Thesis for the Degree of Master of Science

Stock assessment of elkhorn sculpin (*Alcichthys alcicornis*) along the Uljin area of Korea

by

Soo Jeong Lee

Department of Fisheries Physics

The Graduate School

Pukyong National University

August 2011

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(동해 울진 연안 빨간횟대 (*Alcichthys alcicornis*)의 자원평가)

Advisor: Prof. Chang Ik Zhang

by

Soo Jeong Lee

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in Department of Fisheries Physics, The Graduate School,
Pukyong National University

August 2011

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Approved by:

(Chairman) Jae Bong Lee

(Member) Sung Il Lee

(Member) Chang Ik Zhang

Contents

한국 동해 연안 빨간횟대 (*Alcichthys alcicornis*)의 자원생태학적 연구

이 수 정

부경대학교 대학원 수산물리학과

요 약

본 연구에서는 2010년 3월부터 2011년 4월까지 매월 동해 연안자망에 의해 어획된 총 527마리의 빨간횟대 (*Alcichthys alcicornis*)를 사용하여 연령과 성장, 생잔율과 사망계수, 숙도지수와 50% 군성숙체장 및 가입체장 등 자원생태학적 매개변수를 추정하였다. 연령은 이석의 표면연마법을 통해 판독한 결과, 윤문은 연 1회 1월에 형성되었으며, 1세에서 8세까지 판독되었다. 네 가지 성장식, 즉 von Bertalanffy 성장식, 일반화된 von Bertalanffy 성장식 (일명 Richards 성장식), Robertson 성장식, Gompertz 성장식을 AIC와 BIC 값 기준으로 비교한 결과, von Bertalanffy 성장식이 가장 낮은 AIC와 BIC 값을 가짐으로써 빨간횟대 성장식으로 가장 적합한 것으로 판명되었다. 추정된 성장 파라미터는 이론적 최대체장 (L_∞)은 29.41cm, 성장계수 (K)는 0.247/년, 체장이 0일때 이론적 연령 (t_0)은 -0.61세였다. 주 산란기는 숙도지수가 암수 모두 가장 높은 2월로 추정되었다. 붓스

트랩 방법에 의해 추정된 50% 군성숙체장은 암컷이 14.30cm, 수컷이 17.42cm 였다. 생잔율과 순간전사망계수는 각각 0.334/년과 1.096/년으로 추정되었다. 순간자연사망계수는 7가지 다른 방법으로 추정된 7개의 추정치를 사용하여 메타분석을 수행하였다. 방법내의 불확실성을 추정하기 위해 여러 요소들, 다시 말해 최대 수명, 최대 체장, 성장률 등의 범위와 각 요소들 내에서 변동 범위가 사용되었다. 각 방법의 효과크기에 대한 역변량가중치를 부여하였고, 무작위효과를 이용하여 산정된 자연사망계수는 0.467/년으로 추정되었다. 어획개시연령은 어획물 곡선법을 이용하였으며, 추정된 빨간횟대의 어획개시연령은 2.41세였다. 가입당생산량 분석에서 현재의 순간어획사망계수는 0.629/년, 어획개시연령이 2.41세일 때 가입당생산량은 20.63g으로 나타났고, $F_{0.1}$과 F_{MAX}는 각각 0.476/년, 2.103/년으로 추정되었다. 가입당산란자원량 분석에서 현재의 순간어획사망계수와 어획개시연령 수준에서의 가입당산란자원량은 37.77g이었으며, $F_{35\%}$와 $F_{40\%}$는 각각 0.658/년, 0.540/년으로 추정되었다. $F_{40\%}$를 목표기준점으로 설정하여 현재의 자원상태를 평가한 결과 가입당산란자원량 측면에서 현재의 가입당산란자원량은 $F_{40\%}$시의 가입당산란자원량의 90%수준으로 추정되었다. 어획개시연령 측면에서는 적정 어획개시연령 2.10세에 비해 현재의 어획개시연령이 0.31세 높게 추정되었다. 하지만 두 경우 모두에서 현재의 순간어획사망계수가 $F_{40\%}$를 초과한 상태이기 때문에 동해 연안 빨간횟대 자원은 남획된 상태는 아니었으나, 과도어획의 초기상태인 것으로 평가되었다.

Introduction

It is known that sculpins are relatively small, demersal, and teleost fishes, consisting of 4 diverse families (Cottidae, Hemitripteridae, Psychrolutidae, and Rhamphocottidae). Sculpins are distributed throughout the Bering Sea and Aleutian Islands regions where they occupy all benthic habitats along continental shelf and slope areas (TenBrink and Aydin, 2009). Elkhorn sculpin (*Alcichthys alcicornis*) of the family Cottidae distributes from east coast of Korea to the Sea of Okhotsk (NFRDI, 2004).

While this species has been caught constantly along the east coast of Korea, it was not important in the economic respect in Korean fisheries. In recent year, however, the consumption of raw fish as sashimi has been increasing, this species is getting more popular than before. Nevertheless, catch is reported in aggregate as “others” and it used not to be traded in public auction, therefore more rigid management is needed.

There are several biological studies of sculpins not only age and growth but also spawning and copulating behavior (Munehara, 1988; Panchenko, 2002, 2010; Shelekhov and Panchenko, 2007; TenBrink and Aydin, 2009). In Korea, however, the biology of sculpins has been poorly studied thus far. Only the studies of mesh selectivity of elkhorn sculpin (Park *et al.*, 2004) and maturity and spawning of black edged sculpin were performed (Park *et al.*, 2007).

There are various growth models that describe growth of fish well. In general, von Bertalanffy growth function (VBGF) was used the most commonly (Kim *et al.*, 2010; Yang *et al.*, 2008; Seo *et al.*, 2007; Robillard *et al.*, 2009). However, the statistical check would be necessary using statistical criteria for the choice of the best fitted growth model.

The magnitude of natural mortality (M) is one measure of the productivity of the stock. It is important in the calculation of population dynamics and biological reference points (Piner and Lee, 2011). M was estimated by 7 different method and then estimates of uncertainty are also generated using a range of plausible biological and environmental factors. A random effects meta-analysis (Piner and Lee, 2011) of M is used to synthesize a single M estimate.

Even though the catch data of elkhorn sculpin hasn't been collected, this species has been caught in the commercial fisheries consistently so we should know the current state of this species.

The purpose of this study is to estimate ecological parameters by more statistical methods and assessing the current stock state of elkhorn sculpin along the Uljin area of Korea.

Materials and methods

1. Field sampling

A total of 527 elkhorn sculpin (*Alcichthys alcicornis*) were collected in the Uljin-gun, Gyeongsangbuk-do, Korea by the trammel net, between March 2010 and April 2011 (Fig. 1). In August, no sample was collected. All specimens were measured for total length (TL, mm), total weight (TW, g) and sex and degree of maturement was recorded with the naked eye.

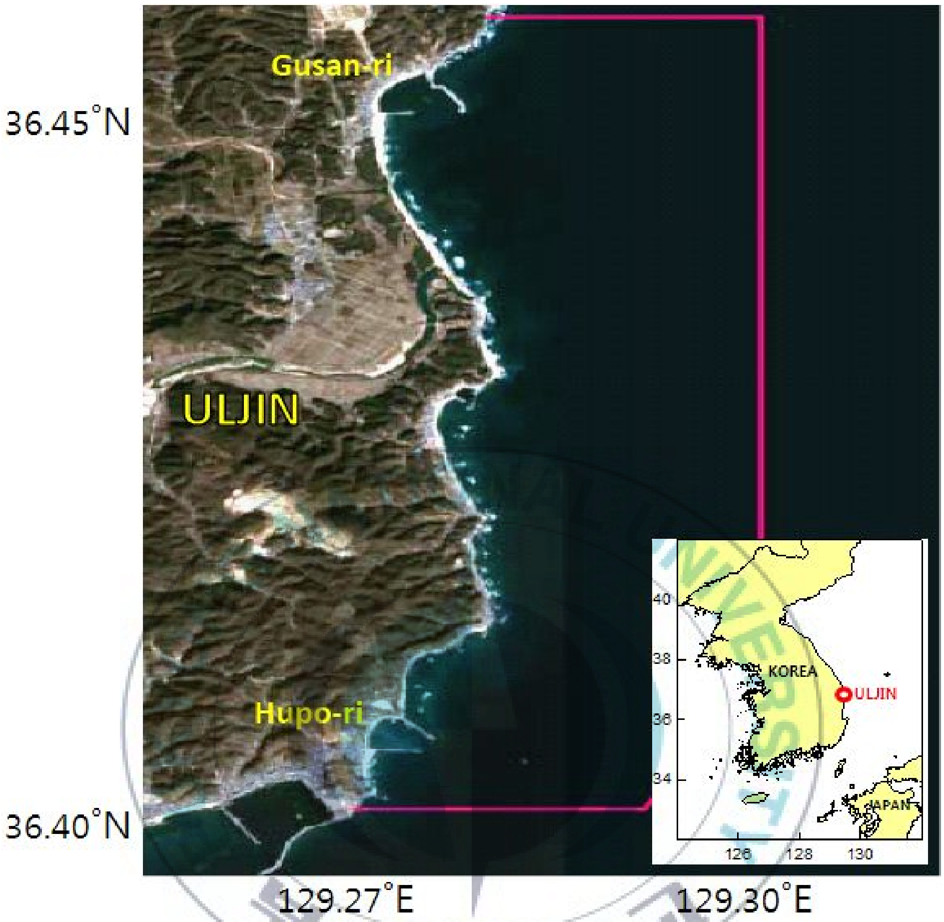

Fig. 1. Sampling area of the elkhorn sculpin (*Alcichthys alcicornis*) in the Uljin-gun, Gyeongsangbuk-do, Korea.

2. Sexual maturity and Spawning

2.1 Gonadosomatic index (GSI)

Gonosomatic index (GSI) was calculated for elkhorn sculpin by the following equation as an index of maturity.

$$GSI = \frac{Gonad\ weight(g)}{Total\ weight(g)} \times 10^{3} \qquad (1)$$

2.2 Group maturity

The length at which 50% of all specimens were sexually mature (L_{50}) was estimated using a logistic function described as

$$P_i = \frac{1}{1+e^{(b_1 - b_2 TL_i)}} \times 10^{3} \qquad (2)$$

where P_i is the maturity fraction of mature females, L_i the body length (TL), and the parameters, the constant b_1 and b_2 were to be estimated.

To describe the uncertainty surrounding the L_{50} estimate, bootstrapping was performed using MATLAB® software, in other words size at maturity data was randomly re-sampled with replacement 1,000 times. For each resampled dataset, the L_{50} statistic was recalculated. The non-parametric bootstrapped data was used to place 95% confidence intervals around the L_{50} estimate.

3. Age and growth

3.1 Age determination

Sagittal otolith was used to estimate the age of the elkhorn sculpin by surface reading method. Collected otoliths were cleaned using 30% ethyl alcohol and surface grinded. They were examined using a image analyzer, Moticam 2500 and a measurement software, Motic Images plus 2.0. The periodicity of opaque zone formation was validated by marginal increment analysis and the proportion of otoliths with opaque margins that were observed through the year.

Monthly marginal index (MI) was calculated to identify the season of the ring formation.

$$MI = \frac{R - r_n}{r_n - r_{n-1}} \quad (3)$$

3.1.1 Within reader

For not only increasing accuracy but upskilling, two readers read all samples twice unaffectedly from former result. After two readers had two set of age data respectively, the case of high match rate between readers was chosen to check the agreements between readers.

3.1.2 Between readers

All samples were aged without knowledge of previously estimated ages or the specimen lengths. Two readers independently read the age of the sagittal otoliths. Using one of two judgements of each readers, age cross checking was conducted. After that, only the samples which were judged as the same age between readers were used to estimate growth parameters.

3.2 Growth functions

3.2.1 Standard von Bertalanffy growth function

Length at age data was fitted with a standard von Bertalanffy growth function (von Bertalanffy, 1938), by non-linear method using MS EXCEL solver.

$$L_t = L_\infty (1 - e^{-K(t - t_0)}) \quad (4)$$

where L_t is observed total length (TL, mm) at age t; L_∞ is asymptotic maximum total length (TL, mm); K is instantaneous growth coefficient; t is age (years); and t_0 is theoretical age (years) at L_t is 0.

3.2.2 Generalized von Bertalanffy growth function

A generalized von Bertalanffy growth curve (Richards, 1959) was fitted to the ages derived from sagittal otolith by non-linear method using MS EXCEL solver.

$$L_t = L_\infty (1 + n e^{-K(t - t_0)})^{-\frac{1}{n}} \quad (5)$$

where n is the fourth growth-equation parameter.

3.2.3 Robertson growth function

The third function is Robertson growth function derived from logistic growth. For estimating parameters, non-linear method by MS EXCEL solver was used.

$$L_t = \frac{L_\infty}{1 + e^{c - Kt}}, \quad (c = \ln\left(\frac{L_\infty - L_0}{L_\infty}\right) + K t_0) \tag{6}$$

There are three parameters in this function; L_∞, K, c.

3.2.4 Gompertz growth function

The last function is, on an experimental basis, Gompertz growth function (Gompertz, 1825). For estimating parameters, non-linear method by MS EXCEL solver was used like all others.

$$L_t = L_\infty e^{-a \cdot e^{-Kt}}, \quad (a = \ln\left(\frac{L_\infty}{L_t}\right) e^{Kt}) \tag{7}$$

There are three parameters in this function; L_∞, K, a.

3.2.5 Comparison of functions

After the models are fitted to the data, it needs to know how accurately each model describes the data. In this study therefore two statistics were used. Akaike Information Criteria (AIC) (Akaike, 1974) and Bayessian Information Criterion (BIC) (Schwarz, 1978) were used to assess model performance. The model which had the smallest AIC and BIC value was chosen as the best fitted model that represented the growth pattern.

$$AIC = -2 \ln L + 2k \tag{8}$$

$$BIC = -2 \ln L + k \ln(n) \tag{9}$$

where L is the maximum likelihood, k is the number of parameters and n is the number of observations.

4. Survivalship and motalities

4.1 Survival rate (S) and instantaneous coefficient of total mortality (Z)

Length at age data based on the sagittal otolith was used to estimate survival rate of this species and Chapman and Robson method was adapted.

$$\hat{S} = \frac{\overline{X}}{1+\overline{X}-\frac{1}{\Sigma N_i}},\ \overline{X} = \frac{\Sigma(i \cdot N_i)}{\Sigma N_i} \tag{10}$$

where $\overline{X}$ is mean of age, i is age and N_i is specimen number at age i.

Instantaneous coefficient of total mortality (Z) can be estimated using S value by follow equation.

$$Z = -\ln S \tag{11}$$

4.2 Instantaneous coefficient of natural mortality (M)

4.2.1 M estimation models

First model is the general regression equation of Hoenig (1983)

$$\ln M = 1.46 - 1.01(\ln t_{max}) \quad (12)$$

where, t_{max} is the maximum age in years.

Second model is the general regression equation of Pauly (1980) based on parameters of the VBGF and mean water temperature (T, °C)

$$\log M = -0.0066 - 0.279(\log L_{\infty}) + 0.6543(\log K) + 0.4634(\log T) \quad (13)$$

and during the study, the bottom water temperature at appearance of this species raged 3.45°C to 12.35°C.

Third model is using K method of Jensen (1997).

$$M = 1.50K \quad (14)$$

where, K is growth coefficient of the von Bertalanffy growth equation.

Fourth model is using t_m of Jensen (1997).

$$M = \frac{1.65}{t_m} \quad (15)$$

where, t_m is age at maturity.

Fifth model is using the life historical parameter Roff model (1984).

$$M = \frac{3K}{e^{t_m K} - 1} \quad (16)$$

where, t_m is age at maturity and K is growth coefficient of the von Bertalanffy growth equation.

Sixth model is using GSI, Gunderson model (2003).

$$M = 1.79\,GSI \tag{17}$$

where, GSI is Gonosomatic index.

Last model is Zhang and Megrey model (2006) that is revised from Alverson and Carney (1975).

$$M = \frac{\beta K}{e^{K(t_{mb} - t_0)} - 1} \tag{18}$$

where, $t_{mb} = C_i \times t_{\max}$ and C_i is the coefficient (pelagic is 0.302, demersal is 0.440), t_{max} is observed maximum age, β is coefficient in the length-weight relationship ($W = \alpha L^{\beta}$).

4.2.2 Meta analysis for integrated M

By meta analysis (Piner and Lee, 2011) the M estimates relied on a range of factors (e.g. maximum age, maximum size, growth rate) and a broad range of levels within each factor was used to estimate within-method uncertainty.

The plausible ranges of factor levels (Table 1) were used to estimate within method uncertainty in the magnitude of M. The final estimate of M was random effects inverse variance weighted mean (an un-weighted estimated of mean M is given for comparison). The methods of estimation of the weighted mean are taken from (Borenstein *et al.*, 2009);

Table 1. Assumed levels of variability in key factors in this study

Factors	Range of level	Source
t_{max}	8 to 15	estimated
K (/yr)	0.2 to 0.6	estimated
L_{∞} (cm)	25 to 30	estimated
t_0 (yr)	-0.04 to -1.04	estimated
t_m (yr)	2 to 4	estimated
Temperature (°C)	3 to 15	NFRDI, 2010
GSI	0.00 to 0.94	estimated

Total variance (Q) is:

$$Q = \Sigma w_i (X_i - \overline{X})^2 \quad (19)$$

Where w_i is the 1/ within method variance and X_i is the method mean and $\overline{X}$ is the weighted mean across methods.

The between methods variance (t) is:

$$\text{if } Q>df,\ t = (Q - df)/C \quad (20)$$

$$\text{if } Q<df,\ t = 0$$

Where df is the number of methods and C is a scaling factor and w_i is inverse variance of the method (1/variance).

$$C = \Sigma w_i - \frac{\Sigma w_i^2}{\Sigma w_i} \quad (21)$$

The weight given to a method (w^*_i) is given by:

$$w_i^* = \frac{1}{v_i^*} \quad (22)$$

Where v^*_i is the within component of total variance:

$$v_i^* = v_i + t_i \quad (23)$$

Where v_i is the within method variance.

The weighted mean is calculated as:

$$weighted\ mean\,(M) = \frac{\Sigma w_i^* x_i}{\Sigma w_i^*} \quad (24)$$

The variance (V)*of the weighted Mean (M) is given by:

$$V^{*} = \frac{1}{\Sigma w_i^{*}} \quad (25)$$

4.3 Instantaneous coefficient of fishing mortality (F)

Based on total mortality and natural mortality, instantaneous coefficient of fishing mortality can calculated as

$$Z = M + F \quad (26)$$

5. Age at first capture (t_c)

Age at first capture (t_c) was estimated from the length-converted catch curve as per Pauly (1984). In this method, total mortality was calculated by equation below;

$$\ln(C/\triangle t) = c - Z\,(t + \triangle t/2) \quad (27)$$

where, C is number of catch, t is age, △t is age gap between length classes and c is a constant. Expected catch number was calculated as

$$CT = \triangle t \exp(c - Z_t) \quad (28)$$

Selectivity curve can be expressed in a linear equation

$$\ln(1/S - 1) = T_1 - T_2 t\,(L_1 + L_2) \quad (29)$$

where, S is the proportion of real catch number per expected catch number, L_1 and L_2 is length and T_1 and T_2 are constants. Using T_1 and T_2, t_c can be estimated

$$t_c = T_1 / T_2 \quad (30)$$

6. Stock assessment

6.1 Yield-per-recruit model

Yield-per-recruit (YPR) was estimated by Beverton and Holt model (1957).

$$\frac{Y}{R} = F \cdot \exp[-M(t_c - t_r)]\, W_\infty \sum_{n=0}^{3} \frac{U_n \exp[-nK(t_c - t_0)]}{F+M+nK}$$

$$(1-\exp[-(F+M+nK)(t_L - t_c)]) \qquad (31)$$

where, F is fishing mortality, M is natural mortality, t_c is age at first capture, t_r is age at first recruitment, W_∞ is asymptotic maximum total weight, t_0 is theoretical age at length is 0, t_L is maximum age and $U_0 = 1$, $U_1 = -3$, $U_2 = 3$, $U_3 = -1$.

Based on YPR, biological reference points, such as F_{max} and $F_{0.1}$ were estimated. F_{max} was defined as the fishing mortality that results in the highest YPR and $F_{0.1}$ was the fishing mortality where the slope of the YPR curve was 10% of the maximum slope.

6.2 Spawning biomass-per-recruit model

Spawning biomass-per-recruit (SBPR) was estimated by equation (32) and (33) as followed;

if F=0 was

$$\frac{SB}{R}|_{F=0} = \sum_{t_c=t_r}^{t_\lambda} m_t \cdot e^{-M(t_c-t_r)} \cdot e^{-M(t-t_r)} \cdot W_\infty (1-e^{-K(t-t_0)})^3 \qquad (32)$$

if $F=F_1$ was

$$\frac{SB}{R}|_{F=F_1} = \sum_{t_c=t_r}^{t_\lambda} m_t \cdot e^{-M(t_c-t_r)} \cdot e^{-(M+F)(t-t_r)} \cdot W_\infty (1-e^{-K(t-t_0)})^3 \qquad (33)$$

where, m_t is mature rate at age t, and others are same as YPR model. The mature rate at age was derived from the group maturity curve in length. It assumed that if $t < t_c$, F is 0. $x\%$ at $F_{x\%}$ is like equation (34) as followed;

$$\frac{SB/R|_{F=F_1}}{SB/R|_{F=0}} = x\% \qquad (34)$$

The biological reference points ($F_{35\%}$ and $F_{40\%}$) were estimated.

6.3 Assessing current status of the stock

$F_{40\%}$ was set as a target reference point because it was adjudged that ecological factor is more important than yield for elkhorn sculpin. The current status of the stock was assessed by revised Kobe plot simply and easily. The Kobe plot is used to evaluate the status of a stock based on the fishing mortality (F) and biomass (B) associated with maximum sustainable yield (Maunder and Aires-da-Silva, 2011). In this study, Kobe plot was revised. In revised Kobe plot, $SBPR/SBPR_{MSY}$ on the x-axis and F/F_{OTY} on the y-axis. F_{OTY} means the fishing mortality at overfished threshold yield. F_{OTY} can calculated as below

i) When $SBPR > SBPR_{MSY}$, $F_{OTY} = F_{MSY}$

ii) When $SBPR \leq SBPR_{MSY}$, $F_{OTY} = F_{MSY} \times (SBPR / SBPR_{MSY})$

Same as the original version, there are four sections with three colors, red, yellow and green to describe the stock state. The fundamental concept is same with the original version but it has been stricter than the original one (Fig. 2). If the value of $SBPR/SBPR_{MSY}$ is below 0.5, it means current stock is in red (danger) section regardless of F value; if the value of $SBPR/SBPR_{MSY}$ is over 1.0 and F/F_{OTY} is below 1.0, it means current stock is in green (safe) section. Additionally, to evaluate current t_c compared with optimum t_c ($t_{c\ opt}$) which is the tc that has the highest YPR at F_{MSY}, substitute $t_c/t_{c\ opt}$ on the x-axis instead of $SBPR/SBPR_{MSY}$.

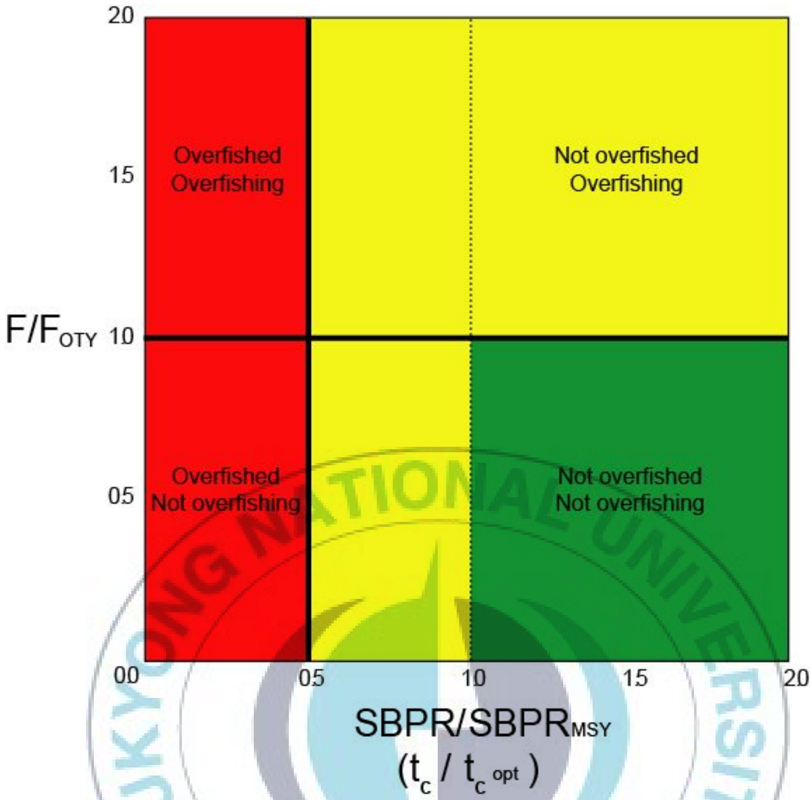

Fig. 2. Revised Kobe plot showing the overfished condition and the overfishing condition based on SBPR (t_c) and F.

Results

1. Size structure and length-weight relationship

In this study, elkhorn sculpin was in the 7.4cm to 28.3cm length range and about 60% of samples distributed between 14cm and 20cm. Length class between 16cm and 17cm was the highest frequency (15.7%) (Fig. 3).

Monthly changes of length and weight are shown in Fig. 4. In April 2010, both length and weight of this species were the highest and the lowest point was October.

Based on a total of 527 samples, length-weight relationship was $W = 0.0051 L^{3.2979}$ (Fig. 5).

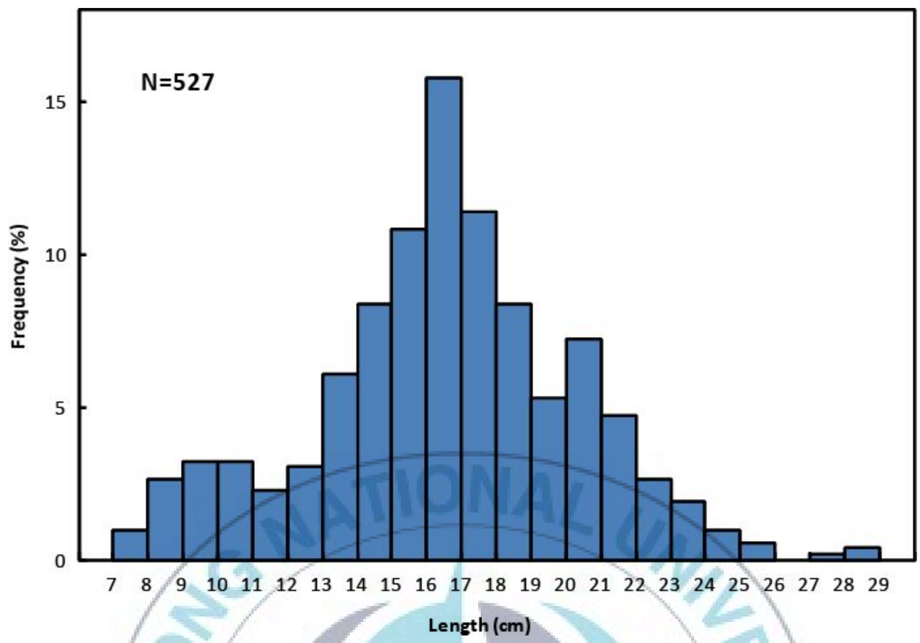

Fig. 3. Length - frequency histogram (N=527) for elkhorn sculpin (*Alcichthys alcicornis*) along the Uljin area of Korea.

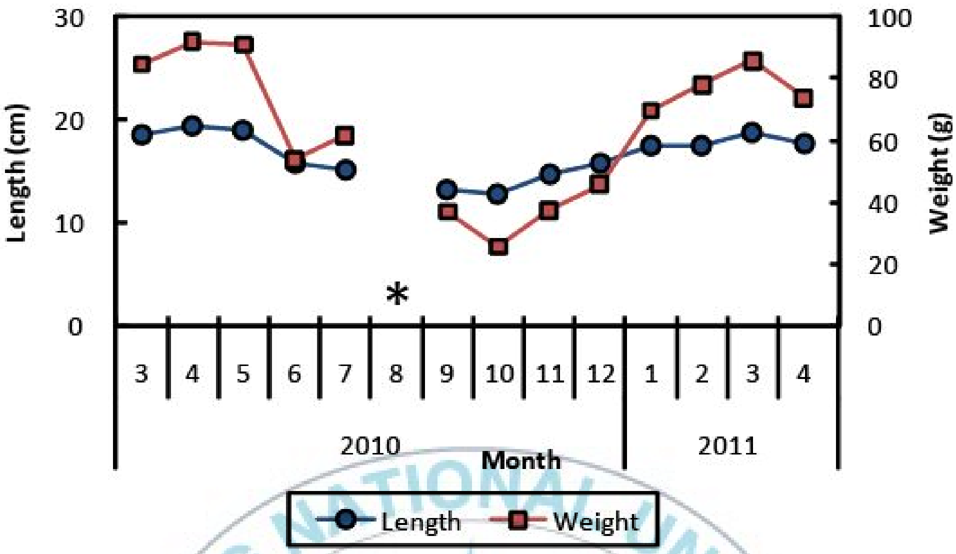

Fig. 4. Monthly change of length and weight for elkhorn sculpin (*Alcichthys alcicornis*) along the Uljin area of Korea (*No samples in August).

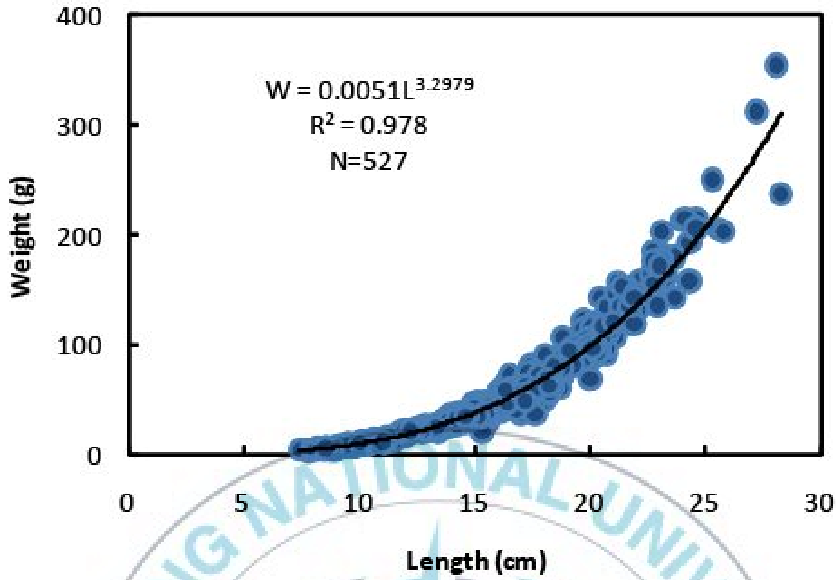

Fig. 5. Length-weight relationship for elkhorn sculpin (*Alcichthys alcicornis*) along the Uljin area of Korea.

2. Sexual maturity and Spawning

2.1 Gonadosomatic index (GSI)

The GSI values varied throughout the year as shown in Fig. 6. It showed that the GSI value has increased since January and it was the highest in both sexes in February (GSI 34.31, SE 4.31% for females and GSI 38.62, SE 2.36% for males). Therefore it was identified that the spawning season of this species was winter, February.

3.2 Group maturity

For estimating length at group maturity, during the distinct spawning season, from December to February, it was assumed that maturing, mature, spent fish that was within the range of reproduction. Based on that hypothesis, frequencies of reproductive fish according to length classes are shown in Fig. 7. Based on bootstrapped data, lengths at which 50% of the female and male fish had attained maturity, were 14.30cm and 17.42cm, respectively in logistic curve and 95% CI was 13.74~14.88cm in female, 16.16~18.77cm in male, respectively (Fig. 7).

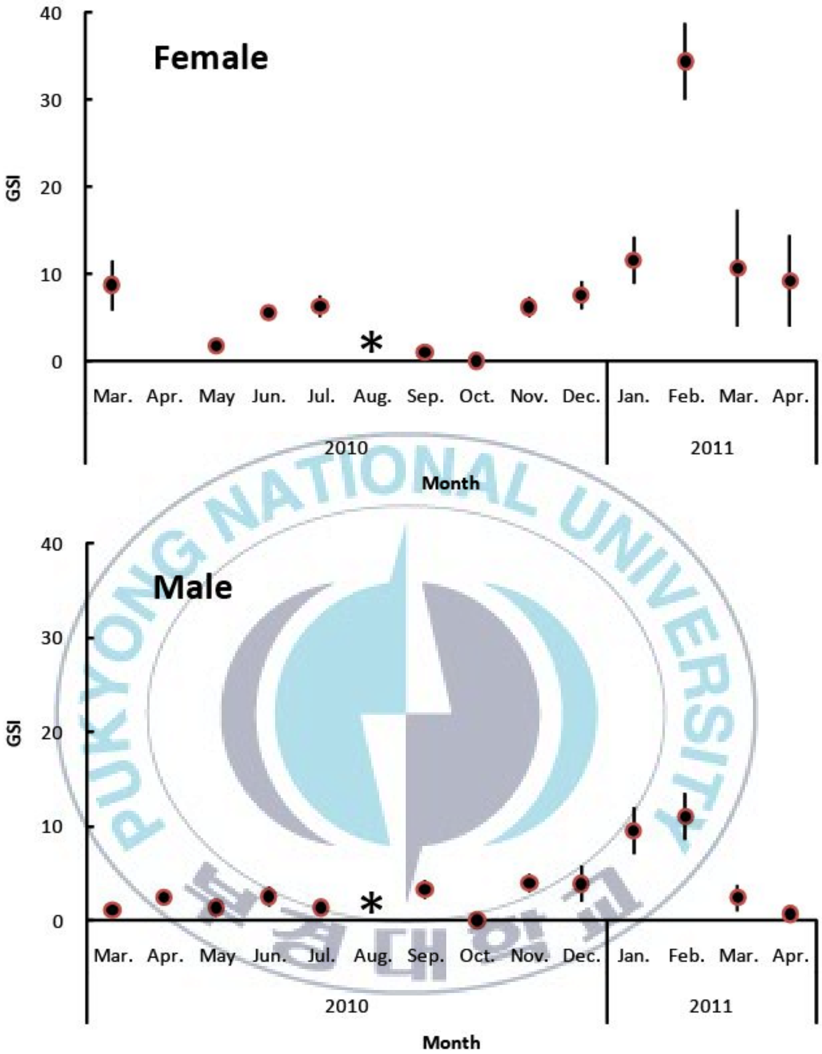

Fig. 6. Monthly changes of Gonadsomatic index (GSI) for elkhorn sculpin (*Alcichthys alcicornis*) along the Uljin area of Korea (*No samples in August).

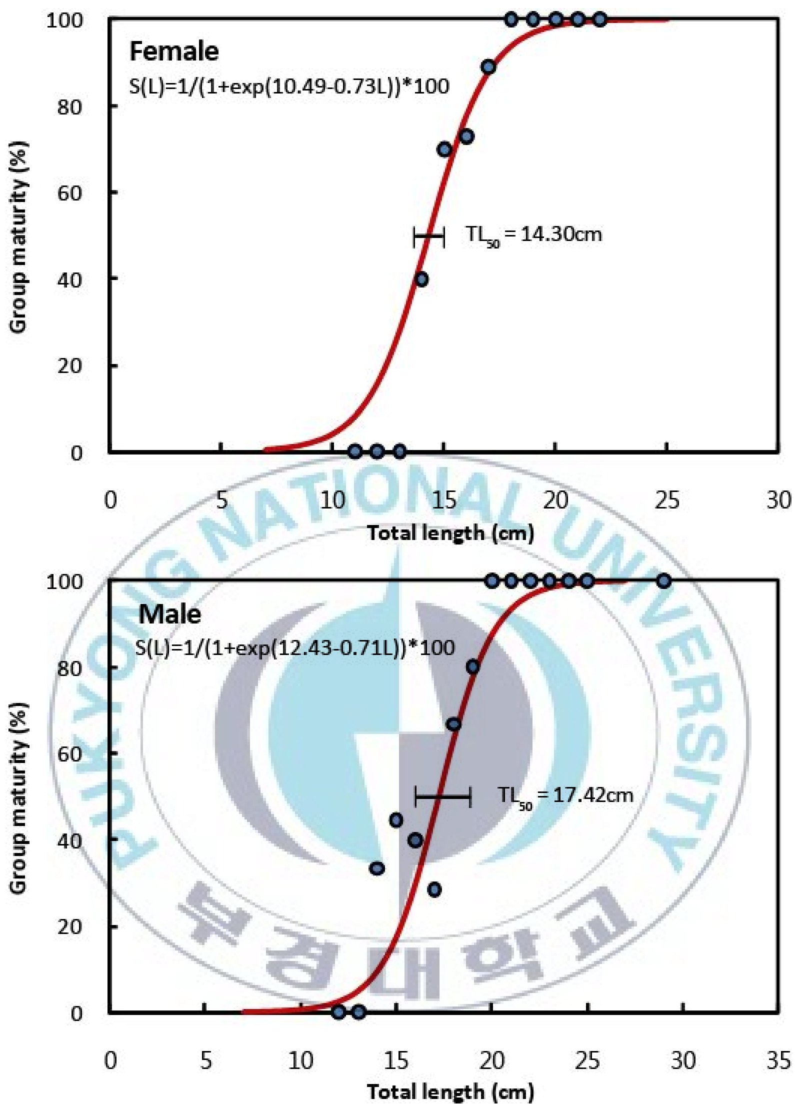

Fig. 7. Relationship between total length and group maturity of female and male elkhorn sculpin (*Alcichthys alcicornis*) along the Uljin area of Korea (Brackets are 95% bootstrap confidence intervals of the L_{50}).

3. Age and growth

3.1 Age determination

A total of 468 otolith samples were aged and 59 otolith samples were considered unreadable. A clear pattern of the alternation of zones with different optical density was observed in the sagittal otolith of elkhorn sculpin. The end of the opaque zone was measured as 1 year (Fig. 8).

Marginal index (MI) of this species was the lowest in January. Therefore, it was determined that a hyaline zone is formed on otoliths in the summer growing period, and an opaque one is formed during the winter, a stagnant growth period. Hence, each opaque rings were made once a year in January (Fig. 9). Also the season of the ring formation was winter same as the spawning season so it means that the rings were made by stimulation of spawning.

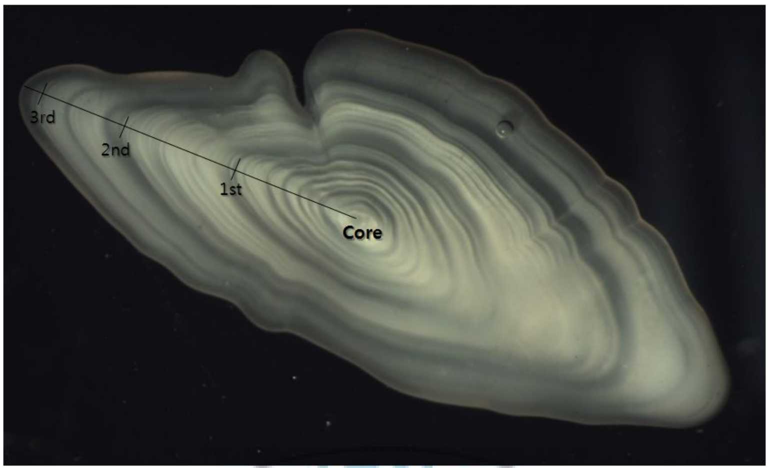

Fig. 8. Measurements for the annuli of a 3 year old elkhorn sculpin (*Alcichthys alcicornis*) along the Uljin area of Korea.

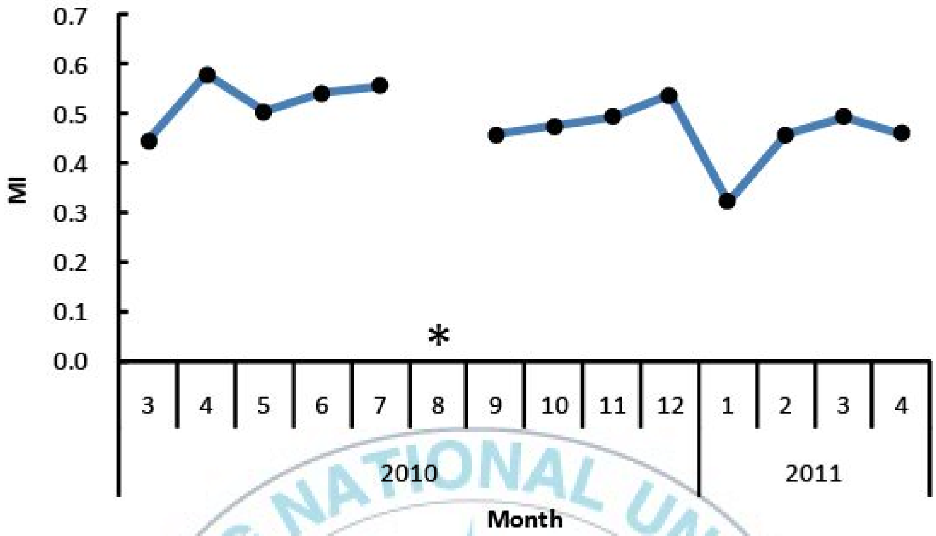

Fig. 9. Monthly changes in otolith marginal index of elkhorn sculpin (*Alcichthys alcicornis*) along the Uljin area of Korea (*No samples in August).

3.1.1 Within reader

Within-reader agreements for age readings were high (reader 1 = 83.8% and reader 2 = 91.2%) and the measurement of reader self-precision was also high for both readers (reader 1's CV = 8.2% and reader 2's CV = 9.4%). Disagreements at five-year-old fish were the highest in both readers (reader 1's CV = 34.4% and reader 2's CV = 26.2%) (Fig. 10).

(a)

(b)

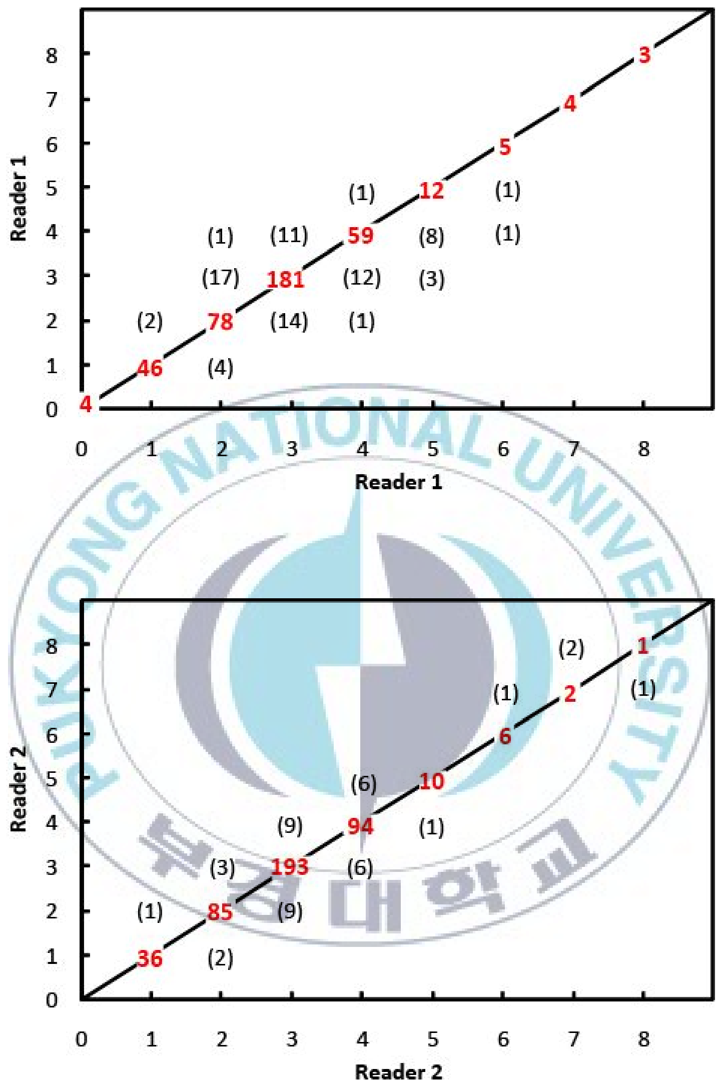

Fig. 10. Agreement plots for pair-wise comparisons between replicate annulus counts for sagittal otolith of elkhorn sculpin (*Alcichthys alcicornis*) for (a) within reader 1, (b) within reader 2. The 45° line represents 100% agreement. Numbers mean observations.

3.1.2 Between readers

The match rate between the second readings of each reader were the highest (82.3%) so they were chosen to cross-check (Table 2).

Between-readers agreements for age readings were 82.3% overall and for disagreements that were within a year, 99.6% (Fig. 11). Between-readers CV was 23.3%. Disagreements at below 1 year old fish were the highest because reader 2 judged no fish was below 1 year.

A total of 385 age data derived from 100% agreement between readers was used for growth function.

Table 2. Match rate of age reading between readers

Reader 1 / Reader 2	1st reading	2nd reading
1st reading	74.4%	77.8%
2nd reading	82.1%	82.3%

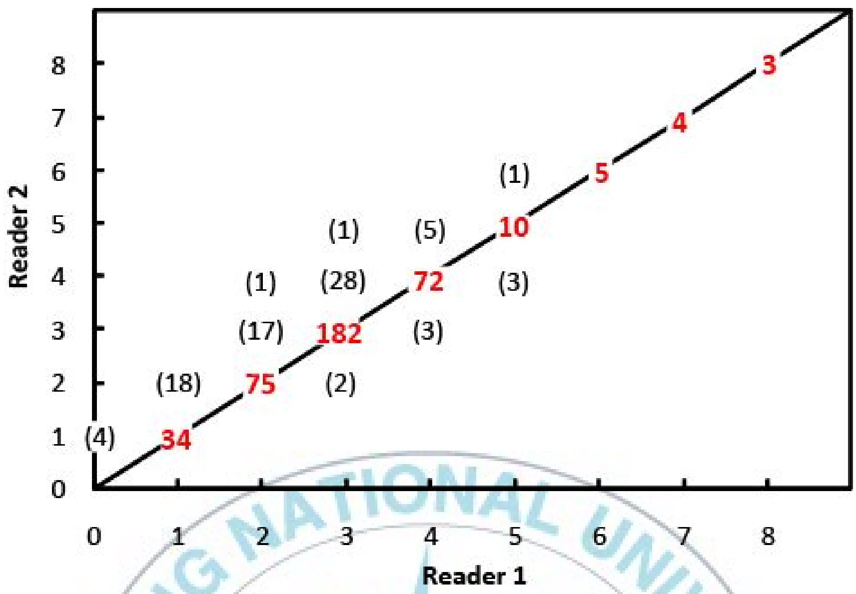

Fig. 11. Agreement plots for pair-wise comparisons between replicate annulus counts for sagittal otolith of elkhorn sculpin (*Alcichthys alcicornis*) for between reader 1 and reader 2. The 45° line represents 100% agreement. Numbers mean observations.

3.2 Growth functions

3.2.1 Standard von Bertalanffy growth function

Ages used for growth function ranged from 1 year to 8 years. In this method, the asymptotic length (L_∞) was 29.41cm, the growth coefficient (K) value was 0.247/year and the theoretical age at L_t=0 (t_0) was -0.609 year.

3.2.2 Generalized von Bertalanffy growth function

In this function, L_∞ was 28.78cm, K was 0.283/year, t_0 was -0.046 year and the fourth growth parameter, n was -0.75. n was close to -1, so it could say that this function is a similar type with standard von Bertalanffy function.

3.2.3 Robertson growth function

In this function, L_∞ was 26.67cm, K was 0.538/year, the third parameter, mean c ($\ln\left(\frac{L_\infty - L_0}{L_\infty}\right)+K t_0$) of ages at complete recruitment was 1.039.

3.2.4 Gompertz growth function

In this function, L_∞ was 27.48cm, K was 0.392/year, the third parameter, mean a ($\ln\left(\frac{L_\infty}{L_t}\right)e^{Kt}$) was 1.520.

3.2.5 Comparison of functions

Estimated catch curves are shown in Fig. 12. There is not significant difference among four functions. All growth models were powerful to describe the data obtained from elkhorn sculpin.

The model performance evaluation criteria is shown in Table 3. Standard von Bertalanffy growth function shows the minimum AIC and BIC values (AIC = -8.957, BIC = -8.719), followed by Gompertz (AIC = -8.941, BIC = -8.703), Robertson (AIC = -7.462, BIC = -7.224) and Richards (AIC = -7.137, BIC = -6.820).

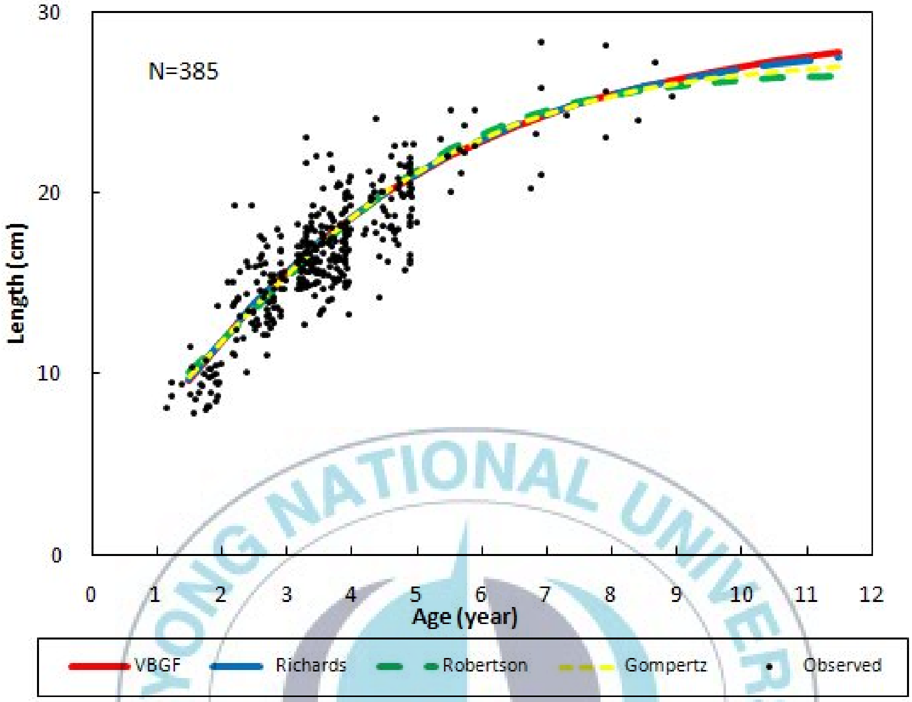

Fig. 12. Fitted growth curves from four growth functions for elkhorn sculpin (*Alcichthys alcicornis*) along the Uljin area of Korea.

Table 3. AIC and BIC values for each function

Growth functions	AIC	BIC
Standard von Bertalanffy growth function	-8.957	-8.719
Generalized von Bertalanffy growth function (i.e. Richards)	-7.137	-6.820
Robertson	-7.462	-7.224
Gompertz	-8.941	-8.703

4. Ecological parameters

4.1 Survival rate (S) and instantaneous coefficient of total mortality (Z)

Survival rate and instantaneous coefficient of total mortality of this species were 0.334 and 1.096/year, respectively (Table 4).

Table 4. Estimated survival rate (S) and instantaneous coefficient of total mortality (Z) for elkhorn sculpin (*Alcichthys alcicornis*) along the Uljin area of Korea

Method	S	var.(S)	Z
Chapman and Robson	0.334	0.0005	1.096/year

4.2 Instantaneous coefficient of natural mortality (M)

4.2.1 M estimates

M estimates by 7 different methods are shown in Table 5. It raged from 0.377/year to 0.815/year. The lowest M was 0.377/year (variance 0.0073) in Hoenig method using maximum age followed by Pauly method (0.571/year, variance 0.0394), Jensen method using mature age (0.596/year, variance 0.0441), Jensen method using K (0.600/year, variance 0.0563), Roff method (0.613/year, variance 0.1031), Zhang and Megrey method (0.677/year, variance 0.1174), and in Gunderson method M was the highest as 0.815/year (variance 0.3097).

Table 5. Estimated various instantaneous coefficient of natural mortality (M) by different 7 methods for elkhorn sculpin (*Alcichthys alcicornis*) along the Uljin area of Korea

Method	Parameters used	M estimates	Variance
Hoenig	maximum age	0.377	0.0073
Jensen	K	0.600	0.0563
Jensen	Age at maturity	0.596	0.0441
Roff	K, Age at maturity	0.613	0.1031
Pauly	K, L_∞, temperature	0.571	0.0394
Gunderson	Gonadosomatic index (GSI)	0.815	0.3097
Zhang & Megrey	t_0, β, K, maximum age	0.677	0.1174

where, K is instantaneous growth coefficient; L_∞ is asymptotic maximum total length; t_0 is theoretical age at L_t is 0; β is coefficient in the length-weight relationship ($W=\alpha L^{\beta}$)

4.2.2 Meta analysis for integrated M

The inverse variance weighted average M across all methods was 0.467/year and 95% confidence interval was 0.336 to 0.597/year.

4.3 Instantaneous coefficient of fishing mortality (F)

Based on total mortality and natural mortality, instantaneous coefficient of fishing mortality (F) was estimated as 0.629/year.

5. Age at first capture (t_c)

Age at first capture that was derived from VBGF and length composition of samples was 2.41 year (Fig. 13).

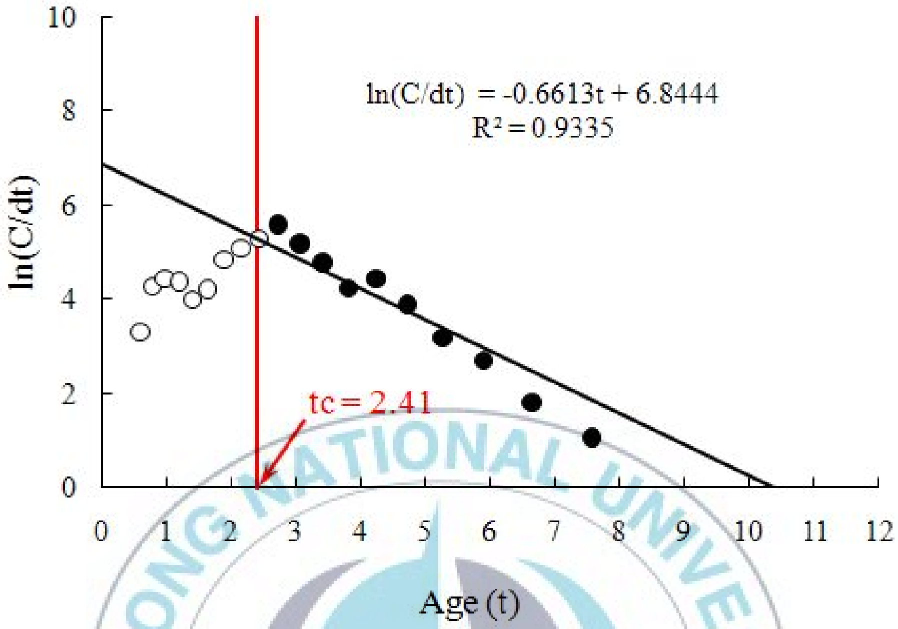

Fig. 13. Length converted catch curve of elkhorn sculpin (*Alcichthys alcicornis*) along the Uljin area of Korea. Closed circles indicate points used for deriving Z.

6. Stock assessment

6.1 Yield-per-recruit model

To estimate YPR, used input data was like Table 6.

Current yield per recruit was 20.68g with F = 0.629/year at t_c is 2.41 years. If F increases, YPR also will increase and when F was 2.103/year, YPR was the highest (22.71g) at current t_c. At current F, YPR was the highest (20.75g) when t_c was 2.21 years. (Fig. 14, 15)

Estimated F_{max} and $F_{0.1}$ were 2.103/year and 0.476/year, respectively and estimated YPR at F_{max}, $F_{0.1}$ and $F_{current}$ were 22.71g, 19.35g and 20.68g, respectively (Fig. 16).

Table 6. Input data for Yield-per-recruit model

W_∞ (g)	K (/yr)	t_0 (yr)	M (/yr)	t_c (yr)	t_r (yr)	t_m (yr)
355.24	0.247	-0.609	0.467	2.41	0.564	8

6.2 Spawning biomass-per-recruit model

Mature rate derived from mature length was 0 at 1-year-old group, 0.4 at 2-year-old group, 0.97 at 3-year-old group, 1 at over 4-year-old group. Estimated $F_{35\%}$ and $F_{40\%}$ were 0.658/year and 0.540/year, respectively and estimated SBPR at $F_{35\%}$, $F_{40\%}$ and $F_{current}$ were 36.62g, 41.85g and 37.77g, respectively (Fig. 16).

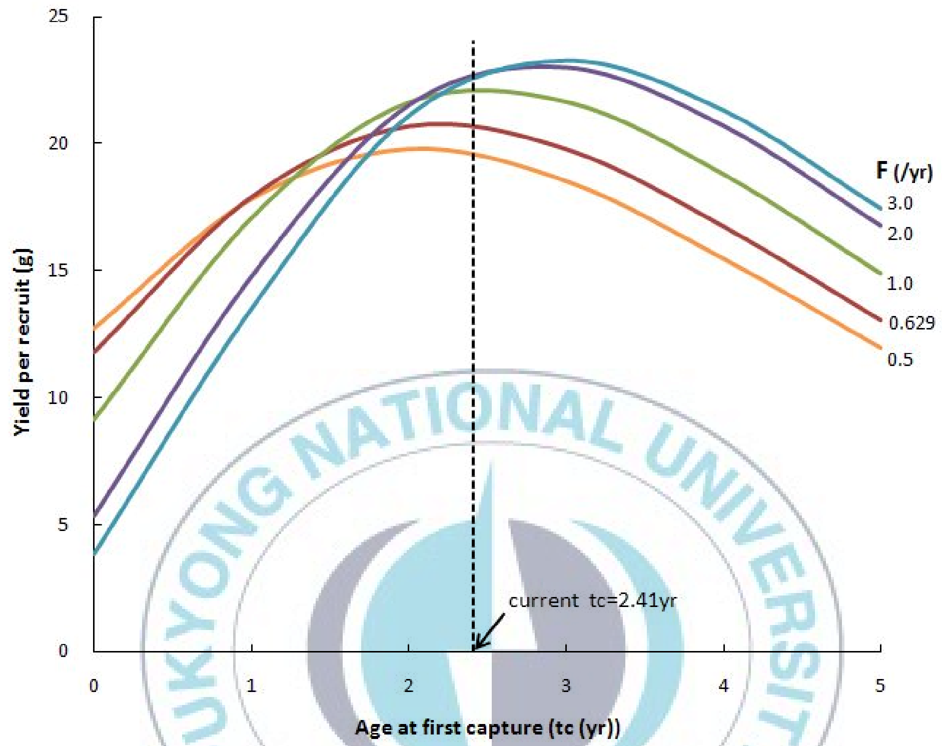

Fig. 14. YPR against the age at first capture (t_c) for various fishing mortalities (F) of elkhorn sculpin (*Alcichthys alcicornis*) along the Uljin area of Korea.

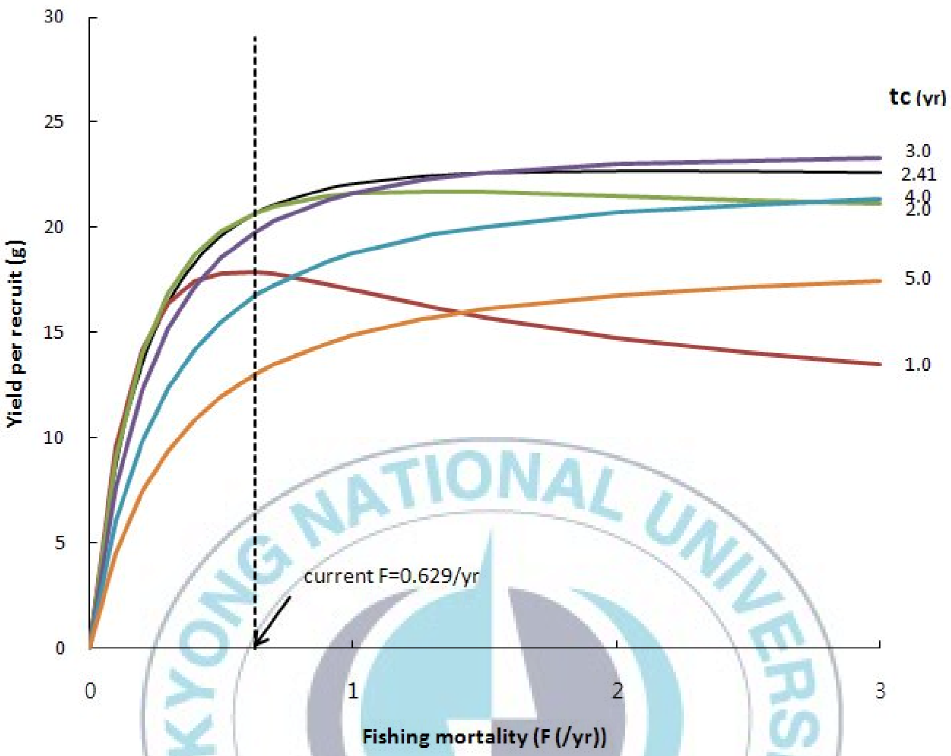

Fig. 15. YPR against fishing mortality (F) for various ages at first capture (t_c) of elkhorn sculpin (*Alcichthys alcicornis*) along the Uljin area of Korea.

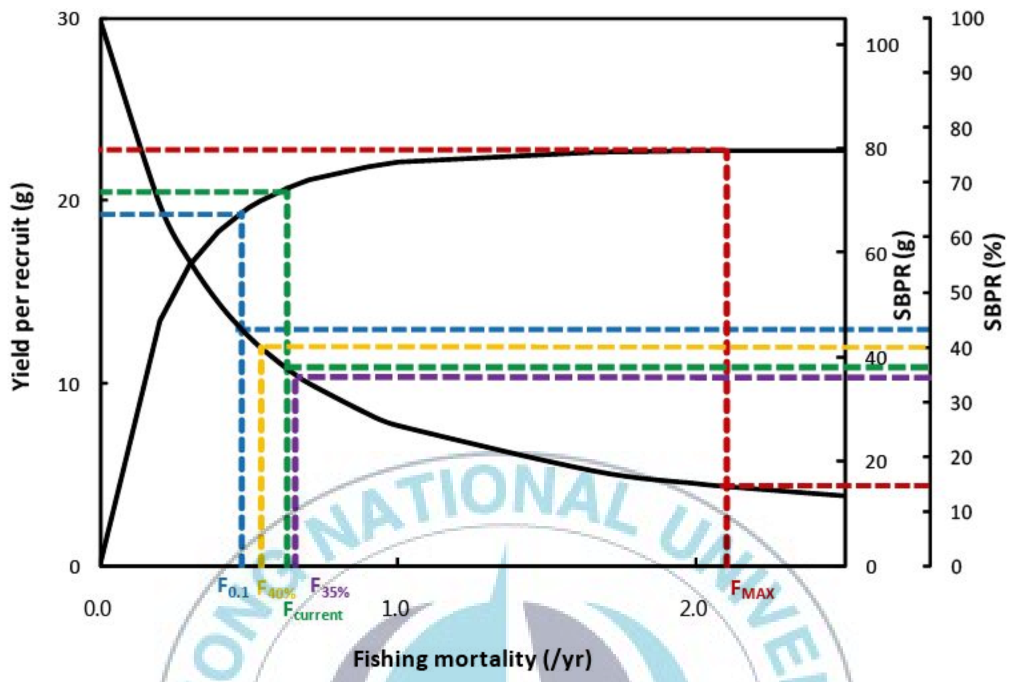

Fig. 16. YPR and SBPR against various reference points of fishing mortalities (F) of elkhorn sculpin (*Alcichthys alcicornis*) along the Uljin area of Korea.

6.3 Current status of the stock

$F_{40\%}$ was set as the F_{MSY}. Estimated F_{OTY} was 0.49/year. The ratio of $SBPR/SBPR_{MSY}$ was calculated as 0.90 and that of F/F_{OTY} was 1.05. Estimated t_{copt} was 2.10 years and F_{OTY} was 0.54/year. The ratio of t_c/t_{copt} was calculated as 1.15 and that of F/F_{OTY} was 1.17.

Therefore, in the case of both fishing mortality and age at first capture, the current stock condition of elkhorn sculpin along the Uljin area of Korea has been not overfished, however, it indicates that a light overfishing is going on this stock (Fig. 17, 18).

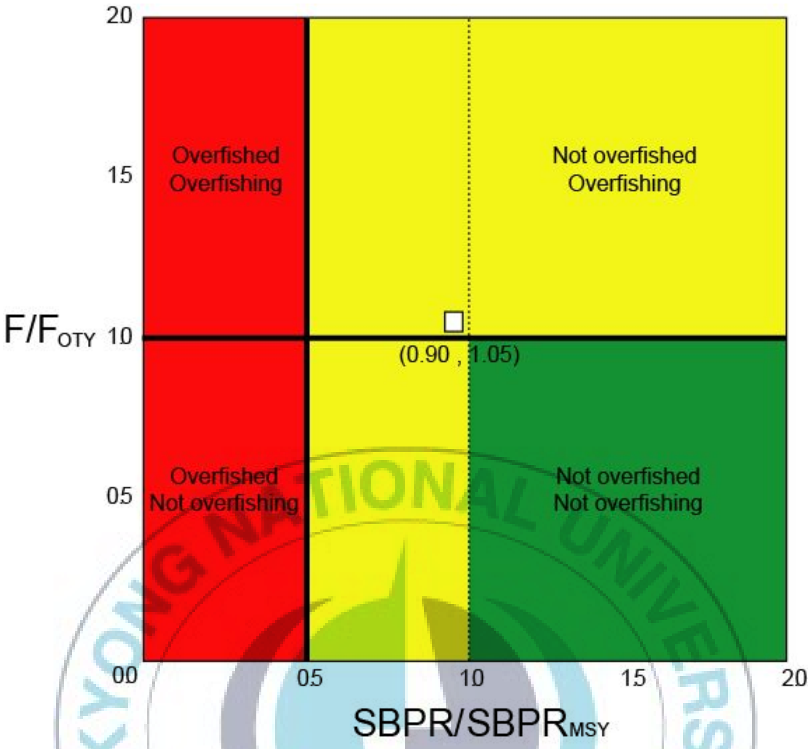

Fig. 17. Revised Kobe plot of the estimate of SBPR and F relative to $F_{40\%}$ for elkhorn sculpin (*Alcichthys alcicornis*) along the Uljin area of Korea. The white square indicates the current state of this stock.

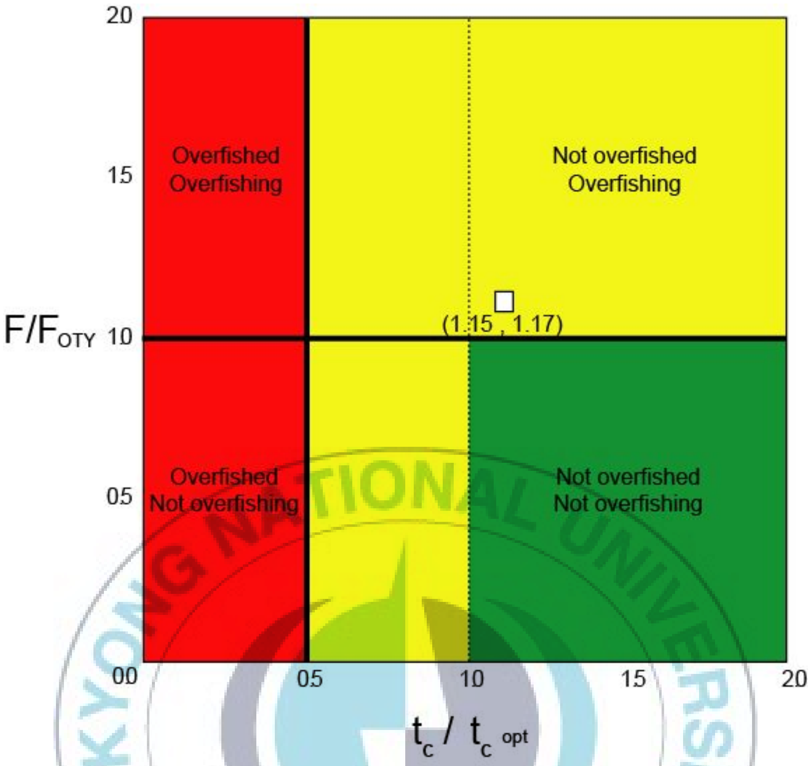

Fig. 18. Revised Kobe plot of the estimate of t_c and F relative to $F_{40\%}$ for elkhorn sculpin (*Alcichthys alcicornis*) along the Uljin area of Korea. The white square indicates the current state of this stock.

Discussion

In this study, no samples were collected in August, because this species moves to the deep sea bottom (below 200m) during the summer season (NFRDI, 2004). This characteristic feature is like as other sculpins in previous study (Park *et al.*, 2007). Furthermore, big size specimens were inferior in number. It is considered that the main fishing gear was trammel net (mesh size 7.6~12.1cm) so the length selectivity was limited.

Marginal increasement of otolith was the lowest in January. The spawning season of this species was winter so it is considered that the main reason of the ring formation is stimulation of spawning. Also during the cold winter fish couldn't feed enough because of food shortage, so it could be another reason of ring formation.

When two readers cross-check the age determination, disagreements for over five-year-old classes were higher than younger classes because of numerical inferiority. That is a problem in situation lacking an old age class.

When researchers choose the best fitted growth model, statistical check would be necessary. However VBGF has been used as a most common model without statistical verification. In this study, the two most commonly used penalized model selection criteria, AIC and BIC were used as a criteria for goodness of fit. As the result, VBGF was the lowest AIC and BIC values so that model was chosen to describe growth pattern of this species. Quinn and Deriso (1999) state that the AIC tends to be a conservative criterion because a model with more parameters is often selected, which breaks the parsimonious principle. However, BIC is more likely to result in a parsimonious model, it more seriously penalizes the introduction of additional parameters seriously by adding the term of m ln(n) in the BIC function, where m is the number of parameters and n is the number of observations. In this study, AIC and BIC ranks were determined as a same order.

The method of averaging estimates of M across a range of methods and levels of factors is based on how sensitive the estimate is to a realistic range of levels within factors. An inverse weighting approach gives more weight to the method with less variation in M estimates. A random effects approach was used because it is unclear if M based on different approaches should give the same M value and to include the within and between components of variance. It assumed that each method provides an independent measure of M.

The current state of this stock was assessed to be not overfished but it tends to be a light overfishing. However, the catch data hasn’t been reported at all even though this species has been caught continually.

Thus, measures to manage this stock are urgently needed and the first step of management should be an accurate observation of catch.

This study represents the first documented attempt at estimating the ecological parameters and assessing the stock condition of elkhorn sculpin along the Uljin area of Korea. Results from this study have contributed to our knowledge on the biology of this species that hopefully will lead to improvements in management of sculpins in Korea.

Summary

This study was performed to estimate population ecological parameters and assess the current stock condition of elkhorn sculpin along the Uljin area of Korea. Age and growth of elkhorn sculpin were examined based on the otolith and the annuli were formed once a year in January. Generalized von Bertalanffy growth function was the best fitted based on AIC and BIC statistics among four functions. The estimated growth parameters for this species were L_∞ = 29.41cm K= 0.247/year and t_0=-0.609year. GSI for both sexes was the highest in February, indicating February as the main spawning month. Based on bootstrapped data, lengths at which 50% of the female and male fish had attained maturity were 14.30cm and 17.42cm, respectively. Survival rate and total mortality was estimated to be 0.334, 1.096/year, respectively. Natural mortality (M) estimates for the elkhorn sculpin were derived from a meta-analysis of 7 different M estimators. The overall M estimate was based on a random effects inverse variance weighting of each method. M was estimated to be 0.467/year for the elkhorn sculpin along the Uljin area of Korea. The age at first capture of this species was estimated to be 2.41 years.

To assess the state of the stock, yield per recruit (YPR) and

spawning biomass per recruit (SBPR) analyses were performed. Estimates of F_{max} and $F_{0.1}$ were 2.10/year and 0.48/year, respectively, and those of $F_{35\%}$ and $F_{40\%}$ were 0.66/year and 0.54/year, respectively. Current fishing mortality was estimated at 0.63/year and the current age at first capture was 2.41years. $F_{40\%}$ was set as the target reference point of the stock. SBPR at $F_{40\%}$ and current SBPR were estimated to be 41.85g and 37.77g, respectively. Estimated F_{OTY} which is the fishing mortality for the overfished threshold yield was 0.49/year. The ratio of $SBPR/SBPR_{MSY}$ was calculated as 0.90 and that of F/F_{OTY} was 1.05 and the ratio of t_c/t_{copt} was calculated as 1.15 and that of F/F_{OTY} was 1.17. Therefore, the current stock condition of elkhorn sculpin along the Uljin area of Korea has been not overfished, however, it indicates that a light overfishing is going on this stock.

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감사의 글

남들보다 늦게 출발한 학문의 길이었지만, 무탈하게 잘 마무리 할 수 있게 되어서 기쁜 마음을 금할 길 없습니다. 그리고 본 논문이 완성되기까지 아낌없는 조언과 격려로 큰 도움을 주신 모든 분들에게 감사의 마음을 전하고자 합니다.

부족한 저에게 끊임없는 가르침과 따뜻한 관심과 격려로 지도해 주신 장창익 교수님께 진심으로 감사드리고, 존경합니다.

또한, 제가 수산자원학에 입문할 수 있도록 도와주시고 견인차 역할을 해주시는 이재봉 연구사님과 바쁘신 와중에도 부족한 저의 논문을 정성껏 다듬어주신 이성일 연구사님께도 깊은 감사드립니다.

항상 따뜻한 관심과 조언으로 큰 힘이 되어주신 국립수산과학원 동해수산연구소 최영민 연구관님, 윤상철 연구사님, 독도수산연구센터 손명호 연구사님, 남서해수산연구소 이선길 연구사님, 서영일 연구사님, 고래연구소 박겸준 선배님, 한국연안환경생태연구소 이만우 선배님, 김광훈 선배님, 부경대학교 수산과학연구소 송경준 선배님, 권혁찬 선배님께 감사의 마음을 드립니다. 그리고 옆에서 큰 도움을 주신 수산자원학 실험실의 이종희 선배님, 박희원 선배님, 권유정 선배님과 늘 웃을 수 있도록 도와준 볼매 정현이, 민하, 인영이, 정은이, 주호, Salvador와 여러 선후배님들에게도 감사드립니다.

매월 빨간횟대 시료 채집에 힘써주신 동해수산연구소 박정호 연구사님과 울진 오정환 선장님, 동진 오빠, 병선 오빠께도 많은 감사드립니다.

존재만으로도 힘이 되는 미정이, 원진 언니, 성현 형부, 윤희, 한나, 정원 언니, 승희, 은미에게도 고마움을 전합니다.

마지막으로 언제나 저의 선택을 믿어주시고 아낌없이 지원해주시는 아버지, 어머니와 든든한 오빠에게 이 논문이 작은 보답이 되었으면 합니다. 사랑합니다.