Length-weight Relationships of Dolphinfish, *Coryphaena hippurus*, and Wahoo, *Acanthocybium solandri*: Seasonal Effects of Spawning and Possible Migration in the Central North Pacific

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Introduction

In the Hawaii commercial longline, troll, and handline fisheries for highly migratory pelagic species, both dolphinfish (mahimahi), *Coryphaena hippurus*, and wahoo (ono), *Acanthocybium solandri*, are incidentally caught and are of secondary importance to tunas, Scombridae, and billfishes, Istiophoridae. Their relative abundance, market demand, and relatively smaller size contribute to their secondary role. However, as people became more health conscious in the late 1970's, coupled with the decline of many fisheries, the demand for both dolphinfish and wahoo increased.[1] In 2003, the last year for which complete Hawaii state fishery landings were compiled, 596 t of dolphinfish and 446 t of wahoo were landed by the commercial fishery in Hawaii.[2]

As the focus of fishery management broadens to include a wider range of species in marine ecosystems, a growing need exists to evaluate catch data on species caught incidentally. Weight-on-length (W-L) and length-on-weight (L-W) relationships are needed to convert at-sea length measurements to weights, market weight data to length, and to examine patterns in fish condition that may provide insights into reproductive life history and ecology.

Many W-L predictors have been published for dolphinfish; these relationships have been described from the Mediterranean Sea (Bannister, 1976; Massuti et al., 1999); eastern tropical Atlantic (Castro et al., 1999), western tropical Atlantic and the Carribean (Oxenford and Hunte, 1986b; Oxenford, 1999), the Straits of Florida (Beardsley, 1967), Gulf of Mexico and the Gulf Stream (Gibbs and Collette, 1959), and North Carolina waters (Schuck, 1951; Rose and Hassler, 1968). In the Pacific, W-L predictors have been described for dolphinfish caught off Colombia and Panama (Lasso and Zapata, 1999), the entire Pacific Ocean (Takahashi and Mori, 1973); Hawaii (Tester and Nakamura, 1957); and Taiwan in the western Pacific (Wang, 1979). In the Indian Ocean, Chatterji and Ansari (1985) examined sexual dimorphism in W-L relationships for east African dolphinfish. Hence, most of these studies examined fish in populations distant from Hawaii. The lone Hawaiian study—fish caught off Kaneohe Bay, Oahu—was based on a relatively small number of measurements for mostly juvenile fish (Tester and Nakamura, 1957), and it is inadequate for describing the full size range of dolphinfish that is commercially landed in Hawaii.

Where many W-L predictors for dolphinfish have been described globally, only three published reports (Iversen and Yoshida, 1957; Beardsley and

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ABSTRACT—Weight-on-length (W-L) relationships for 2,482 dolphinfish, Coryphaena hippurus, *and 1,161 wahoo,* Acanthocybium solandri, *were examined. Data on fork length, whole (round) weight, and sex were collected for dolphinfish at the Honolulu fish auction from March 1988 through November 1989. Unsexed weight and length data for wahoo were collected at the auction from July 1988 through November 1989. We also used sex specific weight and length data of 171 wahoo collected during 1977–1985 research cruises for analysis. Coefficients of W-L regressions were significantly different between the sexes for dolphinfish. Coefficients did not significantly differ between the sexes for wahoo based on research cruise data. In a general linear model evaluating month as a categorical factor, month was significant for female dolphinfish, male dolphinfish, and wahoo with sexes pooled. W-L and length-on-weight (L-W) relationships were fitted by nonlinear regression for all dolphinfish, female dolphinfish, male dolphinfish, and all wahoo sexes pooled. W-L relationships for monthly samples of female dolphinfish, male dolphinfish, and all wahoo with sexes pooled were also fitted by nonlinear regression. Predicted mean weight at length for wahoo was highest at the beginning of the spawning season in June and lowest after the spawning season in September. Maximum and minimum predicted mean weight at length for both sexes of dolphinfish did not correspond with the peak spawning period (March–May). Plausible migration models in conjunction with reproductive behavior were examined to explain the variability in monthly predicted mean weight at length for dolphinfish.*

Richards, 1970; Santana, et al.[3]) and a PhD. thesis (Hogart, 1976) have described W-L relationships for wahoo. A recently published review on wahoo from the western Central Atlantic region by Oxenford et al. (2003) mentioned three other studies in a table of various morphometric relationships. Beardsley and Richards (1970) provided a W-L relationship for wahoo from southeast Florida using data obtained from taxidermists. Hogarth (1976) described a W-L relationship for wahoo based on data from the sport fishery off the North Carolina coast. Santana et al.[3] described the W-L relationship of wahoo caught around the Canary Islands in the eastern Atlantic Ocean. In the Pacific Ocean, Iverson and Yoshida (1957) provided a W-L relationship for wahoo caught around the Line Islands in the equatorial central Pacific. There has not yet been a thorough evaluation on the W-L relationship for wahoo caught around the Hawaiian Islands.

Highly migratory management species (tunas, billfishes, dolphinfish, wahoo, and other incidentally caught species) are caught by the local fisheries around Hawaii and sold at the local fish auction. The Hawaii-based longline fishery has provided the majority of the dolphinfish and wahoo landed at the fish auction, but the troll fishery, bait boats, and the handline fishery (i.e. deep-sea handline, ikashibi, and palu-ahi) also have contributed significantly to total landings (NMFS, 2001). Wahoo landings peak in weight in May and are lowest in December–January. Dolphinfish landings peak in weight in the spring and again in the fall.[2]

Both dolphinfish and wahoo belong to the species complex of Pelagic Management Unit Species for the Western Pacific Regional Fishery Management Council (NMFS, 2001), where they represent an important component of the commercial landings. Stock assessment analyses and ecosystem models can be improved with more accurate morphometric relationships. Weight-length relationships are also useful for converting metrics in tag and recapture experiments and in databases lacking either metric, and they can be used to indicate body condition or robustness of fish in a stock (Le Cren, 1951). This study on dolphinfish and wahoo landed at the Honolulu fish auction during 1988–89 describes W-L predictor variables based on a large number of measurements covering a wide size range. The effects of sex and month on the variables were also examined.

Material and Methods

Dolphinfish morphometric data[4] were collected at the United Fishing Agency[5], Honolulu's public fish auction, from March 1988 through November 1989, except for December 1988 and June 1989. Wahoo morphometrics[4] were collected from July 1988 through November 1989, except for December 1988 and June 1989. Prior to the opening of the auction, fork-lengths (FL) of dolphinfish and wahoo were measured to the nearest millimeter using a meter-long fish caliper, and corresponding whole weights (W) were estimated using the auction scale.[6] When fish length exceeded 1 m, a mark was scratched on the skin at 1 m and the remainder of the fish length was measured to complete the measurement. Weights were recorded to the nearest 0.5 lb at the auction and later converted to kilograms. Small dolphinfish and wahoo were frequently sold in lots of 2–6 fish with a combined weight. These fish did not have individual weights and were not used in these analyses. The sex of dolphinfish was based on the pronounced forehead crest that is present in sexually maturing or mature male dolphinfish but absent from females (Fischer and Whitehead, 1974).

Data were first checked for outliers. All weight-length data for a species were first fitted to a (natural) log linear W-L regression, and outliers greater than ± 3 Studentized residuals were eliminated from the data file as it was believed that these were measurement or recording errors. Then sexual dimorphism and monthly effects were examined by comparing the slopes and intercepts by multiple regression analysis for the sexes or by a general linear model (GLM) for month of landing. The GLM was a type III sum of squares for unbalanced design analysis which included a battery of linear regression related analyses.

To determine the statistical significance of sex and month effects, data were trimmed so that each category contained data for a similar range of fish lengths, an ANCOVA requirement. Fewer data were removed for testing sex effects than for testing month effects, because of the larger length range for each sex pooled over all months. Less overlap was available among months. To preserve sample size, the monthly data were not trimmed as strictly, and, after trimming, not all months completely overlapped. If no difference in W-L relationships was found between sexes, female and male W-L data were pooled by month.

Sex information for wahoo was unobtainable at the auction, so data collected on Northwest Hawaiian Island research surveys from 1977 to 1985 were used to examine the effect of sex on the W-L coefficients. These cruises were conducted on the NOAA ship *Townsend Cromwell*, where FL of wahoo was measured to the nearest millimeter using a meter long fish caliper; W was obtained using a Maco 25 platform scale[5] to the nearest dekagram (10 g); and sex was determined by macroscopic examination of the gonad.

Once the statistical tests on trimmed data were completed, relationships were fit to the untrimmed data to provide the best empirical description for each sex or month. Log-linearized W-L regressions of dolphinfish and wahoo were calculated so parameters and other statistical data would be available for comparison with W-L relationships

[3]Santana, J. C., A. Delgado de Molina, and J. Ariz. 1993. Estimacion de una ecuacion talla-peso para *Acanthocybium solandri* (Cuvier, 1832) capturado en la Isla de el Hierro (Islas Canarias). Int. Comm. Conserv. Atl. Tunas (Madrid), Collect. Vol. Sci. Pap. 40(2):401–405.

determined by the same method for fish caught in other areas. W-L and L-W relationships without log transformation were solved by seeking a least squares solution to the nonlinear equations:

$$W = a(L^b) \text{ and } L = a(W^b),$$

where W is whole weight (kg), L is fork length (cm), and two fitted parameters, a as coefficient and b as exponent. Nonlinear equations were preferred as more accurate and more convenient to use. Monthly changes in condition (weight at length) were illustrated by estimating predicted weights for three or four reference lengths and plotting the predicted weights with their standard error estimates. Statistical analyses were performed with Statgraphics Plus (Manugistics, 2000).

Results

Dolphinfish

Male dolphinfish achieve larger sizes than females. The largest male during the sampling period measured 149 cm, whereas the largest female measured 137 cm. In the initial data examination consisting of 2,495 paired measurements, 13 observations were identified as outliers and deleted from all further analyses. Using data trimmed to a range of 65–137 cm FL, the differences in W-L parameters based on sex for dolphinfish were both significant (coefficient: p <0.01 and exponent: p <0.01; Table 1). Females and males were separately grouped by month of landing; data were trimmed to only include fish in the 90–135 cm FL range, and then analyzed by GLM. Other than March and April, most months covered about 90% or more of the trimmed length range. Month as a categorical factor was significant for both females ($p < 0.05$; Table 2) and males ($p < 0.01$; Table 3).

After completing hypothesis testing for dolpinfish, remaining analyses used the untrimmed data. Nonlinear W-L and L-W relationships were fitted for female and male dolphinfish (Fig. 1–4; Table 4), and a L-W relationship with sexes pooled is provided for applications where sex is unavailable (Fig. 5; Table

Table 1.—Multiple regression analysis evaluating the effect of sex on log-linearized whole weight-on-fork length (range 65–137 cm) relationships for central North Pacific dolphinfish landed at the Honolulu fish auction.

Parameter	Estimate	se	t test	p-value
Coefficient for males	−12.201	0.122	−99.46	<0.01
Exponent for males	3.111	0.025	120.06	<0.01
Difference in coefficient for females	0.689	0.158	4.34	<0.01
Difference in exponent for females	−0.168	0.033	−4.99	<0.01

$r^2 = 0.93$
$n = 2448$
Durbin-Watson statistics = 1.994, p = 0.44

Table 2.—Summary of generalized linear model type III sum of squares analysis evaluating the effect of month (of landing) on log-linearized whole weight-on- fork length (FL, range 90–135 cm) relationship for female central North Pacific dolphinfish.

Source	Sum of squares	df	Mean square	F-ratio	p-value
log-FL	31.895	1	31.895	3874.98	<0.01
Month	0.153	10	0.015	1.87	<0.05
Month*log-FL	0.154	10	0.015	1.88	<0.05
Residual	10.914	1,326	0.008		
Total	84.617	1,347			

Table 3.—Final reduced model of generalized linear model type III sum of squares analysis evaluating the effect of month (of landing) on log-linearized whole weight-on-fork length (FL, range 90–135 cm) relationship for male central North Pacific dolphinfish.

Source	Sum of squares	df	Mean square	F-ratio	p-value
log-FL	77.571	1	77.571	9350.59	<0.01
Month	0.736	10	0.073	8.88	<0.01
Residual	7.391	891	0.008		
Total	95.141	902			

4). Log-linearized W-L relationships for females and males were also fitted for comparison with published studies that used this model (Table 4). Nonlinear W-L relationships were calculated separately for females and males for each of the 11-month groups using the untrimmed data (Tables 5 and 6).

To examine changes of condition or weight at length over time, monthly mean predicted weights with their standard error estimates were plotted for females at reference lengths of 80 cm, 100 cm, 115 cm, and 125 cm; and for males at reference lengths of 105 cm, 120 cm, and 135 cm FL (Fig. 6, 7, respectively). Reference lengths for male dolphinfish were three equally spaced lengths in the observed monthly length range. Reference lengths for female dolphinfish were selected where specimens were adequately present in monthly samples. Only in April (88 cm FL) and July (83 cm FL) were weights for females at 80 cm FL predicted beyond the minimum observed length for the month. The condition of dolphin-

fish was lowest in February or March and highest in September or October for both sexes and all reference sizes. The maximum differences in monthly predicted mean weights for females were 14.9% at 80 cm FL; 9.7% at 100 cm FL; 6.5% at 115 cm FL; and 7.8% at 125 cm FL for females. Among males, the maximum differences in monthly predicted mean weights were 12.5% at 105 cm FL; 10.6% at 120 cm FL; and 10.5% at 135 cm FL. There was also some evidence of increased condition in April and May, and decreased condition some time in the summer. The data are somewhat suggestive of two oscillations per year, peaking in October and in April–May and declining in summer and in November.

Wahoo

Since the sex of wahoo was unobtainable at the fish auction, length-weight-sex data collected on research cruises were used to examine sexual dimorphism. Female wahoo measurements ranged from 84.5 to 157.5 cm FL (n =
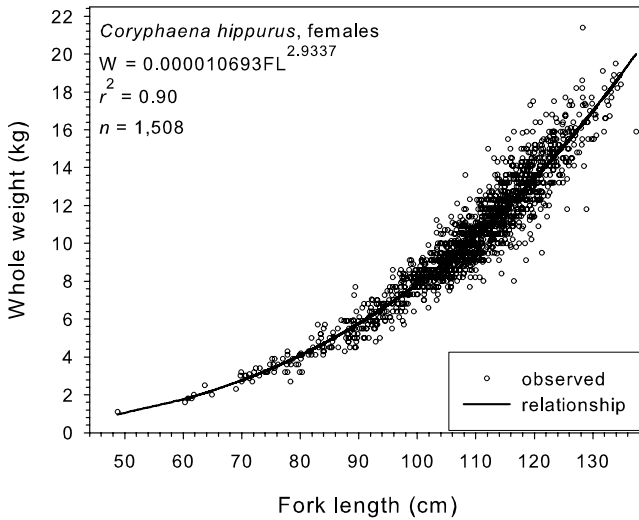
Figure 1.—Whole weight-on-fork length relationship for female dolphinfish measured at the Honolulu fish auction, March 1988–November 1989.
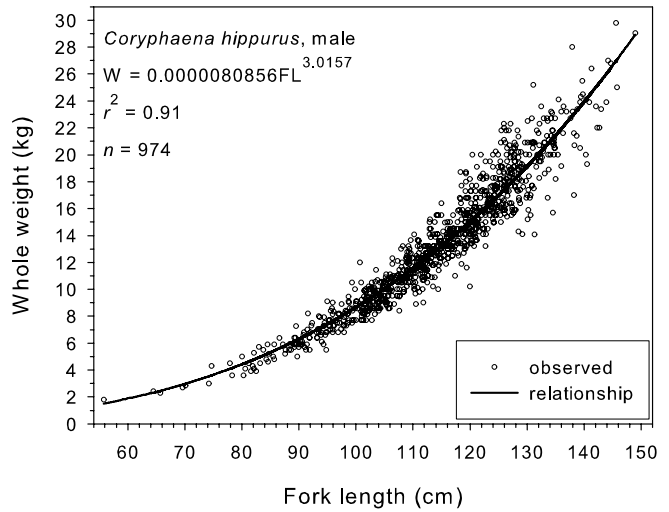

Figure 3.—Whole weight-on-fork length relationship for male dolphinfish measured at the Honolulu fish auction, March 1988–November 1989.
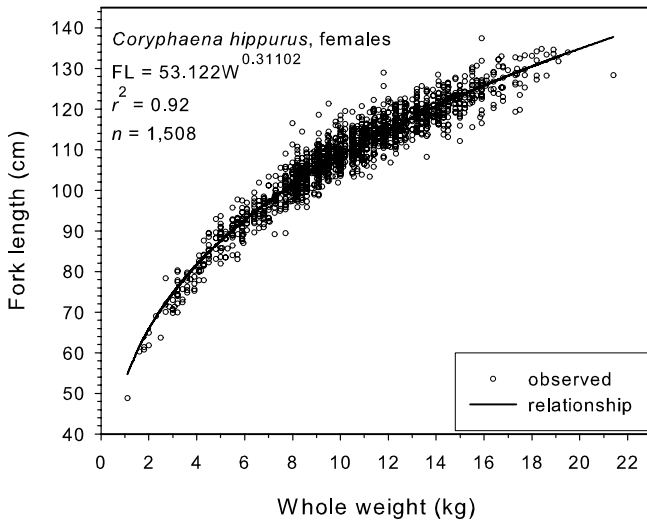

Figure 2.—Fork length-on-whole weight relationship for female dolphinfish measured at the Honolulu fish auction, March 1988–November 1989.
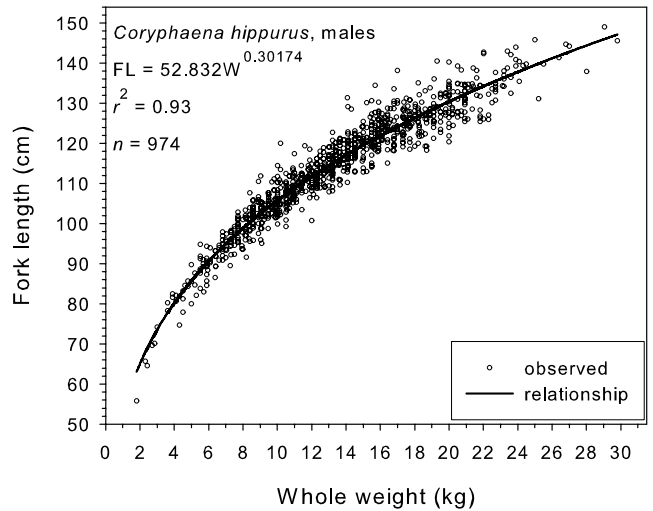

Figure 4.—Fork length-on-whole weight relationship for male dolphinfish measured at the Honolulu fish auction, March 1988–November 1989.

112); males ranged from 79.1 to 148.7 cm FL ($n = 59$). Cursory examination of both cruise and auction measurements indicated four outliers for data collected at the auction. The latter were deleted. With lengths trimmed to include only 110–145 cm FL, the cruise-sampled fish indicated that sex had no significant effect on the wahoo W-L parameters (coefficient: $p = 0.18$, exponent: $p = 0.17$, $n = 144$; Table 7). Wahoo L-W data

collected at the auction were trimmed to include fish in the 108–160 cm FL range. Except for January and July, most months covered about 90% or more of the trimmed range. The effect of month as a categorical factor on W-L coefficients was significant ($p < 0.01$; Table 8).

After completing hypothesis testing, subsequent analyses used untrimmed data. Monthly nonlinear W-L relation-

ships were calculated (Table 9). Non-linear W-L and L-W relationships with sexes pooled (Table 10; Fig. 8, 9) and a log-linearized W-L relationship were also fitted (Table 10). Monthly predicted mean weights at 120, 135, and 150 cm reference FL were plotted to illustrate the variability of condition over the year for wahoo (Fig. 10). Reference lengths were three equally spaced lengths well in the observed length range, except for

Table 4.—Nonlinear and log-linearized whole weight (W)-on-fork length (FL) and FL-on-W relationships for female and male central North Pacific dolphinfish measured at the Honolulu fish auction from March 1988 through November 1989.

| Relation | Sex | Model $Y = aX^b$ | | | Exponent | | Coefficient | | Size range | | | |
		r^2	se	n	b	se	a	se	W (kg) Min.	Max.	FL (cm) Min.	Max.
W on FL	F	0.90	1.003	1508	2.9337	0.024932	1.0693E-5	1.3251E-6	1.1	21.4	48.8	137.4
FL on W		0.92	3.313		0.31102	0.0024477	53.122	0.31096				
W on FL	M	0.91	1.398	974	3.0157	0.028491	8.0856E-6	1.1924E-6	1.8	29.8	55.8	149.0
FL on W		0.93	3.489		0.30174	0.0026917	52.832	0.37804				
FL on W	pooled	0.91	3.694	2482	0.29243	0.0018267	54.917	0.25135	1.1	29.8	48.8	149.0

| | Sex | $\log Y = \log a + b*\log X$ | | | rss | b | se | log a | se | | | | |
		r^2	se	n									
logW on logFL	F	0.93	0.0936619	1508	13.2114	2.93849	0.0202043	−11.4741	0.0946739	1.1	21.4	48.8	137.4
logW on logFL	M	0.94	0.0964733	974	9.0465	3.07984	0.024875	−12.0368	0.117757	1.8	29.8	55.8	149.0

Additional statistical data	Female	Male
mean logFL = mean X	4.68432	4.7323
$\Sigma(\text{logFL–mean logFL})^2 = \Sigma x^2$	21.4901	15.0414
$\Sigma(\text{logFL–mean logFL})*(\text{logW–mean logW}) = \Sigma xy$	63.1485	46.325
$\Sigma(\text{logW–mean logW})^2 = \Sigma y^2$	198.773	151.72
mean logW = mean Y	2.29069	2.53796

Table 5.—Monthly nonlinear whole weight (W)-on-fork length (FL) relationship for female dolphinfish measured at the Honolulu fish auction from March 1988 through November 1989.

| Month | Model: $W = aFL^b$ | | | Exponent | | Coefficient | | Size range | | | |
	r^2	se	n	b	se	a	se	Weight (kg) Min.	Max.	Length (cm) Min.	Max.
January	0.97	0.748	22	3.0011	0.11856	7.8127E-6	4.7181E-6	2.0	18.9	64.9	134.6
February	0.86	0.931	139	2.8589	0.090958	1.4599E-5	6.733E-6	1.8	19.5	60.8	133.9
March	0.86	0.946	186	2.9927	0.087897	7.8866E-6	3.4993E-6	2.7	18.6	77.4	124.9
April	0.85	0.921	209	2.8948	0.078061	1.2882E-5	5.1142E-6	4.8	16.7	87.8	125.7
May	0.86	0.955	312	2.7930	0.06116	2.0688E-5	6.4092E-6	2.3	17.4	69.0	137.4
June	0.91	0.873	53	2.6506	0.10606	4.0557E-5	2.1892E-5	4.2	16.7	80.1	132.9
July	0.91	0.851	41	2.7152	0.12534	2.9755E-5	1.8905E-5	4.8	17.4	83.1	129.9
August	0.91	0.955	148	2.8138	0.075438	1.8811E-5	7.2392E-6	1.6	18.6	60.3	134.8
September	0.91	1.042	109	2.8001	0.096936	2.0609E-5	1.0256E-5	1.1	17.7	48.8	129.8
October	0.93	1.031	161	2.7826	0.072439	2.2767E-5	8.4965E-6	1.8	19.1	61.4	133.4
November	0.91	1.215	128	2.9011	0.086282	1.2437E-5	5.5010E-6	3.0	21.4	70.5	134.2

July when the largest fish was measured at 146 cm FL. The condition of wahoo was highest in May and lowest in July or August for all reference sizes. The differences in monthly predicted mean weights between the highest and lowest condition were 7.5% at 120 cm FL, 8.0% at 135 cm FL, and 8.7% at 150 cm FL. Unlike dolphinfish, there was no suggestion of more than one cycle per year.

Discussion

Previous studies have dealt briefly with sexual dimorphism of dolphinfish. Some have plotted the W-L relationships separately for males and females (Beardsley, 1967; Rose and Hassler, 1968; Chatterji and Ansari, 1985; and Oxenford and Hunte, 1986b) or
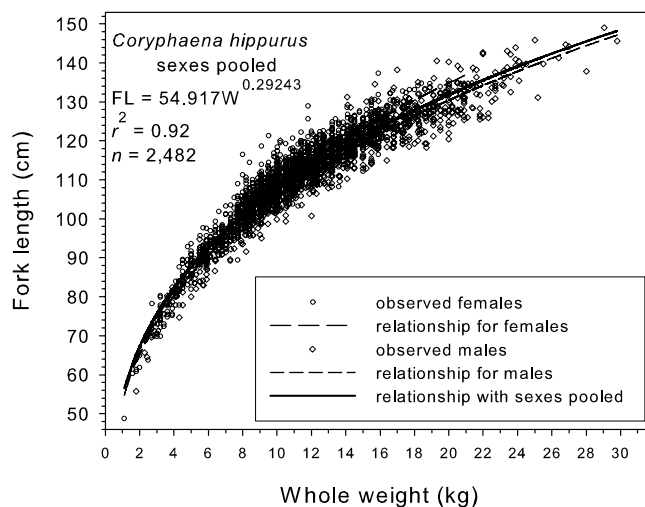
Figure 5.—Fork length-on-whole weight relationship for dolphinfish with sexes pooled.

provided separate equations for males and females (Lasso and Zapata, 1999; Massuti et al., 1999) without providing a statistical justification for the separa- tion. Wang (1979) tabulated the mean W-L separately for males and females. Schuck (1951) and Beardsley (1967) only mentioned that the mean W-L for males was greater than females. This study statistically tested the difference in the W-L coefficients of female and male dolphinfish (Table 1) and the em-

Table 6.—Monthly nonlinear whole weight (W)-on-fork length (FL) relationship for male dolphinfish measured at the Honolulu fish auction from March 1988 through November 1989.

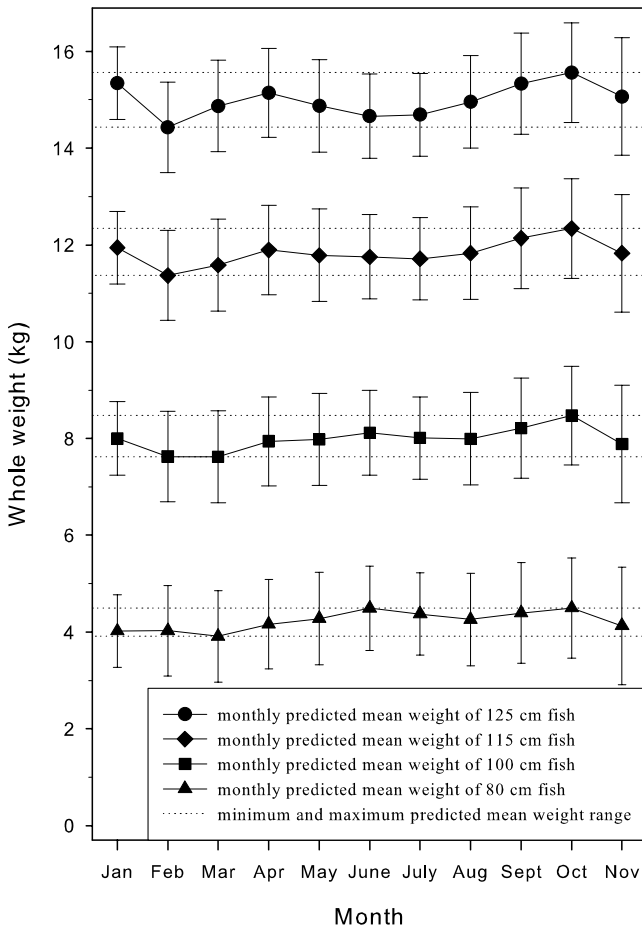| | Model: $W = aFL^b$ | | | Exponent | | Coefficient | | Size range | | | |
| | | | | | | | | Weight (kg) | | Length (cm) | |
Month	r^2	se	n	b	se	a	se	Min.	Max.	Min.	Max.
January	0.98	0.794	10	3.1774	0.14223	3.7031E-6	2.7455E-6	5.2	24.5	84.7	139.8
February	0.94	1.196	63	2.9658	0.086455	9.9674E-6	4.4532E-6	2.7	27.0	69.6	144.2
March	0.94	1.046	133	2.9223	0.05823	1.1973E-5	3.5847E-6	3.6	23.4	80.3	142.7
April	0.91	1.199	191	3.1074	0.065493	5.1216E-6	1.7261E-6	5.5	28.0	88.3	143.0
May	0.91	1.155	224	2.9549	0.056821	1.0779E-5	3.1346E-6	2.4	29.8	64.5	149.0
June	0.90	1.456	33	2.7511	0.16585	2.9241E-5	2.4969E-5	5.7	20.2	83.0	136.0
July	0.97	0.966	19	3.1396	0.16044	4.428E-6	3.7116E-6	2.9	23.2	70.1	136.0
August	0.90	1.680	81	2.9	0.11310	1.4517E-5	8.5439E-6	3.0	26.8	74.2	144.7
September	0.93	1.441	59	2.9870	0.12856	9.6313E-6	6.4295E-6	1.8	22.5	55.8	134.7
October	0.87	1.897	102	2.7954	0.11354	2.4323E-5	1.4378E-6	2.3	25.5	65.7	142.1
November	0.93	1.332	58	2.853	0.10641	1.8129E-5	1.0037E-5	3.9	23.9	82.5	143.9

Figure 6.—Plots of monthly predicted mean whole weights with standard errors for female dolphinfish at 80, 100, 115, and 125 cm fork length.
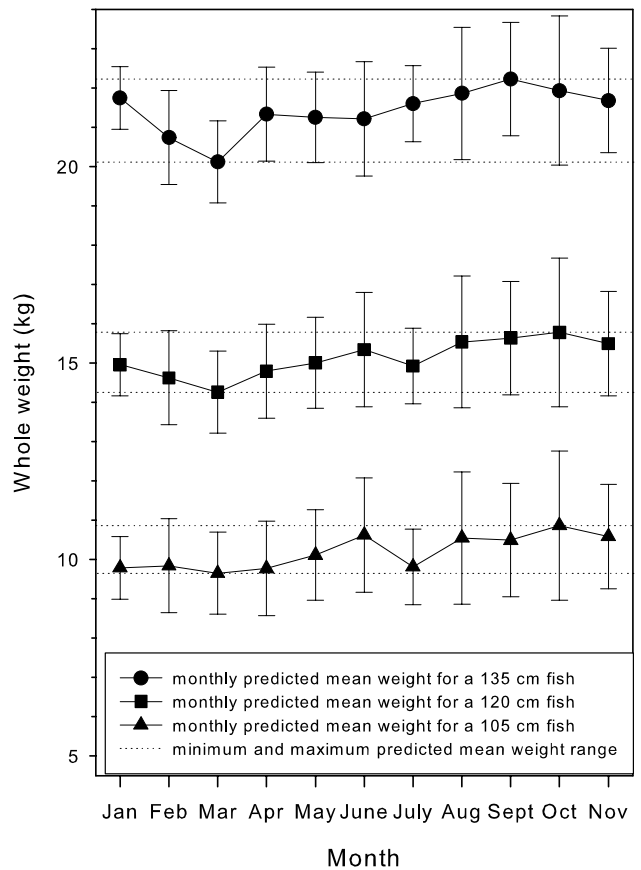

Figure 7.—Plots of monthly predicted mean whole weights with standard errors for male dolphinfish at 105, 120, and 135 cm fork length.

pirical difference in predicted mean W-L can be viewed in Figure 5. Bannister (1976) visually compared plots of W-L relationships of dolphinfish caught in the Mediterranean with those caught off North Carolina in the western Atlantic (Rose and Hassler, 1968). Oxenford and Hunte (1986b) plotted and visually compared the W-L relationships of dolphinfish from North Carolina (Rose and Hassler, 1968), Florida (Beardsley, 1967), and Barbados (their study) and found little difference in the W-L relationships among these locations in the western and central Atlantic. Estimated parameters and other statistical data for log-linearized W-L relationships of Hawaiian dolphinfish are provided so others can statistically compare W-L coefficients of dolphinfish from other areas and especially other areas of the Pacific Basin (Table 4).

The large variances in the W-L relationships for wahoo and dolphinfish were a result of the wide range of well-conditioned-to-poor-conditioned individuals in the samples. Reduced condition was probably a result of energy drain by spawning activities. Based on observation of captive dolphinfish that appeared to spawn every second day at the National Marine Fisheries Service

Table 7.—Multiple regression analysis evaluating the effect of sex on the log-linearized whole weight-on-log fork length (range 110–145 cm) relationships for troll caught wahoo from the Northwestern Hawaiian Islands 1977–1984.

Parameter	Estimate	se	t test	p-value
Coefficient for males	−22.701	0.639	−35.47	<0.01
Exponent for males	3.528	0.089	39.28	<0.01
Difference in coefficient for females	1.321	0.970	1.36	0.18
Difference in exponent for females	−0.187	0.135	−1.37	0.17

$r^2 = 0.95$
$n = 144$
Durbin-Watson statistics = 1.951, p = 0.39

Table 8.—Summary of generalized linear model type III sum of squares analysis evaluating the effects of month (of landing) on the log-linearized whole weight-on-log fork length (FL, range 108–160 cm) relationship for wahoo measured at the Honolulu fish auction from July 1988 through November 1989.

Source	Sum of squares	df	Mean square	F-ratio	p-value
logFL	40.2455	1	40.2455	5226.36	0.00
Month	0.178857	9	0.019873	2.58	<0.01
Month*logFL	0.179448	9	0.0199387	2.59	<0.01
Residual	8.20101	1065	0.00770048		
Total	112.821	1084			

Table 9.—Monthly nonlinear whole weight (W)-on-fork length (FL) relationship for wahoo measured at the Honolulu fish auction from July 1988 through November 1989.

Month	Model: W = aFL^b			Exponent		Coefficient		Size range			
								Weight (kg)		Length (cm)	
	r^2	se	n	b	se	a	se	Min.	Max.	Min.	Max.
January	0.95	1.059	19	3.1191	0.15491	3.3891E-6	2.8705E-6	9.1	27.7	120.7	159.3
February	0.92	1.434	46	2.9131	0.12715	9.5945E-6	6.4853E-6	3.2	23.6	71.3	173.9
March	0.93	1.327	59	3.1704	0.11997	2.6730E-6	1.7757E-6	3.0	33.6	87.4	166.5
April	0.94	1.189	99	3.2147	0.083539	2.1775E-6	9.998E-7	3.6	26.8	90.4	153.3
May	0.92	1.497	276	3.1303	0.053045	3.4287E-6	9.9812E-7	4.1	43.2	94.2	172.5
July	0.91	0.883	87	3.0881	0.093154	3.9022E-6	1.9337E-6	5.4	19.3	103.3	145.5
August	0.92	1.215	379	3.0711	0.044664	4.4064E-6	1.0605E-6	3.9	27.3	91.7	159.3
September	0.90	1.572	85	2.8859	0.085422	1.0734E-5	4.8932E-6	7.7	33.6	107.0	173.1
October	0.91	1.363	77	3.0431	0.10241	4.9982E-6	2.7074E-6	1.8	26.4	71.3	160.9
November	0.96	0.996	34	3.2022	0.10037	2.2782E-6	1.2158E-6	3.0	26.4	84.0	163.3

Table 10.—Nonlinear and log-linearized whole weight (W)-on-fork length (FL) and FL-W relationships for wahoo measured at the Honolulu fish auction from July 1988 through November 1989.

Relation	Model Y = aX^b			Exponent		Coefficient		Size range			
								W (kg)		FL (cm)	
	r^2	se	n	b	se	a	se	Min.	Max.	Min.	Max.
W on FL	0.92	1.330	1161	3.3034	0.024087	1.4157E-6	1.8177E-7	1.8	43.2	71.3	173.1
FL on W	0.94	3.3141	1161	0.27500	0.0020360	63.434	0.33973				

	logW = loga + b*logFL				Slope		Intercept	
	r^2	se	n	rss	b	se	loga	se
logW on logFL	0.95	0.0895019	1161	9.28428	3.45171	0.0236125	−14.1959	0.114339

Additional statistical data for log linearized model

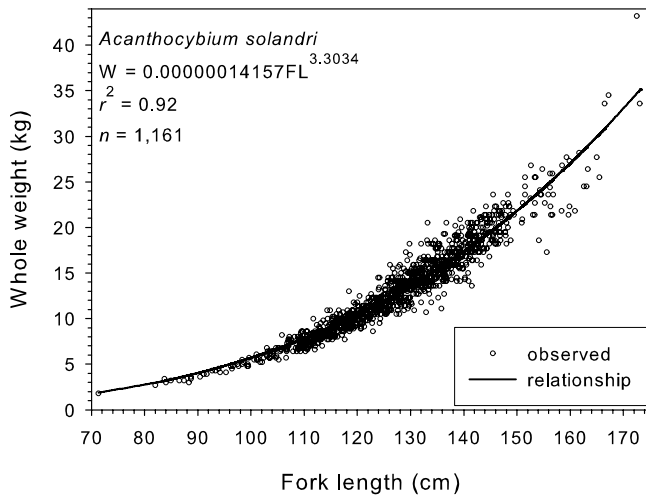|	
mean logFL = mean X	4.84104
Σ(logFL–mean logFL)^2 = Σx^2	14.3675
Σ(logFL–mean logFL)*(logW–mean logW) = Σxy	49.5926
Σ(logW–mean logW)^2 = Σy^2	185.558
mean logW = mean Y	2.58022

Figure 8.—Whole weight-on-fork length relationship for wahoo measured at the Honolulu fish auction, July 1988–November 1989.
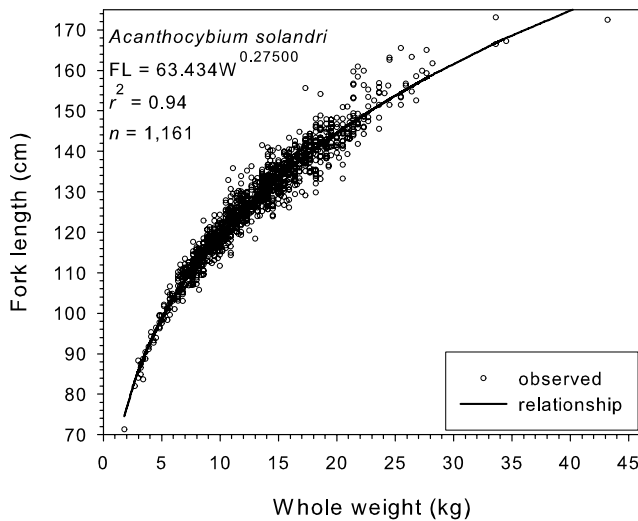

Figure 9.—Fork length-on-whole weight relationship for wahoo measured at the Honolulu fish auction, July 1988–November 1989.

Figure 10.—Plots of monthly predicted mean whole weights with standard errors for wahoo at 120, 135, and 150 cm fork length.

Kewalo Research Facility, weight lost by a mating pair was clearly noticeable after 2 months of spawning. A recovery of condition was also observed when the mating pair was separated.[7]

The classic modal cycle in condition (LeCren, 1951) seen in Hawaii-caught wahoo (Fig. 10) and suggestion of bimodality in the condition factor of dolphinfish (Fig. 6, 7) may have an interesting relationship to patterns of seasonal abundance of these species in Hawaii fisheries. Wahoo catch per trip has one mode during May–September for all three fisheries, whereas dolphin-fish catch per trip in the Hawaii longline, troll, and handline fisheries is bimodal, peaking at its highest in April and high again during October–November.[8,9] The seasonality of the catch mirrors the catch rates, and although there is interannual variation in this pattern, the typical pat-tern was observed during all of the years of this study.[2]
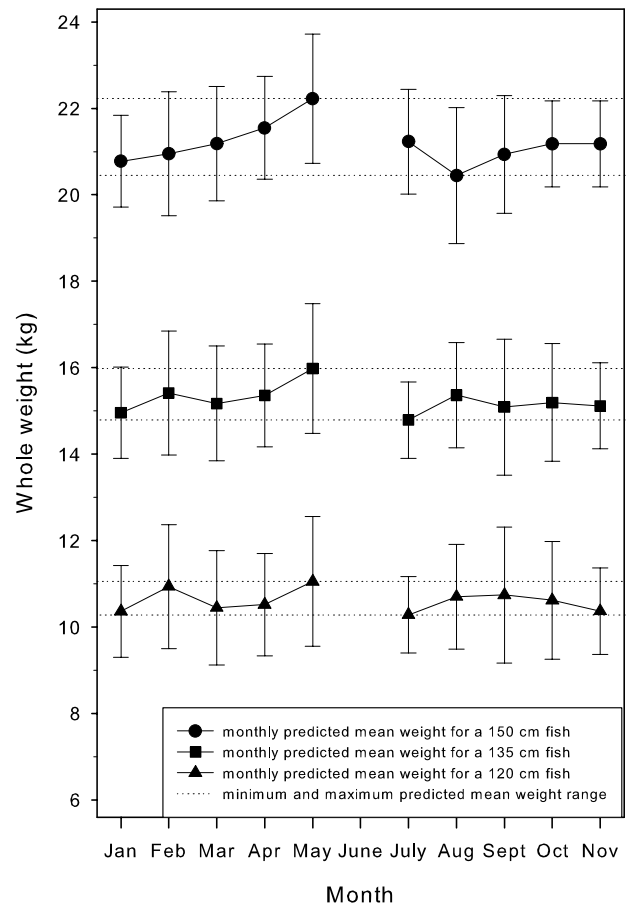
The condition and abundance of wahoo appear to be related to a simple annual reproductive cycle. Ovaries collected from around the main Hawaiian Islands and at the edge of the banks in the Northwestern Hawaiian Islands contain oocytes with yolk globules, oo-

cytes that had begun to hydrate, or have post ovulatory follicles in the summer months. In September, oocytes in ovaries are in the atretic stage[10] indicating the end of the spawning season. The condition of wahoo is highest in May before the spawning season and declines through the spawning season reaching a minimum in July–August (Fig. 10). Catch peaked in summer, during the spawning season, suggesting that wahoo may gather near the islands to spawn.

Such a pattern is also seen in central North Pacific swordfish, *Xiphias gladius*, which spawn close to the islands and large banks of the Hawaiian archipelago (DeMartini et al., 2000). Swordfish condition is highest in February–March (at the beginning of its spawning period) and is lowest in July–August (at the end of the spawning period) (Uchiyama et al., 1999). The Hawaii longline fishery for swordfish follows the concentration of fish from the subtropical convergence far north of the islands in January–February down closer to the islands during March–May (Bigelow et al., 1999). The only appreciable occurrence of swordfish in coastal Hawaii fisheries subsequently occurs in June.[8] This pattern in catch rates suggests a southward reproductive migration during the first 6 months of the year (DeMartini et al., 2000). For the rest of the year swordfish are scarce until they appear again far to the north around the subarctic convergence in November–December (Bigelow et al., 1999).

We postulate that migration related to reproduction may also explain some of the seasonality in catch rates of wahoo near the Hawaiian Islands. Eight wahoo ovaries collected > 50 mi. (>93 km) from shore were undeveloped or in the early stages of development.[10] The occurrence of wahoo larvae in plankton tows within 15 mi. (28 km) from shore of the islands in the main Hawaiian Islands has been reported during June–September by Miller et al. (1979) and by Boehlert and Mundy (1996). It

appears that wahoo may migrate from the open ocean to the islands and banks to reproduce and then leave the islands and banks to feed in the open ocean. Surface currents[11] and eddies generated in the island wakes (Wyrtki et al., 1967; Patzert, 1969; Barkley, 1972) are mechanisms that could transport larvae and juveniles to the open ocean.

Matsumoto (1967) found 38 wahoo larvae and juveniles in 1,643 samples from oblique plankton tows collected from the open ocean, so a limited amount of spawning could also occur offshore. However, a move to nearshore waters in May for spawning throughout the summer would be consistent with the increase in condition and catch rates in the nearshore fisheries. An analysis now underway of geographic patterns and shifting of high catch rate areas visited by the Hawaii-based longline fleet suggests that the highest abundance areas for wahoo within range of the fleet are southwest of the islands year round but spread northward into coastal banks distributed over 1,200 mi. in summer.[12]

The bimodal pattern of relative monthly abundance and how it could relate to spawning and condition of dolphinfish appears more complex than for swordfish or wahoo. Peak spawning occurs in April–May[13] coincident with peak catch rates and increased condition. However, spawning continues year round near the islands[14], the condition maximum occurs late in the year during the second mode in catch rates, and the condition minimum follows in February.

[11]Firing, J., R. Hoeke, and R. Brainard. 2004. Surface velocity and profiling drifters track potential larval pathways in Northwestern Hawaiian Islands. Poster presentation at Northwestern Hawaiian Islands Third Scientific Symposium, 2–4 Nov. 2004, Hawaii Convention Center, Honolulu.

[12]Kobayashi, D. 2004. Unpubl. data on file at Pac. Isl. Fish. Sci. Cent., Natl. Mar. Fish. Serv., 2570 Dole Street, Honolulu, HI 96822-2396.

[13]Burch, R. K. Biologist. Waikiki Aquarium, Honolulu, HI 96815. Personal commun., May 1982.

[14]Uchiyama, J. H., and R. A. Skillman. Unpubl. data on file at Pac. Isl. Fish. Sci. Cent., Natl. Mar. Fish. Serv., 2570 Dole Street, Honolulu, HI 96822-2396.

We suggest that the spring peak in catch rate and the summer decline in catch and condition could be related to spawning aggregation near the Hawaiian Islands. Dolphinfish ovaries collected in the main Hawaiian Islands and around the large shallower banks with low islands or coral atolls to the northwest in the Northwestern Hawaiian Islands all appear ready to spawn or had just spawned, based on presence of hydrated eggs or post-ovulatory follicles. Relatively few ovaries of dolphinfish collected > 70 mi. (>130km) from shore developed hydrated eggs, but the majority of other dolphinfish ovaries were undeveloped or appeared to be reabsorbing the vitellogenic oocytes before they had reached maturity.[14]

The September–October maximum spawning condition coincident with rise in coastal catch rates October–November could result from a return to the islands of the Hawaiian archipelago after a nonspawning interval offshore. However, the increased condition could also suggest that fish return from more productive waters near the southern boundary of the subtropical convergence to the north. An analysis now underway[12] of geographic patterns and shifting of high catch rate areas visited by the Hawaii-based longline fleet suggests that the highest abundance areas shift far to the north during summer. And the February–March minimum condition could reflect energy losses during winter spawning.

Summary

We postulate two possible migration scenarios which might explain changes in dolphinfish condition. In the first scenario, well conditioned fish enter nearshore (< 50 mi. or < 93 km) waters from the open ocean, and engage in intense reproductive activities, resulting in weight loss. The dolphinfish, now in an emaciated state, return to the open ocean. In the summer, the density of dolphinfish near the main Hawaiian Islands is low, perhaps because they migrate offshore to avoid their main predator, the blue marlin, *Makaira nigricans*, which increase in numbers in nearshore waters

[10]Uchiyama, J. H., and J. H. Prescott. 2004. Unpubl. data on file at Pacific Islands Fisheries Science Center, Natl. Mar. Fish. Serv., 2570 Dole Street, Honolulu, HI 96822-2396.

to reproduce (Hopper, 1990). While offshore during the summer, dolphinfish improve their condition during a nonreproductive period. When they return in late September and October, their condition is at their highest level. A similar nearshore-offshore spawning movement for dolphinfish has been suggested by Wheeler and Ommanney (1953), Williams (1953), Kojima (1955), Williams and Newell (1957), and Arocha et al. (1999).

In the second possible complementary migration scenario, juvenile dolphinfish migrate northward in summer up to ~600 mi. (1,100 km) from the main Hawaiian Islands to the southern boundary of the subtropical convergence front where productivity is high. There they fatten up and then migrate southward back to the Hawaiian archipelago to reproduce again nearshore. This model would be similar to the migration model described by Oxenford and Hunte (1986a). A clearer picture may emerge from the longline fleet catch rate analysis. And the February–March condition maxima suggest that field researchers should look for evidence of an early peak in spawning.

Acknowledgments

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