



On a Catch-Forecasting Model for the Pink Salmon *Oncorhynchus gorbuscha* in the Maritime Province of Siberia

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How to cite this paper: Hasegawa, S., Suzuki, N. and Sakuramoto, K. (2017) On a Catch-Forecasting Model for the Pink Salmon *Oncorhynchus gorbuscha* in the Maritime Province of Siberia. *Open Access Library Journal*, 4: e3406.

<https://doi.org/10.4236/oalib.1103406>

Received: January 25, 2017

Accepted: March 11, 2017

Published: March 14, 2017

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Abstract

The aim of this paper is to elucidate the fluctuation mechanism in the catch of pink salmon *Oncorhynchus gorbuscha* harvested in the Maritime Province of Siberia. We used catch data on pink salmon born in odd- and even-numbered years. Monthly indices of the Arctic Oscillation and the Pacific Decadal Oscillation were used as the environmental factors. We assumed that the catch in year t , C_t and that in year $t + 2$, C_{t+2} , could be used to represent the spawning stock biomass and recruitment, respectively, and C_{t+2}/C_t could then be used to represent the recruitment per spawning stock biomass. Under these assumptions, we adopted the equation $C_{t+2}/C_t = g$ (environmental factors) as the model that forecasted the trajectories of the catch. The results were as follows: 1) the trajectories of the catches of pink salmon born in odd- and even-numbered years can be well reproduced by the model mentioned above. No density-dependent effect was detected in the relationship between C_{t+2} and C_t which corresponds to the stock-recruitment relationship (SRR), for catches in both odd- and even-numbered years. The relationship between C_{t+2} and C_t for odd-numbered years showed a clockwise loop; however, that for even-numbered years showed an anticlockwise loop. It is believed that this difference occurs in response to the negative relationship between the catches born in odd- and even-numbered years. Pink salmon is one of the typical fish species to which a density-dependent SRR can be applied; however, this study indicates that the assumption of a density-dependent SRR is not valid.

Subject Areas

Marine Biology

Keywords

Density-Dependent Effect, Maritime Province of Siberia, *Oncorhynchus gorbuscha*, Pink Salmon, Stock-Recruitment Relationship

1. Introduction

One of the most important tasks in fisheries resource management is to elucidate the fluctuation mechanism in fish populations. One of the key factors in those mechanisms is the stock-recruitment relationship (SRR). The typical traditional SRR models are the well-known Ricker model [1] and the Beverton and Holt model [2], which is based on a density-dependent mechanism in SRR. Ricker developed his SRR model to investigate the fluctuation in Salmonidae species [1]. Pink salmon is a typical Salmonidae species; therefore, almost all scientists believe that the SRR of pink salmon follows the Ricker model. Recently, however, the importance of environmental factors has been reported in many studies. For instance, Zhenming *et al.* [3] noted the presence of significant positive effects of the sea-surface temperature (SST) on the survival rates of northern pink salmon stocks, but weak negative effects of SST on the survival rates of southern pink salmon stocks. Kaeriyama *et al.* [4] noted that the carrying capacity of pink salmon was synchronous with long-term trends in climate change. Alan and Gus [5] noted that the wild salmon population in the North Pacific Ocean, particularly pink salmon, had grown greatly since the mid-1970s, apparently due to the bottom-up effects of climate change on ocean physics and production processes. However, it is widely believed among scientists in this field that a density-dependent effect is also an important factor in controlling the population [6] [7].

Recently, however, Sakuramoto proposed a new concept of the mechanism of the SRR which did not assume any density-dependent effect [8] [9] [10] [11] [12]. The purpose of the present study is to elucidate whether or not the density-dependent effect is essential to explain the population fluctuation of pink salmon and to propose a new model that can reproduce the population fluctuation of pink salmon.

2. Materials and Methods

2.1. Data

The data used in this study are shown below: 1) catch in weight for pink salmon landed in the Maritime Province of Siberia from 1950 to 2010 [13]; 2) indices of the Arctic Oscillation (AO) by month from 1948 to 2010 [14]; and 3) indices of the Pacific Decadal Oscillation (PDO) by month from 1948 to 2010 [15].

2.2. Correlation Coefficient between Catch and AO or Catch and PDO

We separated the pink salmon catch data into two groups. One is the catch har-

vested in the odd-numbered year t , which is denoted with C_t^O , and another is that harvested in the even-numbered year t , which is denoted with C_t^E . We calculated the correlation coefficients between C_t^O and AO and between C_t^O and PDO in month m ($m = 1, 2, \dots$, and 12) of year $t - k$ ($k = 0, 1$ and 2), and that between C_t^E and AO and between C_t^E and PDO in month m ($m = 1, 2, \dots$, and 12) of year $t - k$ ($k = 0, 1$ and 2).

2.3. Relationship between C_{t+2} and C_t

The eggs of pink salmon are spawned from September to November in year t and they hatch from February to March in year $t + 1$. The fries swim downstream to the ocean from April to May in year $t + 1$ (Figure 1). They stay in the ocean for about one year, and then they go back to the coastal waters and go upstream in their native rivers from July to August in year $t + 2$. Then, they lay their eggs on the bottom of the rivers and die. To summarize the life circle, the spawning stock biomass (SSB) in year t reproduces the SSB of their next generation in year $t + 2$. That is, there is a two-year difference between the two generations.

Year	Month	Pink salmon born in odd year		Month	Pink salmon born in even year		
t		Catch	R and SSB		Catch	R and SSB	
1950	1			1			
	2			2			
	3			3			
	4			4			
	5			5			
	6			6			
	7			7			
	8			8			
	9			9	C_{t-1}	Going upstream	
	10			10		SSB of j -th generation	
	11			11			
		12			12		
1951	1			1			
	2			2		Hutch	
	3			3			
	4			4		Going downstream	
	5			5			
	6			6			
	7			7			
	8			8			
	9			9			
	10			10			
	11	C_t	Going upstream	SSB of k generation	11		
	12		Spawning		12		
1952	1			1			
	2			2			
	3			3			
	4			4			
	5			5			
	6			6			
	7			7			
	8			8			
	9			9	C_{t+1}	Going upstream	R of j -th generation =
	10			10		SSB of $j+1$ -th generation	
	11			11			
		12			12		
1953	1			1			
	2			2		Hutch	
	3			3			
	4			4		Going downstream	
	5			5			
	6			6			
	7			7			
	8			8			
	9			9			
	10			10			
	11	C_{t+2}	Going upstream	R of k -th generation =	11		
	12		Spawning	SSB of $k+1$ -th generation	12		

Figure 1. Life histories of pink salmon born in odd- and even-numbered years.

The abundance of pink salmon in the maritime Province of Siberia has not been estimated, and so we cannot use abundance data directly. However, when the abundance is high, the catches in the coastal waters and in rivers would also be high. Further, when the catches in the coastal waters and in rivers are high, the SSB that has escaped the harvest in the coastal waters and rivers would also be high. Therefore, we can assume that the SSB in year t (SSB_t) is proportional to the catch in year t (C_t). In this study, we assume that C_t is proportional to SSB_t and the catch in year $t + 2$ (C_{t+2}), is proportional to the recruitment in year $t + 2$, (R_{t+2}), which is reproduced by SSB_t . Therefore, in this study, we assume $SSB_t \propto C_t$ and $R_{t+2} \propto C_{t+2}$ and we analyze the relationship between C_{t+2} and C_t as the SRR, which is the relationship between R_{t+2} and SSB_t .

This study used three regression methods in plotting $\ln(C_{t+2})$ against $\ln(C_t)$, *i.e.*, simple regression analysis, Deming regression analysis [16], and Passing and Bablok regression analysis [17]. A simple regression analysis is problematic because it assumes that the independent variable contains no observation errors. Therefore, parameters estimated using a simple regression analysis usually have serious biases [18] [19] [20] [21] [22]. When both independent and dependent variables contain observational errors, the Deming and Passing and Bablok regression analyses can effectively remove the bias inherent in the results of a simple regression analysis. The programs developed by Aoki [23] [24] were used when the Deming and Passing and Bablok regression analyses were applied to the data.

2.4. Relationship between Catches in Odd- and Even-Numbered Years

Pink salmon born in odd- and even-numbered years are completely separated genetically, because the years when they born are completely separated. Therefore, there may be some competitive relationship between these two stocks in the same way that different species that inhabit the same area sometimes engage in competition. In order to confirm this possibility, we investigated the relationship in the case when $\ln(C_{t+1}^E)$ was plotted against $\ln(C_t^O)$, because there might be a possibility that the fries born in the even-numbered year $t + 1$ are eaten by one-year-old fish born in the odd-numbered year t . The opposite relationship was also checked. That is, $\ln(C_t^O)$ was plotted against $\ln(C_{t-1}^E)$.

2.5. Forecasting Models for Catch Ratio and Catch

According to Sakuramoto [9] [11] [12], we tested the following model, which reproduces the trajectories of the catch ratio,

$$C_{t+2}/C_t = g(x_1, x_2, \dots, x_n) \quad (1)$$

where x_1, x_2, \dots, x_n denote the environmental factors that control C_{t+2}/C_t which corresponds to the R per SSB (RPS). In this model, n denotes the number of environmental factors and $g(\bullet)$ denotes the function that determines how environmental factors affect the ratio C_{t+2}/C_t . We applied stepwise regression analysis using R software, “stepwlm”, to select the optimal model shown in Equation

(1). Using the estimated values of C_{t+2}/C_t we calculated C_{t+2} using the following equation;

$$C_{t+2} = \exp\left[\left\{\ln\left(C_{t+2}/C_t\right)\right\}_{\text{estimated}}\right] \{C_t\}_{\text{observed}} \quad (2)$$

3. Results

3.1. Correlation Coefficient between Catch and AO or Catch and PDO

We calculated the correlation coefficients between C_t^O and AO and between C_t^O and PDO in month m of year $t - k$ ($k = 0, 1$ and 2), and those between C_t^E and AO and C_t^E and PDO in month m of year $t - k$ ($k = 0, 1$ and 2). The AOs and PDOs that showed high correlation coefficients with p -values less than 0.10 are shown in **Table 1**. We used these AOs and PDOs as the candidates for the environmental factors in Equation (1).

3.2. Relationship between C_{t+2} and C_t

Figure 2 shows the relationship between $\ln(C_{t+2}^O)$ and $\ln(C_t^O)$, which corresponds to the relationship between $\ln(R_{t+2})$ against $\ln(SSB_t)$ for odd-numbered years. The parameters of regression lines estimated by the simple, Deming and

Table 1. AO or PDO by month showing correlation coefficients with p -values less than 0.10. The notations ai and pi denote the indices of AO and PDO by month i, respectively. The mark * indicates the variables selected as the environmental factors in Equation (1).

Odd numbered years						
		AO		PDO		
	Variable	r	p -value	Variable	r	p -value
t	a_4^*	0.429	0.020	-	-	
	a_{11}^*	-0.322	0.089			
$t - 1$	a_9	0.327	0.083	-	-	
$t - 2$	a_2^*	-0.410	0.027	p_{11}	-0.324	0.087
	a_5^*	0.408	0.028			
	a_{10}	0.370	0.048			
Even-numbered years						
		AO		PDO		
	Variable	r	p -value	Variable	r	p -value
t	a_4	-0.315	0.096	p_1^*	-0.334	0.076
	a_9	-0.329	0.081			
$t - 1$	a_4	0.513	0.004	-	-	
	a_{12}	0.351	0.062			
$t - 2$	a_2^*	-0.410	0.027	p_{11}^*	-0.324	0.087
	a_5^*	0.408	0.028			
	a_{10}	0.370	0.048			

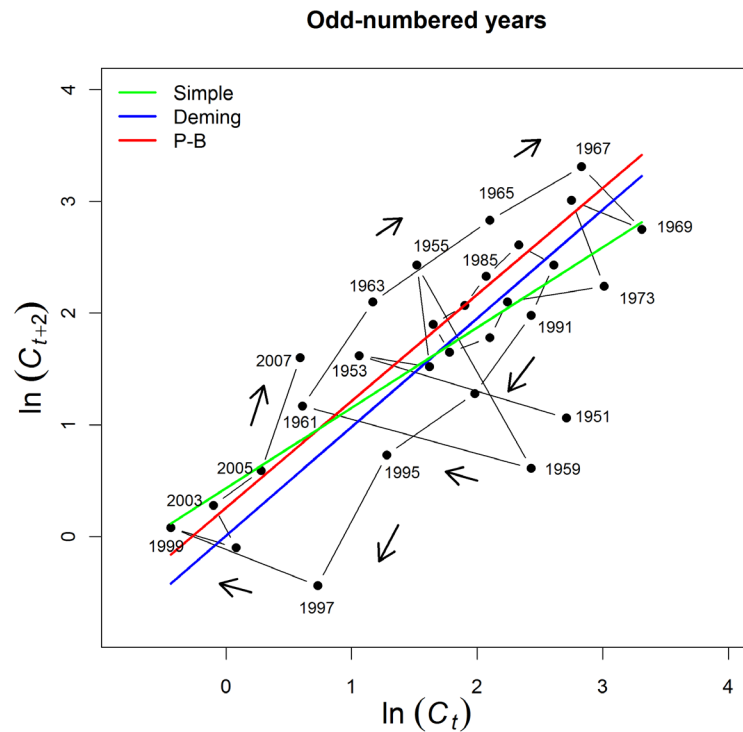


Figure 2. Stock-recruitment relationship for odd-numbered years. We assumed that $SSB_t \propto C_t$ and $R_{t+2} \propto C_{t+2}$, and we analyzed the relationship between C_{t+2} and C_t as the SRR. Three regression methods, the simple, Deming and Passing-Bablok methods, were applied. The figures show the year harvested. A clear clockwise loop is recognized.

Passing-Bablok regression methods are shown in **Table 2**. The 95% confidence intervals of the slope determined by the simple, Deming and Passing-Bablok regression methods were (0.204, 0.852), (0.689, 1.208) and (0.733, 1.470), respectively. That is, the slope estimated by the simple regression analysis was statistically less than unity, and it was judged that a density-dependent effect was detected. However, in the results obtained using the Deming and Passing-Bablok regression methods, neither slope was statistically different from unity, and it was judged that a density-dependent effect was not detected. In **Figure 2**, a clear clockwise loop appeared, a phenomenon that can be explained by the logic proposed by Sakuramoto [8] [10] [11]. That is, the age at maturity is 2 years old, and it is considered that the cycle of environmental condition is much longer than this age at maturity.

Figure 3 shows the relationship between $\ln(C_{t+2}^E)$ and $\ln(C_t^E)$, *i.e.*, the relationship between $\ln(R_{t+2})$ against $\ln(SSB_t)$ for even-numbered years. The parameters of the regression line estimated by the simple, Deming and Passing-Bablok regression methods are shown in **Table 2**. The 95% confidence intervals of the slope determined by the simple, Deming and Passing-Bablok regression methods were (0.164, 0.876), (0.578, 1.592) and (0.430, 1.571), respectively. That is, the slope estimated by simple regression analysis was statistically less than unity, and it was judged that a density-dependent effect was detected. However, in the results obtained by the Deming and Passing-Bablok regression methods,

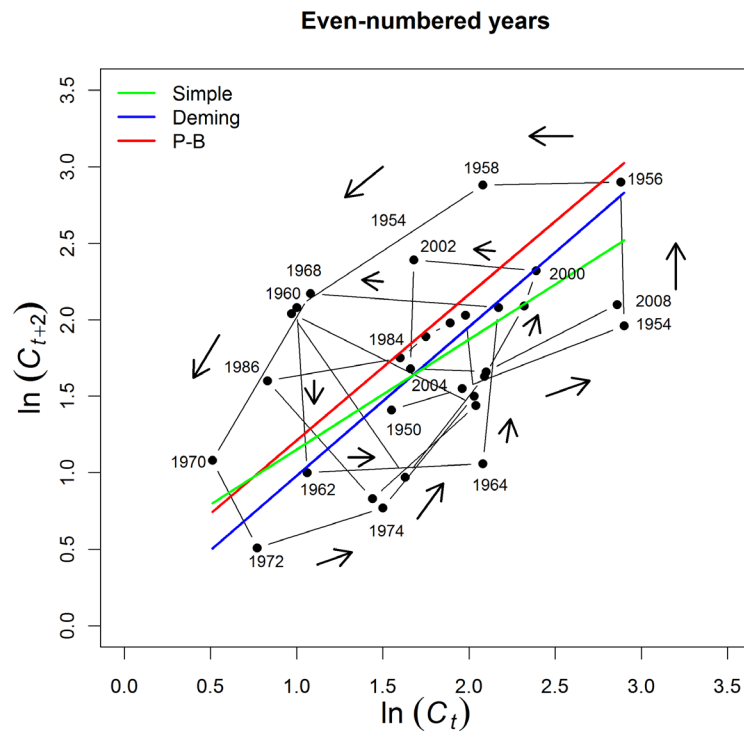


Figure 3. Stock-recruitment relationship for even-numbered years. We assumed that $SSB_t \propto C_t$ and $R_{t+2} \propto C_{t+2}$, and we analyzed the relationship between C_{t+2} and C_t as the SRR. Three regression methods, the simple, Deming and Passing-Bablok methods, were applied. The figures show the year harvested. A clear anticlockwise loop is recognized.

Table 2. Regression line for plotting C_{t+2} against C_t which corresponds to the stock-recruitment relationship. Parameters were estimated by the simple, Deming and Passing-bablok (P-B) regression methods. No density-dependent effect was detected except when the simple regression method was applied.

Odd-numbered years					
	<i>a</i>	<i>b</i>	95% C.L.	<i>b</i> < 1	Detection of density effect
Simple	0.738	0.528	(0.204, 0.852)	<i>b</i> < 1	Detected
Deming	-0.0669	0.918	(0.689, 1.208)	<i>b</i> = 1	Not detected
P-B	-0.0418	1.021	(0.733, 1.470)	<i>b</i> = 1	Not detected
Even-numbered years					
	<i>a</i>	<i>b</i>	95% C.L.	<i>b</i> < 1	Detection of density effect
Simple	0.87	0.52	(0.164, 0.876)	<i>b</i> < 1	Detected
Deming	0.0518	1.015	(0.578, 1.592)	<i>b</i> = 1	Not detected
P-B	-0.153	1.117	(0.430, 1.571)	<i>b</i> = 1	Not detected

the slopes were not statistically different from unity, and it was judged that no density-dependent effect was detected. In **Figure 3**, a clear anticlockwise loop can be recognized, which is opposite what would be expected according to the logic proposed by Sakuramoto [8] [10] [11]. That is, the age at maturity is the same for pink salmon born in odd-numbered years (2 years old), so that a

clockwise loop emerges. We will address in the Discussion section why two opposite phenomena occur in the odd- and even-numbered years.

3.3. Relationship between Catches in Odd- and Even-Numbered Years

Figure 4 shows the trajectories of the catches, $\ln(C_{t+1}^E)$ and $\ln(C_t^O)$. The trajectories seem to have a negative relationship. **Figure 5** shows the plots of $\ln(C_{t+1}^E)$ against $\ln(C_t^O)$. The slope of the regression lines estimated using the simple and Deming regression analyses are shown in **Table 3**. When the dependent variable has a negative relationship to the independent variable, the Passing-Bablok regression method cannot be used. Therefore, only the simple and Deming regression methods were applied in this analysis.

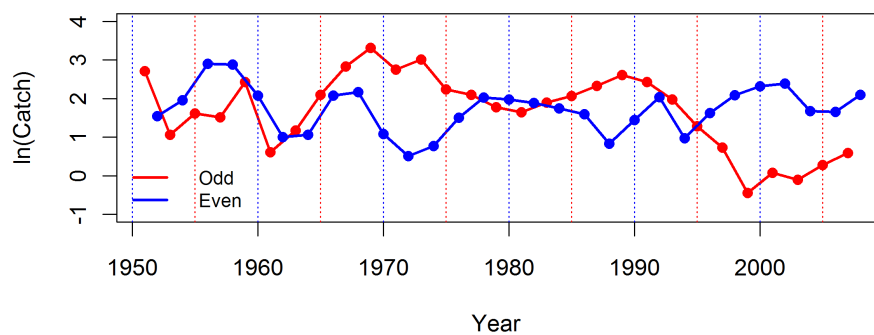


Figure 4. Catch trajectories for odd- and even-numbered years.

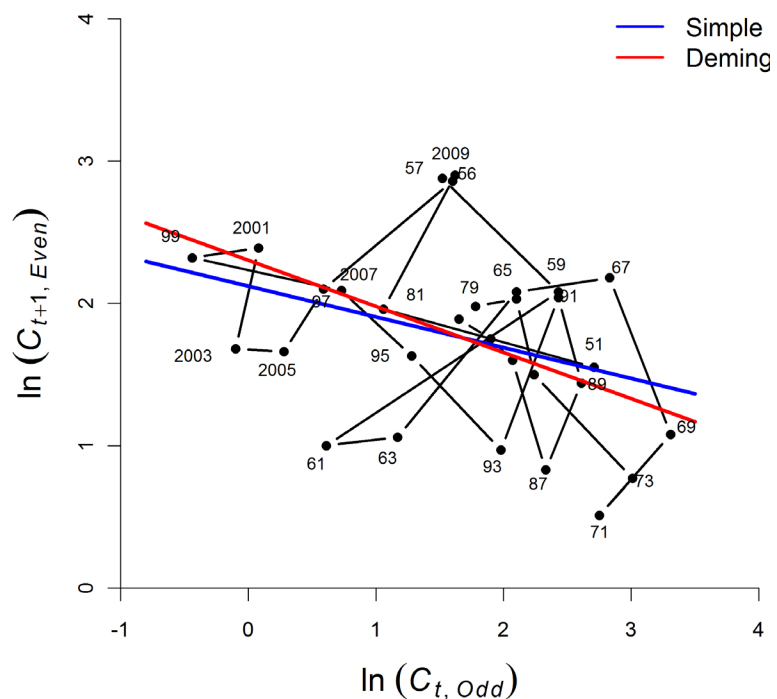


Figure 5. Relationship between catches in odd- and even-numbered years. The slopes of the regression lines that plot $\ln(C_{t+1}^E)$ against $\ln(C_t^O)$ were estimated using simple and the Deming regression analyses.

Table 3. Regression lines of $\ln(C_{t+1})$ against $\ln(C_t)$. Parameters were estimated by the simple, Deming and Passing-bablok (P-B) regression analyses.

ln(C_{t+1}) born in even year $t + 1$ against ln(C_t) born in odd year t						
	a	b	95% C.L.	p -value	r	
Simple	2.122	-0.216	(-0.448, 0.0115)	$b = 0$	0.0663	-0.340
Deming	2.304	-0.325	(-0.476, -0.088)	$b < 0$		
ln(C_{t+1}) born in odd year $t + 1$ against ln(C_t) born in even year t						
	a	b	95% C.L.	p -value	r	
Simple	2.530	-0.500	(-1.113, 0.113)	$b = 0$	0.106	-0.301
Deming	8.139	-3.776	(-18.452, -1.792)	$b < 0$		

The slope was significantly negative with a 10% significance level ($p = 0.0663$) when the simple regression analysis was applied, and the slope was significantly negative with a 5% significance level when the Deming regression analysis was applied. That is, we can conclude that $\ln(C_{t+1}^E)$ has a negative relationship with $\ln(C_t^O)$. The result of the oppositional relationship, that is, $\ln(C_t^O)$ plotted against $\ln(C_{t-1}^O)$ is also shown in **Table 3**. The slope was slightly larger than the 10% significance level ($p = 10.6$) when the simple regression analysis was applied; however, the slope was significantly negative with a 5% significant level when the Deming regression analysis was applied.

3.4. Forecasting Models for Catch Ratio and Catch

In Equation (1), the candidates for the environmental factors are shown in **Table 1**. **Table 1** shows the AOs and PDOs in month m of year $t - k$ ($k = 0, 1, \text{ and } 2$), for which the p -values of the correlation coefficients for C_t were less than 0.10. Using these monthly AOs and PDOs, we estimated the optimal model using the stepwise regression analysis in R software. Here, we assume that $\ln(C_{t+2}/C_t)$ corresponds to $\ln(RPS_t)$.

The results are also shown in **Table 1**. That is, AOs in April and November in year t and in February and May in year $t - 2$ were chosen as the environmental factors for the model forecasting the catch ratio in odd-numbered years. The model estimated was as follows,

$$\ln(RPS_t) = -0.128 - 0.173a_{2,t-2} + 0.504a_{5,t-2} + 0.404a_{4,t} - 0.356a_{11,t} \quad (3)$$

Here $a_{m,t-k}$ denotes the AO in month m of year $t - k$. The result is shown in **Figure 6**, and the Akaike information criteria (AIC) of which was -39.26. The catches forecast by Equation (2) are also shown at the bottom of **Figure 6**.

The AOs in February and May in year $t - 2$ and the PDO in January in year t and the PDO in November in year $t - 2$ were chosen as the environmental factors for the model forecasting the catch ratio in even-numbered years. That is,

$$\ln(RPS_t) = 0.0810 + 0.116a_{2,t-1} + 0.475a_{7,t-2} - 0.132a_{1,t} - 0.218a_{12,t-2} \quad (4)$$

Here $p_{m,t-k}$ denotes the PDO in month m of year $t - k$. The result is shown in **Figure 7**, and the AIC of which was -37.98. The catches forecast by Equation (2)

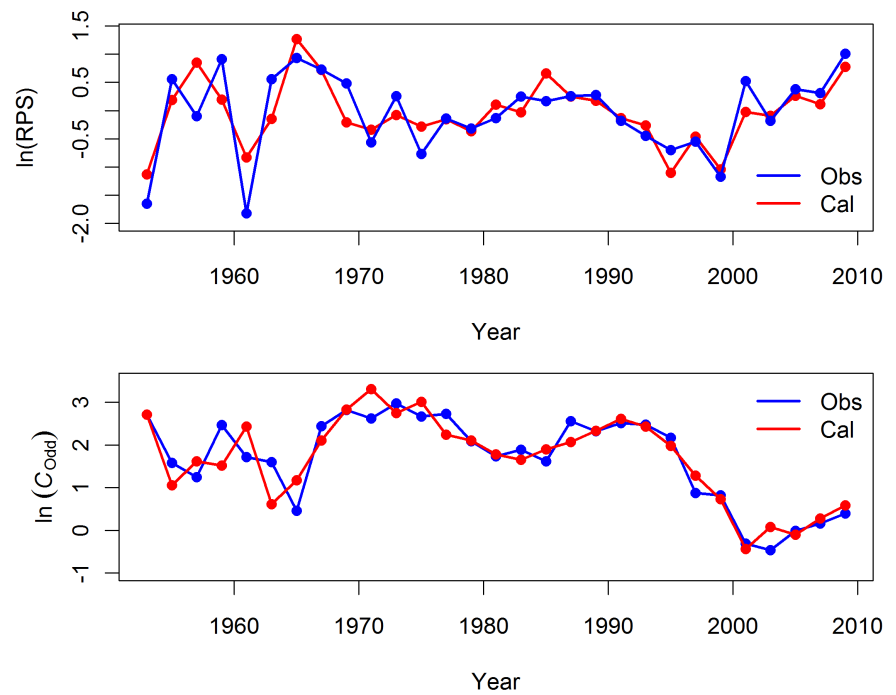


Figure 6. Trajectories of C_{t+2}/C_t and C_{t+2} for odd-numbered years. Top: C_{t+2}/C_t reproduced by the model shown in Equation (1). Bottom: C_{t+2} reproduced by Equation (2).

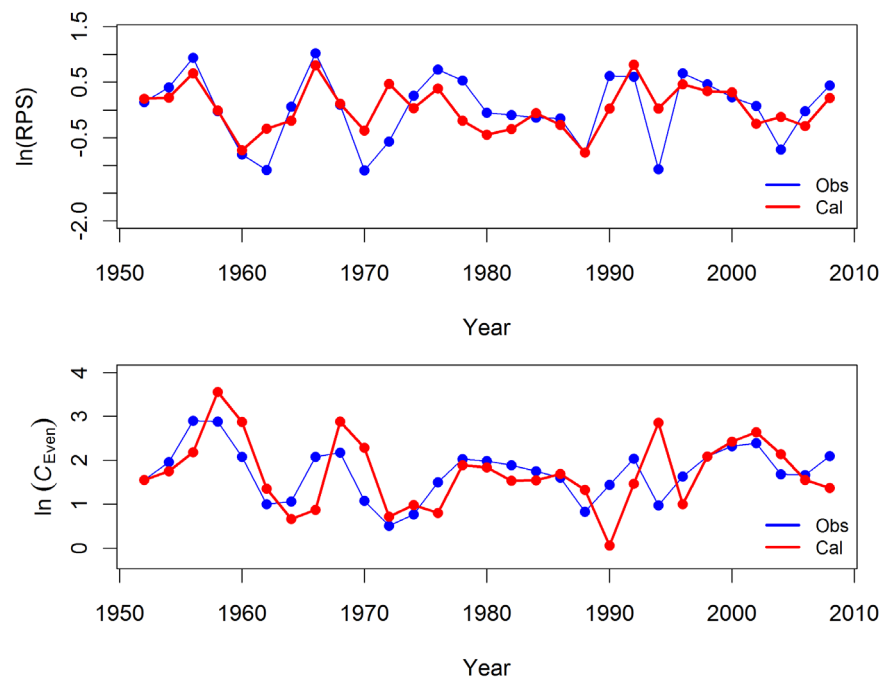


Figure 7. Trajectories of C_{t+2}/C_t and C_{t+2} for even-numbered years. Top: C_{t+2}/C_t reproduced by the model shown in Equation (1). Bottom: C_{t+2} reproduced by Equation (2).

are also shown at the bottom of **Figure 7**. The $\ln(RPS)_t$, which is defined by the ratio of the catch, $\ln(C_{t+2}/C_t)$, in both odd- and even-numbered years, was well reproduced only by these environmental factors, and no density-dependent effect seems to exist in the RPS in both sets of years.

4. Discussion

The relationships of the catches between C_{t+2} and C_t which corresponds to the SRR, for the populations born in odd- and even-numbered years were similar, and no density-dependent effect was detected. That is, when the simple regression analysis was applied, the slopes of the regression lines were statistically less than unity; however, when Deming and Passing and Bablok regression analyses were applied, the slopes of the regression lines were not statistically different from unity. That is, SRR can be expressed by a simple proportional model, and the differences from the line can be explained by environmental factors, as Sakuramoto insisted [11] [12].

The ratio of the catch, C_{t+2}/C_t which corresponds to the RPS, was well reproduced using only environmental factors for both odd- and even-numbered years. This means that the RPS can be reproduced using only the environmental factors, and no density-dependent effect operates in either odd- or even-numbered years. The results coincided well with those for the Pacific stock of Japanese sardines [10] and Pacific bluefin tuna [12].

AO was selected as the only environmental factor when the model was applied to the odd-numbered years. In contrast, AO in year t was not selected and PDO in years t and $t - 2$ was selected when the model was applied to the even-numbered years. AO in February in year $t - 2$ was selected for both the models; however, the signs in the partial coefficients were opposite, *i.e.*, the value was negative for odd-numbered years and positive for even-numbered years.

In **Figure 3** and **Figure 4**, the directions of the loops that appeared in the plots for $\ln(C_{t+2}^o)$ against $\ln(C_t^o)$, which corresponds to the relationship between $\ln(R_{t+2})$ against $\ln(SSB_t)$, were opposite for odd- and even-numbered years. According to Sakuramoto [8] [10] [11], the appearance of a clockwise loop in odd-numbered years is reasonable, because the age at maturity is short compared to the cycle of the fluctuation in environmental factors. However, for even-numbered years, an anti-clockwise loop appeared, and this conflicts with the theory proposed by Sakuramoto [8] [10] [11]. This phenomenon is considered to occur when the Rs for odd- and even-numbered years have a negative correlation. When the R for odd-numbered years has the trajectory of a clockwise loop, and the R for even-numbered years has a negative correlation with odd-numbered years, the trajectory of SRR for even-numbered years shows an anti-clockwise loop.

The mechanism is illustrated in **Figure 8**. As Sakuramoto [11] noted, the direction of R and SSB on the SRR plane was determined by the vectors of both R and SSB. When SRR for fish species A has a clockwise loop, the combination of the vectors of R and SSB shows terms 1, 2, 3 and 4 in the order shown in **Figure 8**. Then the resultant trajectory results in a clockwise loop. However, when the R for fish species B has a strong negative correlation with that of species A, the direction of R for species B is opposite that for species A. Therefore, in term 1, the direction of R is opposite that for species A, and the resultant direction of the combined vectors of R and SSB is southeast, as shown at the bottom of **Figure 8**.

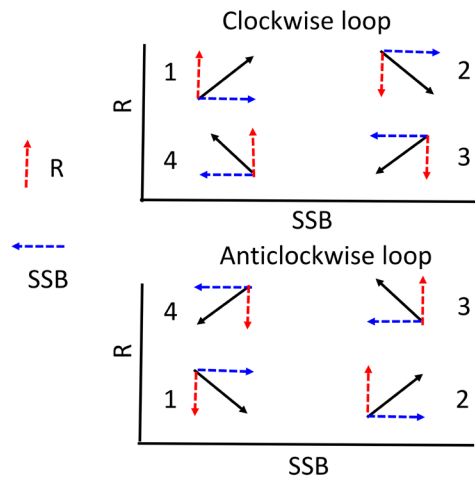


Figure 8. Mechanisms that produce the clockwise or anticlockwise loops. Top: The terms 1, 2, 3 and 4 pass in order, and a clockwise loop emerges on the SRR plane. Bottom: The terms 1, 2, 3 and 4 shown at the top correspond to 1, 2, 3 and 4 shown at the bottom, respectively. The direction of the R in each term is the opposite direction of that shown in the Top, respectively. Then an anticlockwise loop emerges on the SRR plane.

In term 2, the direction of R is opposite that for species A, and the resultant direction of the combined vectors of R and SSB is northeast. In terms 3 and 4, the mechanisms are the same, and the resultant directions of the combined vectors of R and SSB are northwest and southwest, respectively. That is, when time passes from term 1 to term 4, the resultant trajectory of the SSR forms an anticlockwise loop. The opposite case can also occur. That is, the true trajectory of SRR for fish species C shows an anticlockwise loop, and the R for fish species D has a strong negative correlation with that for species C; thus, the trajectory of SRR for species D forms a clockwise loop. However, according to the theory proposed by Sakuramoto [8] [10] [11], the former case is considered to be realistic.

The catches born in odd- and even-numbered years have a negative relationship with each other. There might be cannibalism between the pink salmon born in odd-numbered years and those born in even-numbered years. That is, the fries born in even-numbered year $t + 1$ may be eaten by one-year old fish born in odd-numbered year t , and fries born in odd-numbered year t might be eaten by the one-year old fish born in even-numbered year $t - 1$. Whether it is true or not has not been investigated at this stage; therefore, further investigation is necessary to elucidate this possibility. However, it must be true that the negative relationship between the catches born in odd- and even-numbered years would be a key factor in understanding the fluctuation mechanism in the pink salmon population.

In this study, we did not discuss the effect of fries that have been artificially released. However, this effect is considered to be negligible, because Morita *et al.* [25] concluded that the recent increase in the catch of Japanese pink salmon could be largely explained by climate change, and that increased hatchery releases had little effect.

5. Conclusions

1) We discussed the SRR under the assumption that C_t and C_{t+2} were proportional to SSB_t and R_{t+2} , and analyzed the relationship between the catches as the SRR. The results indicate that no density-dependent effects were detected in SRR for the pink salmon born in both odd- and even-numbered years.

2) The fluctuation of the catch ratio of the pink salmon born in odd- and even-numbered years can be well reproduced by the model that is described by the following equation:

$$C_{t+2}/C_t = g(\text{environmental factors})$$

Here we assumed that C_{t+2}/C_t represents RPS. That is, RPS can be reproduced only by environmental factors. This result coincides well with those obtained and analyzed by Sakuramoto [11] with regard to the Pacific stock of Japanese sardines and Pacific bluefin tuna.

3) The relationships between the catches of pink salmon born in odd- and even-numbered years were negative, which is a key factor in understanding the fluctuation mechanism in the pink salmon population.

Acknowledgements

We thank Dr. Rikio Sato for their useful comments, which improved this manuscript.

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