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Introducing time-varying natural mortality in the length-based assessment model for the *Pandalus Borealis* stock in ICES Div. IIIa and IVa east

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Abstract

This working document describes the development and performance of a predation index intended as a proxy for the natural mortality (M) of northern shrimp (*Pandalus Borealis*) in the Skagerrak and Norwegian Deep. The predation index is based on fish catches in the yearly Norwegian shrimp survey covering the stock area. Based on previously conducted fish stomach investigations in the same area, four of the survey-caught species were identified as primary predators; cod (*Gadus Morhua*), Roundnose Grenadier (*Coryphaenoides rupestris*), Velvet belly lanternshark (*Etmopterus spinax*) and large (> 35 cm) blue whiting (*Micromesistius poutassou*). An index time series was calculated by combining primary predator abundance with species-specific consumption rates obtained from a literature study. The index was set to vary across the time series with different average levels of M, ranging from 0.5 to 1.5 in intervals of 0.05. The resulting set of time-varying M-values was applied to a stochastic length-based stock assessment model, and model diagnostics and estimates were compared. We also investigated the same range of M-values without variation (constant M) across the time series. The results indicate that the current level of natural mortality assumed in the ICES stock assessment in Skagerrak and Norwegians Deep (M=0.75) is too low, and also that the introduction of a variable M in the stock dynamics model can improve the basis of the stock assessment.

Background

The Northern shrimp (*Pandalus Borealis*) in the northern part of ICES Div. IIIa (Skagerrak) and the eastern part of Div. Iva (Norwegian Deep) is managed as a single stock that is harvested by Denmark, Norway and Sweden. The fishery began in the 19th century and came under TAC control in 1992 with a quota divided according to historical landings, giving Norway 60%, Denmark 26% and Sweden 14%. Until 2002, the TACs have been advised using the outcome of a cohort based analytical assessment. This method was, however, abandoned in 2003 and since then the TACs have been recommended on the basis of CPUEs from commercial catches and a directed scientific survey. A main reason for abandoning the cohort based analytical approach in 2003 was the WG-perception that unaccounted natural mortality accounts for at least twice as much removal from the Pandalus stock as the fishery. Such dynamics render it problematic to establish biological reference points, at least if the relative magnitudes of F and M (predation) are independent of stock size. Despite this complication in the assessment of the Pandalus Stock dynamics, a stochastic length-based analytical model (Nielsen et al. 2013) was introduced in a benchmark assessment in 2013. In this model the previously WG-group defined M of 0.75 across years and Pandalus age classes was kept. However, the 2013 model outputs displayed very high estimates of Fishing mortality, at levels which made the WG to believe that the current model assumptions had substantial potential for improvement. Therefore we set out to investigate alternative assumptions/definitions of the natural mortality included in the mode. This exploration was divided in two approaches a) exploring other levels of constant M across time, and b) exploring time-varying M at different average levels with variation predation pressure as a proxy for the variations in natural mortality. The predation pressure was estimated by combining species specific shrimp consumption from literature with scientific survey information of primary predator abundance of the modelled time series.

Material and methods

Norwegian shrimp survey

A trawl survey for *P.Borealis* is conducted annually by the Norwegian Institute of Marine Research in Skagerrak and the Norwegian Deep. This survey stretches back to 1984 and the aim has been to collect population information for stock assessment and management purposes. Details of the survey stratification and sampling can be found in Søvik and Thangstad, 2013. Besides shrimp, the survey has also recorded the occurrence and abundance of other species caught, and a biomass index (catch in kg per towed nm) is available for 21 different fish species from 1984 to 2013 (Søvik and Thangstad, 2013).

Stock assessment model

The benchmark model for Pandalus in ICES areas IIIA and IVA is a length based stochastic assessment model (Nielsen at al. 2013). The model describing stock development is age based, but the model also estimates the relation between age and length assuming a von Bertalanffy growth curve. It is a full parametric statistical model, where the stock development from year to year is an age based model, but the data is given in lengths. The stock dynamics is similar to most fully parametric statistical age based stock assessment models, and the standard outputs are estimates of Fishing mortality (F), Spawning Stock Biomass (SSB) and recruitment index (R) in terms of modelled numbers of shrimp at age-0.

Identification of primary predators

Not all of the species that are caught in the Norwegian survey are necessarily *P.Borealis* predators and it is expected that shrimp consumption varies significantly between species. To best reflect variations in the predation pressure on the *P.Borealis* stock, only the predators for which *P.Borealis* predation is substantial should be included in an index. The first step in this investigation was therefore to review available literature on the feeding ecology of the fish assemblage in Skagerrak and the Norwegian Deep.

The feeding ecology of the fish community in Skagerrak and the Norwegian deep have been explored in detail through stomach content analyses (Bergstad 1991; Albert 1994a; Albert 1994b; Skjæraasen & Bergstad 2000; Bergstad et al. 2003), and information on the average fraction of *P.Borealis* in the stomach of most of the species found in the Norwegian survey is available. These studies are all based on data that was collected in 1984 to 1987 from a total of 13 different survey cruises in the area, and a detailed description of the sampling procedure is available in Bergstad 1990. In all studies the stomach content of P. Borealis in the sampled fish is listed in percentage of total stomach content wet weight (%W). For most species, depending on the amount of stomachs sampled, the stomach content has been calculated for different size-classes, and for some species stomach content in different seasons of the year has also been calculated.

For the purpose of this study an annual average, independent of size-class or season was desired, and this was calculated from the published data. The number of stomachs used to calculate %W are available for most of the species and it was therefore possible to take differences in the sample size of different size-classes into account. For those species where %W had been calculated in different seasons each season was weighed equally by summing the average %W for each season and dividing the value with the number of seasons. For Blue whiting predation on *P.Borealis* was strongly related to size, and occurred predominantly in individuals longer than 35 cm. (Bergstad 1991). For this reason the average stomach content in Blue whiting was only calculated for individuals longer than 35 cm.

The literature-derived stomach content values show a clear segregation between Cod, Roundnose grenadier, Velvet belly lanternshark and Blue whiting > 35 cm, and the remaining species (Table 1). These four species all have stomach contents of *P.Borealis* above 10 %W, whereas in alle the other species stomach contents were below 5 %W. On this basis Cod, Roundnose grenadier, Velvet belly lantern shark and Blue whiting > 35 cm were categorized as primary *P.Borealis* predators, while the other species were categorized as incidental *P.Borealis* predators. For some species no results on feeding ecology were available and *P.Borealis* predation therefore remains unknown. However, on the basis of the morphological trait of some these species, such as body shape or size, it is assumed that they are not *P.Borealis* predators. In any case, the species with no documented consumption of Pandalus Borealis were omitted from the predation index.

Index definition and calculation

The predation index was calculated from the survey biomass index of Cod, Roundnose grenadier, Velvet belly lantern shark and Blue whiting > 35 cm, since these species had been identified as the primary *P.Borealis* predators in the Skagerrak and Norwegian Deep fish assemblage (Table 1). The biomass index values were not yet available for 2014, and the average value over the time period of 1984-2013 were used for each of the four species.

The survey-based biomass index values for Blue whiting integrates all length classes and in order to separate the fraction of the population longer than 35 cm, the assumption was made that the Blue whiting length frequency distribution in Skagerrak is identical to the total stock length frequency distributions. Information on the length distribution of Blue whiting in the eastern part of the North Atlantic was acquired from the latest ICES WGWIDE report (2013). The weight of each length class was calculated using a simple length-weight relationship obtained from www.fishbase.org (Equation 1) and then the fraction in weight, of the population larger than 35 cm, was calculated and multiplied with the total Norwegian survey biomass index for blue whiting.

$$W = 0.00375 \cdot L^{3.082} \qquad \textbf{(1)}$$

The Norwegian survey biomass indices of the four different species were adjusted relative to their consumption of *P.Borealis* by multiplying with their average stomach contents (Table 1). This was done to reflect the relative predation pressure of each of the four different species in the predation index.

The predation index was calculated for the time period between 1984 to 2014 by A) summing the four individually adjusted biomass indices for each year, B) calculate the yearly mean of the summed adjusted biomass indices for the time period, and C) divide A with B, to let the index fluctuate with an average of 1 across the time series.

Exploratory model runs

The input data for the length based assessment model of the *P.Borealis* stock (Nielsen et al. 2013) were updated before running the model with different M-values. Total commercial catch-at-length in numbers were updated to cover the years from 1988 to 2013, and the scientific survey of the length distribution was updated to cover the years from 1988 to 2014. Furthermore, compared to the model specifications used in the 2013 assessment, the L-infinty growth parameter in the underlying von Bertalanffy growth curve were set at a fixed value of 29 mm, to reduce the number of variables in the model. This was done due to complications with model instability (poor convergence), when introducing additional variability in the model by applying time-varying natural mortality values.

The performance of the model was evaluated over a range of yearly average natural mortality values from 0.5 to 1.5 at steps of 0.05 under two different scenarios, 1) constant natural mortality and 2) variable natural mortality. Since the predation index by definition has an average value of 1, variable natural mortality was introduced at different average levels by multiplying the index with the desired average values. The performance of the different M-value model runs was evaluated by comparing the negative log likelihood values as well as comparing the time series plots of F, SSB and R.

Results

Primary predators and predation index

The Pandalus borealis predation index for Skagerrak and Norwegian Deep was based on the individual biomass index values of Cod, Roundnose grenadier, Velvet belly lantern shark, and Blue whiting, from 1984 – 2014 (Figure 1, top-panel). These individual indices were multiplied by the species specific consumption rates (Table 1) and standardized to give a joint predation index times series fluctuating around an average value of 1 for the period (Figure 1, bottom-panel).

The most abundant species of the predation index is Roundnose grenadier, with the other three species contributing approximately equally across time. This abundance pattern is, however, partly ruled out when multiplying with the species specific consumption, and in the adjusted predation index, contributions from cod, roundnose grenadier and blue whiting are almost equal, whereas velvet belly lanternshark only contributes significantly in a few of the years.

The overall effect of applying the species specific consumption is a reduction in the year to year fluctuations. This reduction is, however, relatively modest as seen from the large overlaps between the trajectory of the adjusted and unadjusted biomass indices (Figure 2). The biggest change can be observed for 2008 and 2009, were the abundance of Roundnose grenadier was at its highest.

Exploratory model runs

For the range of constant M values (0.5 to 1.5) the stock assessments were successfully performed in 15 out of 20 cases (Table 2), excluding those model runs that resulted in extreme negative log likelihood values or did not converge. The lowest -log likelihood value (best model fit) was observed at M=1.2 (Table 2). This is considerably higher than the value of 0.75 that is used by the working group.

Estimates of F are generally similar in trends for M=0.75 and M=1.2 (Figure 3 & 4), but the level of F is much lower at M=1.2 and the most recent trend in F decreases while it increases at an M value of 0.75. Estimation of SSB trends of the two M-values are much more similar, but SSB is at a higher level with an M value of 1.2. At an M value of 0.75 the recruitment curve is almost flat, while it is at a higher level and fluctuates far more at an M value of 1.2. In addition, a period of low recruitment from 2008 to 2012 is estimated with an M value of 1.2.

For the range of time-varying M values the assessments were successfully performed in 14 out of 20 cases (Table 2). With a variable natural mortality the best model-fit was achieved with an average M-level of 0.9, at which the negative log likelihood value was lowest (Table 2). The general pattern in the output variables is similar to the output of the assessment with a constant M of 1.2, but the general level of F is higher, the SSB is lower and the R is also lower (Figure 5).

When comparing the negative log-likelihood values of model runs with constant and variable natural mortality, a constant M has slightly lower values across the range of average Ms and the minimum value (best fit) is located differently on the X-axis (average M-values) (Figure 6).

Discussion and Conclusions

- With the assumption of a constant M across the time series, the best statistical model-fit (lowest negative log-likelihood) is observed for M = 1.2.
- With the assumption of a predation based variable M across the time series, the best statistical model-fit (lowest negative log-likelihood) is observed for M = 0.9.
- For both basic assumptions (constant or variable M) the best statistical model fit was obtained at average M-values well above the 0.75 currently assumed in the assessment model.
- Two field experiments estimating natural mortality of *Pandalus Borealis* document average M values above 0.75 (Table 3) .
- Across the examined range of average values, a constant M gives a slightly better model fit than a variable M.
- Model runs with different constant M values produce outputs with generally similar trends in estimates of F, SSB and R, but with levels varying significantly.
- Model runs with different variable M average values produce outputs with generally similar trends in estimates of F, SSB and R, but with levels varying significantly.
- When comparing constant and variable M outputs, they generally have similar long-term trends in estimates of F, SSB and R. However, deviations are observed for F in recent years, where a variable M generally estimates lower (declining) Fs compared to model runs with constant Ms.

In conclusion, both the exploratory model runs and the literature derived estimates of natural mortality suggest that the current assumption of M=0.75 should be adjusted upwards.

The use of a predation-index as a proxy for variable natural mortality, produced F-trajectories, which are assessesd subjectively as more realistic than those from constant Ms. However, the statistical model fit is slightly poorer than for the constant M approach, indicating the need to refine the proxy definition further. This could be by i) including proxies of variation in food availability (e.g. plankton indices), ii) by varying M across age classes, and iii) by further refining the currently used predator biomass indices from the Norwegian shrimp survey. This latter approach is currently ongoing (pers. comm. Jennifer Devine, IMR, Norway).

Some model instability was observed (lack of convergence in model runs) and indicates that improvement/quality assurance of input data other than natural mortality (M) values should be considered.

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Table 1. Published values of the average wet weight content of *P.Borealis* in the stomachs of the 21 species that occur in the Norwegian shrimp survey. Investigations of stomach contents have all been performed on individuals caught in the Norwegian Deep.

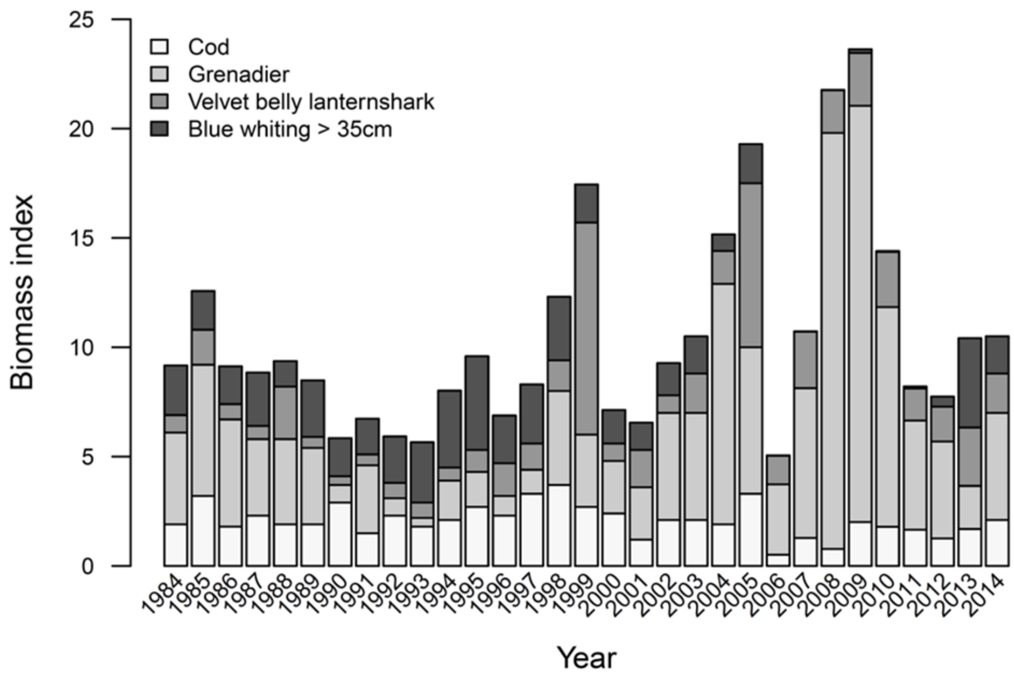
Species	% W *P. Borealis*	Stomachs (n)	Source
***P. Borealis* predators**			
Blue whiting (L>35cm)	18.57	146	Bergstad (1991)
Cod	22.44	779	Bergstad (1991)
Roundnose grenadier	11.05	400	Bergstad *et al* (2003)
Velvet belly lantern shark	11.81	147	Bergstad *et al* (2003)
Incidental *P. Borealis* predators			
Blue ling	0.4	57	Bergstad (2003)
Haddock	2.15	803	Albert (1994)
Hake	1.90	19	Bergstad (1991)
Pollack	3.20	15	Bergstad (1991)
Whiting	0.96	223	Bergstad (1991)
Rabbit fish	0.00	150	Bergstad *et al* (2003)
Saithe	2.69	1342	Bergstad (1991)
Skates	3.80	175	Skjæraasen & Bergstad (2000)
Witch	0.00	134	Bergstad *et al* (2003)
***P.Borealis* predation unknown**			
Angler	-	-	-
Black mouth catshark	-	-	-
Four beard rockling	-	-	-
Halibut	-	-	-
Long rough dab	-	-	-
Redfish	-	-	-
Spiny dogfish	-	-	-
Tusk	-	-	-

Table 2. Calculated negative log likelihood values from model runs, at different levels of average natural mortality (M) with either a constant M or an M that varies relative to the predation index.

Average level of M	Constant M	Variable M
0.50	7847.02	8023.81
0.55	7845.50	Error
0.60	7843.94	7844.13
0.65	8357.59	7843.40
0.70	Error	7842.77
0.75	7839.07	Error
0.80	7837.44	7841.93
0.85	7835.84	8025.73
0.90	783430	7841.80
0.95	7832.86	7842.06
1.00	8008.93	7842.56
1.05	7830.48	7843.31
1.10	7829.62	7844.37
1.15	7829.06	7845.75
1.20	7828.83	Error
1.25	Error	8041.74
1.30	7829.40	7852.03
1.35	7830.21	7854.75
1.40	7831.34	7860.77
1.45	8009.99	8053.97
1.50	7834.42	Error

Table 3. Summary of two previous field experiments estimating natural mortality of *Pandalus Borealis.*

Age classes	N Cohorts (years)	Pandalus total M-estimates	Pandalus Cod-predation (M_{cod})	Stock	Source
3, 4, 5, 6, 7	2	0.07 – 3.34 (Mean 1.44)		W. Gulf of Alaska	Andersson (1991)
0-2, 3, 4, 5+	11		0.06 – 2.23 (Mean 0.76)	Barents Sea	Berenboim et al. (1991)



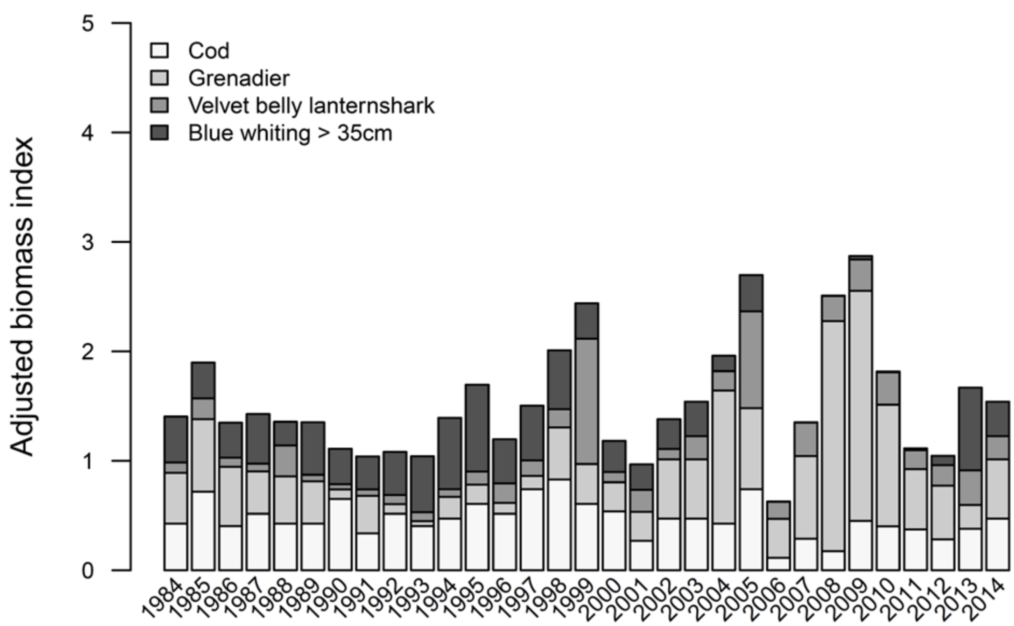


Figure 1. Top-panel: annual biomass indices (Kg per nautical mile) of Blue whiting > 35 cm, Cod, Roundnose grenadier and Velvet belly lanternshark in the Norwegian Deep from 1984 to 2014. Bottom-panel: The biomass indices have been multiplied with the stomach content proportion of P.Borealis for the respective species.

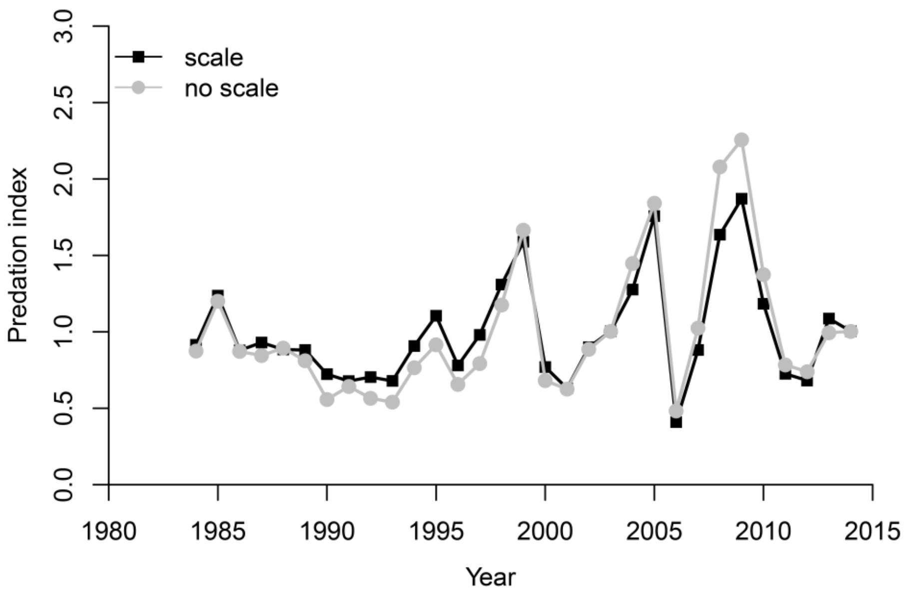


Figure 2. Predation indices calculated from the biomass indices of Blue whiting > 35 cm, Cod, Roundnose Grenadier and Velvet belly lanternshark. The predation index plotted with a black line with square points has been calculated from the species biomass indices weighted with the stomach content of P.Borealis. The predation index plotted with a black line with round points has been calculated from unadjusted biomass indices.

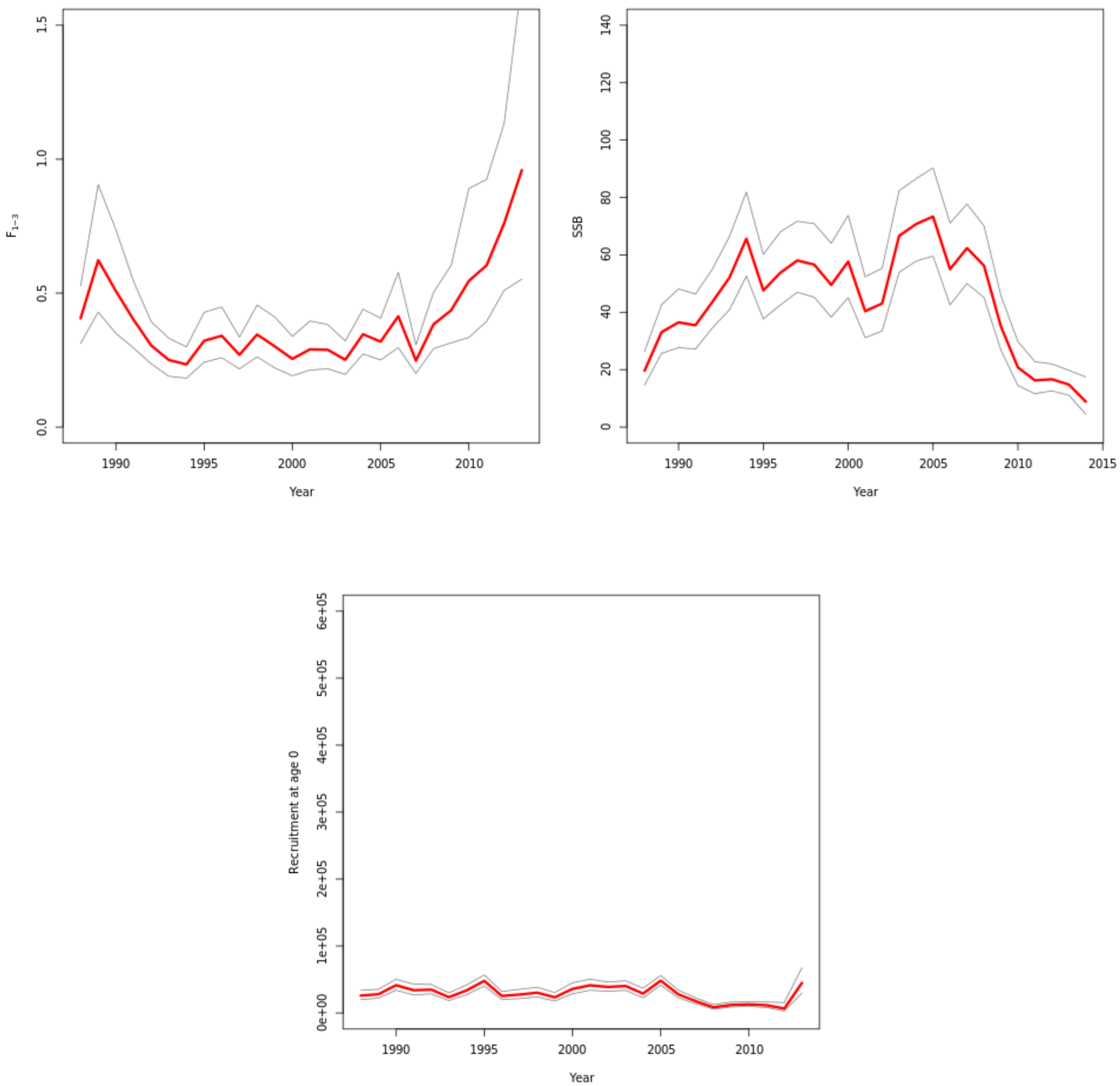


Figure 3. Model run with a constant level of M at 0.75

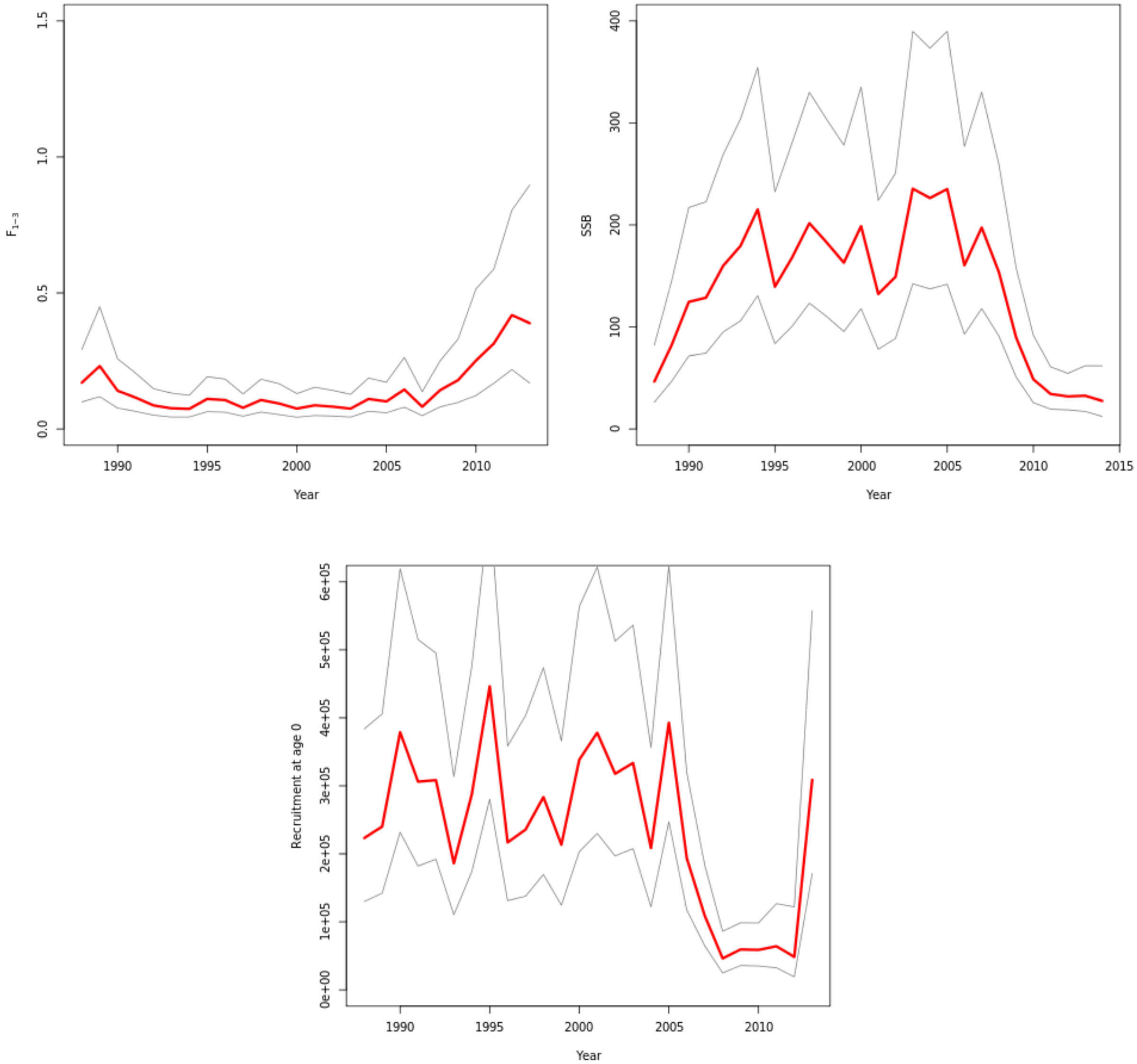


Figure 4. Model run with a constant level of M at 1.2

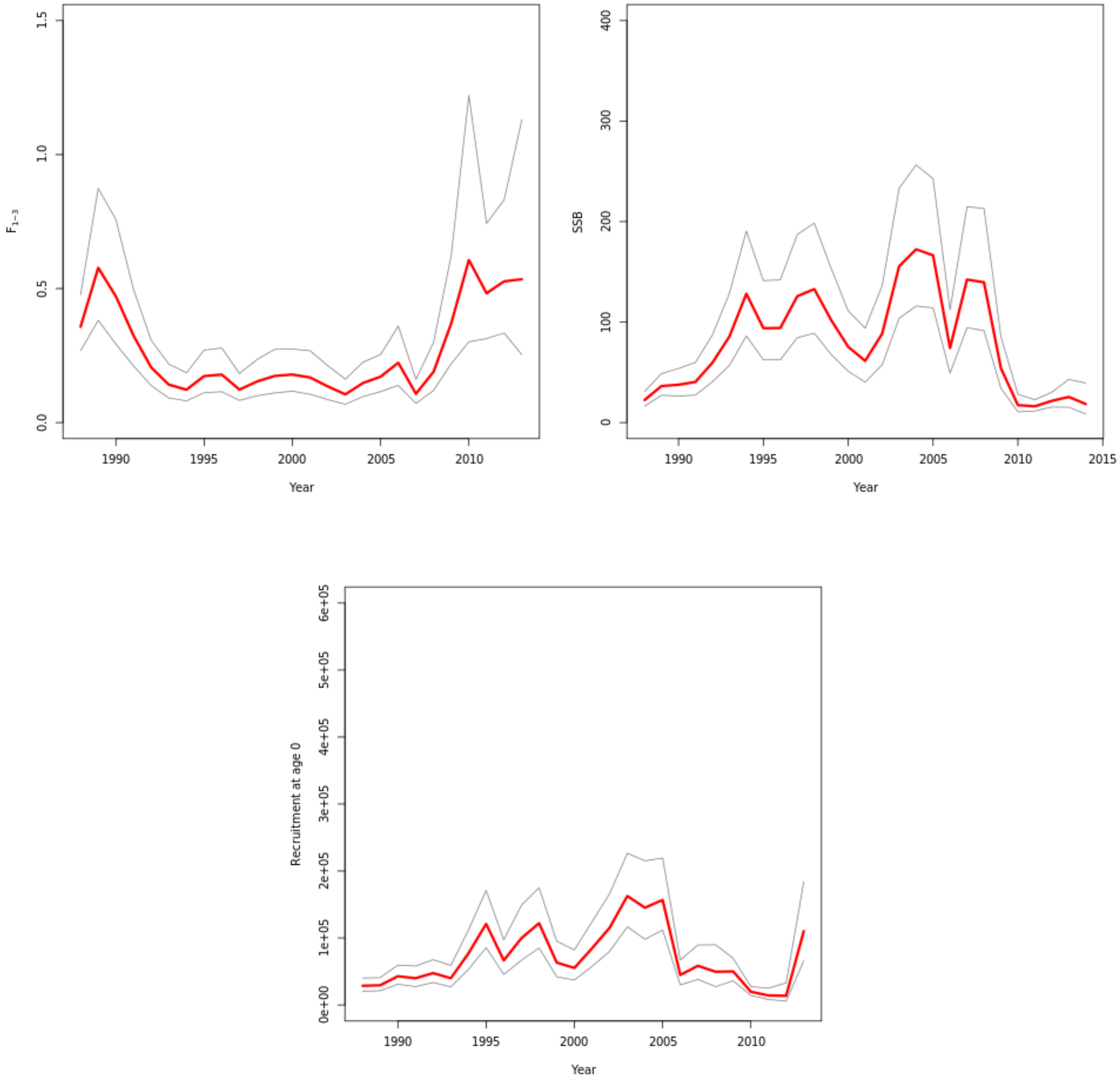


Figure 5. Model run with a variable M at an average level of 0.9.

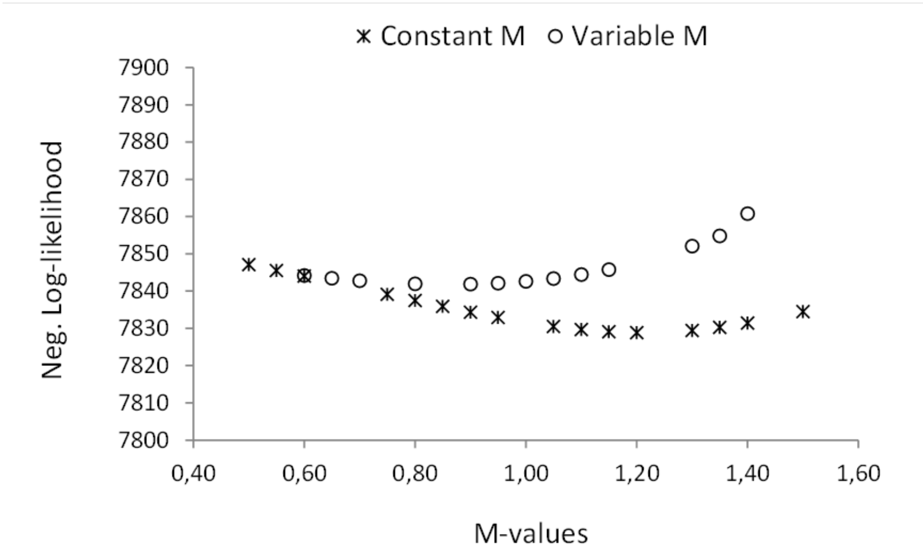


Figure 6. Negative log-likelihood values of model runs with different constant (circles) and time-varying (stars) average values of natural mortality (M).