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Title	Effectiveness of Adaptive Real-Time Closures for Managing Migratory Species in Data-Limited Multispecies Fisheries
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Citation	Asian Fisheries Science, 34(4), 365-372 https://doi.org/10.33997/j.afs.2021.34.4.009
Issue Date	2021-12
Doc URL	https://hdl.handle.net/2115/84401
Rights(URL)	https://creativecommons.org/licenses/by-nc/4.0/
Type	journal article
File Information	AFS-2021-0206-Final.pdf

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Effectiveness of adaptive real-time closures for managing migratory species in data-limited multispecies fisheries

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Abstract
Fixed closure (FC) is a standard fisheries management tool for protecting sensitive species or species requiring conservation. However, an FC might not effectively manage migratory species because of the large uncertainties of their migration. Adaptive real-time closure (ARTC) is a tool that updates closure areas according to the latest information. This study aimed to evaluate the effectiveness of ARTC to conserve sensitive species for data-limited fisheries by a series of simulations using migration models with hotspots. In the single species simulation, the conservation ratio for the sensitive species in FC varies widely at greater migration uncertainty. In ARTC, a longer duration of a hotspot resulted in a higher conservation ratio. When the mean duration of hotspots was medium or long, the conservation ratio for the sensitive species was more than 50 % in more than 99 % of the simulation trials. In multispecies fisheries, a clear trade-off was observed between the conservation ratio of sensitive species and other species. ARTC was more effective than whole closure when the proportion of sensitive species was high or without closure when the proportion was low. Conditions in which ARTC was most appropriate were described for hotspot duration, increased numbers of individuals in a hotspot, and the relative value of conservation, representing the ratio of the value of conserving sensitive species to one of catching other species.

Keywords: Fixed closure (FC), Migration, Simulation, Sensitive species, Sustainable fisheries

1. Introduction

Multispecies fisheries account for most of the world's fisheries (Halls et al., 2006). In tropical regions, biodiversity is higher than in more temperate waters, with more than 100 fish species sometimes being recorded in a particular area and season (Stobutzki et al., 2001; McClanahan and Mangi, 2004; Cohen and Foale, 2013). Fisheries closure has been proposed as an efficient way to reduce catch and fishing mortality for conserving sensitive species, i.e., species requiring conservation (Eliasen and Bichel, 2016; Woods et al., 2018; Munehara et al., 2021) by enhancing selectivity or by protecting critical habitat (Miethe et al., 2014; Ichinokawa et al., 2015). This approach has been applied widely for this purpose, even in multispecies fisheries management (Rijnsdorp et al., 2012).

A fixed closure (FC) is a standard fisheries management measure that involves decisions to close a designated area for a specified period. Once established, the decision is not changed. When the migration of the sensitive species is constant and a closed area or period is appropriately designed, it can effectively manage fish stocks. However, frequently for migratory species, there is considerable uncertainty in the migration route and timing (Breen et al., 2015), and an FC may not work well. Because migrations of the sensitive species are affected by many factors, including water temperature and currents (Punzón and Villamor, 2009; Peer and Miller, 2014; Kanamori et al., 2019), FC sometimes cannot adequately protect the sensitive species because of mismatches in the closure area and timing of migration (Dunn et al., 2016; Woods et al., 2018).

In multispecies fisheries, it may be challenging to reduce the catch of sensitive species while maintaining the catch of other species with FC (Holmes et al., 2011; Woods et al., 2018; Watson et al., 2019). Since multispecies fisheries typically use less-selective fishing gears and exploit mixed fish stocks (Murawski et al., 1983; Murawski, 1991), FC must either expand a closed area or extend the closure period to cover uncertainties in the migration of sensitive species.

Adaptive real-time closure (ARTC) may represent a solution to the problem of FCs. This approach can adapt to uncertainties in the migration of sensitive species by using almost real-time catch data. Such management involves establishing multiple temporary closure periods (Le Quesne and Codling, 2009; Needle and Catarino, 2011) instead of one extensive, continuous closure period. In the undesirable event of a high catch of a sensitive species, an area or period at which an event occurred would be closed immediately, for example, in the Scottish cod fisheries, closure area is triggered by an upper limit on the observed cod density (Needle and Catarino, 2011). Depending on the sensitive species' distribution, ARTC would enable a high level of conservation and limit the unnecessary reduction in catch of other commercially important species. In practice, ARTC is recognised as an effective management tool in temperate waters (Needle and Catarino, 2011; Bethoney et al., 2013; Gullestad et al., 2015; Little et al., 2015).

Despite its theoretical value, the use of ARTC remains uncommon in data-limited fisheries. However, in some European countries and the USA, where appropriate datasets with a high spatiotemporal resolution exist, ARTC is more commonly used. Real-time catch data collection is costly, and establishing an effective data collection scheme for ARTC is time-consuming process (Hobday et al., 2014). Consequently, the limited evaluation of ARTC effectiveness makes it hard to justify establishing expensive data collection schemes (Hobday and Hartmann, 2006; Dunn et al., 2011, 2016).

A hotspot is defined as an area or period in which fish are concentrated above some threshold level. The probability of meeting management goals of conserving sensitive species while maintaining the catch of other commercially important species through ARTC is affected by the duration of a hotspot and the number of fish within it (Lewison et al., 2009; Diamond et al., 2010). Presently, hotspot analysis of catch data (such as autocorrelation analysis) has been used to estimate the effectiveness of ARTC before their implementation (Dunn et al., 2011, 2014). Thus, the migration model in the present study was simulated to evaluate the effectiveness of ARTC for data-limited fisheries that incorporate species hotspots. The objectives were to evaluate the effectiveness of ARTC to conserve sensitive species with uncertain migration in multispecies fisheries and propose simple simulations as evaluation methods for fisheries without datasets.

2. Methods

2.1 Simulation overview

For simple representation, we assume in our simulations that individual fish move on a line at a fixed speed (Fig. 1) (Le Quesne and Codling, 2009; Watson et al., 2019). The fishing ground is defined as a fixed segment on the line. A time step is a duration in which an individual passes through a segment. The period when a fish appears in the fishing ground is defined as the appearance period. Fishing is banned during a closure period, and all fish individuals are conserved. It is assumed that all individuals in a fishing ground outside the closure period are caught.

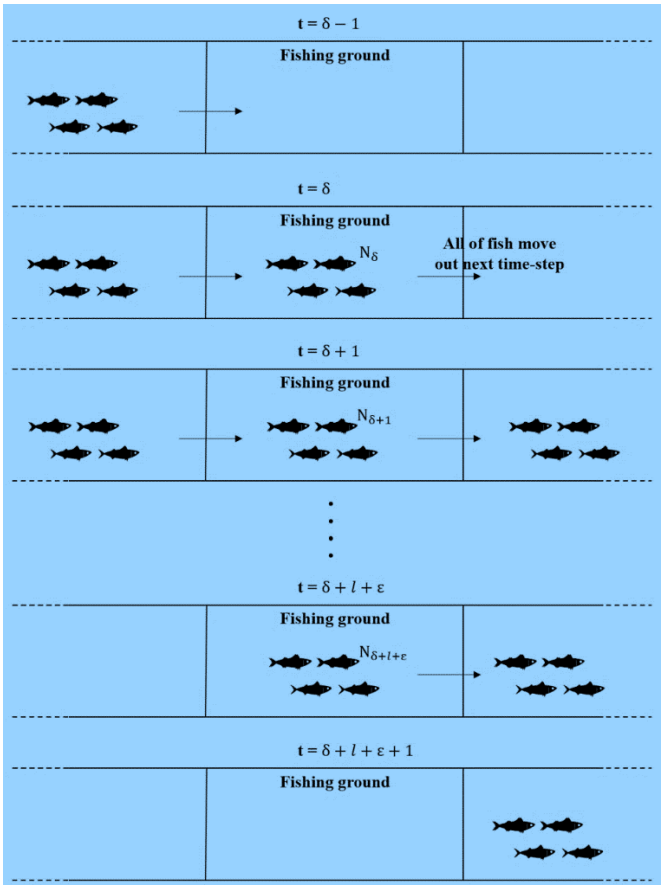

Fig. 1. Representation of space in simulations, with the fishing ground represented by a segment on the line. The fishing ground is defined as a fixed segment on the line. A time step is a duration in which an individual passes

through a segment. δ is the timing when fish appears in the fishing ground. l is the length of the appearance period, and ε is the uncertainty of the length of the appearance period.

Two simulations were conducted. First, single sensitive species were distributed, and the conservation ratio (defined in section 2.3) of FC and ARTC were evaluated. Second, other species occur in the appearance period of the sensitive species, and the effectiveness of the ARTC was examined.

2.2 Simulation model

The number of individuals of a sensitive species in a fishing ground in a given time step t (N_t) is described as follows:

$$N_t \sim \begin{cases} n & \text{for } \delta' \le t < \varepsilon_i, \varepsilon_i + \eta_i < t < \varepsilon_{i+1}, \varepsilon_p + \eta_p < t \le l_a + \delta' \\ n(1+\theta) & \text{for } \varepsilon_i \le t \le \varepsilon_i + \eta_i \\ 0 & \text{for } t < \delta' \text{ or } l_a + \delta' < t \end{cases}$$

where l_a is the length of appearance period in the fishing ground, n is the number of individuals in a time-step outside the hotspot, θ is the rate of increase in the number of individuals in a hotspot compared with outside hotspots, δ' is a random number from a truncated normal distribution to describe uncertainties at the beginning of an appearance period, ε_i and η_i are the beginning time and duration for the ith hotspot, and p is the number of hotspots (Fig. 2). For examining the effect of uncertainties arising from movement, the simulations assume a short period, and other interannual biological processes such as recruitment are ignored. In this model, N_t is adjusted to fulfil the condition below:

$$\sum_{\delta'}^{l+\delta'} N_t = N$$

where N is the total number of sensitive species.

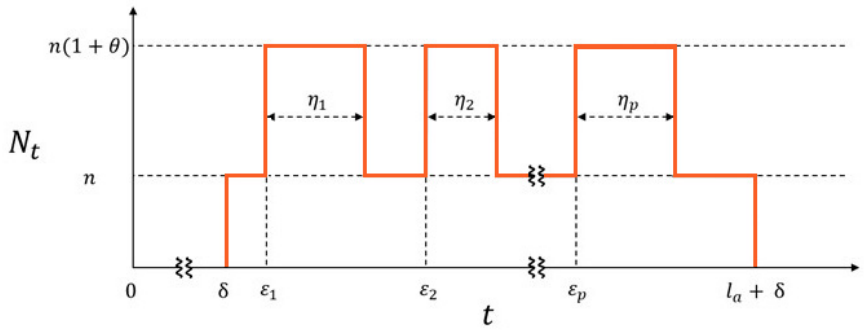

Fig. 2. Dynamics of the number of individuals in a simulation, where θ is the rate of increase in number of individuals, ε_i and η_i are the beginning time and duration for the ith hotspot, p is the number of hotspots.

Table 1. Parameter set for simulations; l is the duration of the appearance period without uncertainties, m is the parameter for truncation, and α_δ is the scale of uncertainties for the beginning and length of the appearance period.

Parameter	Value
l_a	30
m	0.95
α	0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8
l_h	2(short), 7(medium), 14(long)
θ	0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0

The beginning of the appearance period δ is determined by using the truncated normal distribution for describing migration uncertainty:

$$\delta \sim \left\{ \frac{1}{m} N\left(0, \left(\frac{l \times \alpha}{z(0.025)}\right)^2\right) \quad (-l \times \alpha \leq \delta \leq l \times \alpha) \right.$$

where m is the parameter for truncation (0.95), z is the normal equivalent deviation (i.e., z (0.025) $\cong$ 1.96), and α is the arbitrary scale of uncertainty (Table 1); and δ is converted to an integer by rounding off the value as follows:

$$\delta' = \text{floor}(\delta + 0.5)$$

The duration for a hotspot η_i follows a poison distribution:

$$\eta_i \sim P(l_h)$$

where three patterns for the mean duration for a hotspot l_η are tested in three cases such as short (2 days), medium (1 week), long (2 weeks) when the appearance period is one month (30 days) (Table 1).

The beginning of a hotspot ε_i is randomly changed by each iteration. It is assumed that hotspots do not occur continuously. The effect of the parameter sets (Table 1) on the results are discussed later. We performed 1000 iterations to consider the uncertainty of the timing of migration.

In the second simulation, the number of individuals of other species in the fishing ground in a given time step t (M_t) is assumed to be constant:

$$M_t \sim \begin{cases} \frac{M}{l_a} & \text{for } 0 \leq t \leq l_a + \delta' \\ 0 & \text{for } \delta' < 0 \text{ or } l_a + \delta' < t \end{cases}$$

$$\sum_{\delta'}^{l+\delta'} M_t = M$$

where M is the total number of other species, and M equals N for simulation simplicity.

2.3 Effectiveness index

In the first simulation (single species), the effectiveness was determined from the conservation

ratio of the sensitive species (ω_u) was calculated as follows:

$$\omega_u = \sum_{t=\delta'}^{l_a+\delta'} \frac{x_t N_t}{N} \quad x_t \in \{0,1\} \; \forall \; t.$$

This value was multiplied by a binomial variable x_t (i.e. 0 or 1), representing whether the time step is included in the closure period. In these simulations, the duration of the FC is $t = 0$ to l_a; in the ARTC, when a hotspot is outside the closure period, the closure period begins in the next time step and continues for λ time-steps. As a default, $\lambda = l_\eta$.

In the second simulation, the effectiveness index (φ) was calculated using two aspects of the conservation ratio of the sensitive species (ω_u) and catch ratio of other species (ω_o).

$$\omega_o = \sum_{t=\delta'}^{l_a+\delta'} \frac{(1-x_t)M_t}{M} \; x_t \in \{0,1\} \; \forall \; t.$$

$$\varphi = \sum_{t=\delta'}^{l_a+\delta'} \left(\rho\omega_{2_c} + \omega_{2_o}\right)$$

where ρ was the relative value of sensitive species when the value of the other species was 1.

The whole closure was defined as the closure through the entire appearance period. The effectiveness of the ARTC was expressed by the differences of the effectiveness index of ARTC, whole closure ($\varphi_{ARTC} - \varphi_{wc}$), and without closure ($\varphi_{ARTC} - \varphi_{woc}$). We define ARTC to be effective when both of $\varphi_{ARTC} - \varphi_{wc}$ and $\varphi_{ARTC} - \varphi_{woc}$ have positive values, and the condition of ρ and θ in which ARTC is effective is detected.

3. Results

In the first simulation, the conservation ratio for sensitive species in FC $\omega_{u_{FC}}$ varies widely at greater uncertainty α (Fig. 3). When $\alpha = 0.8$, the frequency of $\omega_{u_{FC}} > 90$ % was 171 out of 1000 iterations. However, at $\omega_{u_{FC}} < 30$ %, this falls to 36 out of 1000 iterations. In ARTC, a longer duration of a hotspot l_η resulted in a higher conservation ratio $\omega_{u_{ARTC}}$ (Fig. 4). When the mean duration of a hotspot was short ($l_\eta = 2$), $\omega_{u_{ARTC}} < 50$ % was observed in more than half of the iterations at even the largest number of individuals in a hotspot ($\theta = 5.0$). Conversely, when the mean duration of hotspots was medium or long ($l_\eta = 7$ and 14-time steps), the frequency of $\omega_{u_{ARTC}} < 50$ % was 11 and 3 out of 1000 iterations, respectively.

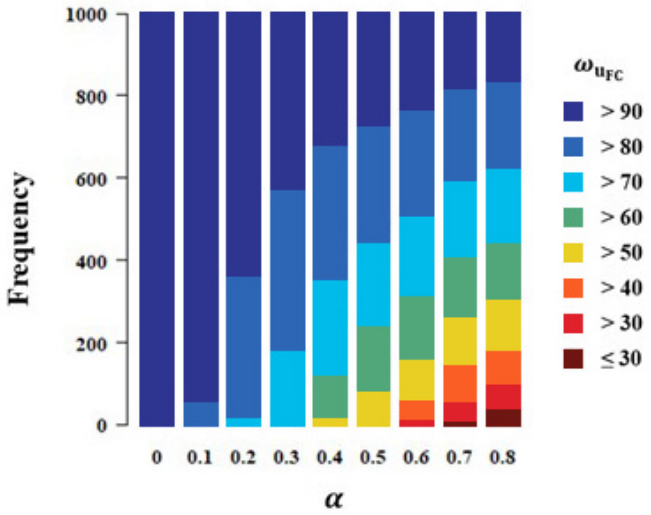

Fig. 3. Frequency of each conservation ratio $\omega_{u_{FC}}$; α is a scale of uncertainty at the beginning of the appearance period, when a fish first appears in the fishing ground.

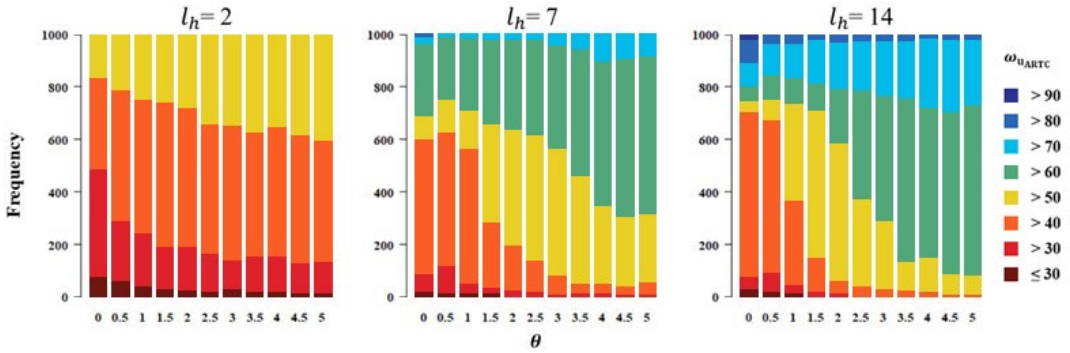

Fig. 4. Frequency of each conservation ratio ($\omega_{u_{ARTC}}$); l_η is the mean duration of a hotspot period, θ is the increased number of individuals in a hotspot.

In the second simulation, a clear trade-off was observed between the conservation ratio of sensitive species ω_u and other species ω_o (Fig. 5). When ω_o was the same in every $l_{\eta,}$, ω_u tends to be highest with long l_η. The range of ω_u was narrower than ω_o across l_η at θ = 2.5 or 5.0. Multiple peaks were observed in density distribution for ω_u or ω_o, mainly when l_η is medium.

Differences in the effectiveness index φ between ARTC and whole closure ($\varphi_{ARTC} - \varphi_{wc}$), and one between ARTC and without closure ($\varphi_{ARTC} - \varphi_{woc}$), are presented in Figure 6. ARTC was more effective than whole closure when ρ was high, and without closure when ρ was low. The combination of ρ and θ in which φ_{ARTC} was higher than φ_{wc} and φ_{woc} was identified (Fig. 7). The area where ARTC was more effective than whole closures or without closure increases as l_η increases.

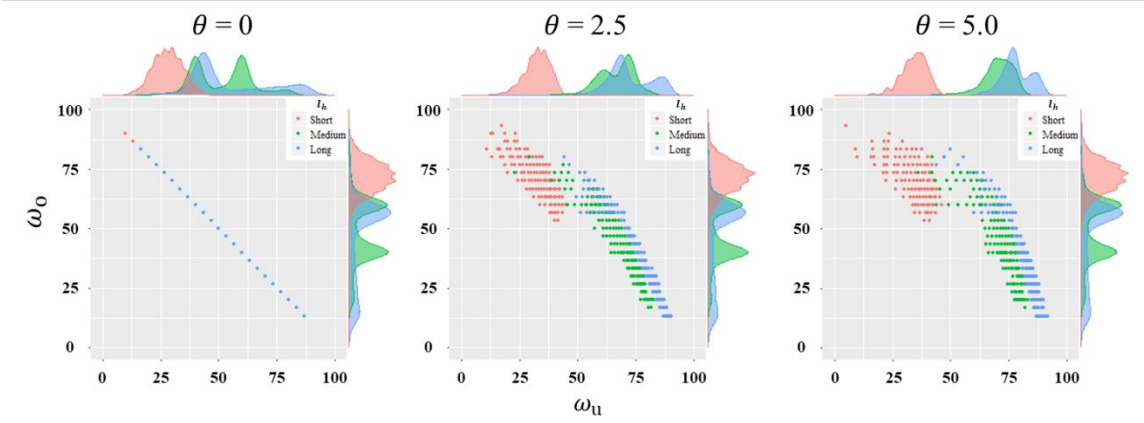

Fig. 5. Adaptive real-time closure scatter plot for conservation ratio (ω_u) and catch ratio (ω_o); l_η is the mean length of a hotspot period, short (red), medium (green), and long (blue). The value of θ is the increased number of individuals in a hotspot. The area graph on the top and rightside of the graph plain shows the distribution of ω_u and ω_o.

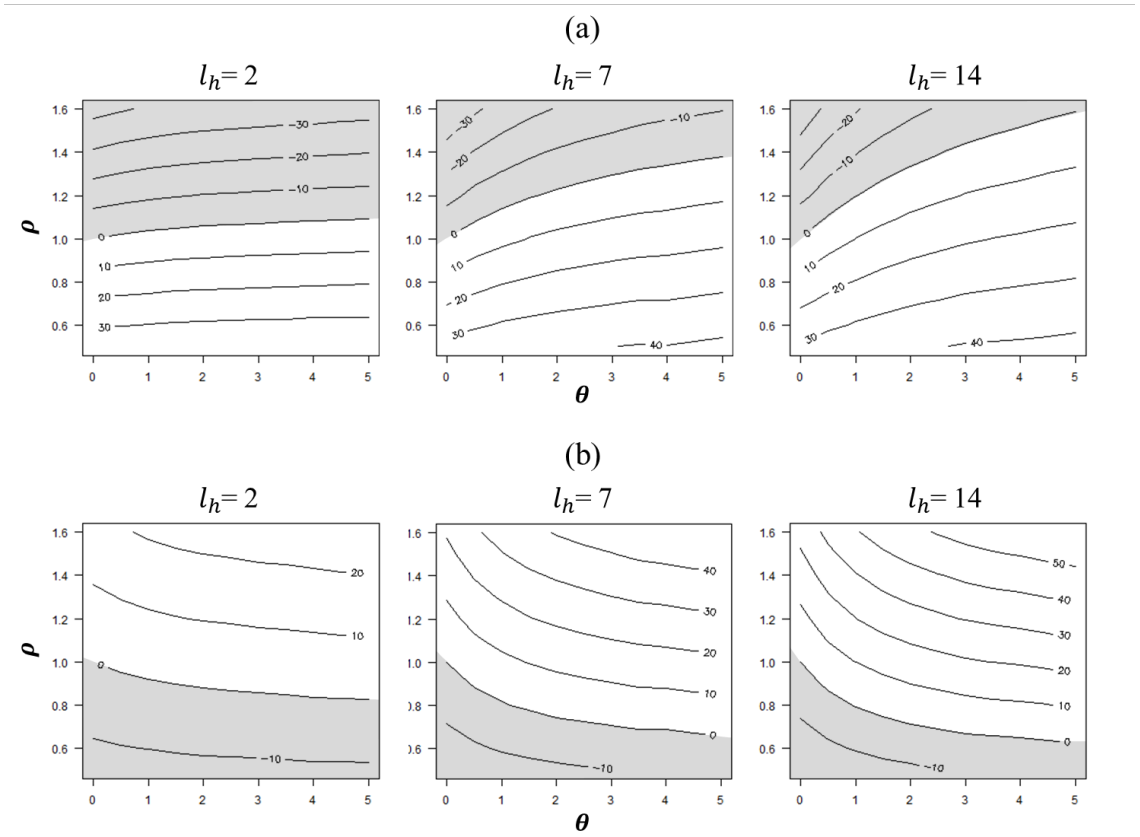

Fig. 6. The difference in effectiveness index φ between (a) adaptive real-time closure (ARTC) and whole closure ($\varphi_{ARTC} - \varphi_{wc}$), and (b) ARTC and no closure ($\varphi_{ARTC} - \varphi_{woc}$). Values are negative in the grey zone; l_η is the mean hotspot duration, θ is the increased number of individuals in a hotspot, and ρ is the relative value, which is the ratio of the value of conserving sensitive species to one of catching other species.

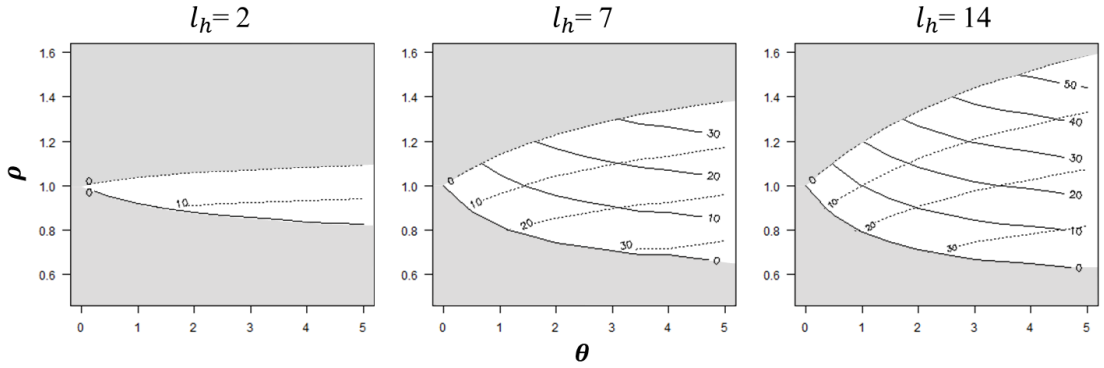

Fig. 7. The combination of ($\varphi_{ARTC} - \varphi_{wc}$) [dotted line] and ($\varphi_{ARTC} - \varphi_{woc}$) [solid line]. Values are negative in the grey zone; θ is the increased number of individuals in a hotspot, and ρ is the relative value (values are negative in the grey zone), which is the ratio of the value of conserving sensitive species to one of catching other species.

4. Discussion

The present study investigated the effectiveness of ARTC for migratory species management in multispecies fisheries. Adaptive real-time closure was demonstrated to be an effective management tool for maximising benefits from conserving sensitive species and catching others. Adaptive real-time closure works well, especially when the differences in value between conserving sensitive species and catching other species are small (Fig. 7).

4.1 Comparison of FC and ARTC in single-species management

The main factor impacting the conservation ratio of FC and ARTC in single-species fisheries differs. The conservation ratio of FC is affected mainly by uncertainty at the beginning of an appearance period. In contrast, the fluctuation in the number of individuals in the appearance period did not significantly impact the FC. On the contrary, the latter is a more critical factor for ARTC (Dunn et al., 2016; Woods et al., 2018). Thus, the conservation ratio of FC and ARTC is evaluated by changing α and θ, respectively.

When the α value was small, FC had a higher conservation ratio than ARTC for any θ and l_η. From these results, FC would be the first choice if the sole objective was to conserve a sensitive species with little uncertainty in its migration behaviour. If there was considerable uncertainty in a species' migratory behaviour, the conservation ratio of an FC fluctuates widely (Fig. 3). In this case, ARTC represents an alternative method to conserve a species, depending on the duration of the hotspot and the number of individuals within it.

4.2 ARTC in multispecies fisheries

The conservation ratio of sensitive species ω_u and catch ratio of other species ω_o are evaluated to appraise the effectiveness of ARTC in multispecies fisheries. The range of ω_o is wider than that of ω_u, and multiple peaks are apparent in the density distribution for ω_u and ω_o (Fig. 5). In this simulation, the duration of the ARTC is determined to be equal to the mean hotspot duration l_η; ARTC commences in the next time step in which a sensitive species is caught within a hotspot. Thus, in ARTC, if an actual hotspot duration η_i is longer than l_η, the next closure period begins immediately after the previous closure period finishes, causing multiple peaks in density distribution.

The optimum closure period of ARTC will change with management objectives (Little et al., 2015). Although estimating the optimum closure duration was not our main objective, we performed a further simulation that involved changing the ARTC closure duration to estimate the period required to maximise φ_{ARTC} (Table 2). The ω_u and ω_o scatter plots for this simulation are presented in Fig. 8. When l_η was medium, the closure duration was shortened, the points shift from the upper right to the bottom left, and the range in ω_o decreases further than in Fig. 5. Conversely, when l_η was long, the closure duration was extended, and the points shift to enhance ω_u.

Table 2. The ARTC closure period required to maximise φ_{ARTC}. Default values for l_η are 2 (short), 7 (medium) and 14 (long).

l_h	$\theta = 0$	$\theta = 2.5$	$\theta = 5.0$
Short	1	1	1
Medium	1	4	16
Long	1	3	15

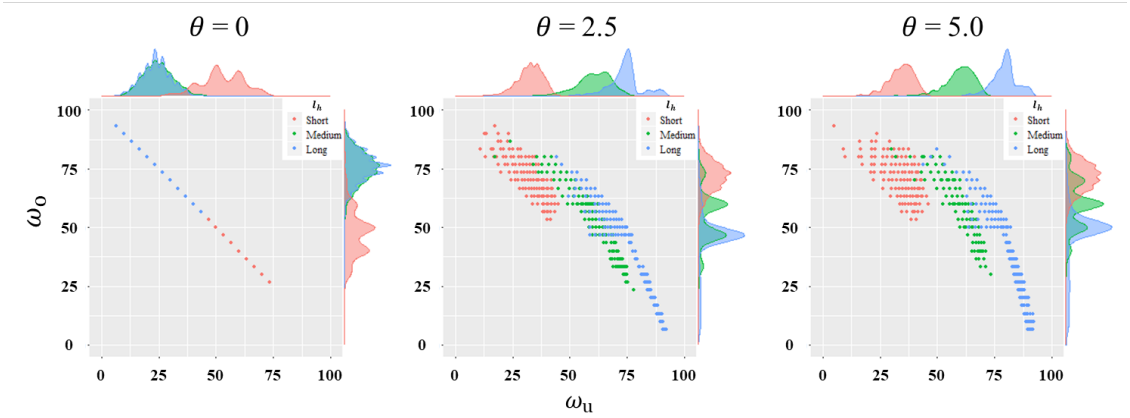

Fig. 8. Adaptive real-time closure scatter plot for conservation ratio (ω_u) and catch ratio (ω_o), when closure periods are applied from Table 2; l_η represents the mean hotspot duration: short (red), medium (green), and long (blue). The value of θ is the increased number of individuals in a hotspot.

The present study identified the combination of the relative value of sensitive species ρ and the number of individuals in a hotspot θ for which an ARTC approach is most effective. When $\varphi_{ARTC} - \varphi_{woc}$ was negative, it was more effective to close during the entire appearance period of sensitive species than ARTC. Conversely, fisheries closure is unsuitable when $\varphi_{ARTC} - \varphi_{wc}$ is negative. These results enable estimation of the value of ARTC to facilitate effective management because there is a compromise between the benefits of enhanced conservation of species provided by an ARTC and the cost of its introduction.

4.3 Model assumptions

There has been considerable development and evaluation of spatial modelling techniques to improve fisheries management in recent years (Goethel et al., 2011; Berger et al., 2017; Punt, 2019). Several models have been developed to evaluate fisheries closure by simulation, such as individual-

based models (Moustakas and Silvert, 2011; Cornejo-Donoso et al., 2017), diffusion-based models (Le Quesne and Codling, 2009; Watson et al., 2019), and preferred habitat models (Ono et al., 2013). The most crucial factor affecting ARTC is hotspots in species distribution (Little et al., 2015; Eliasen and Bichel, 2016). If hotspots are incorporated into these models, many parameters would be needed, and they would become complicated. Dunn et al. (2016) simulated the effects of ARTC in the management of Atlantic cod fisheries by analysing autocorrelation for past high-resolution fishing data. However, no previous study has evaluated the effectiveness of ARTC in simulations, and thus, this study establishes a new simple model that can assess ARTC even in data-limited fisheries. From this result, if the hotspot duration and the increased number of individuals in a hotspot compared with outside hotspots are roughly estimated, ARTC can be evaluated without a high-resolution dataset.

The present model assumes that individuals move along a line at a fixed speed and that the fishing ground represents a segment on this line. The present study simulates the dynamics of several fish in a particular fishing ground. The hotspot duration and the relative value of conserving sensitive species are focused on as the factors affecting the effectiveness of ARTC. Adaptive real-time closure prevents the continuous occurrence of adverse events, such as catching in hotspots of sensitive species after their initial occurrence (Gaines et al., 2010; Dunn et al., 2011). Thus, hotspot duration was incorporated into the simulation as a variable, in addition to a coefficient for an increased number of individuals within a hotspot.

The relative value is the conservation value of a sensitive species divided by the value of catching other species. In multispecies fisheries, it is necessary to consider the conservation of sensitive species and the economic loss resulting from the reduced catch of other species. Thus, the relative economic value was incorporated into our simulation to evaluate these two aspects. A conservation value can be calculated by estimating the financial loss resulting from the catch of a sensitive species. For example, if a juvenile fish is considered a sensitive species, catching an immature juvenile contributes to decreased recruitment and loss of future benefit (Noranarttragoon, 2007; Najmudeen and Sathiadhas, 2008). Thus, the value of juvenile fish can be estimated by calculating the economic loss resulting from failing to conserve it.

5. Conclusion

The present study evaluated the effectiveness of adaptive real-time closure (ARTC) with simple movement models. While spatial-temporal population dynamic modelling has increased rapidly over the last two decades, no previous model has described hotspots or used them to evaluate the effectiveness of ARTC. The simulation of ARTC in the present study represents a step towards sustainable management of migratory species in multispecies fisheries while contending with data-limited conditions. Future improvements to movement assumptions of the fish and spatial-temporal data availability will enable the application of more sophisticated simulation models. Although the practical use of ARTC remains limited, the results of these simulations may be used as a reference to expanding their use in multispecies and data-limited fisheries.

Acknowledgements
GI-Core, Hokkaido University, supports this research. We also thank Steve O'Shea, PhD, from Edanz Group (https://en-author-services.edanzgroup.com/ac) for editing a draft of this manuscript.

Conflict of interest
The authors have no conflicts of interest to declare.

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