



ALTERNATIVE ASSESSMENT METHODS APPLIED TO THE HAIRTAIL (TRICHIURUS LEPTURUS) STOCK IN THE ARU SEA AS AN EXAMPLE

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ALTERNATIVE ASSESSMENT METHODS APPLIED TO THE HAIRTAIL (*Trichiurus lepturus*) STOCK IN THE ARU SEA AS AN EXAMPLE

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and Chuan-Hung Ho¹

Key words: *Trichiurus lepturus*, stock assessment, depletion method.

ABSTRACT

The Aru Sea off Indonesia is a major fishing ground for Taiwanese distant-water otter trawlers. The hairtail, an economically important demersal fish, is abundant in that area. The assessment methodology in this paper extends previous studies on hairtail fisheries by considering migration within the fishing grounds. This model is based on conventional Leslie-Delury method but makes different assumptions on stock movement and the relationship between stock abundance and catch per unit effort. It was applied to retrospective data from the hairtail fisheries in the Aru Sea. In addition, the depletion method was used to estimate the abundance of hairtail and to assess the status of the hairtail stock. The hairtail stock was estimated at three periods of a year: aggregation in March, dispersion between April and September, and aggregation again between October and December. Fishing mortality coefficients for the three periods were estimated to be 0.728, 0.232 and 0.395 month⁻¹, respectively. Clearly, the hairtail population was under high fishing pressure. This study revealed that the hairtail population was overexploited. The stock status and the high fishing mortality indicated that appropriate management measure is required.

I. INTRODUCTION

The hairtail, *Trichiurus lepturus* is a cosmopolitan coastal species in tropical and sub-tropical waters worldwide [23]. It is commonly found in the Aru Sea off Indonesia, a major

conventional fishing ground for Taiwanese distant-water otter trawlers. *Trichiurus lepturus* is an important commercial species and its biology and ecology have been well documented in various waters [1, 2, 18-20, 28, 32]. However, very little is known on this species in this area.

Misu [18] and Shiokawa [28] documented that the hairtail exhibits two migratory aggregation patterns. These aggregations occur around the wintering grounds in the cold season and the spawning grounds in the warm season. Our previous study [7] suggested that the fishing season can be divided into three episodes: aggregation in March and April, dispersion in May and June, and aggregation again from July to December. Two seasonal peaks of the hairtail abundance reflect this aggregation-dispersion pattern. The first peak in May-June can be explained in terms of the overwintering migration of hairtail. The second peak in October-December is likely to be the result of spawning aggregation. The hairtail thus appear to occupy the fishing ground seasonally, either for spawning, as indicated by distribution of fishing effort and CPUE and fluctuations in the population size, or for overwintering in, or close to, the same area.

As this stock is subject to increase (immigration) and loss (emigration) during the fishing season, it is possible to develop depletion estimators for initial population size and combined rates of immigration and emigration [11]. The depletion method provides a useful means of stock assessment when there is a paucity of data. It examines how measured removals of individuals (catch) influence the relative abundance of the remaining stock. In this method the catch rate (CPUE) is normally considered proportional to population size, often as an abundance index.

This study presents a method for hairtail fisheries applied to retrospective data from the Aru Sea. It extends previous studies by considering migration within the fishing grounds. This method is based on standard Leslie-Delury analysis but makes appropriate assumptions about stock movement and the relationship between stock abundance and CPUE. The aim

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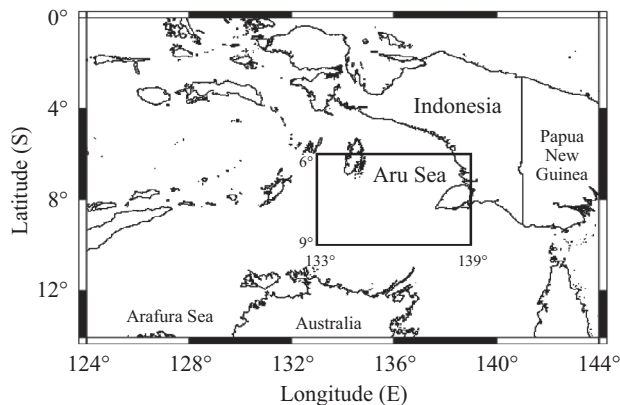


Fig. 1. Fishing area in the Aru Sea off Indonesia.

of this study is to evaluate the applicability of “depletion” methods to the estimation of initial stock size and fishing mortality, and assess how the hairtail stock in the Aru Sea has been influenced by fishing activities.

II. MATERIALS AND METHODS

The catch and effort data were obtained from the logbooks of Taiwanese otter trawlers operating in the Aru Sea during the period of 1994-1999. Among them, the data of six vessels were starting from 1994 and two were from 1995. Detailed analysis of the “depletion” approach therefore focused on 1994. As Taiwanese fishermen did not operate in January and February, no fishing data were available for these two months.

As the information of stock boundaries is not available, we assumed the operating area of Taiwanese otter trawlers as the assessment unit. The waters around 6~9°S, 133~139°E (Fig. 1) is shallow, with the water depth of 20-80 meters. Fishing records in this area from March to December were compiled from the logbooks of the fishing vessels, all of which were similar in terms of gross tonnage (218~299 ton), horse power (1000~1200 hp) and net specifications. The fishing records provided the location of the fishing operation, as well as net shoot-time and haul-time data for each operation. The nominal fishing effort (fishing hours) was not standardized and daily catch per unit effort (CPUE) was calculated as catch in weight divided by fishing hours.

The monthly mean sea surface temperature (SST) data used in this study were obtained from the IGOSS (Integrated Global Ocean Services System) products bulletin of Columbia University. Representative monthly temperatures for the whole fishing ground were calculated by taking the mean of the temperatures at the center of the six one-degree quadrants that comprised the main fishing area.

Conventional depletion methods assume that stocks decrease only from capture. It is also assumed that CPUE is proportional to population size over short time periods. The Leslie and Davis have a linear form and can be fitted graphi-

cally or by linear regression [15].

The initial population size (N_0) and catchability coefficient (q) are used to describe the change in population size [10, 15].

If we assume that CPUE is proportional to abundance,

$$(C/f)_t = qN_t \quad (1)$$

$$N_t = N_0 - K_t \quad (2)$$

where C and f are the catch, and the nominal (or recorded) fishing effort, (C/f) is catch per unit effort (CPUE; catch weight in kg per hour), t is the time period under consideration, N_t is the population size at the beginning of time period t , and K_t is the cumulative catch since the beginning of the season.

By substituting Eq. (2) into Eq. (1), a linear relationship is obtained:

$$(C/f)_t = qN_0 - qK_t \quad (3)$$

This relationship implies that the absolute value of slope equals to the catchability coefficient and the intercept equals to the initial population size.

Review of fisheries models and relationships covered mortality and survival. An alternative expression of Eq. (2) is continuous or the exponential fishing model,

$$N_t = N_0 e^{-qEt} \quad (4)$$

$$N_t = N_0 e^{-(F+M)t} \quad (5)$$

where Et is the cumulative effort up to time t (summation of f_t), F is the coefficient of fishing mortality, and M is the coefficient of natural mortality. For the purposes of stock assessment, it is necessary to have a measure of fishing effort that has a constant effect upon the fish population. This measure, commonly used in the population dynamics literature, is the so-called fishing mortality. The fishing mortality (F) is simply defined as the fraction of the average population taken by fishing [13]. F can be considered as an invariant measure of effort [25]. It can be defined as $F = qf_t$, without reference to the nominal effort, the configuration of the fishing gear, or the manner in which the gear is employed [13]. Suppose the population is removed in a fishing season, the behavior of this population under fishing can be described by the following equations.

$$N_t = N_0 e^{-Ft} \quad (6)$$

$$N_0 - K_t = N_0 e^{-Ft} \quad (7)$$

Both the initial population size and the fishing mortality can be estimated by assuming Eq. (2) and Eq. (6). Migration is a common phenomenon for organisms in the marine ecosystem, and it is usually governed by the various needs of the organism at different life stages [3]. One salient feature that seems to

hold true for most migratory species is that their spawning grounds are in a fixed area [9].

From the point of view of fisheries, the migration phenomenon (immigration and/or emigration phase) presents conditions similar to mortality. Caddy [4] developed an approach to analyze the population trends based on the assumption that these phases are recognizable. He proposed the following expressions:

$$\begin{aligned} \text{Fishing phase} & Z_1 = F_1 + M_1 \\ \text{Immigration phase} & Z_2 = F_2 + M_2 - I \\ \text{Emigration phase} & Z_3 = F_3 + M_3 + E, \end{aligned}$$

where Z is total mortality, I is the rate of immigration and E is the rate of emigration. It is assumed here that there are no net migration effects during the fishing phase.

Hairtails also exhibit life-stage related migrations, and their distribution in the Aru Sea may be associated with the seasonal changes in abundance that result from migration for overwintering and spawning. This immigration or emigration takes place during the fishing season, and to take this into account Eq. (6) can be modified as follows:

$$N_t = N_0 e^{-(F+E-I)t} \tag{7}$$

$$= N_0 e^{-(F-R)t} \tag{8}$$

where R is the net value of migration effects ($R = E - I$). Based on the aggregation-dispersion pattern, the fishing season can be divided into three episodes: aggregation in March, dispersion between April and September, and aggregation again between October and December. In order to detect these changes, the model was modified for each of these three periods during the fishing season: (A) the first month of the fishing season (March), (B) the main months (April-September) and (C) the remaining months (October-December).

Fitting a depletion model to CPUE data from the first period of decreasing abundance allows an estimation of the population size at the start of the fishing season. It is assumed to be the first period of the fishing phase which is unaffected by net migration.

III. RESULTS

The sea surface temperatures of the fishing ground varied sinusoidally and ranged from 25.6°C to 29.4°C (Fig. 2). The Aru Sea is located in the South Hemisphere, and its surface temperature fell from an initial high in January-April to a minimum in August, after which it began gradually to increase again.

Monthly changes in catch and CPUE (Fig. 3) indicated that the bimodal stock size distribution and the aggregation-dispersion pattern were related to the sea surface temperatures.

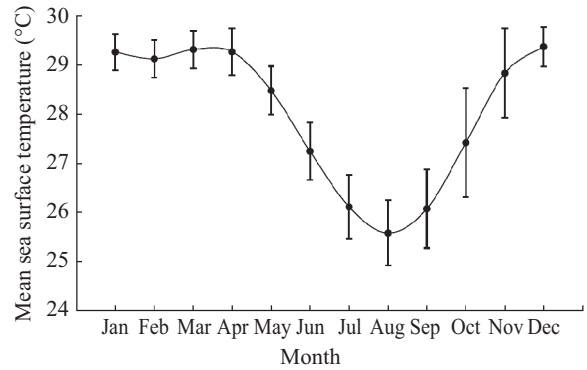


Fig. 2. Monthly variations of mean sea surface temperatures (\pm SD) in the fishing ground 1993~1999.

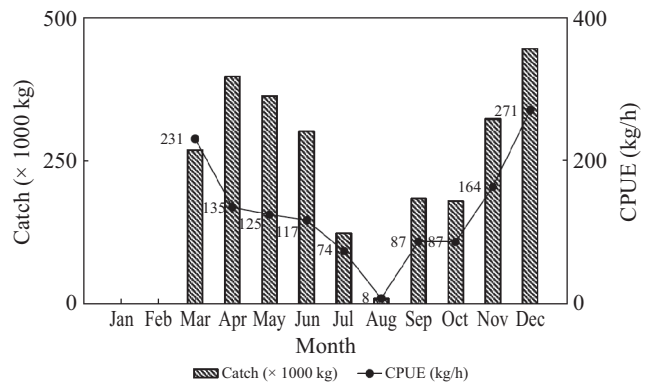


Fig. 3. Monthly total hairtail catch and CPUE from the six sample boats.

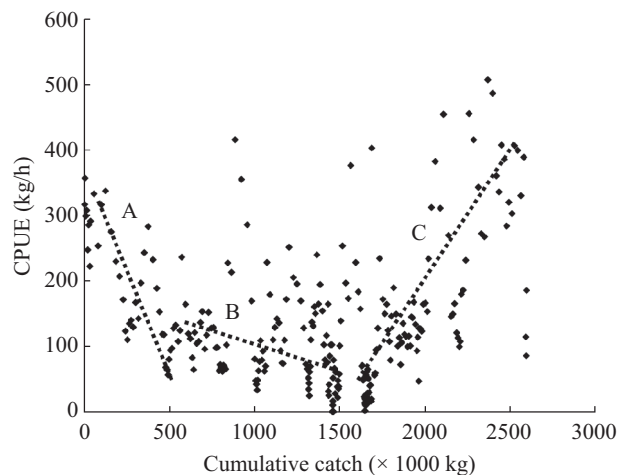


Fig. 4. Catch per unit effort vs. cumulative catch of hairtail in 1994.
.....: trend line.

The CPUE in March (231 kg/h) and April (135 kg/h), and in November (164 kg/h) and December (271 kg/h) were higher than in other months. The CPUE was lower between May and October (125~87 kg/h), followed by an increase thereafter.

The relationship of CPUE against cumulative catch is shown in Fig. 4. Catches per unit effort did not decline as trawling proceeded, and even increased at the end of the fishing

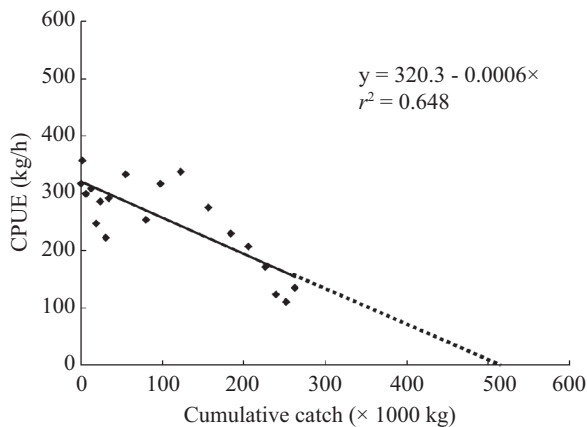
Table 1. Estimates of initial population size, cumulative catch and effort using Eqs. (2) and (3) in various periods.

Type	$(C/f)_t = qN_0 - qK_t$	N_0 (ton)	Cumulative		qE_t	$N_t = N_0 - K_t$
			Catch (ton)	Effort (h)		
*A	$(C/f)_t = 320.3 - 0.0006K_t$	507.5	262.5	1084.3	0.684	245
*B	$(C/f)_t = 166.3 - 0.00009K_t$	1922.6	1379.1	13316.7	1.152	543.5
*C	$(C/f)_t = 66.9 + 0.0003K_t$	---	945.4	5671.1	-1.718	---

*A: March, B: April~September, C: October~December.

Table 2. Estimates of fishing mortality using Eq. (8) under different hypothesis in various periods.

Type	$N_t = N_0 \exp(-(F+E-I)t) = N_0 \exp(-(F-R)t)$	Hypothesis	F	R(= E-I)
			Month ⁻¹	
*A	$N_4 = N_3 \exp(-(F_A - R_A)1)$	$E_A \cong I_A, R_A = 0$	0.728	0
*B	$N_{10} = N_4 \exp(-(F_B - R_B)6)$	$F_B > R_B$	0.232	0.197
*C	$N_{12} = N_{10} \exp(-(F_C - R_C)3)$	$F_C \ll R_C$	0.395	> 0.586

**Fig. 5. Catch per unit effort vs. cumulative catch in period A (March).**

season. In the first month of the fishing season (March), a clear depletion pattern was seen within the range 0~300 tons of cumulative catch. After March, the CPUE showed dramatic variations, with a cumulative catch of 300~1600 tons (April – September). During this period, the trend was much less obvious (Fig. 4). In contrast, the remaining months (October – December) showed a positive correlation.

In the first period, stocks decreased only as a result of capture, and the natural mortality rate was negligible in the short term. It was reasonable to assume that the stock was initially at equilibrium (movement into the fishing ground balancing movement out). The linear relationship between catch per hour and cumulative catch fitted quite well ($r^2 = 0.648$, $P < 0.001$) (Fig. 5). An estimate of the initial population size ($N_0 = 507.5$ tons; Table 1) was obtained from Eq. (3). The total catch was therefore 262.5 tons, and cumulative effort was 1084.3 h. Fishing mortality at the start of the fishing season was measured by the exponential fishing model of Eq. (6). The fishing mortality in March was $F_A = 0.728$ month⁻¹, under the assumption $E_A \cong I_A$ (Table 2).

In October-December, dramatic variations in the population

size index and fluctuations in the hairtail population size were synchronized with increasing sea temperature [7]. This suggests that the population size distribution was related to spawning behavior. Clearly, the stock is subject to immigration and emigration during period C. The initial population size could not be obtained directly, and it was assumed that the migration effect (R) was greater than the fishing effect.

Since there are six parameters in three functions (equations A, B and C), the estimate of the fishing mortality coefficient and R (migration effect) could not be obtained. In addition to putting forward different hypotheses for each time period (Table 2), the ratio of fishing mortality was calculated proportionally by using the monthly cumulative fishing effort from six sample trawlers in 1994. This ratio was $F_A : F_B : F_C = 1 : 1.92 : 1.63$, and mortality was estimated for periods A, B, and C as 0.728, 0.232 and 0.395 respectively (Table 2). The ratio was substituted into Eq. (8) to solve the simultaneous equations. The simplified factor R (migration effect) was also taken into consideration in the exponential fishing model.

Due to substantial migration in period C, the linear relationship indicated a positive correlation. The initial population size could not be obtained directly. To combine the Eqs. (4) and (8), they may be conveniently expressed in the following expression form. The migration (immigration) was happened. The right part is larger than left part of this expression. The power of equation is used to find the approximation of R. The value of qE_t was substituted to solve the coefficients as follows:

$$N_0 e^{-qE_t} < N_0 e^{-(F-R)t}$$

$$-(qE_t) < -(F_c - R_c)t$$

$$(-1.7176) < (1.63F_a - R_c)2$$

$$R_c > 1.757$$

By using this estimating technique, the net migration effect

was obtained. Recruitment in periods B and C was 1.183 times and more than 1.757 times the initial stock at the beginning of the fishing season.

IV. DISCUSSION

There are many local populations of hairtail, some of which have been reported as different species or subspecies [16, 22, 27, 30, 31]. Nakamura and Parin [23] indicated that *T. lepturus* is one of the most extensively distributed species of hairtail in tropical and temperate waters, and we have tentatively followed them for the scientific name in the present study.

The distribution and movement of hairtail stock in the Aru Sea have previously been examined. Fluctuations in the hairtail CPUE (Fig. 3) followed the variations of SST (Fig. 2). In order to assess the stock status of hairtail in each of the time periods, an appropriate hypothesis needs to be made which accords with the state of hairtail fishing, as well as its biology and ecology. The simple depletion model assumes that there is either no immigration or emigration, or that those two are in near balance, and that CPUE is proportional to population size. When fish die only from capture over short time period, the cumulative catch will increase as CPUE decreases with time. Thus, the initial stock (N_0) is estimated by regressing CPUE against cumulative catch. The slope of this regression is also an estimator of q , the “catchability coefficient”. However, the reality is that in many cases, recruitment (immigration) is taking place. The steepness of slope q is in fact affected by fishing, emigration, immigration and natural mortality [12], and the calculated initial stock size will vary accordingly. The present study suggests that there is a substantial aggregation–dispersion pattern in the hairtail stock. This means that the simplified factor R needs to be taken into account in the exponential fishing model (8) and that the parameters in the equations A, B and C can be reduced.

In period A, a strongly negative linear relationship is observed (Fig. 5). R is assumed to be zero in this period. It is reasonable to assume that when the initial fishing activity commenced, the stock was at equilibrium even if immigration and emigration were in fact taking place. Applying the conventional Leslie-Delury method to the data produced an estimate of the stock size at the beginning of the trawling season for period A. Although the most common error in the application of depletion methods is to overestimate catchability and thus to underestimate the initial stock [11], such short-term variation does not seriously affect the stock estimates in this study [24]. In line with falling sea surface temperatures, this paper found that the hairtail dispersed in period B. This led to dispersed fishing efforts, in fact the lowest density of the entire fishing season, and also a lower CPUE (Fig. 3). The extensive distribution of trawling locations can be explained in terms of the hairtails’ overwintering migration [7]. Owing to the migration effect, the CPUE did not fall significantly with increasing cumulative catch. It is reasonable to assume

that fishing mortality was still larger than recruitment during this period. Although the linear trend remained negative (Fig. 4), the steepness of the slope was not as pronounced as in the first period.

The mating systems and distribution patterns of hairtails have also been studied in the western Wakasa Bay spawning grounds [20, 21]. A similar movement of *T. lepturus* was found in both the western Wakasa Bay and in the central part of Japan [28]. The sex ratio of *T. lepturus* was close to 1.0 before inshore migration for feeding prior to the spawning season (the warm season). Before mating, the sexes were separately distributed. The mature females then moved in an orderly way to the spawning grounds. After spawning, they returned, again in an orderly fashion, to the coastal area to feed [19–21, 28]. It is probable that hairtails in the Aru Sea exhibit similar distribution, movement, and mating patterns. The second population peak occurred during period C (at a time when temperatures were increasing towards a maximum). The concentrated distribution of trawling locations reflects the condensed high density schools that formed during this period. Aginaldo Silva Martins and Manuel Haimovici [1, 2] have stated that *T. lepturus* in southern Brazil spawns in late spring and summer (September–December) on the continental shelf and probably year round over the shelf break. This supports our hypothesis that the second peak is the result of spawning aggregation. Clearly, the stock is subject to immigration and emigration in period C. Massive recruitment [6, 7] may explain why, as trawling proceeded, CPUE did not decline, but actually increased during period C, resulting in a positive correlation between CPUE and cumulative catch (Fig. 4). These results suggest that our assumption about the relationship between F and R is correct, and that the migration effect (R) is greater than the fishing effect (F). This indicates that it is reasonable to use Eq. (8) to estimate the parameters.

The simplest depletion model assumes a closed fishery with no immigration or emigration, and a short interval for which $M \approx 0$. Chien and Condrey [8] have stated that basic depletion models tend to underestimate catchability and overestimate the initial stock. This may be a key reason why there is a tendency to overestimate fishing mortality under the assumptions that fish die only from capture, and that there is no immigration or emigration, or at least a near balance during the initial period.

In terms of hairtail resource utilization, for central Japan, $F = 0.103 \text{ yr}^{-1}$ was considered appropriate at age at first capture = 1.63 yr, while an F value over 1.1 yr^{-1} may result in over-fishing [28]. In the Kii Channel, a significant impact of catch on hairtail recruitment was observed when the fishing mortality was 1.22 yr^{-1} and the age at first capture was 0.5 yr. To ensure sustainable utilization of fish stock, the fishing pressure should be reduced by one third [26]. The stock status of hairtail in the northern South China Sea is at the high end of the high risk zone for age at first capture = 0.5 yr and $F = 2.6 \text{ yr}^{-1}$ [33]. In order to conserve hairtail resources and ensure sustainability, either the age at first capture should

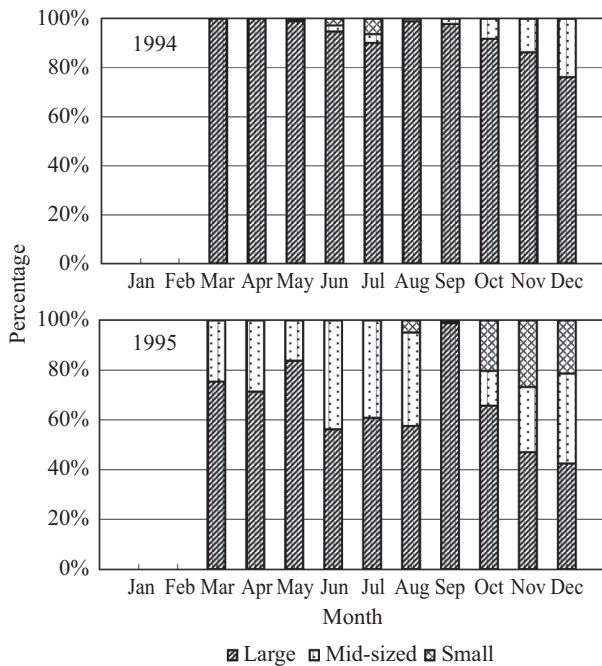


Fig. 6. Monthly size category composition of the hairtails in 1994 and 1995.

be increased or the fishing mortality should be reduced in the northern South China Sea. Fishing mortality ($F = 3.97 \text{ yr}^{-1}$) may have been overestimated in the present study as it is much higher than those in other regions. This revealed that the hairtail stock in the Aru Sea was under intensive fishing pressure.

The annual CPUE in the Aru Sea was about 130kg/h in 1994, but then fell dramatically to 40kg/h in 1995. Due to the poor fishing conditions, Taiwanese trawlers moved to other oceans in 1997. They returned in 1998, but catches were still poor, with a CPUE of only 8kg/h level in 1999. Using the CPUE as an index, this clearly suggests that the relative abundance of the exploited hairtail stock has shrunk in the Aru Sea.

In the present study, the stock was mainly composed of large individuals. The pre-anal length ranged from 26.8 to 39.2cm for large hairtails and from 24.7 to 30.9 cm for mid-sized hairtails. The large individuals were estimated to be 2 to 3 years old, while the mid-sized individuals were estimated to be 1 to 2 years old [5, 6, 14, 29]. In terms of size category composition (Fig. 6), the number of months in which mid-sized hairtail appeared increased in 1995. The monthly proportion of mid-sized hairtail ranged from 20~40%, while that of large hairtail fell to about 60%. The proportion of small hairtail reached 20% from October to December. Compared with 1994, although the stock was still mainly composed of large hairtail, the proportion of both mid and small-sized hairtail increased significantly. It has a relatively stable pattern of fluctuation in abundance, meaning that the stock is less affected by environmental conditions. However, the species

is highly sensitive to overfishing, both in terms of fishing mortality and age at first capture. Once hairtail resources have been overexploited, it will not be easy for the stock to recover [17]. Based on the estimated high fishing mortality found in this study, we suggest that appropriate management of the hairtail fishery is required. Analysis of trends in CPUE, distribution and movement indicate that the aggregation-dispersion pattern of the hairtail stock is complex and variable [6], but can be categorized into three fishing season phases [8] - aggregation in March, dispersion between April and September, and aggregation again between October and December. For the purposes of stock assessment in each phase, it is important to establish an appropriate hypothesis based on the fishing state, which takes both immigration and emigration into account. The results of this study prove that it is applicable to use the depletion method and the exponential fishing model to assess the status of a fish stock.

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