# DEVELOPMENT AND INITIAL EVALUATION OF FUZZY-CONTROLLED MANAGEMENT PROCEDURES FOR SOUTHERN BLUEFIN TUNA

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**Abstract :** This document provides a rough sketch of development and initial evaluation of fuzzy-controlled management procedures (MP's) for Southern Bluefin Tuna. The fuzzy control is an engineering technology that applies fuzzy reasoning to control systems. Actual operation of fuzzy control built in the MP was briefly described in the document giving an example. Major findings of this initial evaluation were: trends of TAC change and values of performance measures differed between combinations of target probabilities and target year; shorter target year and higher target probability resulted in lower mean, minimum, and maximum catches; both options of maximum TAC change and implementation time lag did not affect on TAC change patterns and performance; the year/probability target was achieved for most of robustness trials as in the reference case, except for "highCPUECV", "STwin", "omega75", and "upq" scenarios. The evaluated management procedure was consisted of only one particular set of rules and specific forms of fuzzy set membership functions (although testing the very limited numbers of its variants were conducted). So, there may be some room to modify those rules and/or forms of membership functions and to explore variants to get different TAC change patterns and better performance.

# ミナミマグロのファジー制御管理方式の開発とその初期評価

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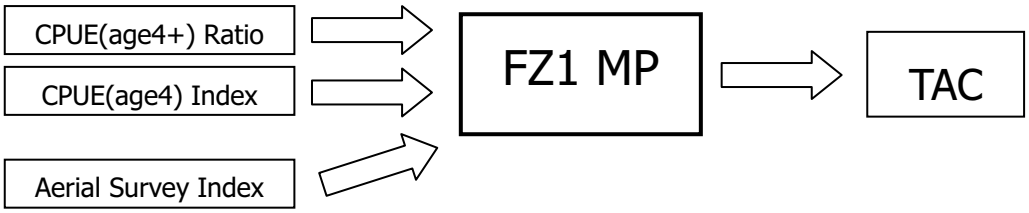
**要旨**：この文書では、ミナミマグロ資源を対象にしたファジー制御管理方式の開発とその初期評価の概要について述べる。ファジー制御とは、ファジー推論を制御システムに応用した工学技術である。この管理方式の中で実際に行われているファジー制御の操作については、例を示しつつ文書の中で簡単に説明した。今回の初期評価から以下の結果が得られた：目標達成確率と目標達成年の組み合わせにより、TAC 変化のトレンドと管理方式のパフォーマンスは異なる；短い目標達成年、高い達成確率であるほど、平均、最小、最大の漁獲量は低くなる；最大 TAC 変更、及び TAC 実施タイムラグのどちらのオプションの違いも結果にほとんど影響しない；ロバストネス・テストでは、"highCPUECV", "STwin", "omega75", and "upq"のシナリオを除き、リファレンス・ケースと同様に目標を達成できた。今回評価された管理方式は、特定のルール・セット及び特定の関数形を持ったファジー集合会員関数でのみ構成されている（非常に限定された数の変形版のテストは行ったが）。異なる TAC 変更パターンやより良いパフォーマンスを得るために、これらのルールや関数形を変更し、この管理方式の変形版を開発・模索する余地はあるだろう。

# 1. Introduction

This document provides a rough sketch of development and initial evaluation of fuzzy-controlled management procedures (MP's) for Southern Bluefin Tuna. The fuzzy control is an engineering technology that applies fuzzy reasoning (Cox 1994) to control systems. The fuzzy control has many applications, for example, to household appliances such as washing machines, and automatic operation of unmanned trains. Major advantages of applying the fuzzy control are: specification of complicated mathematical formulae for controlling is not necessary when building systems; empirical or expert knowledge can be incorporated into the control systems; uncertainty that humans handle in decision-making process is quantified and can be dealt with in the systems.

# 2. Schematic Representation of Fuzzy-Controlled MP ("FZ1")




The "FZ1" MP uses the following three indicators as inputs to evaluate stock status and then to specify the next year's TAC:

(1) CPUE(age4+) Ratio - Use as an indicator of change in spawning stock biomass (the ratio of the most recent 3-year average to the 3-year average before those 3 years);

(2) CPUE(age4) Index – Use as an indicator of change in recruitment level (the most recent 3-year average, evaluated comparing to historical minimum and maximum levels)

(3) Aerial Survey Index – Also use as an indicator of change in recruitment level (the most recent 3-year average, evaluated comparing to historical minimum and maximum levels)

# 3. Feedback Control in FZ1 MP using Fuzzy Reasoning

This section briefly explains how feedback control using fuzzy reasoning is incorporated into the FZ1 MP and also provides relevant information of the fuzzy reasoning used in the

management procedure (for further details of fuzzy reasoning, see Cox 1994). The first step of building a fuzzy control system is to consider and determine a set of rules (IF-THEN rules) such as "If the current condition is ... , then do ... ." Here is an example,

"IF CPUE(age4+) ratio indicates Medium Increase of the stock AND CPUE(age4) is Medium level AND Aerial Index is Strong level, THEN TAC change action is Positive Medium"

This set of rules can be given in the table form below (called "fuzzy associative memory (FAM)"). By defining these rules, empirical or expert knowledge can be embodied into the control system, and also resulting TAC change actions for certain stock conditions can be explicitly described.

IF CPUE(age4+) is MI (Medium Increase) AND:

| | | CPUE(age4) | | |
|---|---|---|---|---|
| | | WK | MM | SG |
| AI | WK | PS | PS | PM |
| | MM | PS | PM | PM |
| | SG | PM | PM | PL |

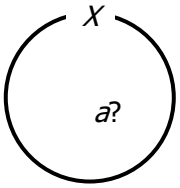
For instance, this square represents the following rule:
"IF CPUE(age4+) ratio indicates MI AND CPUE(age4) is SG level AND AI is MM level, THEN TAC change action is PM"

AI (Aerial Survey Index)
WK (Weak), MM (Medium), SG (Strong)
PS (Positive Small), PM (Positive Medium), PL (Positive Large)

Now, suppose that we have some values for CPUE(age4+) ratio, CPUE(age4), and Aerial Survey Index, respectively. In most cases, it is not 100% certain to state that, for example, the age4+ CPUE ratio indicates "Medium Increase" of the stock. It may be 70% certain or only 30% reliable in some cases. Furthermore, the degree of "Increase" itself is ambiguous (e.g., In what range of the CPUE ratio do we state that the stock is in Medium Increase status?). The same notion is true for other two indicators as well. Given such fuzziness in the premise for stock status, there may be uncertainty in resultant TAC change action (e.g., Is it 100% reasonable to say that TAC change action is "Positive Medium" when our knowledge of the stock status is ambiguous?). In control systems using fuzzy logic, the idea of fuzzy set theory is applied to deal with such ambiguity pertinent to such approximate reasoning.

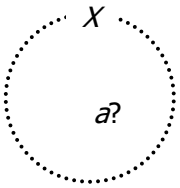
In general crisp set theory, whether an element $a$ is a member of the set $X$ is either 0% or 100% (yes/no or 0/1 dichotomy). In contrast, the fuzzy set theory defines whether an element $a$ is a member of the set $X$ by the degree of membership between 0% and 100% (called "membership function", usually represented as $\mu(a)$) (compare the two figures below and note the nebulous boundary of the fuzzy set).

General crisp set



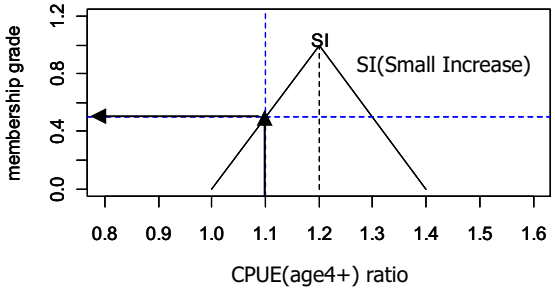

a?

Fuzzy set




a?

Example of a membership function for the fuzzy set "SI (Small Increase)" for CPUE(age4+)




Actual operation of TAC control using fuzzy reasoning in the FZ1 is described below giving an example. For illustrative purpose, only the two indicators, CPUE(age4+) ratio and Aerial Survey Index, are used as inputs for the MP in the example. The operation can very easily be expanded to the case of using all three indicators.

Suppose we have some values of CPUE(age4+) ratio and Aerial Survey Index (AI), respectively. The CPUE ratio falls within the domain of two CPUE ratio fuzzy sets, MI (Medium Increase) and LI (Large Increase), and AI falls within the MM (Medium) level fuzzy set region (see the figure below). Then, consider the following rules:

[Rule 1] IF CPUE(age4+) ratio is MI (Medium Increase) AND AI is MM (Medium)
THEN TAC change action is PM (Positive Medium)

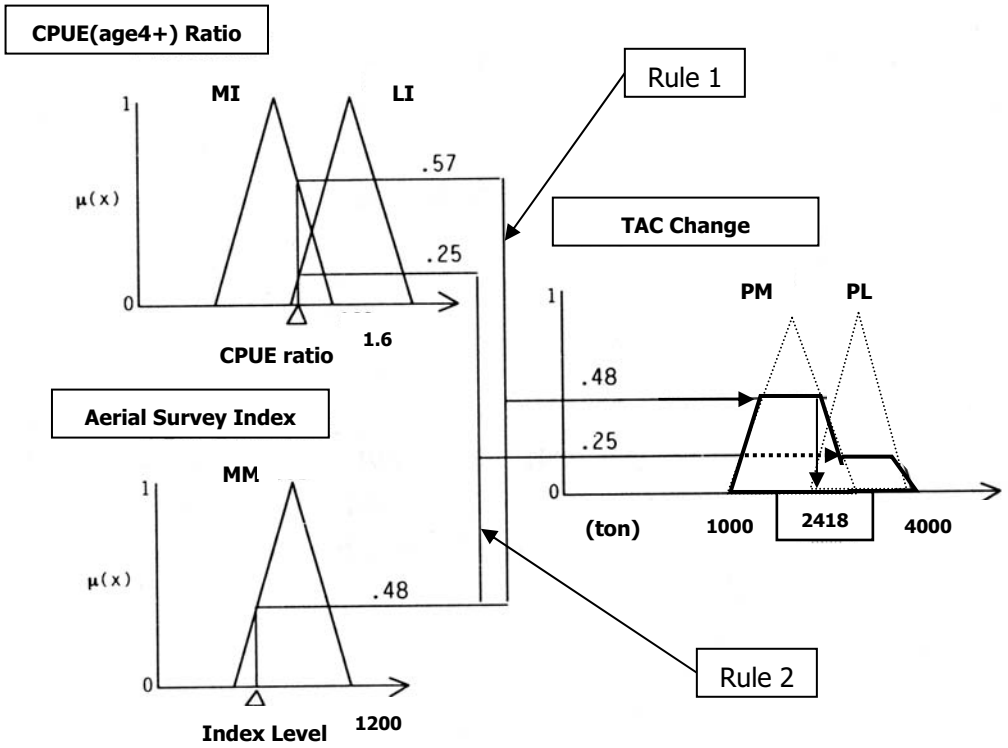
[Rule 2] IF CPUE(age4+) ratio is LI (Large Increase) AND AI is MM (Medium)
THEN TAC change action is PL (Positive Large)

The first rule causes the PM TAC action to be copied into the output TAC action fuzzy set. But before doing this its membership (height) is truncated at the truth of the rule's premise (the minimum[1] of [.57] and [.48]). The figure below shows how this works and how the TAC action output fuzzy region looks after the first rule is fired.

The second rule is selected because the CPUE(age4+) ratio has some degree of

[1] The basic Zadeh type "AND" operation is to take the minimum of memberships in the predicate (Lotfi Zadeh is its inventor of fuzzy logic).

membership in MI (Medium Increase) as well a small degree of membership in LI (Large Increase). When the second rule is fired, the PL (Positive Large) fuzzy set is also truncated at the truth of its premise (the minimum of [.25] and [.48]) and then copied into the output TAC action region. Since the region is not empty, however, this modified fuzzy set is "OR[2]" -operated with the PM fuzzy set. The figure below shows the final TAC action output fuzzy set. When the centroid defuzzification method (Cox 1994) is applied, an TAC change action of +2418 t is calculated as the expected value.




For tuning purpose in the MP evaluation, the final TAC specification is defined as below:

$$TAC(year) = TAC(year-1) + \begin{cases} \Delta TAC \times \alpha & if\ \Delta TAC \geq 0 \\ \Delta TAC \times \beta & if\ \Delta TAC < 0 \end{cases},$$

where $\Delta TAC$ is a centroid-defuzzified TAC from the fuzzy reasoning described as above, and $\alpha$ and $\beta$ are tuning parameters.

[2] The basic Zadeh type "OR" operation is to take the maximum of memberships in the predicate.

The actual set of rules (9 rules/table x 7 tables = 63 rules) embedded in the FZ1 are provided below. In each table, the following abbreviations are used.

CPUE(age4+):

Large Decrease (LD), Medium Decrease (MD), Small Decrease (SD), Stable (ST), Small Increase (SI), Medium Increase (MI), Large Increase (LI)

CPUE(age4) & Aerial Survey Index:

Weak (WK), Medium (MM), Strong (SG)

TAC change action:

Negative Large (NL), Negative Medium (NM), Negative Small (NS), Zero (ZR), Positive Small (PS), Positive Medium (PM), Positive Large (PL)

(1) IF CPUE(age4+) ratio indicates LD AND

| | | CPUE(age4) | | |
|---|---|---|---|---|
| | | WK | MM | SG |
| AI | WK | NL | NL | NL |
| | MM | NL | NL | NM |
| | SG | NL | NM | NM |

(2) IF CPUE(age4+) ratio indicates MD AND

| | | CPUE(age4) | | |
|---|---|---|---|---|
| | | WK | MM | SG |
| AI | WK | NL | NM(NL)* | NM(NL) |
| | MM | NM | NM | NM |
| | SG | NM | NM | NS |

Note *: All output TAC change actions in parentheses were built in the FZ2 (a variant of the FZ1)

(3) IF CPUE(age4+) ratio indicates SD AND

| | | CPUE(age4) | | |
|---|---|---|---|---|
| | | WK | MM | SG |
| AI | WK | NM(NL) | NS(NM) | NS(NM) |
| | MM | NS | NS | NS |
| | SG | NS | NS | ZR |

(4) IF CPUE(age4+) ratio indicates ST AND

| | | CPUE(age4) | | |
|---|---|---|---|---|
| | | WK | MM | SG |
| AI | WK | NS(NM) | NS(NM) | ZR(NS) |
| | MM | NS | ZR | ZR |
| | SG | ZR | ZR | PS |

(5) IF CPUE(age4+) ratio indicates SI AND

| | | CPUE(age4) | | |
|---|---|---|---|---|
| | | WK | MM | SG |
| AI | WK | ZR(NS) | ZR(NS) | PS(NS) |
| | MM | ZR | PS | PS |
| | SG | PS | PS | PM |

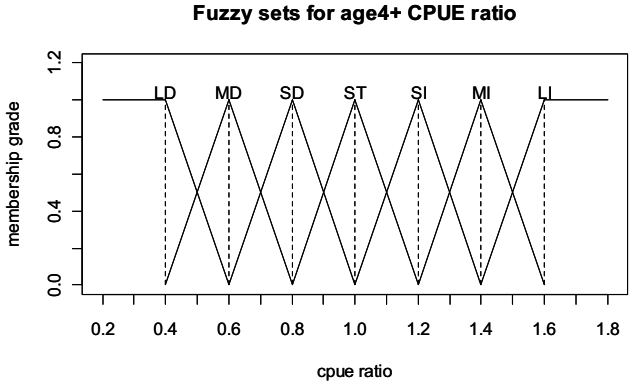
(6) IF CPUE(age4+) ratio indicates MI AND

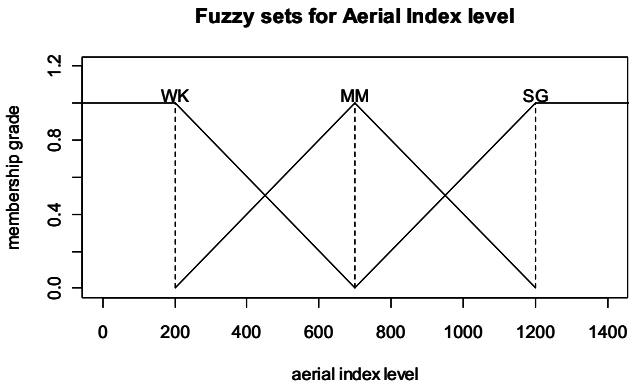
| | | CPUE(age4) | | |
|---|---|---|---|---|
| | | WK | MM | SG |
| AI | WK | PS(ZR) | PS(ZR) | PM(PS) |
| | MM | PS | PM | PM |
| | SG | PM | PM | PL |

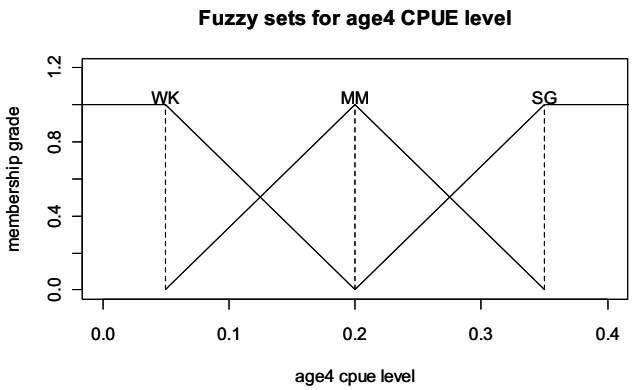
(7) IF CPUE(age4+) ratio indicates LI AND

| | | CPUE(age4) | | |
|---|---|---|---|---|
| | | WK | MM | SG |
| AI | WK | PM(PS) | PM(PS) | PL(PM) |
| | MM | PM | PL | PL |
| | SG | PL | PL | PL |

The actual membership functions for fuzzy sets defined in the FZ1 MP are provided below. The same abbreviations as above are used to represent the fuzzy sets.

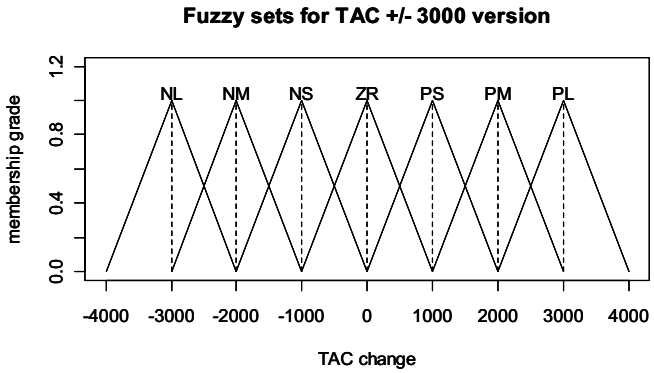


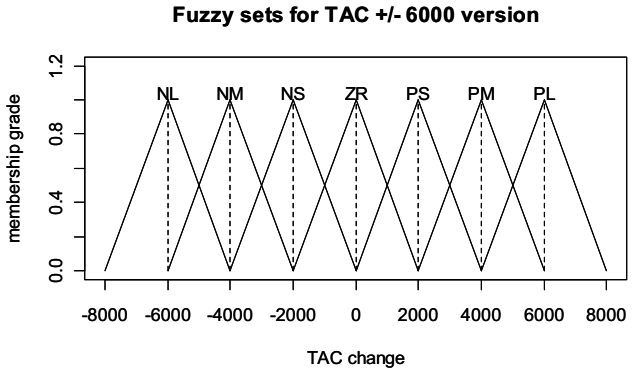




Two types of membership functions for output TAC change actions were used.

(a) For the FZ1 and the FZ2 (a variant of the FZ1)




(b) For the FZ1b (a variant of the FZ1)



# 4. Preliminary Results

Simulation tests were conducted using the following combinations of tuning options (squares in tables given tuning parameter values) for the reference case and robustness trials. The selected combinations were based on the management guidance from the SFMWG to the ESC in April 2010 for MP development (CCSBT 2010). For each combinations, first the FZ1 MP was tuned using the reference set and then all robustness trials were done with the same values of tuning parameters as the reference. For all combinations, TAC change frequency was set to every 3 years. Tuning exercises were done allowing the error range between -1% and +1% (e.g., 69%-71% when the tuning option is 70%). In addition, two variants of the FZ1 (named "FZ1b" and "FZ2", see the tables and figures in pages 6-8 for the specifications) were explored. Simulation tests were conducted using the projection software "sbtprojv118.exe" (distributed on 19 May 2010) based on conditioning results obtained by the conditioning program "sbtmod22.exe" (distributed on 21 April 2010).

(1) Max TAC change = 5000 t, implementation time lag = 0 year

| | | probability | | |
|---|---|---|---|---|
| | | 60% | 70% | 90% |
| year | 25 | α=1.0<br>β=1.42 | α=1.0(0.76[a], 0.8[b])<br>β=1.9(1.24[a], 1.0[b]) | α=0.2<br>β=2.3 |
| | 30 | α=1.68<br>β=1.0 | α=1.28<br>β=1.0 | α=1.0<br>β=1.58 |

Note a: Values used for the FZ1b (a variant of the FZ1)
b: Values used for the FZ2 (a variant of the FZ1)

(2) Max TAC change = 5000 t, implementation time lag = 1 year

| | | probability | | |
|---|---|---|---|---|
| | | 60% | 70% | 90% |
| year | 25 | | α=1.0<br>β=1.9 | |
| | 30 | | | |

(3) Max TAC change = 3000 t, implementation time lag = 0 year

| | | probability | | |
|---|---|---|---|---|
| | | 60% | 70% | 90% |
| year | 25 | | α=0.95<br>β=2.0 | α=0.15<br>β=4.0 |
| | 30 | | | |

Major findings of this initial evaluation were summarized below:

- Trends of TAC change and values of performance measures differed between combinations of target (tuning) probabilities (compare a, b, and c in Fig. 1, or a, b, and c in Fig. 2) and target (tuning) year (compare Fig. 1a with 2a, 1b with 2b, and 1c with 2c), also see Table 1)
- Two combinations (25-year/70% and 30-year/90% targets) showed similar trends of TAC change and performance measures (Fig. 1b and Fig. 2c, Table 1)
- Shorter target year and higher target probability resulted in lower mean, minimum, and maximum catches (Fig. 1 and Fig. 2, Table 1)
- For the combination of 25-target-year and 90% target probability (maximum TAC change was set to 5000 t), TAC could not be increased after reducing TAC in large amounts in the early part of the projection period (Fig. 1c)
- There was no noticeable difference found in TAC change trends and performance measures between implementation year lag 0 and 1 options (Fig. 3a and 3b), but the 0-year lag option tended to give a bit larger mean, minimum, and maximum catches (Table 1)
- The year/probability target was achieved for most of robustness trials as in the reference case, except for "highCPUECV", "STwin", "omega75", and "upq" scenarios (Fig. 4 and Fig. 5)
- Two maximum TAC change options (5000 t versus 3000 t) gave quite similar TAC change patterns and performance measures (compare Fig. 1b and Fig. 2a, Fig. 1c and Fig. 2b, also see Table 1)
- Variants of the FZ1 which give different TAC change patterns and performance are possible to be developed and explored by modifying IF-THEN rules and/or forms of fuzzy set membership functions (compare Fig. 7a to Fig. 1b, also see Table 1)
- Some variants give similar TAC change patterns and performance to the original FZ1 even if different IF-THEN rules and/or forms of fuzzy set membership functions are embedded (compare Fig. 7b to Fig. 1b, also see Table 1)

## 5. References

Cox, E. (1994) *The fuzzy systems handbook: a practitioner's guide to building, using, and maintaining fuzzy systems*. Academic Press Professional, MA, USA. 615 pp.

CCSBT (2010) Report of the Second Meeting of the Strategy and Fisheries Management Working Group Meeting. 14-16 April 2010. Tokyo, Japan

## Acknowledgements

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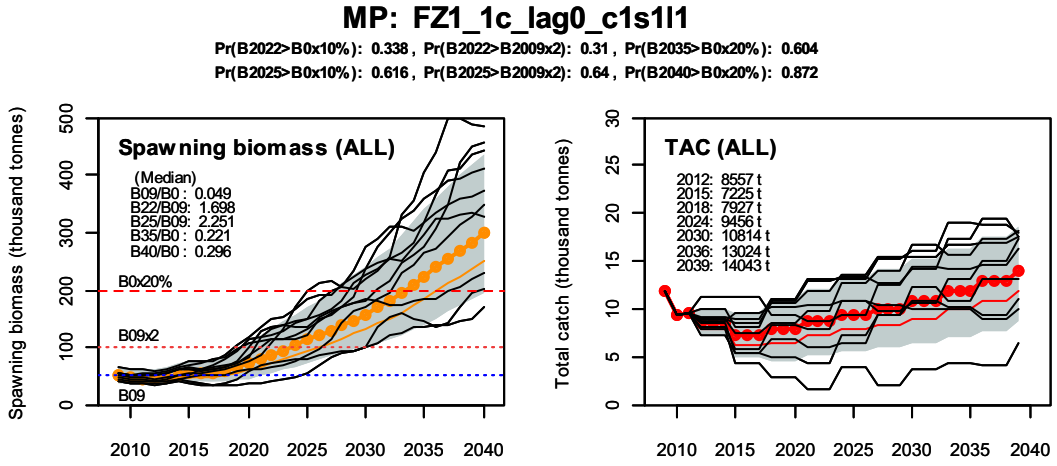
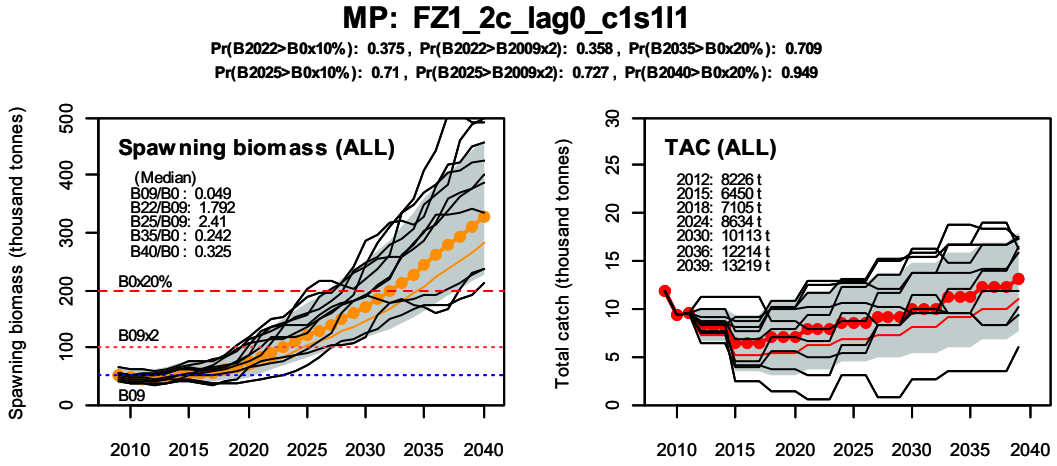
(a) 60%




(b) 70%




(c) 90%

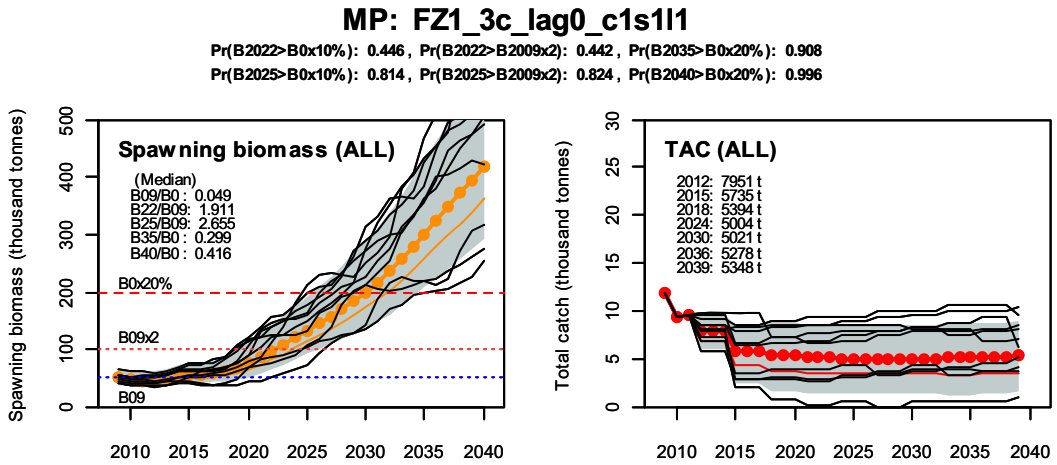
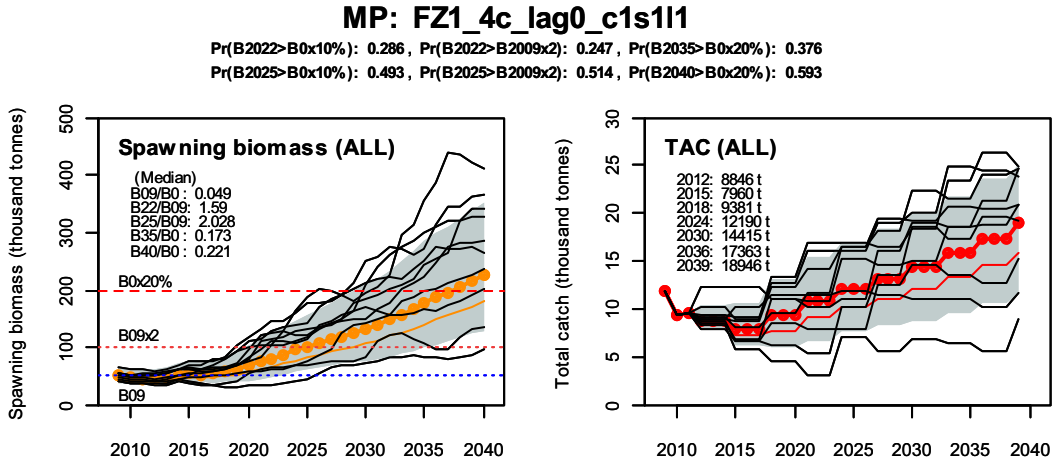
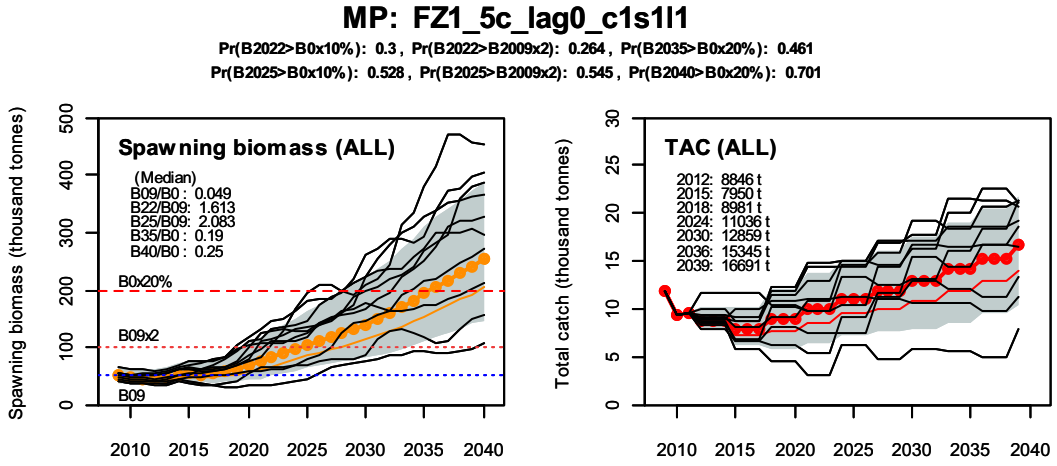



Fig. 1. Comparisons of spawning biomass and TAC trends between different target (tuning) probabilities. Reference case; target (tuning) year is 25; maximum TAC change is 5000 t; implementation time lag is 0 year.

(a) 60%




(b) 70%




(c) 90%

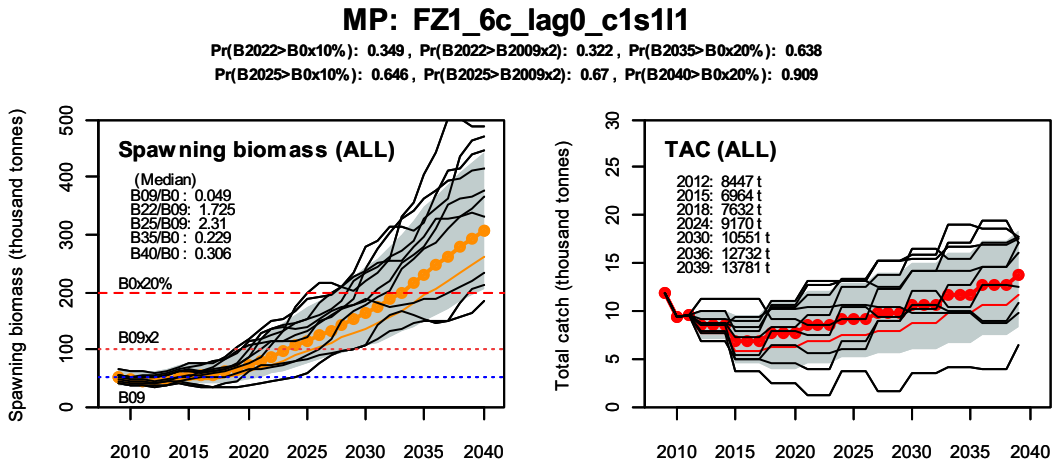
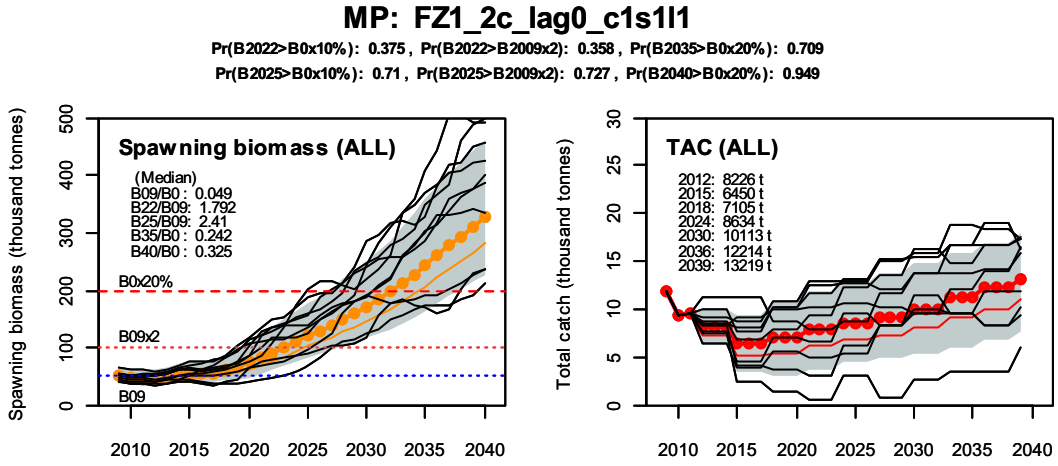



Fig. 2. Comparisons of spawning biomass and TAC trends between different target (tuning) probabilities. Reference case; target (tuning) year is 30; maximum TAC change is 5000 t; implementation time lag is 0 year.

(a) 0 year




(b) 1 year

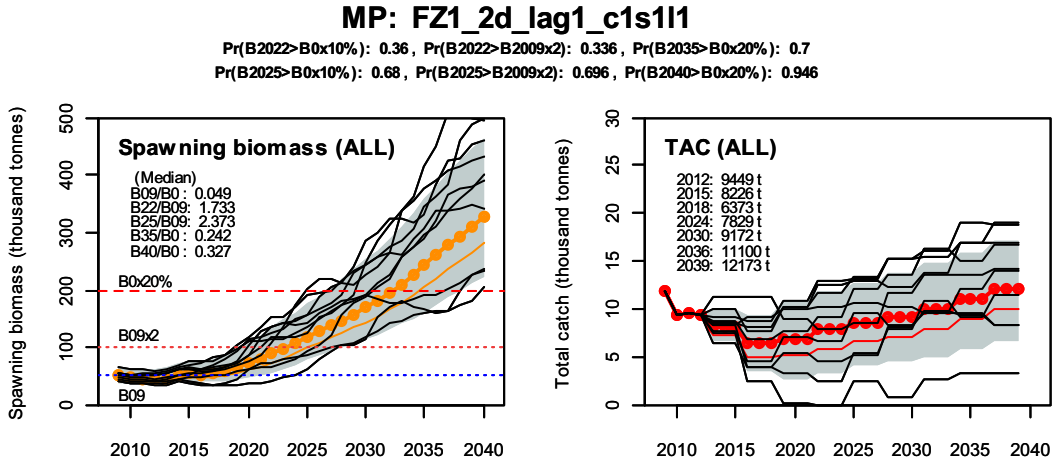



Fig. 3. Comparisons of spawning biomass and TAC trends between different implementation time lags. Reference case; target (tuning) year is 25; target (tuning) probability is 70%; maximum TAC change is 5000 t.

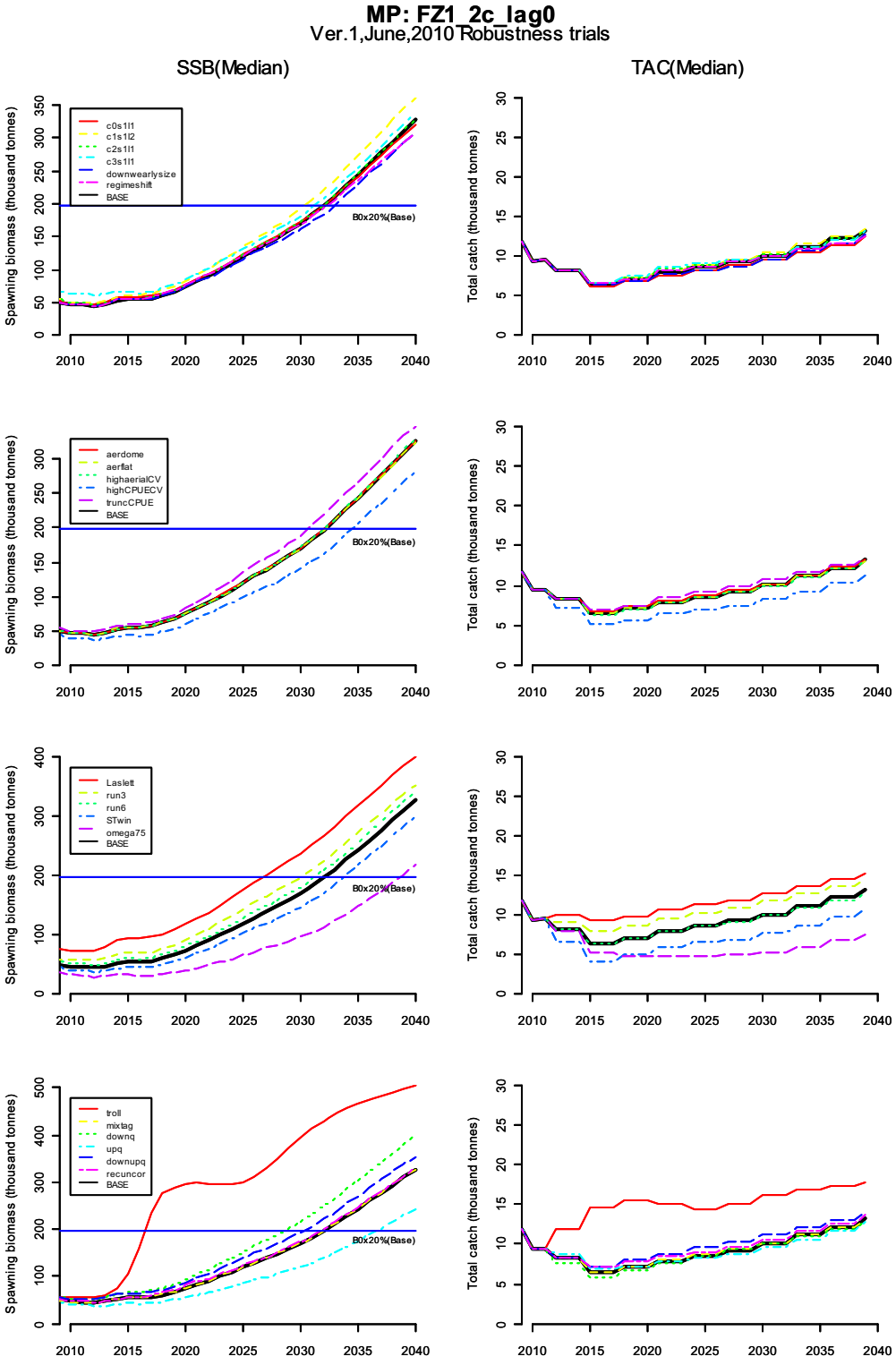



Fig. 4. Comparisons of spawning biomass and TAC trends between different robustness trials. Target (tuning) year is 25; target (tuning) probability is 70%; maximum TAC change is 5000 t.

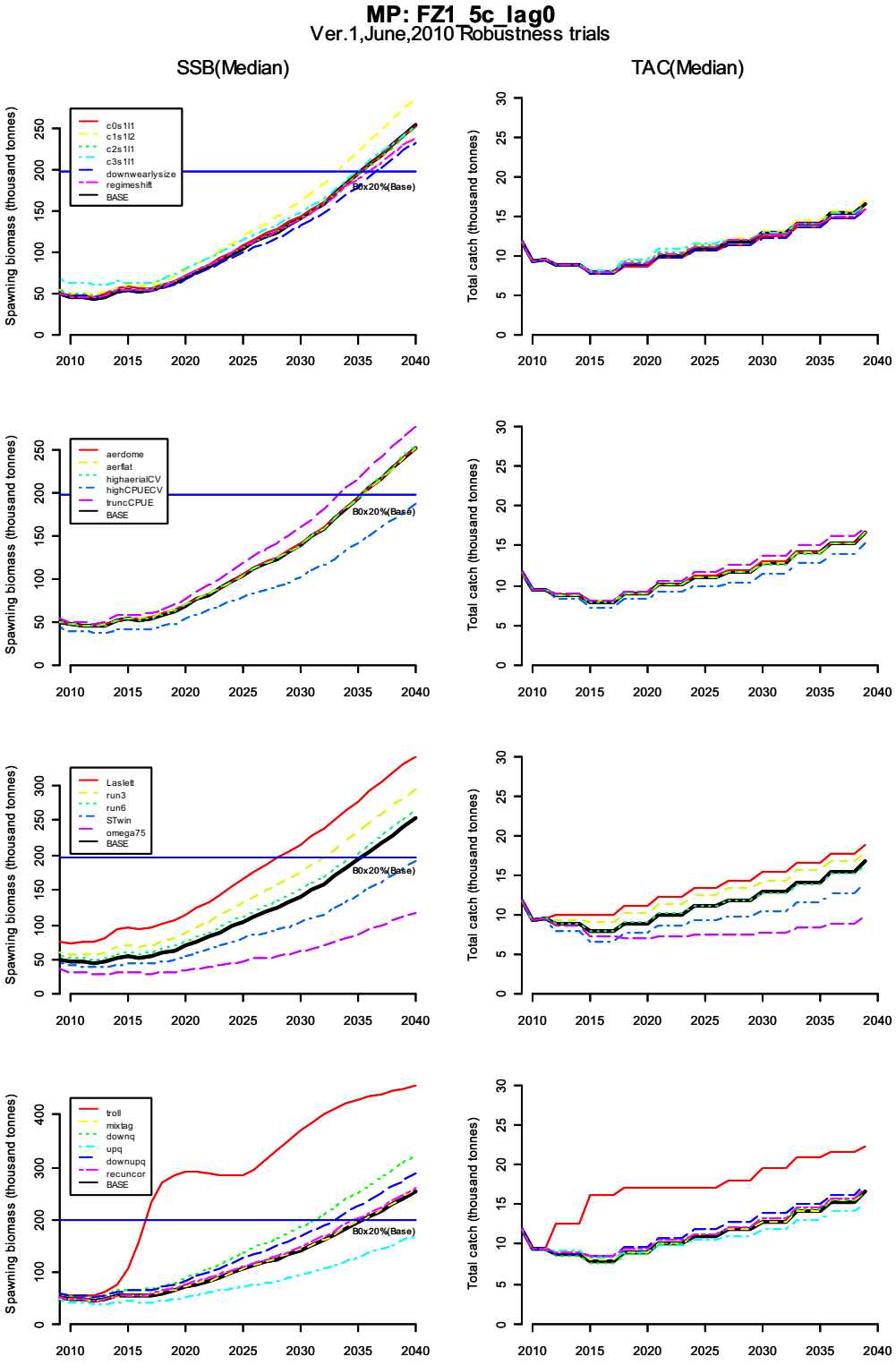
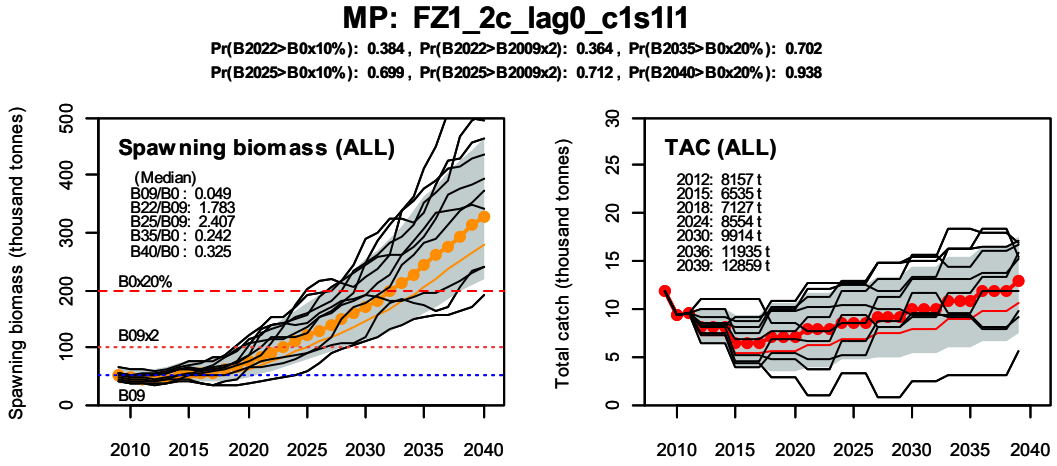



Fig. 5. Comparisons of spawning biomass and TAC trends between different robustness trials. Target (tuning) year is 30; target (tuning) probability is 70%; maximum TAC change is 5000 t.

(a) 70%




(b) 90%

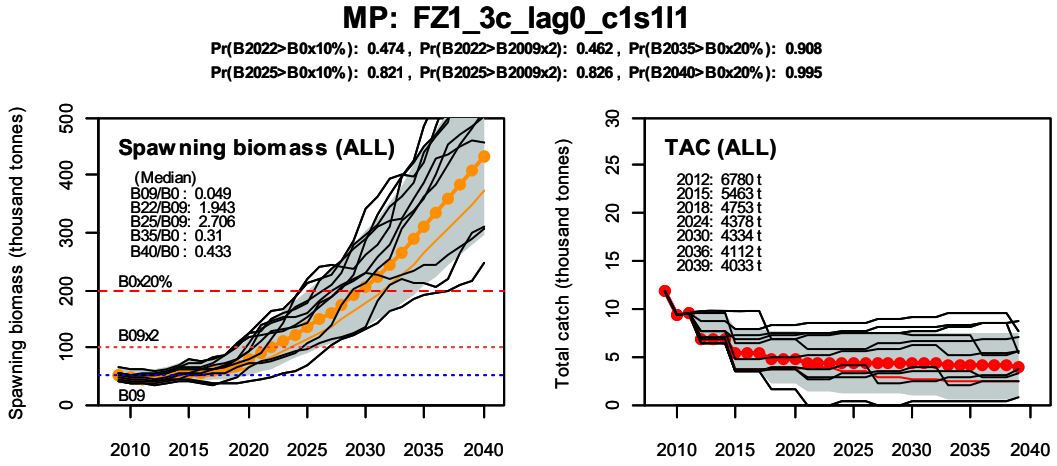
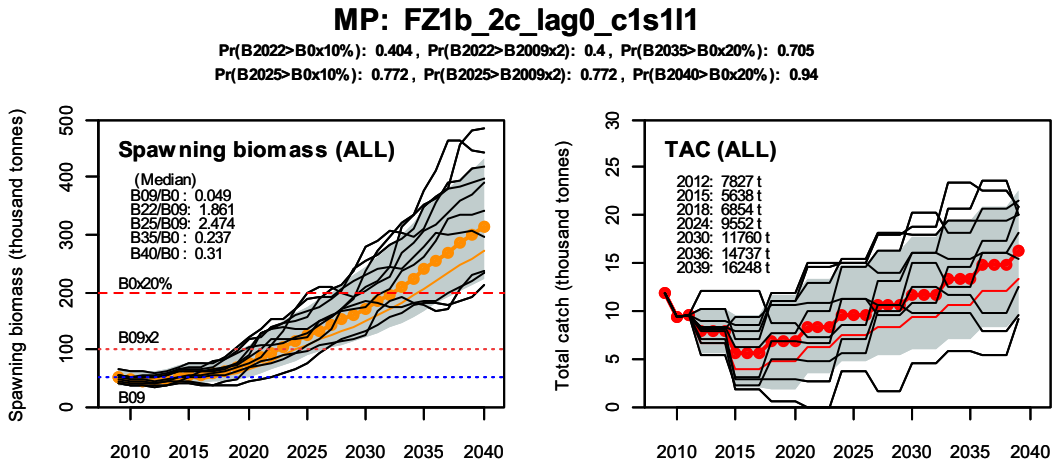



Fig. 6. Comparisons of spawning biomass and TAC trends between different target (tuning) probabilities. Reference case; target (tuning) year is 25; maximum TAC change is 3000 t; implementation time lag is 0 year.

(a) FZ1b




(b) FZ2

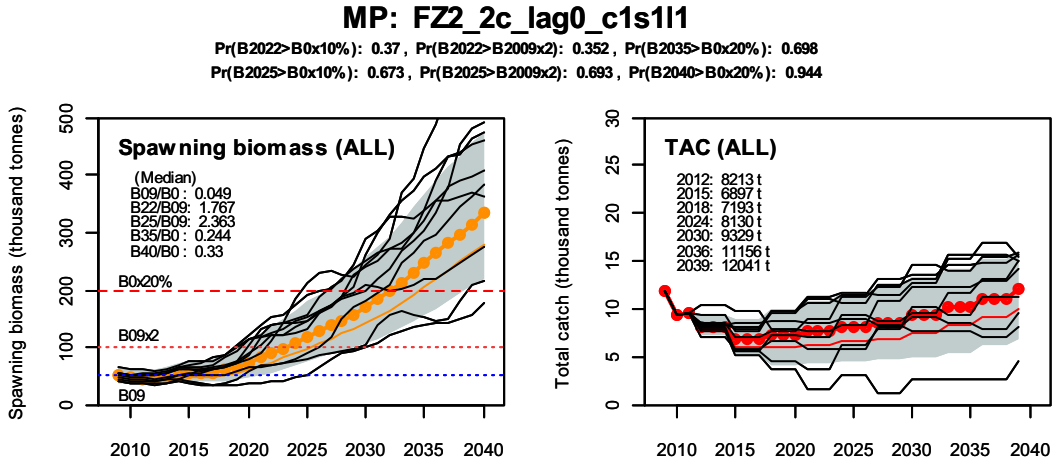



Fig. 7. Spawning biomass and TAC trends of two variants, FZ1b and FZ2, of the FZ1. Reference case; target (tuning) year is 25; maximum TAC change is 5000 t; implementation time lag is 0 year. (a) The FZ1b embodied a different form of fuzzy set membership function for the output TAC change action (see the bottom figure in page 8); (b) the FZ2 incorporated a different set of IF-THEN rules (see the tables in pages 6-7).

Table 1. Summary of performance measures (Reference case)

| | | | Target | | Checkpoint | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MP name | Year | % | Pr[B2035 >0.20*B0] | Pr[B2040 >0.20*B0] | Pr[B2022 >=0.10*B0] | Pr[B2022 >=2*B2009] | Pr[B2025 >=0.10*B0] | Pr[B2025 >=2*B2009] | Mean Catch [2009:2031] | Min Catch [2009:2039] | Max Catch [2009:2039] | Median [B2032/B2009] | 10%tile [B2032/B2009] | AAV | Mean Catch [2009:2039] | Median [B2040/B2009] | Min Catch [By/B2009] | 10%tile Min [By/B2009] |
| FZ1 | 2035 | 60 | **0.605** | 0.872 | 0.338 | 0.310 | 0.616 | 0.641 | 9031 | 7223 | 14040 | 3.6 | 2.2 | 0.055 | 9943 | 5.936 | 0.9 | 0.8 |
| | | 70 | **0.709** | 0.949 | 0.375 | 0.358 | 0.710 | 0.727 | 8371 | 6449 | 13217 | 3.9 | 2.5 | 0.067 | 9269 | 6.507 | 0.9 | 0.9 |
| | | 90 | **0.909** | 0.997 | 0.446 | 0.442 | 0.814 | 0.824 | 6192 | 4984 | 11810 | 4.7 | 3.0 | 0.046 | 5970 | 8.277 | 0.9 | 0.9 |
| | 2040 | 60 | 0.376 | **0.593** | 0.287 | 0.247 | 0.493 | 0.515 | 10755 | 7960 | 18942 | 2.9 | 1.6 | 0.057 | 12273 | 4.458 | 0.9 | 0.8 |
| | | 70 | 0.461 | **0.701** | 0.301 | 0.264 | 0.528 | 0.545 | 10151 | 7950 | 16688 | 3.2 | 1.8 | 0.050 | 11311 | 5.023 | 0.9 | 0.8 |
| | | 90 | 0.638 | **0.909** | 0.349 | 0.323 | 0.646 | 0.670 | 8808 | 6963 | 13778 | 3.7 | 2.3 | 0.059 | 9712 | 6.110 | 0.9 | 0.8 |
| FZ1 lag1 | 2035 | 70 | **0.700** | 0.946 | 0.360 | 0.336 | 0.680 | 0.696 | 8274 | 6373 | 12173 | 3.9 | 2.4 | 0.064 | 9060 | 6.506 | 0.9 | 0.8 |
| FZ1 3000t | 2035 | 70 | **0.703** | 0.939 | 0.384 | 0.364 | 0.699 | 0.713 | 8375 | 6535 | 12859 | 3.9 | 2.4 | 0.065 | 9172 | 6.506 | 0.9 | 0.9 |
| | | 90 | **0.909** | 0.995 | 0.474 | 0.463 | 0.821 | 0.826 | 5664 | 4032 | 11810 | 4.8 | 3.0 | 0.050 | 5263 | 8.608 | 0.9 | 0.9 |
| FZ1b | 2035 | 70 | **0.705** | 0.941 | 0.404 | 0.401 | 0.772 | 0.772 | 8632 | 5636 | 16247 | 3.9 | 2.5 | 0.097 | 10089 | 6.216 | 0.9 | 0.9 |
| FZ2 | 2035 | 70 | **0.698** | 0.944 | 0.370 | 0.353 | 0.673 | 0.693 | 8234 | 6897 | 12037 | 3.9 | 2.4 | 0.051 | 8881 | 6.625 | 0.9 | 0.8 |

FZ1: Maximum TAC change was 5000 t, implementation time lag was 0 year, TAC change frequency was every-3-year.

FZ1 lag1: All conditions were equal to FZ1 except for 1 year implementation time lag.

FZ1 3000t: All conditions were equal to FZ1 except for 3000 t maximum TAC change

FZ1b: All conditions were equal to FZ1 except for embodying a different form of fuzzy set membership function for the output TAC change action (see the bottom figure in page 8).

FZ2: All conditions were equal to FZ1 except for incorporating a different set of IF-THEN rules (see the tables in pages 6-7).