The status of Japanese fisheries relative to fisheries around the world

Momoko Ichinokawa1*, Hiroshi Okamura1, and Hiroyuki Kurota2

1Research Center for Fisheries Management, National Research Institute of Fisheries Science, Japan Fisheries Research and Education Agency, 2-12-4 Fukaura, Kanazawa, Yokohama, Kanagawa, 236-8648, Japan
2Fisheries Management and Oceanography division, Seikai National Fisheries Research Institute, Japan Fisheries Research and Education Agency, 1551-8, Taira-machi, Nagasaki-shi, Nagasaki, 851-2213, Japan

*Corresponding author: tel: +81 45 788 7645; fax: +81 45 788 5001; e-mail: ichimomo@affrc.go.jp.


Received 20 September 2016; revised 28 December 2016; accepted 31 December 2016; advance access publication 17 February 2017.

We present the first quantitative review of the stock status relative to the stock biomass (B) and the exploitation rate (U) that achieved the maximum sustainable yield (MSY) (BMSY and UMSY, respectively) for 37 Japanese stocks contributing 61% of the total marine capture production in Japan. BMSY and UMSY were estimated by assuming three types of stock-recruitment (S-R) relationships and an age-structured population model or by applying a surplus production model. The estimated stock status shows that approximately half of the stocks were overfishing (U/UMSY > 1), and approximately half of the stocks were overfished (B/BMSY < 0.5) during 2011–2013. Over the past 15 years, U decreased and B slightly increased on average. The rate of decrease in the U of the stocks managed by the total allowable catch (TAC) was significantly greater than that of the other stocks, providing evidence of the effectiveness of TAC management in Japan. The above statuses and trends were insensitive to the assumption of the S-R relationship. The characteristics of Japanese stocks composed mainly of resources with relatively high natural mortality, i.e. productivity, suggest that Japanese fisheries have great potential of exhibiting a quick recovery and increasing their yield by adjusting the fishing intensity to an appropriate level.

Keywords: Asian fisheries, biological reference points, global marine fisheries, hockey stick, maximum sustainable yield, stock assessment.

Introduction

The question of whether fishery resources are currently globally overfished is among the most concerning and important issues in marine ecosystem assessments. At present, this question is not sufficiently answered because the statuses and trends of fishery resources differ greatly among different regions of the world, and there is a substantial information gap (Worm et al., 2009; Hilborn and Ovando, 2014; Komori et al., 2016). Fishery management effectively reduces the fishing impact in many well-assessed fisheries in developed countries, such as the United States (Melnychuk et al., 2013) and Europe (Fernandes and Cook, 2013), and tuna regional fisheries management organizations (Pons et al., 2017). These well-assessed fisheries, however, represent only part of the world, and the stock statuses in other regions, such as Asia, Africa, and South America, are not sufficiently understood to predict the future global fishery sustainability (Hilborn and Ovando, 2014).

Japan is one of the most important fishery countries, with the fifth highest marine production, and currently contains 5% (15% at one time) of the world’s fisheries (FAO, 2016, Figure 1), although its stock status is not fully known. A historical review of Japanese catches in the northwest Pacific revealed peaks during the late 1980s and 1970s with and without Japanese sardine, respectively, and after these peaks the levels exhibited a gradual decline. If this decrease in catches reflects a decrease in the population size (Pauly et al., 2013), the total population size of the northwest (NW) Pacific ecosystems surrounding Japan during the last...
10 years would equal half of that during the 1970s and 90% of that during the 1990s. However, catch does not necessarily reflect abundance, particularly when stock management efficiently reduces fishing mortality (Branch et al., 2011). In 1997, the Fishery Agency of Japan introduced fishery management using total allowable catches (TACs) in conjunction with traditional effort management (Makino, 2011). Without an estimation of stock abundance, it is unknown whether the decline in Japanese catches, particularly during the last 15 years after TAC implementation, can be attributed to decreased stock abundances or to TAC management.

The main difficulty in understanding the status of Japanese fisheries based on an estimation of abundance is the absence of estimated maximum sustainable yield (MSY) reference points. The primary objective of fishery management according to the United Nations Convention on Law of the Sea (UNCLOS) is to maintain the stock level above the level that produces MSY. MSY reference points are commonly used for evaluations of stock statuses throughout the world (Hilborn and Stokes, 2010). However, an estimating MSY reference points is generally difficult, particularly due to the uncertainty in the stock-recruitment (S-R) relationship. The difficulty in estimating the S-R relationship is ubiquitous in fishery sciences and generally annoys most fishery scientists (Walters and Martell, 2004; Szewalski et al., 2015), including many Japanese fishery scientists dealing with Japanese stock data (cf. Matsuda et al., 1991; Sakuramoto, 2005; Shimoyama et al., 2007). The harvest control rule (HCR) adopted by the Japanese Fisheries Agency also proposes MSY as a primary management reference point (Fisheries Agency and Fisheries Research Agency of Japan, 2015). However, the empirical reference points such as historical stock sizes are commonly used in Japanese stock assessment, and MSY reference points are not estimated in most cases to avoid the large uncertainty associated with their estimation.

We addressed the difficulty in estimating MSY reference points by using all of the available biological information in combination with the uncertainty of the assumed S-R relationship. The estimated MSY reference points allowed us to evaluate Japanese stocks from the point of view of MSY and to compare the sustainability of Japanese fisheries with that of other fisheries throughout the world. We also investigated potential factors, such as biological parameters, wholesale prices and the application (or not) of TAC management, using a linear mixed model (LMM, Zurr et al., 2009) to determine whether these could explain the current stock statuses and historical trends.

**Material and methods**

**Japanese fishery resource data**

Important Japanese fisheries consisting of 52 species and 84 stocks have been assessed by the Japan Fisheries Research and Education Agency (FRA) every year since 1998. These stocks are assessed because of their relatively high total weight of landings and/or wide distribution across many prefectures. The main objective of this assessment is to estimate the acceptable biological catch (ABC) for the following year and to provide indicators of the stock statuses (high, middle, or low) and trends (increase, constant or decrease). A threshold stock size between “middle” and “low” is generally derived from the reference point “Blimit” as the spawning or total biomass below which strong recruitment cohorts rarely occur due to a low spawning biomass (Fisheries Agency and Fisheries Research Agency of Japan, 2015). The biomass level is determined based on the characteristics of individual stocks mostly through visual inspection and sometimes using objective definitions (e.g. the spawning biomass achieving half of the maximum number of recruits in the assumed S-R relationship). $B_{\text{limit}}$ is used as a threshold of the HCR below which the fishing mortality should present a linear decrease.

In this paper, we reviewed Japanese 37 stocks with abundance estimates. The abundance of 26 stocks among these 37 stocks is estimated using classical virtual population analysis (VPA) or tuned VPA (Ichinokawa and Okamura, 2014) (Supplementary Appendix S1). The abundance of the remaining 11 stocks are estimated using species-specific population dynamics models with survey data (nine stocks), sex-specific VPA (one stock), or monthly-based VPA (one stock). The stock assessments are updated every year and are publicly available at http://abchan.fra.go.jp in Japanese. We used the results of the stock assessments published in 2015, which include stock status estimates through 2013 (Fisheries Agency and Fisheries Research Agency of Japan, 2015).

Among the 37 stocks that were reviewed in this study, 16 stocks (eight species) have been managed using TACs (TAC stocks). TAC management has been implemented for Japanese sardine, Japanese jack mackerel, chub mackerel, spotted mackerel, Pacific saury, walleye pollock, and snow crab since 1997 and for Japanese flying squid since 1998. The TAC stocks need to have reliable abundance estimates and meet any of the following three criteria (Japan Fisheries Information Service Center, 2002): (1) the
stock must have a high amount of landings or high consumption, (2) the abundance must be so depleted that TAC management is urgently needed, and (3) part of the stock must be utilized by foreign countries. Most of the 16 TAC stocks meet the first and third criteria. ABCs provide a basis for determining the TACs for the following fishing year. For some species, the TACs were often markedly higher than the ABCs (Matsuda et al., 2010). However, in 2008, the Fisheries Agency of Japan recommended, as suggested by an advisory panel of well-informed independent personalities, maintaining the TAC below the ABC (Anonymous, 2008), and the discrepancy between the ABC and TAC has recently diminished.

The other 21 stocks are not managed by TACs (non-TAC stocks), but some are managed by various management methods often referred to as "self-management" by various management bodies, such as fishery associations. According to the stock assessment reports from 2015 (Fisheries Agency and Fisheries Research Agency of Japan, 2015), the most frequently observed tactics are restricting the size of caught fish and enhancement. Limitation of the number of fishing days and the catch per operation and the marine protected areas for spawning fish are also observed. Because of the nature of self-management, it is difficult to collect comprehensive quantitative information for all of the implemented management strategies. This study focused on the effect of the TAC management and not on other management tools, even though management tools other than TAC are often implemented in conjunction with TAC and are effective (Ichinokawa et al., 2015).

MSY reference points
We estimated MSY reference points for the 37 stocks with abundance estimates. We defined B_{MSY} as the total or spawning biomass (B) that produces MSY and U_{MSY} as the exploitation rate (U, total catch relative to the total biomass) achieving MSY. The time-series for B and U relative to B_{MSY} (B/B_{MSY}) and U_{MSY} (U/U_{MSY}), respectively, were then calculated to evaluate the statuses of stock abundance and fishing impact.

For the 26 stocks assessed by classical and tuned VPA and with an estimate of the annual number of recruits and spawning biomass, we estimated MSY reference points assuming an S-R relationship and age-specific biological parameters (Supplementary Appendix S2). The following functional types of the S-R relationships were investigated: Beverton-Holt (BH) (Beverton and Holt, 1957), Ricker (RI) (Ricker, 1954), and hockey stick (HS) (Clark et al., 1985). We applied these functions to the time-series data for spawning biomass and number of recruits with appropriate offset by the age of recruitment to estimate the parameters of the functions under the assumption of lognormal error distributions. The parameters were estimated using the nls function of the statistical analysis software R (R Development Core Team, 2016). We then conducted 100-year stochastic future projections using an age-structured model assuming an S-R relationship and observed the recruitment variability to determine the U_{MSY} and B_{MSY} values at which the geometric average of the annual catches after 100 years is maximized. We used geometric rather than arithmetic averages because the assumption of a log-normal error distribution for recruitment variability resulted in a long-tailed distribution for the annual catches after 100 years and geometric averages provided more stable estimations of MSY reference points compared with arithmetic averages. The age-structured model and biological parameters were equal to those used in the stock assessment models (VPA) for individual stocks.

For the other 11 stocks, we fitted a surplus production model to the catch and biomass time-series data (Supplementary Appendix S3). The method of fitting the surplus production model was generally similar to that used to compile the RAM Legacy database (Ricard et al., 2012). Note that the value of B_{MSY} estimated with the production model is the “total” biomass that produces MSY in this study, whereas the value of B_{MSY} estimated by the age-structured model is the spawning biomass. This inconsistency is inevitable due to a lack of information regarding the spawning biomass.

We compared the median trends for the U, B/B_{MSY} and U/U_{MSY} of the 37 stocks with those of stocks around the world. The global data were derived from the RAM Legacy database (v2.5 with production model fits, http://ramlegacy.org/, Ricard et al., 2012). The B_{MSY} and U_{MSY} values provided in the RAM Legacy database are mixtures of estimates from the original stock assessment models and those estimated by database compilers using a surplus production model, but we did not distinguish between these estimates in this analysis. We classified the world into five regions where the stock status has been reviewed relatively well: northeast (NE) Atlantic (European Union, Europe non-EU, and Mediterranean-Black Sea), northwest (NW) Atlantic (US East Coast, Canada East Coast, and US Southeast/Gulf), northeast (NE) Pacific (US Alaska, US West Coast, and Canada West Coast), southwest (SW) Pacific (Australia and New Zealand) and open ocean (Indian, Atlantic and Pacific Oceans, mainly tuna and billfishes). We also compared the life history parameter of M and the estimated U_{MSY} of Japanese stocks with those of stocks around the world. The worldwide M and U_{MSY} values were derived from the RAM Legacy database. Due to missing data, we used 194 and 182 data points to obtain the worldwide M and U_{MSY}, respectively.

Statistical analyses of the stock status and fishing mortality
We explored factors that can affect the statuses and trends of abundances and fishing mortalities of the Japanese stocks using LMMs. The candidates of the predictors are the logarithm of natural mortality coefficient (M), the age at which 50% of the individuals are sexually mature (maturity), the maximum recorded length (max length), and the wholesale price (price). We also included the following categorical variables: habitat (1 for pelagic species and 0 for demersal species) and stock management (1 for TAC stocks and 0 for non-TAC stocks). M and maturity were derived from those used in the stock assessment models or scientific studies. The max lengths of the fish were derived from FishBase (Froese and Pauly, 2016), those of snow crab (maximum recorded carapace width) and Japanese flying squid (maximum dorsal mantle length) were obtained from Ueda et al. (2007) and Sugawara et al. (2013), respectively. The price information was derived from the database provided by the Fisheries Agency at http://www.market.jaic.or.jp/suisan/ (in Japanese).

We then used log(B/B_{MSY}) or log(U/U_{MSY}) as the response variable y_i and X_{ip} and Z_{it} as the above-described predictors, where i and t represent the stock and year, respectively. To facilitate the interpretation of the estimated coefficients, we defined
the “year” $t$ as the actual year ($Y$) minus 2013 ($t = Y - 2013$).

The equation of the model is:

$$y_t = a + r_1 + t + r_2 (Z_{it} + \eta_i) + \epsilon_t$$

where $x$ and $\beta$ are the vectors of the regression effect of $X_{it}$ and $Z_{it}$, respectively. $\gamma_1$ and $\eta_i$ are random effects for each stock following $N(0, \sigma^2)$ and $N(0, \tau^2)$, respectively, and $\epsilon_t$ is a residual error term following $N(0, \nu^2)$. The LMM can be separated into two parts: the first part, $aX_{it} + \gamma_i$ (intercept), represents log(B/BMSY) or log(U/UMSY) for the most recent year (2013), and the second part, $t(Z_{it} + \eta_i)$ (annual trend), explains the annual trends of the response variables.

We performed model selection to determine the most parsimonious model using the bias-corrected Akaike information criterion (AICc; Burnham and Anderson, 2002). Considering the uncertainty of model selection, we present the parameter estimates of the averaged models with $\Delta$AICc < 2 as well as the model that achieved the minimum AICc. Because we were particularly interested in how the TAC and/or biological characteristics affected the statuses and trends of Japanese stocks, we mainly focused on the data from the years after 1997.

Results

Data overview

The total landings of the 37 stocks in 2013 were approximately 2.2 million metric tons (MT), representing 61% of the total marine capture production in Japan (3.6 million MT: Figure 1 and Supplementary Appendix S1). The 16 TAC stocks contributed to 75% of the total landings of the 37 stocks in 2013. The average duration of the stock abundance estimates is 27 years, and the number of the stocks with abundance estimates increased from 19 before 1990 to 31 in 1998.

S-R relationship and MSY estimates

When applying three different S-R functions, BH, RI and HS, to the spawning and recruitment data, the minimum AICc was achieved assuming BH in eight, RI in nine, and HS in five stocks (Supplementary Table S2). The three functions yielded the same AICc values for three stocks because the S-R relationships in these stocks became completely linear. Both BH and HS yielded the minimum values for one stock, in which recruitment does not depend on the spawning biomass. However, the $\Delta$AICc values obtained for the three S-R functions were less than two in many cases (20 stocks). According to Burnham and Anderson (2002), models with $\Delta$AICc < 2 cannot be rejected statistically. These results indicate the lack of statistically strong evidence for determining a single S-R function for these stocks.

We then classified the 26 stocks into five categories based on the robustness of the estimated BMSY and UMSY to the assumed S-R functions (Supplementary Table S2). The $B_{MSY}$ and $U_{MSY}$ estimates were relatively robust to the assumed S-R functions in eight stocks (four of which were managed by TACs), and these were denoted type I stocks (robust, Figure 2a). The seven type II stocks (three TAC stocks; linear, Figure 2b) show an almost linear relationship between the spawning biomass and recruitment. The $B_{MSY}$ estimates based on the BH and RI in these seven stocks were at least fivefold higher than the maximum historical spawning biomass, whereas HS provided realistic $B_{MSY}$ estimates. This result is due to the characteristics of HS: recruitment is assumed to be constant above a spawning biomass threshold to avoid extreme extrapolation within the range in which the spawning biomass or recruitment was not observed. In the six type III stocks (no TAC-manged stocks; strong density dependence in RI, Figure 2c), the estimates of $B_{MSY}$ based on RI were markedly lower than those based on BH and HS due to the strong density dependence estimated in RI. This strong density dependence resulted in a relatively large $U_{MSY}$ (0.27 for RBRMSETOW and 0.42–0.53 for the others, Supplementary Table S2) compared with their assumed M of 0.2–0.3. The three remaining TAC stocks were categorized as type IV (regime shift), in which the historical maximum spawning biomass was at least 30-fold higher than the historical minimum. These three stocks appeared to be highly subject to environmental factors, i.e. regime shift; thus, we applied the S-R function only to the recent data. A sensitivity analysis using data from different time periods did not reveal a significant effect on the conclusions presented below. The final category, type V, included the remaining two stocks that could not be categorized as any of the other types.

In summary, almost linear S-R relationships resulted in an implausibly high (outside of the range of the historically observed spawning biomass) $B_{MSY}$ for seven stocks when assuming BH or RI. The strong density dependence in RI resulted in an implausibly high (compared to M) $U_{MSY}$ for six stocks. In contrast, we could derive “realistic” $B_{MSY}$ and $U_{MSY}$ estimates using HS. We therefore used the results derived from HS as the basis for the subsequent stock overview and statistical analysis.

For the 11 stocks assessed using a production model, $U_{MSY}$ was positive, and $B_{MSY}$ ranged between the minimum and maximum historical biomass; thus, both $B_{MSY}$ and $U_{MSY}$ can be considered biologically plausible estimates for all of these stocks with the exception of a Pacific stock of snow crab (SNOWCRPAC) and a Pacific stock of cod (CODNIP). Because negative intrinsic growth rates were estimated for SNOWCRPAC and CODNIP, we fixed the fishing mortality rates that achieved MSY ($F_{MSY}$) for these two stocks, and only $K$ was estimated. The fixed $F_{MSY}$ was assumed to equal half of $M$ because $F_{MSY}/M$ is generally less than 1 and is approximately 0.5 for long-lived animals (Zhou et al., 2012). Further details of the results and fitted surplus production curves are presented in Supplementary Appendix S3.

Stock status

The individual trends of $B/B_{MSY}$ and $U/U_{MSY}$ of the 37 assessed stocks (Supplementary Figure S4) and median trends with data coverage (Figure 3) are shown assuming different S-R functions. Roughly similar annual trends of the median $B/B_{MSY}$ and $U/U_{MSY}$ values were obtained for the different S-R assumptions: after 1997, $B/B_{MSY}$ tended to increase, and $U/U_{MSY}$ tended to decrease. Assuming HS, the median absolute values of $B$/$B_{MSY}$ ranged from 0.5 to 0.7, and those of $U/U_{MSY}$ ranged from 1 to 1.3. This result indicates that half of the stocks had a $B/B_{MSY}$ below 0.5–0.7 and a $U/U_{MSY}$ above 1–1.3 for the last 15 years. The BH assumption provided a more pessimistic view: half of the stocks had a $B/B_{MSY}$ below 0.5–0.7 and a $U/U_{MSY}$ above 1–1.3 for the last 15 years. The BH assumption provided a more pessimistic view: half of the stocks had a $B/B_{MSY}$ below 0.6–0.9 and a $U/U_{MSY}$ above 0.8–1.2. This optimistic view was
achieved the MSY (BMSY) and the number of recruits at BMSY (RMSY) based on each S-R function. The upward arrows indicate that BMSY and/or RMSY is out of range.

Figure 2. Examples of the stock-recruitment (S-R) relationships applied to Japanese fishery stock data. Types I (a), II (b), and III (c) are categories based on the uncertainty of the estimated maximum sustainable yield (MSY) reference points. Details of the categories are provided in the main text and Supplementary Appendix S4. Solid: hockey stick (HS); dashed: Beverton-Holt (BH); and dotted: Ricker (RI). All of the figures for the 26 stocks are shown in Supplementary Figure S3. The data points are connected based on year. Denser black points represent more recent data, and the most recent year is indicated with a cross. The downward arrows indicate the stock biomass that achieved the MSY (BMSY) and the number of recruits at BMSY (RMSY) based on each S-R function. The upward arrows indicate that BMSY and/or RMSY is out of range.

Figure 3. Median of historical biomass (B) relative to the BMSY (B/BMSY, a) and exploitation rates (U, total catch relative to the total biomass) relative to the U achieving MSY (U/UMSY, b) among the 37 Japanese stocks assessed. The assumed S-R functions are HS, BH and RI. The grey areas show the proportion of stocks where abundance estimates are available [p of stocks with abundance estimates/all 37 stocks, %].
attributed to the six type III stocks in which a strong density dependence was estimated under RI.

The current stock status (geometric mean of the most recent 3 years) indicates that approximately half of the stocks fall into the category of "overfished" (tentatively defined by U/UMSY > 1) and that half are classified as "overfished" (tentatively defined by B/BMSY < 0.5) regardless of the assumed S-R functions (Figures 4 and Supplementary Figure S5). The actual percentages of overfished and overfished stocks varied depending on the assumed S-R functions. Under HS, BH and RI, 54, 59, and 44% of the stocks, respectively, were considered to be overfished. The current status determined using the BH and HS S-R functions of the TAC stocks appeared to be better than that of the non-TAC stocks. The RI S-R function yielded similar statuses for the TAC and non-TAC stocks because the stock statuses of the five type III non-TAC stocks improved when using RI instead of BH or HS. The total estimated MSY under the assumption of HS was approximately 3.5 million metric tons (Supplementary Table S2), and the total MSYs of the stocks under the conditions of B2011−2013 < BMSY and B2011−2013 > BMSY were 1.8 and 1.7 metric tons, respectively.

Comparison with other fisheries throughout the world

The median trends of the B/BMSY and U/UMSY of the 37 stocks determined based on HS were compared with those of other five regions of the world (Figure 5a and b). The results revealed that Japanese fisheries were similar to those of the NE Atlantic and presented the most overfished and overfishing conditions among all of the regions investigated. When we compared the stock status of TAC or non-TAC stocks, the median B/BMSY of the TAC stocks in the most recent year of 2013 was comparable to that of the more successful regions, namely SW and NE Pacific. The median U/UMSY of the TAC stocks appeared to decrease at greater rates than those of the non-TAC stocks and gradually approached those of the more successful regions. In contrast, the status of the non-TAC stocks was by far the worst.

Factors affecting stock status and fishing mortality

The results of the LMMs in Supplementary Table S1 and Table S2. To investigate the intercept of the B/BMSY model (Table 1), max length with negative coefficients was included in the minimum AICc model, which indicates that stocks with larger max lengths tended to have a smaller B/BMSY (i.e., were more vulnerable). Regarding the annual trend of the B/BMSY model, no interactions with the year effect were included in the minimum AICc model, but the main effect of "year" was included with a positive coefficient of 0.02. Because the lower limit of the 90% confidence interval (CI) was almost 0 in the minimum AICc model and negative, at −0.02, in the averaged model, this effect was not strongly supported. Nevertheless, the positive coefficient indicates that the B/BMSY has gradually increased since 1998.

Regardless of the intercept of the U/UMSY model (Table 2), the AICc minimum model included the effects of TAC, M, maturity, max length, and price but not pelagic. This result indicates that TAC stocks tended to have a smaller U/UMSY when considering other biological factors. Similar results were observed for the annual trend of U/UMSY: the AICc minimum model included the biological factors of maturity and max length and the effect of TAC with a negative coefficient of −0.02. The interaction effect of year and TAC of −0.02 demonstrates that the reduction rate of the TAC stocks was higher than that of the other stocks. However, because the 90% CI of the interaction effect of year and TAC was −0.04 to 0.00 in the AICc minimum model and −0.05 to 0.00 in the averaged model, the uncertainty of the interaction effect was relatively high.

The estimated annual trends of U and B for each stock in the LMMs, corresponding to the term $\beta Z_{it} + \eta$, in Eq. 1, show a negative relationship (Figure 7). Thirty-one stocks show the negative trend of U, and the median values were −0.025 for TAC stocks (2.5% reduction in U per year) or −0.012 for non-TAC stocks (1.2% reduction in U per year). Twenty-two stocks show the positive trend of B and the median value was 0.011 (1% increase in B per year). The slope and intercept of the simple regression of B against U trends with excluding the outlier of SNOWCRAP were −1.03 (p = 0.011) and −0.002 (p = 0.863), respectively, which indicates that a reduction in U can potentially increase biomass although there is the large variance in the data.

A sensitivity analysis of the LMMs was conducted with BMSY and UMSY assuming BH and RI instead of HS (Supplementary Table S3).
Appendix S7). Although the parameter estimates on annual trends were similar to the results obtained using HS, the factors that explain the intercept of $B/B_{MSY}$ in the minimum AICc model differed under the BH and RI assumptions. Assuming BH and RI, the main factors that affected $B/B_{MSY}$ were $M$ and maturity, whereas max length was the main factor under HS, probably due to the potential relationship among $M$, maturity and max length. However, the qualitative results did not change substantially, even assuming different S-R functions. In other words, $B/B_{MSY}$ has slightly but significantly increased over the past 15 years, and $U/U_{MSY}$ has significantly decreased, particularly for the TAC stocks.

**Discussion**

**Current stock status in Japan**

The current stock status of 37 Japanese stocks is not very good because approximately half of the stocks are in the “overfishing” ($U/U_{MSY} > 1$) range and half are “overfished” ($B/B_{MSY} < 0.5$) (Figure 4 and Supplementary Figure S5). However, LMMs indicated that the fishing mortality significantly decreased and that the total biomass slightly increased over the past 15 years (Tables 1 and 2). In particular, the rate of decrease in the fishing mortality in the stocks that were managed by TACs was greater than that of the other stocks (Table 2). These results provide complementary information to proceeding studies that review statuses and trends of fisheries in various regions that have undergone stock assessment (Worm et al., 2009; Costello et al., 2012; Hilborn and Ovando, 2014) and show the effectiveness of TAC management (Melnychuk et al., 2013; Pons et al., 2017). Although the main analysis was conducted assuming an HS S-R relationship, the sensitivity analyses using MSY reference points that were estimated with BH and RI (Figure 3 and Supplementary Appendixes S6 and S7) also yielded conclusions similar to those described above.

The higher rates of decrease of $U$ obtained for the TAC stocks compared with those found for the non-TAC stocks are particularly important, as this study details the world’s first quantitative evaluation of Japanese fishery management using TAC. In addition, $U$ decreased not only in the TAC stocks but also in the non-TAC stocks. The combination of various management tools, such as input control, is common in Japanese self-management even for the non-TAC stocks (Makino, 2011; Ichinokawa et al., 2015). Therefore, the decrease in $U$ obtained for the non-TAC stocks can be considered the outcome of such self-management using management tools other than TACs. We could not incorporate the effect of self-management into the statistical analysis of explanatory variables due to insufficient information, but a collection of all of the management efforts and an evaluation of the quantitative effects are needed in future studies.

The abundances of the TAC stocks did not significantly increase at greater rates than those of the non-TAC stocks, whereas...
the overall abundance slightly increased. An insufficient reduction in U is the first possible reason for this result. The significant negative relationship between the trends of U and B (Figure 7) indicates that we can expect an increase in stock abundance as an outcome of the reduction in fishing mortality. However, a large variation was observed in this relationship. According to the estimated prediction interval shown in Figure 7, the achievement of stock recovery, i.e. obtaining a positive B trend, with a 90% probability requires an annual reduction in U of –0.066 for 15 years, i.e. at least 6% per year. The large variation in this relationship might obscure the effect of a greater reduction in U obtained for

Table 1. Parameters estimated using linear mixed models (LMMs) with the response variables log (B/B_{MSY}).

<table>
<thead>
<tr>
<th></th>
<th>AICc minimum model</th>
<th>Averaged model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Estimate</td>
<td>5%</td>
</tr>
<tr>
<td>Intercept (Intercept)</td>
<td>3.22</td>
<td>1.96</td>
</tr>
<tr>
<td>TAC</td>
<td>0.38</td>
<td>–0.06</td>
</tr>
<tr>
<td>Pelagic</td>
<td>–0.49</td>
<td>–1.01</td>
</tr>
<tr>
<td>M</td>
<td>0.36</td>
<td>–0.11</td>
</tr>
<tr>
<td>Maturity</td>
<td>–0.19</td>
<td>–0.51</td>
</tr>
<tr>
<td>Max length</td>
<td>–0.96</td>
<td>–1.27</td>
</tr>
<tr>
<td>Price</td>
<td>0.14</td>
<td>–0.07</td>
</tr>
<tr>
<td>Year:</td>
<td>0.02</td>
<td>0.002</td>
</tr>
</tbody>
</table>

The results of the model achieving the minimum AICc (AICc minimum model) and the average of the models with ΔAICc < 2 (averaged model) are shown.

Table 2. Parameters estimated using linear mixed models (LMMs) with the response variable log (U/U_{MSY}).

<table>
<thead>
<tr>
<th></th>
<th>AICc minimum model</th>
<th>Averaged model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Estimate</td>
<td>5%</td>
</tr>
<tr>
<td>Intercept (Intercept)</td>
<td>–0.92</td>
<td>–2.02</td>
</tr>
<tr>
<td>TAC</td>
<td>–0.65</td>
<td>–0.90</td>
</tr>
<tr>
<td>Pelagic</td>
<td>–0.62</td>
<td>–0.98</td>
</tr>
<tr>
<td>M</td>
<td>–0.36</td>
<td>–0.61</td>
</tr>
<tr>
<td>Maturity</td>
<td>0.46</td>
<td>0.21</td>
</tr>
<tr>
<td>Max length</td>
<td>–0.19</td>
<td>–0.29</td>
</tr>
<tr>
<td>Price</td>
<td>–0.08</td>
<td>–0.15</td>
</tr>
<tr>
<td>Year:</td>
<td>–0.02</td>
<td>–0.04</td>
</tr>
</tbody>
</table>

The caption is the same as that of Table 1.
the TAC stocks on abundance recovery. This large variation could be attributed to various factors, such as time-lag in the response of abundance to a reduction in fishing intensity, environmental effects on recruitment deviation, regime shift, and uncertainty of the catch statistics from foreign countries.

Our statistical analysis indicates that $B/B_{\text{MSY}}$ tended to be smaller in the stocks with a larger max length (Table 1). The negative effect of max length on $B/B_{\text{MSY}}$ is supported by previous studies using the RAM Legacy database (Costello et al., 2012; Thorson et al., 2012; Komori et al., 2016). These previous studies reported significant effects of species category, max length, and trophic level on $B/B_{\text{MSY}}$ or the probability of $B/B_{\text{MSY}}$ being less than 0.2. We did not incorporate the trophic level because it appeared to correlate with max length and other biological parameters, and such information for crabs and squids is not available. Pinsky et al. (2011) and Pinsky and Byler (2015) reported possible interaction effects between growth rates and $U$, but our dataset was not large enough to detect such complex interaction effects.

According to our finding that approximately half of the 37 stocks are overfished, we can expect a substantial increase in the future yield if appropriate management measures are applied to these overfished stocks. Currently, the total catch in 2013 for the overfished stocks ($B_{2011-2013}/B_{\text{MSY}} < 0.5$) among the 37 stocks was approximately 1.1 million MT, whereas the total MSY of these stocks was 1.8 million MT. We can theoretically expect an additional yield of 0.7 million MT if the overfished conditions of these stocks are improved. Japan had the fifth largest marine production of 3.6 million MT in 2014 and one of the greatest consumers of marine products (> 60 kg per capita per year, corresponding to 7.2 million MT) throughout the world (FAO, 2016). Japan relies on imports for the shortfall, but the potential addition of 0.7 metric tons can keep up with approximately 1/4 of the shortfall, which would largely affect the trade flows of marine products and food provision at the global scale.

Figure 7. Annual trends of $U$ (U trend) and $B$ (B trend) estimated using the LMMs for each stock. The solid diagonal line is the predicted regression line for the B trend against the U trend, and broken lines show the 90% prediction interval. The regression line was fitted to all of the points with the exception of an outlier at $-0.20$ along the x-axis and 0 along the y-axis (for SNOWCRPAC), which $U$ was substantially reduced by the Great East Japan Earthquake while $B$ did not increased probably due to the predation by the tsunami. The solid diagonal line is the predicted regression line for the B trend against the U trend, and broken lines show the 90% prediction interval. The regression line was fitted to all of the points with the exception of an outlier at $-0.20$ along the x-axis and 0 along the y-axis (for SNOWCRPAC), which $U$ was substantially reduced by the Great East Japan Earthquake while $B$ did not increased probably due to the predation by the tsunami.

Japan in the world fisheries
This study clearly identified some characteristics of Japanese fishery resources through a comparison with those from fishery around the world. A higher $M$ and consequently a higher $U_{\text{MSY}}$ (Figure 6) were the first noteworthy characteristics. These characteristics can be attributed to the large contribution of small pelagic fish and squid to Japanese fishery resources. Sixteen of the 37 assessed stocks consisted of small pelagic fish or squid and contributed 79% of the total landings in 2013. Note that having a majority of small pelagic fish does not mean that “fishing down” (Pauly et al., 1998) has occurred in recent years because the mean trophic level of Japanese catches did not show a long-term decline (Matsuda et al., 2010). The large contribution of small pelagic resources to Japanese stocks with relatively high natural mortality, i.e. productivity, suggests that Japanese fisheries have great potential to exhibit quick recovery and therefore increase their yield through an adjustment of fishing intensity to an appropriate level.

We could also characterize the coefficient of variation (CV) of recruitment deviation in Japanese fishery resources (Supplementary Table S2). Thorson et al. (2014) reported that the average CV of recruitment deviation in the world is 0.74 (SD = 0.34), whereas that in Japan is 0.39 when assuming HS or BH (SD = 0.2 or 0.21, respectively), and 0.38 when assuming RI (SD = 0.2). The average first-order autocorrelation coefficients of residuals were 0.36 (SD = 0.26), which are lower than those of the world (0.43, SD = 0.28) (Thorson et al., 2014). In general, the recruitment variation is considered higher in pelagic fish than in demersal fish, and interestingly, the CVs of recruitment deviation in Japanese stocks dominated by pelagic species are lower than those of other fisheries around the world on average. Thorson et al. (2014) also found no significant differences in the CVs of recruitment deviation among taxonomic groups. We expect the fishery management of stocks with a smaller CV in recruitment deviation to be more tractable. A HCR considering these advantages, lower CVs in recruitment deviation and high productivity, is required to utilize the great potential of Japanese fisheries stocks.

The third characteristic is large uncertainties in the S-R relationships and MSY reference points, although similar uncertainty is generally observed in any fishery stock. In half of the 26 Japanese stocks examined, it was difficult to apply the commonly used S-R functions of BH and RI due to an implausibly high $B_{\text{MSY}}$ in seven stocks (type-II) and an implausibly high $U_{\text{MSY}}$ in six stocks (type-III) (Supplementary Table S2). The difficulty in estimating MSY reference points when using BH or RI, particularly with stocks in which an almost linear S-R relationship is estimated, has been a challenge for many Japanese fishery scientists (cf. Matsuda et al., 1991; Sakuramoto, 2005; Shimoyama et al., 2007).

Faced with the large uncertainty of MSY reference points in BH and RI, we utilized the HS function and evaluated the Japanese stock statuses based on HS S-R relationship. HS could provide a biologically and empirically plausible estimation (within the range of historical spawning biomass) of MSY reference points, even for stocks for which a naive application of BH or RI is difficult, because we can avoid extreme extrapolation. This characteristic of HS is preferred and HS has thus been recommended as an alternative SR function in many studies (Clark et al., 1985; Barrowman and Myers, 2000; Mesnil and Rochet, 2012).
HS can also overcome the problem of predicting an increase in the number of recruits per spawner at low population sizes in BH and RI (Barrowman and Myers, 2000). However, HS has some drawbacks. For example, the nondifferentiability of the HS function frequently results in multiple local minima on the likelihood surface, and the grid search method is recommended (Barrowman and Myers, 2000). In addition, when recruitment appears to be independent on spawning biomass or increase almost linearly against spawning biomass, we cannot determine the single break point of HS based on likelihood. In these cases, we cannot help but arbitrarily set the minimum or maximum historical spawning biomass as the break point of HS. In particular, the almost linear S-R relationship might suggest that these stocks have been so depleted that we cannot observe recruitment compensation within the observed range. Therefore, \( B_{MSY} \) estimates under the HS assumption would serve as a lower limit of the possible range of \( B_{MSY} \).

The large uncertainty in the estimation of MSY reference points frequently forces us to use many ad hoc assumptions in stock assessments to derive a tactical management target or use an implausible management target. Although the use of MSY reference points as the primary management reference is now widely accepted, the concept to MSY itself has a history of near-death and reincarnation (Larkin, 1977; Mace, 2001). The perception of \( F_{MSY} \) as a limit to be avoided rather than a target is a solution to the use of the concept in fisheries management when considering a precautionary approach under the potential uncertainty and the ecosystem and economy points of view (Mace, 2001). Although we used MSY reference points according to their use in other studies evaluating global fisheries trends (Worm et al., 2009; Costello et al., 2012), MSY is not a single management target. Individual management authorities would take into account a wide range of management targets considering inter-species relationships and ecosystem aspects.

The statuses and trends of fisheries differ among the different regions of the world. Forecasting the worldwide future of fisheries is an interesting issue for many fishery scientists and also for the public (Worm et al., 2006, 2009). Forecasting should be based on the accumulation of knowledge on individual regional fisheries around the world. However, Asian fisheries have never been sufficiently reviewed using stock abundance estimates and have not been included as part of the “world” in some high-impact studies evaluating global fisheries trends (Worm et al., 2009; Costello et al., 2012) and Neubauer et al. (2013). However, the most recent study by Costello et al. (2016) suggests the great potential of Asian fisheries. Japanese fishery resources are on their way to reaching the target level with respect to MSY reference points, but we expect that this quantitative evaluation will aid future improvements in the fishery and management systems in Japan and help us understand the global stock status of fisheries in more detail.

Acknowledgements

We are very grateful to all of the scientists who were involved in the stock assessments of the 37 fishery stocks in the FRA and the local fishery institutes. These assessments are funded by the Fisheries Agency of Japan. Our sincere thanks are extended to Dr. Y. Oozeki, three anonymous reviewers and the associate editor Dr. Shijie Zhou for the useful and constructive comments provided, which greatly improved the manuscript. This work was supported by CREST, JST and JSPS KAKENHI Grant Number JP26520313.

Supplementary data

Supplementary material is available at the ICESJMS online version of the manuscript.

References


Handling editor: Shijie Zhou