5.4 Assessing fish condition: Index-based determination of the physiological condition of Pacific halibut

Bryan A. Briones Ortiz[1]

Abstract

Pacific halibut (*Hippoglossus stenolepsis*) is an ecologically and commercially important flatfish species in North America. The International Pacific Halibut Commission (IPHC) performs research in various areas to better manage and preserve the North American stock of Pacific halibut. In this study, the applicability of methods to assess the physiological condition of Pacific halibut was investigated. Physiological condition, commonly related to the amount of energy available in organisms, is linked to fat storage. Several methods were explored to determine the physiological condition in Pacific halibut: Fulton's condition factor (*K*), relative condition factor (*Kn*), hepatosomatic index (HSI), gonadosomatic index (GSI), somatic lipid content measures by microwave-based fat meter as well as by bioelectric impedance analysis (BIA), and, finally, landmark-based geometric morphometric (shape) analyses. Data was collected during IPHC's fishery-independent setline survey in the summer of 2016 in SE Alaska. *K* was discarded as a viable condition index for Pacific halibut as it was confounded by fork length. However, K_n was positively correlated to somatic lipid content and HSI, measures that directly reflect energy availability. Although BIA was negatively correlated with fat meter readings, no significant correlations between BIA nor shape and any other method were found. In addition, GSI was found to be a better proxy to determine temporal gonadal condition rather than general fish condition. Therefore, GSI, BIA, and shape analyses were considered not suitable to assess the overall physiological status of Pacific halibut. It was concluded that K_n and microwave-based fat meter determinations could be used to determine the physiological condition of Pacific halibut, as they may reflect the amount of energy available in the fish. These methods can now be used to investigate temporal and spatial changes in physiological condition in Pacific halibut throughout its distribution range and to link these changes with environmental conditions.

Introduction

Pacific halibut (*Hippoglossus stenolepsis*) is a flatfish species that belongs to the Pleuronectidae family. Commercially, Pacific halibut are highly demanded species due to their firm texture, large size, and reduced number of bones compared to other fish species (IPHC 2014). With more than 23,900,000 pounds (~10,841 t) of Pacific halibut landed in 2015, the Pacific halibut fishery remains one of the most valuable in North America (Gilroy et al. 2015). In an attempt to sustainably maintain the North American stock of Pacific halibut, the International Pacific Halibut Commission (IPHC) conducts annual fishery-independent setline surveys to evaluate the overall status of the species. In addition, other complimentary ecological and environmental studies are performed to enhance and expand the knowledge regarding Pacific halibut (IPHC 2014).

---

[1] The IPHC provides opportunities for undergraduate student interns and encourages them to prepare reports of their projects conducted at the IPHC. Reports by interns are included here with only minor editing.

A paramount aim in ecological studies is the development of methods that assess the nutritional and physiological statuses of living organisms. The relevance of these types of studies relies on the influence of body conditions on the performance of the organism (Brosset et al. 2015b). For instance, an animal with a relatively healthier physiological condition is considered to have improved fitness for activities such as reproduction, migration, etc. (Brosset et al. 2015a). Most commonly, the physiological status of an organism is related to its energy availability, which is also referred to as its energy storage. All in all, it has been generally concluded that an individual with greater stored energy has improved or better physiological condition (Mesa and Rose 2015). Studies focusing on the relationship between energy stores and performance are helpful to examine the condition of organisms over time and predict the outcomes of seasonal biological phenomena for species populations of interest.

Physiological condition can be assessed in a variety of ways. Ideal methods for achieving accuracy in analyzing the body condition of organisms require technical biochemical analyses. These approaches are known to be expensive, time-consuming, and disruptive for the animals; thus making these procedures impractical for application in the field or at broad scales (Cox and Heintz 2009, Mesa and Rose 2015). As a result, many other surrogate methods for attempting to assess the physiological condition of fishes have been developed, all of which have been largely debated (Bolger and Connolly 1989). Most of these methods, referred to as traditional morphometric indices, base their analyses on the assumption that the fat storage content of an individual reflects the amount of energy stored, with greater fat presence indicating a healthier individual (Davidson and Marshall 2010).

Some of the simplest methods for assessing physiological condition, due to the easiness of their application, are those known as condition factors. Firstly, Fulton's Condition Factor (*K*) relates the total length and round body weight of a fish with the assumption that, for a certain given length, the heavier individuals are in better conditions (Bolger and Connolly 1989). However, controversy for this index has arisen based on the argument that the weight-length relationship does not account for specific individual condition since factors such as diseases and unusual body tissue makeup could potentially cause a deviation from the regular condition factor pattern, thus making Fulton's *K* unreliable in some cases (Froese 2006). Another index with similar applications and controversies is the relative condition factor (*Kn*). This index relates observed weights to the calculated weights of each individual based on the entire population sampled in order to avoid confounding ontogenic (age-related) or allometric (size-related) growth effects in the analyses. Regardless of the dispute about the effectiveness of these traditional morphometric indices, they are still widely used due to the relative simplicity of their application (Bolger and Connolly 1989; Froese 2006; Brosset et al. 2015).

Additional morphometric methods for studying body condition include the gonadosomatic (GSI) and hepatosomatic (HSI) indices, which directly relate the weights of the gonads and liver, respectively, to the fish's body weight (Bolger and Connolly 1989). These methods have been developed with the consideration that some fishes do not always rely on muscle somatic tissue as their primary energy storage reserve, but on specific organs such as the liver or the gonads. The peculiar presence of fat in these organs tends to indicate specific allocations of energy reserves to metabolic or reproductive processes primarily (Medford and Mackay 1978).

More technological analyses include sophisticated devices that attempt to obtain non-intrusive measurements directly from the fish muscle. A common type of electrical conductivity method used is the Bioelectrical Impedance Analysis (BIA). This approach measures the resistance and reactance of electric currents passing through the fish muscle, which are affected by the composition of nutrients, water, and lipids in the tissue being tested. BIA calculates the Phase Angle, which can be used to estimate the quality of the tissue sampled and reflect fish condition and health (Hartman et al. 2015). Another alternative method performs a similar type of examination but uses microwave technology to estimate the fat content in the fish; these are hand-held devices commonly known as "fat meters" (Davidson and Marshall 2010). Despite their extensive use, much discussion about the effectiveness of these two procedures for different types of fishes has occurred. In essence, studies discussing the performance of the BIA and fat meter analyses agree that both methods can provide reliable results but are extremely dependent on the type of fish being studied and other external factors influencing the examination, such as temperature and time postmortem (Cox et al. 2011; Klefoth et al. 2013).

Lastly, landmark-based morphometric examinations base their analyses on shape differences of the bodies of the target organisms. The outcomes of these studies are ecologically important to characterize body shape differences between distinctive populations, track evolutionary changes in related taxa through time, and potentially assess body conditions of organisms (Cadrin and Silva 2005; Alós et al. 2014).

Research was performed by the IPHC staff in 2016 to explore the effectiveness of the abovementioned indices in assessing the physiological condition of Pacific halibut. Statistical analyses were performed in an attempt to find correlations between indices and fish condition. The purpose of this study regards the search and establishment of optimal condition factors that can potentially provide valuable information about the health and energy statuses of the North American Pacific halibut stock.

Methods

1. Sampling

Data collection took place during the months of June through August of 2016 in Southeast Alaska, USA. A total of 488 randomly-selected fish were sampled at sea aboard the F/V *Kema Sue* (an IPHC survey vessel) from 65 IPHC setline survey stations (Fig. 1 & Table 1). Other data regarding offloads was obtained at the fishing ports of Sitka, Petersburg, and Juneau, AK, USA.

2. Indices of Physiological Condition – Data Collection and Analyses

Sufficient data for performing analyses with the seven abovementioned indices were gathered by the principal investigators or obtained from the IPHC regular survey data collection database. Statistical analyses performed include linear regressions between the main indices with each other and with complimentary data (length, weight, and station depth) – these analyses were performed using R Studio[1] software. In addition, all the statistical tests were executed for the entire sample group and for females and males only, separately (Tables 3 & 4). Collection and analyses methods are detailed as follows:

2.1 *Fulton's Condition Factor (K)*

Round fish fork lengths were measured from the tip of the snout to the end of the middle caudal fin rays using HAMA Technologies measuring cradle. Round fish weights were measured using a motion-compensated BIBBICO[2] Marine Scale B5440, Ryco 820 display (Table 1).

---

[1] R Studio, 250 Northern Avenue, Boston, MA, 02210, USA.

[2] BIBBICO, LLC, 922 NW 50th Street #1, Seattle, WA, 98107, USA.

The traditional formula for obtaining Fulton's K (Le Cren 1951) was used for this study. This analysis uses round fish length (L) measured in cm, weight (W) measured in grams, and a scaling factor (c) to approximate the values to 1 (Eq. 1).

$$K = c * \frac{W}{L^3} \tag{1}$$

2.2 *Relative Condition Factor (Kn)*

Round fish lengths and weights were used for this analysis. This formula (Le Cren 1951) takes into account observed fish weight (W) and calculated fish weight (), both in grams (Eq. 2).

$$Kn = \frac{W}{\widehat{W}} \tag{2}$$

A parabolic equation was used to estimate the calculated weight, where L and W are the length in cm and weight in grams of each individual fish, respectively, and a and b are constants determined by the coefficients of the linear regression between length and weight (Eq. 3).

$$\widehat{W} = aL^b \tag{3}$$

Because the length-weight relationship of Pacific halibut is not linear but exponential (Fig. 2), a logarithmic transformation was used to better meet the assumptions of statistical inference, which modified the original formula (Eq. 4).

$$Log(W) = Log(a) + bLog(L) \tag{4}$$

2.3 *Hepatosomatic Index (HSI)*

Livers were obtained from randomly-selected fish and weighed using a motion-compensated BIBBICO B3220 / 3Kg Marine Scale – Ryco 820. A total of 190 livers (14-872 g) were measured. The total liver weight (H), in grams, was used to calculate the percentage of liver weight to round fish body weight (Eq. 5).

$$HSI\ (\%) = \frac{H * 100}{W} \tag{5}$$

2.4 *Gonadosomatic Index (GSI)*

Gonads were obtained from randomly-selected fish and weighed using a motion-compensated BIBBICO B3220 / 3Kg Marine Scale – Ryco 820. A total of 141 ovaries (10-1,080 g) and 43 testes (6-96 g) were measured. The total gonad weight (G), in grams, was used to calculate the percentage of gonad weight to round fish body weight (Eq. 6).

(6) $$GSI\ (\%) = \frac{G * 100}{W}$$

2.5 *Somatic Fat Content*

Somatic fat content was estimated using the Distell[3] Fish Fatmeter Model FFM 692 (Fig. 4), with the standard calibration for Sea Bass II. The readings were obtained from the blind side of the fish, which was divided into four sites (Fig. 3). Two readings were recorded from each site and averaged. A grand mean of the averaged readings from each of the four sites was used as a primary somatic fat content index for this study.

2.6 *Phase Angle*

A bioelectrical impedance device from Seafood Analytics[4] (Fig. 4) was used to obtain a single reading on site 1 of the fish. The device was equipped with two signal electrodes and two detecting electrodes that introduce an 800µA, 50kHz, AC current that is capable of voltage changes between 3.75-10.60V. Both reactance (*Xc*) and resistance (*R*) of the samples were measured. These values were used to calculate individual phase angles (Eq. 7).

(7) $$Phase\ Angle\ (°) = \frac{tan^{-1}\left(\frac{X_c}{R}\right) * 180°}{\pi}$$

2.7 *Landmark-Based Geometric Morphometrics (Shape)*

A GoPro[5] Hero4 Black was used to obtain images of the fish as they were measured on the cradle. A system of mounts was used to position the camera about 1 m above the fish, coinciding with the middle line of the cradle (Fig. 5). The GoPro Studio software was used to correct the fisheye effect for proper image analysis. The landmark-based morphometric analysis method was applied in this study. tpsUtil32 and tpsDig232 software were used to digitize the images and acquire the landmark coordinates, respectively. A total of 15 landmarks were defined for the image analyses (Table 2 & Fig. 6). The analyses were completed using the R statistical software[6] packages *geomorph* and *car* and their dependencies to perform Procrustes fits and the subsequent tests.

3. Fish Condition at Offloads

Somatic fat content and phase angles were obtained from offloaded (gutted and iced) fish measuring over 81 cm using the previously described devices. For fat content, sampling was performed on the four defined sites of the blind side of the fish, whereas only site 1 was sampled for phase angle.

---

[3] Distell, Old Levenseat, Fauldhouse, West Lothian EH47 9AD, Scotland, UK.

[4] Seafood Analytics, 33939 Harper Avenue, Clinton Township, MI 48035, USA.

[5] GoPro, www.gopro.com.

[6] The R Project for Statistical Computing, https://www.r-project.org.

Results

Indices of Physiological Condition

1. Fulton's Condition Factor

1.1 ***Entire Sample***

Fulton's *K* ranged from 0.558 to 1.434 and showed statistically significant positive correlations with four other major indices: *Kn* (R^2= 0.754), HSI (R^2= 0.135), GSI (R^2= 0.138), and somatic fat content (R^2= 0.118). In addition, significant positive correlations were found between *K* and fork length (R^2= 0.250) and round weight (R^2= 0.323). No significant correlations were found with the phase angle and shape, as well as with station depth (Tables 3 & 5).

Significant differences were found between males (= 0.968) and females (= 0.968), and fish caught in inside (= 1.011) and outside (= 0.991) water stations (Tables 6 & 7).

1.2 ***Females***

The values of Fulton's *K* for females ranged from 0.553 to 1.421. Statistically significant positive correlations were found between Fulton's *K* and *Kn* (R^2= 0.763), HIS (R^2= 0.181), GSI (R^2= 0.129), and somatic fat content (R^2= 0.157), whereas a significant negative correlation was found with Phase Angle (R^2= -0.028). Likewise, positive correlations were found with fork length (R^2= 0.238) and round weight (R^2= 0.331). No significant correlation was found with the shape or with station depth (Tables 4 & 5).

A significant difference was found between females caught in inside (= 1.011) and outside (= 0.990) water stations. In addition, maturity stages 1 (= 0.966), 2 (= 1.075), and 4 (= 1.018) showed significant differences among themselves when tested independently as pairs (Tables 7 & 8).

1.3 ***Males***

The values of Fulton's *K* for males ranged from 0.809 to 1.418. A statistically significant positive correlation was found between Fulton's *K* and *Kn* (R^2= 0.912) only. Positive correlations were also found with fork length (R^2= 0.211) and round weight (R^2= 0.385). All the other major indices, as well as station depth, showed no significant correlations with Fulton's *K* for males only (Tables 4 & 5).

No significant differences were found between male Pacific halibut caught in inside and outside water stations (Table 7).

2. Relative Condition Factor

2.1 Entire Sample

Kn ranged from 0.518 to 1.345 and showed statistically significant positive correlations with three other major indices: Fulton's *K* (R^2= 0.754), HSI (R^2= 0.046), and somatic fat content (R^2= 0.005). In addition, a significant positive correlation was found between *Kn* and round weight (R^2= 0.0138), and a negative correlation with station depth (R^2= -0.013). No significant correlations were found with the GSI, phase angle, and shape, or with fork length (Tables 3 & 9) (Fig. 7).

No significant differences were found between males and females or between fish caught in inside and outside water stations (Tables 10 & 11).

1.2 *Females*

The values of *Kn* for females ranged from 0.518 to 1.317. Statistically significant positive correlations were found between *Kn* and Fulton's *K* (R^2= 0.763), HIS (R^2= 0.058), and somatic fat content (R^2= 0.068). Likewise, a positive correlation was found with round weight (R^2= 0.331) and a negative correlation with station depth (R^2= -0.020). No significant correlations were found with the GSI, Phase Angle, and shape, or with fork length and station depth (Tables 4 & 9).

No significant difference was found between females caught in inside and water stations. Maturity stages 1 (= 0.997), 2 (= 1.030), and 4 (= 0.973) showed significant differences among 1 & 2 and 2 & 4 when tested independently as pairs (Tables 11 & 12).

1.3 *Males*

The values of *Kn* for males ranged from 0.766 to 1.308. A single statistically significant positive correlation was found with Fulton's *K* (R^2= 0.912). In addition, a positive correlation was also found with round weight (R^2= 0.066). All the other major indices, as well as fork length and station depth, showed no significant correlations with Relative *K* for males only (Tables 4 & 9).

No significant differences were found between male Pacific halibut caught in inside and outside water stations (Table 11).

3. **Hepatosomatic Index**

3.1 *Entire Sample*

HSI ranged from 0.353 % to 2.243 % and showed statistically significant positive correlations with four other major indices: Fulton's *K* (R^2= 0.135), *Kn* (R^2= 0.046), GSI (R^2= 0.281), and Fat content (R^2= 0.179). In addition, significant positive correlations were found between HSI and fork length (R^2= 0.181) and round weight (R^2= 0.163). No significant correlations were found with the phase angle and shape, as well as with station depth (Tables 3 & 13).

Significant differences were found between males (= 0.852 %) and females (= 0.966 %), whereas no significant difference was found between fish caught in inside and outside water stations (Tables 14 & 15).

3.2 *Females*

The values of HSI for females ranged from 0.353 % to 2.243 %. Statistically significant positive correlations were found between HSI and Fulton's *K* (R^2= 0.181), *Kn* (R^2= 0.058), GSI (R^2= 0.398), and somatic fat content (R^2= 0.217). Likewise, positive correlations were found with fork length (R^2= 0.229) and round weight (R^2= 0.201). No significant correlation was found with the Phase Angle index, shape, or with station depth (Tables 4 & 13).

No significant difference was found between females caught in inside and outside water stations. In addition, maturity stages 1 (= 0.814), 2 (= 1.218), and 4 (= 0.991) showed significant differences among themselves when tested independently as pairs (Tables 15 & 16) (Fig. 8).

3.3 *Males*

The values of HSI for males ranged from 0.382 % to 1.913 %. No statistically significant correlations were found between HSI and the other major indices. In addition, no significant correlations were found with fork length, round weight, and station depth (Tables 4 & 13).

No significant differences were found between male Pacific halibut caught in inside and outside water stations (Table 15).

4. Gonadosomatic Index

1.1 *Entire Sample*

GSI ranged from 0.163 % to 2.778 % and showed statistically significant positive correlations with three other major indices: Fulton's *K* (R^2= 0.138), HSI (R^2= 0.281), and Fat content (R^2= 0.092). In addition, significant positive correlations were found between GSI and fork length (R^2= 0.436) and round weight (R^2= 0.365). No significant correlations were found with the Phase Angle, *Kn*, and shape, as well as with station depth (Tables 3 & 17).

A significant difference was found between males (= 0.421 %) and females (= 1.127 %), but not between fish caught in inside and outside water stations (Tables 18 & 19).

1.2 *Females*

The values of GSI for females ranged from 0.385 % to 2.778 %. Statistically significant positive correlations were found between GSI and Fulton's *K* (R^2= 0.129), HSI (R^2= 0.398), and Fat content (R^2= 0.135). Likewise, positive correlations were found with fork length (R^2= 0.378) and round weight (R^2= 0.307). No significant correlation was found with the *Kn*, Phase Angle, and shape, or with station depth (Tables 4 & 17).

No significant difference was found between females caught in inside and outside water stations. In addition, maturity stages 1 (= 0.787), 2 (= 1.651), and 4 (= 1.389) showed significant differences among themselves when tested independently as pairs (Tables 19 & 20) (Fig. 8).

1.3 *Males*

The values of GSI for males ranged from 0.163 % to 0.912 %. No statistically significant correlation was found between GSI and the other indices, or with fork length, round weight, and station depth (Tables 4 & 17).

No significant differences were found between male Pacific halibut caught in inside and outside water stations (Table 19).

5. Somatic Fat Content

1.1 *Entire Sample*

Somatic fat content (FC) ranged from 0.625 % to 3.125 % and showed statistically significant positive correlations with Fulton's *K* (R^2= 0.118), *Kn* (R^2= 0.005), HSI (R^2= 0.179), and GSI (R^2= 0.092), and a significant negative correlation with Phase Angle (R^2= -0.054). In addition, significant positive correlations were found between fat content and fork length (R^2= 0.118) and round weight (R^2= 0.119). No significant correlations were found with shape or with station depth (Tables 3 & 21).

A significant difference between fish caught in inside (= 0.857 %) and outside (= 0.985 %) water stations was found, but not between males and females (Tables 22 & 23).

1.2 *Females*

The values of somatic fat content for females ranged from 0.625 % to 3.125 %. Statistically significant correlations were found between Fat content and Fulton's *K* (R^2= 0.157), *Kn* (R^2= 0.068), HSI (R^2= 0.217), GSI (R^2= 0.135), and Phase Angle (R^2= -0.073). Likewise, positive correlations were found with fork length (R^2= 0.114) and round weight (R^2= 0.144). No significant correlation was found with shape or with station depth (Tables 4 & 21).

No significant difference was found between females caught in inside and outside water stations. In addition, maturity stages 1 (= 0.775 %), 2 (= 1.212 %), and 4 (= 0.914 %) showed significant differences among themselves when tested independently as pairs (Tables 23 & 24).

1.3 *Males*

The values of somatic fat content for males ranged from 0.625 % to 3.125 %. No statistically significant correlation was found between fat content and the other indices, or with fork length, round weight, and station depth (Tables 4 & 21).

No significant difference was found between male Pacific halibut caught in inside and outside water stations (Table 23).

6. **Phase Angle**

1.1 *Entire Sample*

Phase Angle ranged from 22.99° to 60.30°, and showed a statistically significant negative correlation with somatic fat content only (R^2= -0.054) (Fig. 9). In addition, significant correlations were found between Phase Angle and round weight (R^2= -0.016) and station depth (R^2= -0.024). No significant correlations were found with the other indices or with fork length (Tables 3 & 25).

A significant difference between fish caught in inside (= 32.42°) and outside (= 29.85°) water stations was found (Fig. 10), but not between males and females (Tables 26 & 27).

1.2 *Females*

The values of Phase Angle for females ranged from 22.99° to 60.30°. Statistically significant correlations were found between Phase Angle and Fulton's K (R^2= -0.028) and somatic fat content (R^2= -0.002). Likewise, positive correlations were found with fork length (R^2= 0.033) and round weight (R^2= 0.053). No significant correlation was found with the *Kn*, HSI, GSI, and shape, or with station depth (Tables 4 & 25).

A significant difference was found between female Pacific halibut caught in inside (= 32.47°) and outside (= 29.94°) water stations, but not among maturity stages (Tables 27 & 28).

1.3 *Males*

The values of Phase Angle for males ranged from 26.52° to 40.20°. No statistically significant correlation was found between Phase Angle and the other indices, or with fork length, round weight, and station depth (Tables 4 & 25).

A significant difference was found between male Pacific halibut caught in inside (= 32.25°) and outside (= 29.39°) water stations (Table 27).

7. **Morphometrics**

1.1 *Entire Sample*

The average shape for the entire sample is pictured in Figures 11 & 12. No significant correlations were found between shape and the rest of indices. In addition, no significant correlations were found with the fork length, round weight, and station depth (Tables 3 & 29).

No significant difference between fish caught in inside and outside water stations was found, or between males and females.

1.2 *Females*

The average shape for the female Pacific halibut sampled is pictured in Figure 13. A single significant correlation was found for shape: GSI (R^2= 0.345). Likewise, positive correlations were found with fork length (R^2= 0.281) and round weight (R^2= 0.229). No significant correlation was found with the Fulton's *K*, Relative *K*, GSI, Fat content, and Phase Angle, as well as with station depth (Tables 4 & 29) (Fig. 15).

No significant difference was found between female Pacific halibut caught in inside and outside water stations, or among female maturity stages.

1.3 *Males*

The average shape for the male Pacific halibut sampled is pictured in Figure 13. No statistically significant correlation was found between shape and the other indices, or with fork length, round weight, and station depth.

No significant difference was found between male Pacific halibut caught in inside and outside water stations.

Offload Condition

Somatic fat content was estimated to be the highest at site 1, and decreased as it approached the caudal end of the fish (Fig. 14). In addition, the values of Phase Angle decreased more as the fish remained in the fish hold of the survey vessel for longer time (Fig. 16). Finally, the rate of decrease of Phase Angle showed to be greater during the first days that the fish were stored in the fish hold than in subsequent days (Fig. 17).

Discussion

The use of the Fulton's Condition Factor formula for fishes has long been debated, considering that most fish species do not maintain a constant length-weight relationship (isometric growth) as the equation assumes (Froese 2006). According to such formula, weight varies as a cube of length, but in reality most fish species experience a more pronounced increase in weight relative to length, and Pacific halibut is not the exception (Fig. 2). As a result, Fulton's K highly favors greater length fish, thus making this specific index unreliable for assessing condition of Pacific halibut (Froese 2006) (Fig. 18).

Relative condition factor, in turn, shows no correlation with Pacific halibut length (Fig. 19), and has been considered as an effective alternative method for assessing the condition of fish that show variations in length and belonging to a population that maintains a single length-weight relationship (Le Cren 1951; Froese 2006). In this present study, Pacific halibut data was collected in IPHC Regulatory Area 2C. Given that this area presents considerably low yearly net immigration and emigration rates of 6.3 % and 9.8 %, respectively, for O32 halibut (Webster et al. 2013), it could be safe to assume that no significant disruption in the length-weight relationship of the Pacific halibut population in this area has occurred. In this study, Kn was highly correlated with the HSI and with somatic fat content, both of which indicate a greater presence of fat in the fish. As many other studies have shown, greater presence of fat is an indicator of greater energy stored, thus also an indicator of better physiological condition (Davidson and Marshall 2010).

Although no significant difference in relative condition factor was found in fish caught in inside and outside stations, it appears that depth does have an effect on fish condition, as evidenced by the negative correlation of Kn and station depth. A possible explanation for this phenomenon might be prey availability throughout the depth cline. The type of diet and amount of prey consumed by Pacific halibut settled at different depths could influence nutrient and fat assimilation, therefore affecting fish condition (Vetter et al. 1994; Best and St-Pierre 1986). In addition, females in maturity stage 2 showed significantly higher values of Kn than females in stages 1 and 4. An explanation for the observed differences could be the accumulation of fat as energy reserves for migrating to spawning grounds and for mating (production of energy-demanding substances such as hepatic vitellogenin) (Copeland et al. 1986) (Fig. 8). In this case, relative condition factor values could be biased by the reproductive state of female Pacific halibut, which might confound the actual determination of condition for individual fish.

The Gonadosomatic Index has long been regarded as a proxy to determine temporal gonadal stage rather than overall fish condition (Crupkin et al. 1988), as evidenced by the significant differences between males and females and among female maturity stages (Fig. 8). This argument would suggest that Gonadosomatic Index is not convenient to fully assess the physiological status of Pacific halibut.

As expected, the quality of Pacific halibut tissue decreased at the offload after being iced on board, as evidenced by BIA measurements. The Phase Angle values of fish sampled at port show a greater decrease as fish spent more time in the fish hold of the survey vessel, which could have been caused by the accumulation of cell membrane breakdown, drip loss, and evaporation from the tissue (Fig. 16). However, the average rate of Phase Angle decrease was greater during the first days in storage than in subsequent days (Fig. 17).

Somatic fat content, measured as a percentage, was found to be higher in site 1 than in the other sites sampled (Fig. 14), suggesting that fat is stored mostly at the middle part of the fish body as opposed to the caudal end. Pacific halibut are known to be strong swimmers capable of migrating long distances between feeding and mating areas (IPHC 2014). The fat reserves in the caudal end of the fish would be burned at a higher rate than those in rostral areas due to the energy-demanding necessity of swimming for Pacific halibut.

Somatic fat content was significantly and positively correlated with length and weight. These relationships indicate that larger and heavier Pacific halibut are fatter, thus possessing relatively greater fat reserves, or energy available, in comparison to the smaller and lighter fish. Another significant, but negative, correlation of somatic fat content was with Phase Angle. Considering that Phase angle values rely on the conductivity of the tissue sampled (Cox et al. 2011), it is logical to conclude that fatter fish possessing greater amounts of non-conductive tissue components (fat) will yield lower values of Phase Angle as Resistance increases in Equation 7. These two indices were significantly different for fish caught in outside and inside stations. Just like with depth, dietary differences and well as environmental factors might be the causes of these observed discrepancies in fat content and Phase Angle values. It is relevant to note that Phase Angle depends on tissue composition and further exploration would allow for accurate analysis of Pacific halibut tissue to determine the exact causes of the difference observed. Additionally, the devices used for measuring fat content were not specifically calibrated to sample Pacific halibut. Additional tests including bomb calorimeter of halibut tissue are necessary to more accurately estimate the somatic fat content and Phase Angles of Pacific halibut.

Regarding the landmark-based morphometric analyses, only females showed statistical correlations with shape. Both length and weight were significantly correlated to shape, indicating that female Pacific halibut maintained a shape change pattern as they grew in size and weight. In addition, shape was positively correlated with the GSI for females, which suggests that an increase in energy storage in the female gonads, reflected by increased ovary mass, might be linked to shape.

Additional steps that could improve the analyses regarding the major indices would be to include complimentary data such as fish age, lipid composition analyses, etc., as well as an improved protocol for data collection for the landmark-based morphometric analyses. The major shortcoming for the shape analysis study included non-standardized handling of the fish during image recording in the field and limitations in the placement of landmarks due to the quality of images obtained. In order to improve to improve such analysis, other methods should be pursued, such as surface or contour analysis, or the addition of other homologous landmarks.

Conclusion

Granted that a strong correlation exists between Relative Condition Factor and the indices that measure fat body content directly, it is safe to assume that *Kn* could be used as a proxy to determine halibut condition. Fish lengths and weights can be easily measured during the IPHC survey trips and *Kn* can be promptly calculated to assess the physiological status of Pacific halibut. Measurements of fat content of the fish could also prove to be useful to determine halibut condition, as it directly reflects the energy storage of the fish.

These indices will not only be useful to determine individual and general halibut condition, but they can now be used to investigate temporal and spatial changes in physiological condition in Pacific halibut throughout its distribution range and to link these changes with environmental conditions.

Acknowledgements

I would like to extend my gratitude to the IPHC for the internship opportunity granted to me during the summer of 2016. I also thank the IPHC Staff who were very helpful throughout the course of the project, but especially to Josep Planas, Claude Dykstra, and Lauri Sadorus for their special guidance and advice. I would also like to thank the crew of the *F/V Kema Sue* for their help at sea while collecting data for the project. And finally, a special thanks to the advisers in the Biology Department of the University of Washington who helped with logistics that made my participation in this internship possible.

References

Alós, J., Palmer, M., Linde-Medina, M. and Arlinghaus, R. 2014. Consistent size-independent harvest selection on fish body shape in two recreationally exploited marine species. Ecology and evolution. 4(11): 2154-2164.

Best, E. and St-Pierre, G. 1986. Pacific Halibut as Predator and Prey. Int. Pac. Halibut Comm. Tech. Rep. 21.

Brosset, P., Fromentin, J.M., Ménard, F., Pernet, F., Bourdeix, J.H., Bigot, J.L., Van Beveren, E., Roda, M.A.P., Choy, S. and Saraux, C. 2015a. Measurement and analysis of small pelagic fish condition: A suitable method for rapid evaluation in the field. Journal of Experimental Marine Biology and Ecology. 462: 90-97.

Brosset, P., Ménard, F., Fromentin, J.M., Bonhommeau, S., Ulses, C., Bourdeix, J.H., Bigot, J.L., Van Beveren, E., Roos, D. and Saraux, C. 2015b. Influence of environmental variability and age on the body condition of small pelagic fish in the Gulf of Lions. Marine Ecology Progress Series. 529: 219-231.

Bolger, T. and Connolly, P.L. 1989. The selection of suitable indices for the measurement and analysis of fish condition. Journal of Fish Biology. 34(2): 171-182.

Cadrin, S.X. and Silva, V.M. 2005. Morphometric variation of yellowtail flounder. ICES Journal of Marine Science: Journal du Conseil. 62(4): 683-694.

Copeland, P.A., Sumpter, J.P., Walker, T.K. and Croft, M. 1986. Vitellogenin levels in male and female rainbow trout (*Salmo gairdneri Richardson*) at various stages of the reproductive cycle. Comparative Biochemistry and Physiology Part B: Comparative Biochemistry. 83(2): 487-493.

Cox, *K*.W. and Heintz, R. 2009. Electrical phase angle as a new method to measure fish condition. Fishery Bulletin. 107(4): 477-487.

Cox, M.*K*., Heintz, R. and Hartman, *K*. 2011. Measurements of resistance and reactance in fish with the use of bioelectrical impedance analysis: sources of error. Fishery Bulletin. 109(1): 34-48.

Crupkin, M., Montecchia, C.L. and Trucco, R.E. 1988. Seasonal variations in gonadosomatic index, liver-somatic index and myosin/actin ratio in actomyosin of mature hake (*Merluccius hubbsi*). Comparative Biochemistry and Physiology Part A: Physiology. 89(1): 7-10.

Davidson, D. and Marshall, C.T. 2010. Are morphometric indices accurate indicators of stored energy in herring *Clupea harengus*?. Journal of Fish Biology. 76(4): 913-929.

Froese, R., 2006. Cube law, condition factor and weight–length relationships: history, meta-analysis and recommendations. Journal of applied ichthyology. 22(4): 241-253.

Gilroy, H., Erikson, L., Kong, T., MacTavish, *K*. 2015. 2015 commercial fishery and regulation changes. Int. Pac. Halibut Comm. Report of Assessment and Research Activities 2015: 23-35.

Hartman, *K*.J., Margraf, F.J., Hafs, A.W. and Cox, M.*K*. 2015. Bioelectrical Impedance Analysis: A New Tool for Assessing Fish Condition. Fisheries. 40(12): 590-600.

IPHC. 2014. The Pacific Halibut, Biology, Fishery, and Management. Int. Pac. Halibut Comm. Tech. Rep. 59.

Klefoth, T., Skov, C., Aarestrup, *K*. and Arlinghaus, R. 2013. Reliability of non-lethal assessment methods of body composition and energetic status exemplified by applications to eel (*Anguilla anguilla*) and carp (*Cyprinus carpio*). Fisheries Research. 146: 18-26.

Le Cren, E.D. 1951. The length-weight relationship and seasonal cycle in gonad weight and condition in the perch (Perca fluviatilis). The Journal of Animal Ecology: 201-219.

Medford, B.A. and Mackay, W.C. 1978. Protein and lipid content of gonads, liver, and muscle of northern pike (*Esox lucius*) in relation to gonad growth. Journal of the Fisheries Board of Canada. 35(2): 213-219.

Mesa, M.G. and Rose, B.P. 2015. An assessment of morphometric indices, blood chemistry variables and an energy meter as indicators of the whole body lipid content in *Micropterus dolomieu*, *Sander vitreus* and *Ictalurus punctatus*. Journal of fish biology. 86(2): 755-764.

Vetter, R.D., Lynn, E.A., Garza, M. and Costa, A.S. 1994. Depth zonation and metabolic adaptation in Dover sole, *Microstomus pacificus*, and other deep-living flatfishes: factors that affect the sole. Marine Biology. 120(1): 145-159.

Webster, R.A., Clark, W.G., Leaman, B.M. and Forsberg, J.E. 2013. Pacific halibut on the move: a renewed understanding of adult migration from a coastwide tagging study. Canadian Journal of Fisheries and Aquatic Sciences. 70(4): 642-653.

Table 1. Lengths and weights of Pacific halibut used for this study, divided by sex and station of origin.

Parameters		Entire Sample	Sex		Station	
			Females	Males	Inside	Outside
Length (cm)	Mean	98.4	103.3	81.92	103.0	94.8
	St. Dev.	25.4	25.6	11.3	26.6	23.8
	Max	170	170	135	163	170
	Min	60	60	65	60	65
Weight (g)	Mean	14,890.6	16,994.6	7,105.6	17,832.9	12,895.0
	St. Dev.	13,880.9	14,402.7	4,294.1	15,458.7	12,139.6
	Max	73,840	73,840	39,820	73,840	69,660
	Min	2,230	2,230	2,940	2,230	2,940

Table 2. Landmarks used for morphometric analyses.

Number	Landmark
1	Tip of upper jaw
2	Anterior insertion of dorsal fin
3	Anterior insertion of lateral fin
4	Anterior insertion of pectoral fin
5	Anterior insertion of anal fin
6	Posterior insertion of dorsal fin
7	Posterior insertion of anal fin
8	Dorsal insertion of caudal fin
9	Ventral insertion of caudal fin
10	Intersection between end of lateral line and beginning of caudal fin rays
11	Posterior tip of anterior opercular bone – measured at 45 from the link from landmarks 1 and 10
12	Posterior tip of posterior opercular bone – measured at 45 from the link from landmarks 1 and 10
13	Highest point of fish body, before the insertion of dorsal fin rays – measured at 90 from the link between landmarks 1 and 10
14	Lowest point of fish body, before the insertion of anal fin rays – measured at 90 from the link between landmarks 1 and 10
15	Intersection between links from landmarks 1 to 10 and 13 to 14

Table 3. Index-index correlations for the entire sample. Significant tests highlighted if available.

Entire Sample Indices						
	R^2= 0.754 p= 3.54 x 10^{-150}	R^2= 0.135 p= 1.88 x 10^{-7}	R^2= 0.138 p= 2.14 x 10^{-7}	R^2= 0.118 p= 4.88 x 10^{-7}	R^2= -0.015 p= 0.11	R^2= -0.056 p= 0.700
		R^2= 0.046 p= 0.003	R^2= 0.005 p= 0.347	R^2= 0.005 p= 0.001	R^2= -0.009 p= 0.206	R^2= -0.083 p= 0.922
			R^2= 0.281 p= 8.4 x 10^{-14}	R^2= 0.179 p= 1.28 x 10^{-9}	R^2= -0.012 p= 0.17	R^2= 0.129 p= 0.104
				R^2= 0.092 p= 2.88 x 10^{-5}	R^2= -0.017 p= 0.102	R^2= -0.023 p= 0.482
					R^2= -0.054 p= 0.002	R^2= -0.051 p= 0.650
						R^2= 0.002 p= 0.376

Table 4. Index-index correlations for females and males only. Significant tests highlighted if available.

	Females						
Males		R^2= 0.763 p= 1.64 x 10^{-109}	R^2= 0.181 p= 8.04 x 10^{-8}	R^2= 0.129 p= 1.26 x 10-5	R^2= 0.157 p= 2.6 x 10^{-7}	R^2= -0.028 p= 0.052	R^2= -0.089 p= 0.7434
	R^2= 0.912 p= 2.23 x 10^{-69}		R^2= 0.058 p= 0.003	R^2= 0.005 p= 0.402	R^2= 0.068 p= 0.001	R^2= -0.014 p= 0.176	R^2= -0.129 p= 0.974
	R^2= 0.017 p= 0.402	R^2= 0.027 p= 0.290		R^2= 0.398 p= 8.54 x 10^{-16}	R^2= 0.217 p= 3.07 x 10^{-9}	R^2= -0.027 p= 0.073	R^2= 0.056 p= 0.281
	R^2= 0.012 p= 0.481	R^2= 0.004 p= 0.670	R^2= -0.007 p= 0.607		R^2= 0.135 p= 8.24 x 10^{-6}	R^2= -0.025 p= 0.089	R^2= 0.345 p= 0.025
	R^2= 0.022 p= 0.323	R^2= 0.016 p= 0.401	R^2= 0.055 p= 0.131	R^2= 0 p= 0.911		R^2= -0.073 p= 0.002	R^2= 0.213 p= 0.073
	R^2= 0 p= 0.890	R^2= -0.006 p= 0.630	R^2= 0.017 p= 0.436	R^2= -0.002 p= 0.815	R^2= 0.005 p= 0.646		R^2= -0.050 p= 0.552
	R^2= -0.3539 p= 0.815	R^2= 0.5357 p= 0.096	R^2= -0.4216 p= 0.898	R^2= -0.200 p= 0.611	R^2= -0.438 p= 0.919	R^2= 0.603 p= 0.070	

Table 5. Fulton's *K* correlations with complimentary data for the entire sample and for females and males only. Significant tests highlighted if available.

Index	Gender	Length (cm)	Weight (g)	Depth (F)
Fulton's *K*	All	R^2= 0.250 p= 2.81 x 10^{-32}	R^2= 0.323 p= 4.05 x 10^{-43}	R^2= 0 p= 0.573
	Females	R^2= 0.238 p= 4.67 x 10^{-22}	R^2= 0.331 p= 7.66 x 10^{-32}	R^2= -0.007 p= 0.117
	Males	R^2= 0.211 p= 3.79 x 10^{-8}	R^2= 0.385 p= 3.55 x 10^{-15}	R^2= 0.001 p= 0.691

Table 6. T-test for Fulton's *K* between males and females. Significant tests highlighted if available.

Index	Parameter	Sex	
		Males	**Females**
Fulton's *K*	**Mean**	0.968	1.010
	St. Dev.	0.092	0.104
	t-test	4.019	
	***p*-value**	6.79 x 10^{-5}	

Table 7. T-tests for Fulton's *K* between Pacific halibut caught in inside and outside waters for the entire sample and for females and males only. Significant tests highlighted if available.

Index	Parameter	All		Females		Males	
		Inside	**Outside**	**Inside**	**Outside**	**Inside**	**Outside**
Fulton's *K*	**Mean**	1.011	0.991	1.012	0.990	0.996	1.002
	St. Dev.	0.110	0.096	0.107	0.099	0.113	0.083
	t-test	2.174		2.001		-0.341	
	***p*-value**	0.030		0.046		0.734	

Table 8. T-tests for Fulton's *K* between female maturity stages. Significant tests highlighted if available.

Index	Parameter	Female Maturity Stage		
		1	**2**	**4**
Fulton's *K*	Mean	0.966	1.075	1.018
	St. Dev.	0.073	0.111	0.109
	Test	**1 & 2**	**1 & 4**	**2 & 4**
	t-test	-9.180	-3.471	3.276
	p-value	1.46 x 10^{-16}	0.001	0.001

Table 9. *Kn* correlations with complimentary data for the entire sample and for females and males only. Significant tests highlighted if available.

Index	Gender	Length (cm)	Weight (g)	Depth (F)
Relative K	All	R^2= 0 p= 0.822	R^2= 0.014 p= 0.010	R^2= -0.013 p= 0.012
	Females	R^2= 0 p= 0.800	R^2= 0.020 p= 0.009	R^2= -0.020 p= 0.009
	Males	R^2= 0.001 p= 0.686	R^2= 0.066 p= 0.003	R^2= 0.004 p= 0.459

Table 10. T-test for *Kn* between males and females. Significant tests highlighted if available.

Index	Parameter	Sex	
		Males	**Females**
Relative K	**Mean**	1.00612	1.00354
	St. Dev.	0.08611	0.08843
	t-test	-0.28556	
	***p*-value**	0.77533	

Table 11. T-tests for *Kn* between Pacific halibut caught in inside and outside waters for the entire sample and for females and males only. Significant tests highlighted if available.

Index	Parameter	All		Females		Males	
		Inside	**Outside**	**Inside**	**Outside**	**Inside**	**Outside**
Relative K	Mean	1.005	1.003	1.009	1.000	0.994	1.009
	St. Dev.	0.085	0.090	0.082	0.094	0.092	0.080
	t-test	0.289		0.848		-0.968	
	p-value	0.772		0.397		0.335	

Table 12. T-tests for *Kn* between female maturity stages. Significant tests highlighted if available.

Index	Parameter	Female Maturity Stage		
		1	**2**	**4**
Fulton's K	Mean	0.9974	1.02989	0.97302
	St. Dev.	0.07049	0.10324	0.09547
	Test	**1 & 2**	**1 & 4**	**2 & 4**
	t-test	-2.891	1.828	3.5431
	p-value	0.0043	0.0710	0.000511

Table 13. HSI correlations with complimentary data for the entire sample and for females and males only. Significant tests highlighted if available.

Index	Gender	Length (cm)	Weight (g)	Depth (F)
HSI	All	$R^2 = 0.181$ $p = 9.37 \times 10^{-10}$	$R^2 = 0.163$ $p = 7.67 \times 10^{-9}$	$R^2 = 0$ $p = 0.950$
	Females	$R^2 = 0.229$ $p = 9.01 \times 10^{-10}$	$R^2 = 0.201$ $p = 1.27 \times 10^{-8}$	$R^2 = 0$ $p = 0.802$
	Males	$R^2 = 0$ $p = 0.998$	$R^2 = -0.001$ $p = 0.882$	$R^2 = 0.020$ $p = 0.366$

Table 14. T-test for HSI between males and females. Significant tests highlighted if available.

Index	Parameter	Sex	
		Males	Females
HSI	Mean	0.852	0.966
	St. Dev.	0.322	0.341
	t-test	1.952	
	p-value	0.052	

Table 15. T-tests for HSI between Pacific halibut caught in inside and outside waters for the entire sample and for females and males only. Significant tests highlighted if available.

Index	Parameter	All		Females		Males	
		Inside	Outside	Inside	Outside	Inside	Outside
HSI	Mean	0.916	0.981	0.938	1.010	0.852	0.853
	St. Dev.	0.337	0.341	0.340	0.340	0.326	0.324
	t-test	-1.287		-1.262		-0.013	
	p-value	0.280		0.209		0.990	

Table 16. T-tests for HSI between female maturity stages. Significant tests highlighted if available.

Index	Parameter	Female Maturity Stage		
		1	2	4
HSI	Mean	0.8139	1.2179	0.99095
	St. Dev.	0.257	0.373	0.203
	Test	**1 & 2**	**1 & 4**	**2 & 4**
	t-test	-6.467	-2.909	3.211
	p-value	1.10×10^{-8}	0.005	0.002

Table 17. GSI correlations with complimentary data for the entire sample and for females and males only. Significant tests highlighted if available.

Index	Gender	Length (cm)	Weight (g)	Depth (F)
GSI	All	R^2= 0.436 p= 2.09 x 10^{-24}	R^2= 0.365 p= 1.17 x 10^{-19}	R^2= 0.016 p= 0.086
	Females	R^2= 0.378 p= 5.15 x 10^{-16}	R^2= 0.307 p= 9.99 x 10^{-13}	R^2= 0.014 p= 0.158
	Males	R^2= 0.018 p= 0.392	R^2= 0.019 p= 0.377	R^2= -0.01 p= 0.514

Table 18. T-test for GSI between males and females. Significant tests highlighted if available.

Index	Parameter	Sex	
		Males	Females
GSI	Mean	0.421	1.127
	St. Dev.	0.168	0.507
	t-test	14.190	
	p-value	3.36 x 10^{-31}	

Table 19. T-tests for GSI between Pacific halibut caught in inside and outside waters for the entire sample and for females and males only. Significant tests highlighted if available.

Index	Parameter	All		Females		Males	
		Inside	Outside	Inside	Outside	Inside	Outside
GSI	Mean	0.9119	1.0352	1.095	1.168	0.429	0.401
	St. Dev.	0.548	0.526	0.528	0.479	0.188	0.112
	t-test	-1.525		-0.850		0.613	
	p-value	0.129		0.397		0.543	

Table 20. T-tests for GSI between female maturity stages. Significant tests highlighted if available.

Index	Parameter	Female Maturity Stage		
		1	2	4
GSI	Mean	0.787	1.651	1.389
	St. Dev.	0.197	0.501	0.287
	Test	1 & 2	1 & 4	2 & 4
	t-test	-10.472	-9.215	2.6125
	p-value	1.04 x 10^{-13}	7.81 x 10^{-10}	0.011

Table 21. Somatic Fat Content correlations with complimentary data for the entire sample and for females and males only. Significant tests highlighted if available.

Index	Gender	Length (cm)	Weight (g)	Depth (F)
Somatic fat	All	R^2= 0.118 p= 4.86 x 10^{-7}	R^2= 0.119 p= 4.43 x 10^{-7}	R^2= 0.005 p= 0.329
	Females	R^2= 0.114 p= 8.52 x 10^{-7}	R^2= 0.144 p= 8.8 x 10^{-7}	R^2= 0.003 p= 0.474
	Males	R^2= 0.012 p= 0.471	R^2= 60.006 p= 0.598	R^2= 0.007 p= 0.585

Table 22. T-test for Somatic Fat Content between males and females. Significant tests highlighted if available.

Index	Parameter	Sex	
		Males	Females
Somatic fat	Mean	0.845	0.923
	St. Dev.	0.403	0.442
	t-test	1.072	
	p-value	0.285	

Table 23. T-tests for Somatic Fat Content between Pacific halibut caught in inside and outside waters for the entire sample and for females and males only. Significant tests highlighted if available.

Index	Parameter	All		Females		Males	
		Inside	Outside	Inside	Outside	Inside	Outside
Somatic fat	Mean	0.857	0.985	0.884	0.980	0.780	1.010
	St. Dev.	0.376	0.508	0.413	0.478	0.227	0.657
	t-test	-1.9241		-1.3538		-1.2307	
	p-value	0.05658		0.1777		0.240	

Table 24. T-tests for Somatic Fat Content between female maturity stages. Significant tests highlighted if available.

Index	Parameter	Female Maturity Stage		
		1	2	4
Somatic fat	Mean	0.775	1.220	0.914
	St. Dev.	0.295	0.584	0.318
	Test	1 & 2	1 & 4	2 & 4
	t-test	-4.757	-1.976	2.742
	p-value	1.35 x 10^{-5}	0.051	0.008

Table 25. Phase Angle correlations with complimentary data for the entire sample and for females and males only. Significant tests highlighted if available.

Index	Gender	Length (cm)	Weight (g)	Depth (F)
Phase Angle	All	R^2= -0.016 p= 0.096	R^2= -0.035 p= 0.013	R^2= -0.024 p= 0.039
	Females	R^2= 0.033 p= 0.036	R^2= 0.053 p= 0.007	R^2= 0.018 p= 0.127
	Males	R^2= 0.040 p= 0.207	R^2= 0.008 p= 0.584	R^2= 0.075 p= 0.082

Table 26. T-test for Phase Angle between males and females. Significant tests highlighted if available.

Index	Parameter	Sex	
		Males	Females
Phase Angle	Mean	31.694	31.720
	St. Dev.	2.754	3.695
	t-test	0.048	
	p-value	0.962	

Table 27. T-tests for Phase Angle between Pacific halibut caught in inside and outside waters for the entire sample and for females and males only. Significant tests highlighted if available.

Index	Parameter	All		Females		Males	
		Inside	Outside	Inside	Outside	Inside	Outside
Phase Angle	Mean	32.418	29.849	32.476	29.944	32.252	29.388
	St. Dev.	3.415	2.989	3.657	3.169	2.649	1.931
	t-test	4.589		3.816		2.866	
	p-value	8.54×10^{-6}		0.0002		0.007	

Table 28. T-tests for Phase Angle between female maturity stages. Significant tests highlighted if available.

Index	Parameter	Female Maturity Stage		
		1	2	4
Phase Angle	Mean	32.159	31.479	30.272
	St. Dev.	4.157	2.945	3.269
	Test	1 & 2	1 & 4	2 & 4
	t-test	1.019	1.655	1.320
	p-value	0.310	0.102	0.193

Table 29. Landmark-based geometric morphometric analyses correlations with complimentary data for the entire sample and for females and males only. Significant tests highlighted if available.

Index	Gender	Length (cm)	Weight (g)	Depth (F)
Shape	All	R^2= -0.046 p= 0.632	R^2= -0.041 p= 0.601	R^2= -0.041 p= 0.596
	Females	R^2= 0.281 p= 0.033	R^2= 0.229 p= 0.056	R^2= 0.008 p= 0.3676
	Males	R^2= -0.481 p= 0.974	R^2= -0.488 p= 0.984	R^2= 0.036 p= 0.416

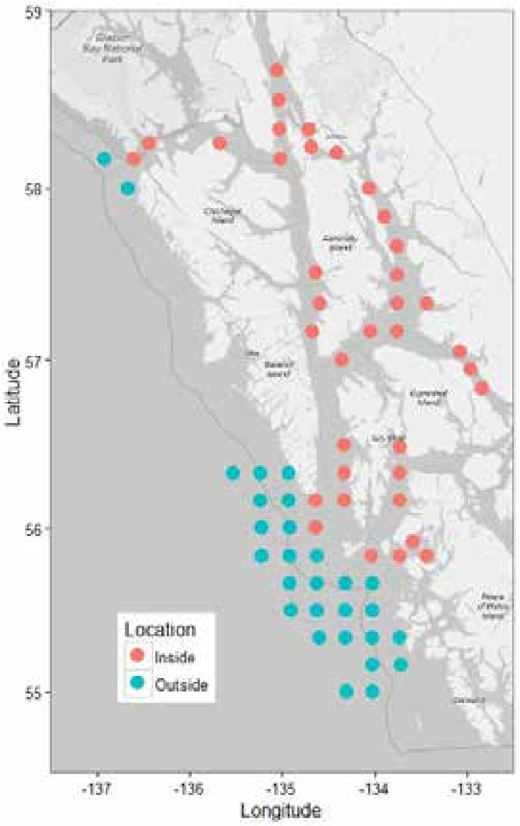

Figure 1. IPHC stations sampled in SE Alaska, divided into outside and inside areas according to the Alaska Department of Fish and Game.

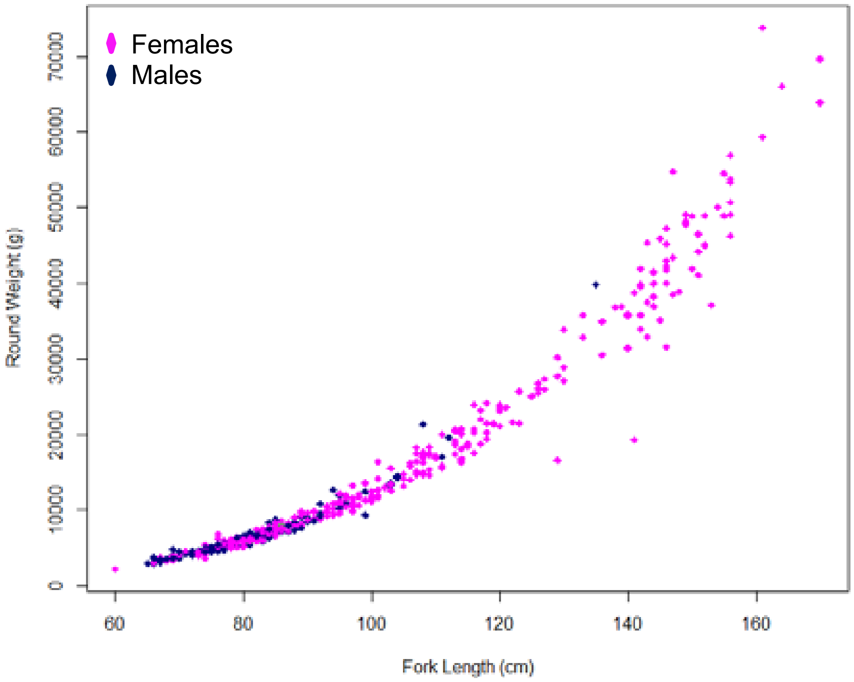

Figure 2. Length-weight relationship of the Pacific halibut sample used for this study.

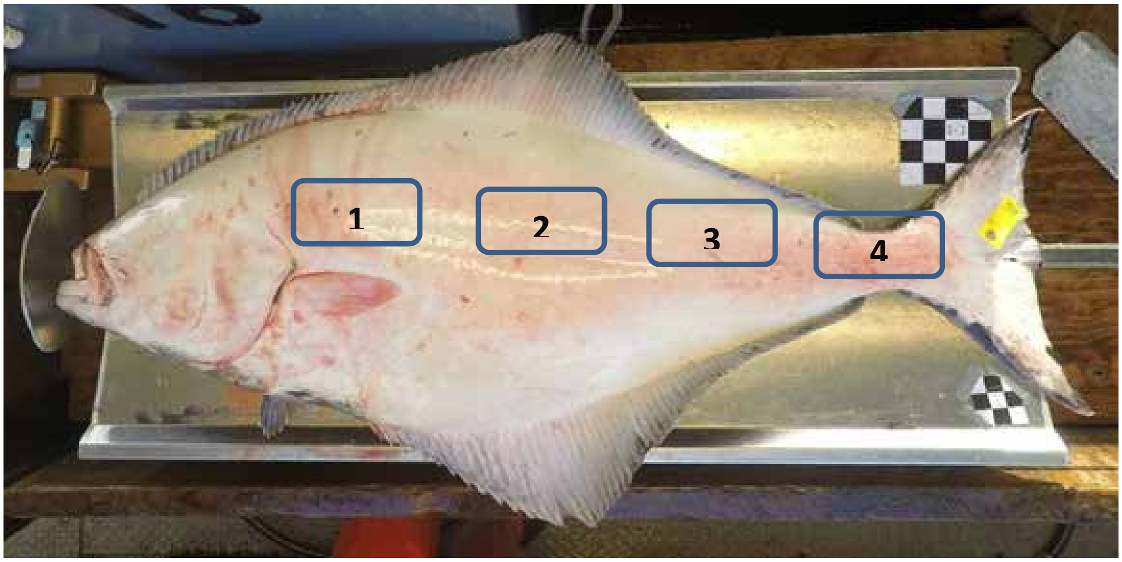

Figure 3. Sites defined for fat content and phase angle sampling on the blind side of fish: (1) interior of lateral line arch, (2) in between the outmost extensions of the dorsal and anal fins, above the lateral line (3) middle section between site 2 and 4, above the lateral line, and (4) area of caudal peduncle, above the lateral line.

Figure 4. Hand-held device used to estimate somatic fat content using microwave-technology (left) and quality reader used to obtain Phase Angle values (right).

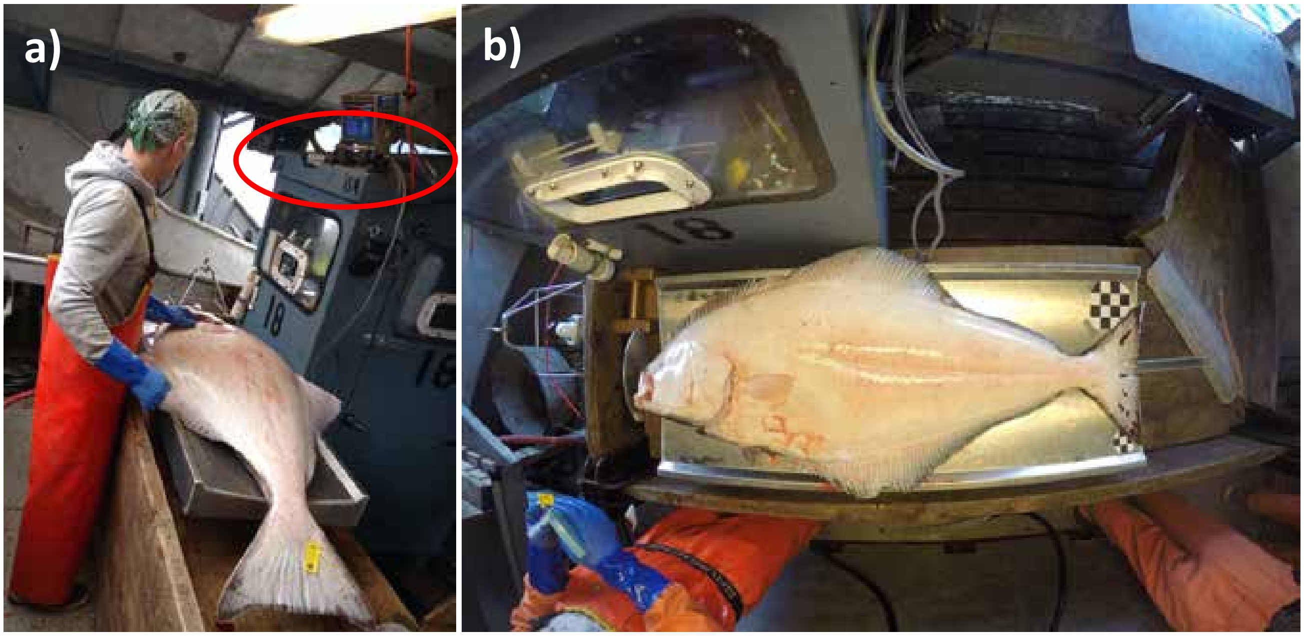

Figure 5. a) GoPro assemblage for image recording. b) Example of image obtained with fisheye effect still present.

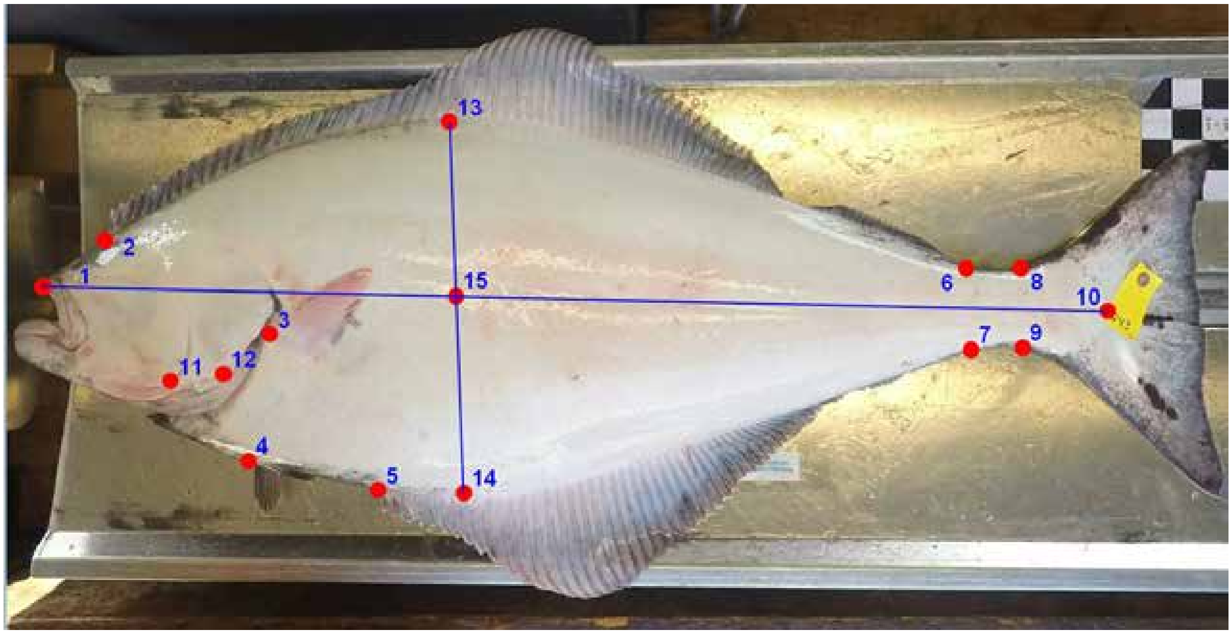

Figure 6. Landmarks on blind side of the halibut used for morphometric analyses.

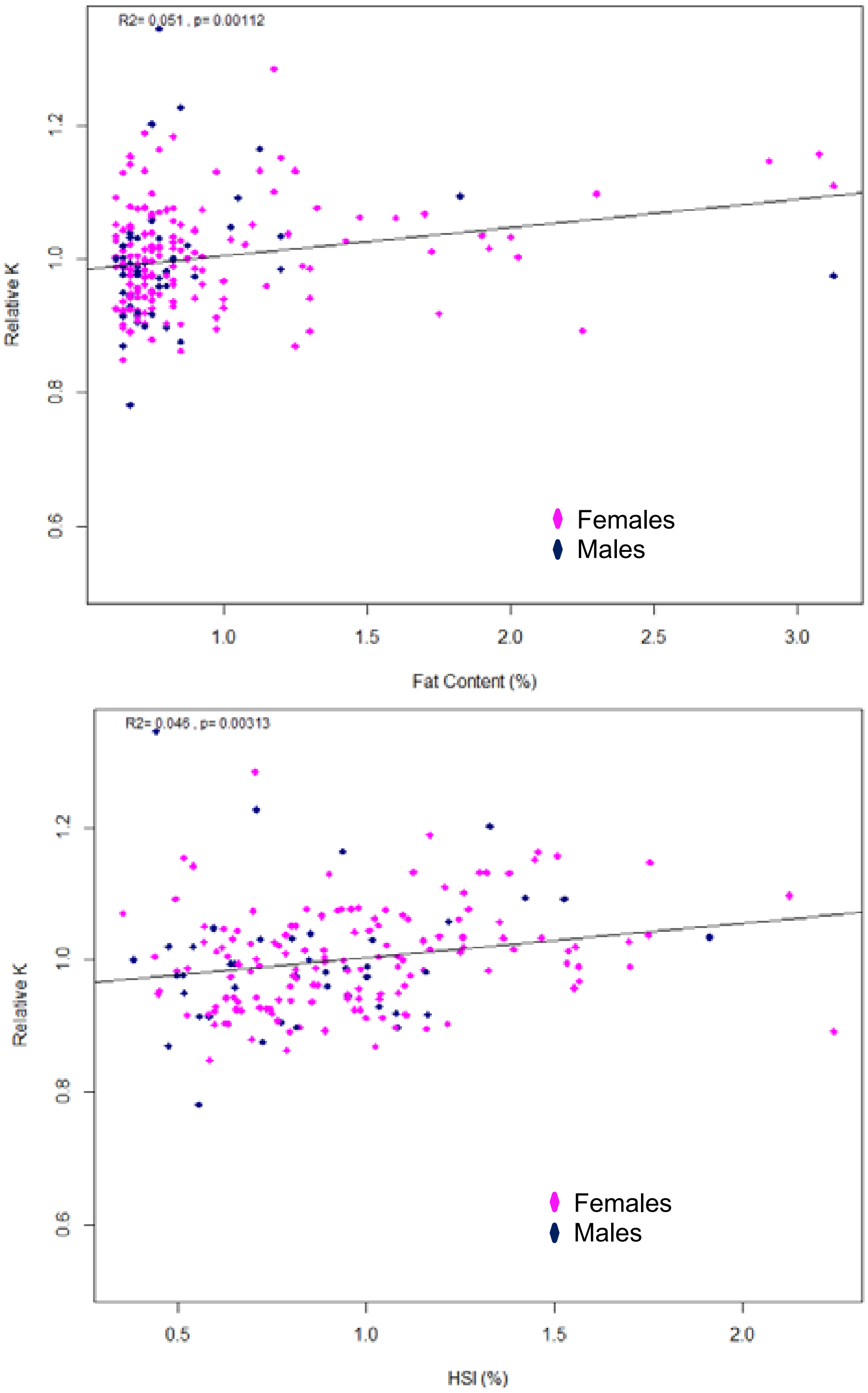

Figure 7. Correlations of Kn with somatic fat content (top) and HSI (bottom).

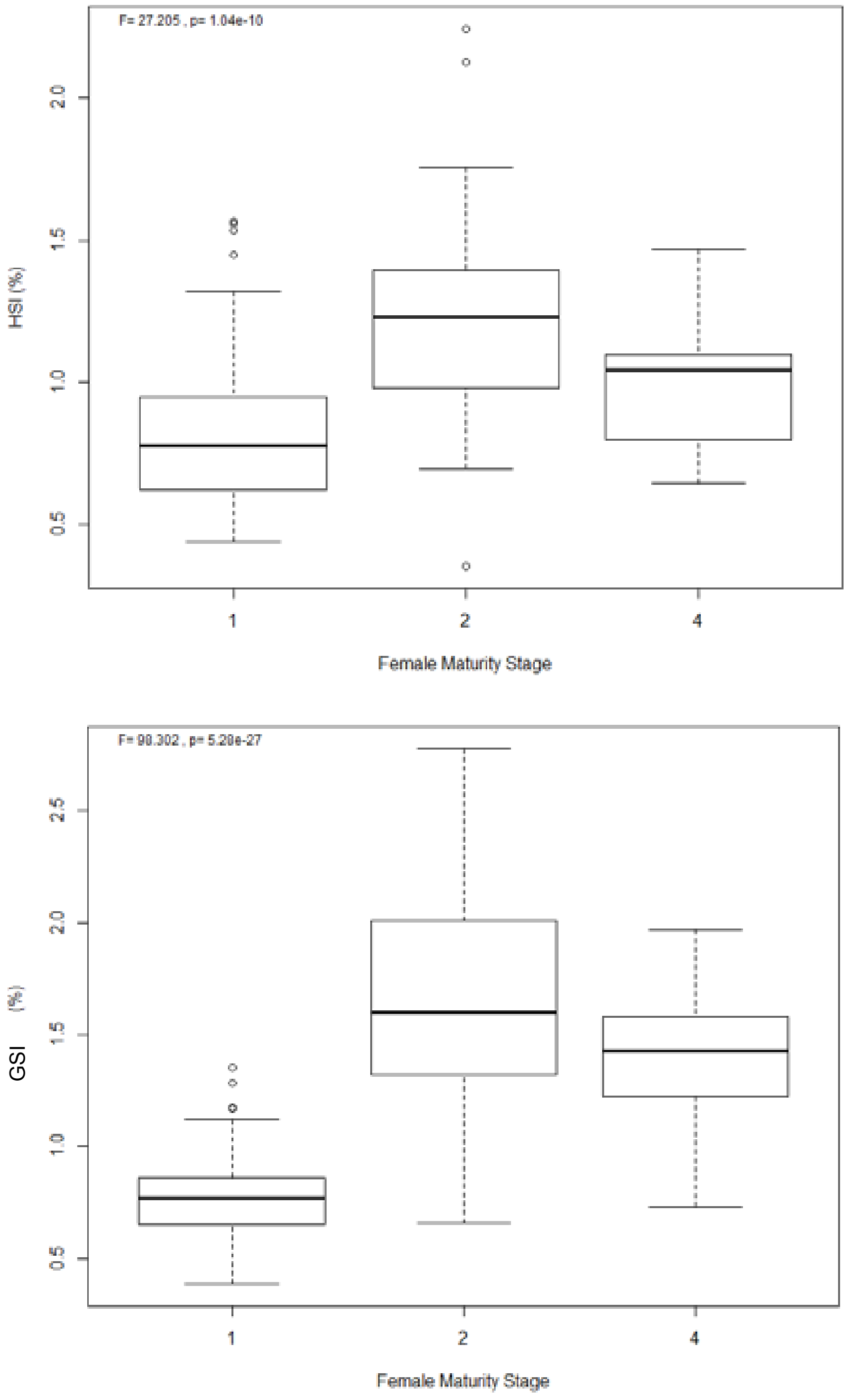

Figure 8. Differences among female maturity stages for HSI (top) and GSI (bottom)

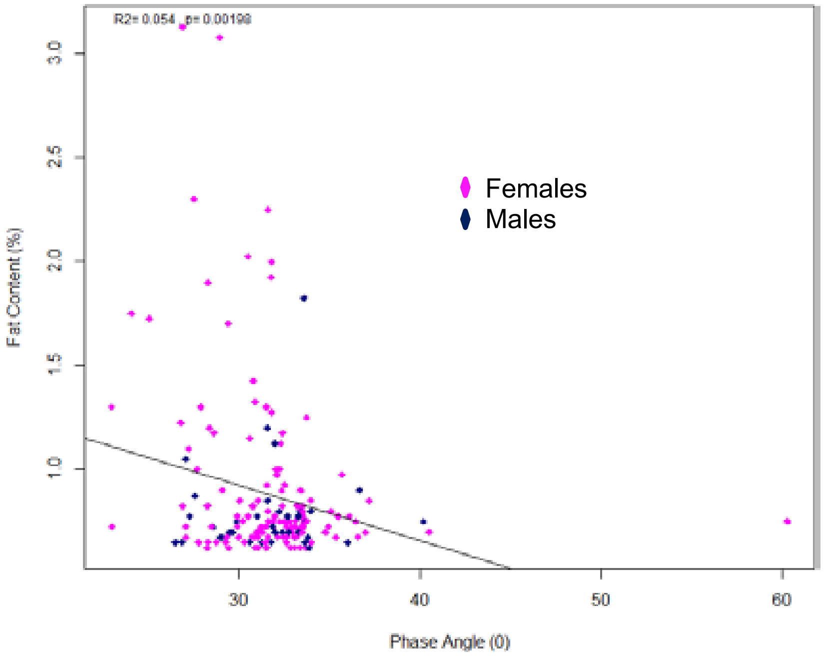

Figure 9. Negative correlation between Phase Angle vs. somatic fat content.

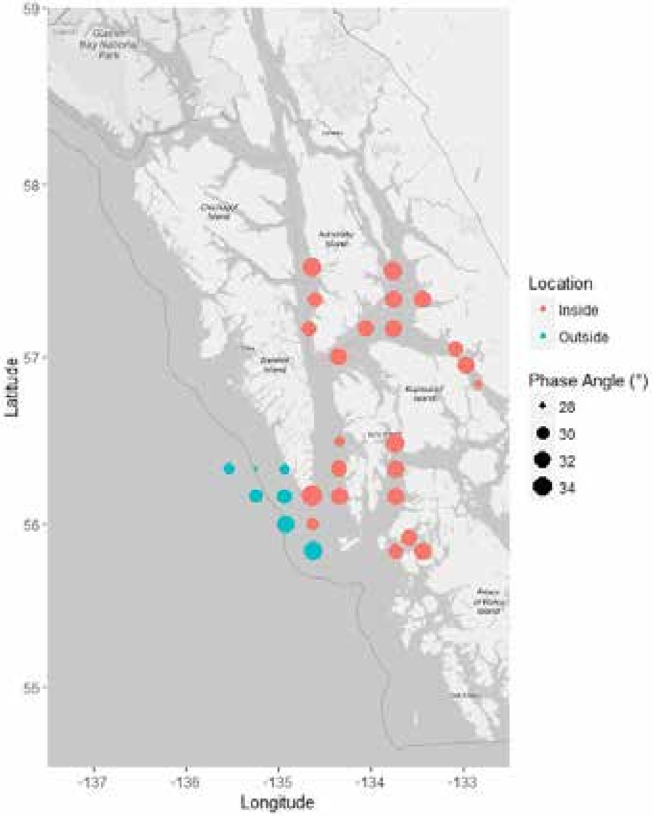

Figure 10. Phase angle values according to the location of stations sampled, based on the geographical distinction established by the Alaska Department of Fish and Game.

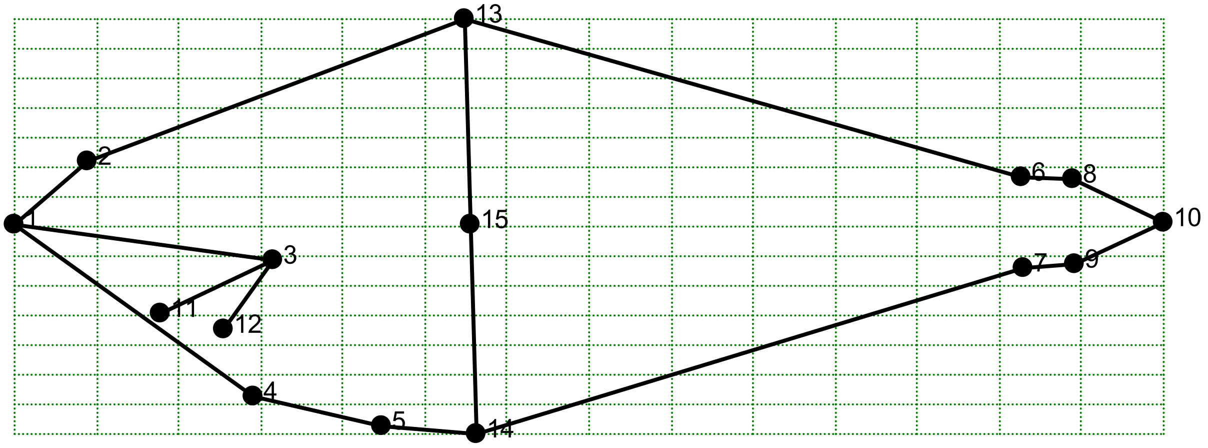

Figure 11. Consensus image of the entire Pacific halibut sample used for landmark-based geometric morphometric analyses.

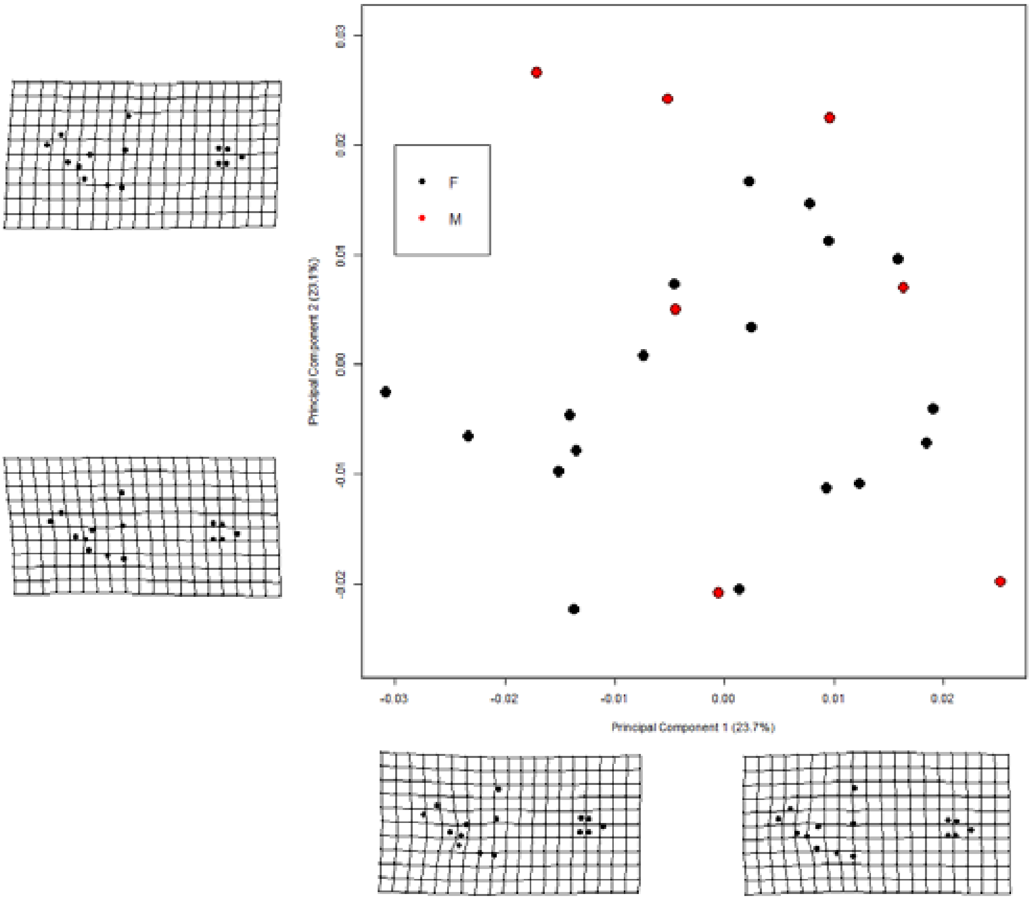

Figure 12. Shape space for Pacific halibut sampled in this study. Extreme shape distortions located relative to the axes.

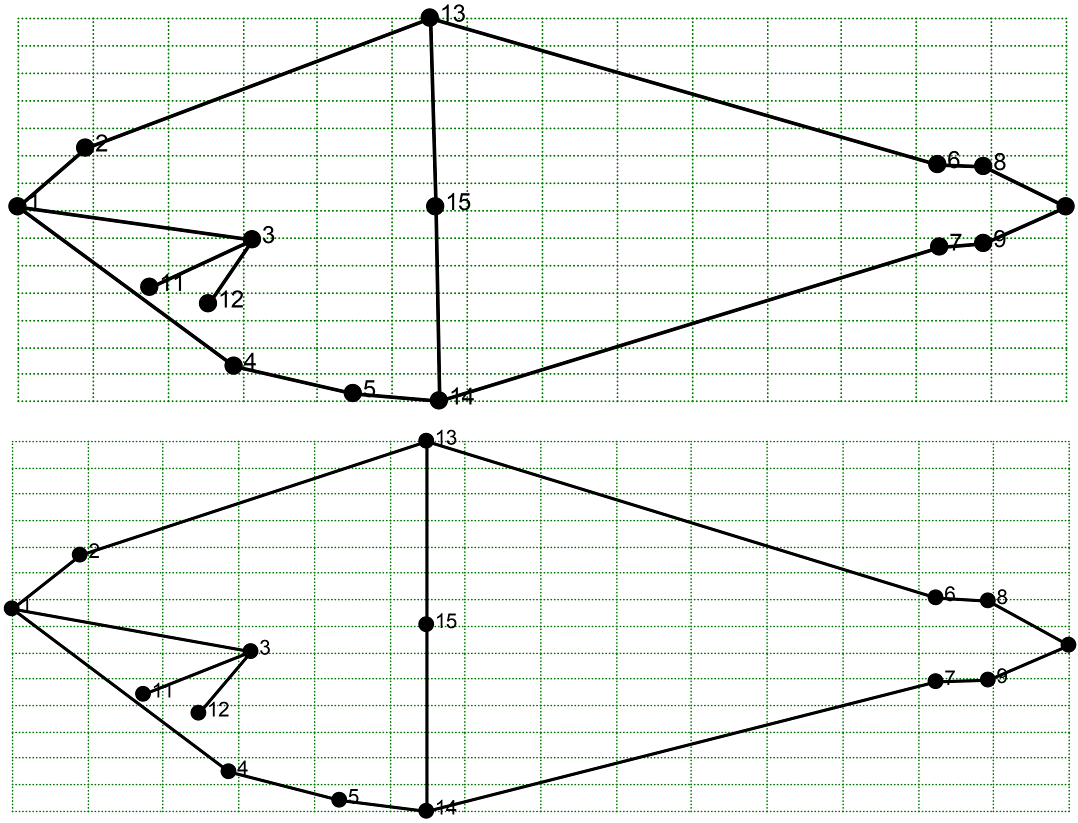

Figure 13. Consensus shapes for female (top) and male (bottom) Pacific halibut samples used for shape analyses.

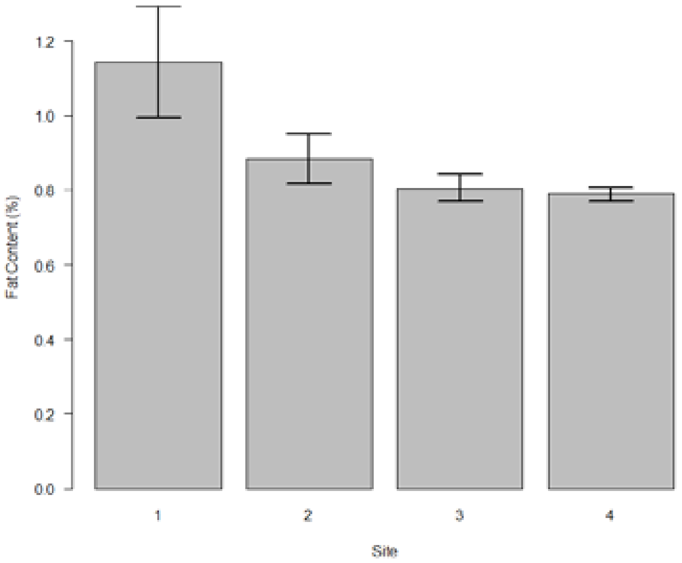

Figure 14. Average fat content on the sites of the blind side of halibut, sampled with the fat meter device.

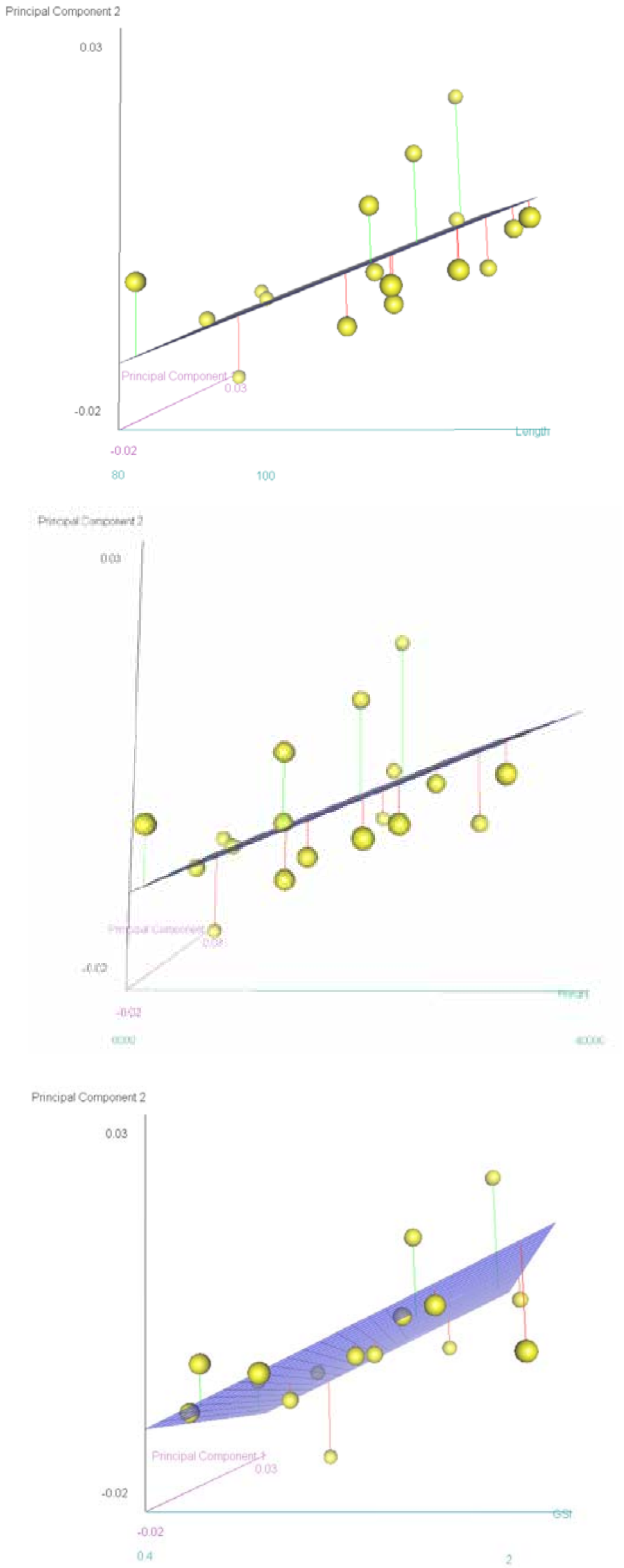

Figure 15. Correlations of female Pacific halibut shape with fork length (top), round weight (middle), and GSI (bottom).

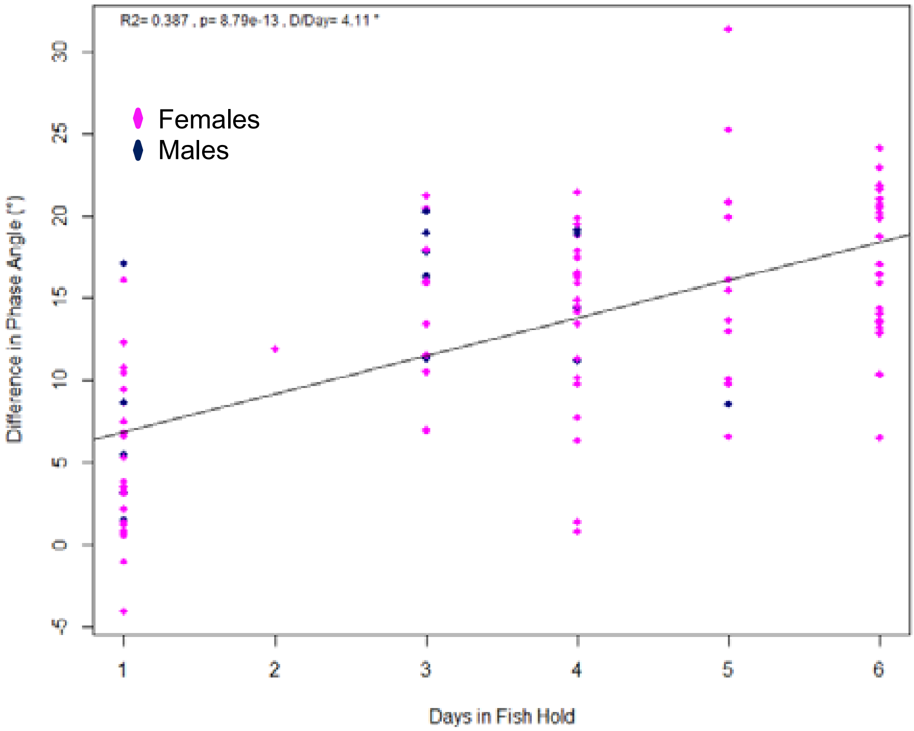

Figure 16. Decrease in Phase Angle values from recently caught fish to offload condition, according to days spent in the fish hold of the *F/V Kema Sue*.

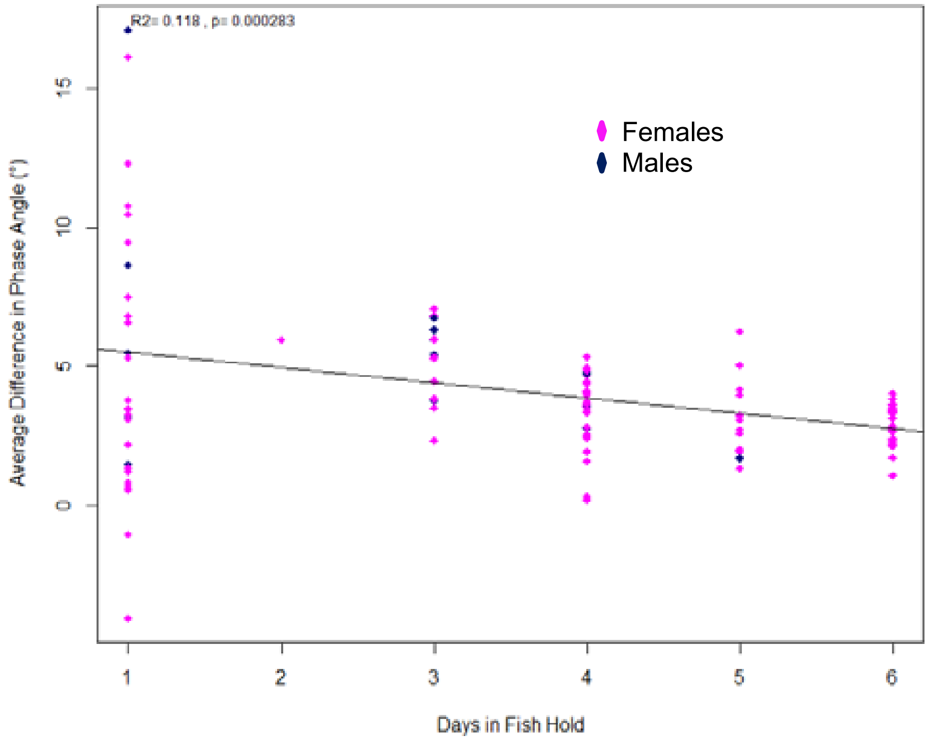

Figure 17. Average change in Phase Angle values in fish stored in the fish hold of the *F/V Kema Sue*.

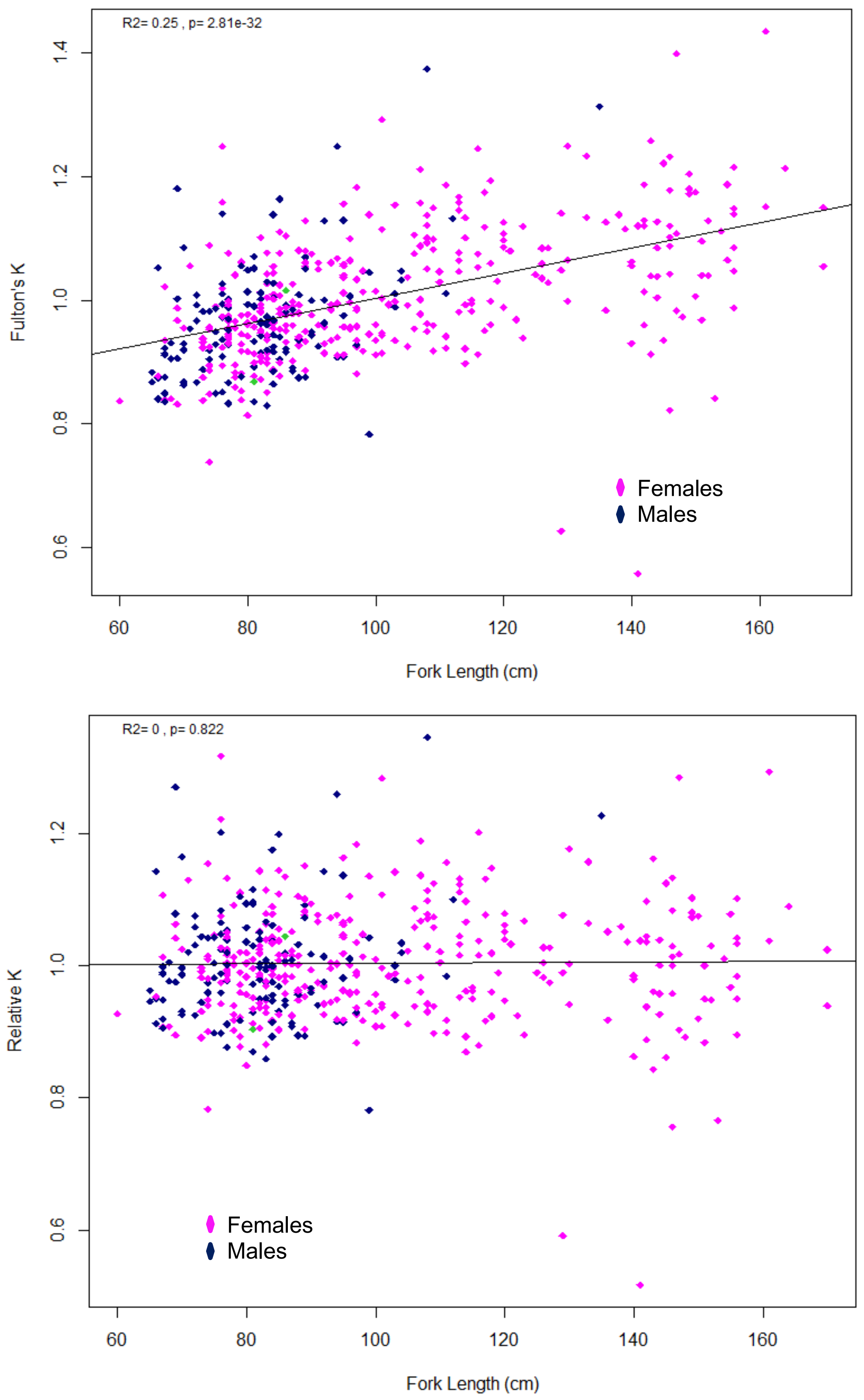

Figure 18. Calculated *K* (top) and *Kn* (bottom) in relation to sampled halibut fork length.

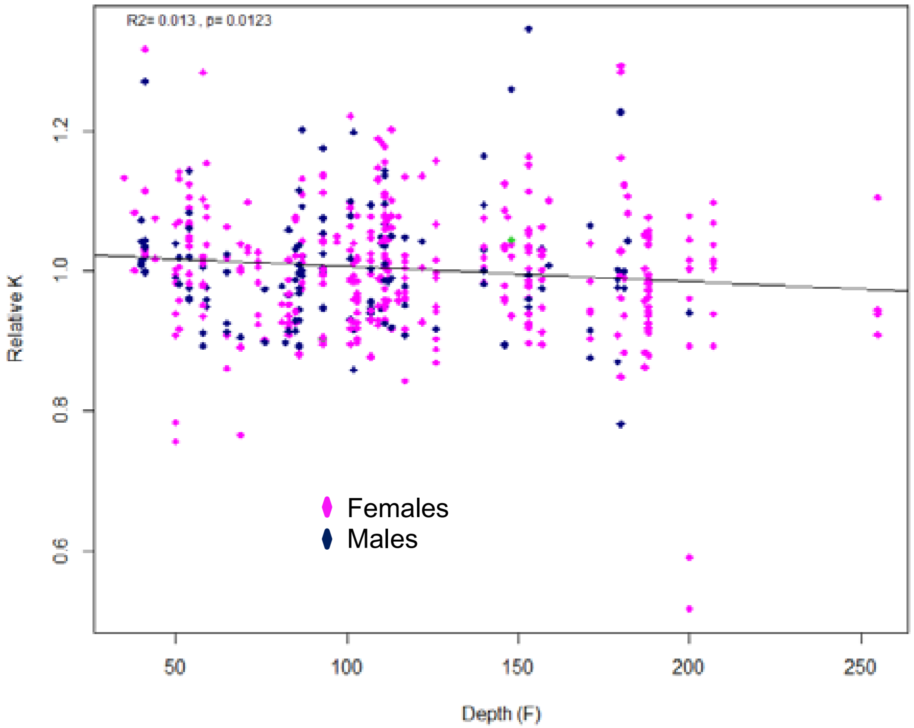

Figure 19. Negative correlation between *Kn* and station depth.