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Methodology to Estimate Fishery Resources using Catch Data and its Application to Pacific Bluefin Tuna

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【abstract】

Regulatory measures for Pacific bluefin tuna fisheries have just been introduced by the Western and Central Pacific Fisheries Commission (WCPFC). Whether stricter regulations will be adopted is crucial in determining tuna prices and the profitability of tuna farming worldwide. As reliable resource data for this species are not available, we developed a new methodology to estimate fishery resource movement using catch data. The method is a combination of the surplus production model, which has an environmental factor term in addition to the original specification, and the supply function, which explains catch amount with respect to resources and other variables such as price and time trend. This methodology can be applied to open access fisheries, in which the bluefin tuna fishery in the Pacific Ocean has been the typical one. The results indicate that both environmental factors, represented by the Pacific Decadal Oscillation (PDO), and fishing activity are crucial in determining changes in resources. However, appropriate combinations of PDO coefficient (θ), intrinsic growth rate (r) and carrying capacity (K) that satisfy the parametric conditions of the supply function were widely distributed; thus it was difficult to specify them by statistical criteria. Therefore, the estimated bluefin tuna resource trends based on such parameters were also widely distributed: as some of them were over maximum sustainable yield (MSY) and others were are below it for the latest decade.

【keywords】

Pacific bluefin tuna, surplus production model, supply function

1. Introduction

Japan is the market that consumes the most bluefin tunas in the world. However, resources of Atlantic and Southern bluefin tuna have become so depleted(1) that the International Commission for the Conservation of Atlantic Tunas (ICCAT) and the

Commission for the Conservation of Southern Bluefin Tuna (CCSBT) have strictly regulated the catches.

Consequently, the trend of Pacific bluefin tuna catching is crucial for determining the price of bluefin tuna in the Japanese markets, which will be transmitted to foreign markets and affect the profitability of tuna farming in the Mediterranean Sea, Australia and Mexico.

Regulatory measures for the bluefin tuna fisheries in the Pacific Ocean have just been introduced by the Western and Central Pacific Fisheries Commission (WCPFC). As the resource analyses for this species have not been robust as mentioned in the next section, it is unclear whether stricter measures will be introduced.

Therefore, we analyzed factors that cause changes in the resource levels of Pacific bluefin tuna by developing a new methodology to estimate resource trends, which is a combination of the surplus production model and the supply function.

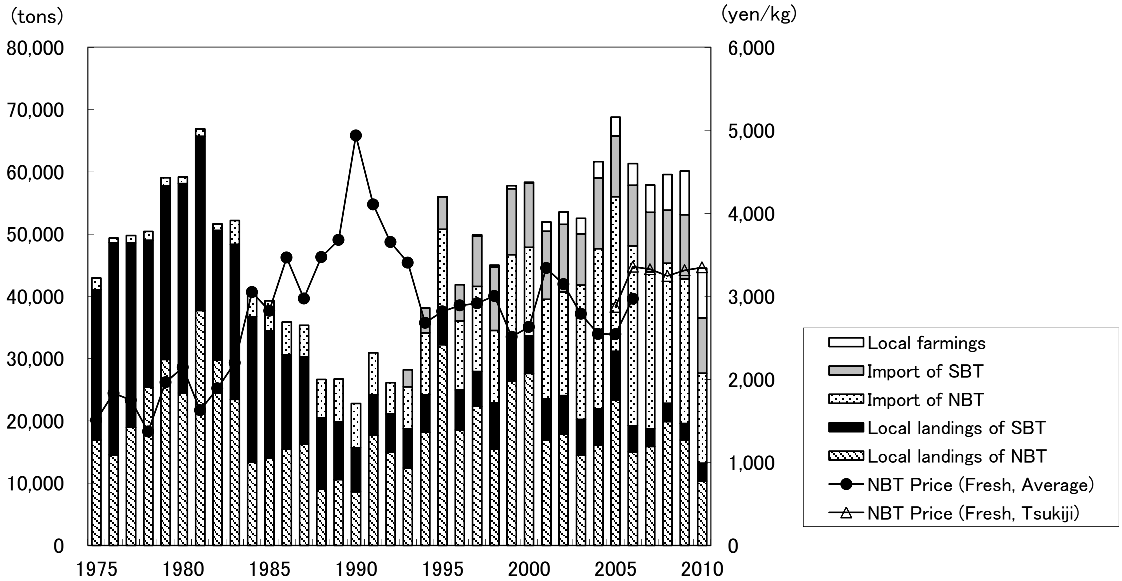


Figure 1 Supply of bluefin tunas to the Japanese market and the price

Sources:

1) Local landings, “Production Statistics of Fisheries and Aquaculture”, MAFF.

2) Imports, “Trade Statistics”, MOF.

3) Local farmings, Various sources including those based on the interviews to business persons related to bluefin tuna.

4) Prices: Nominal prices of the year average, “Statistics of Fisheries Distribution” (1965-2006), Fishery Agency and “Statistics of Tokyo Central Wholesale Markets” (2004-2011), Tokyo.

2. The Japanese bluefin tuna market

Bluefin tuna is mostly used for *sashimi* and *sushi* in Japan. As Miyake *et al.* (2010) described, there are two types of consumers in the Japanese market: those who prefer red meat and those who prefer fat content, and the latter has increased due to the influence of a westernized diet. Belt conveyer *sushi* restaurants have been popular since the 1990s, and the demand for farmed bluefin tuna with high fat content has grown. The recent supply of bluefin tuna into the Japanese markets is composed of domestic landed wild tuna, domestic farmed tuna, and imported farmed tuna.

Before 1980, almost all bluefin tunas were domestically landed as shown in Figure 1, where the northern bluefin tuna (NBT) is an aggregation of the Atlantic bluefin tuna (ABT) and the Pacific bluefin tuna (PBT). However, domestic landings began to decrease in the late 1980s, whereas the demand for tunas increased due to the economic bubble. The sharp decrease in domestic landings was a result of resource reduction caused by over-fishing and/or climate change. Subsequently, the wholesale price of northern bluefin tuna sharply rose from 3,000 yen/kg to more than 4,000 yen/kg. This accelerated the imports of bluefin and bigeye tunas. Bigeye tuna is a substitutional good for wild bluefin tuna and it has a standard class position in the *sashimi* market.

The imports of southern bluefin tuna (SBT) began in 1991, after the successful application of fattening technology. At the same time, the imports of ABT, which comprise most of the NBT imports, also increased, and the proportion of farmed tuna among imported bluefin tuna has been increasing since then (Ono (2012), pp.124-126). However, both SBT and ABT face serious resource constraints and catch controls, and their catch amount has recently become stagnant.

The CCSBT was established in 1994 to conserve SBT resources, with Japan, Australia and New Zealand as the initial members. Before that, these countries introduced a catch quota system in 1985, and the quota of each country has since decreased. For example, the countries' total catch quota was 38,650 tons in 1985; however, this decreased to 11,750 tons in 1989 and has remained at that level until 1997.

Even after the issues of non-member involvement (Pintassilgo and Duarte (2001)) and the Japanese experimental fishery plan (Polacheck (2002) and Komatsu and Endo (2002)) ended, the CCSBT continued to reduce the quota, but the tuna resources never recovered. Historically, the lowest quota was 9,449 tons for the year 2011, which was one-fourth of the quota for 1985. Of this quota, 2,261 and 4,015 tons were allocated to Japan and Australia, respectively. The 2012 quota was slightly relaxed to 10,449 tons.

Regarding the east ABT, which comprises most of the ABT including the west ABT, the catch ratio has rapidly increased to more than 25%, and the estimated spawning stock biomass in 2005 was nearly 100,000 tons which is one-third of the estimation in 1975 (ICCAT (2009)). Therefore, the catch quota that exceeded 30,000 tons when it was established in 1998 was reduced to 13,500 tons in 2010, and then reduced to 12,900 tons again for the years 2011-12 after the annual meeting was held in November 2010. The quota was slightly relaxed to 13,400 tons for the year 2013.

In Japan, the production of farmed tuna has been steadily increasing, and reached approximately 10,000 tons in 2010, which exceeds the each production of farmed SBT and ABT, and this production growth has compensated for the reduction of imports. In addition, full-cycle tuna farming technology is spreading in Japan, and accounts for nearly 10% of local farm production (Kumai (2012), pp.11), and the ratio is currently rising.

However, the production of farmed tuna is not expected to grow as rapidly as it did previously because of the limitation of appropriate farming sites in Japan. In addition, rising feed cost is another concern, because the Japanese farming technology adopts a long-term fattening process, whether it utilizes full-cycle technology or not, and it takes 2-3 years to raise wild or artificial seedlings to the 50-60 kg size suitable for sale.

Therefore, the trend of the wild PBT catch is a key factor that will determine the supply and price of bluefin tuna in the future. Most of the Japanese locally landed PBT from the West Central Pacific Ocean is caught by purse seine, longline, troll, or set net. Other major countries catching the tuna include Taiwan, USA and Mexico.

Resource evaluations for bluefin tuna in the Pacific Ocean are not yet robust. The International Science Committee (ISC) presented very different resource estimates derived by applying different methodologies such as virtual population analysis and stock synthesis (ISC (2006), ISC (2008)). In addition, the ISC (2012) presented a sharp decreasing trend in the spawning stock biomass after the 2000 year in particular.

Therefore, regulatory measures have just been introduced by the WCPFC. The annual meeting held in 2010 resulted in regulating fishing efforts for 2011-12 below the 2002-04 level, and in keeping the annual juvenile catch amount below the 2002-04 level. Before this decision by the WCPFC, the Ministry of Agriculture, Forestry and Fisheries (MAFF) of Japan decided on an action plan toward the effective conservation and management of resources (MAFF (2010) (2)). The plan includes a closure period, a catch size limit, an individual quota system for large and medium scale purse seine offshore fisheries, and the registration of vessels with a mandatory catch reporting requirements for small scale coastal fisheries. In addition, the plan was encouraged to include a catch limit for fish under and over 30kg weight respectively for offshore fisheries as announced on March 25, 2011.

3. Methodology

Fishing effort is a concept that refers to the "aggregated inputs for fishing" and includes vessels, fishing gears, number of labor days, etc. Catch per unit effort (CPUE) data are generally used for resource estimates, and those of longline fisheries are widely used to estimate tuna resources. However, CPUE data are generally collected in high-density resource areas where fisheries operate rather than in randomly sampled areas (Ishii (1996), pp.176). This was the central issue in the Australia-Japan dispute concerning the Japanese experimental fishery plans for SBT. Furthermore, standardizing of CPUE between different fishing gears such as longline and purse seine (Fisheries Research Agency (2010)(3)), and the CPUE before/after introducing catching innovations such as fish-find sonar, aerial observation and fish aggregating devices (FADs) are the additional constraints of using CPUE data.

Therefore, we estimate resources by applying the surplus production model developed by Schaefer (1954) and Clark (1985). With the model, resources can be estimated using catch data. There is an alternative method that applies a long-term supply curve that has a backward-bending portion for octopus resources in Morocco (Yagi *et al.* (2009)). This method can be applied to the fishery because the price is exogenous for Morocco as it is a small producer. However, the price is endogenous for PBT producers, and the price-quantity relation draws a demand curve rather than a supply curve(4).

Based on the surplus production model, resources at the end of each period (S_t) are represented as follows:

$$S_t = S_{t-1} + rS_{t-1}(1 - S_{t-1}/K) - Q_t \qquad \text{(Eq.1)}$$

where K is the maximum carrying capacity of the species, r is the intrinsic growth rate, Q is the catch amount, and the subscript t is the year. On the right side of (Eq.1), if the catch is equal to the second term which is growth of the resource (dS/dt), then the resource is stable as $S_t = S_{t-1}$, and the catch is termed a sustainable yield (SY). In addition, if $\mathrm{S} = K/2$, then dtS/dt is maximized, and the catch is termed a maximum sustainable yield (MSY). If the resource data are available, the parameters K and r can be estimated by applying the least squares regression method. For example, Grafton *et al.* (2000) estimated that the intrinsic growth rate was 0.3 by providing an exogenous K for Canadian cod.

For the case of PBT, however, environmental conditions as well as catch amounts are crucial for determining the resource fluctuations. This phenomenon is known as a "regime shift" and is observed for ABT as well (Ravier and Fromentin (2001)). Kawasaki (2005), pp.133-137 presented a drastic change in catch amount per fishing day for the Japanese coastal longline bluefin tuna fisheries before and after 1990. Miller (2007) presented a negative correlation between the El Niño 3 Index and the catch amount of skipjack by purse seine fisheries in the West Central Pacific Ocean, in which the author mentioned that the Pacific Decadal Oscillation (PDO) had recently been recognized as having significant impacts on marine fisheries.

PDO represents the deviation in sea surface temperatures against the warming trend, and a positive PDO indicates low sea surface temperature in the North Central Pacific Ocean with the exception of the East Pacific Ocean beside the North American Continent. There are some alternatives to PDO such as the Southern Oscillation Index (SOI), a representative indicator of the El Niño phenomenon, and the Aleutian Low Pressure Index (ALPI), which correlate each other. We selected PDO based on the statistical criteria used for estimating supply functions as shown in (Eq.3).

Regarding the further precise PDO-resource relation for tuna species, Lehodey *et al.* (2003) showed opposite recruitment patterns of tropical species such as skipjack and yellowfin and of subtropical species such as albacore against PDO index and SOI. A similar relation was found between SOI and PBT recruitment (Inagake and Uehara (2003)). In addition, Lima and Naya (2011) presented a close relation between skipjack CPUE data in the Western Pacific Ocean and SOI and PDO.

Then we modified (Eq.1) to

$$S_t = S_{t-1} - \theta * D * PDO5_t * rS_{t-1}(1 - S_{t-1}/K) - Q_t \qquad \text{(Eq.2)}$$

where the second term on the right side represents the influence of environmental change in which $PDO5$ is the 5-years moving average of the PDO index. θ is the coefficient representing the degree of influence to the resources when environmental conditions are not favorable, and D is the dummy variable that is 1 when $PDO5 > 0$ and is 0 when $PDO5 \leq 0$, indicating that existing resources decrease when the environmental conditions are unfavorable for the species(5).

Because reliable resource data are unavailable, we generated data by giving various values to θ, r and K in (Eq.2), based on the assumption that $S = K$ in 1945 because of a long fishing moratorium during the World War II[(6)]. Then, we selected the combinations of the three parameters that provide an appropriate supply function, which are specified as follows:

$$ln\,Q_t = a\,ln\,S_t + b\,ln\,P_t + c\,ln\,POIL_t + d\,T + e \quad \text{(Eq.3)}$$

where P and $POIL$ represent a series of past prices of bluefin tuna and crude oil, respectively, and T is the time trend representing technological progress to catch bluefin tuna. In the equation, a, b, c and d are coefficients to be estimated, and e is a constant term. The coefficients have constraints such as $0 < a < 1$, $b > 0$, $c < 0$ and $d > 0$. The sources of the variables are listed in Table 1.

The original specification of (Eq.3) was used by Eide *et al.* (2003) as the Cobb-Douglas function as $Q = Const.\cdot Effort^{\alpha} \cdot S^{\beta}$, which is a further flexible modification of $Q = Const.\cdot Effort \cdot S$ developed by Schaefer (1954). (Eq.3) modifies such relations by converting the quantity of inputs into price terms as used in micro economic analysis.

4. Analysis and results

4-1. Preliminary analysis

Bluefin tuna prices affected the catch amount through changes in catch efforts, and their relation is presented in Figure 2. The catch amount sharply grew during 1950-55, which was an adjustment process for fishing efforts from the period the World War II destruction to the restart of normal fishing. The catch amount was very high during 1955-65 because of the high amount of resources. A negative correlation was observed between the two variables after 1965.

Regarding the influence from the price to catch amount, about a five year' time lag was observed, implying that it takes around five years for fishermen to recognize changes in long-term price level and adjust their effort levels to the new economic profitability of bluefin tuna fisheries. However, the drastic decline in catch during the early 1980s following the price decline in the late 1970s, and the prolonged low catch level that continued into the early 1990s may have been too extreme compared with the decline in catch amount around 1970 against the very low price level around 1965.

Next, we compared the catch amount with environmental conditions represented by PDO as shown in Figure 3. The drastic decline in the catch amount in the 1980s was

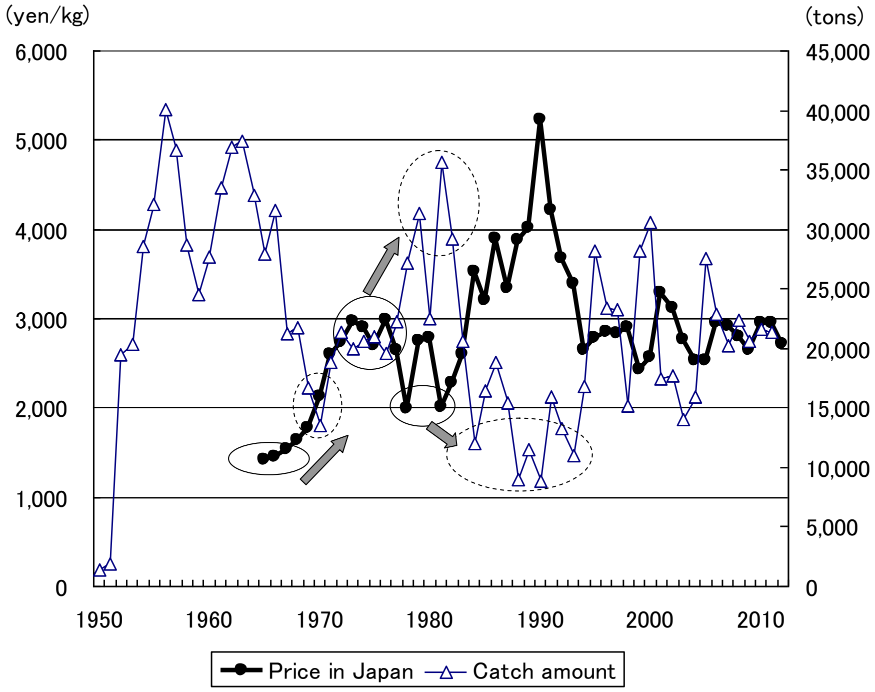


Figure 2 Price of Pacific bluefin tuna in Japan and the catch amount

Sources:

1) Catch amount, "Fish Stat", FAO.

2) Price, Same as Figure 1. Price is deflated by consumer price index (2010 year base). The Tokyo price is discounted by 13% to adjust the price difference between average in Japan (1965-2006) and that in Tokyo (2004-2012), and is connected to the average wholesale prices(7).

negatively correlated with the PDO index, whereas the correlation was unclear in other periods.

4-2. Estimate of supply function

(Eq.3) was estimated by the ordinary least squares regression for 1971-2011. FAO Fishstat data, which is available for long-term periods after 1950 and is almost identical to the WCPFC data, was used for catch amount (Q).

We employed the average of the 4-6 year lagged price of bluefin tuna; i.e. $((P_{t-4}+P_{t-5}+P_{t-6})/3)$ deflated by the Japanese consumer price index for the price (P). This was based on the preliminary analysis shown above and a trial and error process to estimate (Eq.3), implying that it takes 4-6 years to adjust fishing efforts such as vessels and labor to price changes. In addition, we could not obtain a negative sign for

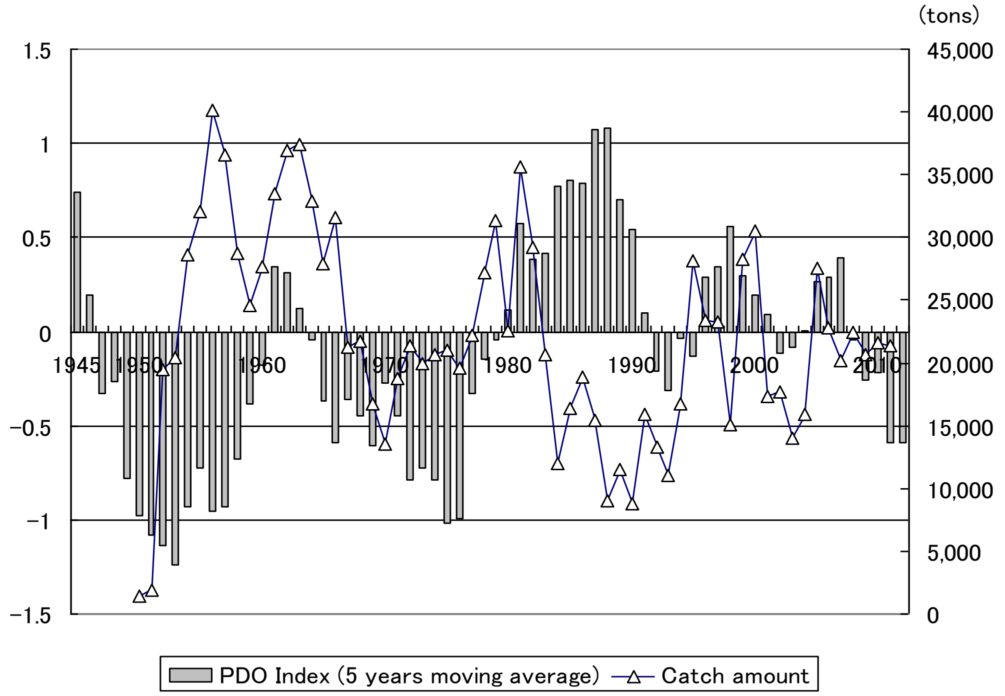


Figure 3 Pacific Decadal Oscillation index and the catch amount of Pacific bluefin tuna

Sources:

1) PDO Index: Japan Meteorological Agency.

2) Catch amount: "Fish Stat", FAO.

the coefficient c. This is because changes in the crude oil price can be applied across all types of fisheries, not only those dedicated to PBT. Therefore, the oil price variable ($POIL$) was eliminated from (Eq.3) for the estimate.

Regarding the resource variable (S), we prepared various values for parameters θ, r and K in (Eq.2), and calculated S that should have taken place for the period of 1950-2011, under each combination of the three parameters. Here, the catch data for 1945-49 were considered as zero because the catch amount in 1950 was very small(6). After that, appropriate combinations of the three parameters that satisfied the conditions $0 < a < 1$, $b > 0$ and $d > 0$ in (Eq.3) were selected.

4-3. Results

The summary of the estimated results is presented in Figure 4, and the estimated parameters for each equation are listed in Table 1. In the figure and the table, the upper limit of K is set to 2 million tons, as the estimated supply functions with $K > 2$ million tons presented almost identical determinant coefficients and parameters. This is because the catch amount was very small compared with the resources, and the

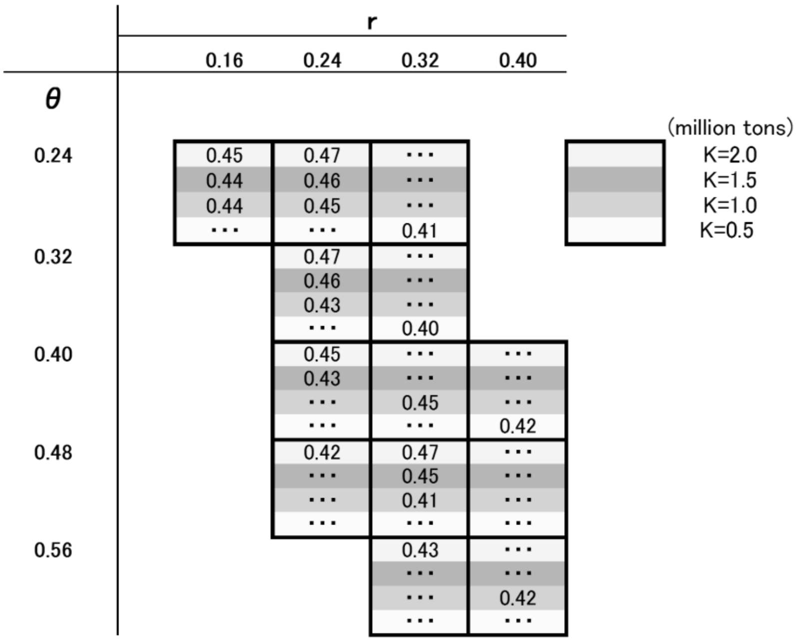


Figure 4 Appropriate combinations of parameters in surplus production model (Eq.2)

Notes:

1) Value in each cell is a determinant coefficient of estimated supply function (Eq.3).

2) θ: influence of PDO to the stock, r: intrinsic growth rate, K: maximum carrying capacity

influence of the catch to resources is very limited when $K > 2$ million tons.

As shown in Figure 4, the possibility that $K \leq 0.5$ million tons was very small. The ranges of θ and r were $0.24 < \theta < 0.56$ and $0.16 < r < 0.40$. respectively. The left upper area of the θ-r matrix was probable due to the high density of cells that can satisfy the (Eq.3) parameter conditions.

In addition, the cells with $\theta = 0$ or $r = 0$ could not provide a satisfactory supply function. The estimates of $\theta < 0.16$ or $r < 0.08$ provided unsatisfactory signs for the elasticity of resources; i.e. $a > 1$ or $a < 0$ in (Eq.3), Otherwise the estimated resources presented were fully depleted. These estimates are presented in the Appendix. These results indicate that both environmental factors and fishing activities are crucial in determining resource changes.

The estimated parameters, a, b and d in (Eq.3) were widely distributed as shown in Table 1. The production elasticity of resources (a) ranged from 0.31 to 0.95, and this was consistent with a harvest function study of the Norwegian cod fisheries that estimated an elasticity of 0.424 (Eide *et al.* (2003)). The price elasticity of supply (b)

Table 1 Estimated parameters of supply function (Eq.3)

$ln\, Q_t = a\, ln\, S_t + b\, ln\, P_t + c\, ln\, POIL_t + d\, T + e$ (Estimated period: 1971-2011)

K	θ	r	a (t-value)	b (t-value)	d (t-value)	R^2	DW
0.5	0.24	0.32	0.838 (5.0)	0.291 (1.4)	0.002 (0.5)	0.41	1.5
0.5	0.32	0.32	0.617 (4.9)	0.294 (1.4)	0.014 (2.9)	0.40	1.5
0.5	0.40	0.40	0.490 (5.1)	0.418 (1.9)	0.001 (0.4)	0.42	1.5
1.0	0.24	0.16	0.951 (5.3)	0.130 (0.7)	0.043 (4.8)	0.44	1.6
1.0	0.24	0.24	0.821 (5.4)	0.380 (1.8)	0.003 (0.8)	0.45	1.6
1.0	0.32	0.24	0.573 (5.2)	0.407 (1.9)	0.009 (2.1)	0.43	1.5
1.0	0.40	0.32	0.489 (5.5)	0.447 (2.1)	0.001 (0.3)	0.45	1.6
1.0	0.48	0.32	0.404 (5.0)	0.346 (1.6)	0.018 (3.4)	0.41	1.5
1.0	0.56	0.40	0.328 (5.1)	0.497 (2.2)	0.002 (0.5)	0.42	1.5
1.5	0.24	0.16	0.757 (5.3)	0.379 (1.8)	0.014 (3.0)	0.44	1.5
1.5	0.24	0.24	0.848 (5.6)	0.374 (1.8)	0.001 (0.4)	0.46	1.6
1.5	0.32	0.24	0.594 (5.5)	0.437 (2.1)	0.004 (0.9)	0.46	1.6
1.5	0.40	0.24	0.442 (5.2)	0.426 (1.9)	0.010 (2.4)	0.43	1.5
1.5	0.48	0.32	0.391 (5.5)	0.487 (2.2)	0.002 (0.4)	0.45	1.6
2.0	0.24	0.16	0.756 (5.4)	0.412 (1.9)	0.010 (2.4)	0.45	1.5
2.0	0.24	0.24	0.861 (5.6)	0.369 (1.8)	0.001 (0.2)	0.47	1.6
2.0	0.32	0.24	0.606 (5.6)	0.436 (2.1)	0.002 (0.6)	0.47	1.6
2.0	0.40	0.24	0.449 (5.4)	0.462 (2.1)	0.006 (1.5)	0.45	1.6
2.0	0.48	0.24	0.397 (5.1)	0.331 (1.6)	0.024 (4.0)	0.42	1.5
2.0	0.48	0.32	0.405 (5.6)	0.479 (2.2)	0.000 (0.0)	0.47	1.6
2.0	0.56	0.32	0.310 (5.2)	0.485 (2.2)	0.005 (1.4)	0.43	1.5

Note: Coefficient c was eliminated from the equation due to the positive sign of the estimated value.

Sources:

1) Q: "Fish Stat," FAO (ref. Figure 2 and Figure 3).

2) S: Generated by (Eq.2).

3) P: "Statistics of Fisheries Distribution (1965-2006)," Fishery Agency, and "Statistics of Tokyo Central Wholesale Markets (2004-2011)," Tokyo Metropolitan Central Wholesale Market (ref. Fig. 1 and Fig. 2).

4) POIL: Toyokeizai Data Bank, Original Source: "Trade Statistics," MOF.

5) T: Time trend, 1950 year=1, 2011 year=62.

ranged from 0.13 to 0.50, and the technological progress rate (d) ranged from 0.0% to 4.3% per year.

Then, we compared the estimated parameters for PBT with those for ABT (Tada *et al* . (2011)) and SBT (Tada (2012)). The estimated K values were not much different across the species. The probable K ranged 1.1-1.5 and 1.6-2.2 million tons for ABT and SBT, respectively. However, the estimated r value for PBT was 0.16-0.40. This value was much higher than that for ABT and SBT, which were 0.03-0.06 and 0.015-0.04, respectively. This difference in r is considered to be caused by the functional difference in the surplus production model. The model used in this study includes a regime shift factor, while others did not. Therefore, PBT resources in this model sharply decreased when environmental conditions were unfavorable for the species.

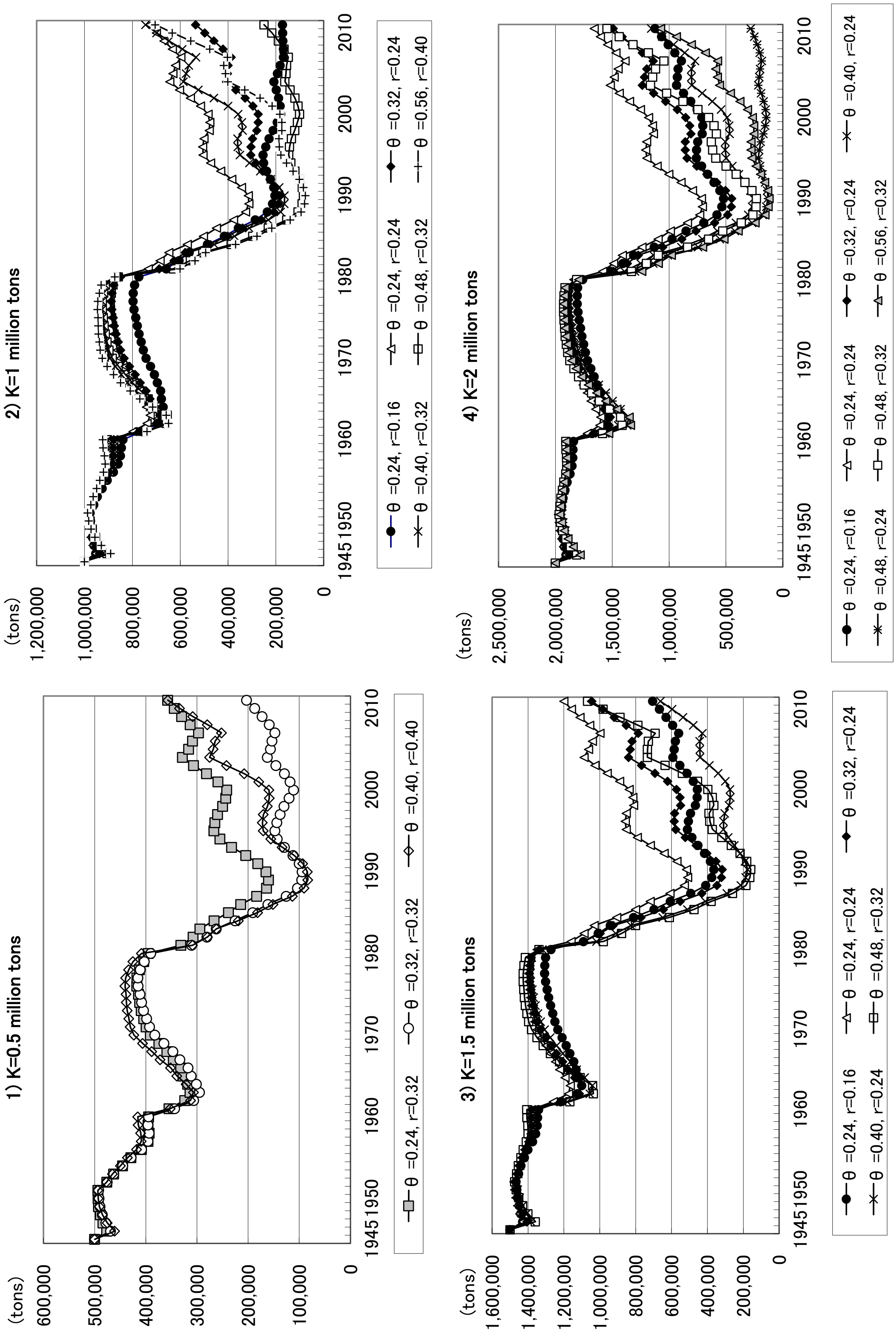


Figure 5 Estimated resource trends

The r value in this study was higher than those of other species to recover from depletion under favorable environmental conditions. This result indicates that r value depends on the model specification.

Finally, the resource trends were calculated based on the parameters K, θ and r, and the result is presented in Figure 5. As known in the figure, some recent estimates resource levels were over MSY, which is equal to $K/2$, and some were below MSY, indicating that the ranges of the three parameters were not narrow enough to see clear resource trends.

5. Conclusion

We developed a methodology to estimate fishery resource movement using catch data. The model is a combination of the surplus production model, which has an environmental factor term in addition to the original specification, and the supply function that explains catch amount with respect to resources and other variables such as tuna price and time trend. This methodology is applicable to open access fisheries, in which the bluefin tuna fishery in the Pacific Ocean has been the typical one. It has an advantage in being able to provide information needed to discuss resource trends with catch data that is more accessible than CPUE data.

Our results indicate that both environmental factors, represented by PDO, and fishing activity are crucial in determining resource changes. However, the appropriate combinations of the coefficient of PDO (θ), intrinsic growth rate (r) and carrying capacity (K) were widely distributed, and so it was difficult to specify them by statistical criteria. Therefore, the estimated trends in bluefin tuna resources based on such parameters were also widely distributed, as some were over MSY and others were below it for the latest decade.

As this methodology can be applied to various types of open access fisheries for which reliable resource data and fishing efforts data are unavailable, a further refined simultaneous estimation procedure using the surplus production model and supply function are needed so that more parameters can be used in the surplus production model (Eq.1) and more environmental variables representing regime shifts can be used in the modified surplus production model (Eq.2).

Notes

(1) The latest spawning stock biomass reports are presented in ICCAT (2012) and CCSBT

(2011).

(2) MAFF (2010) "Announcement by the Ministry of Agriculture, Forestry and Fisheries on Actions toward Effective Conservation and Management for Pacific Bluefin Tuna," May 11. http://www.jfa.maff.go.jp/j/kokusai/kanri_kyouka/index2.html

(3) Fisheries Research Agency [FRA] (2010) "Fluctuations and Evaluations of Fisheries Resources (gyogyoshigen no hendo to shigenhyouka nitsuite)," Status of international fisheries resources (heisei 22 nendo kokusai gyogyoushigen no genkyo) (in Japanese). http://kokushi.job.affrc.go.jp/H22/H22_02.pdf

(4) Regarding the case of Atlantic bluefin tuna and Southern bluefin tuna, for which the catch quota was applied and there are strong evidences of resource depletion, Tada *et al*. (2011) and Tada (2012) applied the surplus production model (Eq.1) to estimate resource trends. The parameters r and K that satisfied $0 < S < K/2$ for the latest period were selected for the estimates.

(5) Instead of the specification (Eq.2), we applied alternative specifications such as $r = r_0 + \theta * PDO5_t$ or $K = K_0 + \theta * PDO5_t$ in (Eq.1), in which r_0 or K_0 is a constant. However, the estimated resource trends based on the specifications could not trace the drastic decline in the catch that occurred in the early 1980s.

(6) The Japanese catch of bluefin tuna was very limited during the World War II (Okamoto (2004), p.19 and p.24). In addition, the bluefin tuna catch in the early 1950s by countries other than Japan was limited. We applied an alternative assumption of $S = 0.8K$ in 1945, and estimated the resource trends. Using this assumption, it took 8-13 years for the estimated resource trends to catch up with the trend using the assumption of $S = K$ in 1945.

(7) As shown in Figure 1, the average wholesale price data terminated in 2006. Therefore, we connected it to the Tokyo wholesale price data as indicated in Figure 2.

References

[1] CCSBT (2011) *Report of the Sixteenth Meeting of the Scientific Committee*, Indonesia, Bali, July 19-28.

[2] Clark C. (1985) *Bioeconomic Modeling and Fisheries Management*, John Wiley & Sons, Inc.

[3] Eide A., Skjold F., Olsen F. and Flaaten O. (2003) "Harvest Functions: The Norwegian Bottom Trawl Cod Fisheries," *Marine Resource Economics,* 18, 81-93.

[4] Grafton R.Q., Sandal L.K. and Steinshamn S.I. (2000) "How to Improve the Management of Renewal Resources: The Case of Canada's Northern Cod Fishery,"

American Journal of Agricultural Economics, 82, 570-580.

[5] ICCAT (2009) *Report of the Standing Committee on Research and Statistics*, Madrid, Spain, October 5-9.

[6] ICCAT (2012) *Report of the 2012 Atlantic Bluefin Tuna Stock Assessment Session*, Madrid, Spain, September 4-11.

[7] Inagake D. and Uehara K. (2003) "Resource Fluctuations of Tuna Resources and Atmosphere/Ocean Fluctuations (magurorui no shigenhendou to taiki/kaiyouhendou)," *Monthly Kaiyo*, 35, 180-195 (in Japanese).

[8] ISC (2006) *Report of the Sixth Meeting of the International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean*. Plenary Session, La Jolla, California USA. March 23-27.

[9] ISC (2008) *Report of the Pacific Bluefin Tuna Working Group Workshop*, *International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean,* Shimizu, Japan. May 28-June 4.

[10] ISC (2012) *Report of the Twelfth Meeting of the International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean. Plenary Session*, Sapporo, Japan, July 18-23.

[11] Ishii T. (1988) "Index of Resource Quantity (shigenryoshisuu)," in Nose *et al. Marine resources (suisan shigengaku),* Tokyodaigakushuppannkai, 173-184 (in Japanese).

[12] Kawasaki T (2005) *Fishery Resources: Why We Cannot Control? (gyogyoshigen-naze kanri dekinainoka)*, Seizandoshoten, (in Japanese).

[13] Komatsu M. and Endo H. (2002) *International Tuna Trial (kokusai maguro saiban)*, Iwanami (in Japanese).

[14] Kumai H. (2012) "History, Current Status and Perspective of Bluefin Tuna Aquaculture," in Kumai H., Miyashita S., Sakamoto W. and Ono S. *Full-life Cycle Aquaculture of the Pacific Bluefin Tuna.* Agriculture and Forestry Statistics Publishing Inc.

[15] Lehodey P., Chai F. and Hampton J. (2003) "Modeling Climate-Related Variability of Tuna Populations from a Coupled Ocean-Biogeochemical-Populations Dynamics Model," *Fisheries Oceanography*, 12, 483-494.

[16] Lima M. and Naya D. (2011) "Large-Scale Climate Variability Affects the Dynamics of Tropical Skipjack Tuna in the Western Pacific Ocean," *Ecography*, 34, 597-605.

[17] Miller K. (2007) "Climate Variability and Tropical Tuna: Management Challenges for Highly Migratory Stocks," *Marine Policy,* 31, 56-70.

[18] Miyake M., Guillotreau P., Sun C. and Ishimura G. (2010) "Recent Development in the

Tuna Industry,"*FAO Fisheries and Aquaculture Technical Paper,* 543.

[19] Okamoto H. (2004) "Search for the Japanese Tuna Fishing Data before and just after World War II," *Bulletin of Fisheries Research Agency*, 13, 15-34 (in Japanese).

[20] Ono S. (2012) "The Current State of the Bluefin Tuna Aquaculture Industry, Including Challenges and Prospects, " in Kumai *et al. Full-Life Cycle Aquaculture of the Pacific Bluefin Tuna,* Agriculture and Forestry Statistics Publishing Inc., 123-133.

[21] Pintassilgo P. and Duarte C. (2001) "The New-member Problem in the Cooperative Management of High Seas Fisheries," *Marine Resource Economics*, 15, 361-378.

[22] Polacheck T. (2002) "Experimental Catches and the Precautionary Approach: The Southern Bluefin Tuna Dispute," *Marine Policy,* 26, 283-294.

[23] Ravier C. and Fromentin J.M. (2001) "Long-term Fluctuations in the Eastern Atlantic and Mediterranean Bluefin Tuna Population," *ICES Journal of Marine Science,* 58, 1299-1317.

[24] Schaefer M.B. (1954) "Some Aspects of the Dynamics of Populations Important to the Management of the Commercial Fisheries," *Bulletin of the Inter-American Tropical Tuna Commissions*, 1, 27-56.

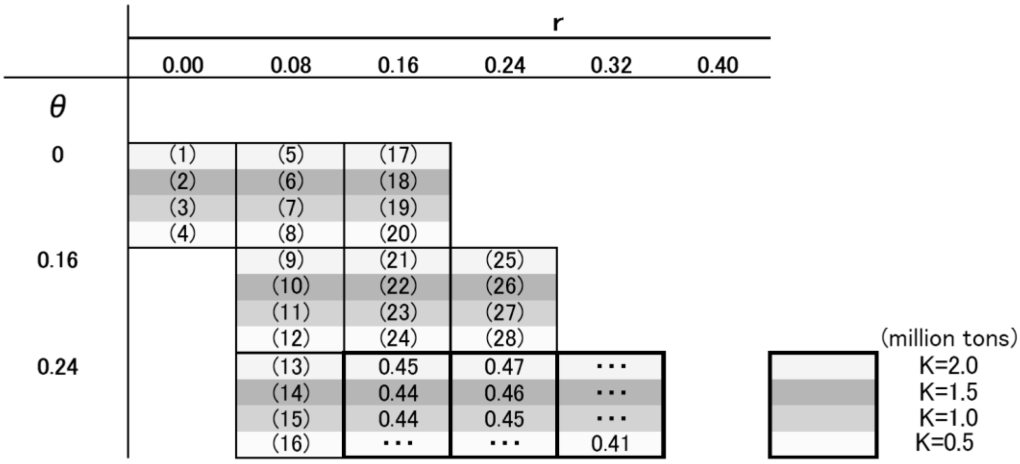
[25] Tada M., Matsui T. and Harada S. (2011) "Trends of Atlantic Bluefin Tuna Catches, Resources and the Prices," *Journal of International Fisheries*, 9, 1-12 (in Japanese).

[26] Tada M. (2012) "Resource Constraints in the Development of the Australian Southern Bluefin Tuna Industry," *Journal of Australian Studies*, 25, 45-55.

[27] Yagi N., Ariji M., Takahara A. and Senda Y. (2009) "Application of a Bioeconomics Model to Examine Sustainability of Fishery Resources in the Global Market: The Case of Octopus Resource in Morocco," *Fisheries Science*, 75, 43-46.

Appendix

Estimated results of (Eq.3) under the condition of $\theta < 0.24$ or $r < 0.16$



Estimated a, b and d of (Eq.3) under the conditions of each cell (1)−(28) above.

$$ln\,Q_t = a\,ln\,S_t + b\,ln\,P_t + c\,ln\,PDOL_t + d\,T + e \quad (0 < a < 1,\ b > 0,\ c < 0,\ d > 0)$$

	K	θ	r	a (t−value)	b (t−value)	d (t−value)	R^2	DW
(1)	2.0	0	0	−8.490 (−2.8)	0.640 (1.8)	−0.170 (−2.8)	0.19	1.0
(2)	1.5	0	0	−1.826 (−2.5)	0.514 (1.5)	−0.080 (−2.5)	0.16	1.0
(3)	1.0	0	0		Resource depletion			
(4)	0.5	0	0		Resource depletion			
(5)	2.0	0	0.08	−9.946 (−1.8)	0.023 (0.1)	0.001 (0.2)	0.09	0.9
(6)	1.5	0	0.08	−5.523 (−1.4)	−0.025 (−0.1)	−0.000 (−0.1)	0.07	0.8
(7)	1.0	0	0.08	−1.561 (−0.8)	−0.089 (−0.3)	−0.003 (−0.5)	0.03	0.9
(8)	0.5	0	0.08		Resource depletion			
(9)	2.0	0.16	0.08	1.274 (5.1)	0.213 (1.0)	0.041 (4.4)	0.43	1.5
(10)	1.5	0.16	0.08	1.473 (4.9)	−0.036 (−0.2)	0.068 (4.6)	0.41	1.5
(11)	1.0	0.16	0.08		Resource depletion			
(12)	0.5	0.16	0.08		Resource depletion			
(13)	2.0	0.24	0.08	0.402 (2.2)	−0.358 (−1.4)	0.041 (2.2)	0.12	1.0
(14)	1.5	0.24	0.08		Resource depletion			
(15)	1.0	0.24	0.08		Resource depletion			
(16)	0.5	0.24	0.08		Resource depletion			
(17)	2.0	0	0.16	−28.57 (−4.7)	0.504 (2.1)	0.005 (1.1)	0.40	1.1
(18)	1.5	0	0.16	−20.16 (−4.6)	0.495 (2.0)	0.006 (1.2)	0.38	1.0
(19)	1.0	0	0.16	−11.43 (−4.1)	0.451 (1.7)	0.008 (1.5)	0.33	1.0
(20)	0.5	0	0.16	−0.286 (−0.4)	−0.104 (−0.4)	−0.000 (−0.0)	0.01	0.9
(21)	2.0	0.16	0.16	1.248 (5.5)	0.376 (1.8)	0.008 (1.7)	0.47	1.6
(22)	1.5	0.16	0.16	1.242 (5.4)	0.363 (1.7)	0.010 (2.0)	0.46	1.6
(23)	1.0	0.16	0.16	1.248 (5.2)	0.311 (1.5)	0.016 (2.9)	0.44	1.6
(24)	0.5	0.16	0.16		Resource depletion			
(25)	2.0	0.16	0.24	1.373 (5.3)	0.273 (1.3)	0.001 (0.3)	0.45	1.6
(26)	1.5	0.16	0.24	1.358 (5.2)	0.273 (1.3)	0.001 (0.3)	0.44	1.5
(27)	1.0	0.16	0.24	1.324 (5.1)	0.273 (1.3)	0.002 (0.5)	0.43	1.5
(28)	0.5	0.16	0.24	1.262 (4.7)	0.182 (0.8)	0.012 (2.2)	0.39	1.5