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A model for simulating harvest strategies to evaluate the effects of changes in assessment frequency: An application to Northern Shrimp

Hugo Bourdages and Mathieu Desgagnés

Fisheries and Oceans Canada
Maurice Lamontagne Institute
850 route de la Mer
Mont-Joli, Quebec G5H 3Z4

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

An operational model was used to test new decision rules to evaluate the effects of changes in the assessment frequency on management advice for the Northern Shrimp fishery in the Gulf of St. Lawrence. Because the Northern Shrimp is a species subject to abundance variations related to variable recruitment and given its brief lifespan and the short period of availability to the fisheries, frequent adjustments of harvest are needed to track the dynamics of the stock. Simulations have shown that as soon as the TAC adjustment frequency is more than one year, the abundance and landings indicators decline.

RÉSUMÉ

Un modèle opérationnel a été utilisé pour tester de nouvelles règles de décision pour évaluer les effets des changements de la fréquence des évaluations sur l’avis en matière de gestion des pêches pour la crevette nordique du golfe du Saint-Laurent. À cause que la crevette nordique est une espèce sujette à des variations d’abondance reliées au recrutement variable et étant donné sa brève longévité et la courte période de disponibilité à la pêche, des ajustements fréquents des prélèvements sont nécessaire afin de suivre la dynamique de ce stock. Les simulations ont démontré que dès que l’on espace de plus d’un an les ajustements de TAC, les indicateurs de l’abondance et des débarquements diminuent.

INTRODUCTION

The Northern Shrimp (*Pandalus borealis*) fishery in the Gulf of St. Lawrence is conducted by trawlers in four shrimp fishing areas. Shrimp fishing is regulated by a number of management measures, including the setting of total allowable catches (TAC). TAC-based management limits fishing to protect the reproductive potential of the population. The essential elements for the establishment of a precautionary approach were adopted in 2012 (DFO 2012). Reference points were determined and guidelines were established to determine harvest based on the main stock status indicator relative to the stock status classification zones of healthy, cautious and critical (DFO 2011). The harvest guidelines are based on a constant exploitation rate when the stock is in the healthy zone. The harvest rate decreases in the cautious zone until stock status drops below the critical zone, where the exploitation rate is set a constant value that is four times lower than that of the healthy zone. Once the harvest is established, decision rules are applied to determine the TAC.

The resource is assessed every two years to determine whether changes that have occurred in stock status require adjustments to the conservation approach and management plan. In the interim year, an update is done to determine the harvest based on the main stock status indicator and its position in relation to the stock status classification zones.

In 2012, an operational model was used to simulate decision rules to assist the industry in making informed choices concerning harvest strategies (Desgagnés and Savard 2012). This model is used here to test new decision rules and evaluate the effects of changes in the assessment frequency on management advice. The harvest decision rules tested are an annual adjustment of TAC or a constant TAC set for periods of 2 to 5 years. To address any uncertainty concerning the data, the model structure or future environmental fluctuations, six scenarios are explored to gauge the robustness and performance of the decision rules under study.

MATERIAL AND METHODS

OPERATING MODEL STRUCTURE

The model developed to project the evolution of a shrimp stock is applied to population numbers distributed through seven stages of maturity: a larval stage (l), four male stages (m1 to m4) and two female stages (f1 and f2). Males are grouped by age (one to four years) and females by reproductive history, i.e. primiparous (first spawn) and multiparous (second spawn). The model has an annual time step, and a Leslie matrix is used to express equations characterizing the dynamics of the modeled stock:

$$\begin{pmatrix} N_l \\ N_{m1} \\ N_{m2} \\ N_{m3} \\ N_{m4} \\ N_{f1} \\ N_{f2} \end{pmatrix}_{t+1} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & f(n_{f1}) & f(n_{f2}) \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \phi_{it}(1-cs_i) & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \phi_{it}(1-cs_i) & \phi_{it}(1-cs_i) & 0 & 0 \\ 0 & 0 & \phi_{it}(cs_i) & \phi_{it}(cs_i) & \phi_{it}(cs_i) & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \phi_{it} & \phi_{it} \end{pmatrix} \times \begin{pmatrix} N_l \\ N_{m1} \\ N_{m2} \\ N_{m3} \\ N_{m4} \\ N_{f1} \\ N_{f2} \end{pmatrix}_t$$

where N_i is the number of individuals in stage *i*, cs_i is the proportion of individuals in stage *i* that will change sex during the current year, $f(n_i)$ is the relationship between numbers of spawners and of recruits and Φ_{it} is the survival of stage *i* individuals over time *t*, calculated such that:

$$\phi_{it} = e^{\left(-\left(M_t + F_t * s_i^{comm}\right)\right)}$$

where M is natural mortality, F fishing mortality and s_i^{comm} the selectivity of commercial fishing gear for stage i individuals.

In the model, two-year-old males (*m2*) were classified as recruits and their number is estimated by a relationship between spawning stock and recruits. Stages *I* and *m1* are included in the model to represent the time period between hatching and recruitment. Stages *m4* and *f2* represent males aged 4+ and females aged 2+ respectively. Beginning in stage *m2*, males may change sex to become primiparous females (*f1*).

The model is used to calculate an initial indicator of the stock status in the form of the commercial fishery catch rate:

$$I_{i,t}^{comm} = q_{comm} N_{i,t}$$

where q_{comm} is commercial catchability.

The model is also used to calculate a second stock status indicator in the form of estimated biomass from a research survey:

$$I_{i,t}^{rel} = q_{rel} N_{i,t} e^{\left(-\frac{M_t + F_t * s_i^{comm}}{2}\right)} s_i^{rel}$$

where q_{rel} is the survey catchability and s_i^{rel} is the selectivity of survey fishing gear for stage i individuals. Total instantaneous mortality is divided by 2 to represent surveys taking place mid-year.

Model simulations are initiated by reproducing the 21 years (1990 to 2010) of fishery and survey data from the Sept-Îles shrimp fishing area in the Gulf of St. Lawrence (Savard 2011, Savard and Bourdages 2011). The recruitment series estimated from the survey size frequency distribution provides an estimate of recruitment for this time period that is assumed to be exact. Simultaneously, the actual catches are imposed on the model. Beginning in year 22, a relationship between spawning stock and recruits is used instead, and harvests are set according to a predefined rule. Population numbers for year 1 are determined from the 1990 survey size frequency distribution adjusted for gear selectivity (Table 1). A total of 1,001 projections were performed, each for a fixed 25-year duration.

Fishery removal is expressed as weight, and instantaneous fishing mortality (F_t) is adjusted for each time step to produce expected removal values. The maximum allowed value of F in this exercise is 3, which would require effort approximately 2.5 times the maximum observed between 1990 and 2010 in the Sept-Îles fishing area.

TAC DECISION RULES

Savard (2012) describes the manner in which information obtained from commercial data and research surveys is combined to produce an index of the status of Northern Shrimp stocks in the Gulf of St. Lawrence. For simulation needs, a modified version to account for observation error is used:

$$I_t^{tot} = \frac{I_{m,t}^{comm} + I_{f,t}^{comm} + I_{m,t}^{rel} + I_{f,t}^{rel}}{4} + \varepsilon_t$$

where $I_{m,t}^{comm}$ and $I_{f,t}^{comm}$ are standardized commercial indices (number per unit effort) over time t for the male and female stages, $I_{m,t}^{rel}$ and $I_{f,t}^{rel}$ are standardized survey indices (estimated total number) over time t for the male and female stages, and ε_t is a normally distributed observation error. The indices are standardized over the mean of the first 10 years (corresponding to observation years 1990 to 1999).

Guidelines depending on the status of the resource in relation to the reference points are used to determine the allowable commercial catch for the following year. The rule is consistent with a precautionary approach. The rule is as follows:

$$TAC = \begin{cases} 0 & \text{if: } I_t^{tot} \leq b_{\lim} \\ \dfrac{I_t^{tot} - b_{\lim}}{b_{\sup} - b_{\lim}} * Y & b_{\lim} < I_t^{tot} \leq b_{\sup} \\ I_t^{tot} * Y & I_t^{tot} > b_{\sup} \end{cases}$$

Exploitation intensity was adjusted to the stock's status zone (critical, cautious or healthy). The reference value used is 12,000, while the reference point values used are 0.56 for the limit reference point (b_{lim}) and 1.35 for the upper stock reference point (b_{sup}).

This rule is tested to illustrate the impact of an annual adjustment of TAC compared to a constant TAC set for periods of 2 to 5 years.

SENSITIVITY ANALYSIS

A sensitivity analysis is conducted to describe the impact of the choice of parameter values on the simulation outcomes. This allows for adjustment of the importance assigned to the uncertainty associated with these parameters during analysis of the results. This sensitivity is evaluated by starting with a base case and then modifying certain key parameters one by one. However, potential interactions between these parameters are not taken into account.

Parameters for the base scenario (*Base*) are formulated as set out in Table 1 and using an adjusted hockey stick stock-recruitment relationship following a normal distribution. In addition to the base scenario, the following scenarios are tested:

- two variants of the stock-recruitment relationship: a first one of the type Saila-Lorda following a normal distribution (*SL-n*) and a second one of the type Ricker following a log-normal distribution (*Ric-ln*);
- an underestimation of the observation error, i.e. a cv of 0.2 (*CV+*);
- an underestimation of the size at sex change, higher by 3 millimeters (*CS+*);
- the imposition of a series of poor (0 individuals recruited) recruitments for three consecutive years in simulation years 27 to 29 (*MC*); and
- a gradual increase in natural mortality over the projection period to reach a value 60% higher at end than at start (*Pred*).

The only free parameter in the sensitivity analyses is the research survey trawl selectivity for stage *m2*. The selectivity curves used for each scenario depict selectivity for stage *m2* ranging between 5.0 and 31.6% (Desgagnés and Savard 2012). Several scenarios share the same selectivity curve. These include the base scenario (*Base*) as well as the scenarios involving variants of the stock-recruitment relationship (*SL-n* and *Ric-ln*), underestimated variability of the observation error (*CV+*), assumption of very poor recruitment (*MR*) and a gradual increase in natural mortality (*Pred*). The selectivity curve used for any scenario remained the same for all decision rule studies relating to that scenario.

RESULTS AND DISCUSSION

Figure 1 illustrates median values of the estimated female biomass from the 1,001 projections over 25 years for each combination of scenarios and TAC decision rules. The results in Figures 2 to 8 are presented in the form of box-whisker plots indicating the median of 1001 projections and quartiles. All of these figures serve to evaluate the sensitivity of the model through comparison of the performance of the TAC decision rules with one another. On the other hand, some scenarios provide an opportunity to assess the model's sensitivity to parameters not easily measured, such as natural mortality or the coefficient of variation of error in the stock status index, or for which limited conclusive results are available, such as size at sex change.

A comparison of the outcomes of the different scenarios with those of the base case shows that two scenarios have very little impact on the trajectory of mean female biomass (Figure 1). These scenarios are those simulating an underestimated observation error concerning the stock status index (*CV+*) and late sex change (*CS+*). The model is consequently not highly sensitive to these two parameters, whose variations do not lead to any changes in interpretation of the performance of TAC adjustment rules (Figures 2 to 8). Indeed, the performance of rules in relation to one another remains consistent regardless of the indicator examined.

On the other hand, the model was sensitive to parameters relating to the stock-recruitment relationship (*SL-n* and *RIC-n*), a series of poor recruitments and a gradual increase of natural mortality (*Pred*) (Figure 1). All of these parameters have an influence on population numbers and, consequently, on the impact of harvest on the trajectory of the female biomass. The stock-recruitment relationship determines the number of recruits introduced to the system each year based on female abundance, while natural mortality influences the individual survival. The impact of harvest adjustment rules may consequently vary depending on the assumption studied, and it is important to incorporate uncertainties relating to these key parameters into simulations of the impact of decision rules.

Figures 2-8 compare the different combinations of scenario-rule performance indicators, including:

- the proportion of time spent in the healthy and critical zones respectively;
- the mean female biomass for years 22 through 46 resulting from each scenario-rule combination;
- the mean of annual landings for simulation years 22 to 46; and
- annual variations of landings; these values are the mean of the differences in absolute values between landings of a given year and the next year over the projection period (years 22 to 46).

The trajectory of the female biomass remains at a higher level on average with a rule where the TAC is set annually regardless of the scenarios under consideration. The stock stays in the healthy zone for a greater proportion of time and in the critical zone for a lesser proportion of time with the rule by which the TAC is set annually. The uncertainty associated with the simulation outcomes increases with increasing duration of the TAC.

As would be expected, interannual variations in TAC are higher with a rule where the TAC is set annually. This is explained by the fact that the rules providing for changes in TAC at periods of 2, 3, 4 or 5 years have years where interannual variation is zero, but if we look at the interannual variation in the year where there is an adjustment, the variation will be greater than the average of the rule 1 year. The cumulative landings of 25 years are higher with the annual adjustment rule but will decrease as the duration of a constant TAC increases.

CONCLUSION

The Northern Shrimp is a species subject to abundance variations related to variable recruitment. Given its brief lifespan and the short period of availability in the fisheries, frequent adjustments of harvest are needed to monitor the dynamics of the stock. Simulations have shown that as soon as the TAC adjustment frequency is more than one year, the abundance and landings indicators decline. Outcomes of this nature should be taken into account by the fishery manager when they evaluate the advantages and disadvantages of changes in assessment frequency in management advice for fisheries.

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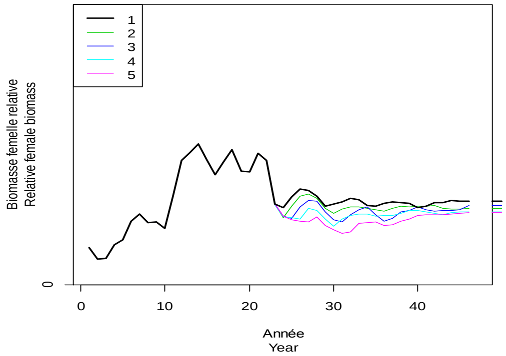
TABLE

Table 1. Parameters of the model.

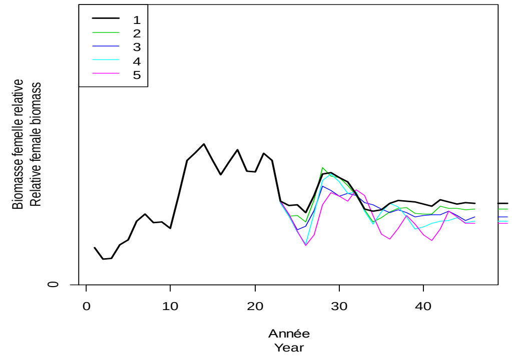
Parameter	Value	Source
Natural mortality		
Year 1 to 5	0.8	Fixed
Year 6+	0.5	Fixed
Fecundity		
a_f	0.05194	Observations
b_f	3.13891	Observations
Growth		
K	0.377	Modal analysis
L_{inf}	25.99	Modal analysis
t_0	0.0997	Modal analysis
Size by stage		
I	0	Fixed
m1	10.68	Modal analysis
m2	15.49	Modal analysis
m3	18.74	Modal analysis
m4	20.95	Modal analysis
f1	25.18	Observations
f2	25.95	Observations
Weight-length relationship		
a_p	0.000735	Observations
b_p	2.92	Observations
Sex change		
$L50_{sex}$	17.8	Drouineau et al. (2012)
SR_{sex}	3.82	Drouineau et al. (2012)
Catchability		
q_{rel}	1	Fixed
q_{comm}	3.94e-08	Model
Commercial trawl selectivity		
$L50_{comm}$	19.8	Drouineau et al. (2012)
$SR_{comm.}$	3.80	Drouineau et al. (2012)
Survey selectivity		
$L50_{rel}$	17.94	Model
SR_{rel}	3.12	Drouineau et al. (2012)
Coefficient variation of the abundance index		
CV	0.05	Fixed
Numbers of the first year		
I	1.12e10	Observations
m1	1.56e10	Observations
m2	1.94e9	Observations
m3	1.15e4	Observations
m4	2.20e9	Observations
f1	9.59e8	Observations
f2	7.73e8	Observations

FIGURES

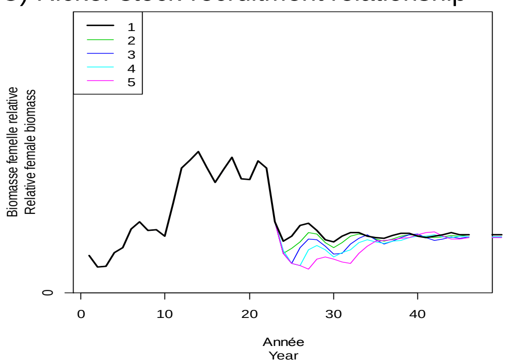
A) Base case



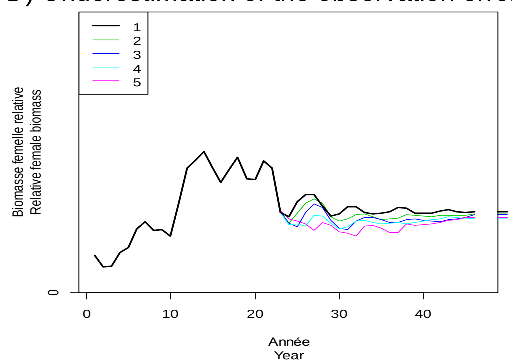
B) Saila-Lorda stock-recruitment relationship



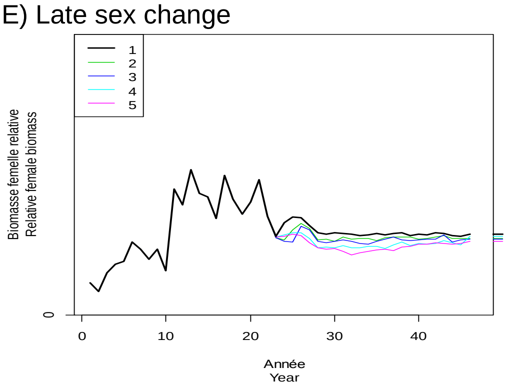
C) Ricker stock-recruitment relationship



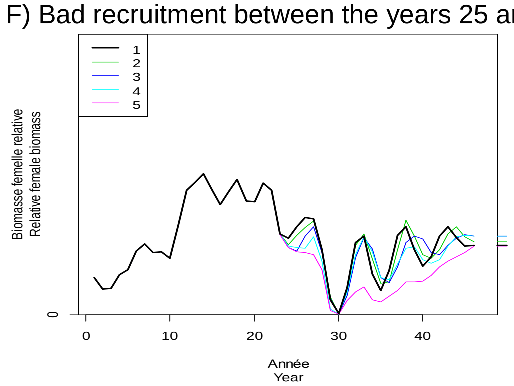
D) Underestimation of the observation error



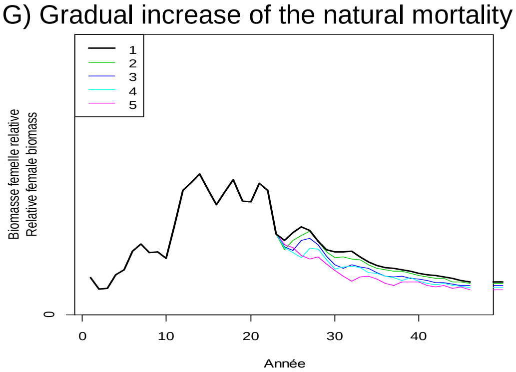
E) Late sex change



F) Bad recruitment between the years 25 and 27



G) Gradual increase of the natural mortality



Legend :

Constant TAC periods
1 : 1 year
2 : 2 years
3 : 3 years
4 : 4 years
5 : 5 years

Figure 1 : Results of the simulation of the harvesting rules (constant TAC periods for 1 to 5 years): adjustment of the model female biomass to the survey data for the years 1 to 21 and 25 year projections (years 22 to 46), for seven scenarios of the sensitivity analysis. The lines represent the median of the 1,001 projections.

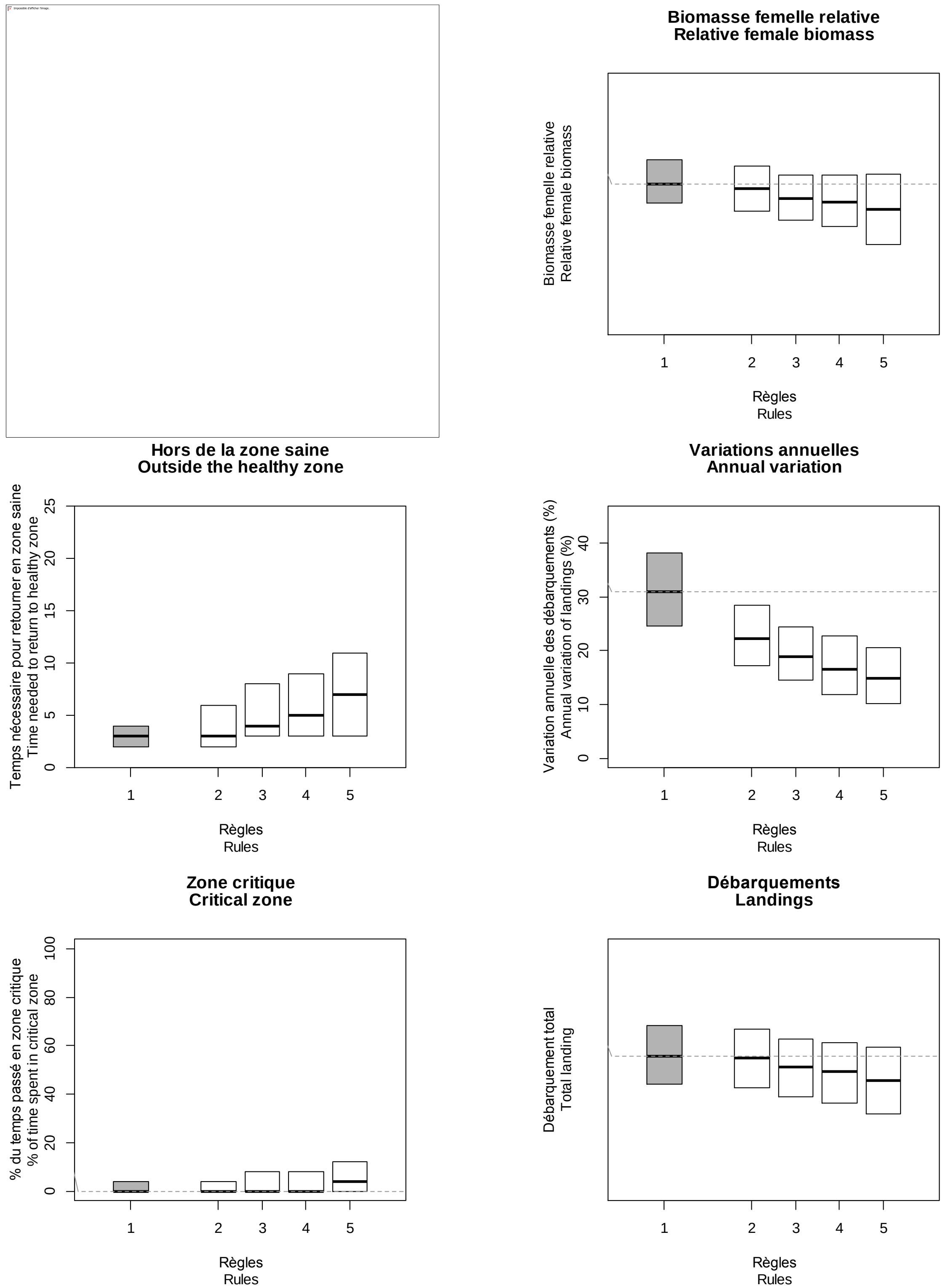


Figure 2 : Indicators of the performance of TAC decision rules (constant TAC periods for 1 to 5 years) simulated under the base scenario.

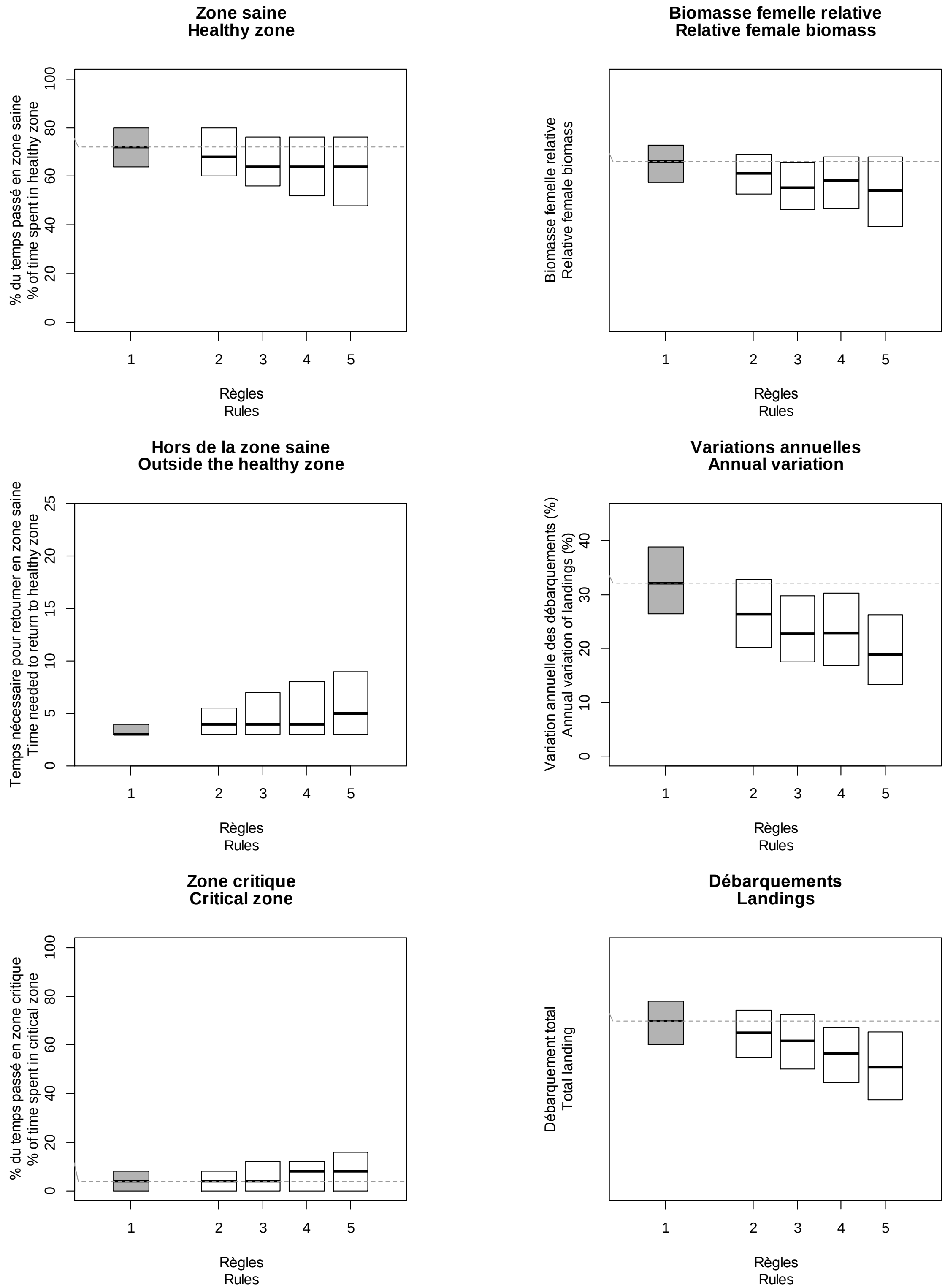


Figure 3 : Indicators of the performance of TAC decision rules (constant TAC periods for 1 to 5 years) simulated under the scenario of a Saila-Lorda stock-recruitment relationship.

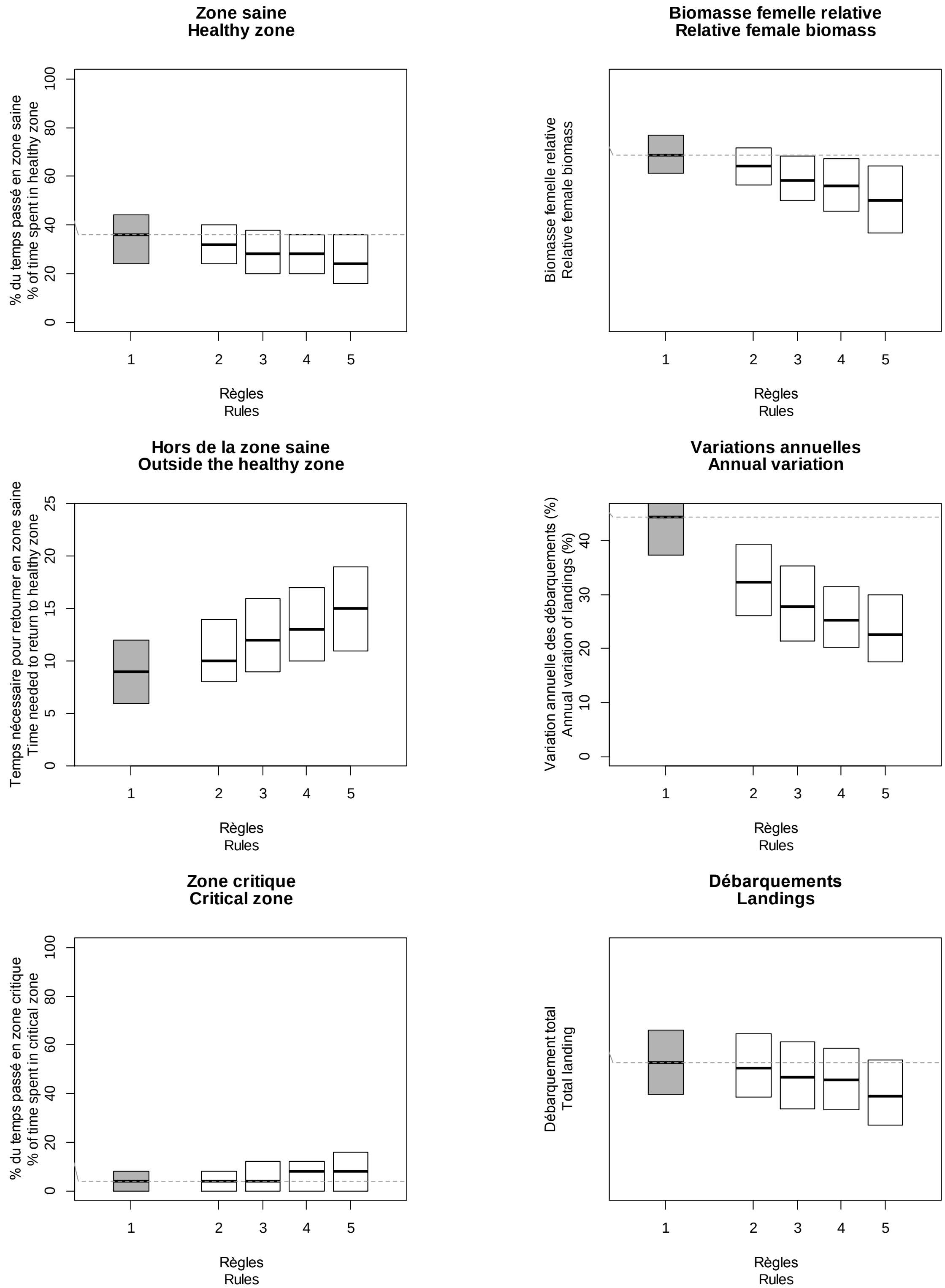


Figure 4 : Indicators of the performance of TAC decision rules (constant TAC periods for 1 to 5 years) simulated under the scenario of a Ricker stock-recruitment relationship.

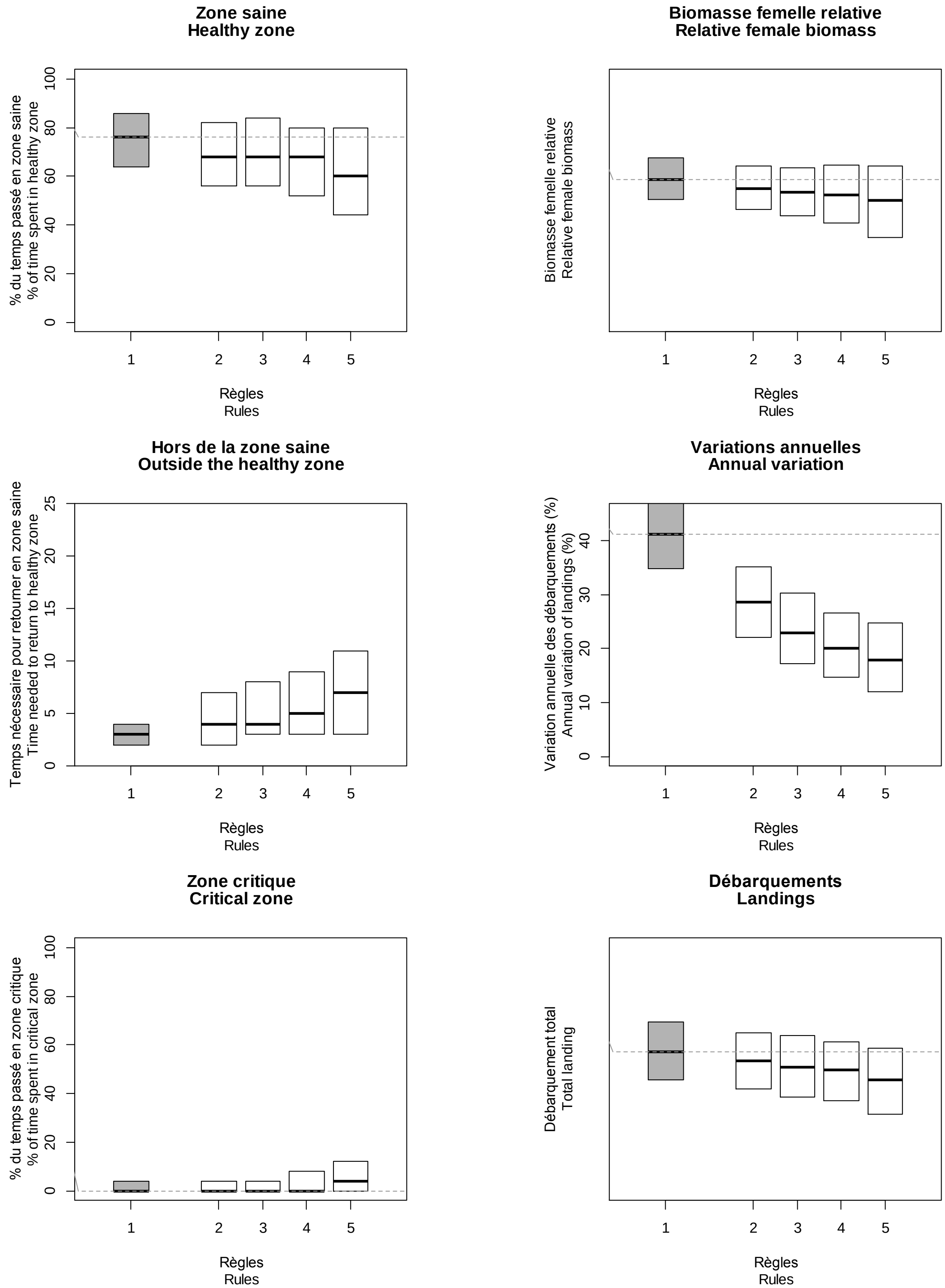


Figure 5 : Indicators of the performance of TAC decision rules (constant TAC periods for 1 to 5 years) simulated under the scenario of an underestimation of the observation error.

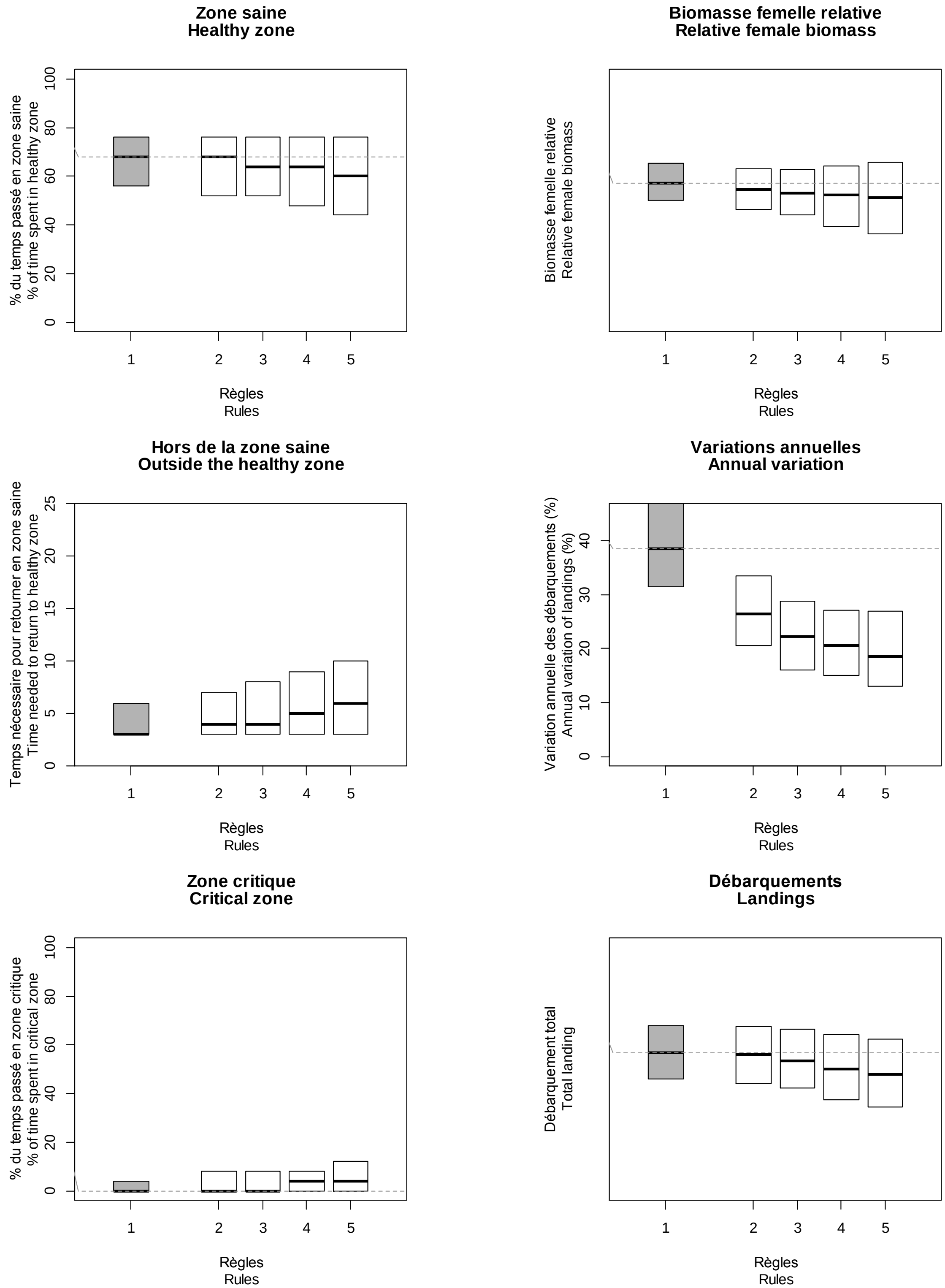


Figure 6 : Indicators of the performance of TAC decision rules (constant TAC periods for 1 to 5 years) simulated under the scenario of a late sex change.

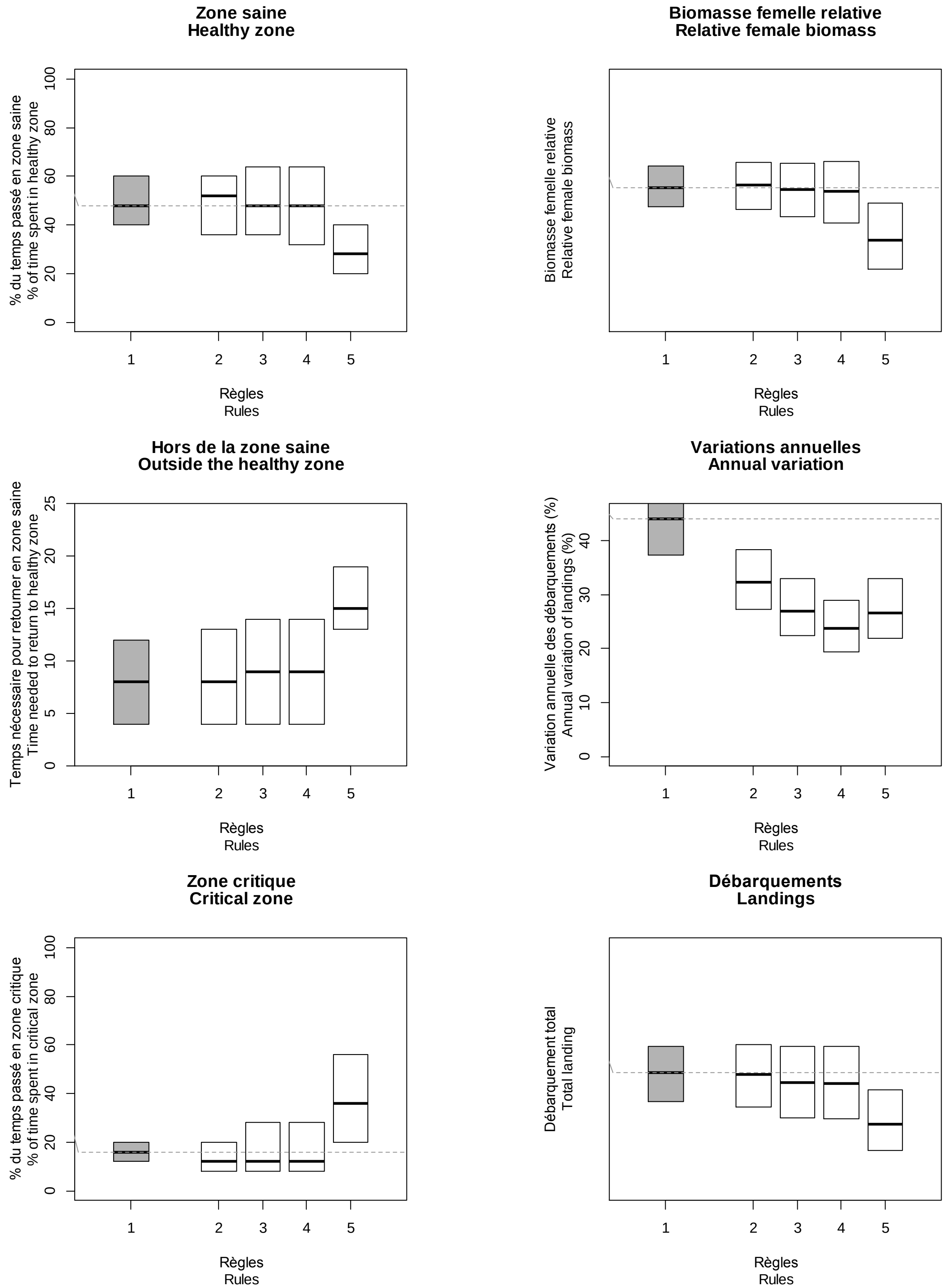


Figure 7 : Indicators of the performance of TAC decision rules (constant TAC periods for 1 to 5 years) simulated under the scenario of a bad recruitment between the years 25 to 27.

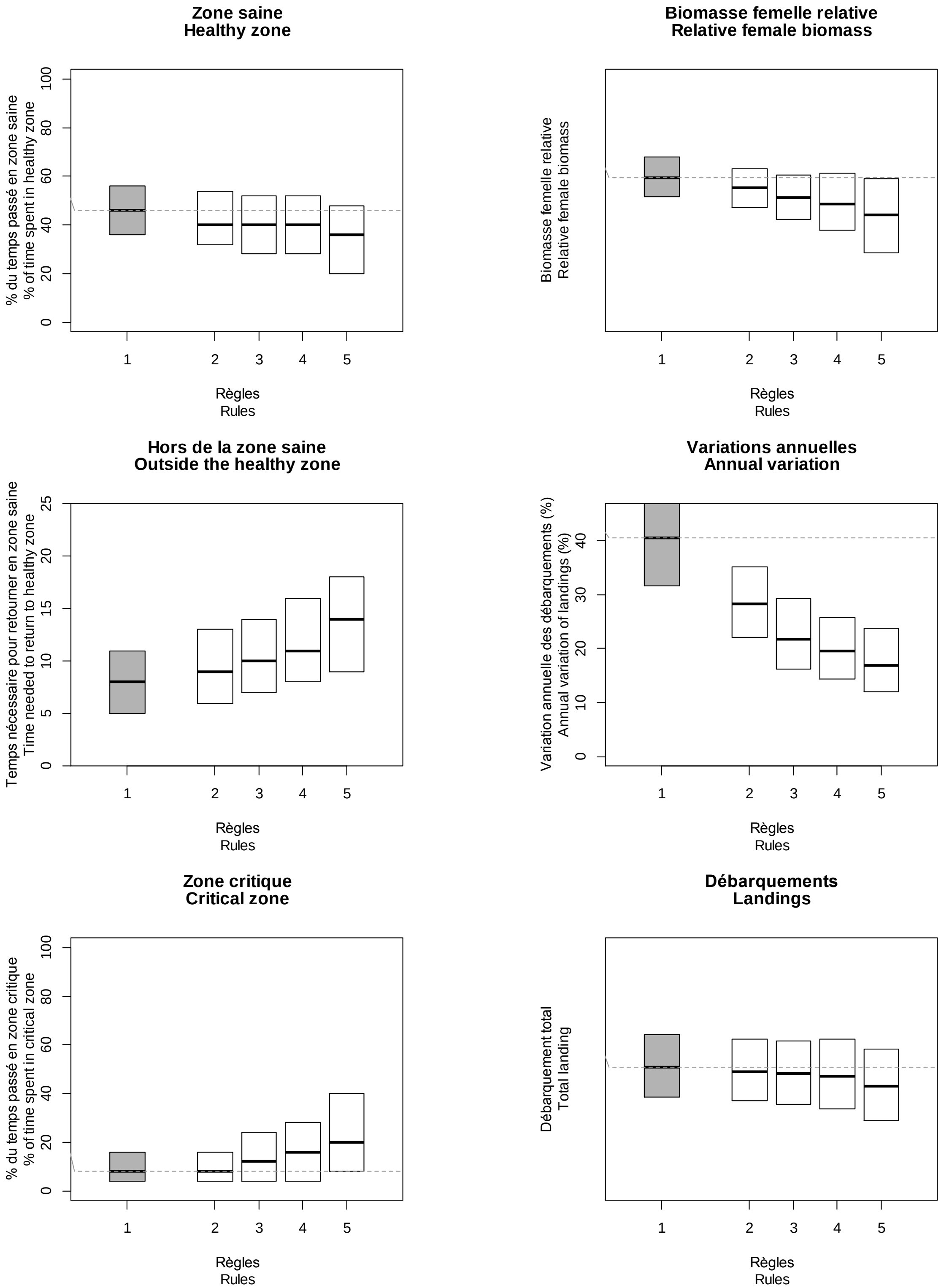


Figure 8 : Indicators of the performance of TAC decision rules (constant TAC periods for 1 to 5 years) simulated under the scenario of a gradual increase of the natural mortality.