1) Title: Bioeconomic assessment of size separators in Pacific saury fishery

2) Running Title: bioeconomic assessment of size separators

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***ABSTRACT*****:** In the middle of 1990s, Pacific saury fishery vessels began to install 'size separators' to selectively land large-size class fish with higher price. Contrary to the expectations, it resulted in the complete removal of separators in 2006 because fishers considered that separators had contributed to the price collapses in the 2000s. The intent of this paper is to investigate the effects of separators on both the fishery economy and stock of Pacific saury through simulating population and economic models under a single framework. For this purpose, we specifically developed (i) an age-structured population dynamics model with stochasticity, and (ii) an economic model spanning both price and inventory dynamics with stochasticity, in which each set of model parameters were estimated based on time series data. In ten year simulation, we set the harvest quota as constant covering from 20 to 400 thousand tons, and the effects of separators were incorporated by controlling the catchability of 0 year old fish. We have identified that separators increase the expected yield and decrease the deficit risk when the annual harvest is set smaller than 160 thousand tons. Otherwise, they decrease the expected yield and increase the deficit risk.

Keywords: fisheries management, bioeconomic simulation, risk analysis, Pacific saury, discarding, size separators, price, population dynamics

## INTRODUCTION

Recent studies on bioeconomic assessment of fisheries management policy in Europe[1-4] and North America[5, 6] seek to integrate the models of population dynamics and socioeconomic factors (e.g. economic cost and price) into a single framework. These studies reflect the perceptions that, in many cases, fishing activities are driven by socioeconomic considerations as well as biological ones; therefore, both evidences are essential to materialize sustainable fisheries. We believe that the paradigm of research in fisheries science will continuously go into this direction.

Unfortunately, however, there is few empirical studies on fisheries management employing bioeconomics in Japan[7]. One possible reason is the unique and complicated co-management fisheries regime established in the long history of Japanese fishery[8]. The management is in fact not only implemented by governmental policies, but also coordinated by management measures of fisheries cooperative associations. This is distinct from the system of Western countries and makes the usage of bioeconomic analysis difficult. In this study, we took a further step and challenged the assessment of size separators via bioeconomic simulations of Pacific saury (*Cololabis saira*) industry in Japan.

Pacific saury is widely distributed in the north western Pacific and one of the important commercial fish in Japan over 60 years. From 2001, Tohoku National Fisheries Research Institute started the precise estimation of the stock abundance[9]. They currently estimated that stock abundance varies in about 3-7 million tons and the current fishing rate is relatively small[10]. These are considered credible evidences that the stock has not been severely depleted.

Despite of the stock richness, Pacific saury fishery in Japan is now facing a severe economic difficulty. One of the most important reasons is price collapses caused by size-biased catch. In the middle of 1990s, Pacific saury fishery vessels began to install ‘size separators’ to selectively land larger fish that could potentially be sold with higher prices. It is said that fishers separated smaller fish from a whole catch by separators and discarded much part of separated smaller fish[10]. After the introduction of separators, the harvest of larger fish increased and that of smaller fish decreased. Separators quickly spread to almost all vessels since yield (equals harvest times the price) per vessel with separators became relatively higher than that without separator. Consequently, however, what happened in the 2000s was a series of price collapses caused by the excessive supply of large-size class fish. Therefore, fishers started to realize that separators had adverse effects on the fishery economy as a whole. In the end, Japan Pacific Saury Fishery Association decided the complete removal of separators on vessels in 2006.

When separators were initially introduced, some of fishers perhaps said that it has a negative effect on the stock persistence. Some researchers also claimed the risk of population decline. Some seafood process companies insisted the removal of separators since separators caused the shortage of small-size class fish for processing. However, almost all did not believe that separators would give negative impacts on the fishery economy after several years. For the sake of better fisheries management in the future, this is the time to untangle the mechanism of price collapses and the effects of separators on it.

The yields of Pacific saury fishery in the past show a peculiar phenomenon of a negative relationship between the harvest and yield (Fig.1a). This implies a high possibility that the price collapsed with increasing fish supply. For the purpose of identifying the important factors in modeling the price collapse, we have made extensive surveys by interviewing fishers and the fishery-related industry as well as collected empirical data on economic and biological factors. At this point, these evidences appear to suggest that the price collapse are mainly attributed to (1) the large fluctuation in the annual harvest (Fig.1a) and size composition (Fig.1b), and (2) the unique characteristics of pricing process in Pacific saury fishery.

With respected to the first factor, in the last thirty years, (i) the annual harvest of Pacific saury in Japan fluctuated from 98 035 tons in 1976 to 367 572 tons in 1978 (Fig.1a), and (ii) the large size ratio (>290mm) of harvest fluctuated from 0.09 in 1977 to 0.93 in 2005 (Fig.1b). The large fluctuations in harvest and size composition are attributed to its biology. The physiological longevity of Pacific saury is 2 years[11]. Pacific saury quickly grows up to around 28-30 cm in the first year and reach 30-33 cm in the second year[11]. It migrates between subtropical and subarctic regions, matures at 0 year old, and spawns for 9 months from autumn to spring. The survival rate highly depends on the local environment during the migration[12, 13]. A series of these characteristics of Pacific saury contribute to the yearly fluctuation in recruitment, making it hard to predict the recruitment of 0 and 1 year old fish in the next year and future. Recently, the annual harvests have been kept between about 200-300 thousand tons (Fig.1a) by TAC settings and other management measures to avoid excessive harvesting.

With respect to the second factor, the price of Pacific saury mainly depends on annual harvest, large size ratio and amount of inventory[14]. The price likely decreases as either harvest or inventory increases. The causality between large size ratio and price are unclear. To understand the potential size dependency in the price, we pay attention to the size-selective use of Pacific saury.

Pacific saury is landed as fresh at Japanese fish market of coast, and then seafood process companies immediately separate the landings into several standardized size groups. The consumptive form of Pacific saury depends on the size. Small-size class fish are used for feeds for aquaculture etc; medium-size class fish are used for canning etc; and large-size class fish are used for other human food which is mainly distributed as fresh. While the price of large-size class fish is much higher than the smaller, the amount of consumption by people is strongly limited. Making matters worse, the ability to distribute “expensive” fresh large-size class fish to the consumers is also limited. So, when the supply of large-size class fish exceeds a certain limit, the price collapses to the price level of smaller fish. At the same time, in such a case, the excess of large-size class fish is stored as inventory. Generally, the increase in inventory decreases the price in the next year. For these reason, even if fishers keep a certain annual harvest, the price greatly fluctuates depending on the large size ratio. This is probably one of the reasons why Pacific saury fishery easily falls in price collapse.

Building upon these empirical evidences, we developed two types of models which incorporate the population dynamics of Pacific saury and the unique features of economy: (i) an age-structured population dynamics model with stochasticity and (ii) an economic model spanning both price and inventory dynamics with stochasticity. From extensive simulations under various scenarios, we investigated the effects of separators on the fishery economy and stock of Pacific saury. We calculated the expected yield, fishery deficit risk and population decline risk as assessment indicators. From the simulation results, we also discussed why separators were introduced and removed in the history.

## MATERIALS AND METHODS

We constructed a 4-box simulation system of bioeconomic assessment shown in Fig.2. The models constructed in this study are explained in detail below. Table 1 provides data sources used to design the models, and Tables 2, 3 and 4 provide summary lists of notation and calibration results used in the equations of the models.

### Models

We constructed a model that describes the population dynamics of Pacific saury (Oyamada, Ueno and Matsuda, unpublished). We modeled only the elementary features of Pacific saury population such as two-age classes[11] and process errors in recruitment of 0 and 1 year old fish [12, 13] as follows:

$$ssb_t = \alpha(n_{0,t} - c_{0,t}) + (n_{1,t} - c_{1,t}) \quad (1a)$$
$$n_{0,t+1} = a(ssb_t)\exp(-b(ssb_t))\exp(d_0) \quad (1b)$$
$$n_{1,t+1} = (n_{0,t} - c_{0,t})s\exp(d_1)$$
$$d_0 \sim \mathrm{N}(0, \sigma_0)$$
$$d_1 \sim \mathrm{N}(0, \sigma_1)$$

where $n_{0,t}$ and $n_{1,t}$ are respectively the numbers of age 0 and 1 year old in the population in year $t$. Both cohorts are subject to be fished. We defined the number of catch of age 0 and 1 year old as $c_{0,t}$ and $c_{1,t}$, respectively. The survival rate from 0 year after recruitment to 1 year old fish is denoted by $s$. We assumed that all of 1 year old fish dies until the next year.

The number of 0 year old fish in the next year, denoted by $n_{0,t+1}$ is given by the Ricker equation linked to the current spawning stock biomass $ssb_t$. $ssb_t$ is the number of fish which reproduce in year $t$. We assumed that a part of 0 year old fish reproduces with the ratio $\alpha$, and all of 1 year old fish reproduce. The value of $\alpha$ is uncertain[10]. In this study, we assumed that $\alpha = 0.5$. We added error terms to the population dynamics with log-normal distributions $\exp(d_0)$ and $\exp(d_1)$ where $d_0$ and $d_1$ have the standard deviation $\sigma_0$ and $\sigma_1$, respectively.

We estimated $a$, $b$, $\sigma_0$, $\sigma_1$ and $s$ with the data of $n_0$, $n_1$, $c_0$ and $c_1$ from 1976 to 2005 (Oyamada et al. unpublished). We show the values of these estimates in Table 2. $c_0$, $c_1$, $n_0$ and $n_1$ were calculated in the following way.

We used the data of efforts (operation number) during 1976-2005, size-specific catch-in-number during 1976-2005, and $n_0$ and $n_1$ during 2003-2005 (Table 1). We estimated $c_0$ and $c_1$ during 1976-2005 by size-specific catch-in-number using the relationship between age and size[11].

We also calculated the mean catchabilities $q_0$ and $q_1$ during 2003-2005 using efforts, $c_0$, $c_1$, $n_0$ and $n_1$[15]. Then, we estimated $n_0$ and $n_1$ from 1976 to 2002 considering $q_0$, $q_1$, $c_0$, $c_1$ and efforts.

A certain part of harvest is kept in freezers as inventory for up to 4 years. The frozen fish is utilized as thawed fish etc. We gave the following inventory model:

$$I_{t+1} = \exp(e + fR_t + gH_t) \tag{2}$$

We defined $I_t$ as the amount of inventory (tons) at the end of July, just before the fishing season. Annual harvest $H_t$ and large size ratio $R_t$ are given by equations (4) and (5), respectively. Annual harvest $H_t$ is mainly responsible for the inventory in the next year $I_{t+1}$. $I_{t+1}$ is also positively related to the large size ratio $R_t$ because the excessive supply of large-size class fish is stored as inventory. Using the data of $R_t$ and $H_t$ during 1976-2004, and $I_t$ during 1977-2005, we estimated the coefficients $e$, $f$ and $g$ by the least-squared method as shown in Table 3 and Fig.3a. The estimates of $e$, $f$ and $g$ were significantly different from 0 (Table 3).

The price of Pacific saury depends on the annual harvest, large size ratio and amount of inventory[14]. We modeled price as follows:

$$\begin{aligned} p_t &= \exp(i + jR_t + kR_tH_t + lI_t + d_p) \\ d_p &\sim \mathrm{N}(0, \sigma_\mathrm{p}) \end{aligned} \tag{3}$$

We defined $p_t$ as ex-vessel price per kg. The product of large size ratio $R_t$ and annual harvest $H_t$ represents the amount of large-size class fish supplied in the market at the year. In the same way with the population dynamics model, we added an error term $\exp(d_p)$ where $d_p$ has the standard deviation $\sigma_p$.

The price $p_t$ is expected to increase as the large size ratio $R_t$ increases. Therefore, the coefficient $j$ is likely positive. $p_t$ also depends on the supply of large-size class fish $R_tH_t$ and the inventory $I_t$. $p_t$ decreases as either of them increases. Therefore, the coefficients $k$ and $l$ are likely negative. Using the data of $p_t$, $R_t$, $H_t$ and $I_t$ during 1976 to 2005, we estimated the coefficients $i$, $j$, $k$, $l$ and $\sigma_p$ by the maximum likelihood method as shown in Table 4 and Fig.3b. The estimates of $i$, $j$, $k$ and $l$ were significantly different from 0 (Table 4).

The bottom price of Pacific saury is almost constant in the historical record. At the price, Pacific saury is utilized as feeds, ingredients or fish meal etc. We assume that the bottom price is 30 yen/kg and $p_t$ is not smaller than 30.

In the models for the price and inventory, we adopted a function form that has rarely seen in conventional studies in economics for the following reasons. We tested the fitness of a Cob-Douglas function which is frequently used. However, a dependent variable such as price greatly elevated due to the functional restrictions when some independent variables (e.g. large-size class fish supply $R_tH_t$ and inventory $I_t$) were close to 0. In such a case, minimizing annual harvest was the optimal action to maximize yield, which is in fact far away from the reality. Pacific saury is fished by other countries, so importation is expected to increase and restrain the price elevation when the harvest is exceptionally small. Therefore, we concluded Cob-Douglas function is not suitable to capture the feature in pricing of Pacific saury. For the other alternatives, we also tested Translog function, which could be considered a more generalized Cob-Douglas function. Unfortunately, we could not get reasonable coefficient values because of the large number of coefficients. Other studies suggested a conventional demand-supply model as a price model[16]. However, it has been identified that, in Pacific saury fishery, the price does not apparently reflect the fishery cost. For these reasons, we decided not to adopt these conventional function forms but adopted the phenomenological model based on the important factors in pricing.

To model the inventory dynamics, we also considered Cob-Douglas function and other conventional functional forms. But, only with the function form used in the price model, we found significant difference (< 5%) in the coefficient estimates. Therefore, we used it in the inventory model.

We assumed that cost $C$ is constant because of no consistent relationship between the total cost and other factors (e.g. efforts) throughout the historical data. Constant cost would not interfere measuring the effects of separators because introduction of separators does affect price rather than cost. We estimated cost $C$ (Table 2) from the historical data (Table 1).

**Simulation of Pacific saury Management Measures**

In the measure box, we defined the combination of harvest quota and the use of separators as a management measure (Fig.2). We considered that the effect of separators changes depending on the annual harvest. From the past annual harvest data (Fig. 1), harvest quota was set from 20 to 400 thousand tons. In every simulation run, we calculated the harvest quota (tons) into age-specific catch in number $c_{0,t}$ and $c_{1,t}$ by using the relationships among $c_{0,t}$, $c_{1,t}$, $n_{0,t}$, $n_{1,t}$, $q_0$, $q_1$, $wc_0$ and $w_1$[15].

$wc_0$ and $w_1$ are the mean body weight of 0 and 1 year old fish that are caught, respectively. $c_{0,t}$ and $c_{1,t}$ were used in the population dynamics model in the stock box (Fig.2).

We assumed that fishers separate 0 year old fish from a whole catch by separators and discard some proportion of separated fish. The percentage of discarded fish highly depends on the large size ratio of the population in the year. Therefore, we introduced $u$ as the ratio of landed 0 year old fish to the sum of landed and discarded 0 year old fish, and redefined the catchability $q_0$ as $q_0u$. Then, only when we simulated the population dynamics model, we redefined $c_0$ as $c_0/ u$. We examined that $u$ is 1, 0.5 or 0.2. These represent the situation that 0, 50 and 80 % of 0 year old fish are caught but discarded. We assumed all of fish once caught dies. We evaluated the effects of separators by comparing three strategies: '$u$=1', '$u$=0.5' and '$u$=0.2'.

To combine the stock box to other boxes, we defined annual harvest $H_t$, large size ratio $R_t$, and stock abundance $S_t$ as follows:

$$H_t = (c_{0,t} wc_0 + c_{1,t} w_1)/10^6 \quad (4)$$
$$R_t = c_{1,t} /(c_{0,t} + c_{1,t}) \quad (5)$$
$$S_t = (n_{0,t} w_0 + n_{1,t} w_1)/10^6 \quad (6)$$

where $w_0$ is the mean body weight (g) of 0 year old fish in the population. We assumed that the mean body weight of 1 year old fish does not differ between the population and catch, and used $w_1$ as the mean body weight (g) of 1 year old fish in the population. In convenience, we expressed annual harvest $H_t$ and stock abundance $S_t$ in the unit of tons. $H_t$ can become smaller than the harvest quota when the stock is small. We defined large size ratio $R_t$ as the ratio of 1 year old fish in number to all fish that are landed. Both annual harvest $H_t$ and large size ratio $R_t$ were used in the price and inventory model in the economy box (Fig.2).

We conducted the simulation from years 2006 to 2015 with 10 thousand simulation runs under three strategies. In the assessment box (Fig.2), we calculated the population decline risk, namely the percentage of simulations that the stock abundance $S_t$ is below a threshold at least once within the 10 years. We assumed that the threshold is 1 % of the initial stock abundance. To examine the economic dynamics, we showed the expected harvests of 0 and 1 year old fish, large size ratio, inventory and price. We also calculated the expected yield and deficit risk which is the frequency that the cost exceeds the yield within the simulated 10 years.

## RESULTS

### Economic effects

Fig.4 shows the expected harvests of 0 and 1 year old fish. According to the trend of recent annual catch (Fig.1a), we define the conventional harvest range as 200-300 thousand tons. Under $u$=1 strategy (no separator is installed), in the conventional harvest range, the harvest of 0 year old fish ranged from 79 to 119 thousand tons, and that of 1 year old fish ranged from 121 to 181 thousand tons. Separators decreased the harvest of 0 year old fish by 31 % and 63 %, and increased that of 1 year old fish by 20 % and 40 % under $u$=0.5 and $u$=0.2 strategies, respectively. The expected large size ratio were 0.51, 0.65 and 0.79 under $u$=1, $u$=0.5 and $u$=0.2 strategies, respectively. These values did not significantly change irrespective of the harvest.

Fig.5 and Fig.6 show the expected inventory and price, respectively. Under *u*=1 strategy, in the conventional harvest range, the inventory ranged from 20 to 35 thousand tons while the price ranged from 141 to 73 yen. These ranges appeared in the historical data (Fig.3a,b).

Separators increased the inventory by 11% and 23% under *u*=0.5 and *u*=0.2 strategies, respectively. On the other hand, the price was not clearly characterized by the harvest and the use of separators. When the harvest is smaller than 160 thousand tons, *u*=0.2, *u*=0.5 and *u*=1 strategies produced higher price in that order. When the harvest is larger than 160 thousand tons, they showed the opposite trend. In the conventional harvest range, separators decreased the price by at most 14 and 25 yen under *u*=0.5 and *u*=0.2 strategies, respectively. The price under three strategies converged to the bottom price of 30 yen.

Fig.7a shows the expected yield and cost. Under *u*=1 strategy, the yield had a unimodal shape and was maximized at 180 thousand tons for the harvest. With the harvest smaller than 160 thousand tons, separators increased the yield. The maximum yield of all strategies was at 120 thousand tons under *u*=0.2 strategy. With the harvest more than 160 thousand tons, separators decreased the yield. In the conventional harvest range, separators decreased the yield by 4.2 and 8.0 billion yen under *u*=0.5 and *u*=0.2 strategies, respectively. The expected profit is considered to be the area above the cost line as well as below the yield line. Because cost was set constant, the profit changed proportionally to the yield. It is notable that the profit was negative under *u*=0.5 and *u*=0.2 strategy with the harvest more than 260 and 240 thousand tons, respectively.

Fig.7b shows the deficit risk. The risk behavior under each strategy was consistent with the result of expected yield. In other words, the deficit risk decreased as the yield increased. In the conventional harvest range, separators increased the deficit risk by 0.24 and 0.45 under $u$=0.5 and $u$=0.2 strategies, respectively. It is worth noting that, under $u$=1 strategy, the minimum deficit risk was 0.15 with the harvest of 180 thousand tons, and, in the conventional harvest range, the deficit risk increased from 0.17 to 0.55.

**The effect on population**

Fig.8 shows the population decline risk. When the harvest was below 60 thousand tons, there was almost no risk. Under $u$=1 strategy in the conventional harvest range, the population decline risk was smaller than 0.05. Even with the harvest of 400 thousand tons, the risk was smaller than 0.1. Separators increased the population decline risk. In the conventional harvest range, the risk was smaller than 0.07 and 0.12 under $u$=0.5 and $u$=0.2 strategies, respectively.

## DISCUSSION

We concluded that, in the conventional harvest range (200-300 thousand tons), separators should not be installed on vessels considering the following economic and biological consequences. First, in the conventional harvest range, separators give deleterious impacts on the economy of fishers. Our results showed that separators decrease the expected price (Fig.6) and yield (Fig.7a), and increase the deficit risk (Fig.7b) with increasing expected harvest of large fish (Fig.4) and inventory (Fig.5). Second, separators harm the economy of seafood process industry. From the hearing investigation on seafood process companies, large size ratio 0.3 is desirable for the conventional harvest range. In our simulation, separators increased the expected large size ratio from 0.5 to the more and decreased the expected harvest of small fish for processing (Fig.4). Third, separators increase the population decline risk under the same amount of harvest (Fig.8). Although the risk was not very high (<0.12), the decrease in population never leads to the benefit of all stakeholders.

In addition to the conclusion, it should be noted that, if fishers do not discard, installing separators on vessels may give positive effects to the fishery economy. This is because a size-sorted catch can be effectively used as the various consumptive forms of Pacific saury. The important problem is that separators on vessels become a cause of discarding smaller fish. When separators were installed, there is a strong incentive of discarding for an individual fisher because discarding increases the individual profit when others do not discard. This situation could be some analogy with a typical situation of prisoners' dilemma[17]. Our simulation system can be a basic material for further discussion in decision making on the adoption of separators as well as the setting of harvest quota in the future.

We explain why separators were introduced and removed in the history based on the results in this paper. From the late 1980s to early 1990s, fishers suffered the prolonged price collapses

(Fig.1a, Fig.3b). Therefore, they had an incentive to increase the catch of large-size class fish which was believed to be sold at high price at that time. This is probably one of the reasons why Pacific saury fishery vessels installed separators in the middle of 1990s.

From the middle of 1990s to 2002, the large size ratio was relatively low, between 0.3 and 0.6 (Fig.1b). Furthermore, in 1998 and 1999, the population seemed to suddenly declined, and both harvests were smaller than 150 thousand tons (Fig.1a). Reflecting the shortage of harvest, a large quantity of inventory was consumed, and consequently the amount fell down (Fig.3a). In these years, the low large size ratio (Fig.1b) and the small amount of inventory (Fig.3a) sustained the high yields (Fig.1a). We consider that separators contributed to the increase in large size ratios and possibly the yields in this period.

On the other hand, inventory drastically recovered from 2000 and peaked in 2003 (Fig.3a). In addition, in 2003 and 2005, the large size ratios were exceptionally as high as 0.82 and 0.93, respectively. The high large size ratios reflected the use of separators and the ratios of the population 0.59 and 0.85 in 2003 and 2005, respectively in accordance with the stock assessment. In these years, the large amount of inventory (Fig.3a) and high large size ratio (Fig.1b) caused price collapses (Fig.1a, Fig.3b). In 2006, Japan Saury Fishery Association decided the complete removal of separators. Our research regime has the potential to explain the downside of separators back in those days.

We set up the population dynamics model as simply as possible to focus on the factors that are important in measuring economic indicators. The population dynamics model is insufficient to do quantitative prediction of population dynamics. Our model is at least useful to investigate the relationship among the use of separators, harvest quota, population decline risk, expected yield and deficit risk.

We simply ignored the decadal variability in the stock abundance of Pacific saury[12]. We also set the ratio of landed 0 year old fish *u* as constant. These simplifications may lead to different results from the reality. When the stock abundance is small, the large size ratio is usually small. Fishers are anticipated to increase the use of separators, and the amount of discarded smaller fish in order to keep a certain amount of large-size class fish. Additionally, the low stock level probably continues for several years due to the decadal variability. If such a state continues for a decade, the population decline risk is probably significantly higher than we estimated. From this perspective, our models may underestimate the population risk.

We conducted sensitivity analyses on the coefficients and parameters to both the fishery economic and biological consequences. We tested $\alpha$, $a$, $b$, $s$, $\sigma_0$, $\sigma_1$ in the population dynamics model, $e$, $f$, and $g$ in the inventory model, $i$, $j$, $k$, $l$, and $\sigma_p$ in the price model, the catchabilities $q_0$, $q_1$, and the body weights $wc_0$, $w_0$ and $w_1$. The sensitivity analysis was done by controlling each value from half to double without changing other values.

The fishery economic consequence is that, in the conventional harvest range, separators have the inferior effects on the economy of fishery. When the constant term $i$ in the price model was the half, the prices under three strategies converged to 30 yen, so the effect of separators was not detected in economic indicators. When the coefficient of $R_t$, $j$ in the price model was the double or when the coefficient of $R_tH_t$, $k$ is the half, the intersection of yield lines under three strategies moved from 160 thousand tons to the middle of 200-300 thousand tons. We identified that the quantities of $i$, $j$ and $k$ in the price model are considered to be particularly important for the fishery economic consequence. The changes in other values were not explicitly related to the consequence.

The biological consequence is that separators increase the population decline risk. This was held in all cases of sensitivity analyses. But the magnitude of risk drastically depended on the value of some parameters. The risk was proportional to $b$, $\sigma_0$, $\sigma_1$ and $q_0$, but inversely proportional to$\alpha$, $a$, $s$, $q_1$, $wc_0$ and $w_1$. The changes in other values were not explicitly related to the risk.

Our simulation system can be modified for other research objectives. For example, it can be used in decision making on the management measure of expanding harvest quota. Pacific saury has plenty of stock and expanding harvest quota is in vigorous discussion. Our models have a large potential to evaluate the biological and economic risks, and expected profit of fisheries. For these purposes, some factors especially the calculations of population decline risk and cost should be improved.

As mentioned in the introduction, the empirical study on bioeconomics is rarely seen in Japanese fisheries science. Our research showed some potential contribution to the choice of fisheries management measures. A key step in the modeling was the hearing investigation on the fishery industry, which enabled us to abstract the nature of socioeconomic processes. Fisheries scientists often take the role to advise about policies or measures taking into consideration the balance between stock persistence and economic profits. The bioeconomic simulation system constructed in this research is useful for this role.

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**Table 1** A summary of data sources.

**Table 2** A summary of notation.

**Table 3** Inventory model calibration result.

**Table 4** Price model calibration result.

**Fig.1** The annual harvest and yield (a), and large size ratio (b). solid line; harvest, broken line; yield, cross; large size ratio.

**Fig.2** The simulation system of bioeconomic assessment.

**Fig.3** The result of calibration on inventory model (a) and price model (b). solid line; data, broken line; model estimation.

**Fig.4** The expected harvests of 0 year old fish (no symbol), and 1 year old fish (circle) under $u$=1 (thick line, without separator), $u$=0.5 (thin line) and $u$=0.2 (broken line).

**Fig.5** The expected inventory under $u$=1 (thick line, without separator), $u$=0.5 (thin line) and $u$=0.2 (broken line).

**Fig.6** The expected price with harvest from 20-400 thousand tons (a) and that with harvest from 180-400 thousand tons (b) under $u$=1 (thick line, without separator), $u$=0.5 (thin line) and $u$=0.2 (broken line).

**Fig.7** The expected yield and cost (a), and deficit risk (b) under $u$=1 (thick line, without separator), $u$=0.5 (thin line) and $u$=0.2 (broken line). A Grey line shows the cost.

**Fig.8** The population decline risk under $u$=1 (thick line, without separator), $u$=0.5 (thin line) and $u$=0.2 (broken line).

Table 1

| data contents | year | source |
| --- | --- | --- |
| efforts, size-based harvest, annual harvest | 1976-2005 | Tohoku National Fisheries Research Institute, Fisheries Research Agency |
| stock abundance | 2003-2006 | Tohoku National Fisheries Research Institute, Fisheries Research Agency |
| price, inventory | 1976-2005 | Annual report of distribution statistics on fisheries products（1977-2006） |
| cost | 2003-2005 | Statistical survey on Fishery Enterprises (2003-2007) |

Table 2

| Subscripts | Definition | range | |
|---|---|---|---|
| $i$ | age | {0,1} | |
| $t$ | time | {1,11} | |
| Variables | Definition | unit | subscripts |
| $ssb$ | spawning stock biomass | number | $t$ |
| $n$ | population abundance | number | $i,t$ |
| $c$ | catch | number | $i,t$ |
| $d$ | normal random number | number | $i,p$ |
| $R$ | large size ratio of harvest | {0,1} | $t$ |
| $H$ | annual harvest | tons | $t$ |
| $I$ | inventory at the end of July | tons | $t$ |
| $p$ | ex-vessel price per kg | yen | $t$ |
| parameters | Definition | value | unit |
| $q_0$ | catchability of 0 year old fish | $1.88 \cdot 10^{-7}$ | |
| $q_1$ | catchability of 1 year old fish | $5.68 \cdot 10^{-6}$ | |
| $\alpha$ | the ratio of 0 year old fish which reproduce | 0.5 | |
| $\sigma_0$ | standard deviation of $d_0$ | 0.66 | |
| $\sigma_1$ | standard deviation of $d_1$ | 0.65 | |
| $a$ | parameter in the Ricker equation in the population dynamics model | 1.75 | |
| $b$ | parameter in the Ricker equation in the population dynamics model | 0.08 | |
| $s$ | survival rate from 0 year after recruitment to 1 year old fish | 0.34 | |
| $wc_0$ | mean body weight of 0 year old fish that are caught | 83.7 | g |
| $w_0$ | mean body weight of 0 year old fish in population | 43.7 | g |
| $w_1$ | mean body weight of 1 year old fish caught, and also that in population | 132.5 | g |
| $C$ | mean total cost of Pacific saury fishery calculated by historical record | 21.5 | billion yen |
| $u$ | the ratio of landed 0 year old fish | 1, 0.5 or 0.2 | |

Table 3

| coefficients | definition | value |
|---|---|---|
| *e* | constant | 8.32** |
| *f* | coefficient of $R_t$ | $0.58 \cdot 10^{-5}$* |
| *g* | coefficient of $H_t$ | 0.79** |
| Indicators of calibration | | |
| $R^2$ | | 0.63 |
| adjusted $R^2$ | | 0.6 |

* 5% significant difference

** 1% significant difference

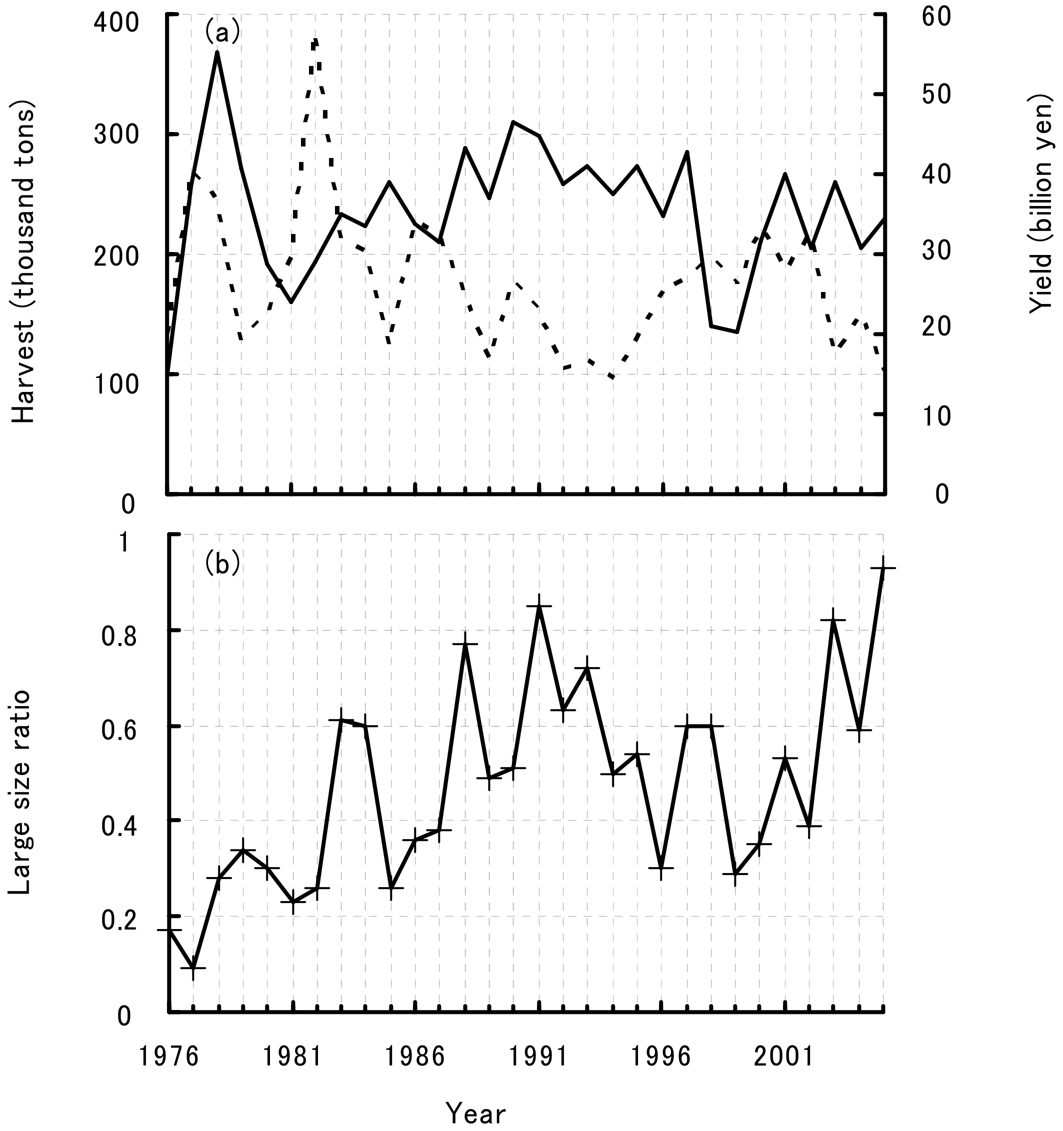
Table 4

| coefficients | definition | value |
|---|---|---|
| $i$ | constant | 5.43** |
| $j$ | coefficient of $R_t$ | 1.49* |
| $k$ | coefficient of $R_t H_t$ | $-0.87 \cdot 10^{-5}$ ** |
| $l$ | coefficient of $I_t$ | -1.72** |
| $\sigma_p$ | standard deviation of $d_p$ | 0.23 |
| Indicators of calibration | | |
| $R^2$ | | 0.73 |
| adjusted $R^2$ | | 0.7 |

* 5% significant difference

** 1% significant difference

Fig.1



(a)
Harvest (thousand tons)
400
300
200
100
0
60
50
40
30
20
10
0
Yield (billion yen)
(b)
Large size ratio
1
0.8
0.6
0.4
0.2
0
1976
1981
1986
1991
1996
2001
Year

Fig.2

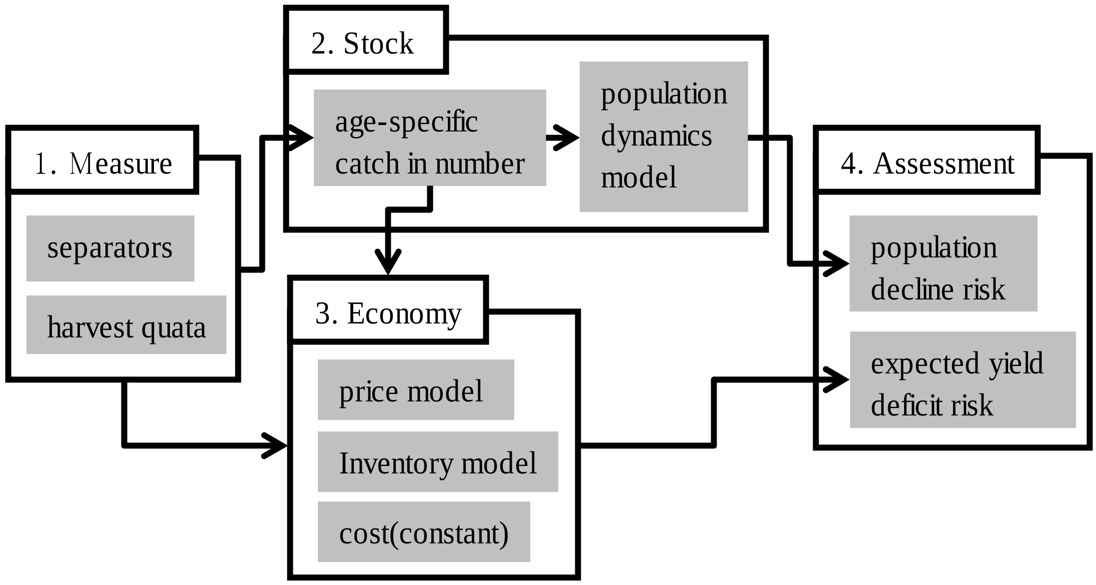

2. Stock
age-specific catch in number
population dynamics model
1. Measure
separators
harvest quata
3. Economy
price model
Inventory model
cost(constant)
4. Assessment
population decline risk
expected yield deficit risk

Fig3

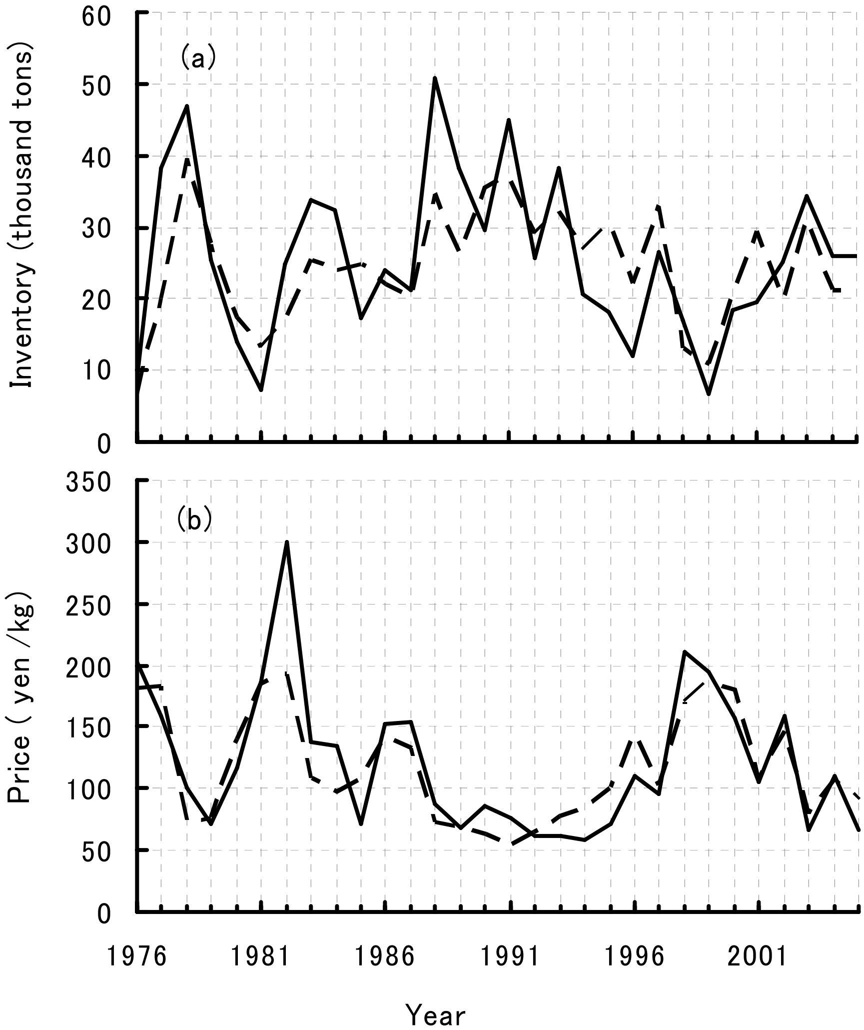

(a)
Inventory (thousand tons)
60
50
40
30
20
10
0
(b)
Price ( yen /kg)
350
300
250
200
150
100
50
0
1976
1981
1986
1991
1996
2001
Year

Fig.4

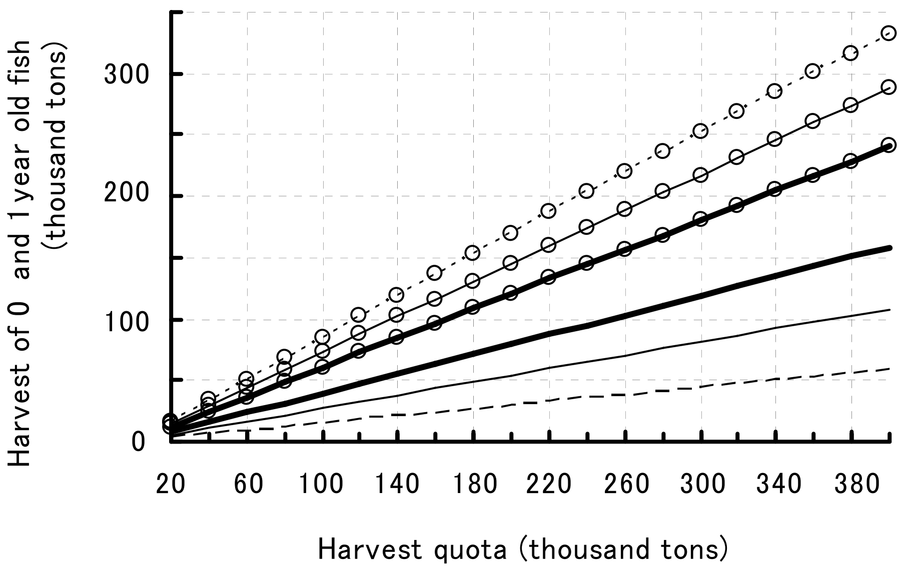
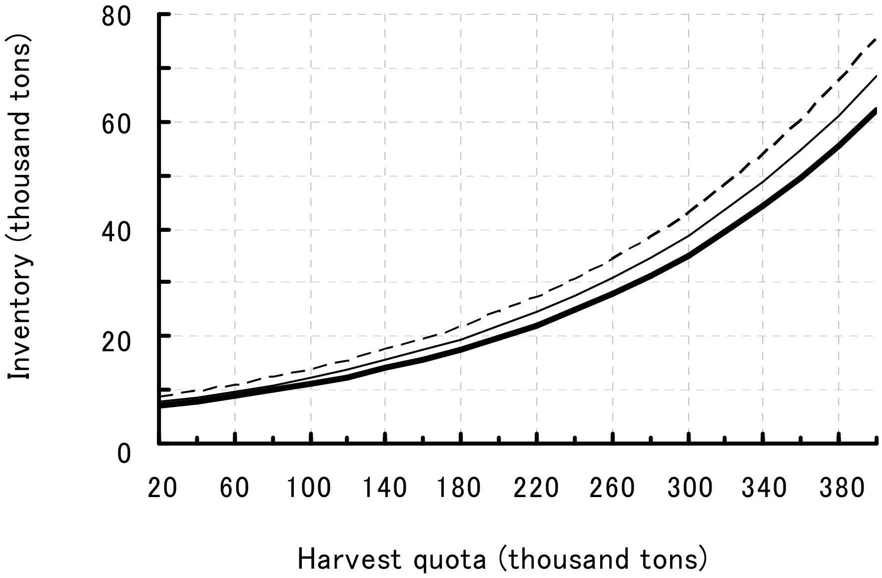
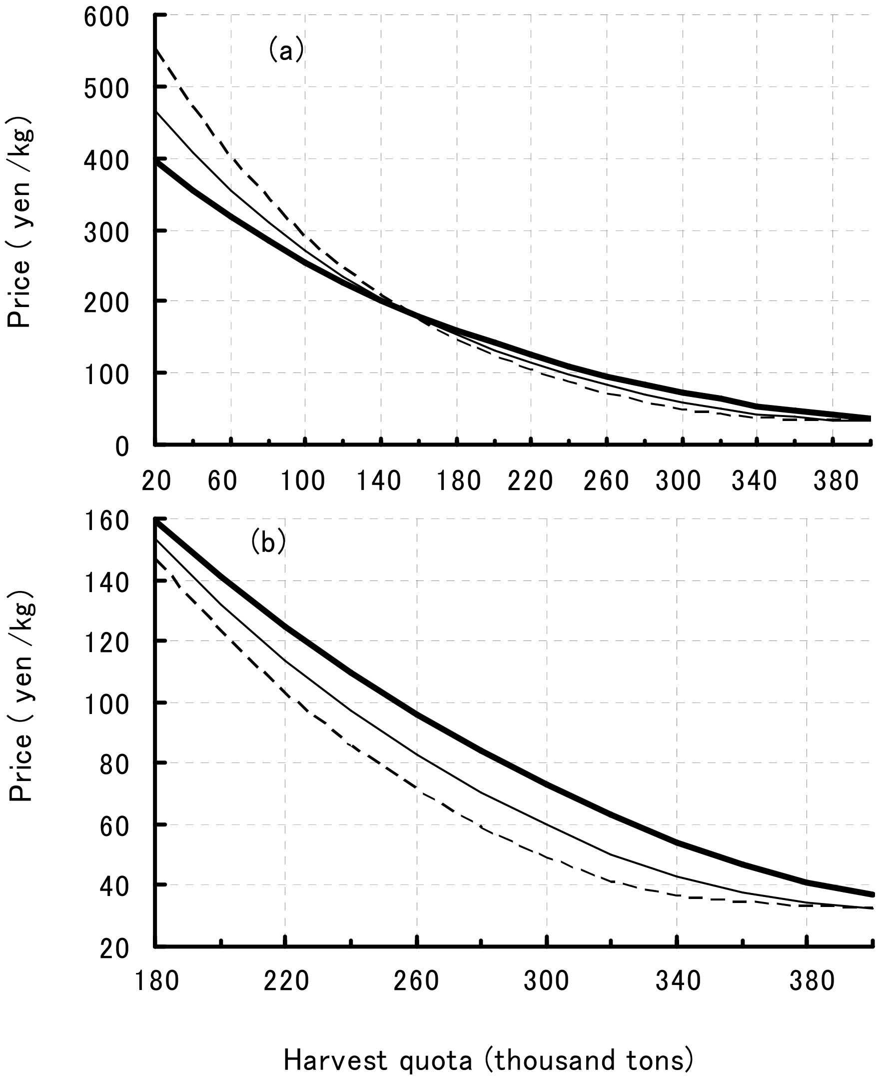

Harvest of 0 and 1 year old fish
(thousand tons)
300
200
100
0
20
60
100
140
180
220
260
300
340
380
Harvest quota (thousand tons)

Fig.5



80
60
40
20
0
Inventory (thousand tons)
20
60
100
140
180
220
260
300
340
380
Harvest quota (thousand tons)

Fig.6



(a)
Price ( yen /kg)
600
500
400
300
200
100
0
20 60 100 140 180 220 260 300 340 380
(b)
Price ( yen /kg)
160
140
120
100
80
60
40
20
180 220 260 300 340 380
Harvest quota (thousand tons)

Fig.7

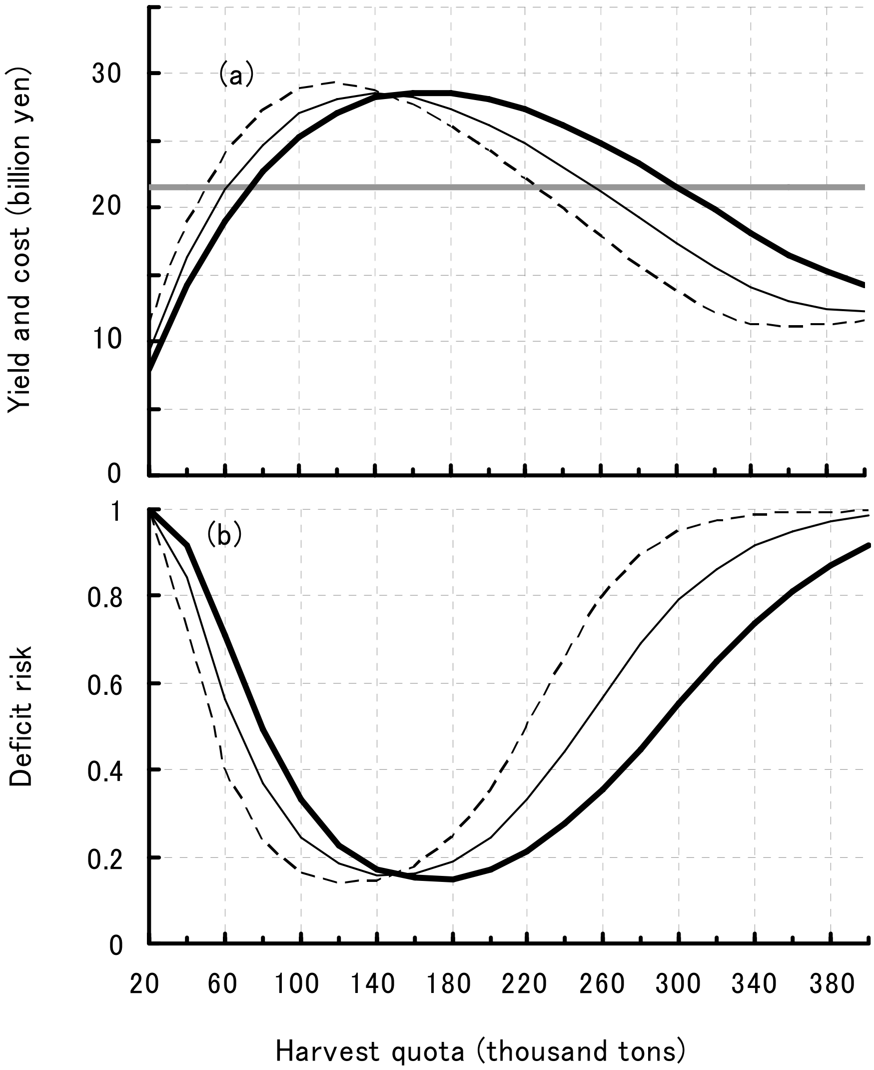
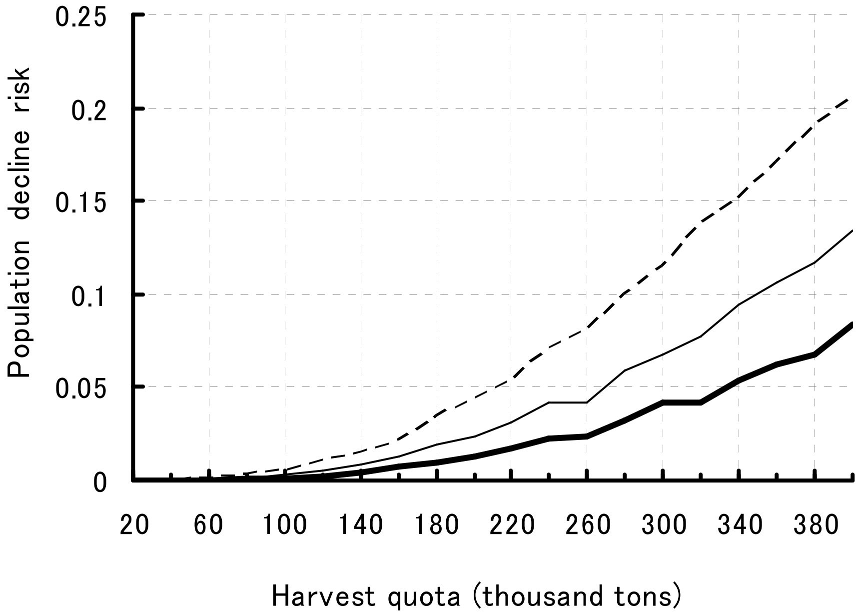

(a)
Yield and cost (billion yen)
0
10
20
30
(b)
Deficit risk
0
0.2
0.4
0.6
0.8
1
20
60
100
140
180
220
260
300
340
380
Harvest quota (thousand tons)

Fig.8


0.25
0.2
0.15
0.1
0.05
0
Population decline risk
20
60
100
140
180
220
260
300
340
380
Harvest quota (thousand tons)