Are 20% B$_0$, 20% B$_{unfished}$, and B$_{MSY}$ Valid as Reference Points for Fisheries Resource Management?

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Abstract

The aim of this paper is to discuss the validity of 20% B$_0$, 20% B$_{unfished}$ and B$_{MSY}$ as reference points for managing fisheries resources. I reanalyzed eight stock-recruitment relationship (SRR) sets of data that were analyzed by Myers *et al.* in 1994, and showed that the theory proposed by Sakuramoto could be applied to the above SRR data. The results showed that: 1) clockwise loops or anti-clockwise loops emerged in the plots of SRR, and the results coincided well with those of 25 stocks that lived around Japan and the stock of Pacific bluefin tuna; 2) the slopes of the regression lines (*b*) drawn on SRR planes for above 34 stocks had a negative relationship with the age-at-maturity (*m*). That is, $b = 0.995 - 0.211 \cdot m$. Therefore, the results of this paper indicate that the SRR is governed by a mechanism that is quite different from that which has been traditionally accepted, and in which the main factor is believed to be a density-dependent effect. The results also indicated that 20% B$_0$, 20% B$_{unfished}$ and B$_{MSY}$, which are derived from traditional SRR models, do not have any scientific basis as reference points for managing fisheries resources. Empirical reference points seem to be more reasonable measures as Hilborn and Stokes emphasized in 2010.

Subject Areas

Marine Biology

Keywords

Bluefin Tuna, B$_{MSY}$, Clockwise Loop, Haddock, Herring, Sardine, Sock-Recruitment Relationship, Saithe, 20% B$_0$, 20% B$_{unfished}$

1. Introduction

Determining reference points is considered one of the most important tasks in fisheries resource management, and they have been broadly used not only by many international organizations but also in many domestic management procedures [1] [2] [3] [4]. Sainsbury [2] reviewed the reference points that have been used in a wide range of fisheries, and noted that two types of reference points are in common use: (1) fishing mortality-based reference points, and (2) biomass-based reference points. He also noted a third type of reference point: (3) empirical reference points, which have not been commonly used but do provide distinct advantages in some circumstances because they are easily understood and communicated, and are often simpler and cheaper to apply. Further, Sainsbury [2] pointed out the shortcoming of (1) and (2) reference points. That is, when we use reference points (1) and (2) above, the status of the stock must be obtained, and the appropriate management response is determined. However, they are not direct measures of the parameters of interest (e.g., current fishing mortality and biomass, unfished biomass, the fishing mortality coefficient giving maximum long-term yield), and so they are estimated by fitting a population model to the observed data that are available. The estimates are therefore model-dependent (in that different estimates arise from the use of different models), as well as data-dependent. Sainsbury [2] criticized reference points (1) and (2) as mentioned above; however, he accepted the use of parameters such as 20% B_0, 20% $B_{unfished}$, and B_{MSY} as reference points (1) and (2). Where B_0, $B_{unfished}$ and B_{MSY} denote the biomass at the initial stage, the biomass was calculated assuming that the resource was not harvested and that the biomass of the maximum sustainable yield (MSY) was achieved.

However, I strongly oppose the use of reference points (1) and (2), including parameters such as 20% B_0, 20% $B_{unfished}$ and B_{MSY}. The reasons I oppose the use of 20% B_0, 20% $B_{unfished}$ and B_{MSY} are as follows:

1) B_0 has never been clearly defined in a scientific manner;

2) $B_{unfished}$ can easily be calculated; however, the relationship between B_0 and $B_{unfished}$ has not been explained, nor has the meaning of $B_{unfished}$ been explained from a biological point of view;

3) There is no clear biological basis for the choice of 20%;

4) B_{MSY} does not exist, because the concept of B_{MSY} itself is not valid.

Here I will explore these problems in detail. Baumgartner *et al*. [5] analyzed the Pacific sardine and northern anchovy fish-scale-deposition rates developed from the anaerobic carved sediments of the Santa Barbara Basin off of southern California. These data were constructed by integrating and adding; they cover the period from A.D. 270 through 1970. Based on these data, they estimated the Pacific sardine and northern anchovy populations over a period of almost 2000 years. The scale deposition record shows nine major recoveries and subsequent collapses of the sardine population over 1700 years (see Figure 7 of Baumgartner *et al*. [5]). Ravier and Fromentin [6] analyzed long-term time-series of bluefin

tuna catches from ancestral Mediterranean and Atlantic trap fisheries. Over a period of about 300 years, 100-year-long periodic fluctuations were detected as well as 20-year cycles (see Figure 8 of Ravier and Fromentin [6]). For these trajectories, it is difficult or impossible to define B_0. Also, it is not possible to conclude that the declines in abundance occurred due to fishing and the increases in abundance occurred in response to fisheries regulations. It is clear that B_0 cannot be defined and does not have any scientific basis as a reference point. That is, B_0 is meaningless.

When the recruitment (R) is estimated using, for instance, virtual population analysis, the $B_{unfished}$ can easily be calculated. However, the relationship between B_0 and $B_{unfished}$ cannot be adequately explained. Scientists who believe that B_{MSY} is valid tend to believe in the existence of a density-dependent effect; however, they do not incorporate a density-dependent effect when they calculate $B_{unfished}$. This is a fatal contradiction. If, as stated above, B_0 itself is meaningless, then $B_{unfished}$ and B_{MSY}, which is a fraction of B_0, are also meaningless. Further, the stock-recruitment relationship (SRR) itself forms the basis of B_{MSY}, as B_{MSY} is derived from SRR models such as those of Ricker [7], Beverton and Holt [8], and Shepherd [9], and thus the SRR is also meaningless as Sakuramoto [10]-[16] and Tanaka *et al.* [17] pointed out.

Myers uploaded the dataset [18], which is freely available to the public through the internet. This database is extremely useful for analyzing many kinds of stocks that are broadly distributed all over the world. Further, Myers *et al.* [19] discussed the reference points used to analyze 72 stocks, and they considered three classes of thresholds defined by: (1) the stock size corresponding to 50% of the maximum predicted average R; (2) the minimum stock size that would produce a good year class when environmental conditions are favorable; (3) the stock size corresponding to 20% of various estimators of virgin stock size. The estimators of the first type are generally preferable because they are easily understood, relatively robust even if only data for small stocks are available, and almost always result in levels of R above the threshold.

The report by Myers *et al.* [19] has been cited as the definitive paper report supporting 20% B_0 as a threshold for overfishing. However, Hilborn and Stokes [20] emphasized that, although fisheries management organizations have often cited Myers *et al.* [19] as supporting 20% B_0 as a threshold for overfishing, this is a serious misinterpretation of the results of that paper. Myers *et al.* [19] showed that the R does decline for most stocks at low stock sizes for which data were available and state that their analysis should help dispel the widely-held notion that the observed R is "usually independent of spawning biomass". The paper does not in any way, however, suggest that 20% B_0 is a useful threshold for defining overfishing. Indeed Myers *et al.* [19] cautioned specifically against using 20% B_0. I strongly support the views of Hilborn and Stokes' [20], because as I mentioned above, 20% B_0 is meaningless and further, I strongly believe that the traditional interpretation of the mechanism that controls SRR is itself

invalid.

Sakuramoto proposed a new mechanism that may underlie SRR [10]-[16]. We will refer to the new concept as "loop theory". Sakuramoto showed the mechanisms that produced clockwise loops or anticlockwise loops that are commonly observed in SRR, using both simulation studies and analyses of actual SRR data [10] [14] [16]. That is, when R fluctuates cyclically in response to environmental factors, and the spawning stock biomass (SSB) also fluctuates cyclically with a time lag (mainly determined by age at maturity), the SRR shows a clockwise loop or an anticlockwise loop for each period of the environmental cycle. The former occurs when the age at maturity is less than half of the environmental cycle, and the latter occurs when the age at maturity is more than half of the environmental cycle [10] [14] [16].

Sakuramoto [14] also discussed the slope of the regression line for the plot of ln(R) against ln(SSB). When the age at maturity is low compared to the length of the cycle of the environmental factors, the slope of the regression line is high and close to unity. However, the higher the age at maturity becomes, the more the slope of the regression line decreases. When the age at maturity comes close to approximately half the length of the cycle of the environmental factors, the slope decreases to almost zero. In this case, the true relationship between R and SSB is masked and cannot be detected. Furthermore, when the age at maturity becomes greater than half the length of the cycle of the environmental factors, the slope of the regression line becomes negative [14] [16]. Tanaka *et al.* [17] found that the loop theory could be applied to 24 stocks that lived around Japan. Incorporating the analyses mentioned above, the present paper further tries to apply the loop theory to other stocks and to show evidence that the parameter 20% B_0 has no scientific basis.

The aim of this paper is to show evidence that the 20% B_0 has no scientific basis using the loop theory. That is, this paper reanalyzes the SRR data for eight stocks that Myers *et al.* [19] analyzed (see Figure 1 of Myers *et al.* [19]) and shows that the loop theory can be applied to those data. Then, I show that 20% B_0, 20% $B_{unfished}$ and B_{MSY} are not meaningful reference points for managing the stocks of fisheries.

2. Materials and Methods

2.1. Data

I reanalyzed eight data sets of R and SSB, which were shown in Figure 1 in Myers *et al.* [19]. The original data set is available at Myer's URL [18]. The age at maturity and the age at recruitment were also obtained at the above URL. The age at maturity for sardine stock in South Africa was obtained from the URL cited in the reference list [21]. The slopes of the SRR and age at maturity for the Pacific stock of Japanese sardines and Pacific bluefin tuna were obtained from Sakuramoto [14]. The slopes of the SRR and age at maturity for the other 24 stocks were obtained from Tanaka *et al.* [17].
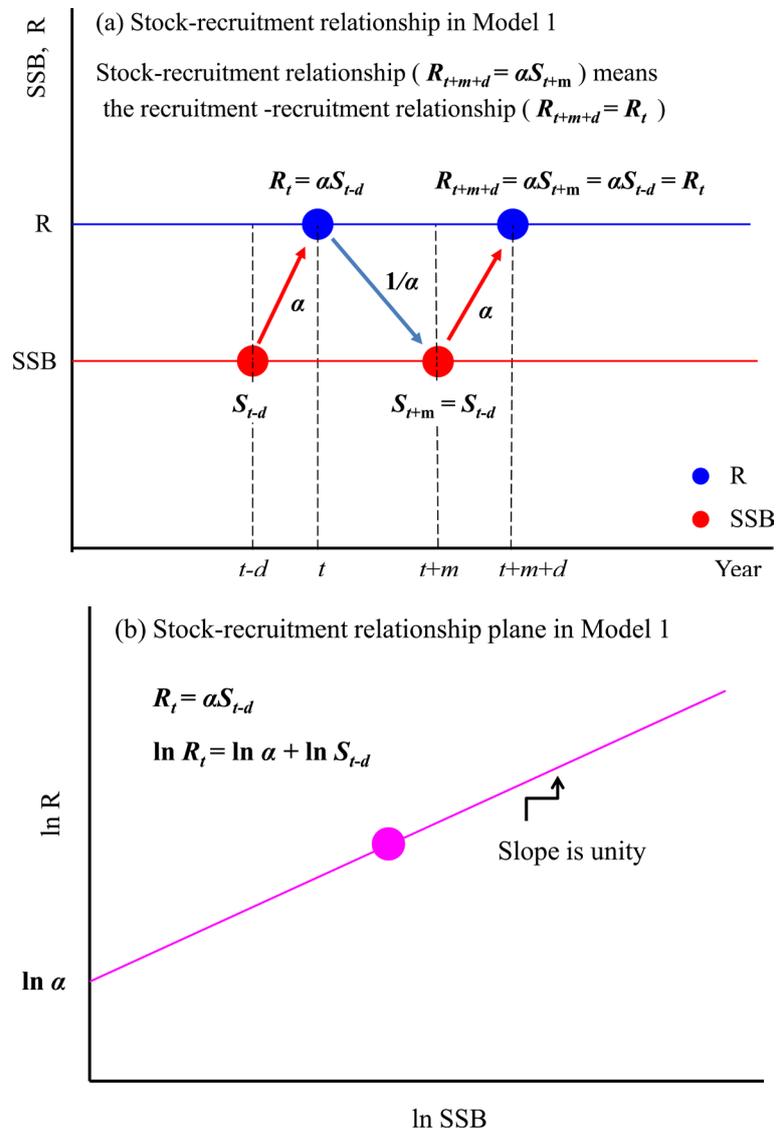
Figure 1. Stock-recruitment relationship when Model 1 is assumed. (a) shows that the relationship between S_{t+m} and R_{t+m+d} merely implies the relationship between R_t and R_{t+m+d}; (b) shows the movements S and R in the SRR plane.

2.2. A Mechanism Produces the Loops

Sakuramoto [14] used four simulation models to reproduce the SRR observed in the Pacific stock of Japanese sardine and Pacific bluefin tuna. Using the same logic [14], the mechanism that loops necessary appear in SRR is again described as follows. The basic model of SRR, which was slightly generalized, is expressed by Equation (1).

$$R_t = \alpha S_{t-d} \cdot f\left(\boldsymbol{x}_t\right). \tag{1}$$

where R_t, S_{t-d} and $f(.)$ denote the recruitment in year t, spawning stock biomass in year $t - d$, and a function that evaluates the effects of environmental factors in year t. The notation d denotes the recruitment age. The vector $\boldsymbol{x}_t = \left[x_{t,1}, \cdots, x_{t,k}\right]$ is a list of environmental factors that affect the strength in R, which comprised

not only of physical factors such as water temperature, but also biological interactions such as prey-predator relationships. Parameters a and k denote a proportional constant and the number of environmental factors, respectively. That is, Equation (1) implies that R_t is proportionally determined by S_{t-d}, and simultaneously, R_t is affected by environmental factors in year t.

Model 1 is the case when environmental effects can be neglected [14]. That is, $f(x_t)$ in Equation (1) can be assumed to be unity. That is,

$$R_t = \alpha S_{t-d}. \tag{2}$$

where a denotes the recruitment per spawning stock biomass (RPS). The survival process is expressed by

$$S_{t+m} = \gamma R_t. \tag{3}$$

For simplicity, m denotes the age at maturity and longevity of the fish [14]. That is, fish reach maturity age at m-year old, then, they spawn their eggs and die. In Equation (3), γ denotes the survival rate during m years or the spawning stock biomass per recruitment (SPR), *i.e.*, $\gamma = 1/\alpha$. Therefore, when the population reproduces according to Model 1, R_t and S_{t+m} are constant regardless of year (Figure 1(a), Figure 1(b)).

Model 2 is the case in which when $f(x_t)$ in Equation (1) can be expressed by 1 + r [14]. That is,

$$R_t = \alpha(1+r)S_{t-d}. \tag{4}$$

The increasing or decreasing rate, r, is determined by environmental factors. When environmental factors are good for the stock, r takes positive values ($r > 0$) and R increases (Figure 2(a), Figure 2(c)). On the contrary, when environmental factors are bad for the stock, r takes negative values ($-1 < r < 0$) and R decreases (Figure 2(b), Figure 2(c)). In this model, the survival process is the same of that shown in Equation (3).

Model 3 is the case when r in year t in Equation (4), r_t, changes cyclically [14]. It can be expressed by a sine curve as defined below:

$$r_t = \beta \sin(\omega t). \tag{5}$$

Thus,

$$R_t = \alpha(1 + \beta \sin(\omega t))S_{t-d}. \tag{6}$$

Here, β and ω denote the amplitude of the sine curve and angular velocity, respectively (Figure 3(a)). In this model, the survival process is the same of that shown in Equation (3).

Generally, the spawning stock biomass in year $t - d$ (S_{t-d}) produces the recruitment in year t (R_t), and the R_t becomes the pawning stock biomass in year $t + m$ (S_{t+m}). Then the pawning stock biomass in year $t + m$ (S_{t+m}) produces the recruitment in year $t + m + d$ (R_{t+m+d}). This cycle repeats infinitely as shown in Figure 1(a), Figure 2(a) and Figure 2(b). In Model 2, when the year is $t + m + d$, the SRR can be expressed by Equation (7),
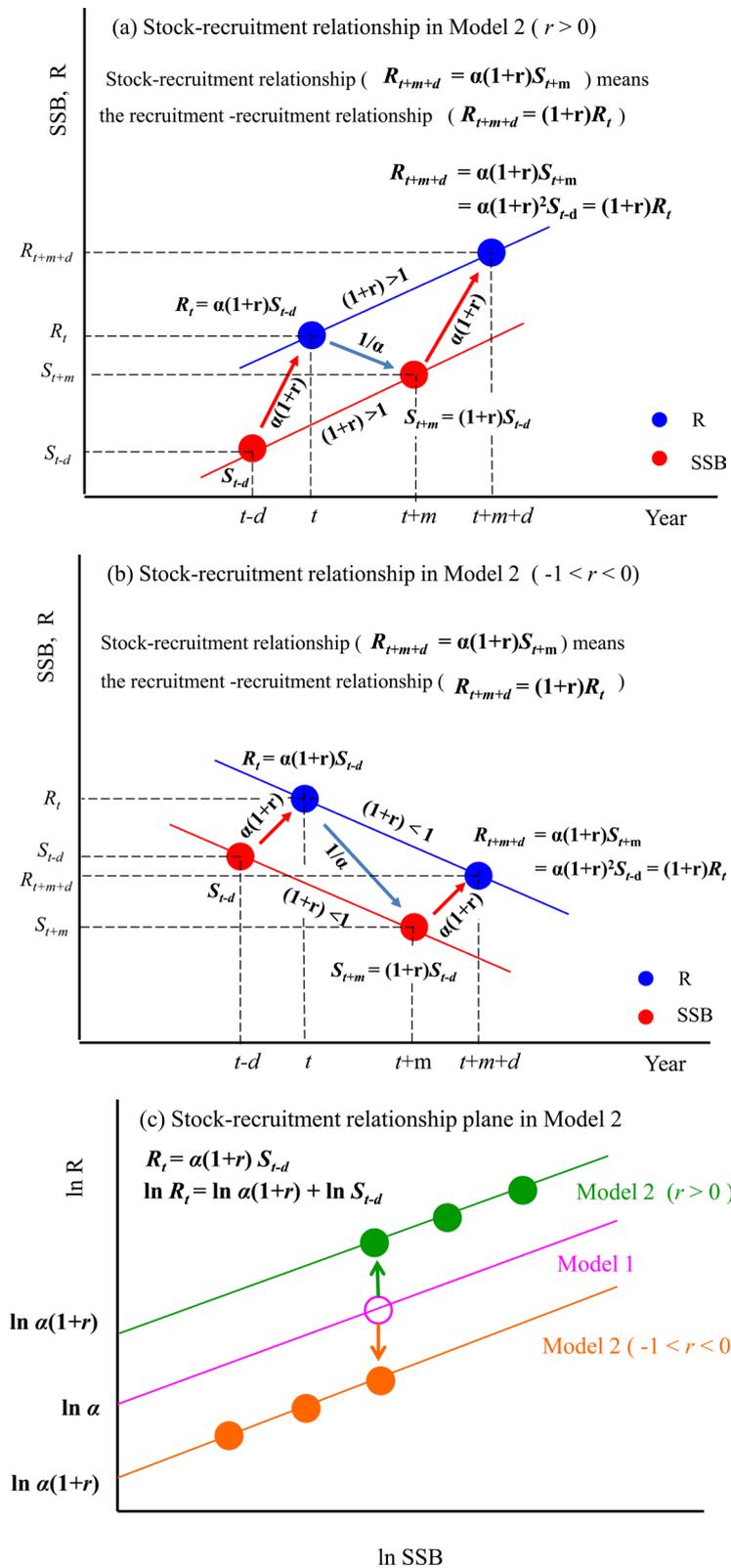
Figure 2. Stock-recruitment relationship when Model 2 is assumed. (a) and (b) show that the relationship between S_{t+m} and R_{t+m+d} merely implies the relationship between R_t and R_{t+m+d}; (a) shows the case when r is positive; (b) shows the case when r is negative; and (c) shows the movements S and R in the SRR plane.

$$R_{t+m+d} = \alpha(1+r)S_{t+m}. \tag{7}$$

As shown in **Figure 2(a)**, **Figure 2(b)**, Equation (7) can be modified by,

$$R_{t+m+d} = (1+r)R_t. \tag{8}$$

That is, the relationship from S_{t+m} to R_{t+m+d} is replaced by the relationship from R_t to R_{t+m+d}. Equations (7) and (8) reveal an important fact that is hidden behind a SRR. That is, the relationship from S_{t+m} to R_{t+m+d}, which is the SRR itself, is the relationship from R_t to R_{t+m+d}, which is so to speak "R to R relationship" (**Figure 1(a)** and **Figure 2(a)**, **Figure 2(b)**). This relationship is the same in Model 3 as shown in **Figure 3(a)**. That is,

$$
\begin{aligned}
R_{t+m+d} &= \alpha\big(1+\beta\sin\big(\omega(t+m+d)\big)\big)S_{t+m} \\
&= \alpha\big(1+\beta\sin\big(\omega(t+m+d)\big)\big)\big(1+\beta\sin(\omega t)\big)S_{t-d} \\
&= \big(1+\beta\sin\big(\omega(t+m+d)\big)\big)R_t.
\end{aligned}
\tag{9}
$$

Therefore, when the environmental factors cyclically fluctuate, such as a sine curve, the SRR simply means the relationship between R_{t+m+d} and R_t. In other words, the SRR shows only a relationship between two different points at t and $t + m + d$ on the same sine curve (**Figure 3(a)**). Therefore, when the R fluctuates cyclically in response to environmental factors, the SRR necessary shows loop shapes. Further the time lag is enough small, the SRR shows clockwise loops (**Figure 3(b)**), and the time lag is enough large, the SRR shows anticlockwise loops (**Figure 3(c)**) [10] [14] [16].

2.3. Rule for Judging the Clockwise or Anticlockwise Direction of Loops in the SRR

According to Sakuramoto [14] [16], I investigated whether or not loop shapes emerge in SRRs by plotting $\ln(R_t)$ against $\ln(SSB_{t-d})$. Further, I investigated the directions of the loops depending on the age at maturity.

I applied the rule [17] that determined the direction of the loops, either clockwise or anticlockwise. The direction of the line from year t to year $t + 1$ is judged based on the direction of the line from year $t + 1$ to year $t + 2$ (**Figure 4**). When the direction of the line from year $t + 1$ to year $t + 2$ is "A" shown in **Figure 4**, the line from year t to year $t + 1$ is judged to be part of a clockwise loop. When the direction of the line from year $t + 1$ to year $t + 2$ is "B", the line from year t to year $t + 1$ is judged to be part of an anticlockwise loop [17]. After all directions of the lines from year t to year $t + 1$ were determined, the judgement was modified regarding the direction. When three successive lines were judged to have clockwise, anticlockwise, and clockwise directions, respectively, the middle anticlockwise direction was replaced with a clockwise direction, and the judgement was replaced with clockwise, clockwise, and clockwise because clockwise or anticlockwise loops must be continuous and does not change year by year [17]. Similarly, if the series of directions was anticlockwise, clockwise, and anticlockwise, the middle clockwise" was replaced with anticlockwise, and
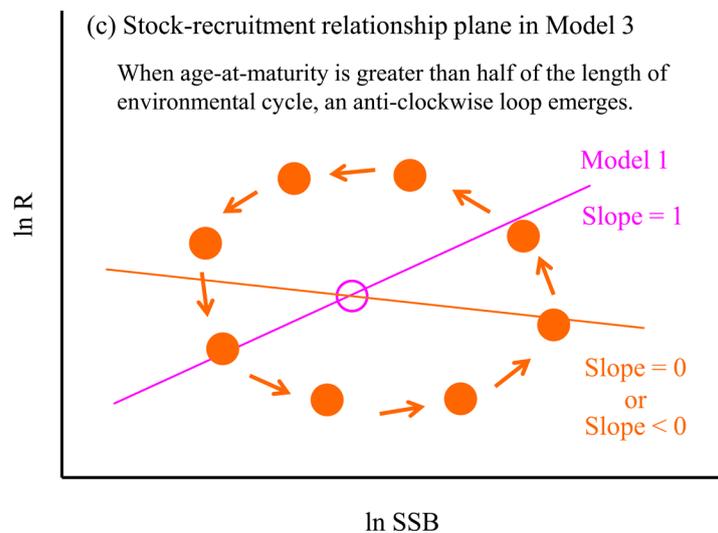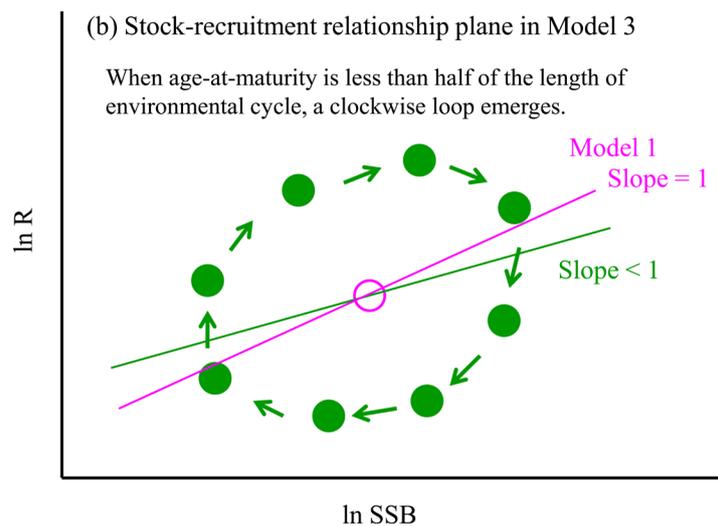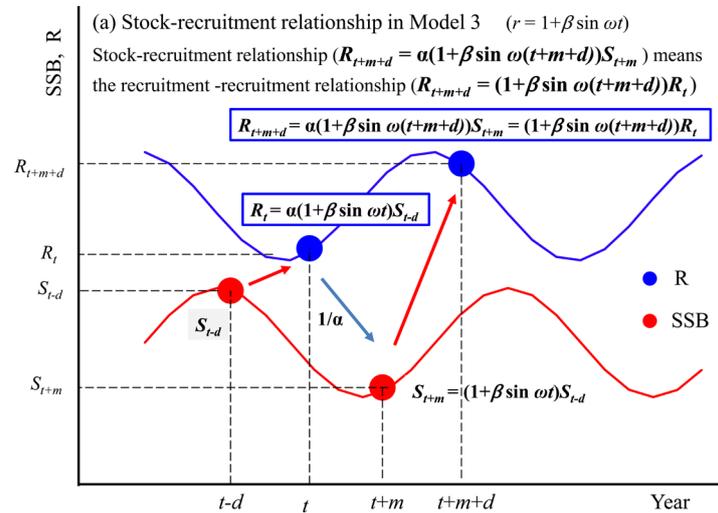
(a) Stock-recruitment relationship in Model 3 ($r = 1 + \beta \sin \omega t$)

SSB, R

Stock-recruitment relationship ($R_{t+m+d} = \alpha(1+\beta \sin \omega(t+m+d))S_{t+m}$) means the recruitment -recruitment relationship ($R_{t+m+d} = (1+\beta \sin \omega(t+m+d))R_t$)

$R_{t+m+d} = \alpha(1+\beta \sin \omega(t+m+d))S_{t+m} = (1+\beta \sin \omega(t+m+d))R_t$

R_{t+m+d}

$R_t = \alpha(1+\beta \sin \omega t)S_{t-d}$

R_t

S_{t-d}

S_{t-d}

$1/\alpha$

R

SSB

S_{t+m}

$S_{t+m} = (1+\beta \sin \omega t)S_{t-d}$

$t-d$ t $t+m$ $t+m+d$ Year

(b) Stock-recruitment relationship plane in Model 3

When age-at-maturity is less than half of the length of environmental cycle, a clockwise loop emerges.

ln R

Model 1
Slope = 1

Slope < 1

ln SSB

(c) Stock-recruitment relationship plane in Model 3

When age-at-maturity is greater than half of the length of environmental cycle, an anti-clockwise loop emerges.

ln R

Model 1
Slope = 1

Slope = 0
or
Slope < 0

ln SSB

Figure 3. Stock-recruitment relationship when Model 3 is assumed. (a) shows that the relationship between S_{t+m} and R_{t+m+d} merely implies the relationship between R_t and R_{t+m+d}; (b) and (c) shows the movements S and R in the SRR plane; (b) shows a clockwise loop; and (c) shows an anticlockwise loop.
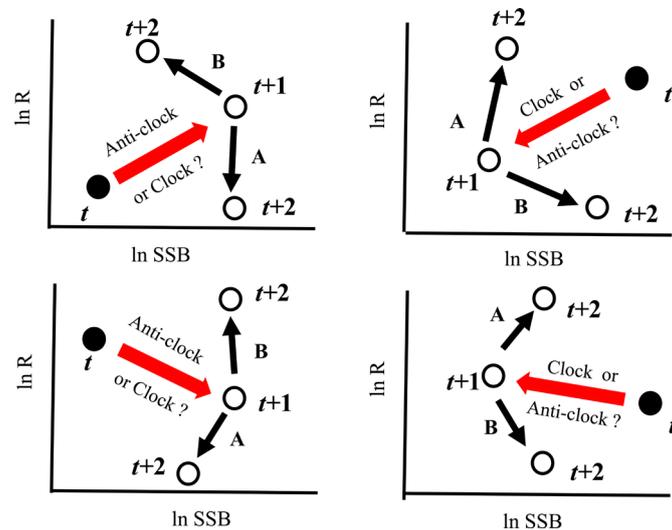
Figure 4. The rule used to judge the direction of the line from t to $t + 1$. When the line from $t + 1$ to $t + 2$ is A, the line from t to $t + 1$ is judged to be part of a clockwise loop. When the line from $t + 1$ to $t + 2$ is B, the line from t to $t + 1$ is judged to be part of an anticlockwise loop.

the directions were concluded to be anticlockwise, anticlockwise and anticlockwise [17].

2.4. Trajectories, Autocorrelation and Cross-Correlation of R and SSB

Sakuramoto [10] [14] [16] found that one of the key factors in the mechanism that controls SRR was a time lag observed from R to SSB that was deeply related to the age at maturity, and further, the slope of the regression line of SRR had a negative relationship with the age at maturity. In order to investigate these points, I calculated the auto-correlation in R and SSB and the cross-correlation between R and SSB using the 3-year moving averages of their trajectories. We denote the 3-year moving averages of R and SBB with R* and SSB*, respectively.

2.5. Relationship between the Slope of the Regression Line of SRR and the Age at Maturity

In this study, I estimated the slope of the regression line that plots $\ln R_t^*$ against $\ln SSB_{t-d}^*$. The eight slopes estimated in this study were plotted in **Figure 5** in Tanaka *et al.*'s paper [17]. That is, **Figure 5** in Tanaka *et al.*'s paper [17] showed the relationship between the slope of the regression line and the age at maturity using the 24 stocks that they investigated.
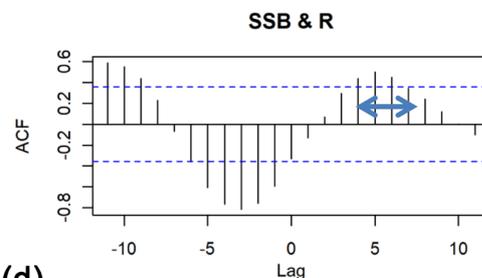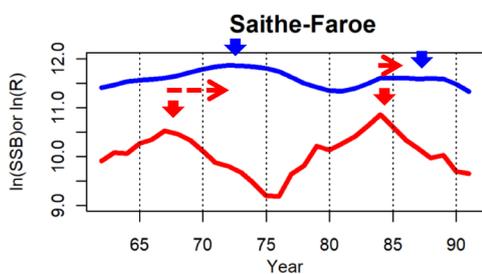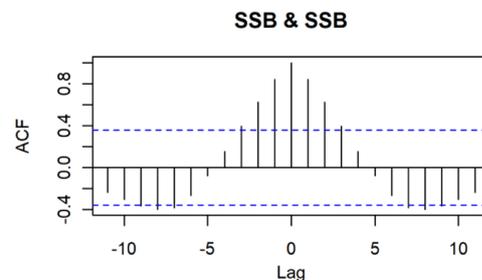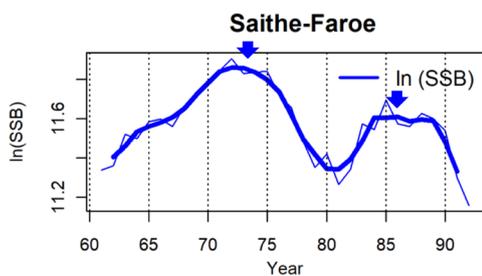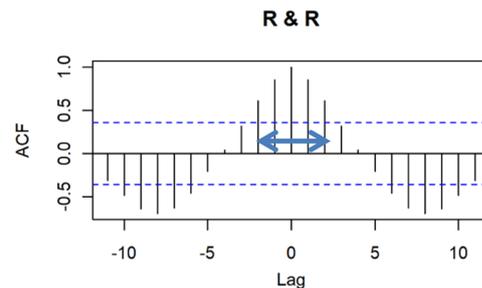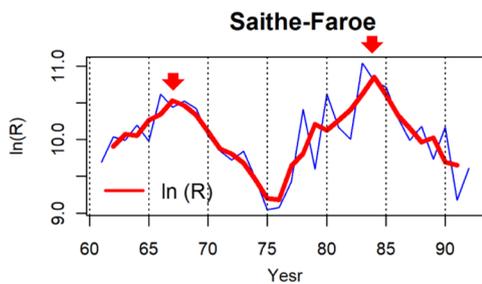
3. Results

3.1. Trajectories, Autocorrelation, and Cross-Correlation of ln R* and ln SSB*

The left panels in **Figures 5(a)-(h)** show the trajectories of the natural logarithms of R and SSB, *i.e.*, ln R and ln SSB, and their 3-year moving averages,

(a)

(b)
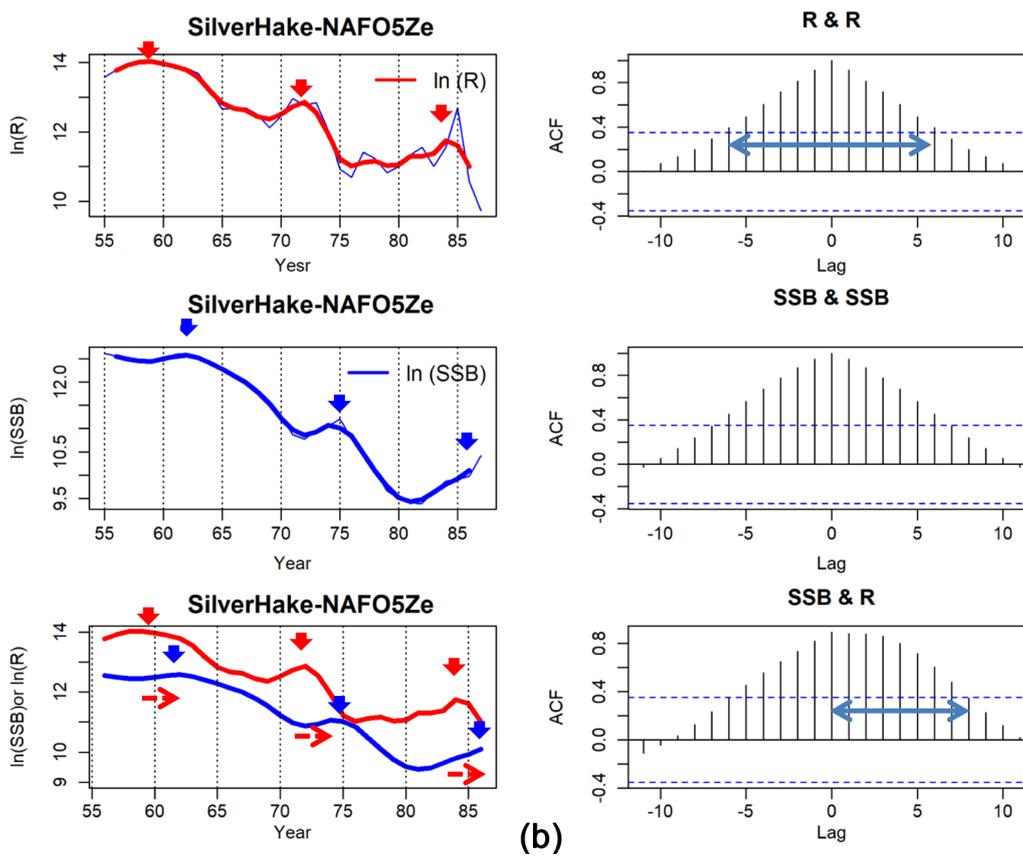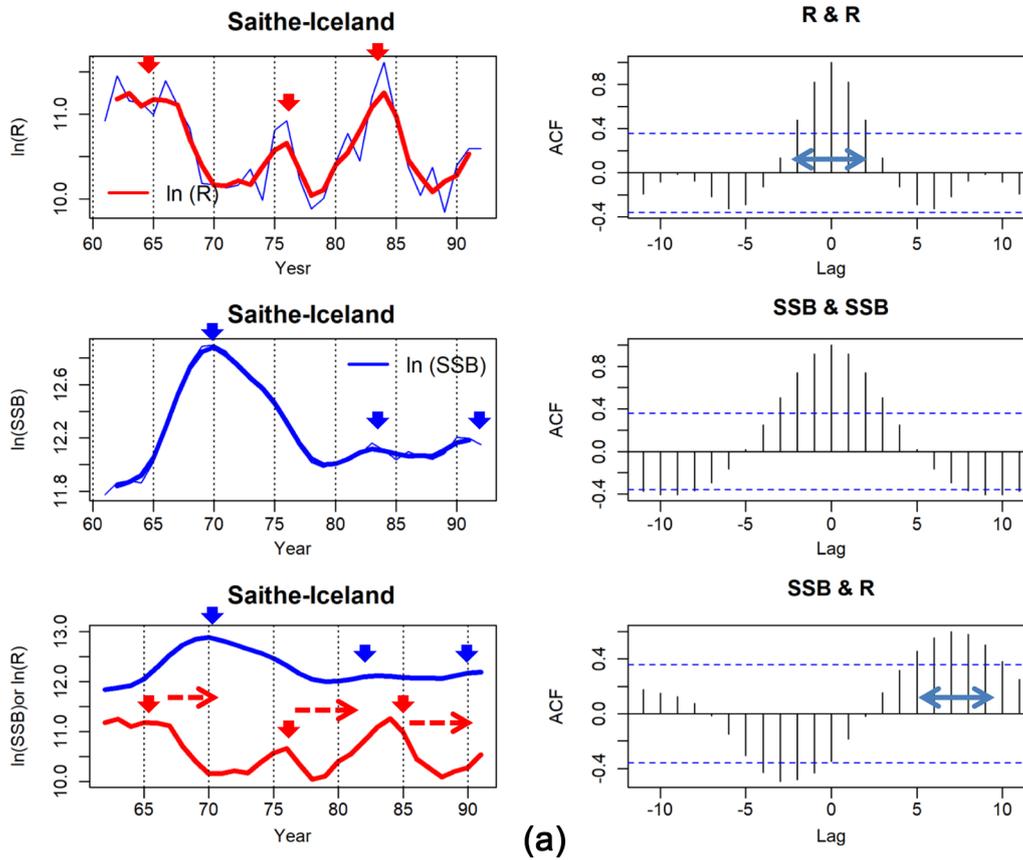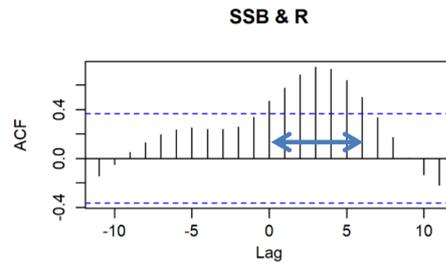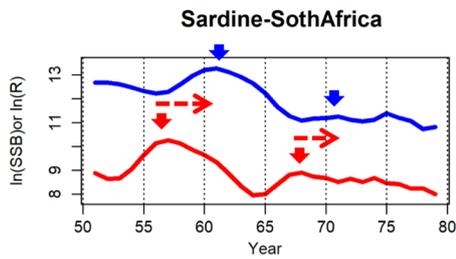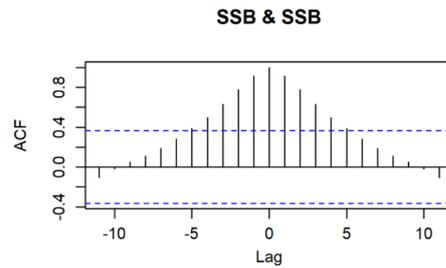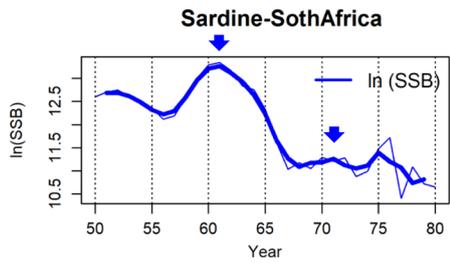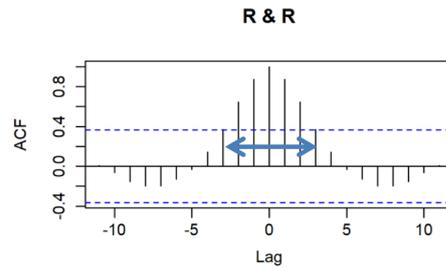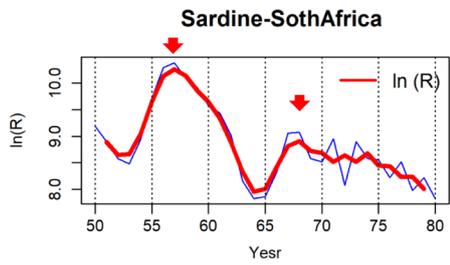
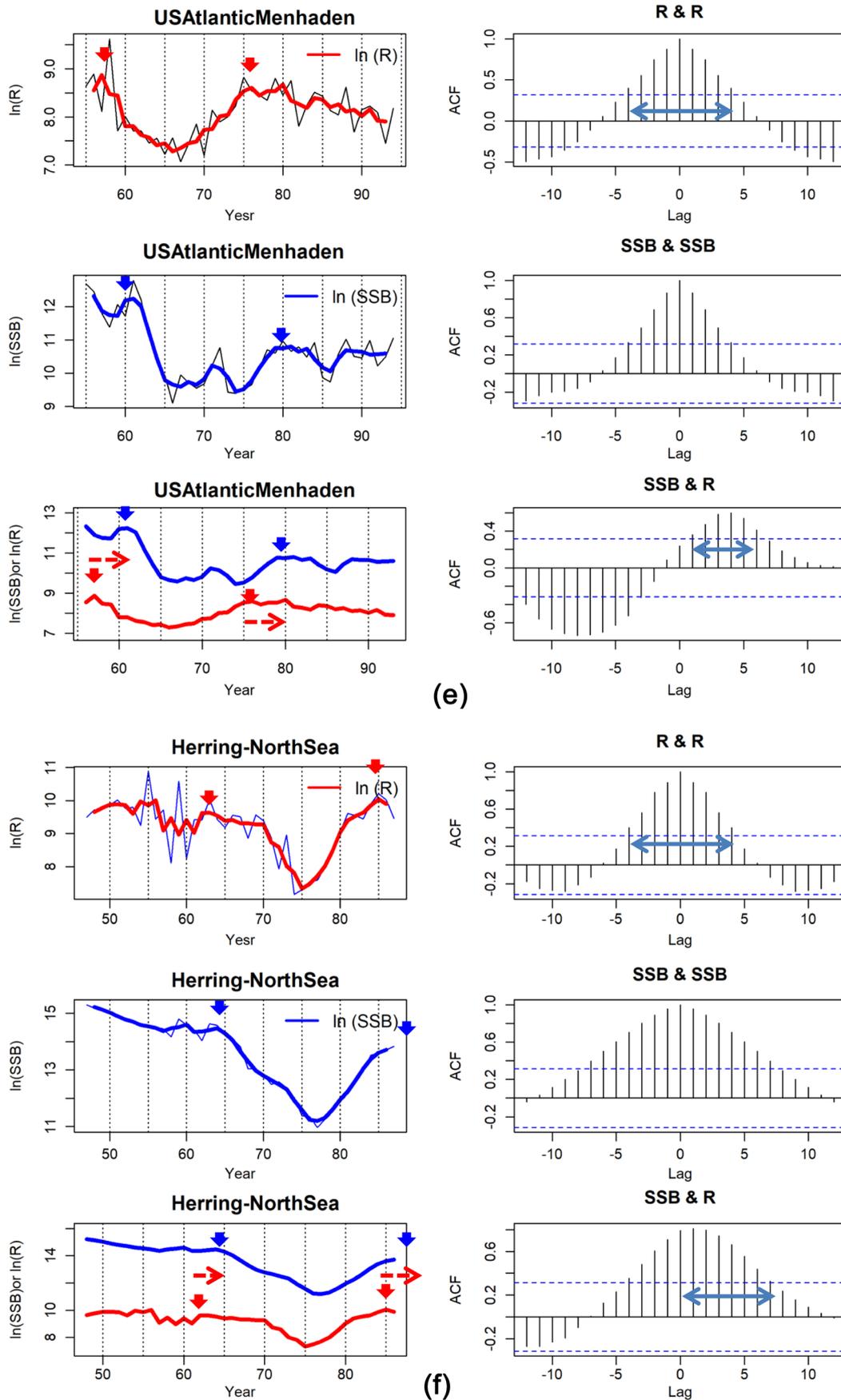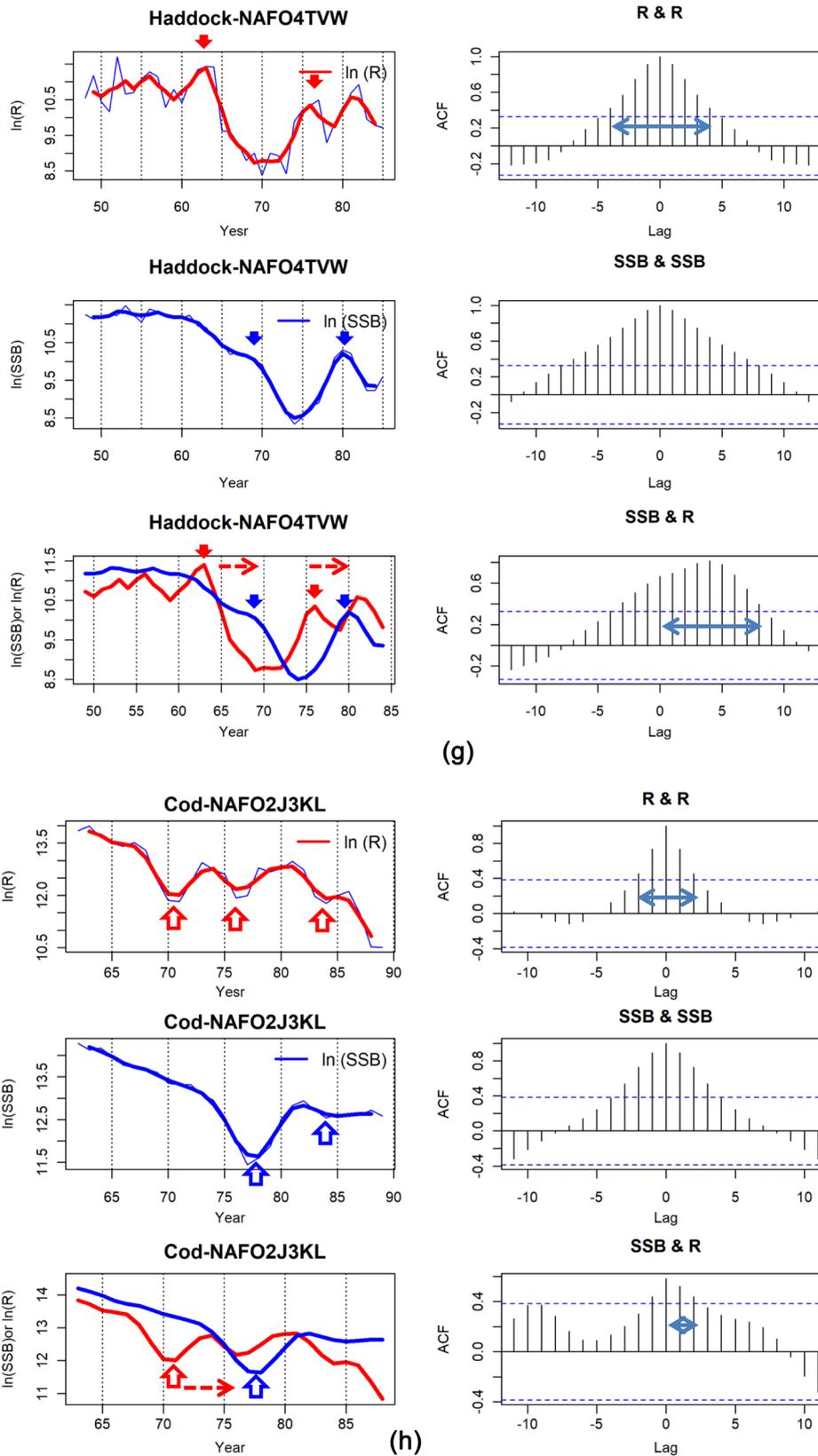**(c)**

(d)

Figure 5. Trajectories of the natural logarithms of R and SSB, *i.e.*, ln R and ln SSB, and their 3-year moving averages, ln R* and ln SSB*, for each stock, respectively (left panel). Auto-correlations of ln R* and ln SSB*, and cross-correlations of ln R* and ln SSB* (right panel) for each stock from (a) to (h), respectively.

ln R* (shown by a red line) and ln SSB* (shown by a blue line), for each stock, respectively. The bottom left panels in Figures 5(a)-(h) simultaneously show the trajectories of ln R* (shown by red line) and ln SSB* (shown by blue line) in the same panel for each stock. The arrows indicate the vertexes observed in the trajectories. The vertexes observed in ln R* were projected to the vertexes observed in ln SSB* with certain time lags corresponding to the age at maturity. The time lags are shown by horizontal red arrows. The right panels in Figures 5(a)-(h) show the auto-correlations of ln R* and ln SSB* and the cross-correlations between ln R* and ln SSB*, respectively.

Figure 5(a) shows the case of Saithe living in the waters off Iceland. The values of ln R* were high around 1965 and then decreased. The second vertex was observed around 1976, and then the values decreased again. The third vertex was observed around 1984, and then the value decreased. The mean period between vertexes was about 10 years. In general, R is considered to be much more seriously influenced by environmental conditions than SSB, because SSB is strongly influenced not only by environmental factors but also by harvesting. The period between vertexes seems to represent the cycle of environmental conditions. The autocorrelation of ln R* had significantly positive values for time lags of −2, −1, 0, 1, and 2, which are indicated with horizontal arrows. This 5-year period corresponds to half of the cycle of environmental conditions, because if the environmental conditions fluctuate cyclically as in a sine or cosine curve, both the positive and negative values of autocorrelation must appear in one cycle. Therefore, the cycle of environmental conditions is constructed by positive 5-year and negative 5-year, *i.e.*, it is estimated at 10 years. This cycle corresponds to the average number of years between the vertexes.

The third panel on the right in Figure 5 shows the cross-correlation of ln R* and ln SSB*. When the time lags were 5, 6, 7, 8, 9 and 10, the values of the cross-correlation were statistically positive with a 5% significance level. The maximum value of the cross-correlation is shown in red in Table 1. These time lags seem to reflect the ages of matured fish. That is, the ages of matured fish range from the age at maturity to their life expectancy.

Figure 5(b) shows the case of Silver Hake in NAFO5Ze. The first, second and third vertexes were observed around 1958, 1972 and 1984, respectively. The significantly positive values of the auto-correlation of ln R* were distributed from −6 to 6. That is, half of the cycle of environmental conditions was estimated to be 13 years; therefore, the cycle of environmental conditions was estimated to be about 26 years, which was more than two times longer than that of Saithe in Iceland. Figure 5(c) shows the case of sardines in South Africa. The first and second vertexes were observed around 1957 and 1967, respectively. The significantly positive values of the auto-correlation of ln R* were distributed from −3 to 3. That is, half of the cycle of environmental conditions was estimated to be 7 years, and the cycle of environmental conditions was estimated to be about 14 years.

Table 1. Basic biological parameters and the results obtained from this analysis for each of the eight stocks. Red shows the highest value of the cross-correlation between ln R* and ln SSB*.

	Stock	Age at recruitment	Age at maturity	Time lags (5% significant)	Cycle in R	Clockwise	Anti-clockwise	Slope	Lower limit	Upper limit	*p*-value
a	Saithe-Iceland	3	5	5, 6, 7, 8, 9, 10	10	16	10	−0.663	−1.073	−0.254	2.67 (10^{-3})
b	SilverHake-NAFO5Ze	1	2	0, 1, 2, 3, 4, 5, 6, 7, 8	26	22	7	0.755	0.561	0.948	1.05 (10^{-9})
c	Sardine-South Africa	1	2	0, 1, 2, 3, 4, 5, 6	14	13	14	0.301	−0.012	0.614	5.86 (10^{-2})
d	Saithe-Faroe	3	5	4, 5, 6, 7	10	24	4	−1.756	−2.253	−0.958	1.11 (10^{-4})
e	US Atlantic Menhaden	1	2.5	2, 3, 4, 5, 6, 7	18	27	9	0.064	−0.120	0.247	0.484
f	Herring-North Sea	1	3	0, 1, 2, 3, 4, 5, 6, 7	18	29	9	0.495	0.381	0.609	1.39 (10^{-9})
g	Haddock-NAFO4TVW	1	4.5	0, 1, 2, 3, 4, 5, 6, 7, 8	18	20	14	0.520	0.271	0.768	1.63 (10^{-4})
h	Cod-NAFO2J3KL	3	7	0, 1, 2	10	8	14	0.235	−0.104	0.574	0.162

Figure 5(d) shows the case of Saithe in Faroe. The first and second vertexes were observed around 1967 and 1984, respectively. The significantly positive values of the auto-correlation of ln R* were distributed from −2 to 2. That is, half of the cycle of environmental conditions was estimated to be 5 years, and the cycle of environmental conditions was estimated to be about 10 years. **Figure 5(e)** shows the case of US Atlantic Menharden. The first and second vertexes were observed around 1958 and 1975, respectively. The significantly positive values of the auto-correlation of ln R* were distributed from −4 to 4. That is, half of the cycle of environmental conditions was estimated to be 9 years, and the cycle of environmental conditions was estimated to be about 18 years.

Figure 5(f) shows the case of herring in the North Sea. The first and second vertexes were observed around 1963 and 1985, respectively. The significantly positive values of the auto-correlation of ln R* were distributed from −4 to 4. That is, half of the cycle of environmental conditions was estimated to be 9 years, and the cycle of environmental conditions was estimated to be 18 years. **Figure 5(g)** shows the case of Haddock in NAFO4TVW. The first and second vertexes were observed around 1963 and 1977, respectively. The significantly positive values of the auto-correlation of ln R* were distributed from −4 to 4. That is, half of the cycle of environmental conditions was estimated to be 9 years, and the cycle of environmental conditions was estimated to be 18 years. **Figure 5(h)** shows the case of Cod-NAFO2J3KL. This case is easier to discuss using the valleys. The first, second and third valleys were observed around 1971, 1976 and 1984, respectively. The significantly positive values of the auto-correlation of ln R* were distributed from −2 to 2. That is, half of the cycle of environmental conditions was estimated to be 5 years, and the average cycle of environmental conditions was estimated to be 10 years. **Table 1** summarizes the results mentioned above.
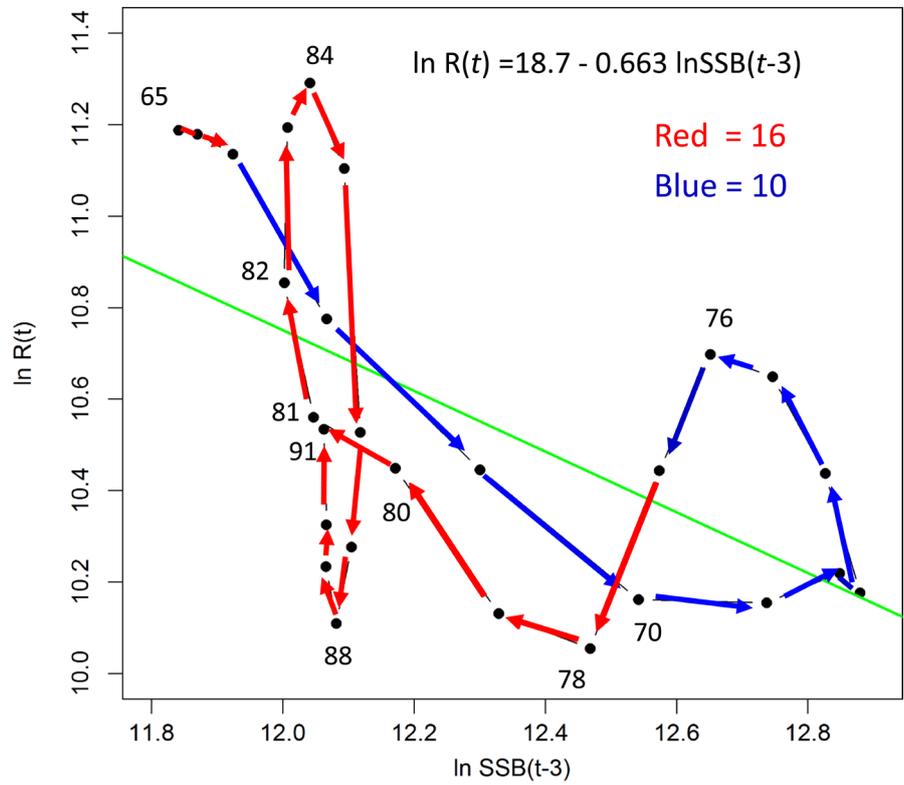
3.2. Clockwise or Anticlockwise Loops in SRR

Figure 6 shows the SRRs for the 8 stocks that corresponds to **Figure 1** of Myers *et al.*'s paper [19]. That is, a pair including ln R⋆ in year *t*, *i.e.* $\ln R_t^*$, and ln SSB⋆ in year *t* − *d*, *i.e.* $\ln SSB_{t-d}^*$, *i.e.*, ($\ln SSB_{t-d}^*$, $\ln R_t^*$), was plotted, and the figures on the graph denoted the year when the R⋆ occurred. Here, *d* denotes the age at R. **Figure 6(a)** shows the case when the data of Saithe that live in the waters off of Iceland were plotted. The arrow colored blue indicates that the line from year *t* to year *t* + 1 is part of an anticlockwise loop. The arrow colored red indicates that the line from year *t* to year *t* + 1 is part of a clockwise loop. According to Sakuramoto, the color of arrow that is dominant deeply relates to the age at maturity and the environmental cycle. If the age at maturity is greater than half of the length of the environmental cycle, blue arrows are dominant, and if the age at maturity is less than half the length of the environmental cycle, red arrows are dominant [10] [14] [16] [17]. In the case of Saithe in Iceland, the age at maturity is equal to half of the length of the environmental cycle, and so the dominant color of the arrows is not clear; in practice, the numbers of blue and red arrows were not much different. In cases (b), (e), (f) and (g), the age at maturity was less than half of the environmental cycle, and the red arrows were more dominant than the blue arrows. In case (c), the age at maturity was less than half the length of the environmental cycle; however, the number of red arrows was smaller than the number of blue arrows, although the difference was not large. In case (d), the age at maturity was equal to half of the length of the environmental cycle; however, the number of red arrows was much higher than the number of blue arrows. These two cases were the exceptions to the loop theory. In the case of cod in NAFO2J3KL, the age at maturity was much greater than half of the length of the environmental cycle, and the number of blue arrows was greater than the number of red arrows.

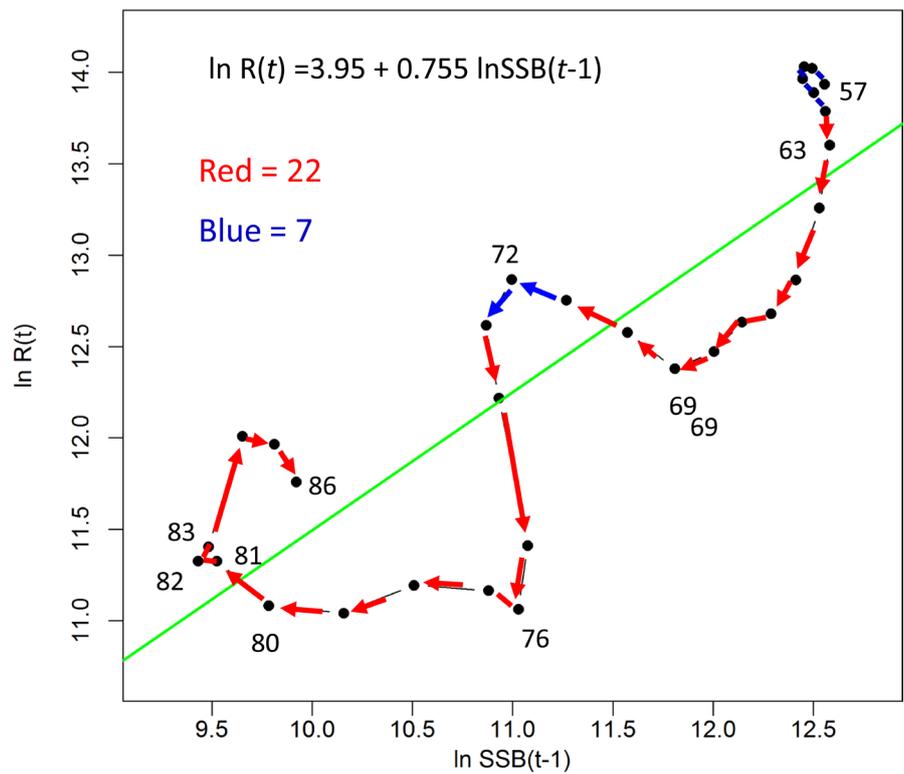## 3.3. The Slope of the Regression Line Drawn on the SRR

Figure 6 also shows the slope of the regression line as a green line drawn on the SRR plain. The slopes seem to have some relationship with their ages at maturity. In the stocks for which the age at maturity was low, the slopes were positive. **Figure 6(b)**, **Figure 6(f)**, and **Figure 6(g)** seem to show such cases. In the stocks for which the age at maturity was high and was close to half the length of the cycle of environmental factors, the slopes were close to zero. Cases (c) and (e) seem to be cases of this. In cases (a) and (d), the ages at maturity were high, and the slopes of the regression lines were both negative. In contrast, in case (h), the age at maturity was extremely large, even though the slope of the regression line was not negative but almost zero. These results were slightly different from those that the loop theory forecasted.

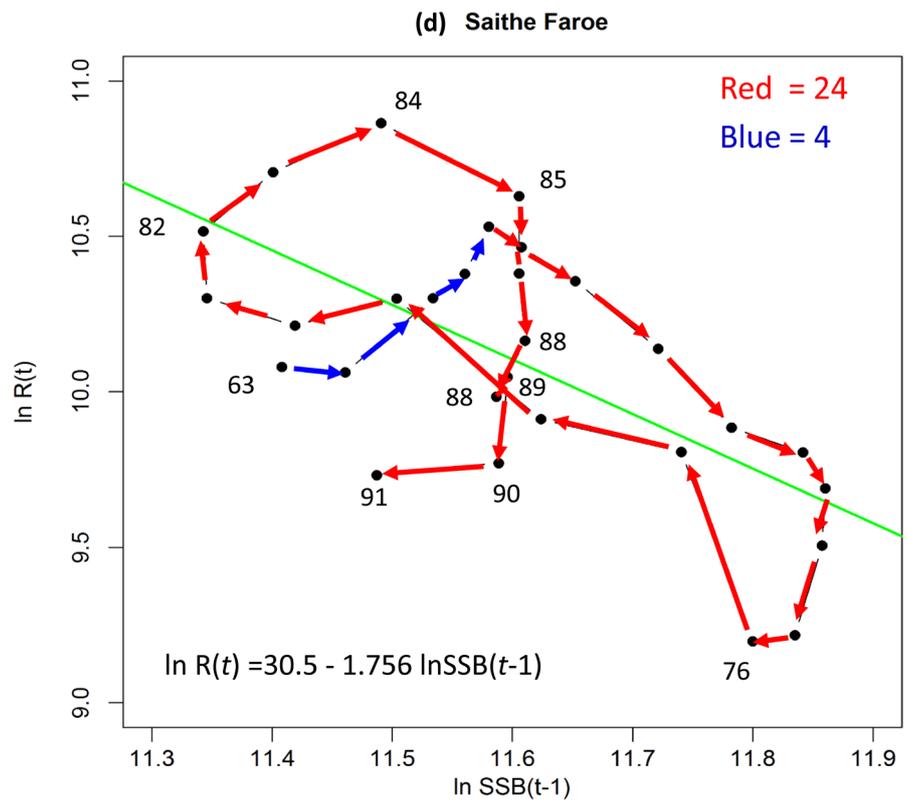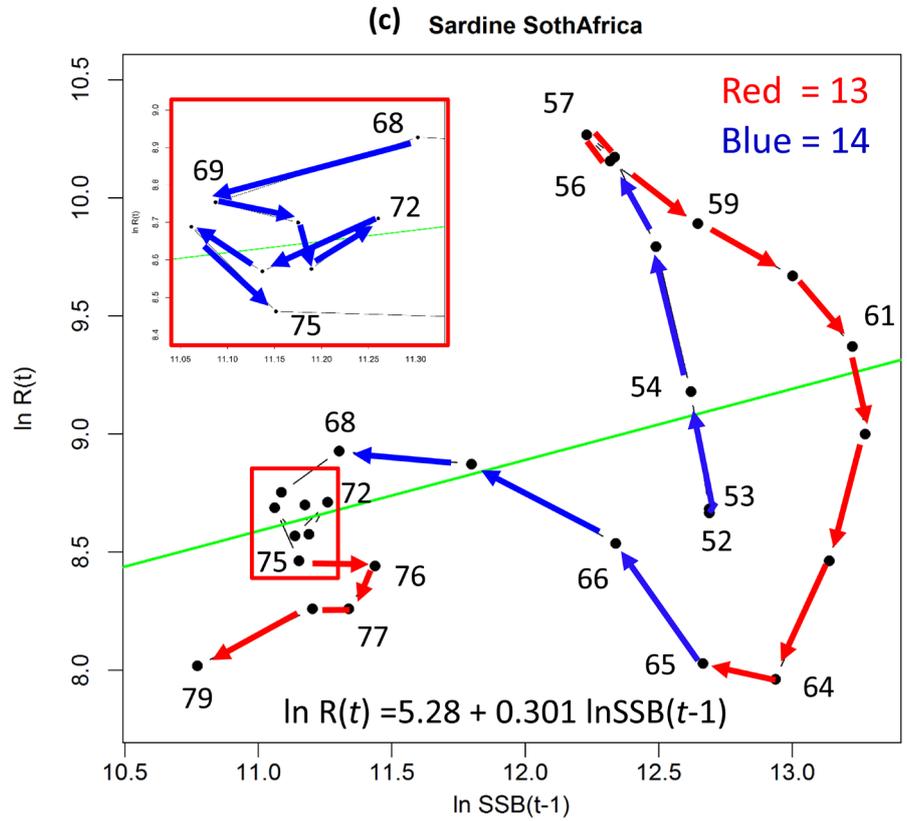**Figure 7** shows the relationship between the slope of the regression lines and the age at maturity for 36 stocks. Eight stocks were estimated in this study and were plotted with red open circles, 24 stocks were estimated by Tanaka *et al.* [17]

(a) Saithe Iceland

$\ln R(t) = 18.7 - 0.663 \ln SSB(t-3)$

Red = 16

Blue = 10

(b) SilverHake NAFO5Ze

$\ln R(t) = 3.95 + 0.755 \ln SSB(t-1)$

Red = 22

Blue = 7

(c) **Sardine SothAfrica**

Red = 13
Blue = 14

$\ln R(t) = 5.28 + 0.301 \ln SSB(t-1)$

(d) **Saithe Faroe**

Red = 24
Blue = 4

$\ln R(t) = 30.5 - 1.756 \ln SSB(t-1)$

(e) **US AtlanticMenhaden**

$\ln R(t) = 7.44 + 0.064 \ln SSB(t-1)$

Red = 27
Blue = 9

(f) **Herring NorthSea**

$\ln R(t) = 2.62 + 0.495 \ln SSB(t-1)$
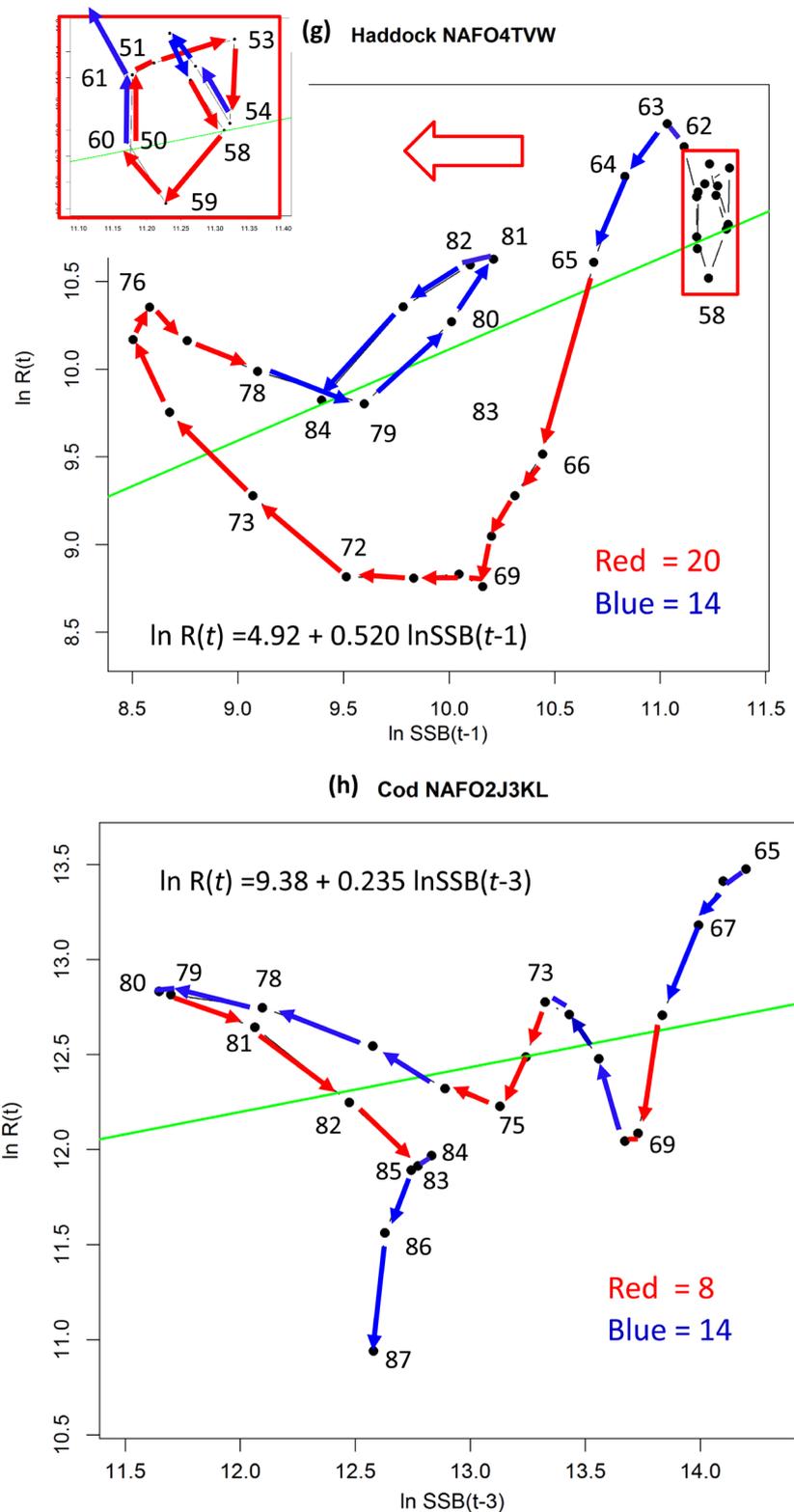
Red = 29
Blue = 9
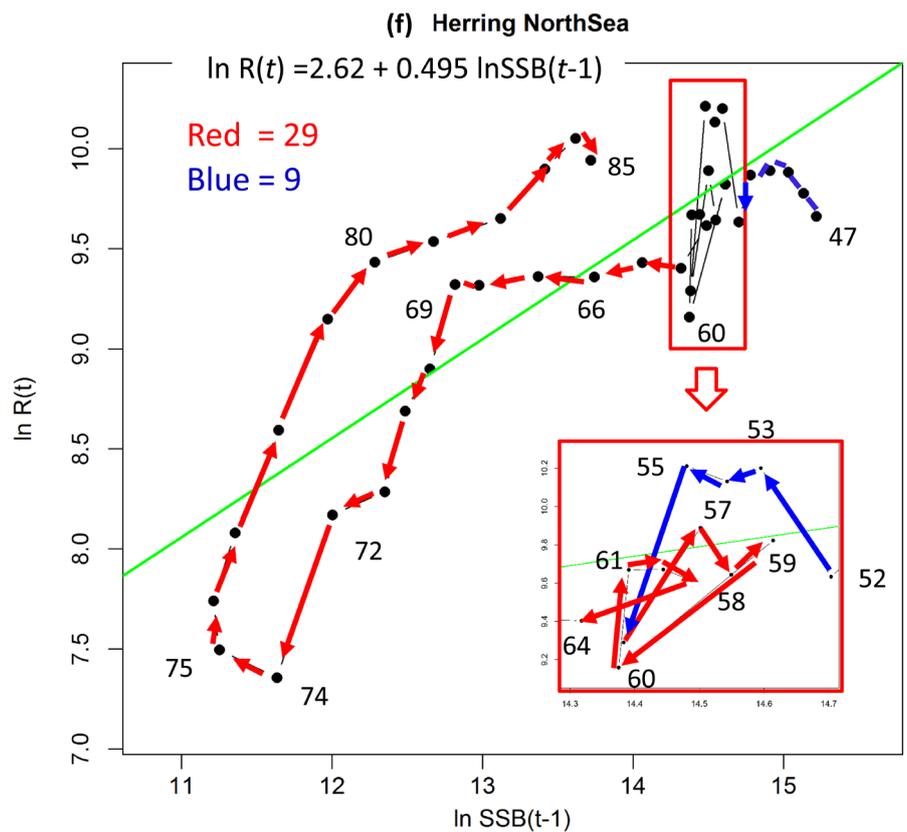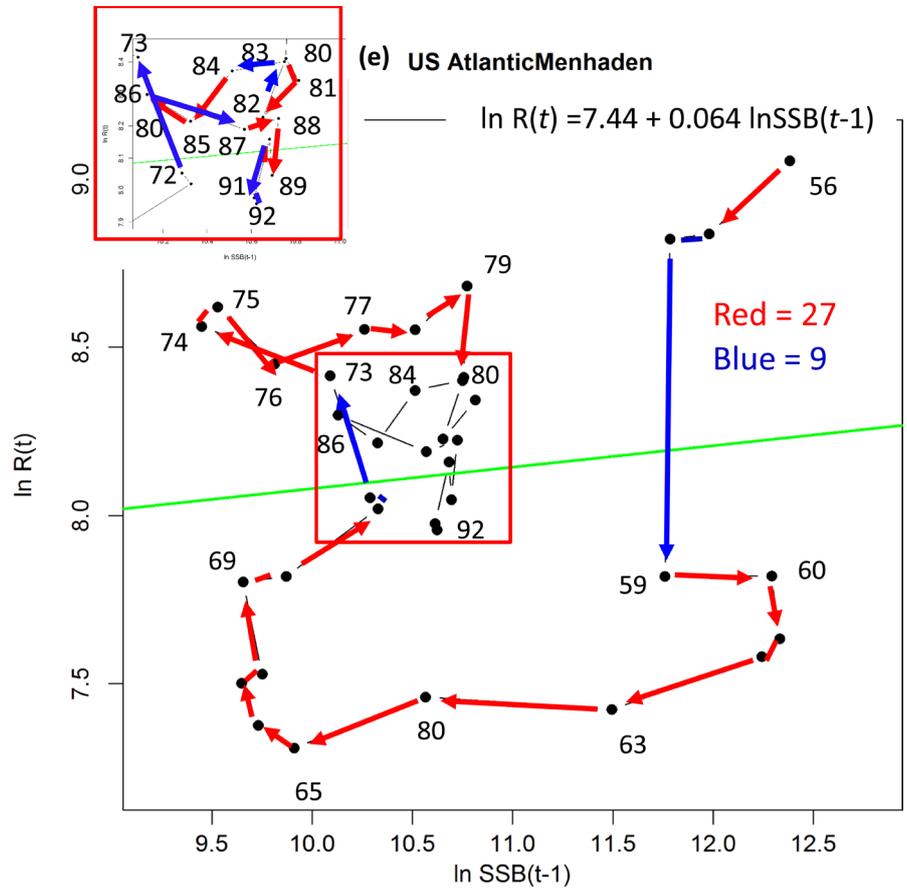
Figure 6. Stock-recruitment relationship for stocks (a) to (h), respectively. That is, a pair consisting of ln R_t and ln SSB_{t-d}, *i.e.*, (ln SSB_{t-d}, ln R_t), is plotted. The figures on the graph denote the year when the recruitment occurred. Here, d denotes the age at recruitment. The red and blue arrows indicate the line segments that are part of the clockwise or anti-clockwise loops. The green line is the regression line drawn on the SRR plane.
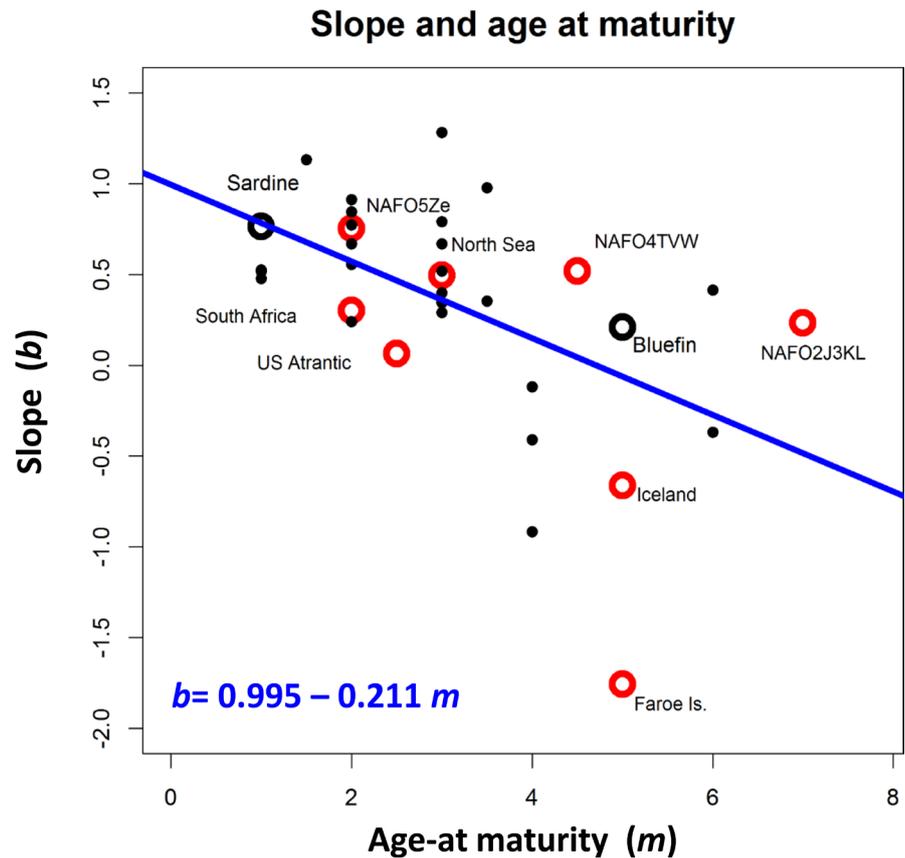
Figure 7. Relationship between the slope of the regression line (b) drawn on the SRR plane and the age-at-maturity (m). The slope was estimated as $b = 0.995 − 0.211\ m$. The 95% confidence intervals of the slopes were (−0.343, −0.097). That is, the negative slope is statistically significant at a 95% significance level.

and were plotted with black closed circles, and 2 stocks were estimated by Sakuramoto [14] and were plotted with black open circles. The slope of the regression line was

$$b = 0.995 - 0.211m. \tag{10}$$

Here, b and m denote the slope of the regression line and the age at maturity, respectively. The 95% confidence intervals of the slopes were (−0.343, −0.097), and those of the intercept were (0.541, 1.450). The p-values of the slope and intercept were 1.02×10^{-4} and 2.70×10^{-3}, respectively. That is, a significant negative relationship was detected between the slopes of the regression lines and the age at maturity. This result coincided well with the results of the simulations proposed by Sakuramoto [14].

4. Discussion

4.1. Clockwise or Anticlockwise Loops in the SRR

When we discuss the SRR, we usually plot R against SSB or ln R against ln SSB, and try to adapt an SRR model, such as the Ricker model, the Beverton and Holt model, or another model. However, we seldom connect the continuous years

from t to $t + 1$. If we draw the SRR as a line connecting the years from t to $t + 1$, an extremely different profile emerges. That is, clockwise loops or anticlockwise loops are commonly observed in the SRR [14] [15] [16] [17]. Few scientists, however, have focused on this fact, and as a natural result, few scientists have tried to elucidate the mechanism by which clockwise loops or anticlockwise loops emerge.

The loop theory proposed by Sakuramoto [14] [15] [16] can explain the mechanism by which clockwise loops or anticlockwise loops commonly appear in SRR. That is, R is proportionally determined by SSB, and R is simultaneously affected by the environmental factors at that time, which usually fluctuate cyclically. Therefore, the loop theory insists that a density-dependent effect is not an important factor in controlling the fluctuation, and the true mechanism that controls SRR must be explained in another way. In other words, the mechanism by which clockwise loops or anticlockwise loops commonly appear in SRR cannot be explained by the density-dependent effect.

In this study, I did not specify the typical environmental factors that controlled the fluctuations in the eight stocks analyzed in this paper, as an analysis of those factors would have been too time-consuming. However, some examples have already been investigated. For instance, the environmental factors that would control the fluctuations in the Pacific stock of Japanese sardines were already investigated in detail [14] [22] [23], as were those of Pacific bluefin tuna [14]. The main environmental factors found in those analyses were the index of Arctic Oscillation (AO) by month and the index of Pacific Decadal Oscillation (PDO) by month. Hasegawa *et al.* [24] also investigated the relationship between the catch fluctuation of pink salmon and environmental factors, and using the AO and/or PDO, they showed that the loop theory could be applied this stock. Therefore, I strongly believe that specifying the environmental factors that affect the population fluctuations of the eight stocks analyzed in this paper is also possible. In the next step in my future research, I will specify the environmental factors for each of the eight stocks.

In this study, I applied the loop theory to the data that Myers *et al.* analyzed in 1994 [19], and showed that the results were the same as those shown in Sakuramoto [14] [15] [16] and Tanaka *et al.* [17]. That is, the clockwise or anticlockwise loops in SRR emerged depending on the age at maturity, and the slope of the regression line had a negative slope with the age at-maturity. When age at maturity was high, however, there were two exceptions in this study. In particular, the age at maturity of Saithe in Faroe is 5 years, which is relatively high; however, the number of line segments with a clockwise direction was greater than the number with an anticlockwise direction.

It is difficult to explain in detail why the exception occurred at this stage; however, some of the possible reasons include the following. Hasegawa *et al.* [24] noted that even when the age at maturity is low, the SRR can show anticlockwise loops when strong species interactions can be assumed to exist. In the case of pink salmon, the stock born in the odd-numbered years had clockwise

loops and the stock born in the even-numbered years had anti-clockwise loops. These two stocks have the same age at maturity; that is, they come back to their native river for spawning 2 years after they were spawned. However, it was found that the catches in odd and even years had a significant negative correlation with each other with 10% significant level. Thus, when a negative correlation was present, the clockwise loops changed to anti-clockwise loops. Therefore, the direction of the loops can be strongly influenced not only by the age at maturity and the cycle of environmental factors, but also by species interactions. Therefore, we should further investigate the biological relationships between the stocks.

The age at maturity seems to be determined on a species-by-species or stock-by-stock basis. However, even in the same species, the environmental conditions that affect the population fluctuations are different in different habitats. Further, even in the same habitat, the length of the environmental cycle itself changes era by era. Therefore, the number of line segments that with a clockwise or anti-clockwise direction differed by stock and by era. In the case of Saithe Faroe, the age at maturity is high, 5 years; however, the number of line segments that show the clockwise loop is much greater than the number of line segments that show the anti-clockwise loop. In order to discuss these phenomena, we should further examine the environmental conditions and species interactions for each stock.

The results obtained for 24 stocks that live around Japan [17] coincided with the results obtained in this study. That is, although the construction mechanism of the SRR is complex, loops always appear for all SRRs. The areas where the stocks that were analyzed by Tanaka *et al.* live [17], and the areas where the stocks that were examined in this paper live were quite different, but the essential results coincided well.

4.2. Slope of the Regression Lines in SRR

Sakuramoto noted that the slopes of the regression lines adapted for SRR were determined by the age at maturity and the cycle of environmental factors [14] [16]. When the age at maturity is low enough compared to the cycle of environmental factors, the slope estimated by a simple regression method, in which $\ln(R_t)$ is plotted against $\ln(SSB_{t-d})$, shows a positive value, although the slope is statistically less than unity. When the age at maturity is close to half of the length of the cycle of environmental factors, the slope of the regression line is close to zero and is not statistically different from zero. Furthermore, the age at maturity becomes greater than the length of half of the cycle of environmental factors, the slope of the regression line becomes negative. Sakuramoto [14] showed that the slope of the Pacific stock of Japanese sardines, the age at maturity of which is one year, was close to unity, at 0.764, although it was statistically less than unity. This finding is very important because it shows that a density-dependent effect is erroneously detected for stocks for which the age at maturity is low. In contrast, the results of this paper show that no relationship between R and SSB is com-

monly observed for stocks with a high age at maturity. For instance, the SRR of Pacific bluefin tuna showed no relationship between R and SSB, and the plots were widely scattered without any relationship [14] [25]. The Beverton and Holt model or the hockey stick model [26] is usually applied as the SRR for Pacific bluefin tuna, and the steepness of the SRR, which is one of the important parameters in the stock assessment, are often discussed to determine the reference points [19] [20] [25]. However, this paper suggests that the Beverton and Holt model or hockey stick model is not appropriate for this stock, and so a discussion based on the steepness would be meaningless.

The intercept of the regression line was 0.995 and the 95% confidence intervals were 0.541 and 1.450. This can be anticipated from the loop theory, the principle of which is shown in Figure 3(a). Generally, the age at recruitment is lower than the age at maturity, because immature fish are commonly harvested. This clearly indicates $d \leq m$. Figures 1-3 show that the SRR corresponds to the R-R relationship. In Model 2, the SRR was expressed by $R_{t+m+d} = \alpha(1+r)S_{t+m}$. When $m = 0$, and $d = 0$, the SRR becomes $R_t = (1+r)S_t$. That is, $\ln(R_t) = \ln(1+r) + \ln(S_t)$. This indicates that the slope of SRR becomes unity. Similarly, in Model 3, the SRR was expressed by $R_{t+m+d} = \alpha[1+\beta\sin(\omega(t+m+d))]S_{t+m}$. When $m = 0$, and $d = 0$, the SRR becomes $R_t = [1+\beta\sin(\omega(t))]S_t$, that is, $\ln(R_t) = \ln(1+\beta\sin(\omega(t))) + \ln(S_t)$. Then, the slope becomes unity.

I set a rule that determines the direction of the line segment from year t to year $t + 1$; however, this rule is only a tentative example. A much more reasonable rule must exist; however, the aim of making the rule is to avoid doing the definition arbitrarily. In any case, if someone determines the direction of the line without any rule, the results will not be very different.

Hilborn and Stokes [20] strongly warned the use of the unfished biomass $B_{unfished}$ to determine the reference points as follows. The standard approaches to biomass reference points in the United States and Australia fail to make clear that they are tied to an almost unknowable quantity, the unfished biomass $B_{unfished}$. The target and limits for fisheries management based on historical stock sizes and stock productivity have the advantage that they are based on experience, are easily understood, and are not subject to the vagaries of model assumptions. The results of this paper strongly support the warning noted by Hilborn and Stokes [20] from a different point of view.

In the scientific committee of the International Whaling Commission, major discussions and simulation studies have been conducted for more than 5 years in order to develop a revised whale management procedure [27]. Tanaka [28] proposed a new management procedure that did not assume any population model; this procedure has been called the "model independent fisheries resources management approach". Using this theory, Sakuramoto and Tanaka [29] proposed a simulation model that could manage baleen whale stocks without any population model, and without any parameters, such as MSY, B_{MSY} and B_0, etc. That procedure only required a relative value for population abundance. The simula-

tion program used the catch per unit of effort (CPUE) as the relative value of population abundance. The procedure commenced using two indexes: the present CPUE level compared to the target CPUE level, and the increasing or decreasing trend of the CPUE. If the present CPUE is lower than the target CPUE, the catch quota is reduced and vice versa. Further, if the CPUE shows an increasing trend, the catch quota is increased, and vice versa. The target CPUE can be determined, for instance, as follows: if the CPUEs of 10 to 15 years ago were reasonable, the average CPUE for those years can be used as the target level for the management. When this procedure is applied to actual fish stocks, very detailed simulation trials should be done to determine which parameters are reasonable, by species. However, previous studies [27] [29] showed that the results of this procedure were acceptable. Therefore, I strongly emphasize that empirical reference points should be used, not B_0, $B_{unfished}$ and B_{MSY}, the scientific basis of which is unclear.

5. Conclusions

The results elucidated in this paper can be summarized as follows:

1) Loop theory can be applied to the eight stocks that Myers *et al.* [19] investigated.

2) When the age at maturity was low enough compared to the length of the cycle of the environmental factors, clockwise loops were dominant, and when the age at maturity was high compared to the length of the cycle of the environmental factors, anticlockwise loops were dominant.

3) The slope of the regression line for SRR had a negative correlation with the age at maturity. When the age at maturity was low, the slope was positive but less than unity. When the age at maturity became high, the slope decreased to zero. In this case, no relationship was observed between R and SSB.

4) Reference points derived from the traditional SRR model do not have any scientific basis. B_0, $B_{unfished}$ and B_{MSY} should not be used as the reference points.

5) Empirical reference points should be used, as Hilborn and Stokes [20] emphasized.

Acknowledgements

Competing Financial Interests

The author declares no competing financial interests.

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