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The Use of Indices of Reproductive Potential in the Setting of Reference Points and Stock Projections

M.J. Morgan and J. Brattey

Dept. of Fisheries and Oceans
PO Box 5667, St. John's, NL, A1C 5X1, Canada

Abstract

Estimates of reproductive potential for Div. 3NO cod were produced by sequentially incorporating estimates of proportion mature-at-age, sex ratio-at-age and potential egg production. The estimates of reproductive potential produced by each method were broadly similar but there were important differences. This leads to differing perceptions of the stock productivity as measured by relative recruitment rate of a stock and in the spawner stock produced per recruit. An example is illustrated of how these different estimates of reproductive potential can be used in the determination of biological limit reference points and in projections of stock size.

Keywords: reproductive potential, maturity, fecundity, sex ratio, reference points

Introduction

Several factors contribute to the number of recruits produced by a fish population. The composition of the spawning stock, particularly the age structure, is important and may affect the spawning success of the population (Lambert, 1990; Kjesbu *et al*., 1996; Marteinsdottir and Thorarinsson, 1998; Trippel, 1998). Variation in condition of the spawners can result in changes in fecundity and/or viability of eggs and larvae, or even in failure to spawn (Marshall *et al*., 1998; Marteinsdottir and Steinarssson, 1998; Lambert and Dutil, 2000; Rideout *et al*., 2000). The sex ratio of the spawning stock can also vary, leading to changes in egg production (Marshall *et al*., 1998; Kraus *et al*., 2002). In addition the proportion of fish that are mature at each age can show substantial changes over time (Jorgensen, 1990; Rijnsdorp, 1989; Hunt, 1996; Morgan and Colbourne, 1999). The combination of these factors will determine a population's reproductive potential (Trippel, 1999).

The relationship between spawning stock biomass and recruitment is the basis for the determination of biological reference points under the precautionary approach. Limit reference points are generally chosen as the spawning stock biomass below which recruitment is seriously impaired (Mace and Sissenwine, 1993; Shelton and Rivard, MS 2003). In addition, predictions about the potential for depleted stocks to rebuild will depend on the underlying assumptions about the stock recruit relationship. The use of spawning stock biomass assumes that it is a good estimate of stock reproductive potential. If spawning stock biomass is not a good predictor of recruitment, then our ability to set limit reference points and predict stock recovery will be seriously impaired.

The purposes of this study were to quantify the extent of the impact of changes in maturity, sex ratio and potential egg production at age in cod in Div. 3NO on estimates of the reproductive potential (*RP*) of the stock. We also explored the impact of variability in these factors on perceived stock productivity by examining differences in recruitment rate and spawner per recruit. Finally we derive example limit reference points from each estimate of *RP* and conduct 10 year deterministic stock projections.

Methods

Maturity

Female maturity data were collected during research vessel bottom trawl surveys from 1971-2002. Data from earlier years came from surveys that were conducted mainly as line transects and the coverage of a stock area would generally not be as complete as the stratified random surveys. Spring survey information was used (mainly May-June). Females were classed as immature or adult according to the classification of Templeman *et al.* (1978) following macroscopic examination of the gonad. Observed proportion mature at age was calculated according to the method of Morgan and Hoenig (1997) to account for the length stratified method of sampling.

Maturities were modelled by cohort using a generalized linear model with a logit link function and binomial error (McCullagh and Nelder, 1983). Age was modelled as a continuous variable. Only cohorts with both a significant slope and a significant intercept were included in the overall model. The 1991 cohort was excluded. For the excluded cohort the average of the two adjacent cohorts was used. For the earliest and latest cohorts for which maturities could not be estimated, the average of the 3 closest cohorts was used.

Sex ratio

Observed sex ratio was calculated as the proportion female at age calculated from estimates of population numbers at age by sex from stratified analysis programs applied to stratified random research vessel data (Smith and Somerton, 1981). These proportions were examined for a significant cohort and age effects using generalized linear models with a logit link function and binomial error. Cohort and age were modelled as class variables. The fitted models were used to produce estimates of sex ratio at age for each cohort.

Fecundity

A time invariant fecundity-length relationship was used to estimate the number of eggs produced at each age. The relationships were taken from Pinhorn (1984). The relationship was:

$$\text{Log fecundity} = 3.97*\text{log length} - 1.45$$

To extend the time series to the period before the collection of length data began, all lengths-at-age in that period were set as equal to the mean lengths-at-age in the first year of the length-at-age data series. The fecundity-length equations were then applied to the mean lengths-at-age to produce a time series of fecundity-at-age.

Indices of reproductive potential

To examine the possible impact of changes in maturity, sex ratio and fecundity (through changes in length and age composition of the spawners) several different indices of reproductive potential (RP) were calculated. The basis for all of the calculations was the number-at-age from sequential population analysis and the mean weight-at-age, both from the beginning of the year (Healey *et al*., MS 2003).

The first estimate of *RP* (knife-edge maturity) assumed that there has been no change in the maturity schedule of the fish and that the spawning stock was simply the sum of the biomass above a certain age. Biomass was calculated by multiplying the weights-at-age described above by half of the estimate of the population number-at-age. This biomass was summed over the age that was used historically in the calculation of *RP* for this stock, age 6. This method of calculating *RP* also assumes that the sex ratio is 50:50 for all ages and all cohorts.

$$RP = 0.5\sum_{a=i}^{j} N_{ay} W_{ay}$$

where: N_{ay} = population number at age a in year y
W_{ay} = weight at age a in year y
a = age from 6 to 12

The second estimate of *RP* (variable maturity) incorporates the estimated proportion mature-at-age for each cohort by multiplying one half of the population number-at-age by the weight-at-age and estimated proportion mature-at-age. This estimate will show the impact of any changes in maturation over time.

$$RP = 0.5\sum_{a=i}^{j} N_{ay} W_{ay} M_{ay}$$

where: M_{ay} = proportion mature at age *a* in year *y*
a = age *2* to *12*
and the other symbols are as defined above.

In the third (sex ratio), we applied the variable sex ratios that were estimated along with the estimates of proportion mature-at -age.

$$RP = \sum_{a=i}^{j} N_{ay} W_{ay} M_{ay} R_{ay}$$

where: R_{ay} = the proportion female at age *a* in year *y*
and the other symbols are defined above.

Last we incorporated estimates of fecundity (egg production). The fecundity-at-age series derived from the fecundity at length relationships and mean length-at-age as describe above was multiplied by the population number-at-age times the proportion mature-at-age times the sex ratio-at-age.

$$RP = \sum_{a=i}^{j} N_{ay} M_{ay} R_{ay} E_{ay}$$

where: E_{ay} = the number of eggs produced at age *a* in year *y*
and the other symbols are defined above

Stock productivity

Number of recruits was taken as number of 2 year olds from *SPA*. The recruitment rate (*RPS*: recruits/*RP*) was determined from each index of reproductive potential. The *RPS* from each index was standardized to the mean rate for the index to facilitate comparison. The biomass of spawners (or number of eggs) produced per recruit (*SPR*) was also calculated using each method of estimating the *RP* of the stock. This was done assuming a fishing mortality equal to zero ($F = 0$) and the fishing mortality estimated in the *SPA* (*F*). Each series of *SPR* was standardized to its mean for comparison.

B_{lim} and projections

As an example of setting B_{lim} the index of reproductive potential predicted to result in 50% of the maximum recruitment was chosen. For each reproductive potential recruit scatter a smoother was fit to determine the level of maximum recruitment. Smoothers were either probability density functions or Lowess.

Once B_{lim} was established, 10 year deterministic projections were carried out for each stock using each index of *RP*. The projections used the following process and assumptions:

population numbers were projected assuming $F = 0$ and $M = 0.2$
recruitment = average *RPS* from last 3 years before projection period × index of *RP* in year cohort born
weights - average last 3 years before projection period
maturities - cohort model or average last 3 years before projection period if no estimates of maturity for a cohort
sex ratio -average last 3 years before projection period

egg production at age – fecundity length relationship applied to average length-at-age over last 3 years before projection period

Results and Discussion

Indices of reproductive potential

The overall trends in *RP* are similar regardless of the method of estimation (Fig. 1). However, there are some important differences. *RP* showed a decrease through the 1980s when calculated using variable maturity-at-age and sex ratio, while estimates using knife-edge maturity and potential egg production both increased over that period.

The absolute level of difference between the indices can be compared for knife-edge maturity, variable maturity and sex ratio. The maximum difference between knife-edge maturity and the other two indices was 27 000 tons. The maximum difference between the index using variable maturity and the one incorporating sex ratio was small at 4 000 tons.

Differences between indices of *RP* are a result of variation in maturity, sex ratio and fecundity (through length-at-age) but also a result of changes in age composition of the spawning stock. The different trends in *RP* lead to variation in the stock recruit relationships derived from these indices. Therefore, limit reference points derived from these relationships, as well as current stock status relative to these reference points, will vary. This highlights the importance of deriving estimates of *RP* that can be used to accurately predict recruitment.

Stock productivity

Trends in the standardized recruitment rate for each index also show the same overall patterns (Fig. 2). There is little difference in the *RPS* for the four indices across the time period for Div. 3NO cod, except for a divergence in indices in the late-1960s.

An assumption of $F = 0$ gives insight into the potential productivity of a stock under no exploitation. The different indices of *SPR* at $F = 0$ were very similar over most of the time period for Div. 3NO cod. However, standardized knife-edge *SPR* began as the highest of the indices but in the mid-1980s became the lowest. *SPR* from egg production is below its overall average at the beginning of the time series and well above it at the end of the period, while knife-edge *SPR* is below average at the beginning of the time series and only average at the end of the time period. The largest divergence in standardized *SPR* was in the recent period beginning in the mid-1990s (Fig 3).

When *SPR* is calculated incorporating the actual *F* estimated in the *SPA*, the standardized SPR is similar using all methods, except when *F* is low (Fig. 4). The greatest difference in Div. 3NO was in the 1995-1999 period when the standardized *SPR* for variable maturity, sex ratio and egg production were all above 3 while that for knife-edge maturity was 2.5.

B_{lim} and projections

An example of the stock recruit scatters and setting of B_{lim} using the various measures of *RP* is given in Fig. 5. Although any index of *RP* can be used in the setting of reference points the current status of a stock relative to the reference point will vary depending on which index of *RP* is used. In this case, the current index of *RP* using knife-edge maturities is about one-half the percentage of B_{lim} that the other indices of *RP* are currently estimated to be. The ranking of stock status derived from the various indices will depend on the current characteristics of the spawning stock, relative to that observed during the period used to construct B_{lim}.

The results of short term determinist projections again show that different measures of *RP* will result in different perceptions of stock status relative to B_{lim} (Fig. 6). In this example, the largest projected increase in stock size is for the index of *RP* incorporating fecundity and the stock is projected to be the highest relative to B_{lim} using this index as well. The variation in the level of the stock relative to B_{lim} at the end of the projection period is despite the fact that all the indices other than knife-edge, started the projection period at the same percentage of their respective B_{lim}. This is the result both of the evolution of age structure during the projection period and the perceived productivity, both *RPS* and *SPR*.

Conclusions

Changes in spawner characteristics will produce different trends in indices of *RP*.
Different indices of *RP* will give different perceptions of stock productivity.
Any index of *RP* can be used to set reference points.
Different indices of *RP* will give different perceptions of current stock status relative to B_{lim}.
Any index of *RP* can be used in stock projections.
The evolution of age structure and differences in perceived stock productivity (*RPS* and *SPR*) will result in different perceptions of stock status relative to B_{lim} in stock projections.

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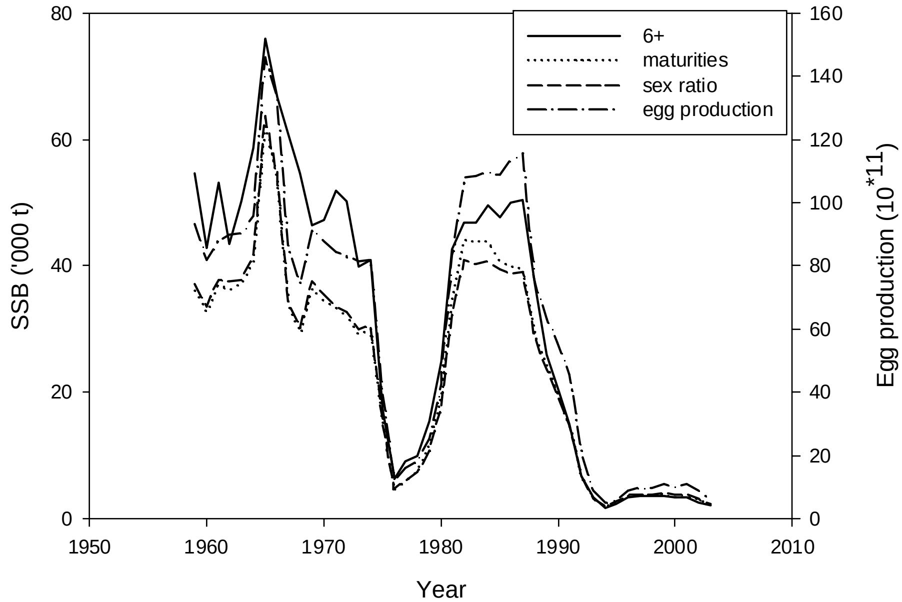

Fig. 1. Estimates of reproductive potential as biomass or egg production for 3NO cod. Estimates are produced using the biomass of all fish greater than a specific age (knife edge), using estimates of proportion mature at age (maturities), using maturities and estimated sex ratio (sex ratio) and by calculating egg production using variable maturity, sex ratio and estimated fecundity at age.

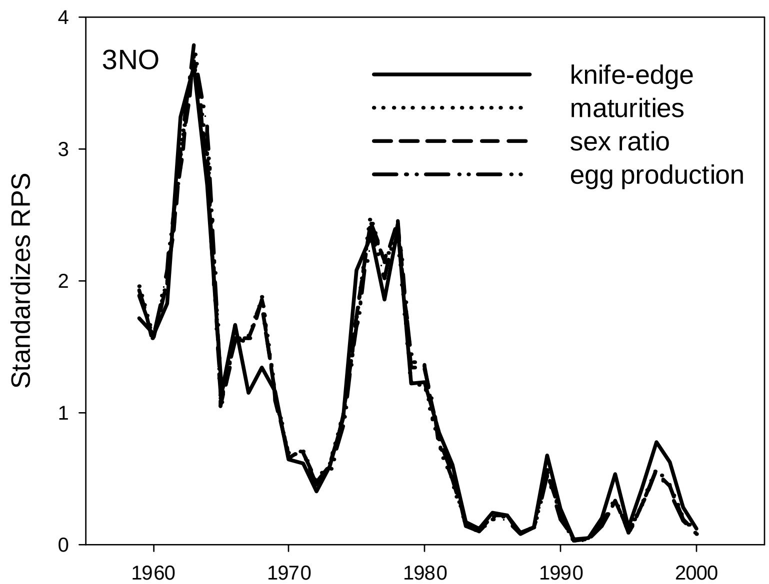

Fig. 2. Standardized recruitment rate (recruits/spawner: RPS) from each estimate of reproductive potential for 3NO cod.

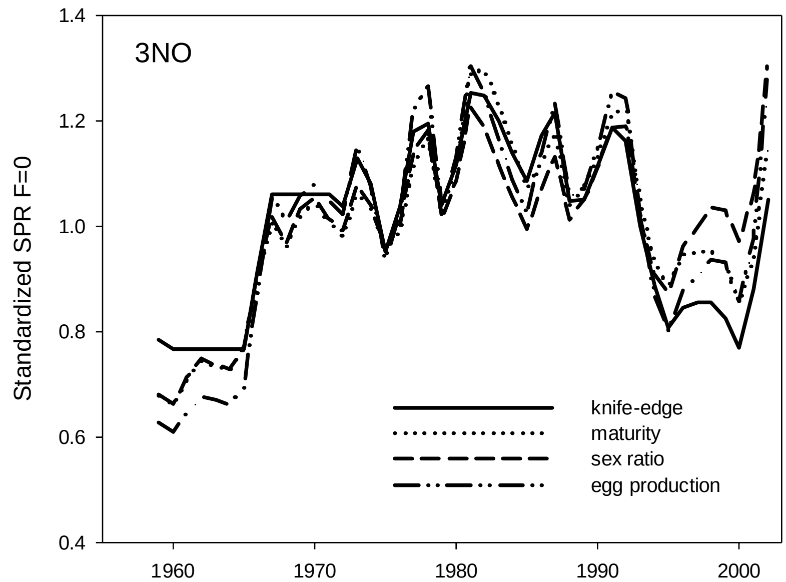

Fig. 3. Standardized spawner per recruit (SPR) at F=0 from each method of calculating reproductive potential for 3NO cod.

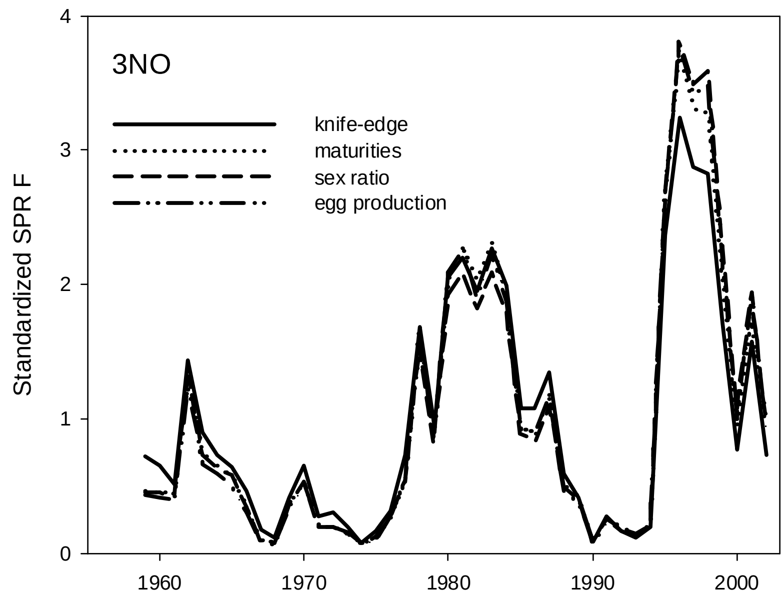

Fig. 4. Standardized spawner per recruit (SPR) at actual F from each method of calculating reproductive potential for 3NO cod.

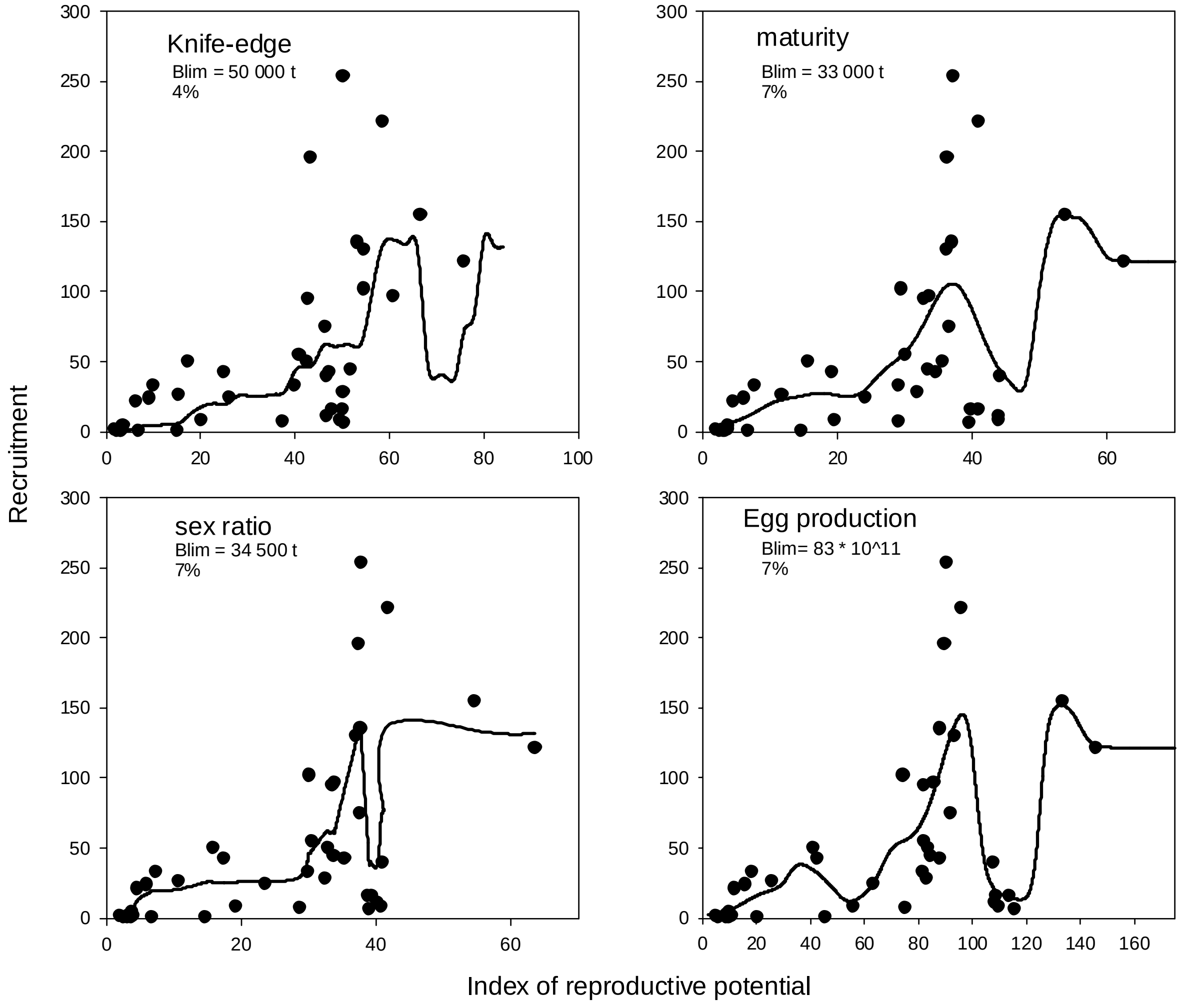

Fig. 5. Example of setting B_{lim} using different indices of reproductive potential. The percentage that the current stock size is of B_{lim} is given for each index of RP.

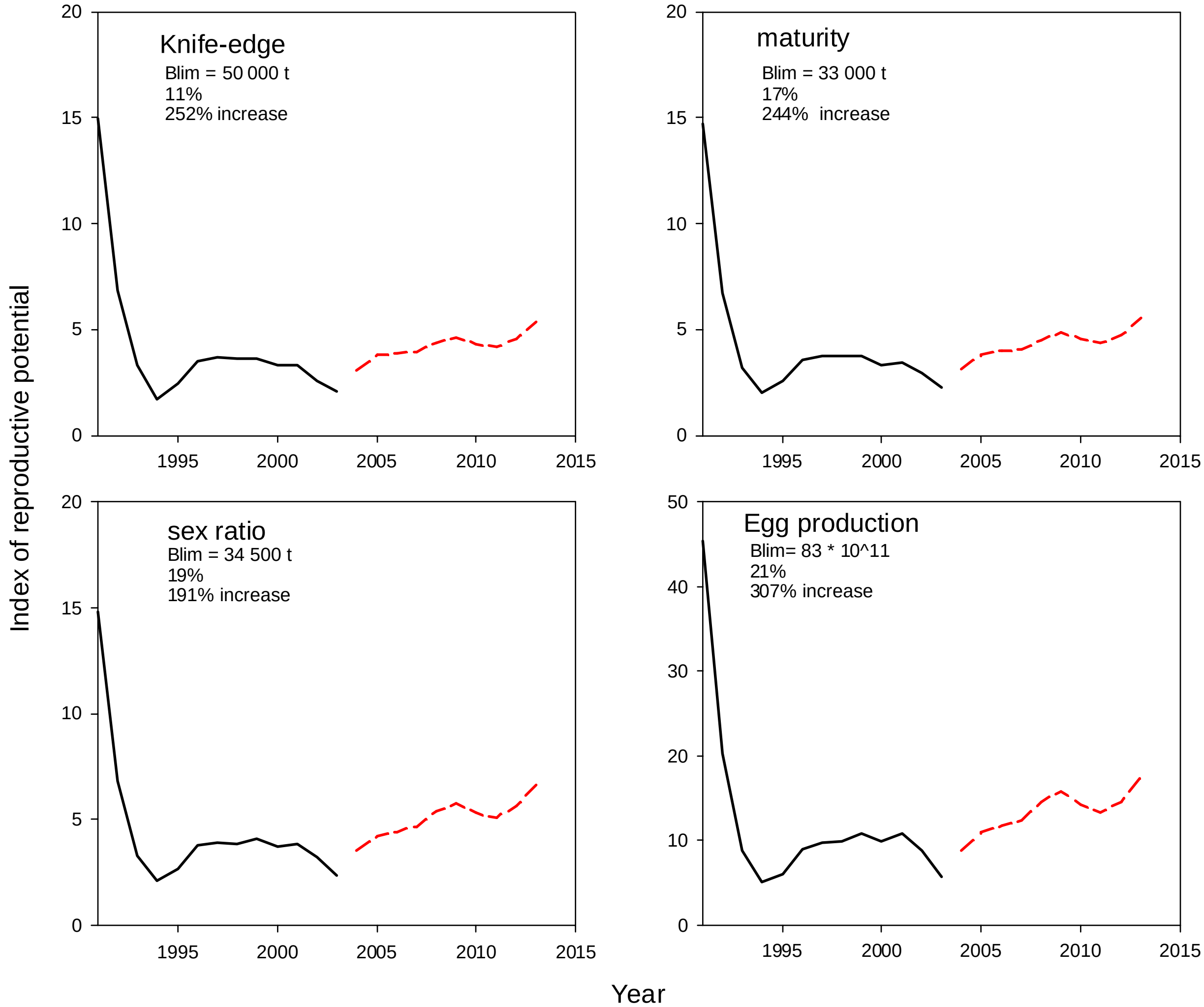

Fig. 6. Example 10 year deterministic projections using different indices of reproductive potential. The level of the stock at the end of the projection period is given in percent, as well as the projected percentage increase in stock size over the period of the projection.