ICES Journal of Marine Science, 62: 841–846 (2005)
doi:10.1016/j.icesjms.2005.04.002

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Evaluation of current and alternative fisheries management scenarios based on spawning-per-recruit (SPR), revenue-per-recruit (RPR), and yield-per-recruit (YPR) diagrams

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Katsukawa, T. 2005. Evaluation of current and alternative fisheries management scenarios based on spawning-per-recruit (SPR), revenue-per-recruit (RPR), and yield-per-recruit (YPR) diagrams. – ICES Journal of Marine Science, 62: 841–846.

Spawning-per-recruit (SPR) and yield-per-recruit (YPR) analyses are widely used in stock assessments of exploited fish populations. In decision-making for fisheries management, the trade-off between fisheries production (YPR) and stock reproduction (SPR) is important. The general outputs of SPR and YPR analysis, such as single variate plots with contour lines or optimal harvest strategies estimated by numerical optimization, are inappropriate in obtaining an overview of the trade-off. This paper introduces a diagram that expresses graphically the bivariate trade-off between YPR and SPR. The method was applied to chub mackerel (*Scomber japonicus*) data, and two management scenarios were compared using the SPR–YPR diagram. Differences between YPR and revenue-per-recruit (RPR) were also considered. The results showed that: (i) current estimated fishing mortality is suggestive of growth-overfishing, and there is room for improving SPR and YPR simultaneously; (ii) increasing the age at first capture is more effective than effort control; (iii) management strategies that maximize landing weight or revenue are significantly different. The management strategy that maximizes landing weight, when considered from the viewpoint of maximizing revenue, results in growth-overfishing.

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Keywords: chub mackerel, revenue per recruit (RPR), size-dependent price, spawning per recruit (SPR), yield per recruit (YPR).

Received 14 May 2004; accepted 5 February 2005.

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Introduction

Yield-per-recruit (YPR) analysis (Beverton and Holt, 1957) and spawning-per-recruit (SPR) analysis (Prager *et al.*, 1987; Gabriel *et al.*, 1989; Goodyear, 1993) are regularly applied to stock assessments of exploited fish populations. YPR analysis, which focuses only on yield, can only be used to assess growth-overfishing. In contrast, SPR analysis focuses only on reproduction and can only be used to assess recruitment-overfishing. To effectively manage stocks, however, fisheries production (YPR) and stock reproduction (SPR) must be considered simultaneously.

The outputs of SPR and YPR analyses are two-dimensional contour plots for combinations of fishing mortality and age at recruitment in each case. Such figures are useful for assessing how to improve YPR and SPR separately, but it may be difficult to consider the trade-off between SPR and YPR. Another popular output involves analytical optimization methods, such as Lagrange's method (Takenaka and Matsuda, 1997; Matsuda *et al.*, 1999). Although optimization methods can identify the harvest policy that maximizes yield under the constraint of the SPR level, they do not provide an overview of the trade-off between SPR and YPR.

This paper introduces a method of graphically representing the trade-off between SPR and YPR. The diagram can be used to express the possible combinations of SPR and YPR under various management scenarios. The diagram can also be used to evaluate the current fisheries practice. I applied this method here to the Pacific population of chub mackerel (*Scomber japonicus*) around Japan, and the results are presented as an example.

Method

SPR–YPR and SPR–RPR diagrams

The SPR–YPR (or SPR–RPR) diagram is a scatterplot whose vertical and horizontal axes are YPR (or RPR) and

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%SPR, respectively. By plotting the performance of alternative management options, the diagram provides an overview of the joint distribution of SPR and YPR (or RPR). Because SPR and YPR (or RPR) analyses are routinely conducted in stock assessments, it is not necessary to present a detailed description of the analyses in this paper. Instead, I present the method by which possible combinations of %SPR and YPR or RPR (i.e. the area occupied for all possible values of fishing mortality during each fishing season) can be drawn on the SPR−YPR and SPR−RPR diagrams.

Model

The lifetime of fish was divided into months; the first month after recruitment is month 1. It is assumed that the fishing mortality occurs instantaneously in the middle of the month, and that spawning is at the end of the month. Natural mortality M is assumed to be constant across months, and F_i denotes the fishing mortality in month i. The survival rate from recruitment to the spawning season of month i is $\exp[-iM - \sum_{j=1}^{i} F_j]$. Thus, SPR is expressed as (see Appendix for details):

$$\begin{aligned}\mathrm{SPR} &= \sum_{i=1}^{\infty} m_i \exp\left[-iM - \sum_{j=1}^{i} F_j\right] \\ &= \sum_{i=1}^{\infty} m_i e^{-iM} - \sum_{i=1}^{\infty}\left[a_i \sum_{j=i}^{\infty} m_j e^{-jM}\right] \\ &= \mathrm{SPR}_{100\%} - \sum_{i=1}^{\infty}\left[a_i \sum_{j=i}^{\infty} m_j e^{-jM}\right] \qquad (1)\end{aligned}$$

where m_i represents fecundity in month i, $\mathrm{SPR}_{100\%}$ is the SPR without fishing mortality, and a_i is a constant defined as follows:

$$a_i = \left(1 - e^{-F_i}\right)\exp\left[-\sum_{j=1}^{i-1} F_j\right] \qquad (2)$$

Although YPR analyses usually focus on the total weight of the harvest, the yield obtained at each age can be rescaled using an appropriate measure of value (Die *et al.*, 1988). In the following section, I refer to YPR as the landing weight per recruit (g), and RPR as the revenue per recruit (yen). The survival rate at the beginning of exploitation in month i is $\exp[-(i-0.5)M - \sum_{j=1}^{i-1} F_j]$. Thus, RPR and YPR can be expressed as follows:

$$\begin{aligned}\mathrm{RPR} &= \sum_{i=1}^{\infty} p_i\left(1 - e^{-F_i}\right)\exp\left[-(i-0.5)M - \sum_{j=1}^{i-1} F_j\right] \\ &= \sum_{i=1}^{\infty}\left[a_i p_i e^{-(i-0.5)M}\right] \qquad (3)\end{aligned}$$

$$\begin{aligned}\mathrm{YPR} &= \sum_{i=1}^{\infty}\left[w_i\left(1 - e^{-F_i}\right)\exp\left(-(i-0.5)M - \sum_{j=1}^{i-1} F_j\right)\right] \\ &= \sum_{i=1}^{\infty}\left[a_i w_i e^{-(i-0.5)M}\right] \qquad (4)\end{aligned}$$

where p_i is the profit expected from yielding an individual in month i (yen) and w_i is the weight of an individual in month i (gram).

Define vector $\vec{v}_i$ as follows:

$$\vec{v}_i = \left(-\sum_{i=j}^{\infty} m_j e^{-jM}, p_i e^{-M(i-0.5)}\right) \qquad (5)$$

The pair (SPR, RPR) for a certain set of a_i can then be expressed as

$$(\mathrm{SPR}, \mathrm{RPR}) = (\mathrm{SPR}_{100\%}, 0) + \sum_{i=1}^{\infty} a_i \vec{v}_i \qquad (6)$$

The definition of (SPR, YPR) is analogous. By changing F_i from 0 to ∞, a_i moves between 0 and $\exp[-\sum_{j=0}^{t-1} F_j]$. Because $\exp[-\sum_{j=0}^{t-1} F_j] = 1 - \sum_{j=1}^{t} a_j$ (see Equation A3), the bounds on a_i are expressed as follows:

$$0 \le a_i \le 1 - \sum_{t=1}^{i-1} a_t \qquad (7)$$

$$(\text{for } i = 1, 2, \ldots, \infty)$$

$$0 \le \sum_{t=1}^{\infty} a_t \le 1$$

The possible combinations of (SPR, RPR) are shown by Equations (6) and (7). If exploitation occurs only between month x and month y, (SPR, RPR) can be expressed as follows:

$$(\mathrm{SPR}, \mathrm{RPR}) = (\mathrm{SPR}_{100\%}, 0) + a_x \vec{v}_x + a_y \vec{v}_y \qquad (8)$$

$$0 \le a_x + a_y \le 1$$

Let o′ be ($\mathrm{SPR}_{100\%}$, 0), and the possible combinations of (SPR, RPR) can then be expressed by the triangle defined by o′, $o' + \vec{v}_x$, and $o' + \vec{v}_y$ (the grey area in Figure 1a). If exploitation occurs at age 1−∞, then the possible combinations of (SPR, RPR) are expressed by the convex closure of $o' + \vec{v}_i$ $(i = 1, 2, \ldots \infty)$ (the grey area in Figure 1b). The upper right edge of the grey area (the dotted line in Figure 1b) represents the maximum %SPR for a given RPR level. On the dotted line, RPR can be improved by sacrificing SPR. Thus, the dotted line represents the trade-off between SPR and RPR.

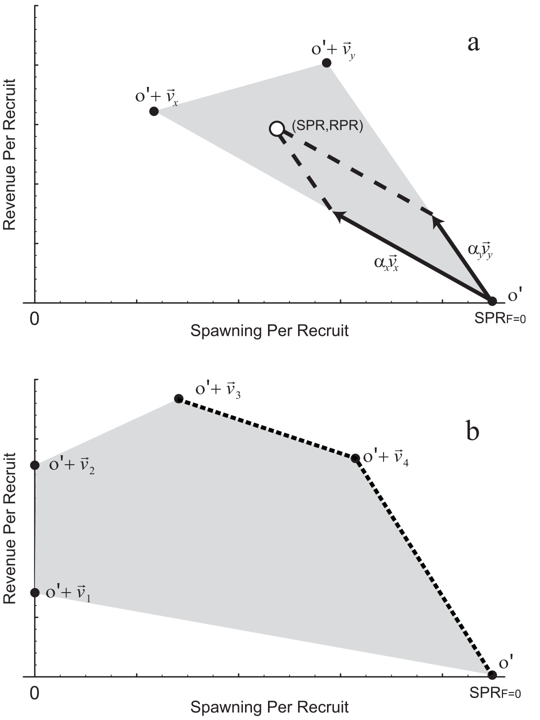

Figure 1. An example of an SPR–RPR diagram. If exploitation occurs only at ages x months and y months, the possible combinations of (SPR, RPR) can be expressed by the triangle defined by o', $o'+\vec{v}_x$, and $o'+\vec{v}_y$ (the grey area in a). If exploitation occurs at age 1–∞ months, then the possible combinations of (SPR, RPR) are expressed by the convex closure of $o'+\vec{v}_i$ $(i=1,2,\ldots\infty)$ (the grey area in b). The upper right edge of the grey area (dotted line in b) represents the maximum %SPR for a given RPR level.

The edge of convex closure consists of the dots and the lines between the dots. Therefore, the (SPR, RPR) on the dotted line (upper right edge of the convex closure) can be achieved by exploitation of one or two stages. For example, the dotted line in Figure 1b consists of the line between dots 3 and 4, and that between dot 4 and o′, the line between dots 3 and 4 can be achieved by harvesting a fraction of age 3 and then harvesting the entire age 4 component. The line between dot 4 and o′ can be achieved by harvesting a fraction of age 4. This result is consistent with the analytical work of Arditi and Dacorogna (1992). The highest dot in the SPR–RPR diagram represents maximum RPR. In the case of Figure 1b, dot 3 is the highest. Therefore, the RPR can be maximized if all individuals are exploited at month 3.

Example of chub mackerel

As an example, I drew the SPR–YPR and SPR–RPR diagrams for chub mackerel (*Scomber japonicus*), and examined the effectiveness of two management scenarios using this diagram. Chub mackerel are commercially important in the Japanese purse-seine fisheries. The stock was abundant in the 1970s, but declined in the early 1980s as a consequence of recruitment failure. Although recruitment successes were recorded in 1992 and 1996, most of the strong year classes were exploited before reaching maturity, and the chances of stock recovery were lost (Kawai *et al.*, 2002).

The time-step was monthly, with the spawning season stretching from May to June. The minimum age of maturity was 3 years (month 29 and month 30), and fecundity m_i in month i was:

$$m=0 \quad (\text{for } i<29)$$

$$m_i=0.2w_i \quad (\text{for } i=29,30)$$

$$m_i=0.5w_i \quad (\text{for } i=29+12j, 30+12j, \text{ where } j=1,2,3,\ldots)$$

Exploitation of the 0+ age class begins in January. The fishing mortality coefficients (mean for 1997–2001) for each age period (in months) are shown in Table 1 (Japanese Fisheries Agency, 2002). The von Bertalanffy growth curve was fitted to age-at-length data provided by the Japanese Fisheries Agency (2002) by maximum likelihood:

$$w_i=2402\{1-\exp[-0.0113(i+47.5)]\}^3$$

where w_i is the body weight (g) of an individual of age i months. The maximum weight is fixed at 1000 g. The price per kg increases with weight. Therefore, I defined the following size-based price function from marked price data:

$$p_i=15\times\left(\frac{w_i}{300}\right)^2 \qquad (9)$$

where p_i is the price (yen) of an individual at age i. The price and weight functions are shown in Figure 2.

Results

SPR–RPR diagram

Figure 3a shows the SPR–RPR diagram for chub mackerel. The dots $(SPR_{100\%},0)+\vec{v}_i$ $(i=1,2,\ldots,\infty)$ represent the SPR and RPR when all individuals of that age are harvested. The possible combinations of (SPR, RPR) are

Table 1. Fishing mortality coefficient of Pacific chub mackerel.

Months	Fishing mortality coefficient
1–5	0.032
6–17	0.049
18–29	0.058
30–41	0.056
42–53	0.074
54–∞	0.090

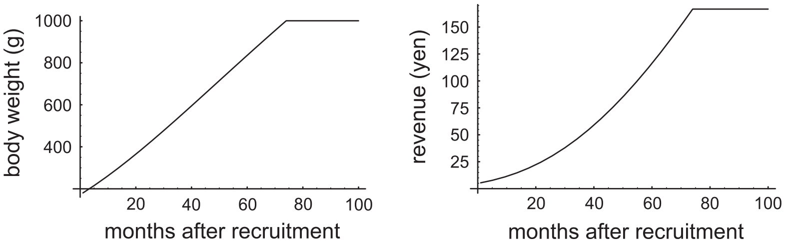

Figure 2. Body weight (g) and price (yen per individual) of chub mackerel.

expressed by the area enclosed by the dots (grey area in Figure 3).

The highest dot in Figure 3 corresponds to month 51. The maximum RPR is obtained if all fish are harvested at month 51. If all individuals are harvested at month 51, %SPR and RPR are 32.9% and 15.8 yen, respectively.

The asterisks in Figure 3 indicate the status of the current fishery. The current %SPR and RPR were estimated to be 7.6% and 10.8 yen, respectively. Because the asterisk is far from the dotted line, there is much room for improving SPR and YPR simultaneously. The current fishery, which exploits most of the stock before maturity, is considered to practice both recruitment- and growth-overfishing.

I evaluated two management plans using the SPR−RPR diagram. If fishing pressure is decreased while maintaining the current selectivity, the status of the fishery moves along the solid line in Figure 3b. The dotted line represents the management scenario that increases the age of recruitment while maintaining the fishing mortality coefficient after recruitment. The result shows that an increase in age at recruitment is more effective than a reduction of fishing effort. By increasing the age at recruitment, virtually the maximum RPR under a given SPR is achieved.

SPR−YPR diagram

Many stock assessments focus on the total weight of the harvest, rather than on the revenue. Therefore, I compared the difference between RPR and YPR analyses. Figure 4 shows the SPR−YPR diagram for chub mackerel. The grey area represents the possible combinations of (SPR, YPR). The grey area in the SPR−YPR diagram is a small band, which means that the YPR is roughly determined by the %SPR level. The YPR peaks at month 15 (186.2 g). Exploitation of young fish is acceptable if the management goal is to maximize YPR. The asterisk in Figure 4b indicates the status of the current fishery. The YPR level is nearly maximized under the current %SPR. In this case, the current age composition of the yield may be acceptable if the exploitation rate can be controlled.

Figure 4b shows the performance of two management scenarios. If we decrease fishing pressure while maintaining the current selectivity, the status of the fishery moves along the solid line in Figure 4b. The dotted line represents the management scenario that increases the age at recruitment, while the fishing mortality coefficient after recruitment remains unchanged. In the case of the SPR−YPR diagram, there is no significant difference between the two policies.

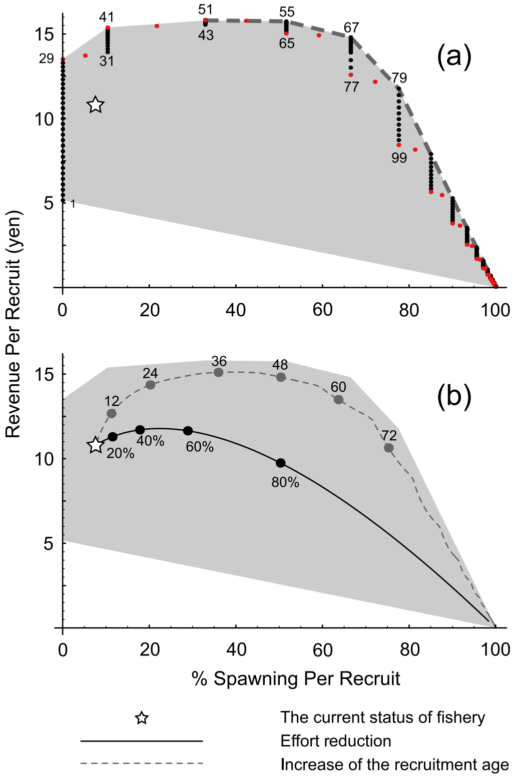

Figure 3. SPR−RPR diagram of chub mackerel. The dots in (a) indicate the points represented by $(\mathrm{SPR}_{100\%}, 0) + \vec{v}_i$ $(i = 1, 2, \ldots \infty)$. The small numbers in (a) represent i for each dot. The black and red dots indicate non-reproduction and reproduction months, respectively. The grey area indicates the possible combinations of RPR and %SPR. The asterisks indicate the current status. The solid and dotted curves in (b) represent management scenarios that involve effort reduction and increasing age at recruitment, respectively. The small number close to the solid curve indicates the percentage effort reduction. The number close to the dotted curve represents the recruitment month.

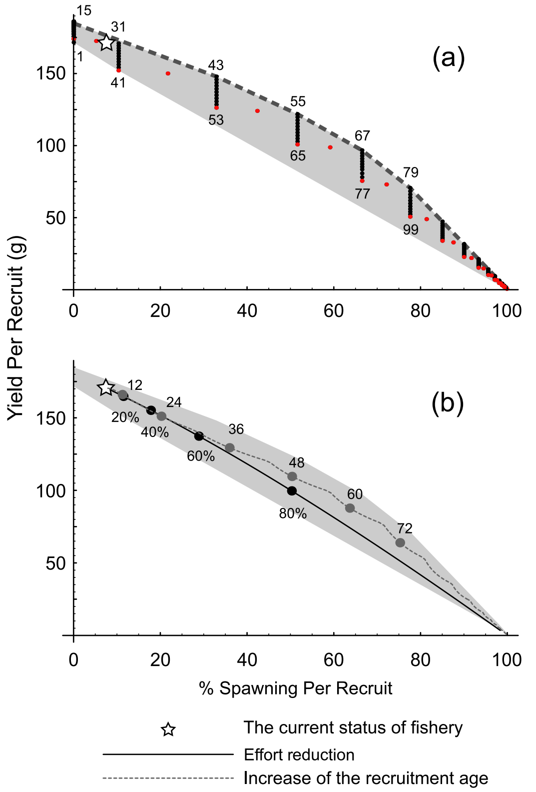

Figure 4. SPR−YPR diagram of chub mackerel. The dots in (a) indicate the point represented by $(\mathrm{SPR}_{100\%}, 0) + \vec{v}_i$ $(i = 1, 2, \ldots \infty)$. The solid and dotted curves in (b) represent management scenarios that involve effort reduction and increasing age of recruitment, respectively. See Figure 3 for full explanation.

Discussion

SPR−YPR diagram

The SPR−YPR diagram is useful for obtaining an overview of the trade-off between SPR and YPR, and may be a good starting point for stock assessment. Here I have presented a method for drawing the area of possible values in the SPR−YPR diagram. The upper right edge of the area of possible SPR−YPR pairs represents the highest YPR under a given %SPR. Achieving the maximum YPR is unrealistic, because we have to harvest whole populations in two specific fishing seasons. Nevertheless, it is useful to know how much YPR may be improved by further optimization of the fishing seasons.

Importance of the price function

Price differentials according to size are the rule rather than the exception in fisheries and should therefore be incorporated into any comparison of harvest strategies (Hilborn and Walters, 1992). This work showed that the optimal selectivity differs depending on whether the aim is to maximize revenue or landing weight. Gallagher *et al.* (2004) also compared the results of yield-per-recruit and revenue-per-recruit, and found that an early season opening date should be selected to maximize YPR; however, because of size-dependent market prices, delaying the season opening could generate higher total revenues.

In general, price per weight is higher for larger fish. Therefore, a high age at recruitment is preferable from the perspective of improving RPR. In the case of chub mackerel, the strategies selected by YPR and by RPR are completely different. Although modelling price is more difficult than modelling growth, it is worthwhile to calculate RPR.

Acknowledgements

I thank Drs Y. Katsukawa, H. Matsuda, T. Matsuishi, and A. Yatsu for valuable comments on the manuscript, and Dr M. Tokimura for helpful comments during the analytical stage of the work. This paper owes much to the thoughtful and helpful comments of two anonymous reviewers.

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Appendix

SPR and the constant a_i are expressed as follows:

$$\begin{aligned} \mathrm{SPR} &= \sum_{i=1}^{\infty} m_i \exp\left[-iM - \sum_{j=1}^{i} F_j\right] \\ &= \sum_{i=1}^{\infty} m_i e^{-iM} \\ &\quad - \sum_{i=1}^{\infty} \left\langle m_i e^{-iM}\left(1 - \exp\left[-\sum_{j=1}^{i} F_j\right]\right)\right\rangle \end{aligned} \qquad \text{(A1)}$$

$$a_i = \left(1 - e^{-F_i}\right)\exp\left[-\sum_{j=0}^{i-1} F_j\right] \qquad \text{(A2)}$$

The sum of a_i is expressed as follows:

$$\begin{aligned} a_1 + a_2 + \ldots + a_i &= \left(1 - e^{-F_1}\right) \\ &\quad + e^{-F_1}\left(1 - e^{-F_2}\right) + e^{-F_1-F_2}\left(1 - e^{-F_3}\right) \\ &\quad + \ldots + e^{-F_1-F_2-\ldots-F_{i-1}}\left(1 - e^{-F_i}\right) \\ &= 1 - e^{-F_1} + e^{-F_1} - e^{-F_1-F_2} \\ &\quad + e^{-F_1-F_2} - e^{-F_1-F_2-F_3} \\ &\quad + \ldots + e^{-F_1-F_2-\ldots-F_{i-1}} - e^{-F_1-F_2-\ldots-F_i} \\ &= 1 - e^{-F_1-F_2-\ldots-F_i} \\ &= 1 - \exp\left[-\sum_{j=1}^{i} F_j\right] \end{aligned} \qquad \text{(A3)}$$

From Equation (A3), the last term of Equation (A1) can be replaced by $\sum_{j=1}^{i} a_j$ because $\mathrm{SPR}_{100\%} = \sum_{i=1}^{\infty} m_i e^{-iM}$. Equation (A1) can be expressed as follows:

$$\mathrm{SPR} = \mathrm{SPR}_{100\%} - \sum_{i=1}^{\infty}\left[m_i e^{-iM}\sum_{j=1}^{i} a_j\right] \qquad \text{(A4)}$$

The last term of Equation (A4) can be expanded as follows:

$$\begin{aligned} &\sum_{i=1}^{k}\left[m_i e^{-iM}\sum_{j=1}^{i} a_j\right] \\ &= \begin{array}{llll} m_1e^{-M}a_1 & & & \\ +m_2e^{-2M}a_1 & +m_2e^{-2M}a_2 & & \\ +m_3e^{-3M}a_1 & +m_3e^{-3M}a_2 & +m_3e^{-3M}a_3 & \\ \quad\vdots & \quad\vdots & \quad\vdots & \\ +m_ke^{-kM}a_1 & +m_ke^{-kM}a_2 & +m_ke^{-kM}a_3 & +\cdots \end{array} \\ &= \sum_{i=1}^{k}\left[a_i\sum_{j=i}^{k} m_j e^{-jM}\right] \end{aligned} \qquad \text{(A5)}$$

From Equations (A4) and (A5), SPR can be expressed as follows:

$$\mathrm{SPR} = \mathrm{SPR}_{100\%} - \sum_{i=1}^{\infty}\left[a_i\sum_{j=1}^{i} m_j e^{-jM}\right] \qquad \text{(A6)}$$