1
9	0.0021	0.0212	0.6453	0.9875	0.9999	1
10	0.0004	0.0068	0.4262	0.9383	0.9987	1
11	0.0001	0.0029	0.2589	0.8230	0.9889	1
12	0.0001	0.0012	0.1472	0.6609	0.9603	0.9999
13	0.0001	0.0002	0.0848	0.4911	0.8946	0.9989
14	0	0.0001	0.0475	0.3567	0.7915	0.9957
15	0	0.0001	0.0290	0.2505	0.6662	0.9856
16	0	0.0001	0.0169	0.1696	0.5381	0.9653
17	0	0.0001	0.0095	0.1151	0.4133	0.9307
18	0	0.0001	0.0051	0.0793	0.3087	0.8740
19	0	0	0.0036	0.0526	0.2251	0.8036
20	0	0	0.0019	0.0364	0.1646	0.7244
21	0	0	0.0012	0.0257	0.1230	0.6358
22	0	0	0.0009	0.0174	0.0925	0.5486
23	0	0	0.0002	0.0125	0.0674	0.4648
24	0	0	0.0002	0.0083	0.0505	0.3841
25	0	0	0.0002	0.0056	0.0371	0.3177

Table 7. Probabilities of screen entrainment of flatfish larvae based on head capsule allometric regressions on notochord lengths to 25 mm.

Notochord	Screen Slot Dimension (mm)					
Length (mm)	0.75	1	2	3	4	6
1	1	1	1	1	1	1
2	1	1	1	1	1	1
3	1	1	1	1	1	1
4	0.9916	1	1	1	1	1
5	0.7689	0.9869	1	1	1	1
6	0.3660	0.8305	1	1	1	1
7	0.1255	0.5220	0.9990	1	1	1
8	0.0410	0.2610	0.9884	1	1	1
9	0.0141	0.1162	0.9374	0.9991	1	1
10	0.0046	0.0505	0.8365	0.9953	0.9999	1
11	0.0023	0.0230	0.6865	0.9789	0.9991	1
12	0.0015	0.0102	0.5234	0.9391	0.996	1
13	0.0011	0.0046	0.3795	0.8768	0.9866	0.9999
14	0.0009	0.0020	0.2636	0.7873	0.9637	0.9993
15	0.0009	0.0011	0.1808	0.6837	0.9269	0.9981
16	0.0009	0.0010	0.1214	0.5748	0.8789	0.9949
17	0.0008	0.0009	0.0814	0.4663	0.8143	0.9884
18	0.0007	0.0009	0.0549	0.3759	0.7364	0.9756
19	0.0005	0.0009	0.0373	0.2962	0.6556	0.9558
20	0.0004	0.0008	0.0255	0.2300	0.5723	0.9285
21	0.0004	0.0007	0.0181	0.1816	0.4882	0.8965
22	0.0003	0.0005	0.0123	0.1391	0.4204	0.8587
23	0.0003	0.0005	0.0084	0.1064	0.3563	0.8152
24	0.0003	0.0004	0.0051	0.0823	0.2940	0.7588
25	0.0003	0.0004	0.0035	0.0623	0.2432	0.7033

Table 8. Probabilities of screen entrainment of monkeyface prickleback larvae based on head capsule regressions on notochord lengths to 25 mm.

Notochord	Screen Slot Dimension (mm)					
Length (mm)	0.75	1	2	3	4	6
3	1	1	1	1	1	1
4	1	1	1	1	1	1
5	0.9973	1	1	1	1	1
6	0.9382	0.9998	1	1	1	1
7	0.7329	0.9940	1	1	1	1
8	0.4575	0.9494	1	1	1	1
9	0.2390	0.8310	1	1	1	1
10	0.1162	0.6592	1	1	1	1
11	0.0546	0.4679	0.9998	1	1	1
12	0.0235	0.3071	0.9997	1	1	1
13	0.0114	0.1961	0.9983	1	1	1
14	0.0058	0.1193	0.9945	1	1	1
15	0.0029	0.0730	0.9842	1	1	1
16	0.0017	0.0409	0.9643	0.9998	1	1
17	0.0008	0.0243	0.9318	0.9998	1	1
18	0.0003	0.0146	0.8820	0.9995	1	1
19	0.0001	0.0100	0.8285	0.9986	1	1
20	0.0001	0.0060	0.7619	0.9972	1	1
21	0.0001	0.0044	0.6923	0.9945	0.9998	1
22	0	0.0026	0.6172	0.9897	0.9998	1
23	0	0.0017	0.5401	0.9801	0.9997	1
24	0	0.0015	0.4666	0.9676	0.9994	1
25	0	0.0006	0.4003	0.9519	0.9987	1

Table 9. Probabilities of screen entrainment of combtooth blenny larvae based on head capsule allometric regressions on notochord lengths to 20 mm.

Notochord	Screen Slot Dimension (mm)					
Length (mm)	0.75	1	2	3	4	6
2	1	1	1	1	1	1
3	0.9994	1	1	1	1	1
4	0.8619	0.9983	1	1	1	1
5	0.3993	0.9293	1	1	1	1
6	0.1228	0.6588	1	1	1	1
7	0.0366	0.3700	0.9991	1	1	1
8	0.0108	0.1764	0.9946	1	1	1
9	0.0049	0.0836	0.9701	1	1	1
10	0.0022	0.0389	0.9119	0.9990	1	1
11	0.0008	0.0182	0.8190	0.9972	1	1
12	0.0002	0.0095	0.7031	0.9886	0.9993	1
13	0.0002	0.0062	0.5875	0.9722	0.9990	1
14	0	0.0037	0.4766	0.9432	0.9977	1
15	0	0.0025	0.3816	0.9048	0.9931	1
16	0	0.0013	0.3044	0.8535	0.9843	0.9999
17	0	0.0007	0.2362	0.7875	0.9716	0.9993
18	0	0.0003	0.1833	0.7191	0.9529	0.9990
19	0	0.0002	0.1427	0.6537	0.9274	0.9986
20	0	0.0002	0.1078	0.5838	0.8996	0.9974

Table 10. Probabilities of screen entrainment of clingfish larvae based on head capsule allometric regressions on notochord lengths to 20 mm.

Notochord	Screen Slot Dimension (mm)					
Length (mm)	0.75	1	2	3	4	6
2	1	1	1	1	1	1
3	0.9783	0.9999	1	1	1	1
4	0.6439	0.9504	1	1	1	1
5	0.3046	0.6941	0.9997	1	1	1
6	0.1393	0.3874	0.9926	1	1	1
7	0.0662	0.2191	0.9473	0.9992	1	1
8	0.0328	0.1271	0.8518	0.9943	0.9998	1
9	0.0171	0.0749	0.7113	0.9738	0.9984	1
10	0.0102	0.0441	0.5621	0.9308	0.9935	0.9999
11	0.0065	0.0271	0.4290	0.8670	0.9796	0.9996
12	0.0044	0.0168	0.3171	0.7800	0.9518	0.9983
13	0.0027	0.0120	0.2354	0.6892	0.9131	0.9963
14	0.0023	0.0084	0.1766	0.5930	0.8637	0.9896
15	0.0018	0.0061	0.1308	0.5002	0.7984	0.9794
16	0.0012	0.0044	0.1033	0.4217	0.7349	0.9621
17	0.0007	0.0034	0.0838	0.3504	0.6642	0.9399
18	0.0006	0.0029	0.0656	0.2916	0.5940	0.9135
19	0.0005	0.0024	0.0513	0.2410	0.5285	0.8803
20	0.0004	0.0019	0.0402	0.2028	0.4656	0.8442

Table 11. Probabilities of screen entrainment of anchovy larvae based on head capsule allometric regressions on notochord lengths to 25 mm.

Notochord	Screen Slot Dimension (mm)					
Length (mm)	0.75	1	2	3	4	6
1	1	1	1	1	1	1
2	1	1	1	1	1	1
3	1	1	1	1	1	1
4	1	1	1	1	1	1
5	1	1	1	1	1	1
6	1	1	1	1	1	1
7	1	1	1	1	1	1
8	1	1	1	1	1	1
9	0.9984	1	1	1	1	1
10	0.9494	1	1	1	1	1
11	0.7000	0.9970	1	1	1	1
12	0.3435	0.9603	1	1	1	1
13	0.1154	0.8014	1	1	1	1
14	0.0319	0.5260	1	1	1	1
15	0.0054	0.2624	1	1	1	1
16	0.0008	0.1047	1	1	1	1
17	0.0002	0.0359	1	1	1	1
18	0	0.0109	0.9999	1	1	1
19	0	0.0022	0.9995	1	1	1
20	0	0.0007	0.9952	1	1	1
21	0	0.0002	0.9699	1	1	1
22	0	0	0.8971	1	1	1
23	0	0	0.7691	1	1	1
24	0	0	0.5960	1	1	1
25	0	0	0.4018	1	1	1

Table 12. Probabilities of screen entrainment of anchovy larvae based on head capsule allometric regressions on notochord lengths less than or equal to 19 mm.

Notochord	Screen Slot Dimension (mm)					
Length (mm)	0.75	1	2	3	4	6
1	1	1	1	1	1	1
2	1	1	1	1	1	1
3	1	1	1	1	1	1
4	1	1	1	1	1	1
5	1	1	1	1	1	1
6	1	1	1	1	1	1
7	1	1	1	1	1	1
8	0.9987	1	1	1	1	1
9	0.9458	1	1	1	1	1
10	0.6768	1	1	1	1	1
11	0.3118	0.9979	1	1	1	1
12	0.0907	0.9738	1	1	1	1
13	0.0200	0.8678	1	1	1	1
14	0.0028	0.6459	1	1	1	1
15	0.0005	0.3832	1	1	1	1
16	0	0.1883	1	1	1	1
17	0	0.0757	1	1	1	1
18	0	0.0288	1	1	1	1
19	0	0.0080	1	1	1	1

Table 13. Probabilities of screen entrainment of anchovy larvae based on head capsule allometric regressions on notochord lengths between 19 and 25 mm.

Notochord	Screen Slot Dimension (mm)					
Length (mm)	0.75	1	2	3	4	6
19	0.1046	0.2292	0.8744	0.9924	0.9996	1
20	0.0831	0.1848	0.8119	0.9838	0.9991	1
21	0.0654	0.1504	0.7501	0.9741	0.9970	1
22	0.0549	0.1202	0.6796	0.9586	0.9950	1
23	0.044	0.0994	0.6101	0.9349	0.9911	0.9999
24	0.0344	0.0825	0.5406	0.9060	0.9847	0.9997
25	0.0300	0.0669	0.4733	0.8730	0.9769	0.9992

Table 14. Probabilities of screen entrainment of croaker larvae based on head capsule allometric regressions on notochord lengths to 20 mm.

Notochord	Screen Slot Dimension (mm)					
Length (mm)	0.75	1	2	3	4	6
1	1	1	1	1	1	1
2	1	1	1	1	1	1
3	1	1	1	1	1	1
4	0.6004	0.9999	1	1	1	1
5	0.0233	0.8344	1	1	1	1
6	0.0002	0.1937	1	1	1	1
7	0	0.0127	1	1	1	1
8	0	0.0007	0.9993	1	1	1
9	0	0	0.9742	1	1	1
10	0	0	0.8307	1	1	1
11	0	0	0.5523	1	1	1
12	0	0	0.2743	0.9987	1	1
13	0	0	0.1066	0.9846	1	1
14	0	0	0.0337	0.9353	1	1
15	0	0	0.0106	0.8255	0.9996	1
16	0	0	0.0032	0.6690	0.9976	1
17	0	0	0.0006	0.4853	0.9861	1
18	0	0	0	0.3177	0.9608	1
19	0	0	0	0.1895	0.9080	1
20	0	0	0	0.1034	0.8225	1

Table 15. Probabilities of screen entrainment of goby larvae based on head capsule allometric regressions on notochord lengths to 25 mm.

Notochord	Screen Slot Dimension (mm)					
Length (mm)	0.75	1	2	3	4	6
1	1	1	1	1	1	1
2	1	1	1	1	1	1
3	1	1	1	1	1	1
4	1	1	1	1	1	1
5	1	1	1	1	1	1
6	0.9396	1	1	1	1	1
7	0.3681	0.9978	1	1	1	1
8	0.0385	0.8661	1	1	1	1
9	0.0015	0.4045	1	1	1	1
10	0	0.0899	1	1	1	1
11	0	0.0100	1	1	1	1
12	0	0.0008	0.9997	1	1	1
13	0	0	0.9933	1	1	1
14	0	0	0.951	1	1	1
15	0	0	0.8209	1	1	1
16	0	0	0.6039	1	1	1
17	0	0	0.3702	0.9995	1	1
18	0	0	0.1914	0.9960	1	1
19	0	0	0.0859	0.9834	1	1
20	0	0	0.0339	0.9474	1	1
21	0	0	0.0115	0.8705	0.9997	1
22	0	0	0.0038	0.7510	0.9991	1
23	0	0	0.0012	0.6038	0.9959	1
24	0	0	0.0004	0.4519	0.9877	1
25	0	0	0	0.3105	0.9691	1

Table 16. Probabilities of screen entrainment of silverside larvae based on head capsule allometric regressions on notochord lengths to 25 mm.

Notochord	Screen Slot Dimension (mm)					
Length (mm)	0.75	1	2	3	4	6
2	1	1	1	1	1	1
3	1	1	1	1	1	1
4	1	1	1	1	1	1
5	1	1	1	1	1	1
6	0.9999	1	1	1	1	1
7	0.7168	1	1	1	1	1
8	0.0408	0.9895	1	1	1	1
9	0	0.5274	1	1	1	1
10	0	0.0454	1	1	1	1
11	0	0.0003	1	1	1	1
12	0	0	1	1	1	1
13	0	0	1	1	1	1
14	0	0	1	1	1	1
15	0	0	0.9969	1	1	1
16	0	0	0.9062	1	1	1
17	0	0	0.5456	1	1	1
18	0	0	0.1648	1	1	1
19	0	0	0.0236	1	1	1
20	0	0	0.0021	1	1	1
21	0	0	0	1	1	1
22	0	0	0	0.9942	1	1
23	0	0	0	0.9475	1	1
24	0	0	0	0.8018	1	1
25	0	0	0	0.5367	1	1

Table 17. Probabilities of screen entrainment of silverside larvae based on head capsule allometric regressions on notochord lengths from 2 to 15 mm.

Notochord	Screen Slot Dimension (mm)					
Length (mm)	0.75	1	2	3	4	6
2	1	1	1	1	1	1
3	1	1	1	1	1	1
4	1	1	1	1	1	1
5	1	1	1	1	1	1
6	0.9898	1	1	1	1	1
7	0.6105	0.9999	1	1	1	1
8	0.0922	0.9752	1	1	1	1
9	0.0043	0.6824	1	1	1	1
10	0	0.2210	1	1	1	1
11	0	0.0354	1	1	1	1
12	0	0.0030	1	1	1	1
13	0	0	1	1	1	1
14	0	0	0.9996	1	1	1
15	0	0	0.9951	1	1	1

Table 18. Probabilities of screen entrainment of postflexion silverside larvae based on head capsule allometric regressions on notochord lengths from 15 to 25 mm.

Notochord	Screen Slot Dimension (mm)					
Length (mm)	0.75	1	2	3	4	6
15	0.0002	0.0016	0.7225	0.9993	1	1
16	0.0001	0.0008	0.5810	0.9967	1	1
17	0.0001	0.0005	0.4472	0.9908	1	1
18	0	0.0003	0.3253	0.9789	1	1
19	0	0.0003	0.2319	0.9531	0.9999	1
20	0	0.0002	0.1615	0.9103	0.9991	1
21	0	0.0001	0.1104	0.8562	0.9976	1
22	0	0.0001	0.0742	0.7896	0.9942	1
23	0	0	0.0482	0.7062	0.9874	1
24	0	0	0.0322	0.6220	0.9777	1
25	0	0	0.0208	0.5361	0.9592	1

Table 19. Probabilities of screen entrainment of Pacific barracuda larvae based on head capsule allometric regressions on notochord lengths to 20 mm.

Notochord	Screen Slot Dimension (mm)					
Length (mm)	0.75	1	2	3	4	6
1	1	1	1	1	1	1
2	1	1	1	1	1	1
3	0.984	0.9998	1	1	1	1
4	0.8381	0.9835	1	1	1	1
5	0.6246	0.9032	1	1	1	1
6	0.4460	0.7769	0.9988	1	1	1
7	0.3218	0.6484	0.9938	1	1	1
8	0.2397	0.5305	0.9798	0.9994	1	1
9	0.1790	0.4381	0.9567	0.9974	1	1
10	0.1399	0.3610	0.9227	0.9949	0.9996	1
11	0.1117	0.3046	0.8861	0.9883	0.9986	1
12	0.0905	0.2591	0.8418	0.9779	0.9967	1
13	0.0769	0.2202	0.7992	0.9636	0.9945	0.9999
14	0.0638	0.1875	0.7549	0.9481	0.9901	0.9996
15	0.0541	0.1632	0.7142	0.9293	0.9839	0.9988
16	0.0471	0.1432	0.6712	0.9081	0.9768	0.9979
17	0.0409	0.1269	0.6330	0.8873	0.9670	0.9969
18	0.0366	0.1140	0.5926	0.8648	0.9557	0.9956
19	0.0335	0.1013	0.5597	0.8384	0.9455	0.9940
20	0.0308	0.0904	0.5266	0.8166	0.9317	0.9912

Table 20. Probabilities of screen entrainment of rockfish larvae based on head capsule allometric regressions on notochord lengths to 25 mm.

Notochord	Screen Slot Dimension (mm)					
Length (mm)	0.75	1	2	3	4	6
2	1	1	1	1	1	1
3	0.9927	0.9998	1	1	1	1
4	0.8799	0.9729	1	1	1	1
5	0.6625	0.8715	0.9997	1	1	1
6	0.4657	0.7121	0.9954	0.9999	1	1
7	0.3262	0.5527	0.9745	0.9996	0.9999	1
8	0.2301	0.4289	0.9305	0.9971	0.9998	1
9	0.1695	0.3297	0.8644	0.9911	0.9992	1
10	0.1245	0.2566	0.7787	0.9752	0.9973	0.9999
11	0.0949	0.2015	0.7000	0.9495	0.9938	0.9997
12	0.0746	0.1633	0.6161	0.9169	0.9859	0.9995
13	0.0584	0.1310	0.5375	0.8791	0.9735	0.9984
14	0.0486	0.1080	0.4657	0.8283	0.9556	0.9973
15	0.0393	0.0900	0.4047	0.7786	0.9343	0.9951
16	0.0332	0.0774	0.3599	0.7309	0.9104	0.9912
17	0.0283	0.0641	0.3208	0.6848	0.8817	0.9862
18	0.0246	0.0554	0.2871	0.6362	0.8475	0.9786
19	0.0212	0.0485	0.2600	0.5881	0.8131	0.9684
20	0.0186	0.0424	0.2312	0.5427	0.7773	0.9578
21	0.0166	0.0378	0.2073	0.5012	0.7445	0.9444
22	0.0141	0.0337	0.1862	0.4638	0.7128	0.9303
23	0.0124	0.0297	0.1675	0.4250	0.6814	0.9147
24	0.0105	0.0272	0.1537	0.3933	0.6482	0.9013
25	0.0097	0.0237	0.1407	0.3644	0.6164	0.8804

Table 21. Probabilities of screen entrainment of cabezon larvae based on head capsule allometric regressions on notochord lengths to 25 mm.

Notochord	Screen Slot Dimension (mm)					
Length (mm)	0.75	1	2	3	4	6
2	1	1	1	1	1	1
3	0.9995	1	1	1	1	1
4	0.9333	0.9970	1	1	1	1
5	0.6827	0.9379	1	1	1	1
6	0.4159	0.7676	0.9996	1	1	1
7	0.2390	0.5591	0.9933	1	1	1
8	0.1655	0.3870	0.9683	0.9994	1	1
9	0.1169	0.2911	0.9174	0.9964	1	1
10	0.0862	0.2229	0.8370	0.9859	0.9991	1
11	0.0649	0.1775	0.7441	0.9657	0.9967	1
12	0.0505	0.1419	0.6608	0.9336	0.9901	0.9999
13	0.0411	0.1131	0.5933	0.8868	0.9780	0.9993
14	0.0334	0.0924	0.5355	0.8321	0.9598	0.9986
15	0.0274	0.0768	0.4822	0.7839	0.9348	0.9957
16	0.0233	0.0642	0.4346	0.7438	0.9013	0.9912
17	0.0203	0.0548	0.3903	0.7012	0.8647	0.9840
18	0.0171	0.0471	0.3535	0.6622	0.8345	0.9736
19	0.0138	0.0417	0.3201	0.6219	0.8059	0.9619
20	0.0120	0.0371	0.2879	0.5830	0.7764	0.9449
21	0.0108	0.0332	0.2616	0.5508	0.7473	0.9256
22	0.0090	0.0290	0.2364	0.5186	0.7187	0.9067
23	0.0077	0.0259	0.2160	0.4829	0.6887	0.8904
24	0.0066	0.0238	0.1987	0.4557	0.6615	0.8744
25	0.0055	0.0211	0.1836	0.4303	0.6357	0.8569

Table 22. Probabilities of screen entrainment of sea bass larvae based on head capsule allometric regressions on notochord lengths to 25 mm.

Notochord	Screen Slot Dimension (mm)					
Length (mm)	0.75	1	2	3	4	6
1	1	1	1	1	1	1
2	1	1	1	1	1	1
3	1	1	1	1	1	1
4	0.9662	1	1	1	1	1
5	0.0002	0.9971	1	1	1	1
6	0	0.0578	1	1	1	1
7	0	0	1	1	1	1
8	0	0	1	1	1	1
9	0	0	0.9995	1	1	1
10	0	0	0.8413	1	1	1
11	0	0	0.1876	1	1	1
12	0	0	0.0069	1	1	1
13	0	0	0	0.9992	1	1
14	0	0	0	0.9385	1	1
15	0	0	0	0.5986	1	1
16	0	0	0	0.1851	0.9999	1
17	0	0	0	0.0282	0.9968	1
18	0	0	0	0.0027	0.9479	1
19	0	0	0	0	0.7526	1
20	0	0	0	0	0.4134	1
21	0	0	0	0	0.1582	1
22	0	0	0	0	0.0407	1
23	0	0	0	0	0.0076	0.9998
24	0	0	0	0	0.0010	0.9985
25	0	0	0	0	0	0.9858

Table 23. Probabilities of screen entrainment of prickleback larvae based on head capsule allometric regressions on notochord lengths to 25 mm.

Notochord	Screen Slot Dimension (mm)					
Length (mm)	0.75	1	2	3	4	6
3	0.9692	0.9998	1	1	1	1
4	0.8252	0.9921	1	1	1	1
5	0.6325	0.9505	1	1	1	1
6	0.4691	0.8772	1	1	1	1
7	0.3450	0.7901	1	1	1	1
8	0.2584	0.6967	1	1	1	1
9	0.1927	0.6010	0.9998	1	1	1
10	0.1476	0.5215	0.9992	1	1	1
11	0.1154	0.4542	0.998	1	1	1
12	0.0908	0.3952	0.9959	1	1	1
13	0.0737	0.3451	0.9929	1	1	1
14	0.0597	0.3000	0.9873	1	1	1
15	0.0492	0.2639	0.9792	1	1	1
16	0.0416	0.2313	0.9712	1	1	1
17	0.0361	0.2049	0.9598	0.9998	1	1
18	0.0324	0.1855	0.9495	0.9994	1	1
19	0.0294	0.1659	0.9377	0.9991	1	1
20	0.0252	0.1496	0.9237	0.9989	1	1
21	0.0217	0.1343	0.9084	0.9983	1	1
22	0.0191	0.1225	0.8937	0.9971	1	1
23	0.0177	0.1110	0.8763	0.9960	1	1
24	0.0153	0.0995	0.8613	0.9945	1	1
25	0.0141	0.0898	0.8438	0.9928	1	1

Table 24. Estimated reductions in mortality (relative to an open intake) to the population surviving past the size where they would be subject to entrainment based on probabilities of screen entrainment for larvae from 15 taxonomic categories of fishes.

		Percentage Reduction in Mortality by Slot Opening Width					
Taxon	**Size Range**	**0.75 mm**	**1 mm**	**2 mm**	**3 mm**	**4 mm**	**6 mm**
kelpfishes	2–25 mm	73.33	64.60	24.80	1.39	0.01	0.00
sculpins	2–25 mm	85.92	81.19	64.57	49.88	36.17	14.05
flatfishes	1–25 mm	78.71	72.74	51.35	32.90	18.67	4.51
monkeyface prickleback	3–25 mm	75.73	62.16	12.78	0.53	0.01	0.00
combtooth blenny	2–20 mm	81.90	72.12	32.54	8.41	1.45	0.03
clingfishes	2–20 mm	83.09	75.88	48.96	27.18	13.23	2.62
anchovies	2–25 mm	55.42	45.19	5.49	0.00	0.00	0.00
croakers	1–20 mm	81.88	74.79	46.07	17.46	1.63	0.00
gobies	1–25 mm	74.61	66.52	35.73	8.34	0.19	0.00
silversides	2–25 mm	76.01	68.49	34.84	3.00	0.00	0.00
Pacific barracuda	1–20 mm	68.21	53.24	15.84	4.43	1.30	0.13
rockfishes	2–25 mm	74.58	66.97	41.67	21.42	10.11	2.23
cabezon	2–25 mm	79.24	70.24	39.11	20.27	10.45	2.90
sea basses	1–25 mm	84.13	79.78	59.86	40.99	22.73	0.06
pricklebacks	3–25 mm	80.52	57.91	4.01	0.10	0.00	0.00
Average % Reduction		**76.89**	**67.45**	**34.51**	**15.75**	**7.73**	**1.77**

References

Fuiman, L. A. 1983. Growth gradients in fish larvae. J. Fish. Biol. 23:117-123.

Gisbert, E., G. Merino, J. B. Muguet, D. Bush, R. H. Piedrahita, and D. E. Conklin. 2002. Morphological development and allometric growth patterns in hatchery-reared California halibut larvae. J. Fish Biol. 61:1217-1229.

Moser, H. G., E. H. Ahlstrom, and E. M. Sandknop. 1977. Guide to the identification of scorpionfish larvae (family Scorpaenidae) in the eastern Pacific with comparative notes on species of *Sebastes* and *Helicolenus* from other oceans. NOAA Tech. Rep. NMFS Circ. 402. 71 p.

Pena, R. and S. Dumas. 2009. Development and allometric growth patterns during early larval stages of the spotted sand bass *Paralabrax maculatofasciatus* (Perdoidei: Serranidae). In C. Clemmenesen, A. M. Malzahn, M. A. Peck, and D. Schnack (eds.). Advances in early life history study of fish. Scientia Marina, Barcelona, Spain. p. 183-189.

Tenera Environmental. 2011. Intake Screening Technology Support Studies: Morphology of Larval Fish Head Capsules. ESLO2011-005.1. Prepared for Pacific Gas and Electric. 26 p.

Appendix

Regression Plots from Intake Screening Technology Support Studies: Morphology of Larval Fish Head Capsules. Tenera. 2011

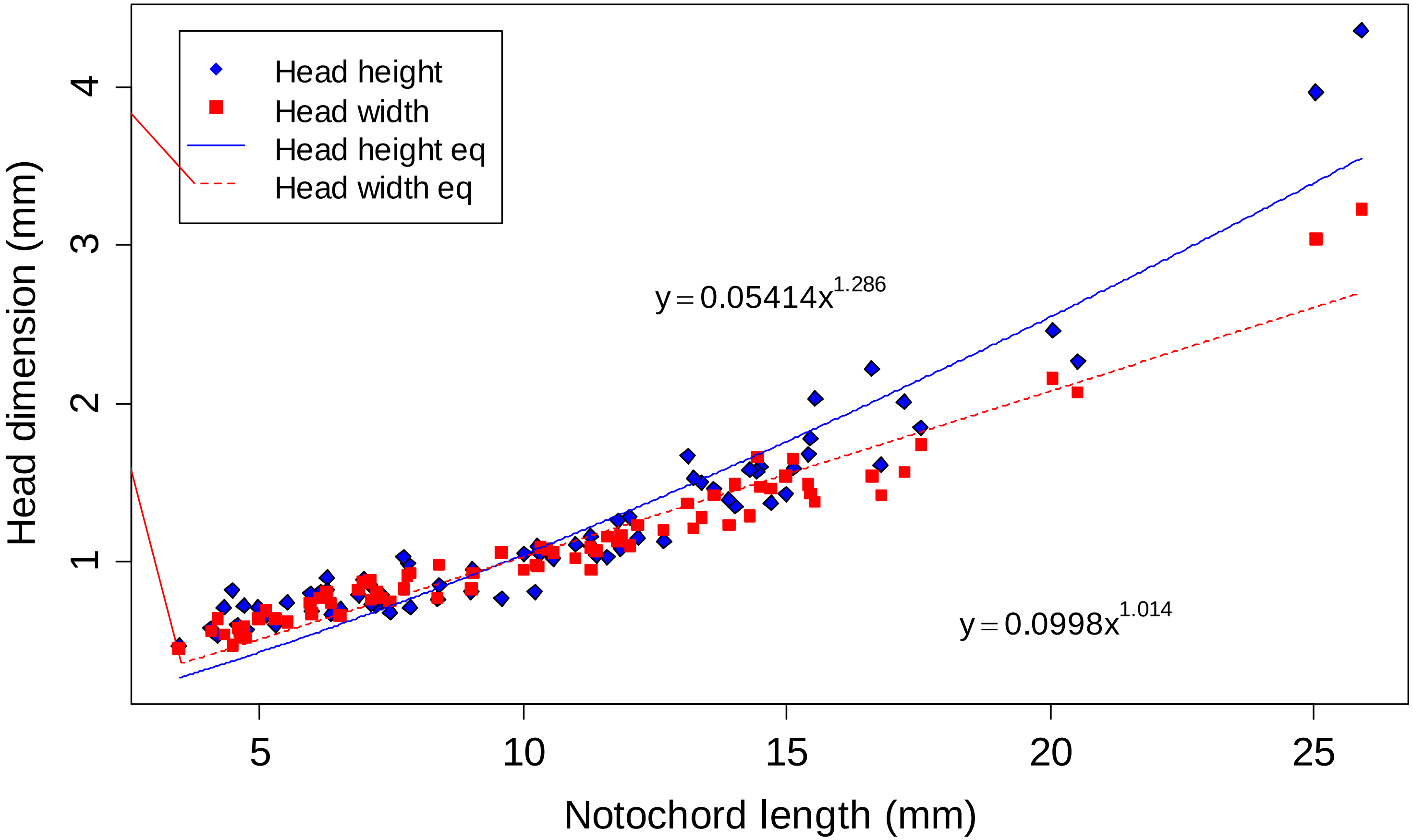

Figure 1. Kelpfishes (*Gibbonsia* spp.) allometric regression plots.

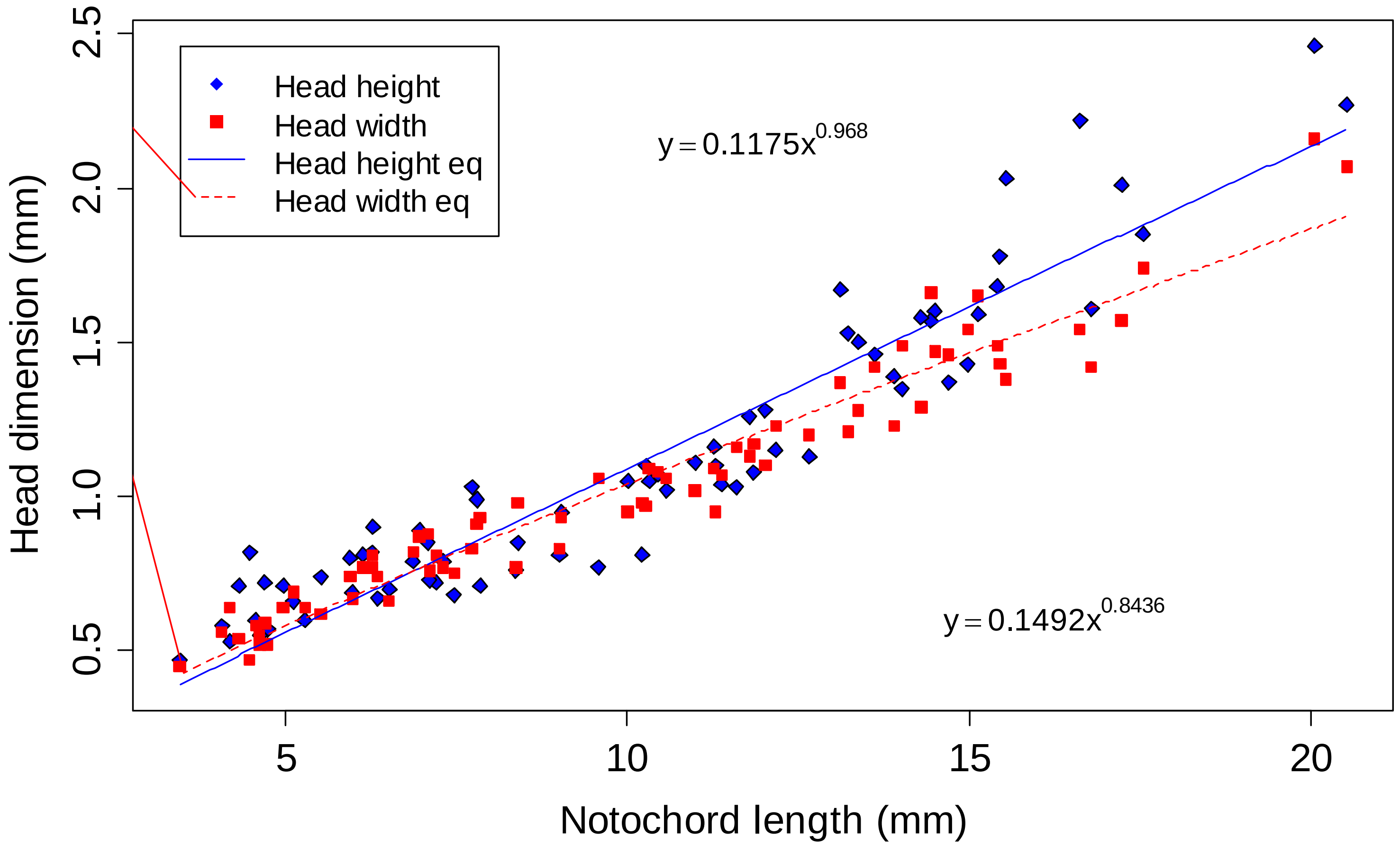

Figure 2. Kelpfishes (*Gibbonsia* spp.) allometric regression plots for fish smaller than 21 mm notochord length.

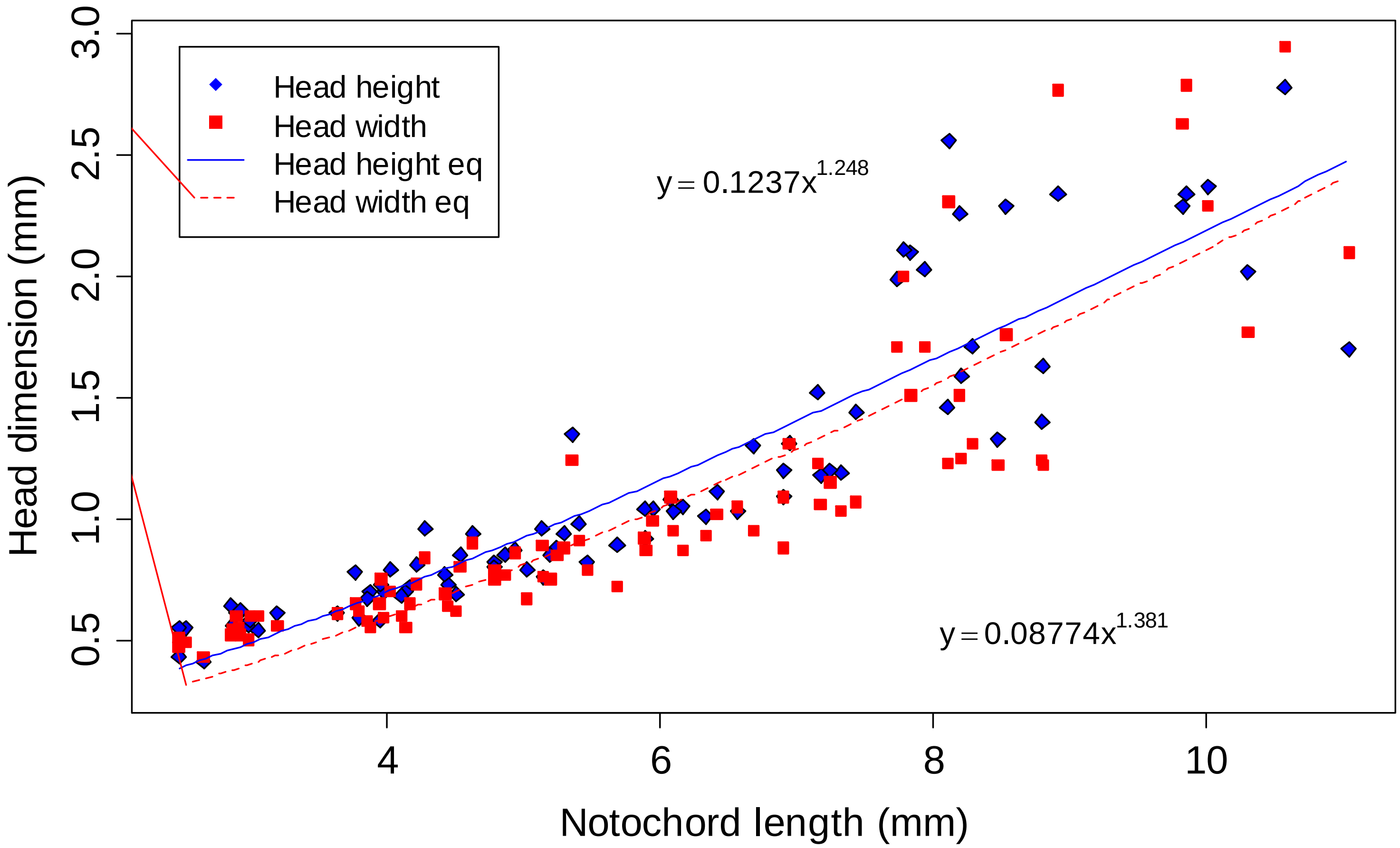

Figure 3. Sculpins (Cottidae) allometric regression plots.

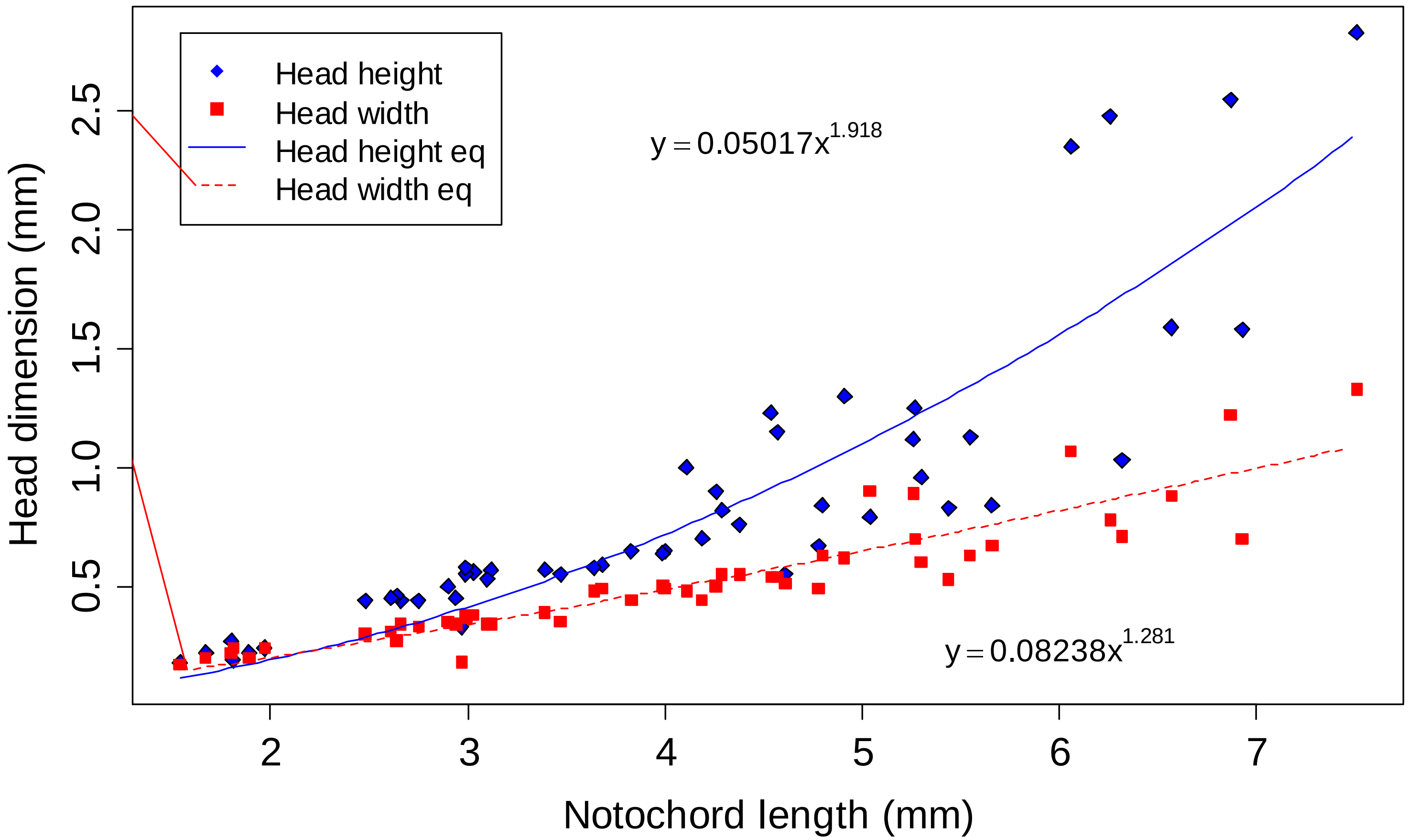

Figure 4. Flatfishes (Pleuronectiformes) allometric regression plots.

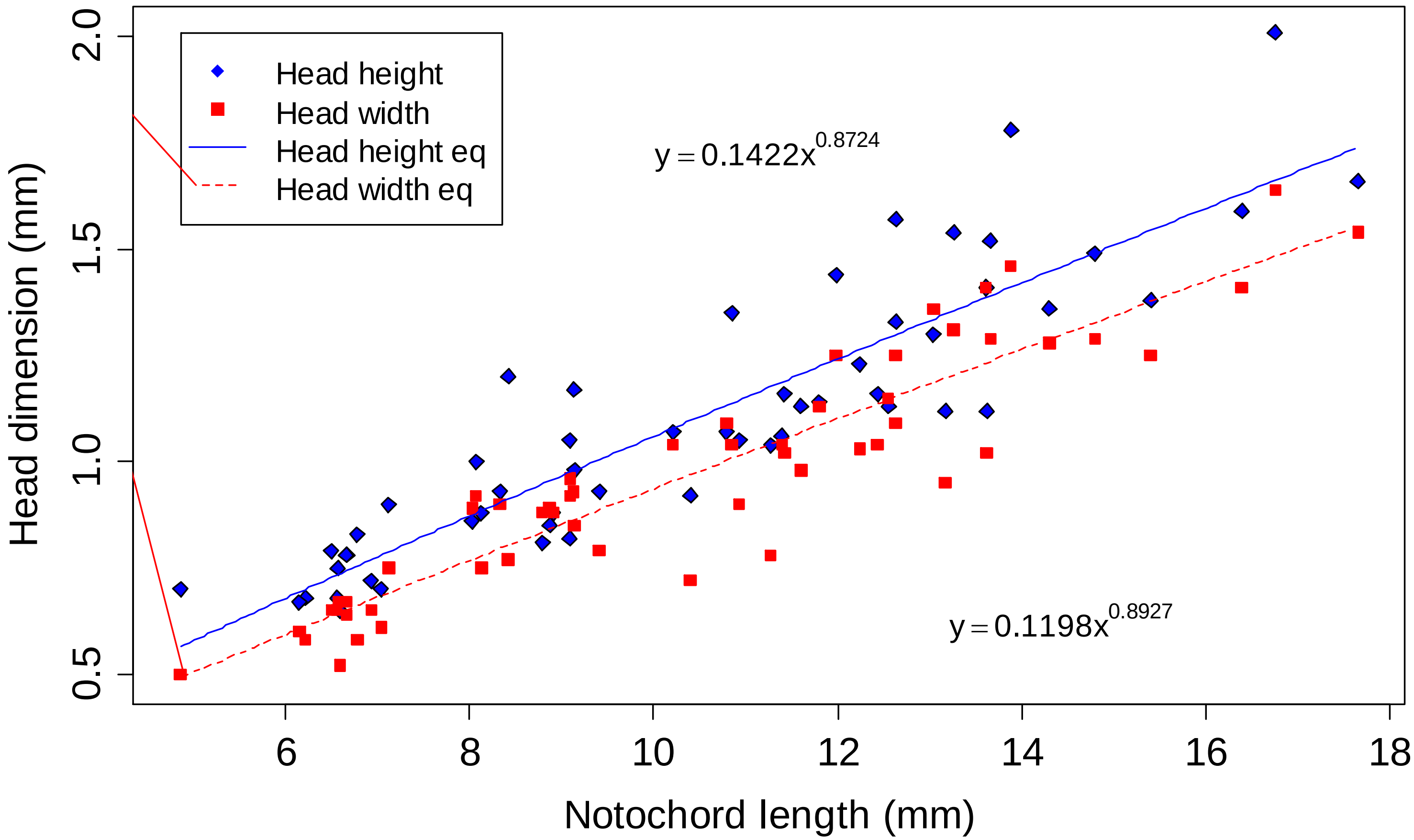

Figure 5. Monkeyface prickleback (*Cebidichthys violaceus*) allometric regression plots.

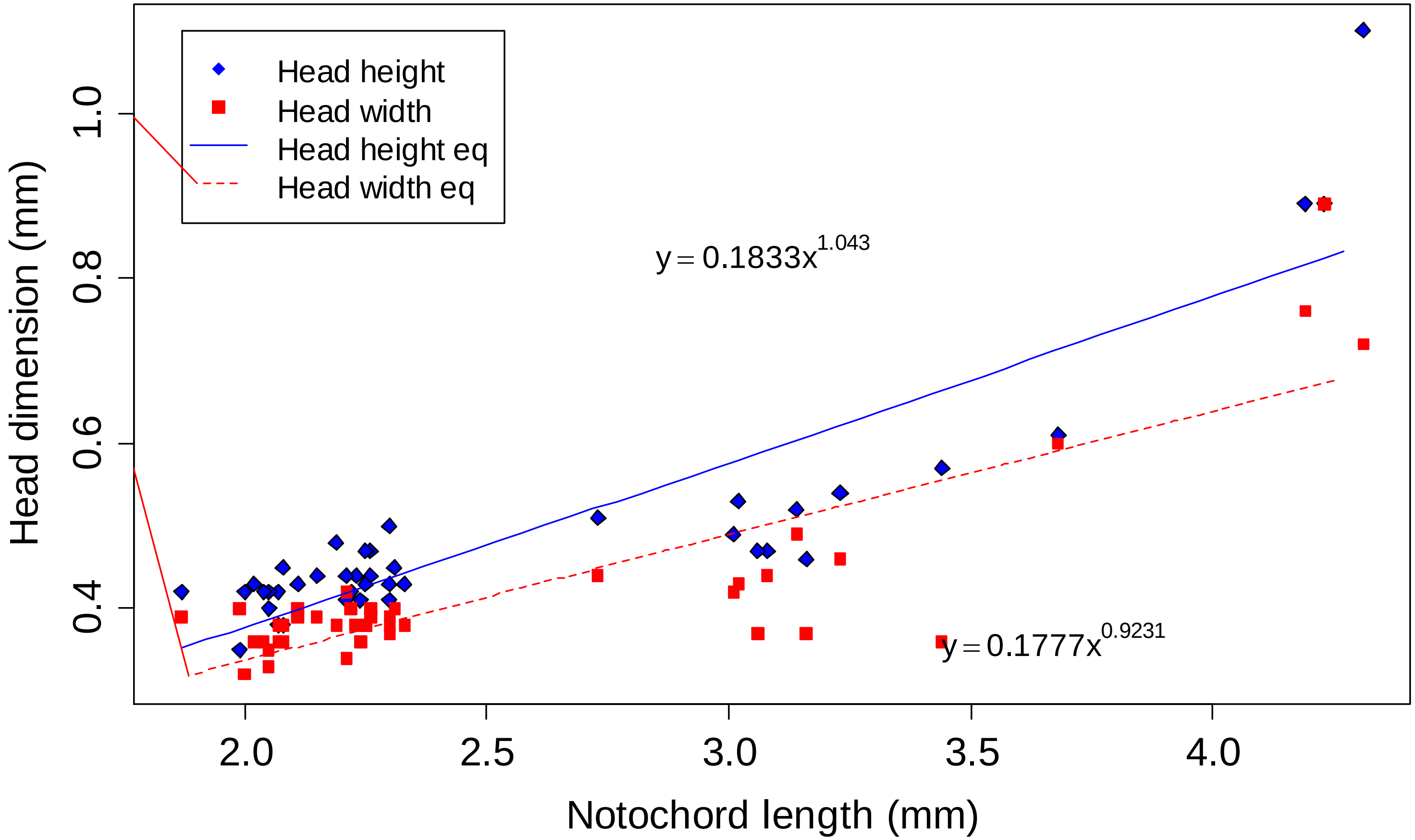

Figure 6. Combtooth blennies (*Hypsoblennius* spp.) allometric regression plots.

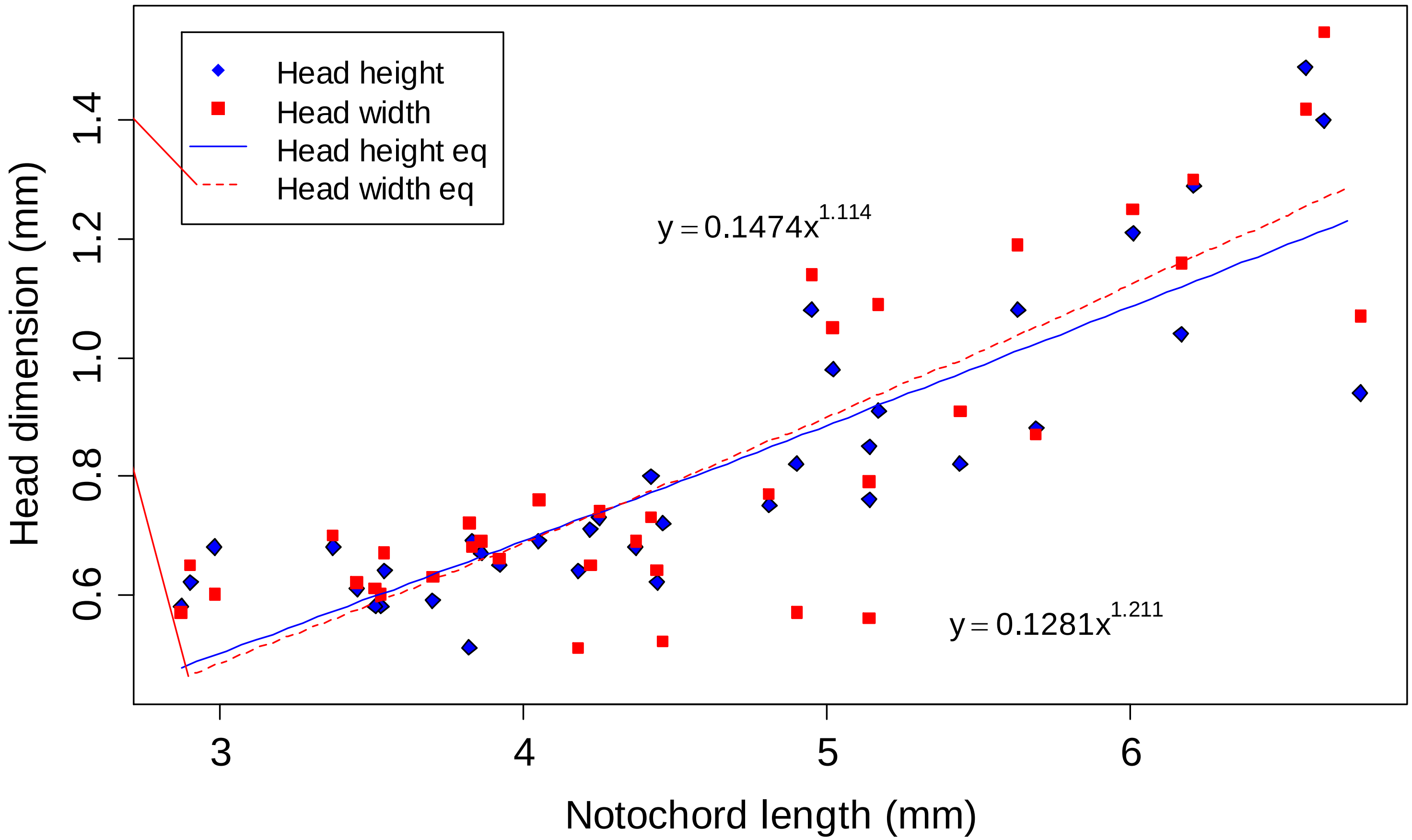

Figure 7. Clingfishes (*Gobiesox* spp.) allometric regression plots.

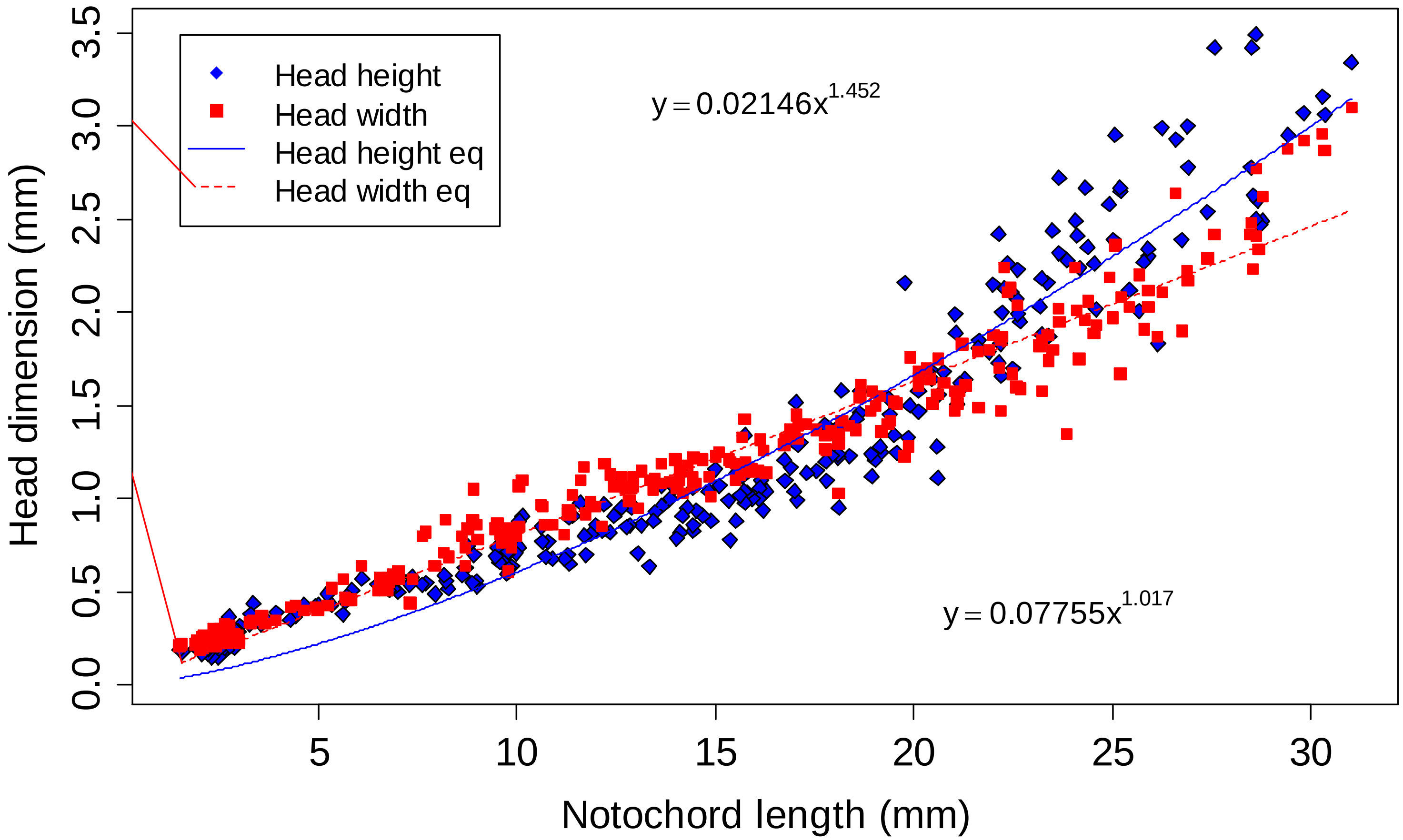

Figure 8. Anchovies (Engraulidae and *Engraulis mordax*) allometric regression plots.

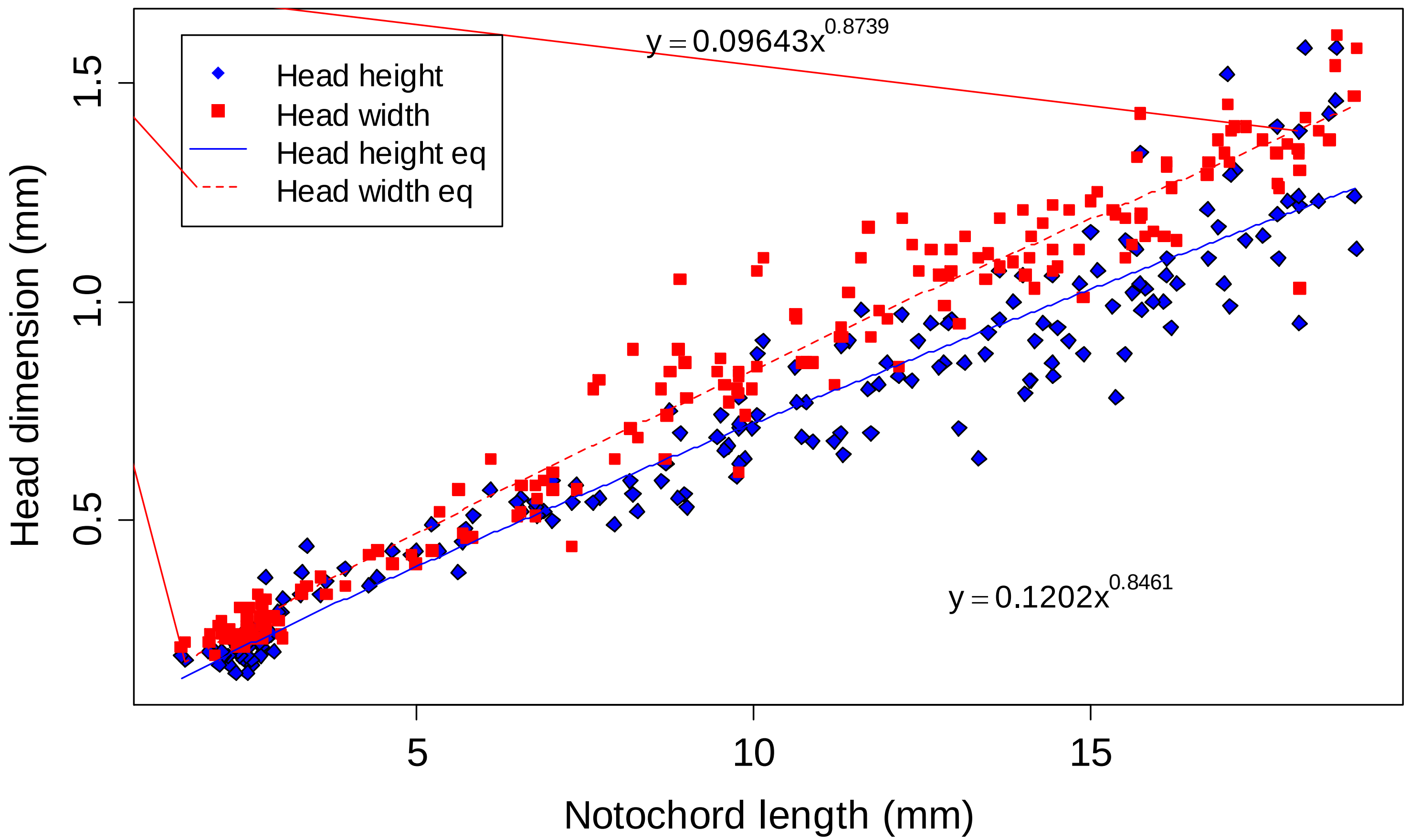

Figure 9. Anchovies (Engraulidae and *Engraulis mordax*) allometric regression plots for fish less than or equal to 19 mm notochord length.

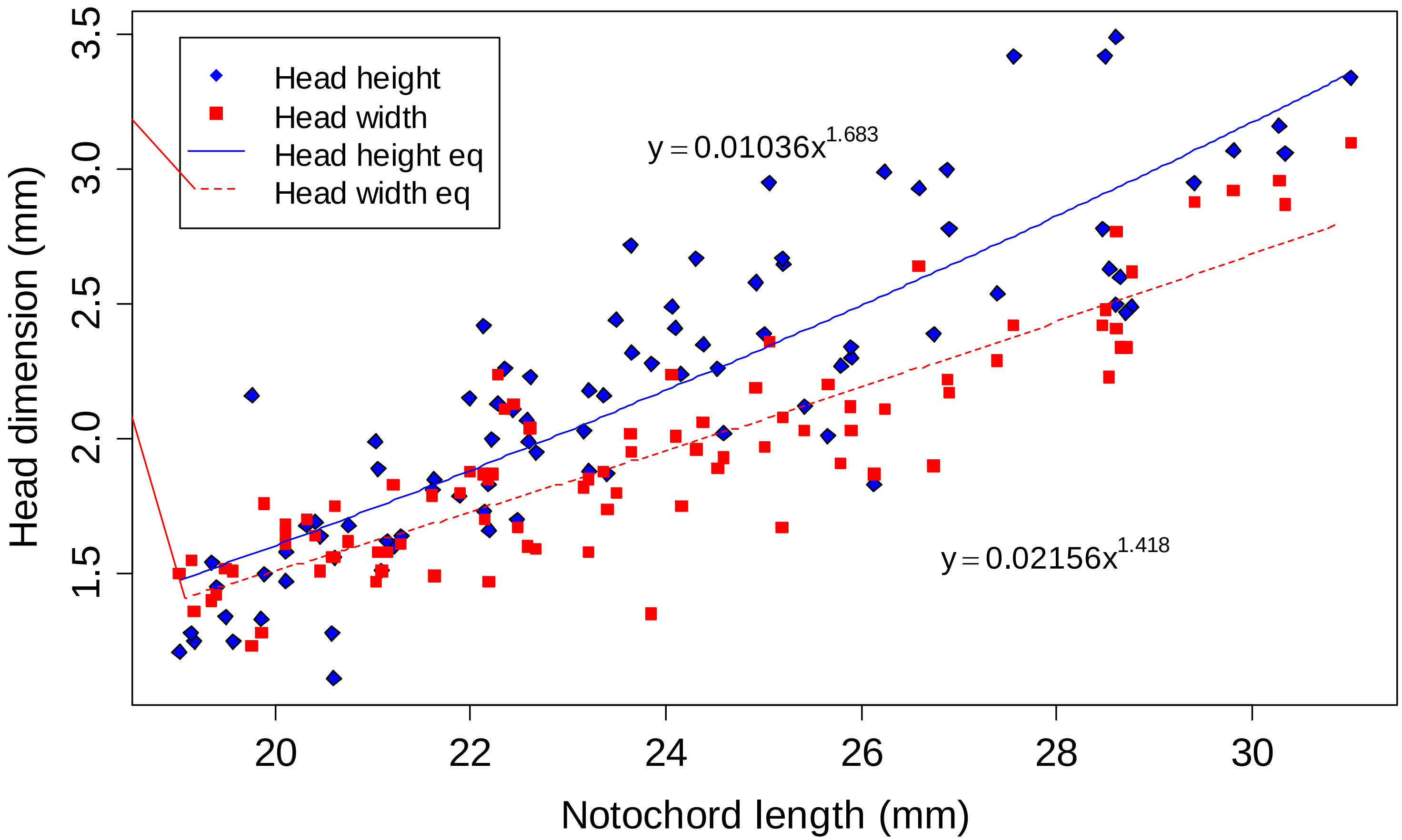

Figure 10. Anchovies (Engraulidae and *Engraulis mordax*) allometric regression plots for fish equal to or larger than 19 mm notochord length.

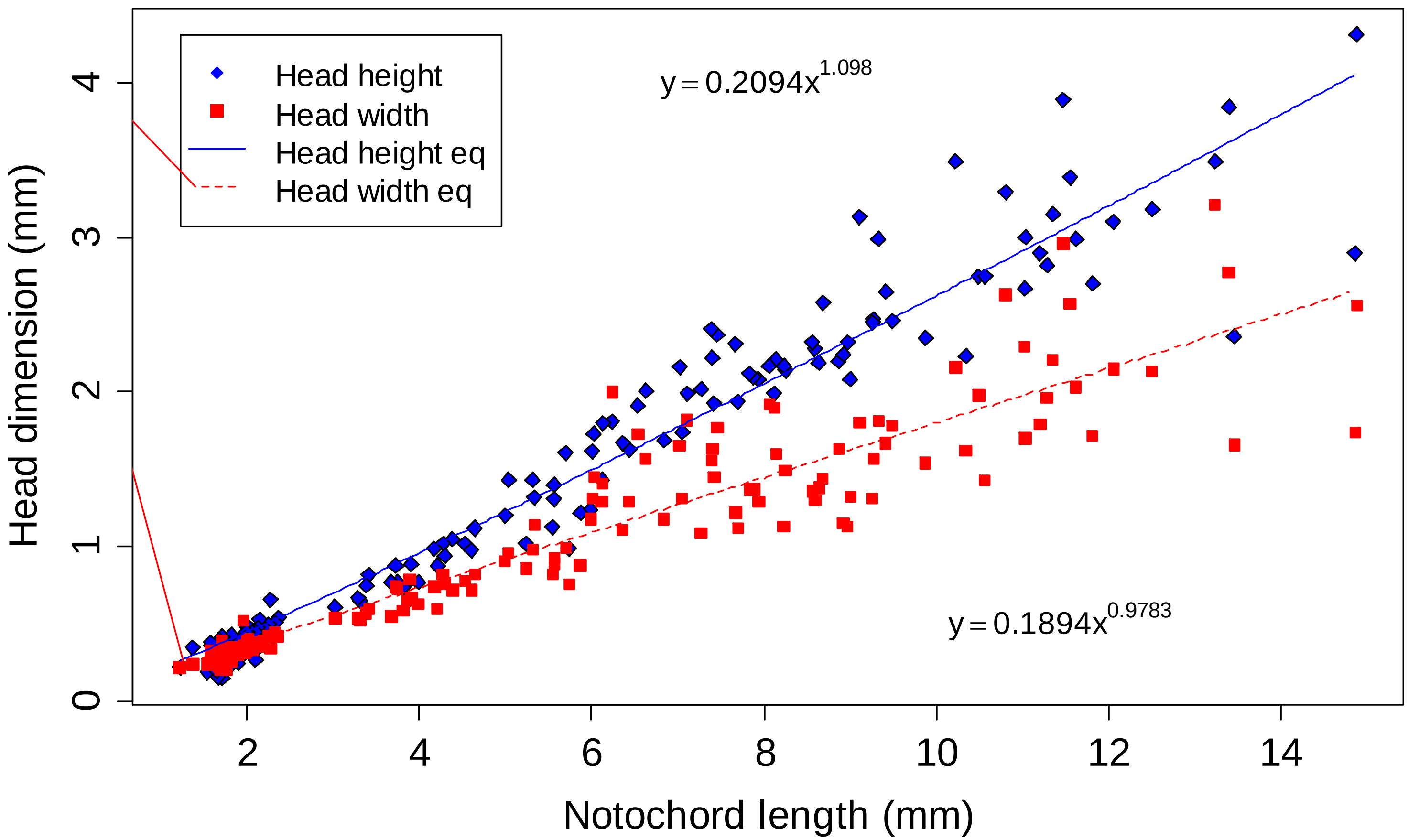

Figure 11. Croakers (*Seriphus politus* and *Genyonemus lineatus*) allometric regression plots.

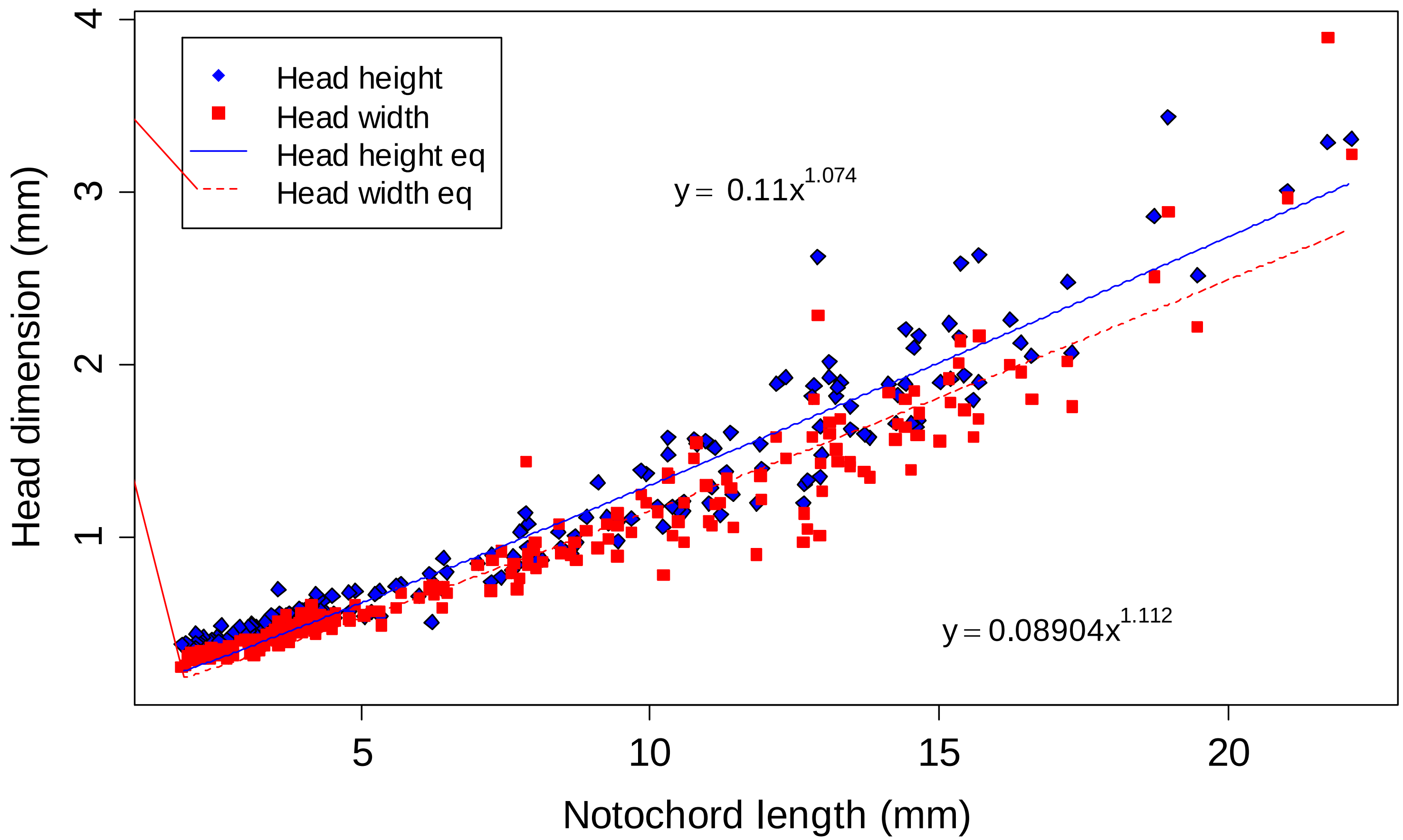

Figure 12. Gobies (*Acanthogobius flavimanus, Lepidogobius lepidus* and CIQ [*Clevelandia, Ilypnus, Quietula]* goby complex) allometric regression plots.

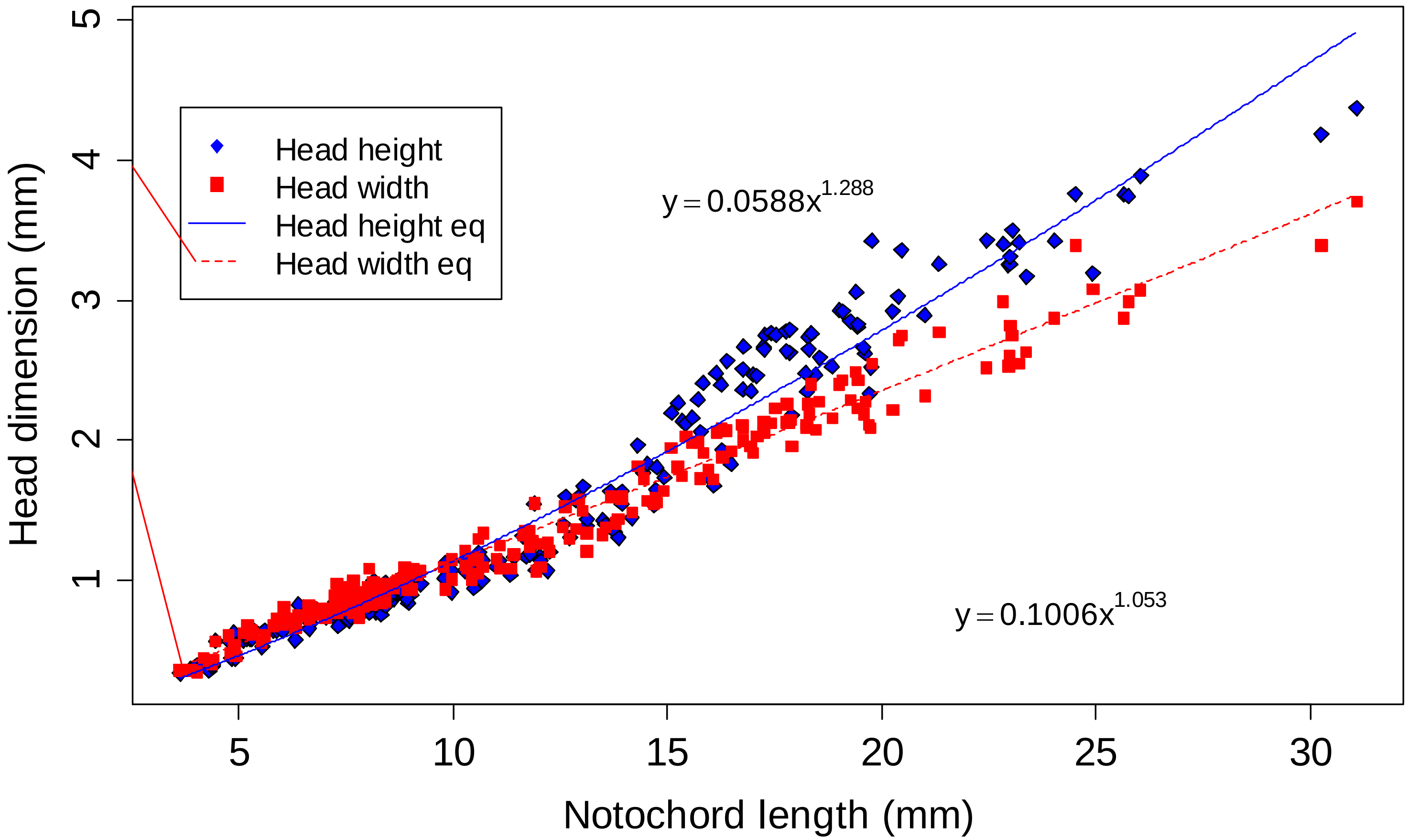

Figure 13. Silversides (Atherinopsidae, *Atherinopsis californiensis, Atherinops affinis, and Leuresthes tenuis*) allometric regression plots.

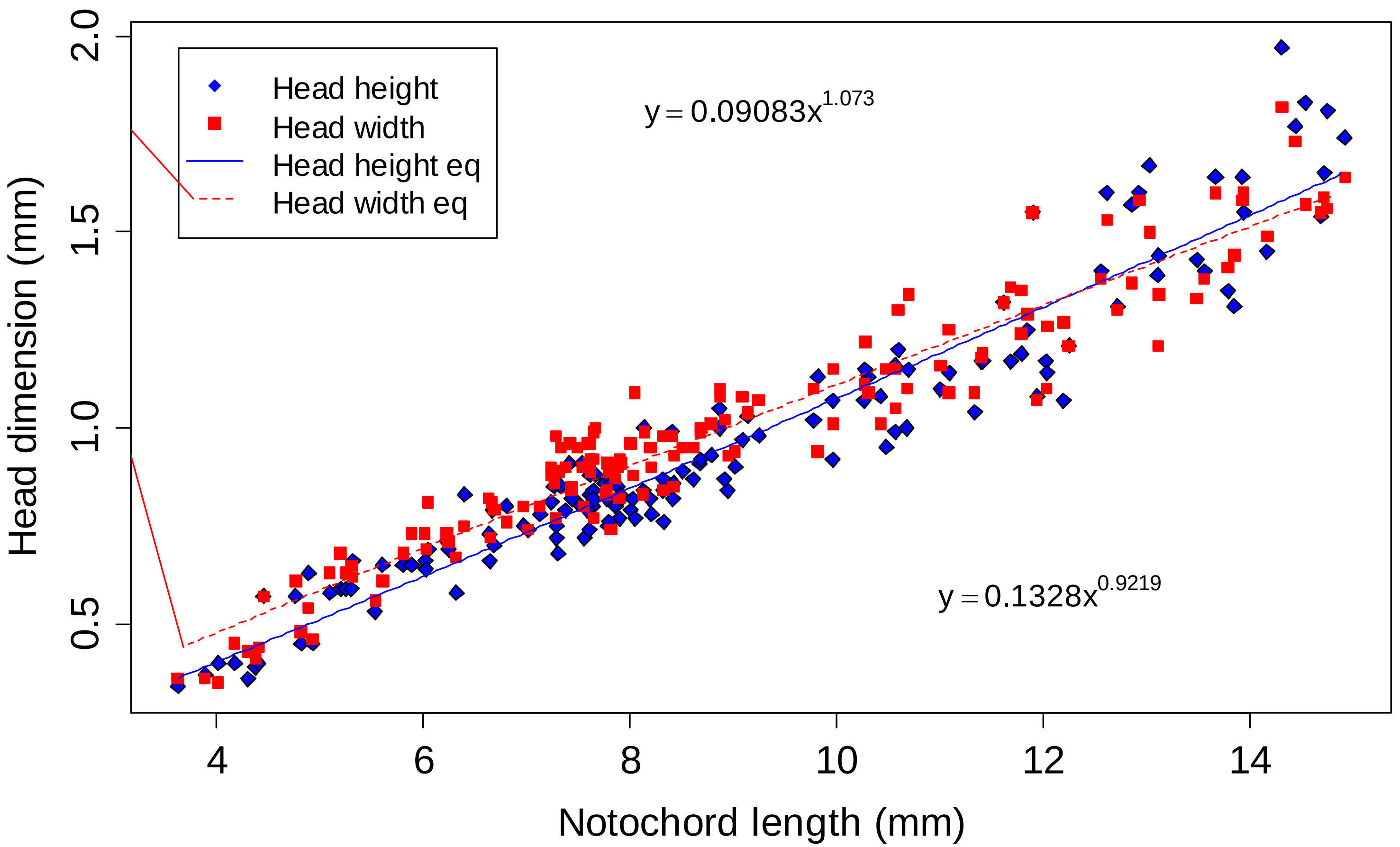

Figure 14. Silversides (Atherinopsidae, *Atherinopsis californiensis, Atherinops affinis, and Leuresthes tenuis*) allometric regression plots for fish smaller than 15 mm notochord length.

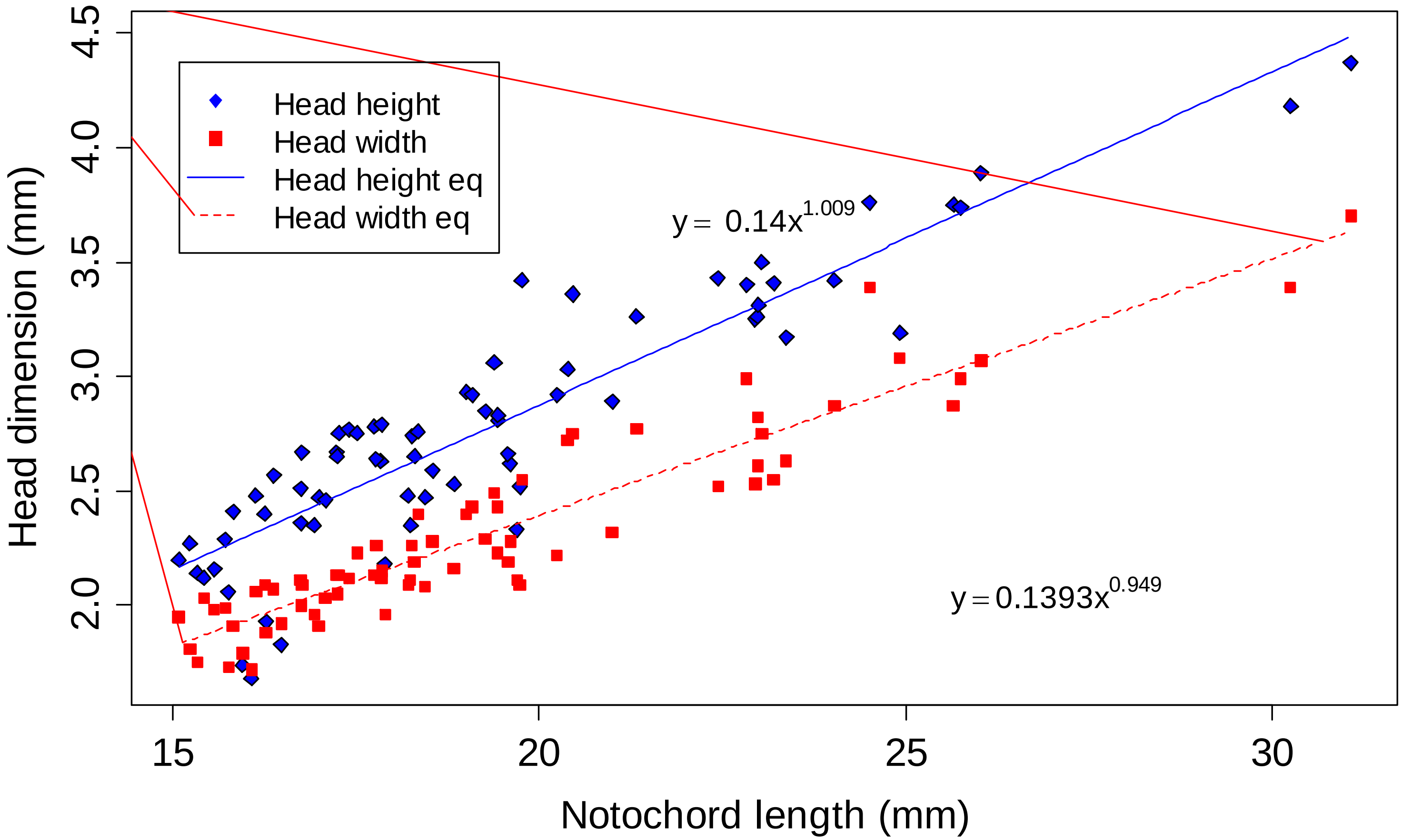

Figure 15. Silversides (Atherinopsidae, *Atherinopsis californiensis, Atherinops affinis, and Leuresthes tenuis*) allometric regression plots for fish larger than 15 mm notochord length.

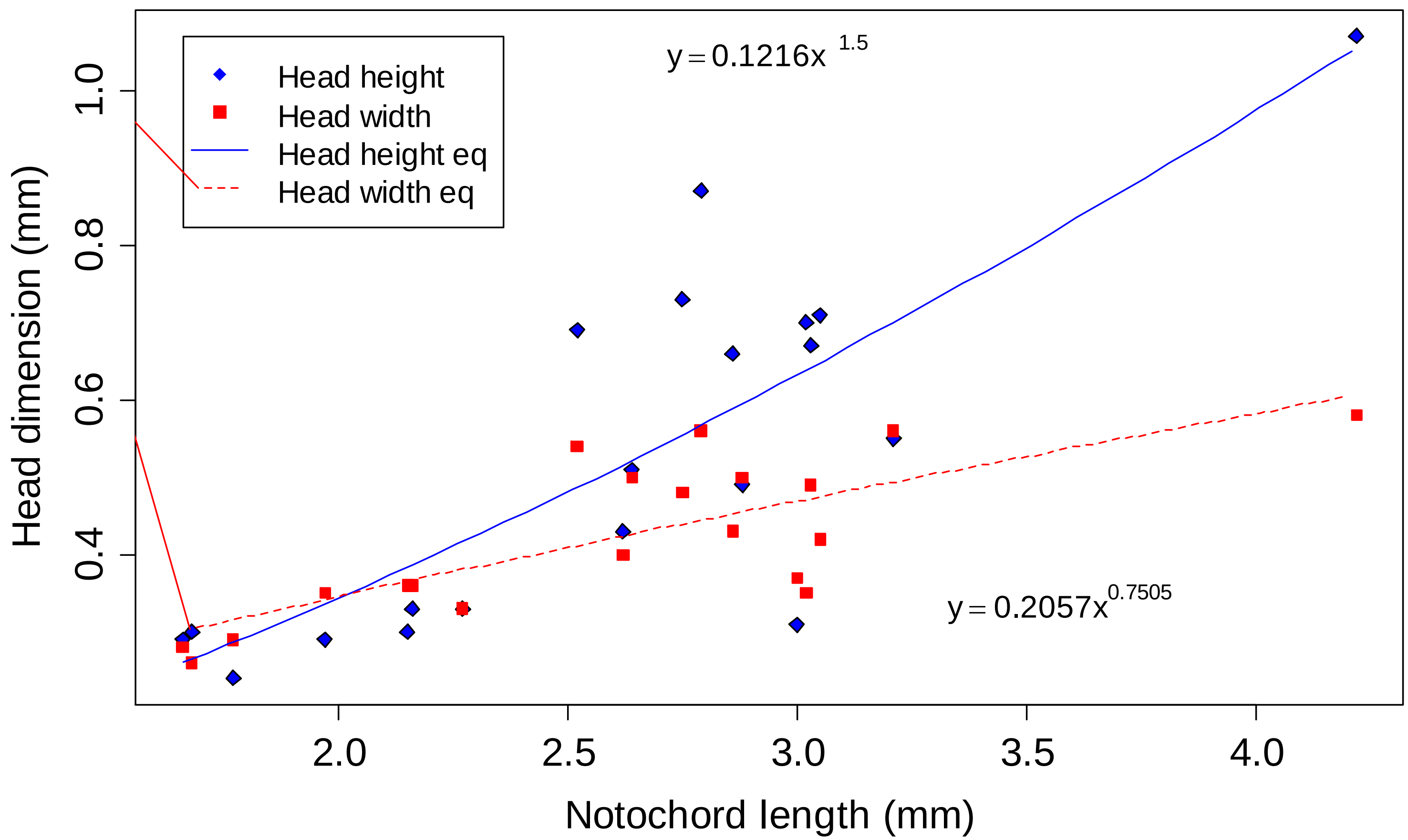

Figure 16. Pacific barracuda (*Sphyraena argentea*) allometric regression plots.

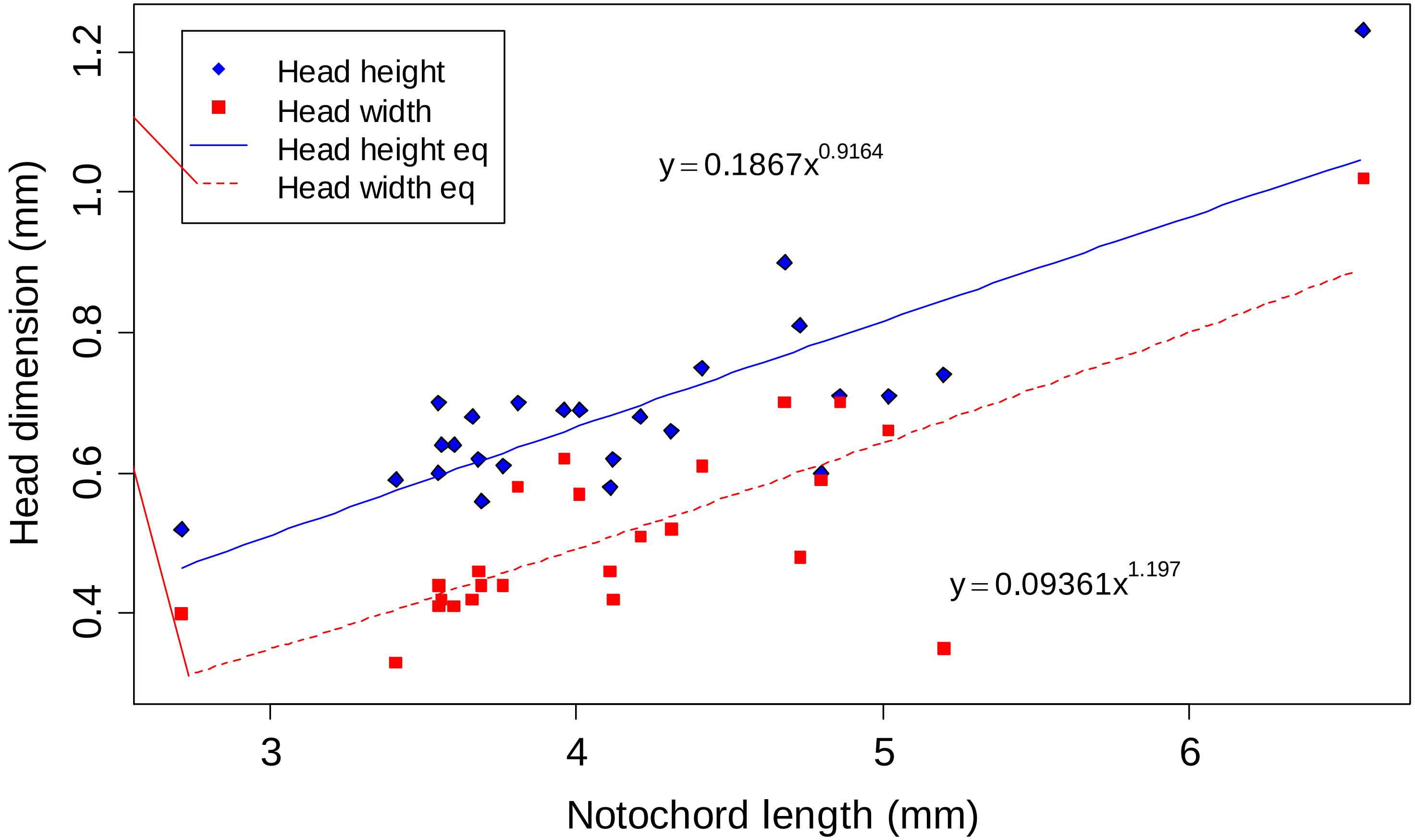

Figure 17. Rockfishes (*Sebastes* spp.) allometric regression plots.

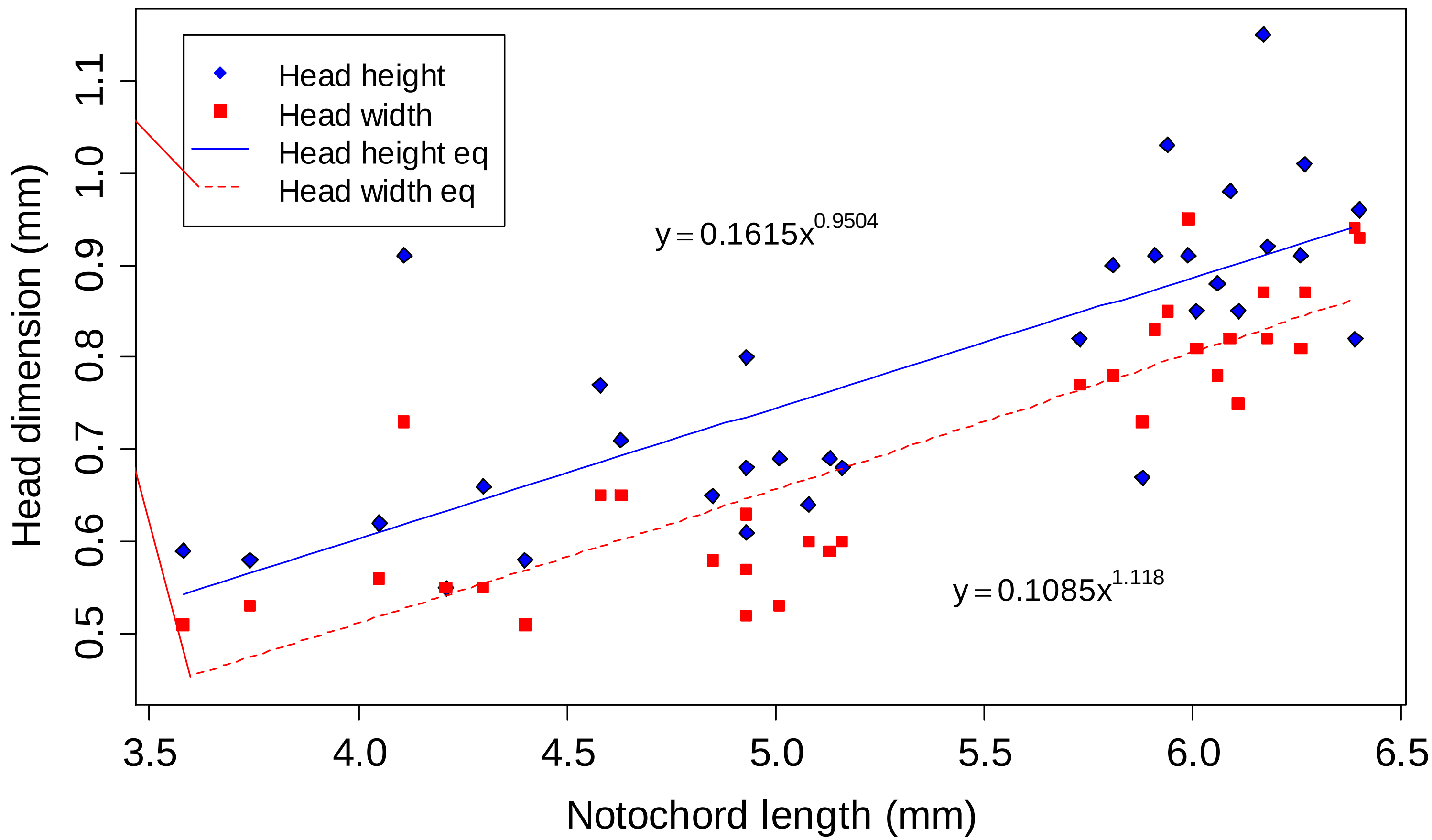

Figure 18. Cabezon (*Scorpaenichthys marmoratus*) allometric regression plots.

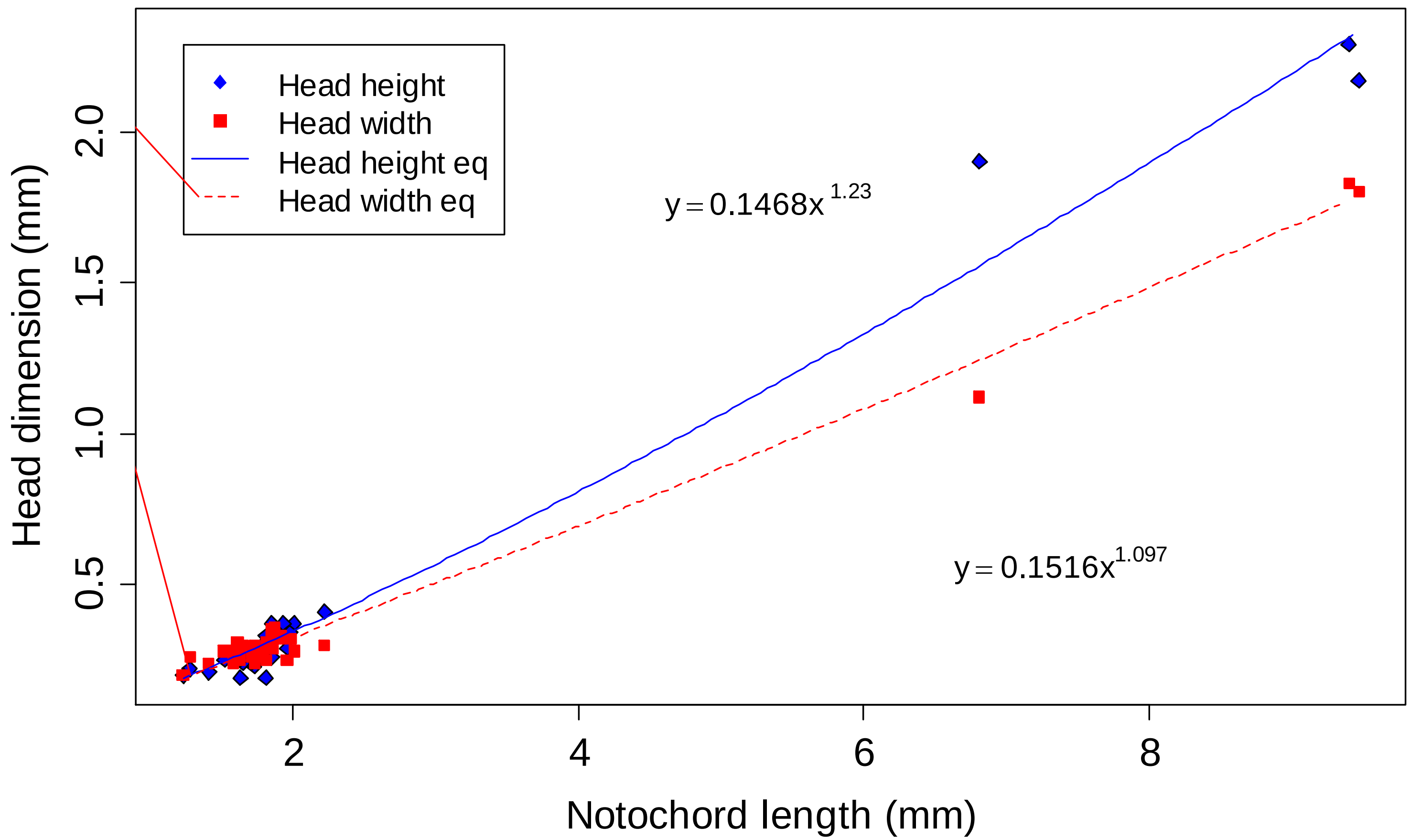

Figure 19. Sea basses (*Paralabrax* spp.) allometric regression plots.

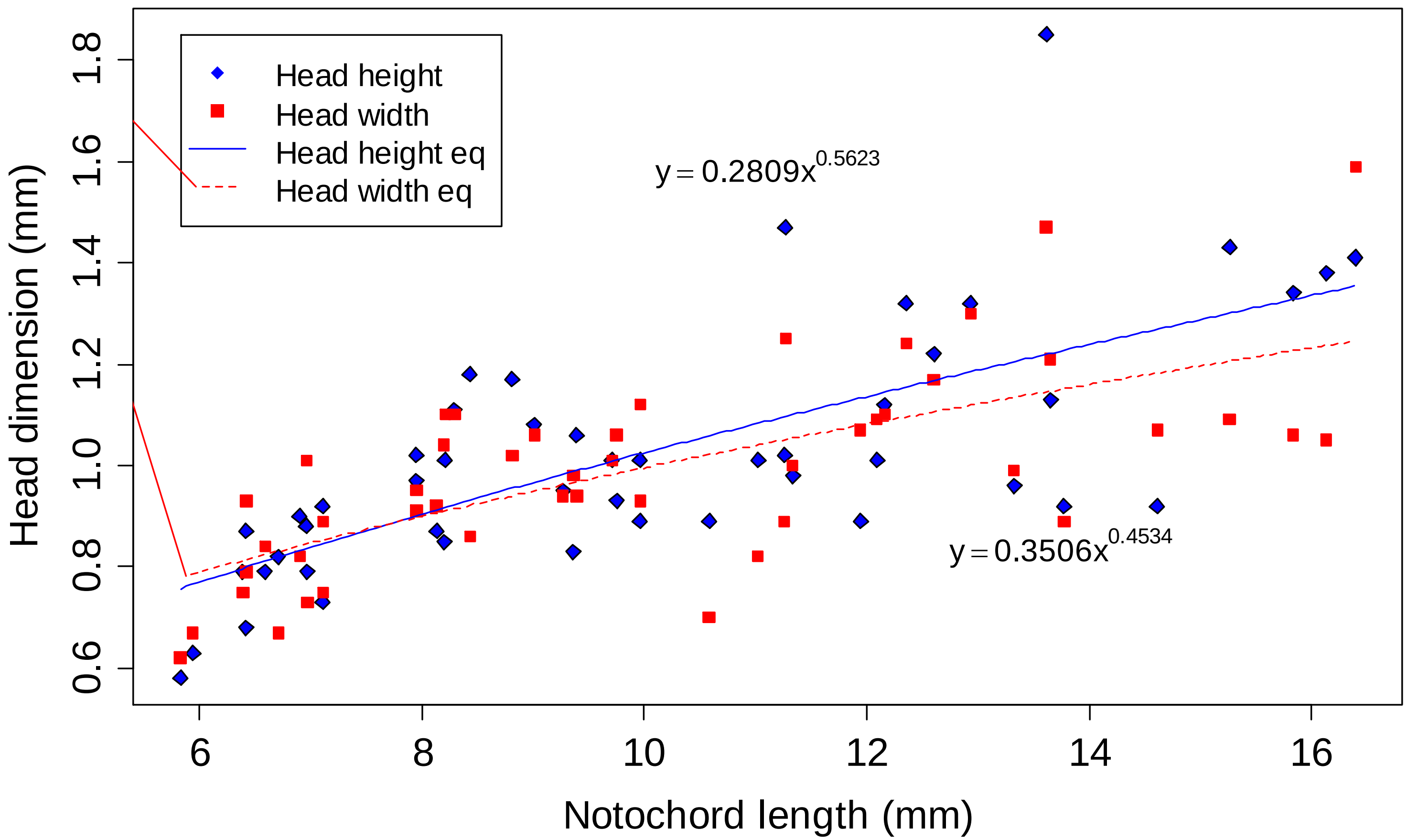

Figure 20. Pricklebacks (Stichaeidae) allometric regression plots.