Stock structure and resource management of hairtail *Trichiurus japonicus* based on seasonal broods around the Bungo Channel, Japan

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Abstract Declines in landings of the hairtail *Trichiurus japonicus* indicate the need for more effective management of this species. Hairtail spawning peaks occur twice yearly in the Bungo Channel, in spring and autumn. Relationships between hairtail stock and brood seasonality were examined to determine if an association between either and a decline in landings existed. Stock assessments show that the biomass of both spring and autumn hairtail broods from within and around the Bungo Channel are decreasing, with a rapid reduction in spring-brood stock abundance after 2007 largely

responsible for decreased landings. Yield and spawning per recruitment analyses indicate current fishing pressure to be higher than several reference points. We suggest that fishing pressure needs to be reduced by at least 20% of the current level for this fishery to remain sustainable, as the projected stock abundance and catch demonstrate that the current fishing pressure is unsustainable. Analysis of time-series data of recruits per spawning revealed spring-brood recruitment to have been strong in year classes 2003 and 2005. Of various options available for improved management of this fishery, we propose that fishing pressure should be reduced in the years following the appearance of strong year classes to increase future biomasses and landings.

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Introduction

Hairtail *Trichiurus japonicus* is a widely distributed commercially exploited fish species found around Japan and the waters of the Yellow, Bohai, and East China Seas [1]. Several major fishing grounds exist around Japan, including the East China Sea, the western region of the Sea of Japan, and the waters around the Kii and Bungo Channels (Fig. 1). Though large numbers of hairtail were landed from both the East China Sea and western region of the Sea of Japan [2, 3] in the 1960s, the annual catch in these areas has decreased since the 1970s. However, landings of hairtail from waters around the Bungo Channel have increased from the 1970s, increasing the importance of these fishing grounds (Fig. 2). Waters within and around the Bungo Channel provide an important hairtail habitat, where most of the life cycle of this

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Fig. 1 Location of survey area

Fig. 2 Catch (landings) of hairtail by year in the Bungo Channel, Japan

species occurs [2, 4]. The area is considered to be a single unit for fisheries resource management. Hairtail landings from the adjacent mid-western part of the Seto Inland Sea and Hyuga-nada are less than those around the Bungo Channel, with tagging experiments suggesting emigration from the Bungo Channel to be limited [2].

Spawning around the Bungo Channel is thought to occur from March to December, with peaks in May–June and September–October [4]. The spring brood comprises individuals spawned during the first peak (May–June), and the autumn brood those spawned during the second peak (September–October). In both broods the annual otolith ring forms from June to August, and thus the radius of the first annual ring in the spring brood is greater than that of the autumn brood. Consequently, spawning season can be determined for each fish, even for older individuals, based on the first otolith ring radius [4, 5]. This characteristic has also been observed in hairtail from other areas [1, 6, 7]. Because of decreased winter growth, an age–length relationship using an extended von Bertalanffy growth model that takes seasonal growth variation into consideration using a periodic function is more suitable than a traditional von Bertalanffy

growth model [4, 5]. At a pre-anal length of 250 mm, 50% of the females were mature [4], which corresponds to 1 year after hatching for both broods.

Around the Bungo Channel, hairtail is caught in trolling and net fisheries, the latter including purse seine and trawl fisheries. The quality of fish caught by trolling is greater than that caught by net, which is reflected in the market price, being higher for the former. The large quantities of hairtail caught using nets are processed mainly into fish paste. Though hairtail is one of the most important catchable resources in this area for both fisheries and the processing industry, landings of it have decreased since the late 1990s (Fig. 2). Preliminary stock assessments suggest it will be difficult to maintain the current biomass with current fishing pressure [8].

Historical catch data reveal that the hairtail population increases and decreases every few years. Although the catch has tended to decrease from 2007 (Fig. 2), the reason for this is not clear. Hairtail stock in the Bungo Channel comprises two different spawning broods, with changes in abundance resulting from changes in the proportions of these two seasonal brood groups [5]. However, previous Japanese hairtail stock assessment studies have not taken these seasonal broods into consideration [3, 8, 9]. We analyzed the stock structure by considering seasonal broods in this study, and identify likely reasons for recent decreases in the catch from this area. We endeavor to describe biological reference points based on yield per recruitment (YPR) and spawning biomass per recruitment (SPR) analysis, and discuss ways for more sustainable management of this fishery.

Materials and methods

We use virtual population analysis (VPA) to estimate hairtail abundance [10]. Generally, VPAs are conducted using

catch-at-age data according to year, but in the case of hairtail, there are two spawning peaks (spring and autumn). To consider spawning peaks separately, catch-at-age data were separately estimated for both broods. VPAs were constructed for 4-month intervals (January–April, May–August, and September–December).

Catch-at-age

Hairtail are caught by both trolling and net fisheries, with catches divided into two size classes: I (> 200 g) and II (< 200 g). Trolling catches only class I fish, which are further divided into five size sub-classes (king, large, medium, small, and mini). Net fisheries catch both class I and II fish. For trolling-caught fish, monthly catch weight data by size sub-category were collected from Kunisaki, Usuki, Himeshima, and Misaki, from 2003 to 2011. For net-caught fish, monthly catch weight data for classes I and II were collected from Yawatahama over the same period.

A total of 3,088 hairtail individuals were collected from 2006 to 2011. Body weight was measured to the nearest 0.1 g, age was estimated from the number of otolith rings, and spawning season was estimated from the first annual ring radius in accordance with Yanagawa [4] and Watari et al. [5]. These data were used to convert size sub-class composition to age composition.

Catch-at-age of fish caught by trolling was estimated using monthly catch weight data (grouped by sub-size), fisheries statistics, and the age–weight relationship described by Kurosaka et al. [11]. For net-caught fish, class I age composition was assumed to be the same as that of troll-caught class I fish. Age composition of class II fish was estimated from total landing data and average weight of fish landed in Yawatahama (160 g). Total catch-at-age was estimated by adding catch-at-age from both trolling and net fisheries.

Stock biomass

The number of fish of brood b [spring brood (1), autumn brood (2)]; age a (0,...,5, spring brood; 1,...,5, autumn brood); period p (1, January–April; 2, May–August; 3, September–December), in year y (2003,...,2011), $N_{b,a,y,p}$, was estimated using the following equations:

$$N_{b,a,y,p} = N_{b,a,y,p+1} \exp(M) + C_{b,a,y,p} \exp(M/2) \quad (1)$$

$$(a = 0, \dots, 4, p = 1, 2)$$

$$N_{b,a,y,p} = N_{b,a+1,y+1,p-2} \exp(M) + C_{b,a,y,p} \exp(M/2) \quad (2)$$

$$(a = 0, \dots, 4, p = 3).$$

Among these, $N_{b,a,y,p}$ of 5-year-old fish of all y and p , and in September–December ($p = 3$) 2011, was estimated as follows:

$$N_{b,a,y,p} = \frac{C_{b,a,y,p}}{1 - \exp(-F_{b,a,y,p})} \exp(M/2). \quad (3)$$

The natural mortality coefficient, M , was estimated from longevity ($M = 2.5/\text{longevity}$) [12]. Longevity was assumed to be 5 years, the known maximum age of hairtail. The fishing mortality coefficient of b , a , p , in year y , $F_{b,a,y,p}$, was estimated as follows:

$$F_{b,a,y,p} = -\ln \left(1 - \frac{C_{b,a,y,p} \exp(M/2)}{N_{b,a,y,p}} \right) \quad (a = 0, \dots, 4) \quad (4)$$

$$F_{b,5,y,p} = F_{b,4,y,p} \quad (a = 5). \quad (5)$$

Among these, $F_{b,a,y,p}$ of September–December 2011 was estimated as follows:

$$F_{b,a,2011,3} = \frac{\sum_{g=1}^G F_{b,a,2011-g,3}}{\sum_{g=1}^G F_{b,4,2011-g,3}} F_{b,4,2011,3} \quad (a = 0, \dots, 4, G = 5), \quad (6)$$

where $F_{b,4,2011,3}$ is assumed to be equal to $F_{b,5,2011,3}$, the same as in Eq. (5). Stock biomass was calculated by multiplying $N_{b,a,y,p}$ and the average body weight of b , a , p , $W_{b,a,p}$, estimated from the relationship between age and pre-anal length, and between pre-anal length and body weight (Table 1) [5]. A retrospective analysis was conducted to detect systematic trends in abundance estimates of the latest year [13]. For sensitivity check, uncertainty derived from Eq. (6) was evaluated by using a different value of G ($G = 4$ and 6).

Spawning stock biomass and recruit per spawning

Spawning stock biomass at both spawning peaks, May ($p = 2$) and September ($p = 3$), was estimated by summing the spawning stock biomass of spring and autumn broods, as follows:

$$SSB_{y,p} = \sum_{b=1}^2 \sum_{a=1}^5 N_{b,a,y,p} \times W_{b,a,p} \times m_{b,a,p}, \quad (7)$$

Table 1 Pre-anal length, body weight and maturity rate by age and month estimated from Yanagawa [4] and Watari et al. [5]

	Age (year)	Pre-anal length (mm)			Body weight (g)			Maturity rate of female	
		January	May	September	January	May	September	May	September
Spring brood	0			183			95		
	1	221	231	289	161	184	343	0.43	0.78
	2	316	323	363	437	465	645	0.91	0.97
	3	381	386	414	739	767	930	0.99	0.99
	4	427	430	449	1,011	1,035	1,169	1.00	1.00
	5	458	460	474	1,233	1,251	1,354	1.00	1.00
Autumn brood	1	115	133	234	26	39	190	0.06	0.46
	2	265	276	338	268	299	527	0.71	0.94
	3	357	363	401	613	645	850	0.97	0.99
	4	412	416	439	919	944	1,097	0.99	1.00
	5	446	449	463	1,147	1,164	1,269	1.00	1.00

where $m_{b,a,p}$ is the maturity rate of female estimated from the relationship between age and pre-anal length, and between pre-anal length and maturity rate (Table 1) [4, 5]. Recruit per spawning (RPS) of year y for spring and autumn spawning seasons was estimated as follows:

$$RPS_{\text{spring}} = N_{1,0,y,3} / SSB_{y,2} \quad (8)$$

$$RPS_{\text{autumn}} = N_{2,1,y,1} / SSB_{y,3} \quad (9)$$

Stock status and management scenarios

Current fishing status was evaluated by using YPR and SPR analyses. YPR and SPR were estimated by summing the age of fish from first capture to 5 years for both broods using the following equations:

$$YPR = \sum_{a=0}^5 \sum_{p=1}^3 \frac{F_{1,a,p}}{F_{1,a,p} + M} (1 - \exp(-F_{1,a,p} - M)) S_{1,a,p} W_{1,a,p} + \sum_{a=1}^5 \sum_{p=1}^3 \frac{F_{2,a,p}}{F_{2,a,p} + M} (1 - \exp(-F_{2,a,p} - M)) S_{2,a,p} W_{2,a,p} \quad (10)$$

$$SPR = \sum_{a=0}^5 \sum_{p=1}^3 m_{1,a,p} S_{1,a,p} W_{1,a,p} + \sum_{a=1}^5 \sum_{p=1}^3 m_{2,a,p} S_{2,a,p} W_{2,a,p} \quad (11)$$

$$S_{b,a,p} = S_{b,a-1,p+2} \exp(-F_{b,a-1,p+2} - M) \quad (p = 1, S_{2,1,1} = 1) \quad (12)$$

$$S_{b,a,p} = S_{b,a,p-1} \exp(-F_{b,a,p-1} - M) \quad (p = 2, 3, S_{1,0,3} = 1) \quad (13)$$

where $S_{b,a,p}$ is the survival rate of b , a , and p . Several biological reference points, $F_{30\%SPR}$ [14], the $F_{0.1}$ [15] and a fishing mortality coefficient that produced the maximum YPR ($F_{\max}$) were calculated and compared with the current fishing mortality coefficient (F_{current}). F_{current} was defined as a mean value of all $F_{b,a,2011,p}$.

Because recent hairtail landings have decreased, future abundance and catch trends for 20 years were estimated under reduced fishing pressure scenarios. The recruitment of both spring and autumn broods was estimated using the following equations:

$$N_{1,0,y,3} = SSB_{y,2} \times \overline{RPS}_{\text{spring}} \quad (14)$$

$$N_{2,1,y+1,1} = SSB_{y,3} \times \overline{RPS}_{\text{autumn}}, \quad (15)$$

where $\overline{RPS}_{\text{spring}}$ and $\overline{RPS}_{\text{autumn}}$ are average values of RPS for both season. Other $N_{b,a,y,p}$ were estimated using the following equations:

$$N_{b,a,y,p} = N_{b,a-1,y-1,p+2} \exp(-M) - C_{b,a-1,y-1,p+2} \exp(-M/2) \quad (p = 1) \quad (16)$$

$$N_{b,a,y,p} = N_{b,a,y,p-1} \exp(-M) - C_{b,a,y,p-1} \exp(-M/2) \quad (p = 2, 3). \quad (17)$$

$C_{b,a,y,p}$ were estimated as follows:

$$C_{b,a,y,p} = N_{b,a,y,p} (1 - \exp(-(1 - \alpha)F_{b,a,y,p})) \exp(-M/2), \quad (18)$$

where α is the rate of reduction in fishing pressure compared with current levels. Four different reduced fishing pressure scenarios were considered: reduction of fishing pressure throughout the year (YE), a halving of fishing pressure for 2 months during the spring spawning season (SP), a halving of fishing pressure for 2 months during autumn spawning season (AU), and a halving of fishing pressure in the year following the appearance of a strong year class (ST). Reduction rate (α) was set at 0, 0.1, 0.2, and 0.3 in YE, 0.25 in SP and AU, and 0.5 in ST, as a large reduction in fishing pressure might be an acceptable short-term measure. The effect of each reduced fishing pressure scenario was evaluated individually and in combination, i.e., SP and YE; AU and YE; ST and YE. For future recruitment, we forecast strong year classes would occur in the 5th and 10th years. For estimation of future spring-brood recruitment, mean RPS values were calculated for years in which year class appearance was strong, and for normal years. Rates of change in

average catch and biomass after 20 years [catch(20 year)/catch(0 year), and biomass(20 year)/biomass(0 year)] were evaluated. The SEs of these values were calculated by a bootstrap method, resampling RPS values 1000 times.

Results

Catch-at-age

Catch-at-age showed a decreasing trend especially for the spring brood following 2007. Age at first capture for spring and autumn brood individuals was 0 year in September–December and 1 year in January–April, respectively. Fishing pressure on fish of ages 1 and 2 years is greater than it is on fish of ages 3–5 years (Appendix 1).

Stock biomass

Both spring and autumn brood stock abundance trended down (Fig. 3; Appendix 1), though spring-brood stock abundance rapidly declined after 2007. Spring-brood recruitment levels in 2003 and 2005 were at least three times greater than in other years. The reduction in stock abundance was less in

Fig. 3 Relationship between stock abundance, age (1–5; years), and spring and autumn hairtail broods

Fig. 4 Retrospective analysis of stock biomass for both spring and autumn hairtail broods

Fig. 5 Relationship between spawning stock biomass and recruitment in spring (*open circles*) and autumn (*closed circles*) hairtail broods

Fig. 6 Temporal variation in recruits per spawning (*RPS*) for spring and autumn hairtail broods

the autumn than for spring broods. Recruitment of autumn brood fish varied among years but remained relatively constant. A retrospective analysis identified no systematic trends in abundance estimates of the latest year (Fig. 4). Sensitivities of Eq. (6) of G of stock biomass including both broods are 5,331 t ($G = 4$), 5,176 t ($G = 5$), and 4,912 t ($G = 6$); those of F_{current} were 0.22 ($G = 4$), 0.22 ($G = 5$), and 0.24

Fig. 7 Yield per recruitment curves (*solid line*) and percentage of spawning per recruitment curves (*dotted line*) for hairtail. Current and reference point levels of fishing mortality coefficient (F) are shown by *closed circle* (F_{current}), *open circle* (F_{max}), *closed square* ($F_{30\%SPR}$), and *open square* ($F_{0.1}$)

($G = 6$). Similar trends are apparent for biomass and the fishing mortality coefficient.

There was no clear relationship between spawning stock biomass and recruitment in either spawning season (Fig. 5). Even at the same age, the maturity rate in the September–December period ($p = 3$) was higher than in the May–August period ($p = 2$) (Table 1). There is a tendency for the autumn spawning stock biomass to be greater than that of the spring (Fig. 5). Spring spawning season RPS values identified strong recruitment in 2003 and 2005, but lower recruitment in other years (Fig. 6). Strong recruitment occurred with a spawning stock biomass of 3,657–5,144 t (average 4,400 t), corresponding to a stock biomass of 5,672–6,823 t (average 6,247 t). Autumn spawning season RPS values varied between years but remained around

Fig. 8 Projected stock biomass (*right*) and catch in weight (*left*) for various combinations of reduced fishing pressure: throughout the year (*YE*) with reduction rate (α) of 0, 0.1, 0.2, 0.3, for 2 months during the spring spawning season (*SP*); for 2 months during the autumn spawning season (*AU*); and in the year after the appearance of a strong year class (*ST*)

a certain level (Fig. 6), similar to the trend observed for recruitment.

Stock status and management scenario

Figure 7 depicts the relationship between the fishing mortality coefficient and YPR and percentage of SPR values. Current YPR levels and SPR percentages were 284 (g individual⁻¹) and 21%, respectively. F_{current} values and reference points are F_{current} (0.22), $F_{0.1}$ (0.13), F_{max} (0.20), and

$F_{30\%SPR}$ (0.16). The current fishing mortality coefficient exceeds these reference points.

Figure 8 depicts projected stock abundance for various simulations, where the current level of fishing pressure will lead to decreases in both biomass and catch. In the event of a strong year class (strong recruitment), biomass and catch will subsequently increase, but if the rate of reduction in fishing pressure is low, any such benefit will disappear after 1 or 2 years (Fig. 8). If current fishing pressure is reduced by 20%, stock levels in 20 years will remain comparable to those today. Of reduction methods of fishing pressure

Table 2 Average catch over 20 years, and rate of change in catch and biomass in 20th year of reduction of fishing pressure: throughout the year (YE), for 2 months during the spring spawning season (SP), for 2 months during the autumn spawning season (AU), and in the year following the appearance of a strong year class (ST)

	Reduction rate of fishing mortality coefficient of YE	Average catch during 20 years	Rate of change in catch in 20th year	Rate of change in biomass in 20th year
YE	0	981 (146)	0.07 (0.03)	0.08 (0.03)
SP		1,195 (220)	0.14 (0.06)	0.15 (0.06)
AU		1,298 (232)	0.20 (0.08)	0.23 (0.09)
ST		1,172 (212)	0.13 (0.06)	0.14 (0.06)
YE	0.1	1,326 (241)	0.20 (0.08)	0.22 (0.09)
SP and YE		1,654 (334)	0.35 (0.14)	0.42 (0.17)
AU and YE		1,832 (395)	0.48 (0.20)	0.62 (0.25)
ST and YE		1,644 (335)	0.34 (0.14)	0.38 (0.16)
YE	0.2	1,942 (404)	0.53 (0.21)	0.66 (0.26)
SP and YE		2,466 (574)	0.87 (0.37)	1.17 (0.49)
AU and YE		2,768 (610)	1.16 (0.45)	1.67 (0.64)
ST and YE		2,480 (564)	0.85 (0.34)	1.07 (0.44)
YE	0.3	3,099 (726)	1.38 (0.53)	1.99 (0.76)
SP and YE		3,957 (1,003)	2.14 (0.85)	3.27 (1.29)
AU and YE		4,459 (1,148)	2.74 (1.09)	4.49 (1.80)
ST and YE		4,017 (1,016)	2.10 (0.84)	3.02 (1.21)

Values in parentheses denote SE

Table 3 Recruit per spawning (RPS) values of spring and autumn spawning seasons

	Spring	Autumn
2003	5.37 ^d	2.48
2004	2.40	1.09
2005	5.42 ^d	3.12
2006	2.04	1.80
2007	1.19	1.40
2008	2.59	3.40
2009	2.71	2.74
2010	1.61	1.84
2011	2.42	
Mean A ^a	2.86	2.23
Mean N ^b	2.14	
Mean S ^c	5.40	

^a Mean RPS value of all years

^b Mean RPS value of normal year classes

^c Mean RPS value of strong year classes

^d RPS of strong year classes

that take reproductive characteristics into consideration, AU is most effective; the effect of both ST and SP is similar for projected stock biomass and catch. The YE + AU combination increases average catch 1.2 or more times over 20 years than YE alone. ST and SP have the same effect as AU (Table 2). For estimation of future stock abundance, RPS values of 5.40, 2.14, and 2.23 were used for the 5th and 10th years of the spring spawning season (strong year

class appearance), spring spawning season in a normal year, and autumn spawning season, respectively (Table 3). In the bootstrap method, the RPS values of normal years, and those in which strong year classes were apparent, were selected randomly from observed values for each brood in each year (Table 3).

Discussion

In Eq. (6) for the VPA we assumed the fishing mortality coefficient in the latest years to be the average of previous fishing mortality coefficient values. As there have been no substantial changes in the hairtail fishery, such as in fishing effort or method, the assumption of Eq. (6) is considered to be satisfied. In addition, the sensitivities of G in Eq. (6) revealed the effect of different G to be minor. Retrospective analysis also revealed no trend (either increasing or decreasing) in the capability of prediction for the latest year. Accordingly, we believe stock abundance in this area to be accurately estimated. To estimate future recruitment, Eqs. (14) and (15) included only RPS and spawning stock biomass values; we did not include limitation of recruitment as a function of spawning stock biomass level, as used in Beverton and Holt [16] and hockey stick [17] models. At most, the predicted biomass after 20 years was about 12,000 t. In 1983, the catch reached more than 10,000 t. The biomass is not predicted to reach a level where the limitation of recruitment by spawning stock biomass level should be considered.

Stock assessment by seasonal brood analysis showed a clear decreasing trend in the spring brood (Fig. 3). RPS values for the spring brood were higher in 2003 and 2005 than they were in other years, though autumn brood RPS values were relatively stable. The high recruitment potential of the spring brood in 2003 and 2005 indicated that these were strong year classes. Differences in RPS over time for spring and autumn broods contributed to fluctuations in both stocks. The recent decrease in hairtail landings is largely a consequence of low-level spring-brood recruitment. Juvenile hairtail prey include copepods, mysids, and juvenile fish, such as the Japanese anchovy *Engraulis japonicus* [18, 19]. The relationship between the spring-brood spawning peak and prey abundance might contribute to strong year classes. Although the mechanism is not clear, ecosystem models, such as individual based model [20], that take prey–predator dynamics into consideration (e.g., models that consider relationships between nutrients, phytoplankton, copepods, anchovy, and hairtail) may be useful for a better understanding of recruitment dynamics.

The main catchable hairtail population was 1 and 2 years of age. Therefore, in the event of a strong year class, larger catches should occur in successive years, as observed in 2003 and 2005 (Fig. 3). Future catch predictions reveal that an increase of recruitment in strong year classes contributes to greater catches in subsequent years (Fig. 8), as occurred several times up to 2007, though the lack of a strong year class after 2007 has resulted in a decrease in recent catches. In the event that similar processes affected historic populations, then recruitment conditions from 1993 to 1995 were better than in other years. The fact that landings have decreased over time suggests that fishing pressure has been constantly high.

YPR and SPR analyses reveal current fishing pressure to be higher than $F_{\max}$, $F_{0.1}$ and $F_{30\%SPR}$ reference points, and that the fishing pressure needs to be reduced by at least 20% of current levels for the fishery to remain sustainable. Predicted stocks in each management scenario indicate reduced fishing pressure will lead to rapid increases in future stock abundance (Fig. 8; Table 2). Moreover, reduced fishing pressure in each spawning season, and years after the appearance of strong year classes, are additional, effective management strategies that will contribute to enhancing future stock abundance. For hairtail, strong year classes can be detected

during research sampling based on the incidence of juvenile fish during winter (Tokumitsu, unpublished data). Although a strong year class occurs only intermittently, reducing fishing pressure when one does occur would facilitate stock recovery. Such management strategies have been applied to Japanese chub mackerel [21].

The effects of four types of management, YR, SP, AU, and ST, and their combination were evaluated in this study. As shown in Fig. 8, ST decreases the catch amount in the year after a strong year class occurrence. When importance is attached to the stability of the yearly catch, a combination of these types of management that result in the least fluctuation in catch, i.e., YE, SP, AU, might be best. Though we cannot be certain when strong year classes will occur, when they do they have the potential to contribute to stock recovery and increased annual landing. Therefore, it is important to manage them, and to use their occurrence in spring broods to improve fishery management, rather than to exploit them without limitation. Although it is difficult to obtain consensus among different types of fisheries working in different areas, early implementation of management strategies like this will ultimately contribute to more rapid recovery and sustainable exploitation of fisheries resources. Using the stock structure and resource management results of this study, we elsewhere discuss the development of effective fishing gear [22] and a transdisciplinary approach to coastal fisheries co-management [23] for improved resource management.

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Appendix 1

See Table 4.

Table 4 Estimated catch, fishing mortality coefficient, stock number and biomass of spring and autumn broods

Spring brood	2003			2004			2005			2006			2007			
	Age	Jan–Apr	May–Aug	Sep–Dec	Jan–Apr	May–Aug	Sep–Dec	Jan–Apr	May–Aug	Sep–Dec	Jan–Apr	May–Aug	Sep–Dec	Jan–Apr	May–Aug	Sep–Dec
Catch in number (individuals)																
0			1,155,969				1,821,837				711,291				1,006,900	562,181
1	1	1,153,991	868,080	1,956,546	1,789,137	1,938,848	2,456,958	976,420	1,431,771	994,547	1,269,648	3,308,548	4,322,590	1,352,754	1,006,658	1,118,172
2	2	168,681	161,261	475,547	211,311	463,683	745,678	240,668	662,570	499,776	160,150	250,559	691,885	1,456,060	1,348,882	1,377,539
3	3	16,235	18,247	63,305	23,964	49,243	87,072	33,545	86,681	93,022	67,744	94,887	260,606	109,001	109,786	121,028
4	4	2,183	2,750	12,983	4,308	6,337	13,903	7,284	16,337	23,850	3,651	5,529	5,234	92,938	97,960	119,068
5	5	1,124	1,396	6,514	1,996	3,082	6,995	3,485	8,171	11,742	1,043	1,580	1,495	29,833	29,652	33,305
Fishing mortality coefficient (trolling line fisheries)																
0			0.020				0.019			0.004			0.011			0.014
1	1	0.067	0.085	0.386	0.112	0.148	0.354	0.082	0.196	0.206	0.026	0.195	0.433	0.123	0.137	0.300
2	2	0.050	0.079	0.497	0.060	0.155	0.515	0.041	0.175	0.196	0.025	0.108	0.501	0.191	0.311	0.979
3	3	0.020	0.035	0.219	0.038	0.087	0.265	0.030	0.115	0.173	0.020	0.075	0.305	0.101	0.150	0.335
4	4	0.007	0.013	0.103	0.019	0.030	0.098	0.024	0.079	0.157	0.005	0.019	0.022	0.126	0.208	0.609
5	5	0.007	0.013	0.103	0.019	0.030	0.098	0.024	0.079	0.157	0.005	0.019	0.022	0.126	0.208	0.609
Fishing mortality coefficient (net fisheries)																
0			0.046				0.146			0.024			0.087			0.082
1	1	0.056	0.039	0.044	0.021	0.054	0.054	0.039	0.056	0.062	0.036	0.024	0.042	0.056	0.053	0.021
2	2	0.042	0.036	0.057	0.011	0.056	0.078	0.019	0.050	0.059	0.035	0.013	0.049	0.087	0.120	0.069
3	3	0.017	0.016	0.025	0.007	0.031	0.040	0.014	0.033	0.052	0.027	0.009	0.030	0.046	0.058	0.023
4	4	0.006	0.006	0.012	0.004	0.011	0.015	0.011	0.023	0.047	0.007	0.002	0.002	0.057	0.080	0.043
5	5	0.006	0.006	0.012	0.004	0.011	0.015	0.011	0.023	0.047	0.007	0.002	0.002	0.057	0.080	0.043
Stock in number (individuals)																
0			19,635,373				12,988,395			27,891,909			11,663,582			6,703,904
1	1	10,864,776	8,135,112	6,087,551	15,557,442	11,523,005	7,970,187	9,318,268	6,989,394	4,599,101	22,955,572	18,263,340	12,415,572	8,946,617	6,328,554	4,430,835
2	2	2,087,191	1,611,575	1,215,802	3,352,892	2,643,746	1,811,274	4,486,108	3,575,983	2,417,410	2,978,028	2,373,501	1,778,600	6,532,580	4,190,070	2,305,786
3	3	485,114	395,703	318,168	591,630	478,756	359,952	847,153	686,236	501,137	1,586,477	1,280,596	996,701	868,987	635,296	436,759
4	4	186,829	156,139	129,638	211,080	174,712	142,060	224,583	183,404	140,217	338,619	283,276	234,701	603,920	425,700	270,220
5	5	96,204	79,267	65,047	97,792	84,976	71,474	107,460	91,731	69,034	96,748	80,936	67,057	193,855	128,856	75,584
Stock biomass (t)																
		3,332	2,810	5,282	4,747	4,003	5,739	4,450	3,780	6,523	6,641	5,839	7,810	5,790	4,203	4,471

Table 4 (continued)

Spring brood		2008			2009			2010			2011		
Age		Jan–Apr	May–Aug	Sep–Dec	Jan–Apr	May–Aug	Sep–Dec	Jan–Apr	May–Aug	Sep–Dec	Jan–Apr	May–Aug	Sep–Dec
Catch in number (individuals)													
0				1,427,997			1,272,585			786,168			1,008,793
1		1,148,599	556,355	627,330	1,066,348	611,771	1,515,271	767,167	343,917	620,291	607,691	329,955	516,114
2		839,369	434,086	567,845	160,495	118,203	225,777	196,770	121,748	246,060	238,108	220,027	392,646
3		62,947	53,331	75,997	27,482	31,895	49,814	33,181	26,377	50,559	33,783	40,175	54,232
4		13,918	11,488	20,275	7,928	11,309	14,644	5,625	5,735	9,708	13,622	14,043	20,796
5		6,421	4,999	9,619	3,627	4,602	6,499	13,453	11,394	25,632	1,336	3,068	955
Fishing mortality coefficient (trolling line fisheries)													
0				0.028			0.035			0.009			0.005
1		0.157	0.172	0.300	0.135	0.114	0.522	0.085	0.086	0.247	0.094	0.123	0.342
2		0.231	0.314	0.989	0.094	0.098	0.295	0.081	0.115	0.412	0.071	0.156	0.579
3		0.060	0.100	0.201	0.092	0.157	0.444	0.042	0.071	0.210	0.045	0.122	0.283
4		0.034	0.053	0.123	0.023	0.042	0.071	0.055	0.126	0.372	0.040	0.090	0.215
5		0.034	0.053	0.123	0.023	0.042	0.071	0.055	0.126	0.372	0.040	0.090	0.215
Fishing mortality coefficient (net fisheries)													
0				0.157			0.175			0.188			0.153
1		0.120	0.030	0.053	0.063	0.046	0.191	0.097	0.026	0.044	0.127	0.050	0.089
2		0.177	0.054	0.176	0.044	0.039	0.108	0.092	0.034	0.073	0.095	0.064	0.150
3		0.046	0.017	0.036	0.043	0.063	0.162	0.048	0.021	0.037	0.061	0.050	0.074
4		0.026	0.009	0.022	0.011	0.017	0.026	0.063	0.038	0.066	0.054	0.037	0.056
5		0.026	0.009	0.022	0.011	0.017	0.026	0.063	0.038	0.066	0.054	0.037	0.056
Stock in number (individuals)													
0				9,176,995			7,295,277			4,778,510			7,532,050
1		5,157,501	3,308,969	2,289,110	6,454,338	4,482,392	3,231,407	5,004,484	3,530,377	2,671,981	3,321,613	2,252,582	1,603,196
2		2,721,853	1,531,742	897,214	1,360,519	1,003,992	741,109	1,341,210	954,273	695,761	1,691,087	1,212,404	823,844
3		684,408	521,425	392,310	237,033	175,359	119,093	419,610	324,664	250,554	362,563	275,821	196,515
4		258,357	205,889	163,712	262,162	214,622	171,268	54,979	41,364	29,737	165,573	127,622	95,110
5		119,189	89,590	77,674	119,925	87,340	76,011	131,502	82,184	78,512	16,240	27,885	4,366
Stock biomass (t)													
		2,936	2,046	2,901	2,224	1,757	2,696	1,922	1,488	2,195	1,730	1,357	2,100

Table 4 (continued)

Autumn brood	2003			2004			2005			2006			2007		
	Jan–Apr	May–Aug	Sep–Dec	Jan–Apr	May–Aug	Sep–Dec	Jan–Apr	May–Aug	Sep–Dec	Jan–Apr	May–Aug	Sep–Dec	Jan–Apr	May–Aug	Sep–Dec
Catch in number (individuals)															
1	365,790	849,244	1,227,878	303,355	1,149,725	565,776	548,430	891,843	505,311	289,453	1,457,859	697,187	164,027	1,324,170	876,024
2	1,320,883	540,643	1,526,241	1,848,577	1,592,086	2,376,356	1,261,823	1,615,529	1,078,961	463,119	359,356	704,419	2,797,049	1,520,110	1,502,992
3	68,269	75,133	236,048	132,049	429,782	636,511	120,262	344,614	312,279	149,124	207,843	491,337	98,175	104,046	126,876
4	5,521	6,520	26,691	16,065	45,131	70,700	15,517	35,994	45,132	26,332	36,473	59,336	59,642	64,278	81,309
5	986	1,183	7,566	3,442	5,819	11,669	4,299	8,493	14,938	2,086	3,159	2,991	13,427	15,600	21,207
Fishing mortality coefficient (trolling line fisheries)															
1	0.113	0.081	0.486	0.182	0.206	0.736	0.121	0.270	0.306	0.062	0.138	0.449	0.244	0.231	0.543
2	0.044	0.079	0.538	0.064	0.267	1.263	0.057	0.270	0.452	0.035	0.137	0.569	0.076	0.115	0.266
3	0.023	0.042	0.323	0.058	0.197	0.729	0.068	0.262	0.692	0.035	0.136	0.348	0.091	0.144	0.374
4	0.023	0.042	0.323	0.058	0.197	0.729	0.068	0.262	0.692	0.035	0.136	0.348	0.091	0.144	0.374
Fishing mortality coefficient (net fisheries)															
1	0.020	0.025	0.011	0.020	0.064	0.008	0.072	0.041	0.027	0.016	0.042	0.005	0.011	0.050	0.006
2	0.094	0.037	0.056	0.034	0.074	0.112	0.057	0.078	0.092	0.084	0.017	0.044	0.111	0.089	0.038
3	0.036	0.036	0.062	0.012	0.096	0.192	0.027	0.078	0.136	0.048	0.017	0.056	0.035	0.044	0.019
4	0.019	0.019	0.037	0.011	0.071	0.111	0.032	0.075	0.208	0.048	0.017	0.034	0.042	0.056	0.026
5	0.019	0.019	0.037	0.011	0.071	0.111	0.032	0.075	0.208	0.048	0.017	0.034	0.042	0.056	0.026
Stock in number (individuals)															
1	20,431,026	16,957,947	13,573,250	16,571,383	13,748,273	10,579,863	8,622,247	6,793,994	4,930,457	20,003,266	16,666,090	12,766,246	16,205,929	13,567,111	10,266,017
2	7,668,394	5,275,884	3,968,524	10,359,806	7,068,614	4,518,662	8,435,121	5,979,243	3,574,961	3,708,634	2,713,201	1,966,052	10,164,950	6,031,035	3,706,593
3	964,259	753,418	568,629	1,955,073	1,533,443	902,613	1,638,612	1,276,409	763,397	2,033,448	1,584,076	1,149,666	1,016,130	769,810	555,903
4	148,176	120,348	95,874	264,159	208,825	135,244	178,427	136,759	82,647	358,891	279,568	203,092	521,120	386,245	267,811
5	26,450	21,827	27,176	56,599	26,925	22,322	49,434	32,267	27,356	28,436	24,216	10,236	117,321	93,738	69,850
Stock biomass (t)															
	3,352	2,862	5,289	4,722	3,866	5,332	3,716	3,043	3,593	3,130	2,772	4,671	4,390	3,302	4,756

Table 4 (continued)

Autumn brood		2008			2009			2010			2011		
Age		Jan–Apr	May–Aug	Sep–Dec	Jan–Apr	May–Aug	Sep–Dec	Jan–Apr	May–Aug	Sep–Dec	Jan–Apr	May–Aug	Sep–Dec
Catch in number (individuals)													
1		418,591	731,885	736,566	86,388	577,844	994,415	876,852	649,820	522,570	929,662	830,697	412,766
2		3,267,814	828,029	1,164,753	1,136,632	395,927	804,053	2,017,445	675,248	1,192,997	1,490,128	608,904	993,840
3		333,301	249,769	322,065	38,892	49,934	69,900	91,044	61,489	120,772	163,187	170,013	306,618
4		24,716	21,928	34,655	14,235	23,203	27,307	17,102	19,501	27,376	24,698	25,845	38,007
5		10,610	8,431	15,745	6,010	7,953	10,885	6,537	5,374	12,622	15,691	14,485	25,040
Fishing mortality coefficient (trolling line fisheries)													
1			0.072	0.121		0.025	0.080		0.035	0.068		0.043	0.078
2		0.339	0.240	0.660	0.223	0.123	0.442	0.153	0.127	0.399	0.139	0.147	0.464
3		0.131	0.223	0.517	0.032	0.055	0.103	0.055	0.080	0.251	0.043	0.100	0.310
4		0.045	0.077	0.164	0.031	0.066	0.106	0.021	0.049	0.098	0.037	0.084	0.196
5		0.045	0.077	0.164	0.031	0.066	0.106	0.021	0.049	0.098	0.037	0.084	0.196
Fishing mortality coefficient (net fisheries)													
1		0.047	0.034	0.021	0.006	0.025	0.029	0.082	0.042	0.012	0.122	0.105	0.020
2		0.259	0.041	0.117	0.104	0.050	0.161	0.173	0.038	0.071	0.188	0.060	0.121
3		0.100	0.039	0.092	0.015	0.022	0.038	0.062	0.024	0.044	0.058	0.041	0.081
4		0.034	0.013	0.029	0.014	0.026	0.039	0.024	0.015	0.017	0.050	0.035	0.051
5		0.034	0.013	0.029	0.014	0.026	0.039	0.024	0.015	0.017	0.050	0.035	0.051
Stock in number (individuals)													
1		9,828,401	7,934,439	6,042,991	15,355,110	12,918,339	10,403,496	12,152,658	9,480,259	7,427,003	8,785,637	6,581,551	4,806,885
2		7,884,014	3,667,140	2,342,344	4,437,608	2,710,602	1,930,204	7,891,463	4,823,840	3,462,034	5,806,035	3,543,718	2,439,474
3		1,754,744	1,178,707	767,955	911,127	735,470	576,620	894,118	673,090	513,185	1,832,938	1,401,410	1,029,848
4		353,830	276,771	214,107	353,746	286,343	221,036	423,788	342,994	272,396	323,286	250,933	188,632
5		151,889	106,409	97,275	149,353	98,142	88,105	161,979	94,524	125,589	205,391	140,640	124,276
Stock biomass (t)													
		3,950	2,551	3,391	2,649	2,171	3,835	3,561	2,679	4,127	3,446	2,620	3,437

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