Evaluating impacts of Density Dependent processes on Blue whiting via MSE simulations

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Version 1.0 (15 March 2023)

Version 1.1 (16 March 2023, fixed error in reference point table)

Version 1.2 (17 March 2023; fixed error in figure 15; added two scenarios)

Contents

Executive summary

The current management of fish stocks is based on achieving the fishing mortality (F_{MSY}) that achieves the maximum sustainable yield (MSY). Estimation of MSY generally only includes the stock recruitment relationship when considering density dependent population regulation mechanisms. Density dependence, however, may also operate in processes such as growth, sexual maturity, and natural mortality. A main aim of this study was to condition Operating Models (OMs) on alternative hypotheses about density dependence for use in Management Strategy Evaluation (MSE). The objective is to evaluate the robustness of the assessments conducted to support the ICES advice framework. To do this OMs were developed that include density dependence in growth, maturity, natural mortality, individually and combined. These OMs were then used to evaluate the consequences of not including density dependence management advice.

The Operating Models were:

- Base Case, with varying M-at-age
- Density dependence in mass-at-age,
- Density dependence in mass, maturity-at-age,
- Density dependence in mass, maturity and M-at-age,

The MSY reference points B_{MSY} and F_{MSY} are generally based on equilibrium assumptions, either from combining yield per recruit and spawner per recruit relationship (Sissenwine and Shepherd 1987) or by conducting long-term projections under constant fishing moralities.

Initial evaluations were conducted based on life history theory, as used by the International Council for the Exploration of the Sea (ICES) to develop advice conducting MSE for data poor stocks (Fischer, DeOliveira, and Kell 2020). **Figure 10** shows the equilibrium curves of catch v SSB assuming a) no density dependence, and density dependence in b) mass-at-age, c) mass & maturity-at-age, and d) mass, maturity and natural mortality-at-age. These allow the relationships between the MSY reference points and virgin biomass to be seen.

Each of the OMs were then projected for the values of F_{MSY} based on the four assumptions about density dependence. This allows a comparison between the yield that could potentially be achieved and that forgone by making an incorrect assumption about density dependence. The OMs were first projected, without process error in recruitment, from the end of the historical estimates for a range of fishing mortality (spanning 0 to F_{crash}) for 30 years into the future. The estimates in the final year of the projections were then be used to construct equilibrium curves (**Figure 15**). The points on the curve correspond to the projected outcomes for the values of F_{MSY} from each OM. This was run as a check, as the equilibrium and projections should agree, I.e. the points at MSY should be the same color as the curve.

The OMs were also projected for the estimates of different estimates F_{MSY}, with stochasticity in the recruitment deviates. This allows the impact of misspecification of density dependence to be evaluated, i.e. if F_{MSY} is underestimated then yield will be less than MSY, while if F_{MSY} is overestimated yield will be lost due to overfishing. Stochastic projections of the four Operating Models for the four estimates of F_{MSY} are shown in **Figures 16-19**. **Figures 20-22** summarizes the yields, SSBs and Fs obtained for each Operating Model under the correct and mis-specified form of density dependence.

Estimating density-dependence from observations was not really possible for Blue whiting because there was no clear relationship between mass-at-age and total biomass. When a second GAMM model was fitted with weight in relation to total biomass, year and age, we found that the mass-at-age is better described by a year effect than a biomass effect. In order to still explore the impacts of density dependence on the performance of the MSE, we used the density dependent factor for Atlantic mackerel (beta=-0.18) to parameterize the weight-biomass relationship.

Including density dependence has a major impact on reference points. Especially F_{MSY} is much higher when including DD. However, the expected yields in equilibrium conditions are expected to be very similar. The main difference is in the initial step from the current F_{MSY} to any new F_{MSY} that would include DD, as the higher F_{MSY} would be applied to a stock that is estimated without DD.

1   Introduction

The purpose of this work is to support the project "F_{MSY}-project for six high profile fish stocks". The project focuses on the current management approach for fish stocks based on single-species F_{MSY} Values where the only density-dependent process that is included is recruitment. The project includes three other density-dependent population dynamics: growth (mass-at-age), sexual maturity and natural mortality.

This report deals with the evaluation of density dependent processes for Blue whiting using Management Strategy Evaluation (MSE). Steps in the analysis:

1.   Conditioning and summaries based on the 2022 ICES assessment (section 2)

2.   Estimating Density Dependent effects based on equilibrium analyses and explore DD before setting up the OMs (section 3)

3.   Setting up the Operating Models (OM) (section 4)

4.   Running MSE's (section 5)

Four alternative OMs have been included in the analyses:

1.   No density dependent processes

2.   DD in growth

3.   DD in growth and maturity

4.   DD in growth, maturity and natural mortality

All MSE's have been developed within the FLR framework (https://flr-project.org/) and all the code is stored on GitHub (https://github.com/martinpastoors/ddmse).

All data and results are available on a dedicated DropBox folder.

All conditioning of the Operating Models and estimation of potential density dependent processes have been based on the ICES 2022 SAM assessment of Blue whiting.

Mass-at-age

Trends in (catch and stock) mass-at-age are shown in figure 1. Mean weight at ages 3-9 has generally decreased in the period 2010-2018, followed by an increase in the most recent years, for the most abundant ages in the catches. In 2022, a decrease in mean weight in almost all ages was observed.
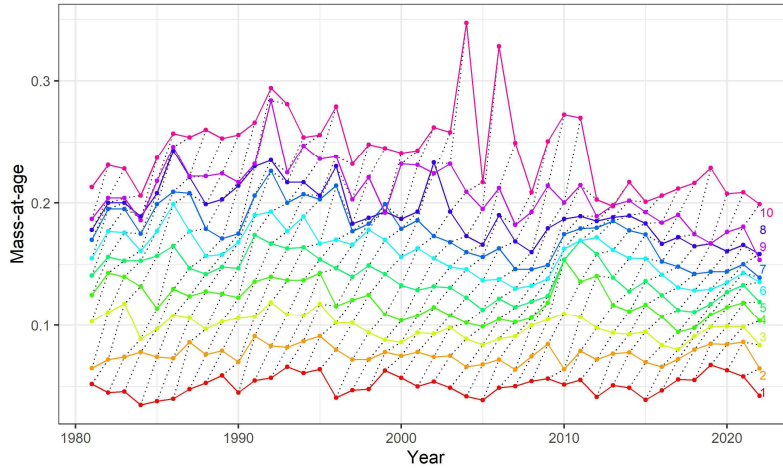

Figure 1: Blue whiting. mass-at-age by year and cohort

Maturity-at-age

The fixed maturity ogive for blue whiting was taken from the ICES assessment, this did not vary by year. Maturity-at-age was obtained by combining maturity ogives from the southern and northern areas, weighted by catch in numbers-at-age ICES (2022a).
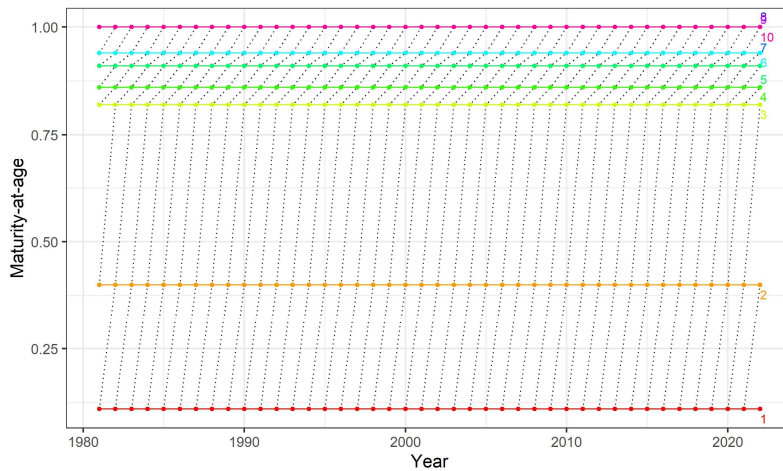

Figure 2: Blue whiting. Maturity-at-age by year and cohort

Natural mortality-at-age

Natural mortality is assumed to be 0.2 for all age groups and constant over time. The current M of 0.2 was derived from investigations undertaken in the 1980s that examined the age distribution of the stock before the industrial fishery started (ICES 1995).

During the WKPELA benchmark (ICES 2012) various methods were explored to estimate how M may vary over ages. The relationship between natural mortality and body weight was applied to the blue whiting data to determine a variable M by age. The values ranged from around 1.1 at age 0 to 0.7 at age 10, which was considerably higher than the values used so far. During the benchmark, it was considered that there was no new information to support a revision of the used estimate of M (=0.2).

In order to assess the impacts of density dependent processes on natural mortality, additional assumptions need to be made about the distribution of natural mortality across ages. This will be done in section 3 of this report.
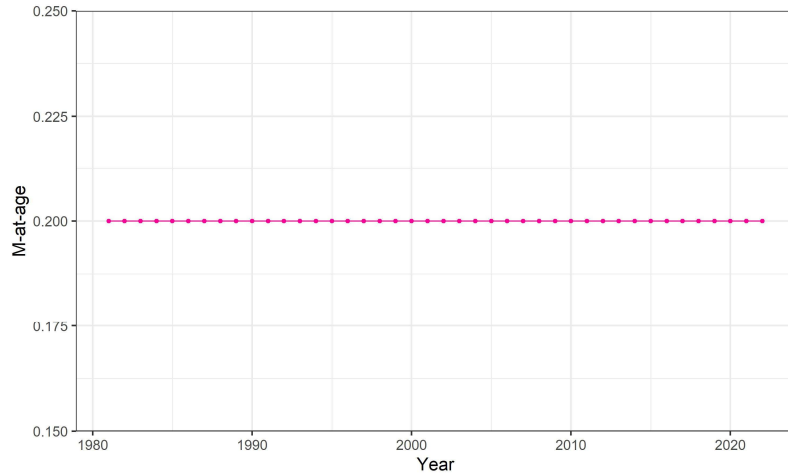

Figure 3: Blue whiting. Natural mortality-at-age by year and cohort (all ages and years the same M)

Density dependence in mass-at-age vs. Total biomass

The variation in mass-at-age is shown in the figure below (left) and the relationship between mass-at-age and total biomass to the right. Consistent negative slopes on the biomass-mass-at-age plots are seen for ages 2-9.
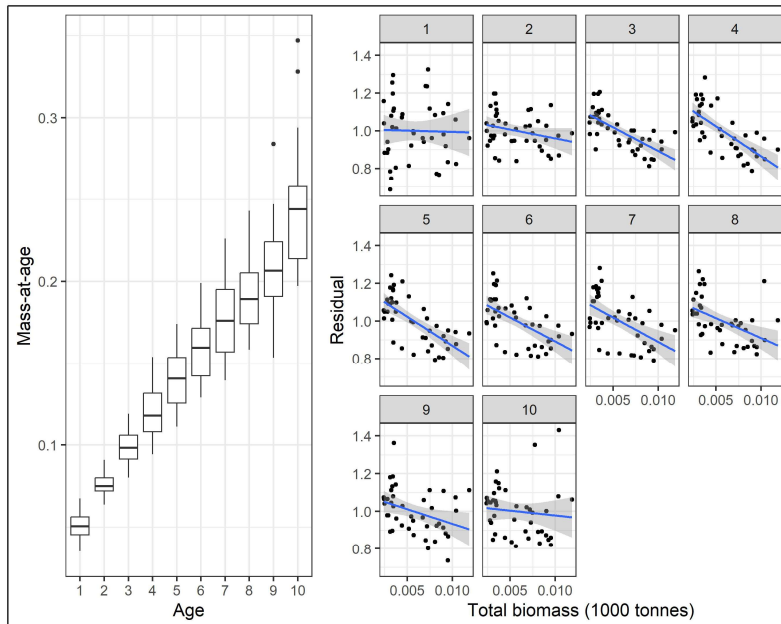

Figure 4: Blue whiting. Density dependence and mass-at-age.

GAMM-at-age: biomass only

A Generalized Additive Mixed Model (GAMM) was estimated to assess the relationship between mass-at-age and total biomass. Weights are predicted from two variables: a smoother of total biomass/mean(total biomass) and age. The resulting factor is shown below. There is no clear relationship between biomass and weight-at-age.
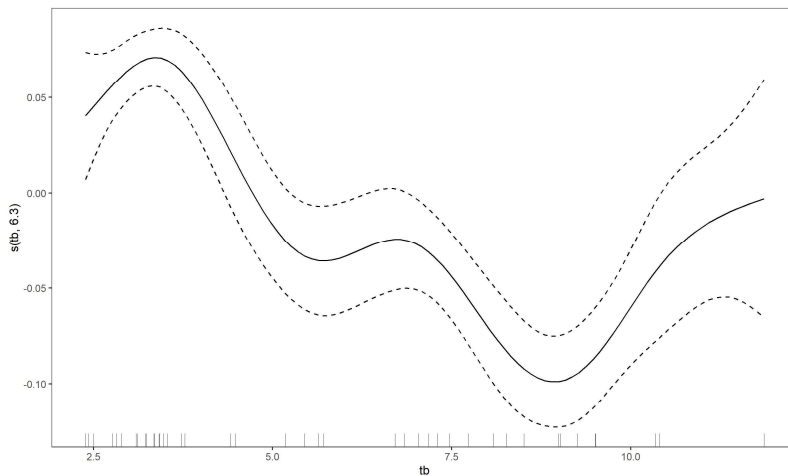

Figure 5: Blue whiting. GAMM analysis of density dependence and mass-at-age.

A summary of the GAMM model is shown in the table below.

```
Family: gaussian
Link function: identity

Formula:
log(data) ~ s(tb/mean(tb), bs = "tp") + age

Parametric coefficients:
```

```
           Estimate Std. Error t value Pr(>|t|)
(Intercept) -2.98905    0.01643 -181.90   <2e-16 ***
age02        0.40741    0.02324   17.53   <2e-16 ***
age03        0.66822    0.02324   28.75   <2e-16 ***
age04        0.86135    0.02324   37.06   <2e-16 ***
age05        1.01576    0.02324   43.71   <2e-16 ***
age06        1.14218    0.02324   49.15   <2e-16 ***
age07        1.24598    0.02324   53.62   <2e-16 ***
age08        1.33367    0.02324   57.39   <2e-16 ***
age09        1.41399    0.02324   60.85   <2e-16 ***
age10        1.56419    0.02324   67.31   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
        edf Ref.df    F p-value
s(tb) 6.304  6.304 22.3  <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.951
  Scale est. = 0.011341  n = 420
```

Table 1: Blue whiting. GAMM summary of density dependence and mass-at-age.

GAMM-at-age: biomass and year smoothers

Because no clear relationship between mass-at-age and total biomass was established, we fitted a second GAMM model with weight in relation to total biomass, year and age. This demonstrated that the mass-at-age is better described by the year effect than the biomass effect (lower p-value).

In order to still explore the impacts of density dependence on the performance of the MSE, we used the density dependent factor for Atlantic mackerel (beta=-0.18) to parameterize the following relationship:

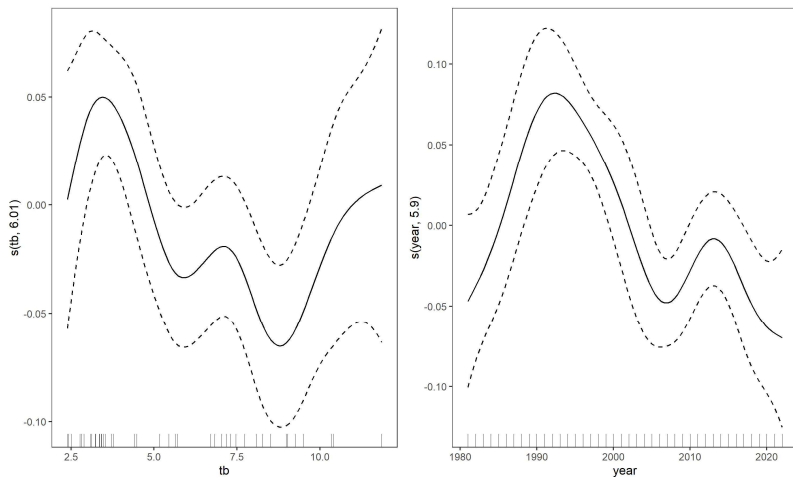$$W_a = \overline{W_a}(B/B_{MSY})^{\beta_a}$$

Figure 6: Blue whiting. GAMM analysis of mass-at-age against biomass, year and age

```
Family: gaussian
Link function: identity

Formula:
log(data) ~ s(tb, bs = "tp") + s(year, bs = "tp") + age

Parametric coefficients:
           Estimate Std. Error t value Pr(>|t|)
(Intercept) -2.98905    0.01512 -197.66   <2e-16 ***
age02        0.40741    0.02139   19.05   <2e-16 ***
age03        0.66822    0.02139   31.25   <2e-16 ***
age04        0.86135    0.02139   40.28   <2e-16 ***
age05        1.01576    0.02139   47.50   <2e-16 ***
```

```
age06          1.14218    0.02139    53.41    <2e-16 ***
age07          1.24598    0.02139    58.26    <2e-16 ***
age08          1.33367    0.02139    62.36    <2e-16 ***
age09          1.41399    0.02139    66.12    <2e-16 ***
age10          1.56419    0.02139    73.14    <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
          edf Ref.df      F  p-value
s(tb)   6.014  6.014  4.568 0.000193 ***
s(year) 5.897  5.897 11.449  < 2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.958
  Scale est. = 0.0096044  n = 420
```

Table 2: Blue whiting. GAMM summary of mass-at-age against biomass, year and age

Density-dependence analysis of maturity-at-age

The distribution of maturity-at-age is shown in the figure below (left) and the relationship between maturity-at-age and total biomass is shown to the right. Obviously, as there is no time-dependent estimate of maturity, there is also no relationship with biomass.
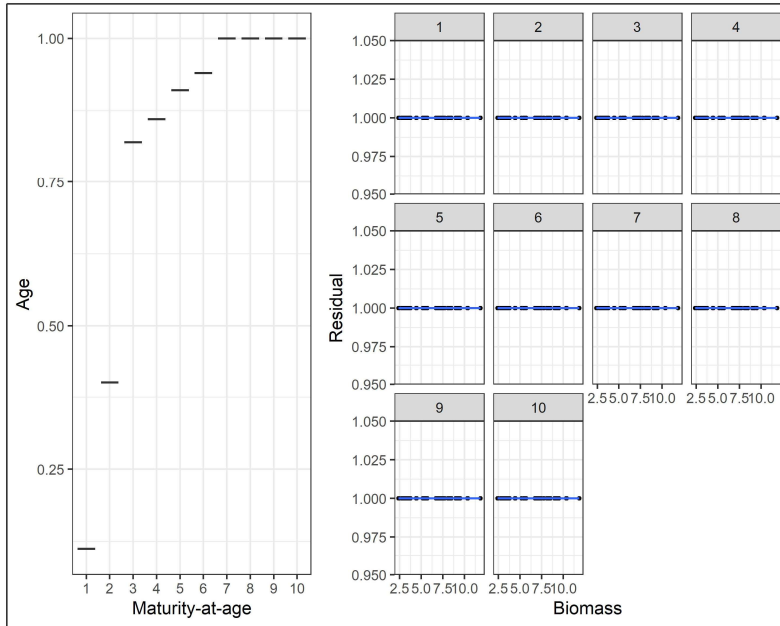

Figure 7: Blue whiting. Analysis of density dependence and maturity-at-age.

Estimated maturity at weight

A maturity at weight ogive was generated from this formula:

$$f(x) = \frac{1}{1 + e^{-k(x-x_0)}}$$

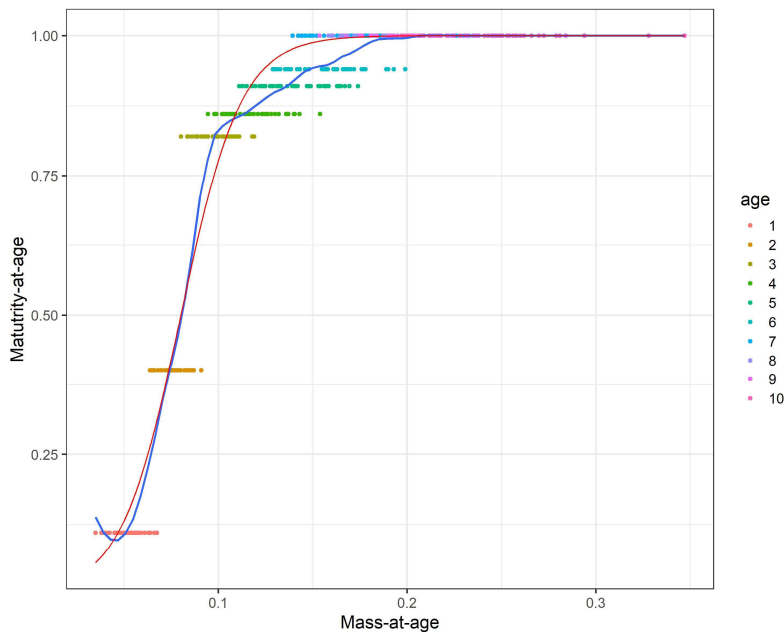This resulted in the parameters k=62.76 and W_{50}=0.08011 which have been used in subsequent simulations.

Figure 8: Blue whiting. Estimated maturity ogive at weight

3 Estimating Density Dependent effects based on life-history parameters

Life history parameters are used to develop an example of modelling density dependence for mass, maturity and natural mortality-at-age. The parameters are first used to construct an *`FLBRP object representing the equilibrium, and are then coerced into an **FLStock** to model the time series dynamics.

3.1 Mass-at-age

Mass-at-age (W_a) is modeled as

$$W_a = \overline{W_a}(B/B_{MSY})^{\beta_a}$$

Where $\overline{W_a}$ and β are estimated from a regression of mass-at-age (W_a) on total biomass (B_a), based on empirical data. W_a is constrained so that sizes do not become unfeasible large or small.

3.2 Maturity-at-weight

Maturity is then modelled as a logistic function of mass-at-age i.e.

$$O(W_a) = 1/\left(1 + e^{k(W_a - W_{50})}\right)$$

3.3 Natural mortality

Natural mortality is assumed to vary at unit length (L_1).

Empirical and theoretical studies (Lorenzen (2000)) have shown that natural mortality (M) decrease with fish length, but increase with the von Bertalanffy parameters of curvature k and asymptotic length L_∞. Therefore, M can be derived from life history parameters, e.g. $M = 1.5kL\infty/L$) (Pope et al. (2021)) or M=1.5k Jensen (1985). Lorenzen (2008) Lorenzen, Camp, and Garlock (2022) showed that natural mortality rates vary with body size and age, often by orders of magnitude over the life cycle and support the existence of an allometric relationship between M and body mass (W) at-age of the form:

$$M = M_u W^d$$

Where M_u is M at unit weight, and d is the allometric exponent from empirical relationships shown to range from -0.3 to -0.37. d is approximately equal to -1/3, which implies that M is inversely proportional to body length, since mass is approximately proportional to the third power of length. This is consistent with (Gislason et al. 2008), who proposed a relationship for natural mortality based on length

$$M = \alpha k(L_\infty \chi)L\beta$$

The plot below shows the equilibrium values by age for simulations initiated with different levels of biomass relative to B_{MSY}. The red line indicates the values from the current assessment (for natural mortality that varies by mass and hence age).
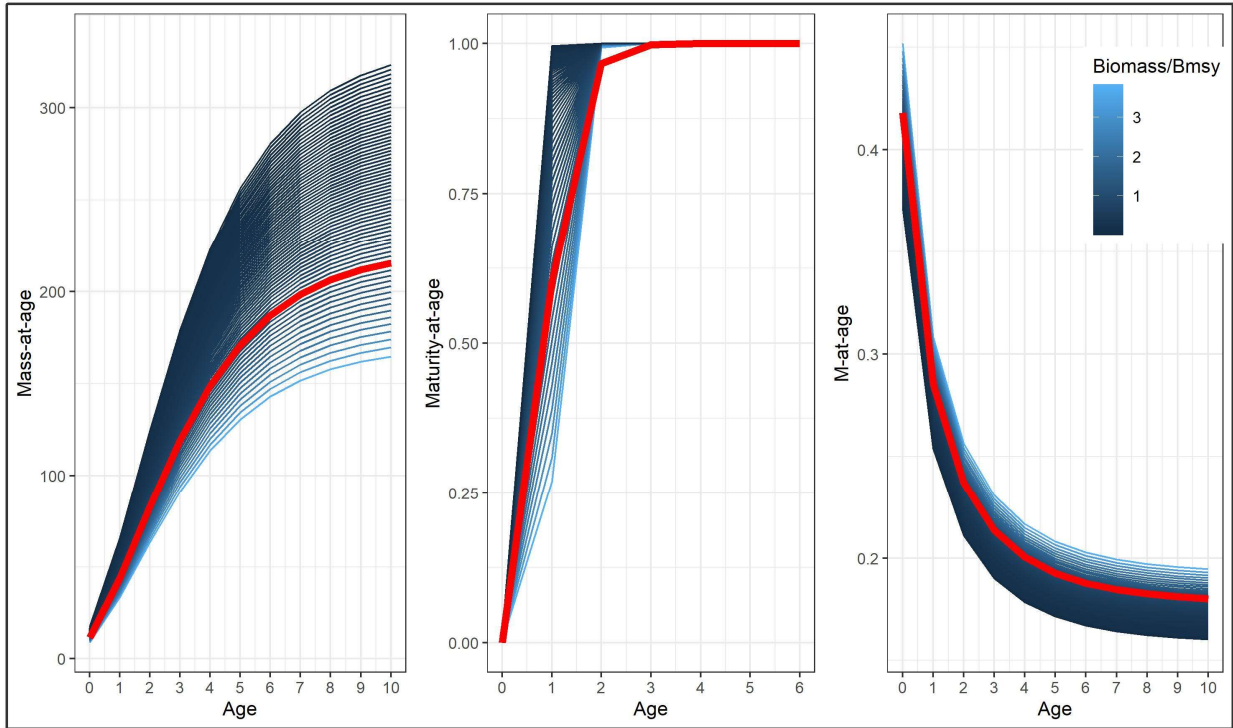
Figure 9: Simulation of density dependence in mass-at-age, maturity-at-age and Natural mortality-at-age for different levels of biomass relative to B_{MSY}. Red line is without density dependence.

From the theoretical life-history parameters and simulations, we can compare the equilibrium total biomass and yield from an assessment without density dependence, and then adding, step-by-step, the density dependent processes for mass-at-age, maturity-at-age and natural mortality-at-age. Comparison of equilibrium yield plots for simulation with and without density-dependent processes indicates that the expected values for B_{MSY} tend to become lower when density dependence is included and that MSY becomes somewhat higher.
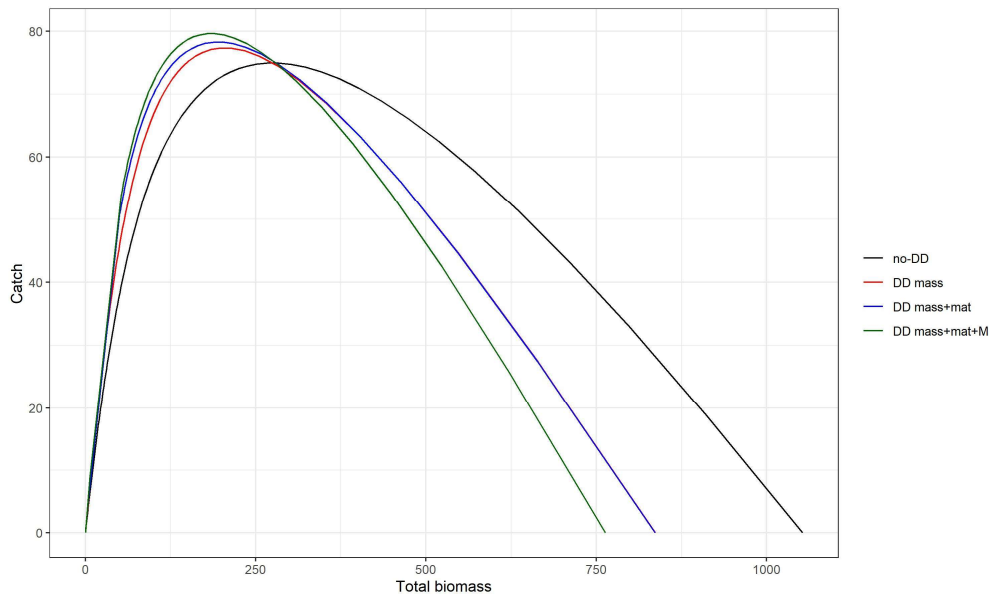

Figure 10: Simulation of density dependence in M-at-age for different levels of biomass relative to B_{MSY}

4   Setting up the Operating Models (OM)

Stock assessments

The Operating Models for this study are derived from the 2022 stock assessment. SAM is a statistical catch-at-age model that estimates error in the catch-at-age. In the case of Blue whiting, the assessment gives a higher weight to the recruitment index than to the catch data for ages 0 and 1. This means that the estimates of recruitment in the assessment can be very different from the actual number of fish that are recruited to the fishery. To ensure the MSE projections and the historical estimates are comparable, a Virtual Population Analysis (VPA) was conducted on the whole catch matrix and the survivors in the most recent year and oldest age. In the next step, we applied a natural mortality-at-age vector derived from the Lorenzen approach which would mimic the VPA assessment with fixed M-at-age. The figure below compares the SAM assessment with the VPA and the VPAM assessment. A main difference is in the recruitment estimates. Using age-varying M tends to flatten the recruitment pattern. The vpaM model was used as the base case to be compared against the density-dependent simulations.
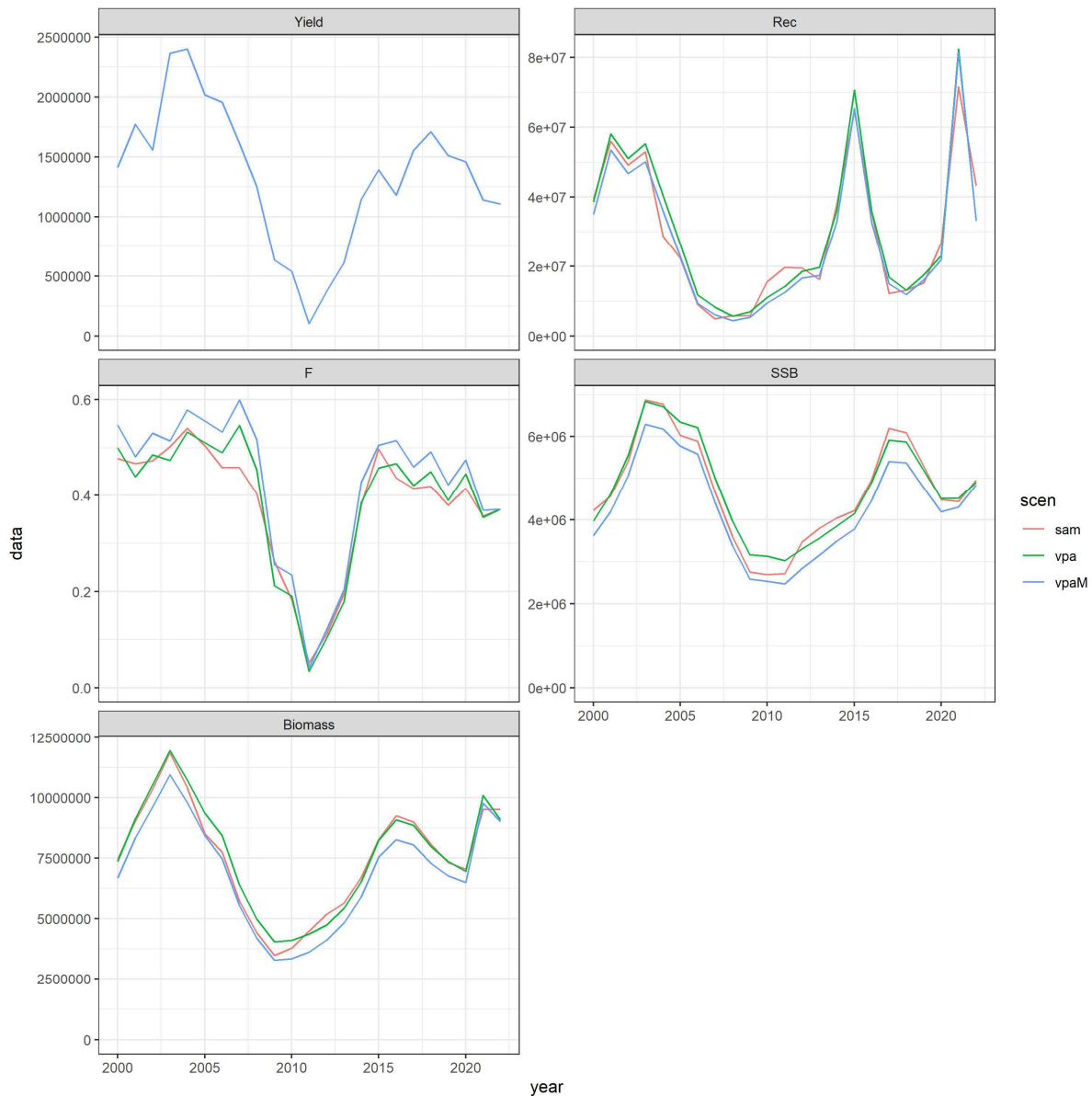

Figure 11: Comparison of different assessments. VPA-M is used as. the base case going forward

Density dependence in mass-at-age

When applying density dependent processes to mass-at-age (i.e. lower mass-at-age for higher biomass), B_{MSY} is expected to be somewhat lower. The expected increase in MSY is small.
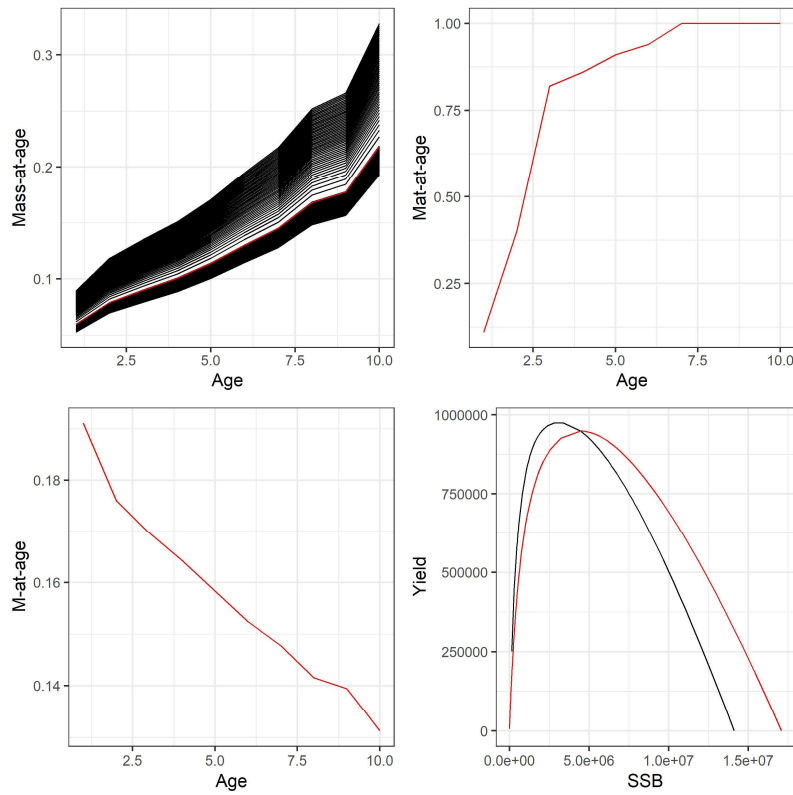

Figure 12: Simulation of density dependence in Mass-at-age. Red lines are the non-density dependent values.

Density dependence in mass-at-age and maturity-at-age

When applying density dependent processes to both mass-at-age and maturity-at-age, B_{MSY} is expected to be lower again and MSY is expected to increase.
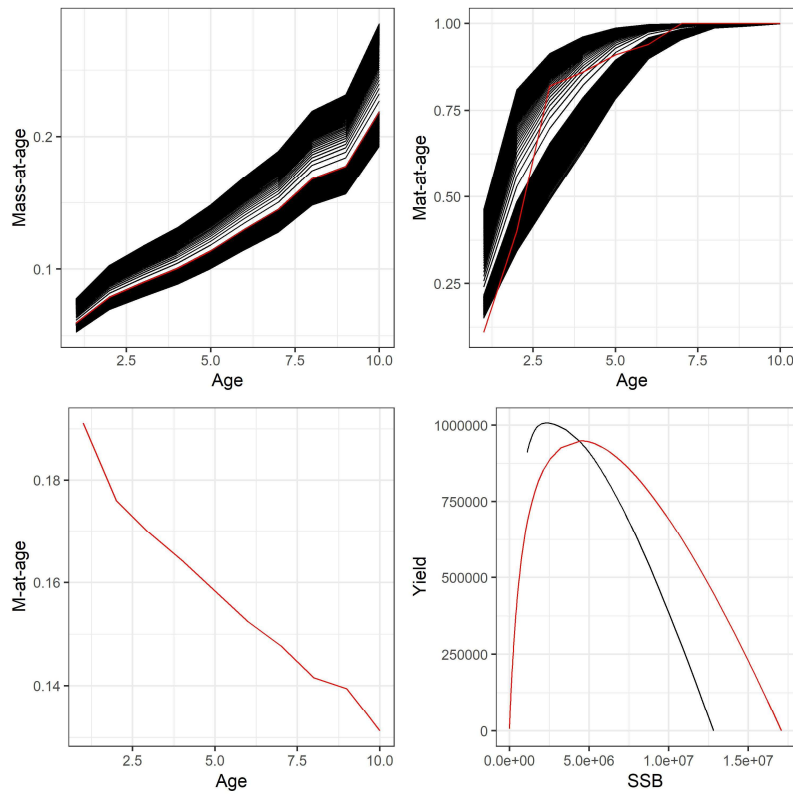

Figure 13: Simulation of density dependence in Mass-at-age and Maturity-at-age. Red lines are the non-density dependent values.

Density dependence in mass-at-age, maturity-at-age and M-at-age

When applying density dependent processes to all three variables, B_{MSY} is expected to be lower again and MSY is expected to increase a bit more.
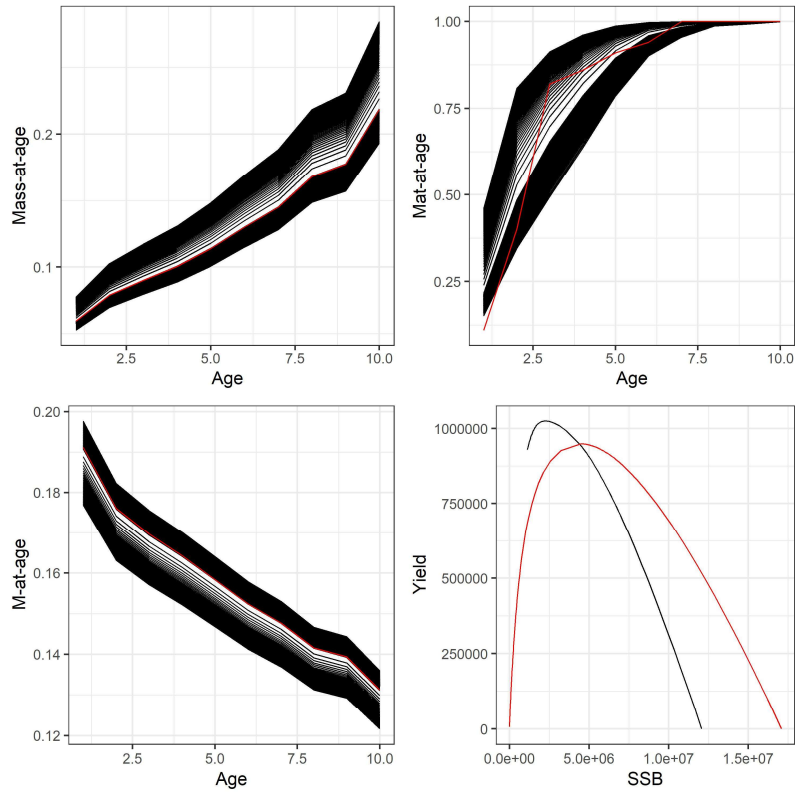

Figure 14: Simulation of density dependence in Mass-at-age, maturity-at-age and M-at-age. Red lines are the non-density dependent values.

Comparison of equilibrium curves for density dependence analyses: biomass against yield and F

The comparison of the equilibrium curves, indicate that B_MSY is expected to decrease by 30%, F_{MSY} is expected to increase by 113% and catch (MSY) is expected to increase by 5%. So, while, inclusion of density-dependent processes, has a substantial impact on biological reference points, the resulting change in equilibrium catch is expected to be small.
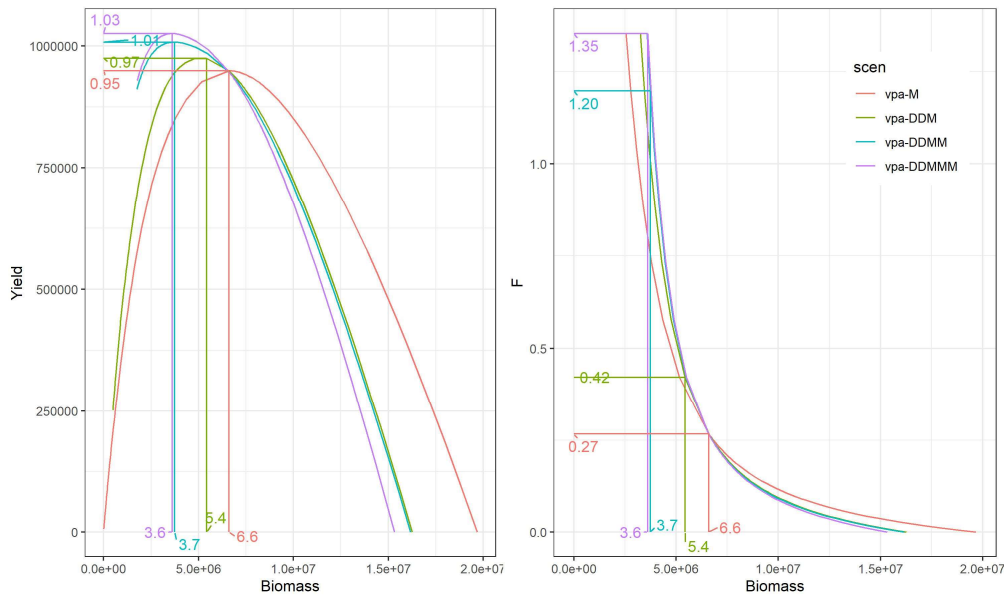

Figure 15: Equilibrium curves for density dependence analyses: biomass against yield and biomass against F

5   Forward projections without feedback

Forward projections were run in two modes. Firstly, in deterministic mode and secondly in probabilistic mode. We used the F_{MSY} to project forward from 2020 until 2050.

Reference points estimated for the different scenarios are in the table below.

```
scen              Bmsy         SSBmsy       MSY          Fmsy     Virgin       B0
----------------  -----------  -----------  -----------  -------- -----------  ------------
Base              6,597,671    4,464,194    948,942      0.2669   17,078,784   19,675,023
DD Mass           5,432,344    3,385,679    974,568      0.422    14,112,533   16,256,375
DD Mass, Mat      3,738,223    2,340,037    1,007,587    1.198    12,806,686   16,163,117
DD Mass, Mat, M   3,614,144    2,256,979    1,025,297    1.353    12,067,545   15,323,083
```

Table 3: Blue whiting. Reference points for the different scenarios

We used both the F_{MSY} that is applicable to the density dependent scenario, but also evaluated what would happen if the 'wrong F_{MSY}' would be used with a particular scenario.

The plot below shows the deterministic runs with the appropriate F_{MSY} value being used to project forward. F_{MSY} is highest when density dependence is taken into account for all three processes. Nevertheless, expected catches are somewhat lower when density dependence is taken into account.
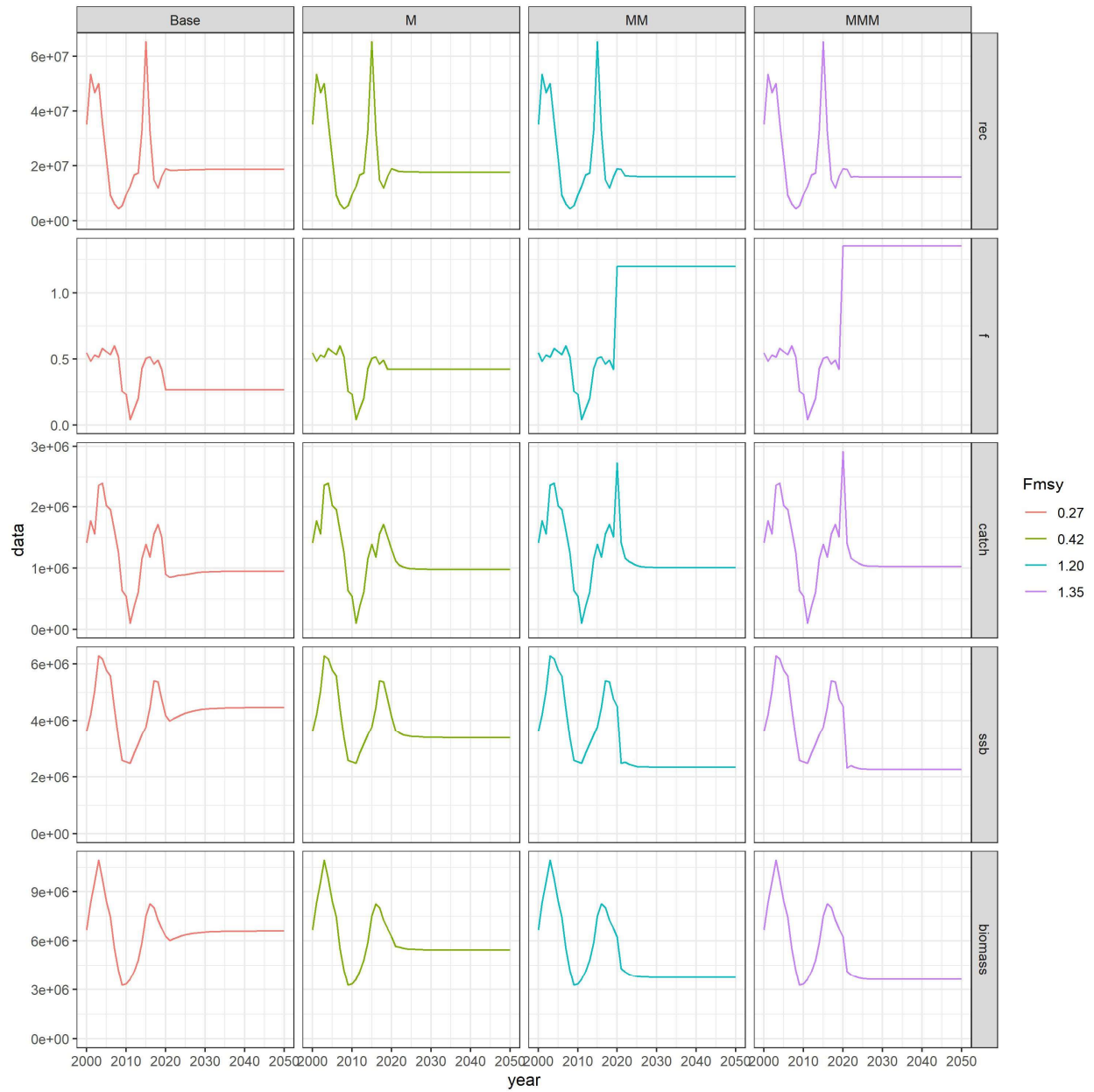
Figure 16: Deterministic projections at F_{MSY} for different scenarios

Deterministic projections at F_{MSY} for different scenarios: trends in weight, maturity and M-at-age

How can we understand the results of the deterministic runs? Below is a plot of the trends in stock mass-at-age, maturity-at-age and natural mortality-at-age, for the most relevant ages (1-6) and for the four different scenarios (Base, DDM, DDMM and DDMMM). The density dependent effect of maturity is strongest when both stock weight and maturity are density dependent. When natural mortality is also density dependent, this has only minor impacts.
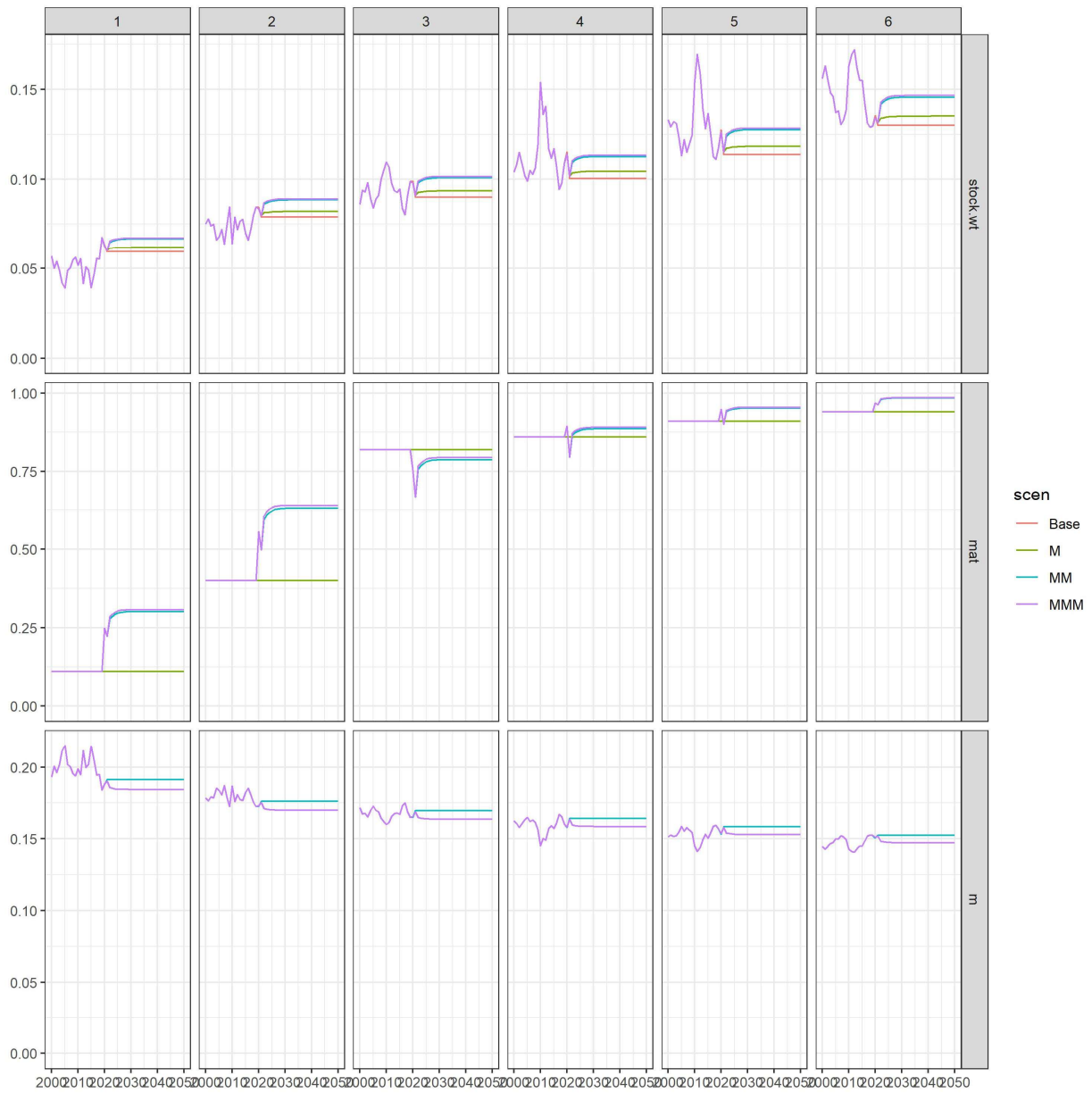

Figure 17: Deterministic projections at F_{MSY} for different scenarios: trends in weight, maturity and M-at-age

Stochastic projections at F_{MSY} for different scenarios

Using stochastic projections by including random processes for recruitment deviations and the F_{MSY} values that are consistent with the different scenarios, leads to the overview below. SSB and total biomass are highest in the case of no density dependence. Biomass tends to be lower when density dependent processes are taken into account. Catches are different in the first years of 'switching' to the new reference points, but afterwards, the catches for the different scenarios are highly comparable.
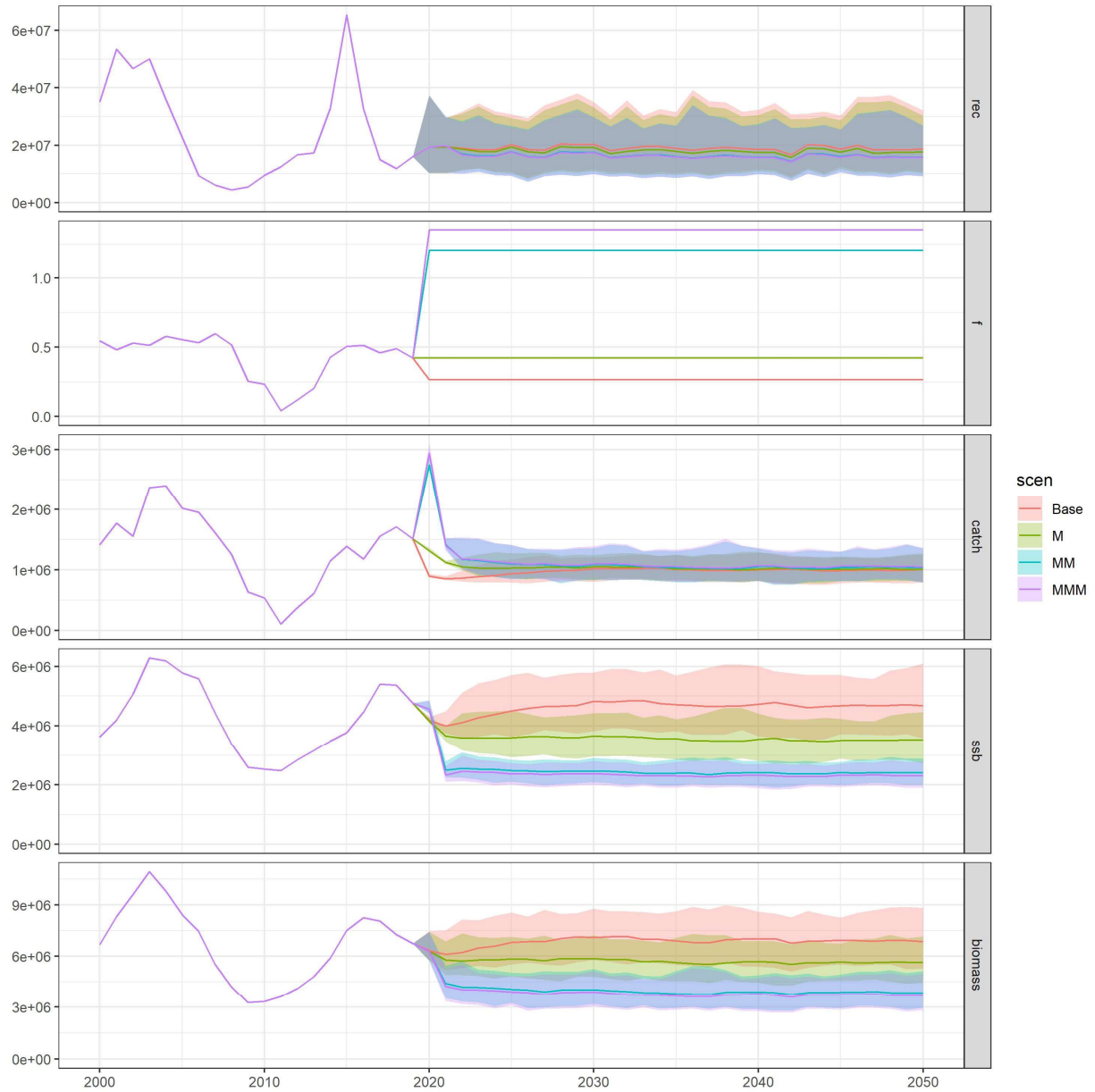

Figure 18: Stochastic projections at F_{MSY} for different scenarios

Histograms of probability distributions in 2050 for different scenarios

The histograms of the probability distributions in 2050 for different scenarios, again demonstrate the expected larger stock size without taking density dependence into account, and only marginal differences in catch.
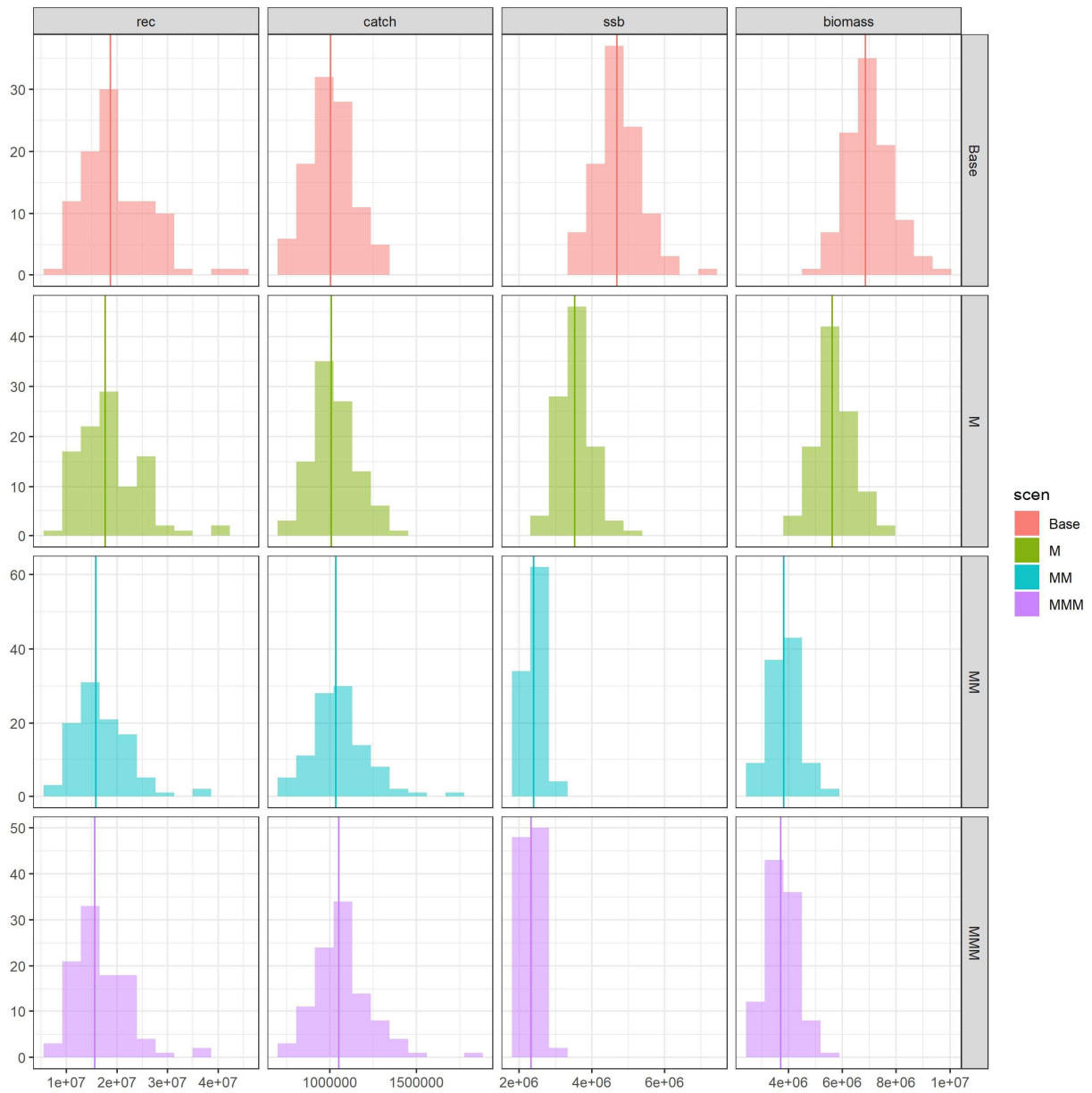

Figure 19: Histograms of probability distributions in 2050 for different scenarios

Stochastic projections at all F_{MSY}'s from all scenarios

For the stochastic projections at all F_{MSY}'s, we added two F scenarios: one with F=0.1 and one with F=2.

Misspecification of Fmsy, i.e. using an Fmsy from one scenario and applying it to a different scenario has only limited impacts on the overall outcomes in terms of recruitment, biomass or yield. In the plot below, the scenarios for density dependence are shown in the columns and the F's are shown as the colours. For example, a valid combination is the Base case with the yellow-brownish curve (Fmsy=0.27) or the M (mass) scenario with the green curve. The misspec-ification of Fmsy does not results in noticeable differences in catch although they do have important difference for biomass. Application of a low F (=0.1) is expected to lead to lower catches in all scenarios.
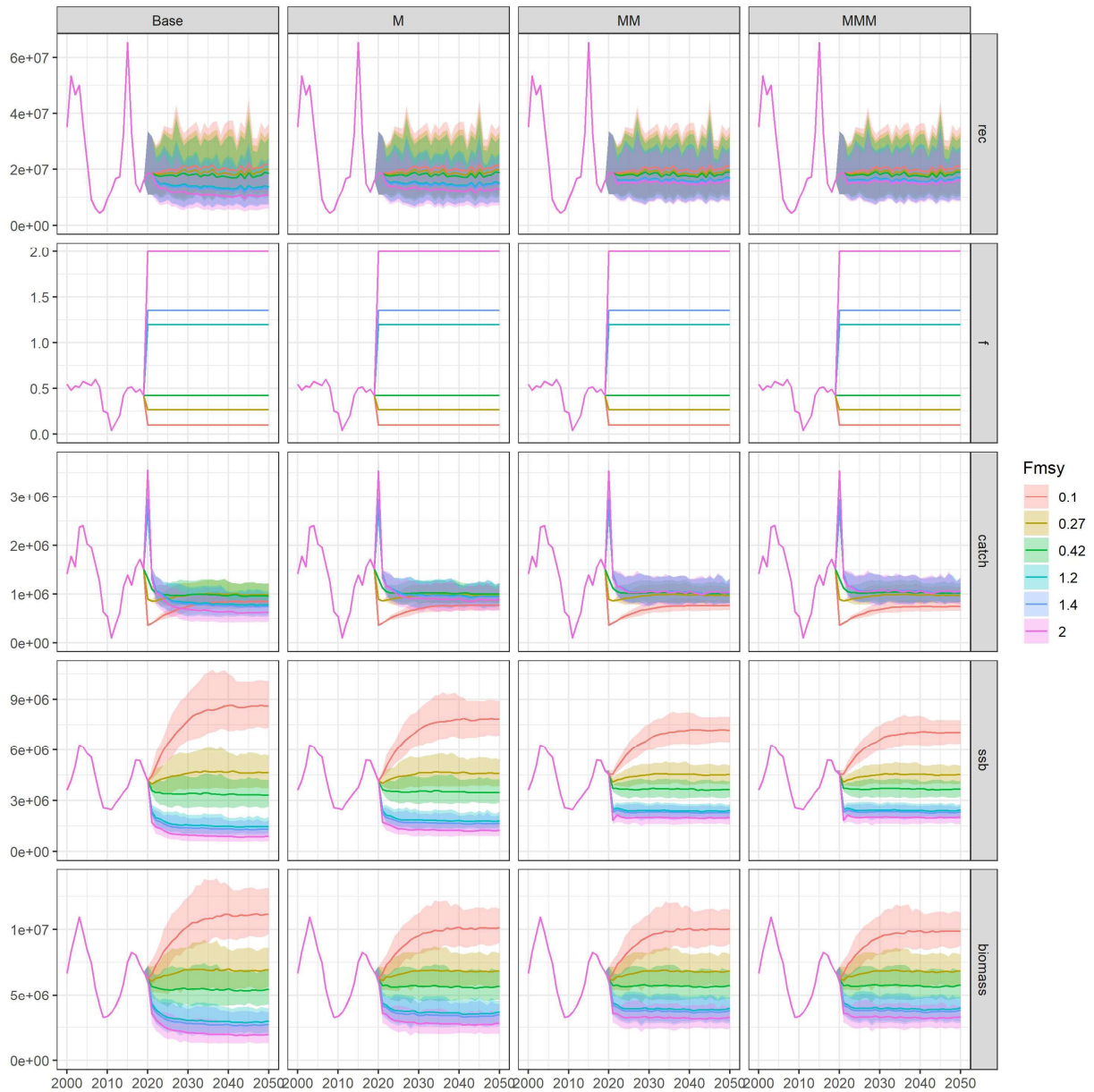

Figure 20: Stochastic projections at all F_{MSY}'s from all scenarios

For the four scenarios, we plotted the Kobe phase plot for 2050 with the associated density functions for B/Bmsy and Catch/MSY. The results confirm the results that equilibrium catch is not really affected by the DD assumptions of the Fmsy applied, but that biomass is sensitive to the assumptions. Application of density dependent reference points when density dependency would not exist, is expected to lead to lower equilibrium biomass levels.
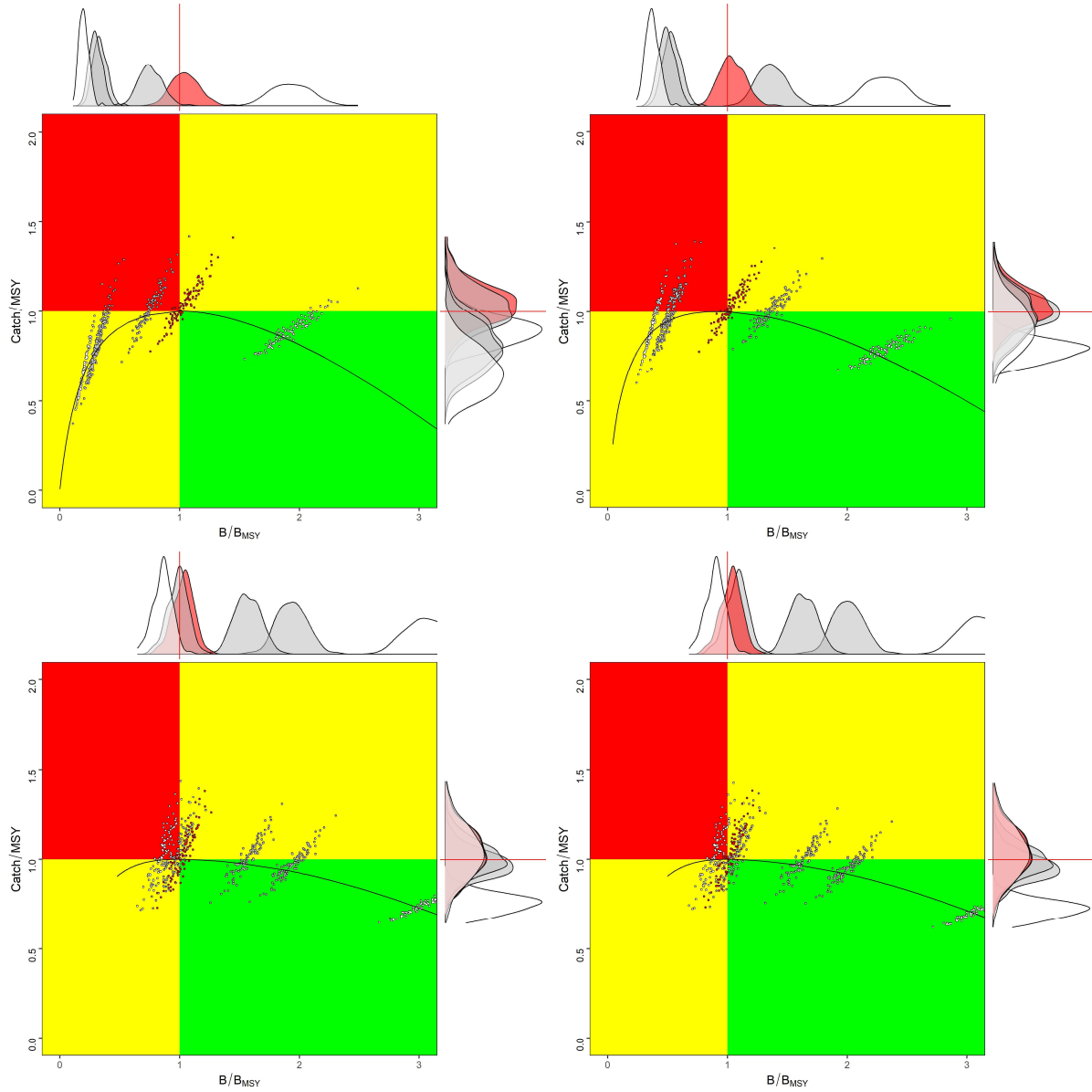

Figure 21: Kobe plot for 2050 for base case (no DD) for all F_{MSY}'s (red is from the right scenario). Topleft: base, topright: M, bottomleft: MM, bottomright: MMM. White densities refer to the low and high F scenarios.

We then plotted the Kobe phase plot for 2050 with the associated density functions for F/Fmsy and Catch/MSY. Because there is no uncertainty included in the fishing mortality during the simulations, the marginal distributions of F do not exist in this plot.
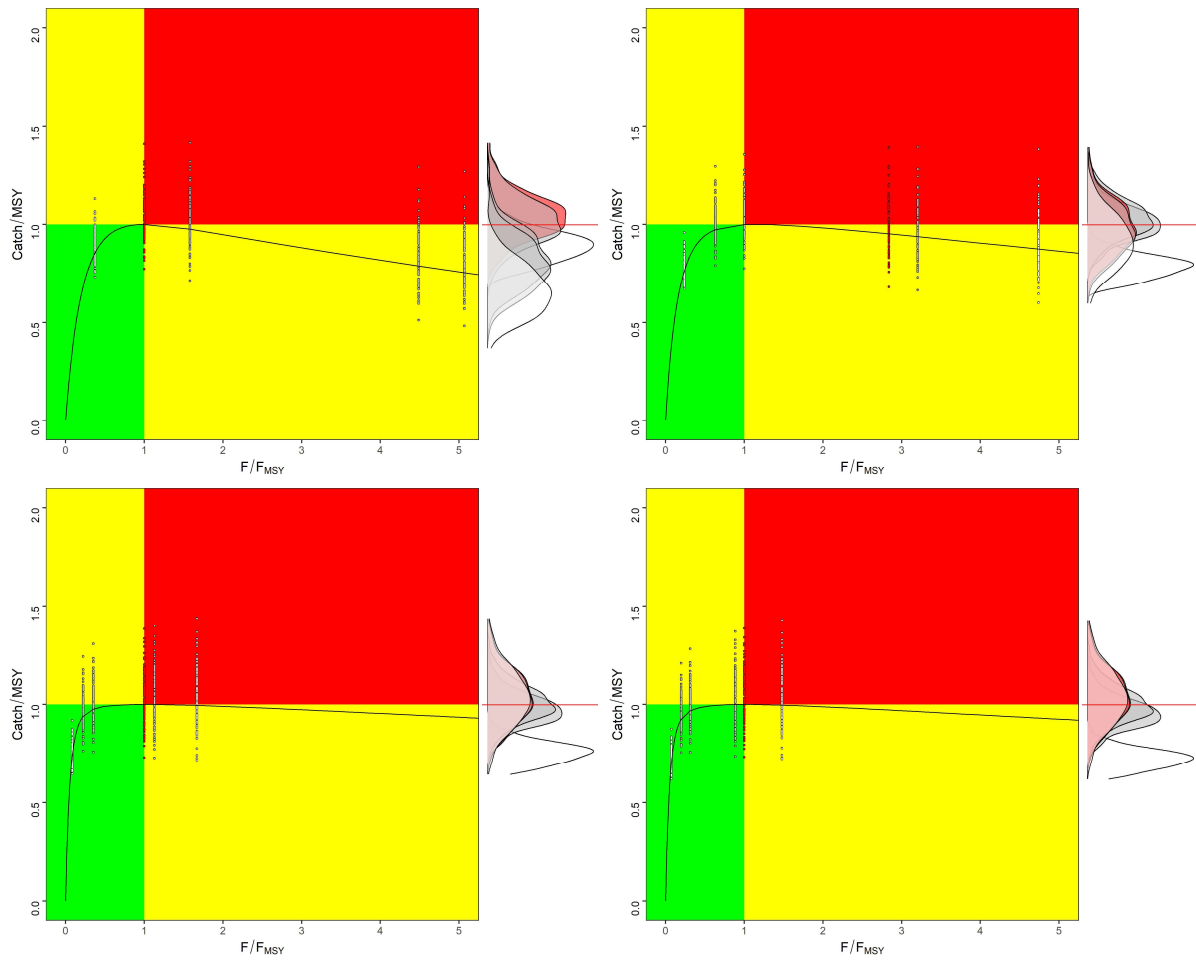
Figure 22: F Kobe plot for 2050 for base case (no DD) for all F_{MSY}'s (red is from the right scenario). Topleft: base, topright: M, bottomleft: MM, bottomright: MMM. White densities refer to the low and high F scenarios

Finally, as a check, we assessed the outcomes of the equilibrium curves from simulating over a wide F range, with the equilibrium values (points) in 2050 from the forward projections at different values of Fmsy (colours). The points fall on the equilibrium curve, thereby confirming the consistency between the two approaches.

Figure 23: Check of equilibrium curves against end points of simulated time series at F_{MSY}'s from all scenarios

6   Discussion and conclusions
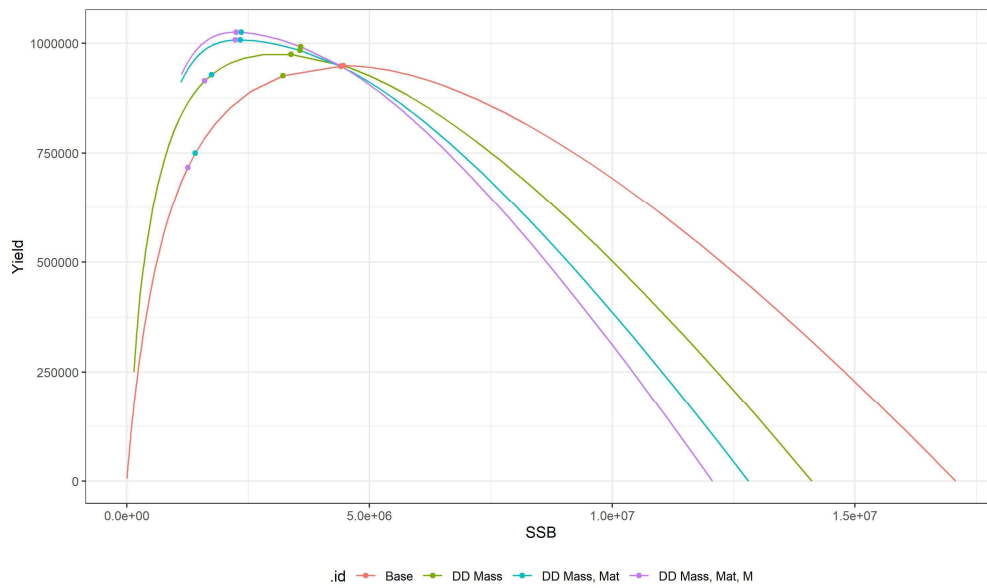
The current management of fish stocks is based on achieving a fishing mortality (F_{MSY}) that is expected to achieve the maximum sustainable yield (MSY). Estimation of MSY generally only includes the stock recruitment relationship when considering density dependent population regulation mechanisms. Density dependence, however, may also operate in processes such as growth, sexual maturity, and natural mortality. A main aim of this study was to condition Operating Models (OMs) on alternative hypotheses about density dependence for use in Management Strategy Evaluation (MSE). The objective is to evaluate the robustness of the assessments conducted to support the ICES advice framework. To do this, OMs were developed that include density dependence in growth, maturity, natural mortality, individually and combined. These OMs were then used to evaluate the consequences of including or not including density dependence in management advice.

Initial explorations of density dependent effect were conducted based on life history theory, as used by the International Council for the Exploration of the Sea (ICES) to develop advice conducting MSE for data poor stocks (Fischer, DeOliveira, and Kell 2020). **Figure 10** shows the equilibrium curves of catch v SSB assuming a) no density dependence, and density dependence in b) mass-at-age, c) mass & maturity-at-age, and d) mass, maturity and natural mortality-at-age. These allow the relationships between the MSY reference points and virgin biomass to be seen.

Estimating density-dependence from observations was not really possible for Blue whiting because there was no clear relationship between mass-at-age and total biomass. When a second GAMM model was fitted with weight in relation to total biomass, year and age, we found that the mass-at-age is better described by a year effect than a biomass effect. In order to still explore the impacts of density dependence on the performance of the MSE, we used the density dependent factor for Atlantic mackerel (beta=-0.18) to parameterize the weight-biomass relationship.

In the next step, we applied a natural mortality-at-age vector based on (Lorenzen 2000) which mimics the VPA assessment with fixed M-at-age. The figure below compares the SAM assessment with a Virtual Population Analysis (VPA) and a VPA with age varying M (VPAM). Trends and absolute levels were similar across all runs. The vpaM model was used as the base case to be compared against the density-dependent simulations.

Next, the Operating Models were constructed. This was done in a number of steps.

1. The ICES (SAM) assessment was taken from the ICES WGWIDE files (2022). SAM is a statistical catch-at-age model that estimates error in the catch-at-age. In the case of Blue whiting, the assessment gives a higher weight to the recruitment index than to the catch data for ages 0 and 1. This means that the estimates of recruitment in the assessment can be very different from the actual number of fish that are recruited to the fishery.

2. Next, VPA was conducted. This was done to ensure the MSE projections, which assumed variable M-at-age, and the historical estimates are comparable. The VPA was conducted on the whole catch matrix and the survivors in the most recent year and oldest age.

3. The third step was to convert the VPA model with fixed natural mortality at age and by year into an age-varying natural mortality vector. We applied a natural mortality-at-age vector derived from the Lorenzen approach (Lorenzen (2000)) which would mimic the VPA assessment with fixed M-at-age. This assessment was then treated as the base case against which the density dependent Operating Models were compared.

4. The density-dependent scenarios were constructed cumulative. First by adding density dependence in mass-at-age (M), then in mass and maturity-at-age (MM) and then in mass, maturity and M-at-age (MMM),

Therefore, the four Operating Models were:

*   Base Case, VPA with varying M-at-age

*   Density dependence in mass-at-age,

*   Density dependence in mass, maturity-at-age,

*   Density dependence in mass, maturity and M-at-age,

The MSY reference points B_{MSY} and F_{MSY} were calculated based on equilibrium assumptions, either from combining yield per recruit and spawner per recruit relationship (Sissenwine and Shepherd 1987) or by conducting long-term projections under constant fishing moralities. Both should agree and so can be used as a check.

Each of the four OMs were then projected for the values of F_{MSY} based on the four assumptions about density dependence. This allows a comparison between the yield that could potentially be achieved and that forgone by making an incorrect assumption about density dependence.

The OMs were first projected, without process error in recruitment, from the end of the historical estimates for a range of fishing mortality (spanning 0 to F_{crash}) for 30 years into the future. The estimates in the final year of the projections were then be used to construct equilibrium curves (**Figure 15**). The points on the curve correspond to the projected outcomes for the values of F_{MSY} from each OM. This was run as a check, as the equilibrium and projections should agree, I.e. the points at MSY should be the same colour as the curve.

The OMs were also projected for the four estimates of F_{MSY}, with stochasticty in the recruitment deviates. This allows the impact of misspecification of density dependence to be evaluated, i.e. if F_{MSY} is underestimated then yield will be less than MSY, while if F_{MSY} is overestimated yield will be lost due to overfishing. Stochastic projections of the four Operating Models for the four estimates of F_{MSY} are shown in **Figures 16-19**

Figure 20 summarizes the yields and SSBs obtained for each Operating Model under the correct and misspecified form of density dependence and the associated reference points, **Figure 21** shows the Kobe plots of the final 2050 distributions of biomass and yield and **Figure 22** the Kobe plots for F and yield. These are for the Base Case, then density-dependence in mass, mass and maturity, and mass, maturity and natural mortality, projected for the four estimates of F_{MSY}. The correctly specified F_{MSY} for each model is indicated by the red points and marginal densities.

The main differences are seen in SSB/B_{MSY}, if no density dependence is assumed then in the operating model the estimate of F_{MSY} is the lowest, therefore projecting for the higher estimates of F_{MSY} assuming density dependence results in an overfished stock. Yield are the same for the two values of F_{MSY} that assume no density-dependence on density dependence in mass-at-age only. In the other two cases yield is reduced by about 10%.

In the cases where density-dependence is assumed in the Operating Model, yields do not vary much, the main effect is seen in the estimates of SSB/B_{MSY},

The impact of including density dependence was primarily on the biological reference points. Especially F_{MSY} is much higher when including density dependence. However, the expected yields in equilibrium conditions are very similar. The main difference is in the initial step from the current F_{MSY} to any new F_{MSY} that would include DD, as the higher F_{MSY} would be applied to a stock that is estimated without DD.

Since the early 1980s, natural mortality (M) for Blue whiting has been fixed within the assessment model at 0.2, for all ages and all assessment years.Natural mortality must, however, vary both by age and over time due to changes in abundance of predators, feeding conditions, disease etc. (Siegfried and Sansó 2009). Particularly any changes in Blue whiting distribution and growth will affect natural mortality.

Given the uncertainty in the assessment and the estimation of density dependence, it is likely that the Pretty Good Yield approach would ensure sustainable exploitation. Also, because we did not yet consider stochastic variability in future developments in mass, maturity and natural mortality which are likely to obscure the impacts of density dependence. Variations in these processes due to changes in climate and range expansion are also likely to occur.

It is suggested that empirical harvest control rules that respond to changes in productivity could be evaluated in contrast to the highly complex harvest rules based on SAM stock assessment models.

The quality of this analyses lives up to the quality standards that are required by ICES and so can potentially be used when providing advice to fisheries managers. The software is publicly available via GitHub (https://github.com/martinpastoors/ddmse). All data is derived from WGWIDE 2022 ICES (2022b).

7   Funding

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