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Author(s)	Munehara, Masami; Kaewnern, Methee; Noranarttragoon, Pavarot et al.
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4   **Simulations of fixed closure and real-time closure to manage migratory fish species for data-**

5   **limited fisheries**

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7   **MUNEHARA Masami**

8   *Graduate School of Global Food Resources, Hokkaido University, Japan*

9   munehara_49@eis.hokudai.ac.jp

10

11   **Methee Kaewnern**

12   *Faculty of Fisheries, Kasetsart University, Thailand*

13   *Global Centre for Food, Land and Water resources, Hokkaido University, Japan*

14   ffismtk@ku.ac.th

15

16   **Pavarot Noranarttragoon**

17   *Marine Fisheries Research and Development Division, Department of Fisheries, Thailand*

18   pavarot_n@yahoo.com

19

20   **MATSUISHI Takashi Fritz***

21   *Global Centre for Food, Land and Water resources, Faculty of Fisheries Sciences, Hokkaido*

22   *University, Japan*

23   catm@fish.hokudai.ac.jp

24

25

26 **Highlights**

- We compared real-time closure and fixed closure of fisheries in simulations.

- Performance of real-time closure is better than fixed closure in all scenarios.

- Real-time closure is effective even with greater uncertainty of species movement.

- The total closure period can be reduced by applying real-time closure.

32 **Abstract**

33 Fisheries closure has been used as a fisheries management tool to protect species that need to be

34 conserved. A commonly used type is fixed closure (FC), which specifies the closure area and period

35 in advance and does not change after that decision is made. It has been claimed that FC is not effective

36 for the management of migratory species, because it is difficult for FC to respond to uncertainties in

37 the predicted distribution of species. Recently, real-time closure (RTC) has been introduced to address

38 this issue. However, the use of RTC is still limited, because its benefits compared with FC have not

39 been evaluated sufficiently. In this study, we conducted simple simulations to evaluate the efficiency

40 of RTC to respond to uncertainties in the movement of migratory species. In terms of the protection

41 of migratory species, the mean performance index of RTC was generally higher than that of FC, and

42 the mean performance index of FC tended to decrease with greater uncertainty of species movement.

43 We also estimated the extent of the reduction of the closure period by applying RTC instead of FC.

44 The results of this study indicate that RTC is an efficient method of fisheries closure, and provide

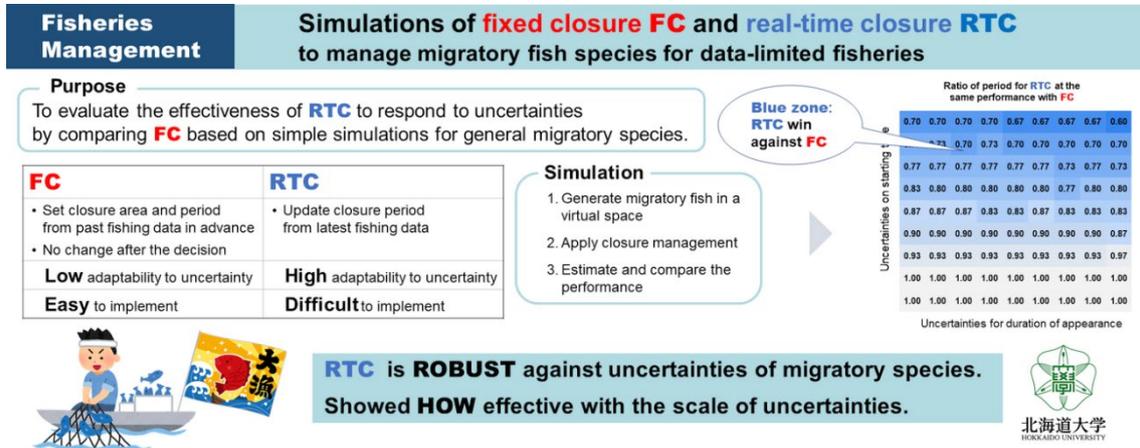45 quantitative information to guide the use of RTC instead of FC.

46 **Key words:** Real-time closure (RTC), Fixed closure (FC), Migration, Data-limited

47 fisheries

49 **Abbreviations:** FC, fixed closure; MSE, management strategies evaluation; RTC, real-

50 time closure

Graphical Abstract

1. Introduction

Fisheries closure is a popular fisheries management strategy for the conservation of fish stocks. It

prohibits the use of specified fishing vessels and gear in a specified area or period of closure

(Ichinokawa et al., 2015; Miethe et al., 2014). It has been used for various purposes, including the

conservation of fish stock and the protection of habitats (Hilborn et al., 2004). The closure period for

pelagic migratory species that need to be conserved is decided on the basis of aspects of the life cycle

such as spawning area and season, and the migration pattern. The selection of an appropriate closure

period can maximize the conservation effect.

Fixed closure (FC) is widely applied in fisheries management (Breen et al., 2015; Little et al., 2015;

Yagi et al., 2010). In FC, the closure area and period are decided in advance, and they are not changed

once that decision is made. The use of FC is effective for some fisheries, especially those for which

important areas for conservation, such as the spawning area, are very limited (Diamond et al., 2010;

Vinther and Eero, 2013).

70

71   However, there are large uncertainties when predicting the migration area and period of migratory

72   species. The actual migration area and period are affected by many factors, including climate change

73   (Kanamori et al., 2019; Peer and Miller, 2014; Punzón and Villamor, 2009). Therefore, there are

74   sometimes mismatches between the FC season and the actual migration of a species through a

75   particular area. Consequently, FC may not protect a migratory species effectively (Dunn et al., 2016;

76   Woods et al., 2018).

77

78   Real-time closure (RTC) has attracted attention recently as it is better suited to dealing with

79   uncertainties in the predicted area and migration period of migratory species (Little et al., 2015;

80   O'Keefe et al., 2014). In RTC, a high-catch area can be closed immediately on the basis of the latest

81   real-time catch data. Since technological innovations have made it easier to collect and share real-time

82   data, RTC has become an increasingly viable option (Eliasen and Bichel, 2016; Lewison et al., 2015).

83   In fact, RTC using vessel monitoring system (VMS) data has been already applied in the USA and

84   some European countries (Bethoney et al., 2013; Gullestad et al., 2015; Little et al., 2015; Needle and

85   Catarino, 2011). It has been recognized to be an effective management tool for fisheries in the

86   temperate zone.

87

88   However, the use of RTC is still limited, especially for fisheries that have no or limited data collection

89   schemes (Maxwell et al., 2015). Real-time catch data collection is costly, and it can take a long time

90   to establish a data collection scheme (Hobday et al., 2014). To justify the establishment of data

91   collection schemes for RTC, its effectiveness should be evaluated in advance, although this usually

92   requires large spatiotemporal datasets (Dunn et al., 2016, 2011; Hobday and Hartmann, 2006).

93

94   Recently, management strategies evaluation (MSE) using simulations has been widely conducted to

95 provide quantitative evidence for selecting appropriate fisheries management strategies (Harlyan et al.,

96 2019; Punt et al., 2016). However, no previous studies have used quantitative information to compare

97 the effectiveness of RTC and FC to manage species with uncertain predicted migration patterns.

98

99 The aims of this study were to prove the effectiveness of RTC to respond to uncertainties in the

100 predicted areas and periods of migratory species, and to propose quantitative information to justify a

101 change to RTC from FC on the basis of simple simulations for general migratory species.

102

103 **2. Methods**

104 **2.1 Simulation overview**

105 In these simulations, it is assumed that individuals move on a line at a fixed speed, for simple

106 representation (Fig. 1) (Le Quesne and Codling, 2009; Watson et al., 2019). The fishing ground is

107 defined as the segment in the line. A time step is the duration in which an individual passes through

108 the fishing ground. The period when fish appear in the fishing ground is defined as the appearance

109 period. The closure performance is defined by the proportion of individuals passing through the fishing

110 ground during the closure period out of the total number of individuals on the line.

111

112 **2.2 Simulation model**

113 The number of individuals in the fishing ground in a given time step t (N_t) is assumed to be constant

114 during the aggregated fish pass across the fishing ground:

115
$$N_t \sim \begin{cases} \dfrac{N}{l + \varepsilon'} & \text{for } \delta' \leq t \leq \delta' + l + \varepsilon' \\ 0 & \text{for } t < \delta' \text{ or } \delta' + l + \varepsilon' < t \end{cases}$$

116 where N is the total number of fish, l is the length of fish appearance period in the fishing ground, and

117 δ and ε are random numbers from a truncated normal distribution to describe the uncertainties in the

118 beginning and length of appearance period, respectively. Other assumptions about the number of

119   individuals in the fishing ground were tested and the results are shown in the supplementary materials

120   (Fig. A.1). Recruitment and natural mortality were not considered in these simulations.

121

122   The beginning and length of the appearance period were decided by using the truncated normal

123   distribution for describing migration uncertainty:

124
$$\delta \sim \left\{ \frac{1}{m} N\left(0, \ \left(\frac{l \times \alpha_\delta}{z((1-m)/2)} \right)^2 \right) \quad (-l \times \alpha_\delta \leq \delta \leq l \times \alpha_\delta) \right.$$

125
$$\varepsilon \sim \left\{ \frac{1}{m} N\left(0, \ \left(\frac{l \times \alpha_\varepsilon}{z((1-m)/2)} \right)^2 \right) \quad (-l \times \alpha_\varepsilon \leq \varepsilon \leq l \times \alpha_\varepsilon) \right.$$

126   where m is the parameter for truncation (0.95), z is the normal equivalent deviation (i.e., $z(0.025) \cong$

127   1.96), and α_δ and α_ε are the scales of the uncertainties. The effect of the parameter sets (Table 1)

128   on the results are discussed later. One thousand iterations were conducted to consider the uncertainty

129   of the timing of migration.

130   α_δ and α_ε are the arbitrary scale of uncertainty, δ and ε are converted to an integer by rounding

131   off the value as follows:

132

133
$$\delta' = \text{floor}(\delta + 0.5)$$

134
$$\varepsilon' = \text{floor}(\varepsilon + 0.5)$$

135   In these simulations, the duration of the FC was $t = 0$ to l; and the RTC started at $t = \delta' + 1$ and

136   ended at $t = \delta' + 1 + \lambda$. As default, $\lambda = l$.

137

138   **2.3 Performance indexes**

139   The performance indexes for FC (ω_{FC}) and RTC (ω_{RTC}) were calculated as follows:

140
$$\omega_{FC} = \sum_{t=0}^{l} N_t / N$$

141
$$\omega_{\text{RTC}} = \sum_{t=\delta'+1}^{\delta'+1+\lambda} N_t / N$$

142 where λ is the length of the RTC $(0 < \lambda \le l)$. As defined in these simulations, the RTC starts at $t =$

143 $\delta' + 1$ and ends at $t = \delta' + 1 + \lambda$. To compare performance between RTC and FC, the performance

144 index ratio ($\omega_{\text{RTC/FC}}$) was calculated as follows:

145
$$\omega_{\text{RTC/FC}} = \frac{\omega_{\text{RTC}}}{\omega_{\text{FC}}} = \frac{\sum_{t=\delta'+1}^{\delta'+1+\lambda} N_t}{\sum_{t=0}^{l} N_t}$$

146 **2.4 Required period ratio**

147 Additional simulations for RTCs with changing λ were conducted. Among the RTCs, the specific

148 RTC with the period that minimized the difference in mean performance index compared with that of

149 FC was defined as the SRTC. The required period ratio (φ) was defined as the ratio of the period for

150 the SRTC (λ_{SRTC}) divided by l, which is the fixed closure period of FC.

151
$$\varphi = \frac{\lambda_{\text{SRTC}}}{l}$$

152 If $\varphi = 1$, then the RTC can achieve the same performance as the FC with the same duration of the

153 closure.

154

155 The difference in the standard deviation of the performance index ($\sigma_{\text{SRTC}-\text{FC}}$) was calculated by

156 subtracting the standard deviation of the performance index of the SRTC (σ_{SRTC}) from that of the FC

157 (σ_{FC}).

158

159 **3. Results**

160 Figure 2 shows the performance index ratio ($\omega_{\text{RTC/FC}}$) as affected by α_δ and α_ε. The range and mean

161 of $\omega_{\text{RTC/FC}}$ tended to increase with larger α_δ. The mean $\omega_{\text{RTC/FC}}$ at $\alpha_\delta = 0.8$ was 1.61-times higher

162 than that at $\alpha_\delta = 0$. The performance ratio $\omega_{\text{RTC/FC}}$ was almost 1.0 for any value of α_ε.

163

164 Figure 3 shows the frequencies of ω_{FC} and ω_{RTC} values. The frequency of ω_{FC} above 90% was

165 199 out of 1000 iterations, while that of ω_{RTC} above 90% was 624 out of 1000 iterations. Furthermore,

166 the frequency of ω_{FC} below 50% was 224 times out of 1000 iterations, but ω_{RTC} always exceeded

167 50%.

168

169 The required period ratio φ was lower than 1.00 when α_δ exceeded 0.2 (Fig. 4). The results were

170 also affected by α_ε, depending on its value. When the uncertainties had the highest values ($\alpha_\delta=$

171 0.8, $\alpha_\varepsilon=0.8$), φ was 0.6.

172

173 The value of $\sigma._{SRTC-FC}$ was negative across the entire scale of uncertainties (Fig. 5).

174

175 **4. Discussion**

176 In this study, the effectiveness of RTC to respond to uncertainties in the appearance of migratory

177 species was evaluated by comparing it with FC in simulations. Most previous studies on RTC have

178 examined the effectiveness of empirical or conventional RTC (Dunn et al., 2014; Woods et al., 2018).

179 Dunn et al. (2016) conducted simulations to estimate the performance of RTC and FC in the

180 management of Atlantic cod fisheries by analyzing past high-resolution fishing data. However, to our

181 knowledge, no previous studies have evaluated the performance of RTC and FC in simulations with a

182 scale of uncertainties in the appearance period of migratory species. In this study, we attempted to

183 evaluate the effectiveness of RTC to conserve migratory species with uncertain timing of appearance

184 by using simple simulations. In addition, we aimed to clarify the period required for an RTC to show

185 the same performance as an FC.

186

187 **4.1 Effectiveness of RTC for migratory species with uncertain timing of appearance**

188 In these simulations, RTC was more effective than FC for conserving migratory species with uncertain

189 timing of appearance (Fig. 2). On the basis of the results of the minimum $\omega_{RTC/FC}$ obtained in this

190 study, the performance of RTC was almost equal to or greater than that of FC. Especially, RTC had

191 much better performance than FC at larger α_δ.

192

193 The $\omega_{\mathrm{RTC/FC}}$ was almost stable at any value of α_ε (Fig. 2b). This was attributed to the features of

194 the RTC applied in this study. We assumed that the closure period was constant. Therefore, it was

195 difficult for even RTC to deal with uncertainties in the length of the appearance period.

196

197 **4.2 Quantitative information to change RTC from FC**

198 The frequency of ω (Fig. 3) can be used to establish a quantitative management goal. As a

199 precautionary approach is widely encouraged to establish robust management strategies (Charles,

200 1998; de Bruyn et al., 2013), policy makers must consider the risks of irreversible damage to fisheries

201 resources. Using the simulations described in this study, policy makers can easily estimate the risks

202 and the probability of success of FC or RTC. The frequency of ω with other scales of uncertainties

203 in other scenarios are included in the supplemental materials (Fig. B.1, Fig. B.2, Fig. B.3).

204

205 In this study, we explored the potential for RTC to reduce the total closure period, which allowed us

206 to roughly estimate the economic benefits of RTC. Fisheries closure management should also consider

207 economic losses from reducing the catch of other valuable species (Diamond et al., 2010; Game et al.,

208 2009; Grantham et al., 2008). Applying RTC rather than FC may increase benefits by reducing the

209 duration or area of the closure while meeting conservation objectives (Armsworth et al., 2010;

210 Maxwell et al., 2015). However, RTC has the economic trade-off between the benefits of reducing the

211 closure and the cost of introduction (Hobday et al., 2014; Little et al., 2015; Maxwell et al., 2015).

212 This quick estimation will be useful for policy makers to decide whether or not to introduce RTC.

213

214 **4.3 Model assumptions**

215   The parameter value of the appearance period, l, was determined at 30 time-steps in these simulations,

216   but the value did not substantially affect the results. The ω_{FC} and ω_{RTC} were mainly determined by

217   the percentage of the appearance period within the closure, and they were estimated by changing the

218   scales of uncertainties (α_δ and α_ε) in these simulations.

219

220   In the default scenario, N_t was assumed to be constant during the aggregated fish pass across the

221   fishing ground. Other assumptions were also tested, as shown in the supplemental materials. In

222   scenarios 2 and 3, aggregated fish were assumed to be concentrated in the center of their distribution.

223   The difference between scenarios 2 and 3 was kurtosis of the distribution of aggregated fish. In

224   scenario 2, the maximum difference of the mean $\omega_{RTC/FC}$ from that of the default scenario was within

225   5% (Fig. 2, Fig. A.2). In scenario 3, the maximum difference of the mean $\omega_{RTC/FC}$ from that of the

226   default scenario was 10.9%, when α_δ = 0.8. (Fig. 2, Fig. A.2). However, except for the result at α_δ

227   = 0.8, the difference in the mean $\omega_{RTC/FC}$ between the default scenario and scenario 3 was also within

228   5%. Therefore, the results were not be greatly affected by the assumptions of the default scenario.

229

230   In this study, we focused only on uncertainties in appearance arising from movement, and we removed

231   other biological processes that could be included in MSE simulations. The parameters and model

232   structure for biological processes such as recruitment and natural mortality are varied because of

233   several factors including climate change and environmental variations, and have large uncertainties

234   (Hill et al., 2007; Punt et al., 2014). Thus, the simulations in this study were for a short-term period,

235   so that interannual biological processes did not have to be considered.

236

237   **Conclusions**

238   In conclusion, the simulations in this study proved the effectiveness of RTC to respond to uncertainties

239   in the appearance time of migratory species, and clarified the scale of uncertainties at which RTC is

240 more effective than FC. This study proposed quantitative information to compare FC with RTC.

241

242 The practical use of RTC is still limited. It will be difficult to use RTC to manage fisheries that lack a

243 reliable data collection scheme, because there are no methods to evaluate RTC in advance. However,

244 RTC might be more useful for data-limited fisheries for which there are insufficient long term catch

245 data to formulate an effective FC (Breen et al., 2015). It might be difficult to apply these findings

246 directly to real fisheries situations, but the results of these simulations will be useful to expand the

247 practical use of RTC to conserve several fisheries, including data-limited fisheries.

248

252

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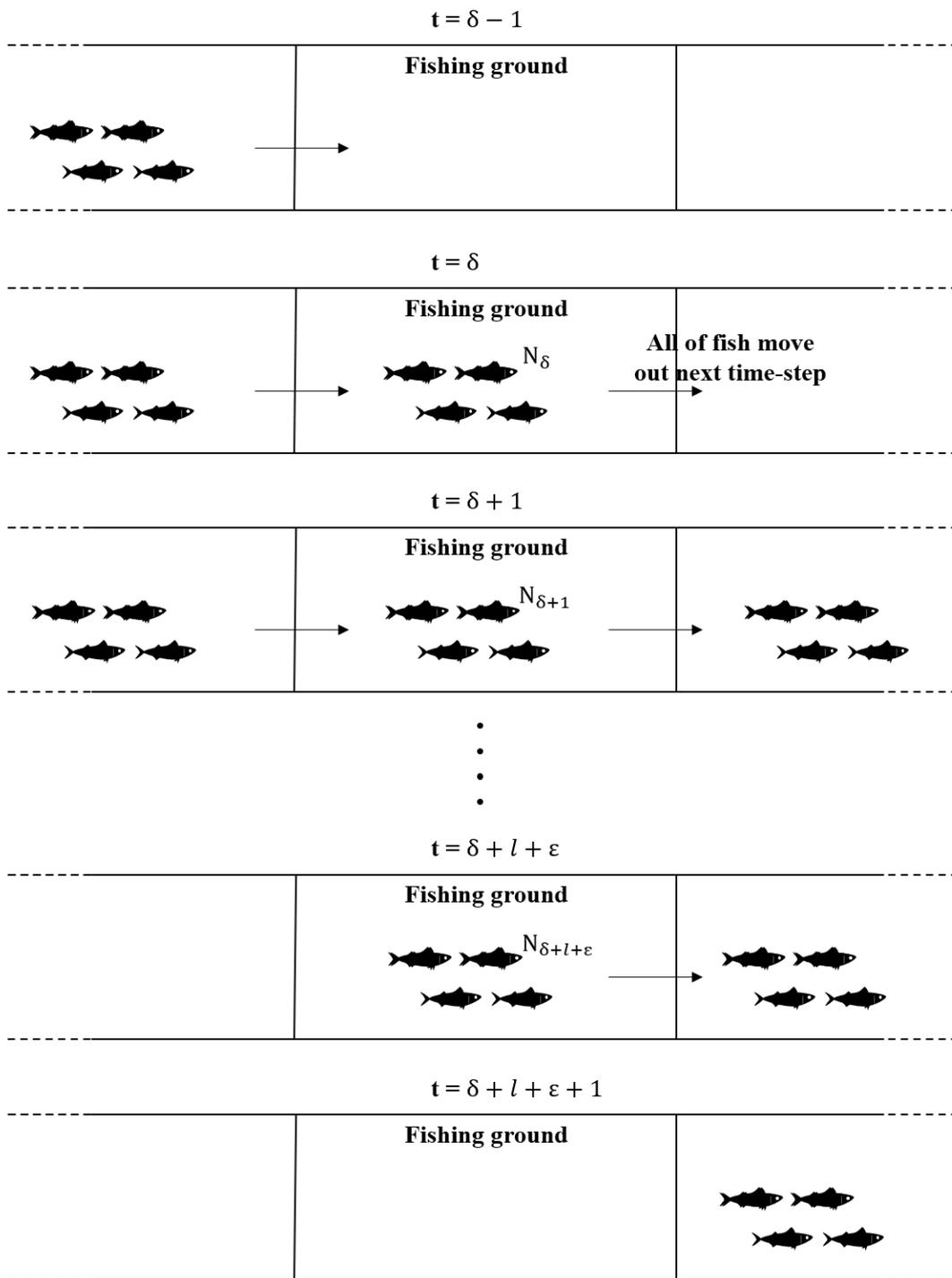
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368

369   Table 1. Parameter set for simulations; l is the length of the appearance period without

370   uncertainties, m is the parameter for truncation, and α_δ and α_ε are the scales of uncertainties for

371   the beginning and length of the appearance period.

Parameter	Value
l	30
m	0.95
α_δ	0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8
α_ε	0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8

372

373

t = δ − 1

Fishing ground

t = δ

Fishing ground

N_δ

All of fish move out next time-step

t = δ + 1

Fishing ground

$N_{\delta+1}$

$\vdots$

t = δ + l + ε

Fishing ground

$N_{\delta+l+\varepsilon}$

t = δ + l + ε + 1

Fishing ground
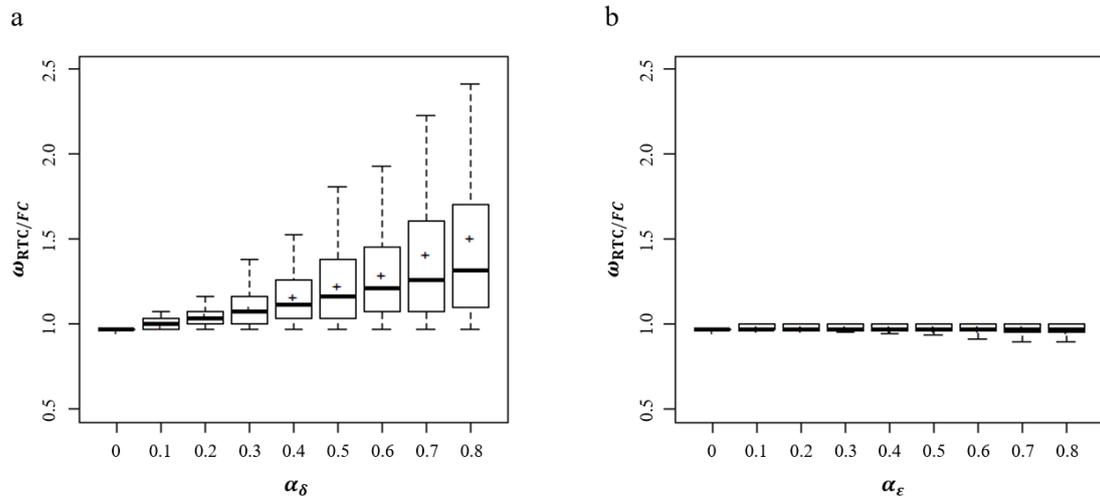
374

375   Fig. 1. Representation of space for these simulations. Fishing ground is represented by a segment in

376   the line.

377

Fig. 2. Performance index ratio ($\omega_{RTC/FC}$) for each scale of uncertainties in the beginning (a) and period length (b) of the appearance period. Lower and upper box boundaries show 25th and 75th percentiles. Line inside box shows median, (+) indicates mean. Lower and upper error lines are largest value within 1.5-times interquartile range above 75th percentile and smallest value within 1.5-times interquartile range below 25th percentile, respectively.

385
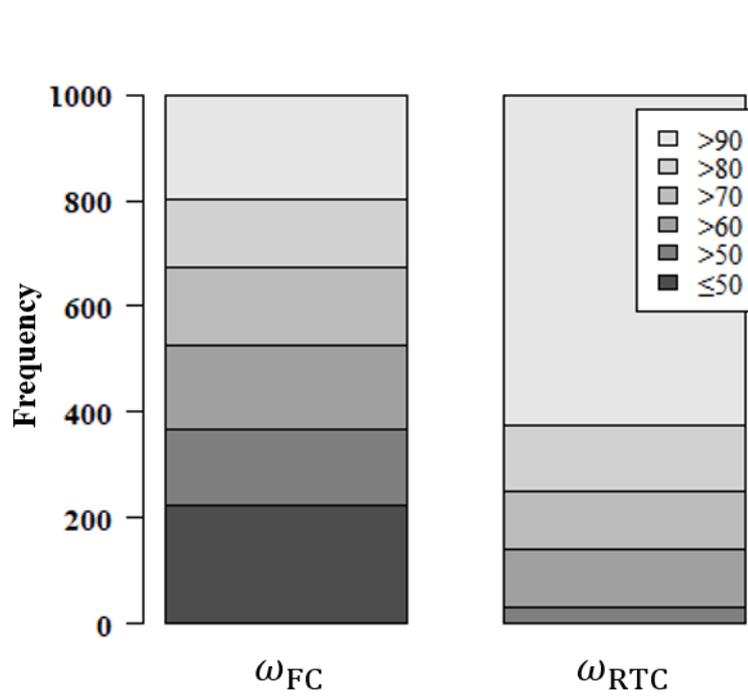
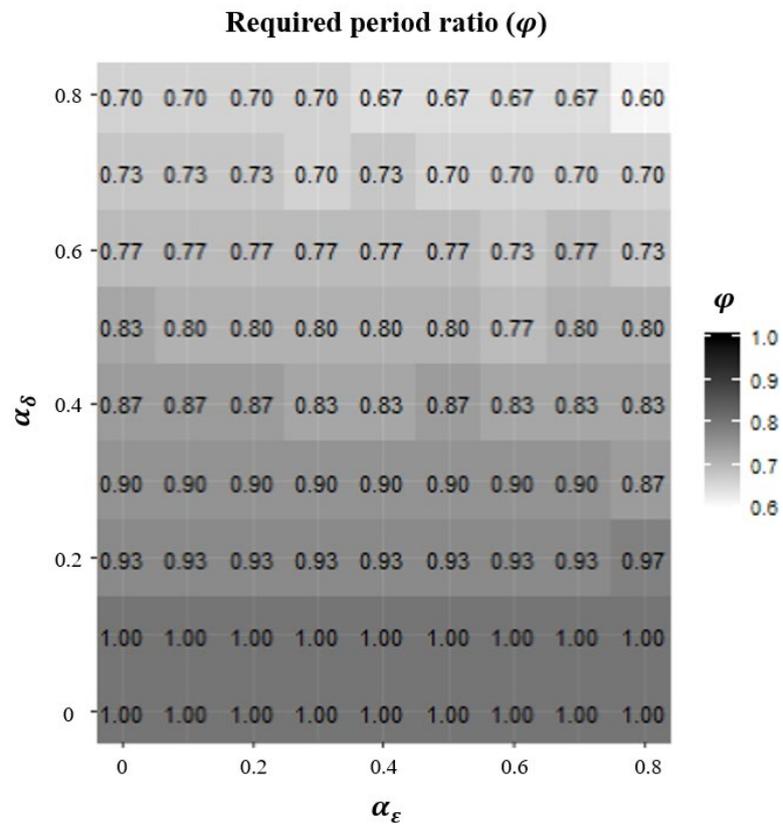Fig. 3. Frequency of each performance index at largest scale for both uncertainties in 1000 trials ($\alpha_\delta=$
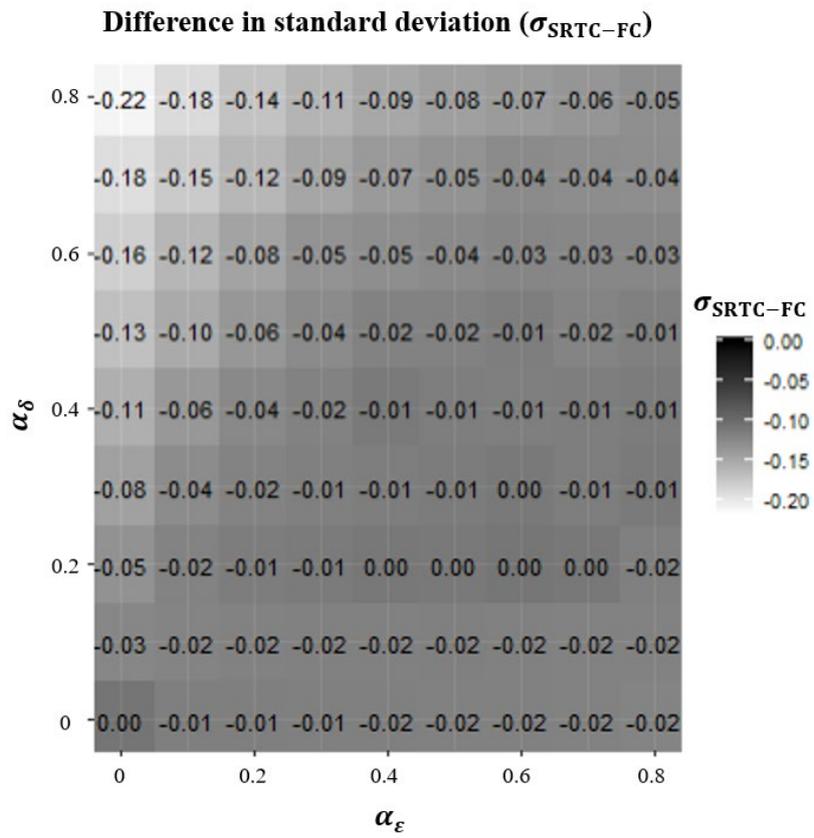
0.8, $\alpha_\varepsilon=0.8$).

Required period ratio (φ)

389

390   Fig. 4. Required period ratio (φ).

391

Difference in standard deviation ($\sigma_{SRTC-FC}$)

-0.22	-0.18	-0.14	-0.11	-0.09	-0.08	-0.07	-0.06	-0.05
-0.18	-0.15	-0.12	-0.09	-0.07	-0.05	-0.04	-0.04	-0.04
-0.16	-0.12	-0.08	-0.05	-0.05	-0.04	-0.03	-0.03	-0.03
-0.13	-0.10	-0.06	-0.04	-0.02	-0.02	-0.01	-0.02	-0.01
-0.11	-0.06	-0.04	-0.02	-0.01	-0.01	-0.01	-0.01	-0.01
-0.08	-0.04	-0.02	-0.01	-0.01	-0.01	0.00	-0.01	-0.01
-0.05	-0.02	-0.01	-0.01	0.00	0.00	0.00	0.00	-0.02
-0.03	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
0.00	-0.01	-0.01	-0.01	-0.02	-0.02	-0.02	-0.02	-0.02

392

393   Fig. 5. Difference in standard deviation of performance index between SRTC and FC ($\sigma_{SRTC-FC}$).

394