The evaluation of potential management procedures

For pikeperch, perch, bream and roach in IJssel-/Markermeer

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Wageningen Marine Research

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Summary (Dutch)

Het ministerie van LNV is verantwoordelijk voor het beheer van de visserij op snoekbaars, baars, blankvoorn en brasem op het IJsselmeer en Markermeer. Het ministerie heeft WMR gevraagd om oogstregels ('management procedures') op te stellen; hiermee dient de visserij de komende jaren op een zodanige manier beheerd te worden, dat de bestanden en visserij zich ontwikkelen naar een gewenste toekomstsituatie ('beleidsdoel'). WMR heeft oogstregels ontwikkeld middels een beheerstrategieëvaluatie (*Management Strategy Evaluation*, MSE) voor elk bestand. Dit rapport beschrijft de MSE's voor de vier bovengenoemde soorten. Deze samenvatting geeft de belangrijkste informatie die nodig is om de resultaten in hoofdstuk 6 te kunnen interpreteren.

Beleidsdoel

Het ministerie heeft beleidsdoelen opgesteld, die gehaald dienen te zijn in 2035-2040:

- (i) de visserijdruk ('F') op en de omvang ('B') van een visbestand voldoen aan het MSY-principe; de hoogst mogelijke visserijopbrengst die duurzaam gehaald kan worden ('maximum sustainable yield', MSY)
- (ii) het bestand voldoet aan het voorzorgsprincipe; de hoeveelheid volwassen vis blijft met grote kans boven de minimale omvang die nodig is voor een stabiel bestand dat voldoende nakomelingen produceert om zichzelf te vervangen ('B_{lim}')
- (iii) er is meer grote vis in het bestand (vanuit de KRW-wetgeving) en
- (iv) er is voldoende vis, van het juiste formaat, beschikbaar als voedsel voor de streefaantallen vogels (vanuit de N2000-wetgeving).

Om deze beleidsdoelen te helpen halen, heeft het ministerie WMR gevraagd om oogstregels op te stellen. Dit zijn rekenregels waarmee jaarlijks de maximale toegestane vangst voor het aankomende seizoen kan worden vastgesteld. Als deze maximale toegestane vangst jaarlijks wordt aangehouden in de visserij, dan zal met grote zekerheid in ieder geval aan het MSY-principe voldaan worden in 2035-2040. WMR ontwikkelt meerdere oogstregels per soort, die allemaal iets anders uitwerken op het mozaïek van beleidsdoelen. Het ministerie kan vervolgens besluiten welke oogstregel het beste past bij haar wensen.

Het ministerie heeft hierbij gevraagd om oogstregels waarbij, na het eerste jaar van implementatie, de maximaal toegestane vangsten van jaar op jaar niet meer dan 20% kunnen veranderen: alleen in het eerste jaar zijn dus grotere veranderingen toegestaan.

Beheerstrategieëvaluatie

Om oogstregels te ontwikkelen en te testen wordt een virtuele vispopulatie ('operating model') gecreëerd, die zo goed mogelijk de daadwerkelijke vispopulatie nabootst. Het model wordt gevoed met tijdseries van de commerciële aanlandingen en surveyvangsten, en met informatie over de biologie en ecologie van het bestand. De virtuele vispopulatie loopt vanuit het verleden de toekomst in. Onze kennis van het daadwerkelijke verleden is niet perfect en dat van de toekomst uiteraard nog minder. Daarom wordt er met deze onzekerheid rekening gehouden: De virtuele vispopulatie bestaat in feite uit 500 varianten, allemaal met een net andere invulling van de gaten in onze kennis.

Deze virtuele vispopulatie is een manier om de relatieve uitwerking van de verschillende oogstregels te kunnen testen; de toekomstige visserij wordt namelijk beheerd via de oogstregel. Elk toekomstig jaar wordt de oogstregel toegepast en houdt de visserij zich aan de maximaal toegestane vangst die volgt uit deze oogstregel. Vervolgens reageert het virtuele bestand hierop en herhaalt de cyclus zich. Door verschillende oogstregels te testen in de virtuele wereld, kan het effect vergeleken worden: welke oogstregel leidt tot de beste resultaten voor elk van de opgestelde beleidsdoelen?

Oogstregel
In een oogstregel wordt informatie over de recente situatie van het bestand gestopt en er volgt de maximale toegestane vangst voor het komende seizoen uit.

Voor alle bestanden worden twee typen oogstregels onderzocht;
- **CPUE**: gebaseerd op de trend in de surveyvangsten van de laatste vijf jaar.
- **CHR**: gebaseerd op de gemiddelde surveyvangsten van de laatste drie jaar en de commerciële vangsten van het afgelopen seizoen.

De oogstregel wordt gericht ('ingeregeld') op het behalen van één bepaald beleidsdoel in 2035-2040, namelijk
- **_F**: een visserijdruk die gemiddeld in de MSY-situatie terecht komt, of
- **_B**: een bestandsomvang die gemiddeld in de MSY-situatie terecht komt, of
- **_both**: beide. Idealiter passen zowel de visserijdruk als de bestandsomvang bij de MSY-situatie.

Samen geeft dit zes mogelijke oogstregels die onderling vergeleken worden: CPUE_F, CPUE_B, CPUE_both, CHR_F, CHR_B en CHR_both.

Uitwerking oogstregel op beleidsdoelen
Nadat de oogstregel is ingeregeld, wordt gekeken hoe deze uitwerkt op alle beleidsdoelen in 2035-2040.
- **F/F_{MSY}**: Komt de visserijdruk[1] gemiddeld in de MSY-toestand terecht?
- **B/B_{MSY}**: Komt de bestandsomvang gemiddeld in de MSY-toestand terecht?
- **B/B_{lim}**: Hoe groot is de kans dat de bestandsomvang onder het minimum (B_{lim}) terecht komt? Het ministerie heeft als doel/voorzorgsprincipe dat deze kans maximaal 10% is in de virtuele wereld.
- **BWML**: neemt de (biomassa-gewogen) gemiddelde lengte toe (ten opzichte van nu)?
- **Bird food**: is er voldoende vis van de juiste lengte beschikbaar voor de streefaantallen van beschermde vogels? Dit wordt vergeleken met een referentiejaar, waarin de streefaantallen vogels wel gehaald werden.
- **Mean Catch**: hoe hoog zijn de vangsten van de beroepsvisserij gemiddeld?

De uitwerking van de oogstregels op de beleidsdoelen is te zien in hoofdstuk 6 in figuren[2] 6-1 (snoekbaars), 6-5 (baars), 6-8 (blankvoorn) en 6-11 (brasem). Idealiter valt voor zowel F/F_{MSY} en B/B_{MSY} de dikke, horizontale zwarte lijn op de groene stippellijn, terwijl voor B/B_{lim} de hele boxplot bóven de rode stippellijn eindigt. In de overige figuren in hoofdstuk 6 zijn de ontwikkelingen door de jaren heen getoond, in de bestandsomvang en in de vangsten van de beroepsvisserij.

De inschatting is dat momenteel de bestandsomvang van brasem en blankvoorn kleiner is dan nodig voor de MSY-toestand (B/B_{MSY}), maar dat de bestandsomvang van snoekbaars en baars wel voldoet aan de MSY-toestand. Voor alle bestanden zijn er oogstregels die in 2035-2040 voldoen aan het voorzorgsprincipe zoals gekwantificeerd door het ministerie; de kans dat de bestandsomvang onder het minimum ($B<B_{lim}$) terechtkomt is bij deze oogstregels hooguit 10%. Bij brasem voldoen bijvoorbeeld alle oogstregels in 2035-2040 aan het voorzorgsprincipe. Bij baars voldoet de helft, namelijk alleen de CPUE oogstregels en voor dit bestand wordt aangeraden een van de CPUE oogstregels te gebruiken. Ook de uitwerking op de andere beleidsdoelen verschilt tussen de oogstregels. Zo leiden sommige oogstregels tot een sterkere daling in vangsten in het eerste jaar maar ook tot een sneller herstel van de bestandsomvang en/of hogere vangsten in 2035-2040. Alleen bij brasem leiden de oogstregels tot beduidende veranderingen in ecologische beleidsdoelen; BWML en voedsel voor vogels. Voor elk bestand zal de keuze gemaakt moeten worden welke van de zes oogstregels het beste de beoogde beleidsdoelen van de overheid realiseert.

[1] De onttrekking van vis door zowel de beroepsvisserij als de vogels valt hieronder. De predatie door vogels is als een vorm van visserij gemodelleerd. Vogelpredatie speelt met name bij baars een beduidende rol.
[2] Voor een uitleg van hoe de variatie in de figuren is samengevat, zie figuur 1-2 op pagina 11.

1 Introduction

This report focuses on the fisheries on four stocks in the lakes IJsselmeer and Markermeer: pikeperch (*Sander lucioperca*), perch (*Perca fluviatilis*), roach (*Rutilus rutilus*) and bream (*Abramis brama*). The sustainable management of these stocks falls under the responsibility of the Ministry of Agriculture, Nature, and Food Quality (Ministerie van Landbouw, Natuur en Voedselkwaliteit), as described in the Visserijwet 1963 (Fisheries Act 1963). The predominant fisheries targeting these stocks are gillnet and seine fisheries[3]. All four stocks have shown strong declines in size, with low points in stock size around 2012 (Tien et al. 2018). As of 2013, the ministry has made a concerted effort to develop more sustainable fisheries within the lake complex.

From 2024/2025 onwards, the ministry intends to take the next step towards sustainability, while also maximizing economic benefit; reaching fisheries with the highest possible yield over the long term (termed maximum sustainable yield), within a precautionary approach, in the period 2035-2040.

1.1 Current management

The season for the gillnet fisheries is from July 1st to March 15th[4] and the minimal mesh size is 101 mm. Gillnets are regulated with 'merkjes', with one *merkje* applying to 100 meters of net. There are roughly 3900 merkjes in circulation for the fisheries on pikeperch, perch, bream and roach in these lakes. Merkjes are coupled to a license and linked to a specific ship. The seine fishery operates in the winter/early spring, with the season running from November 1st to March 15th. Seines in this fishery are limited to a maximum length of 600 meters and are currently spread between 18 licenses within the IJssel/Markermeer complex. Licenses for both types of fisheries can be rented or sold among fishermen.

Two periods of major changes in the management of the four stocks have taken place:

1. In season 2014/2015 the management of both seine and gillnet fisheries was changed[5]. All management decisions were driven by the objective of halting the decline in the stocks. All four stocks are reported to have stopped declining since these changes (Volwater et al. 2023). The changes in management consisted of the following:
   (a) gillnet fisheries were limited to 15% (~ 640 *merkjes*) of the available effort in *merkjes* per license,
   (b) seine fisheries on the open water were limited to 7 days per year per license and tying seine nets together was prohibited,
   (c) seine fisheries in the harbours was prohibited and
   (d) fishing with large passive fishing gear (fykes) with *ruif* on roach in the closed season (for eel fisheries[6]) was prohibited.

2. As of 2021/2022, the ministry has further reduced the number of seine days per license, from 7 to 2 per season[7] with the underlying goal of providing the minimum level of stock protection for the bream stock by 2027, following a 'precautionary approach'. This management approach was deemed to be an essential precondition for sustainable fisheries (see **Box 1** for an explanation and technical translation of the precautionary approach and maximum sustainable yield).

[3] Discards in the fyke fisheries can also be an important factor of stock extraction (Tien et al., 2022).
[4] And for so-called seasonal licenses from October 1st to March 15th
[5] Based on catch and effort advice in Tien et al. 2013a&b
[6] Closed eel season is September 1st to November 30th
[7] Based on the management strategy evaluation in in Tien et al. 2020a&b

1.2 Question to Wageningen Marine Research

The ministry of LNV has asked Wageningen Marine Research to develop Management Procedures (MP) within a Management Strategy Evaluation (MSE) for each of the four stocks. With these MPs, the following three goals should be met for each stock in 2035-2040:

1. Maximum sustainable yields (MSY) for the commercial fisheries on each individual stock, within the precautionary approach for fisheries management.
2. Increased proportion of large fish in each stock, as required by the *Kaderrichtlijn Water*
3. Provision of food reserves to support bird populations, as described in the Natura2000 goals.

Box 1: Fisheries Management Terminology

Maximum sustainable yield (MSY)
This core principle in fisheries sciences aims to achieve the maximum catch that can be sustainably harvested from a stock annually over an indefinite period. MSY can be linked to a relative fishing pressure (F) on the stock. F_{MSY} denotes the fishing mortality needed to maintain MSY. This principle also serves as a reference point for spawning stock biomass (SSB) with B_{MSY} representing the SSB required to sustain MSY. It is important to note that MSY is not directly linked to a specific stock size indefinitely, as the stock size fluctuates naturally, for example due to yearly variation in recruitment strength.

Precautionary approach
This principle is aimed at avoiding an undesired outcome: the chance for harming the stock through recruitment impairment should be low. Recruitment impairment refers to a spawning stock size that is so low that it cannot produce enough offspring to replace the spawning stock. The aim of the precautionary approach is to keep the stock size above the limit reference point for recruitment impairment, namely above B_{lim} (Biomass limit reference point). B_{lim} is defined as 10% of 'virgin biomass', which is the biomass of a fish population before any significant fishing activities have occurred. Virgin biomass is estimated using a combination of historical data, biomass proxies and population models. In this analysis, virgin biomass is sometimes used interchangeably with carrying capacity (K).

F_{MSY} , B_{MSY} and B_{lim} in an MSE: management choice
An MSE is a quantified risk assessment, in which 500 virtual stocks are grouped together to represent the uncertainty of our knowledge of the stock and it's future. Within this uncertainty range, the precautionary approach is translated into a maximal proportion (also called risk) of the virtual stocks that in the future may fall below B_{lim}. In order to protect the stock, this proportion should be low. In this case, the manager wants a management procedure (MP) with which at most 10% of the virtual stocks fall below B_{lim} in 2035-2040. The MSY principle is directly incorporated into the MPs by targeting a 50% probability for the virtual stocks to experience fishing pressure at or below F_{MSY}, maintain an SSB level equal to or above B_{MSY}, or combining these objectives in the period 2035-2040. For additional details regarding these tuning objectives, please refer to section 1.3.3 in this chapter and 5.3.2 in chapter 5.

1.3 Approach

1.3.1 Management Procedure (MP)

Management procedures (MP) serve as fisheries management tools and are employed annually, to determine the total allowable catch (TAC) in the upcoming fishing season. The underlying question in each MP is: Given the present stock status, what quantity can fisheries harvest while still achieving the management goals in 2035-2040?

MPs are mathematical rules or algorithms and can vary from very simple formulas to extensive stock assessment models and are based on current developments in the stock. For example, a simple MP outcome could be: if the survey trend decreases with 10% over the last three years, then the TAC also decreases by 10%. MP's can be based on a trait in the stock (e.g. survey trends), a trait in the fishery (e.g. length distribution of the commercial catch), or a combination of stock and fishery traits. There are many types of MPs to choose from. Which one is suitable depends on the quantity and quality of the available data, the biology, the fishery and the management objectives. Here, two types of MPs have been evaluated (chapter 5), named 'CHR' (constant harvest rate) and 'CPUE' (catch per unit effort).

1.3.2 Operating Model (OM)

Modelling the past
To evaluate and compare the suitability of MPs, they are tested in a 'virtual world' called the operating model (OM; Figure 1-1). The history of the stock and fisheries are simulated as closely as possible, based on historical data from commercial and survey catches, and on biological knowledge of the ecosystem and the species. Empirical data are used as much as possible (versus modelled data or assumptions), using timeseries reflecting traits of the stock and the fisheries.

Modelling the future
Subsequently, the future development ('projections') of this virtual stock is computed under different scenarios. In these projections, the effect of each MP is tested, which gives the TAC for the upcoming fishing season by applying the MP to the virtual stock on an annual basis. This TAC then limits the total catch in that following season and the stock responds accordingly – after which, the cycle is repeated. Subsequently the effect of using this MP is quantified for the target period (2035-2040; also referred to as 'tuned period' in this report), using "performance statistics" which are linked to specific management goals (see chapter 1.2 and 5.3).

Taking uncertainty into account
This method of evaluating MPs is called a *Management Strategy Evaluation* (MSE) and is the international standard in fisheries advice. The goal is to identify a management strategy while taking into account the inherent natural variation in a stock and the uncertainty in one's knowledge of an ecosystem, resulting in a form of 'quantitative comparative risk assessment'. In an MSE, 'true' historical data are used, together with information and assumptions on the biology and ecology of the stock. This information is used to create 500 'potential' virtual stock scenarios, each with their own plausible population dynamics, biological traits, historical stock developments and present-day status. Creating this diversity of potential stock scenarios is how the uncertainty in our perception of the stock is taken into account and quantified. Subsequently, every potential virtual stock is projected into the future. In these projections uncertainty in various processes (for example recruitment) is introduced to provide appropriate variation of future outcomes. The rationale behind this methodology is that (1) we do not know the absolute truth about the current situation, and (2) it is impossible to accurately forecast future conditions. However, it is possible evaluate the ability of MPs to achieve the management goals in a robust manner by encompassing the various uncertainties. In order to create MPs that will fulfil the management goals while providing sufficient protection for the stocks, it is essential to take into account all identified uncertainties.

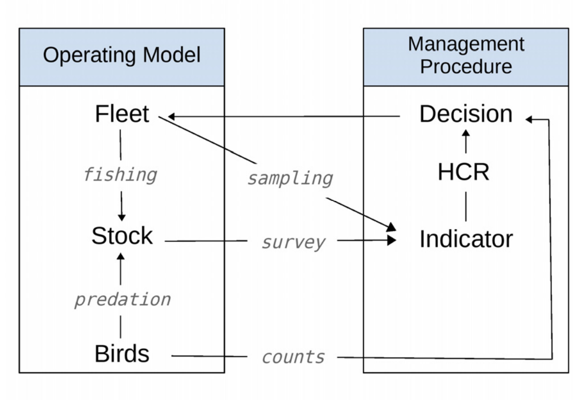

Figure 1-1 *Schematic representation of the simulation model constructed for the MSE analysis of candidate management procedures for the IJsselmeer stocks.*

How to read uncertainty in graphs

In presenting both the results for the OM (chapter 4) and MP (chapter 6), the uncertainty (i.e., the 500 stock trajectories) is plotted. In order to guide the reader through the plots within this report, an example is given in Figure 1-2 for both a boxplot and a timeseries, together with an explanation.

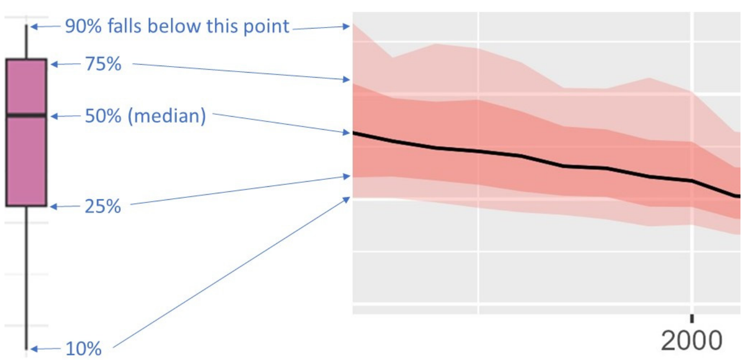

Figure 1-2 *Explanation of how to read boxplots (left) and timeseries (right). The central thick line shows the median; 50% of trajectories fall below this value; this is called the 0.50 quantile. The 0.90, 0.75, 0.25 and 0.10 quantile are also shown in both boxplots and time series.*

The box plots in this report are presented in chapter 6 to display the projected outcomes for various performance statistics during the 2035-2040 tuning period. Further explanation of this aspect is available in chapter 5 (section 5.3.1).

1.3.3 Management decisions

The management goals as defined in section 1.2 are translated into the following management objectives that should be reached in 2035-2040:

1. Exploit the stocks at MSY, both in terms of fishing mortality (F_{MSY}) and spawning stock size (B_{MSY})
2. Keep the risk of recruitment impairment ($B< B_{lim}$) low, to ensure a precautionary approach to the management.
3. Ensure the availability of enough fish of the suitable size range, as estimated necessary for the survival of target numbers of birds as defined by Natura2000.
4. Increase the mean length in the population, as measured through the relevant KRW indicator[8].

The performance of each MP with regard to achieving these objectives in 2035-2040 will be examined and compared. Importantly, the candidate MPs are tuned to achieve one primary management objective with a given probability. One of three objectives is chosen for tuning the MP, related respectively to a sustainable level of exploitation (F_{MSY}), sustainable stock biomass level (B_{MSY}), or both combined:

- To achieve, on average over the 2035-2040 period, a 50% probability of the stock being exploited at or below the fishing mortality associated with MSY (F_{MSY})
- To achieve, on average over the 2035-2040 period, a 50% probability of the spawning stock biomass being exploited at or above the level associated with MSY (B_{MSY})
- To achieve both the previous objectives over the same time frame and with a 50% probability[9].

The other management decisions incorporated in the MSEs are:

- Precautionary measure: To ensure the precautionary approach, any MP needs to achieve *at most* a 10% probability of $B<B_{lim}$ to prevent depletion of the stock population.
- TAC stability measure: After the first year of MP implementation, a TAC stabilizer will be used, in which a maximum TAC change of 20% is allowed, compared to the previous TAC (upwards and downwards).

8 The biomass-weighted mean length, BWML

9 This is often referred to as the Kobe green strategy.

2 Data sources and information

Data used in OMs for fisheries in the IJssel/Markermeer complex have been routinely collected. Biological characteristics, such as growth, maturity, and other aspects, are obtained from samples from the open water survey and market sampling programs. The primary sources of information for the analysis consist of the fisheries catches and changes in abundance inferred from the catch per unit effort (CPUE) index from the survey.

2.1 Fleet catch data

Figure 2-1 presents annual landing estimates for all four stock – bream, perch, pikeperch, and roach – spanning the period 1992-2022. The time series were constructed by harmonizing different data sources: logbooks, ‘Coöperatieve Producentenorganisatie Nederlandse Vissersbond - IJsselmeer U.A.’ (PO) and Productschap Vis (PVIS). For a detailed explanation of the data raising, see Appendix 1 (Fisheries data/Total Catch). For bream and roach, a portion of the landings from the seine fishery were sold outside of the auction and went unregistered in the official records, resulting in unaccounted catches in the earlier years of the dataset. This led to a large uncertainty in the magnitude of the landings in the earlier part of the time series for these two stocks. Insights shared by certain fishermen were used to form estimates of the bream catches which bypassed the auction, resulting in an alternative time series of historical landings. For roach, no such information could be found and only the catch information from 2008 onwards was used in the analysis, due to uncertainty regarding catches in the years prior (although the full range of data is presented in Figure 2-1).

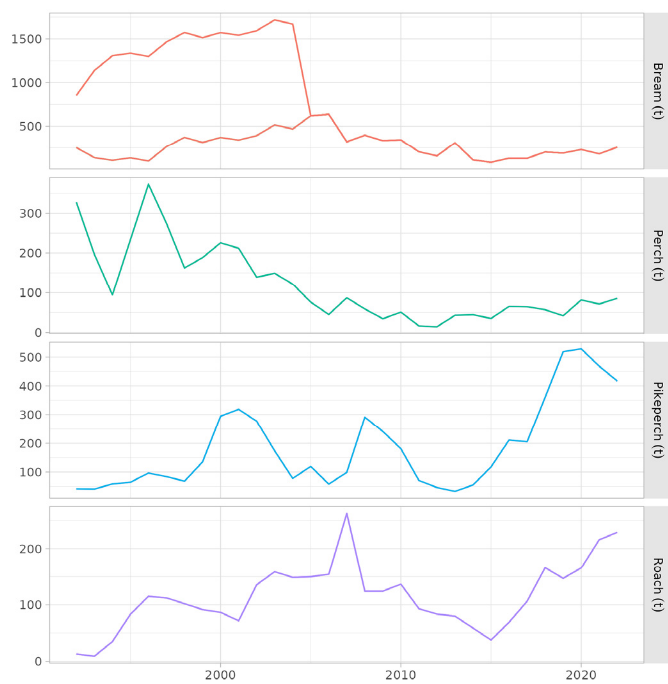

Figure 2-1 *Annual estimates of commercial catches by the IJsselmeer fisheries in tonnes (t). Note that for bream, both minimum (bottom line in top panel) and maximum (top line) estimates are provided for the period 1992-2005. Landings are aggregated per fishery season (April-March, where year on the x-as refers to the year of April-December).*

2.2 Bird catch estimates

Fish intake across the entire avian population in the IJsselmeer and Markermeer serves as an important source of mortality for the fish populations present in the lake complex. Based on the annual avian colonies census, the bird population estimates were combined with 1) calculations on the range of individual lengths of each fish species that the birds were able to ingest, 2) the energetic needs of adult and chicks per year, and 3) the trends in abundance of the suitable fish ages. This resulted in a comprehensive estimate of fish consumption by the IJsselmeer bird community (Appendix 2). These estimates provide an approximate measure of the fish biomass in the selected length and age range that the bird population could be expected to require to sustain its current population levels.

This data source covers the 1992-2020 period (Figure 2-2). At the time of the current study, the 2021 and 2022 bird count data were not available and the average 'bird catches' from 2018-2020 were thus used. The OM's assumed that bird catches for pikeperch, roach and bream remained stable into the future with the mean 2018-2020 estimates carried forward into the projections. For perch, a strong link was found between the strength of recruitment and bird predation on the stock (Tien et al. 2020a), warranting specific calculations to account for this relationship. Historical bird catches for perch were estimated as higher than by human fisheries and were assumed to be linked to the strength of recruitment, as indicated by the abundance of age-0 fish in the survey. A decision was made to consider future perch consumption by the bird population to be determined by the strength of perch recruitment (instead of using the 2018-2020 average as seen in the other stocks).

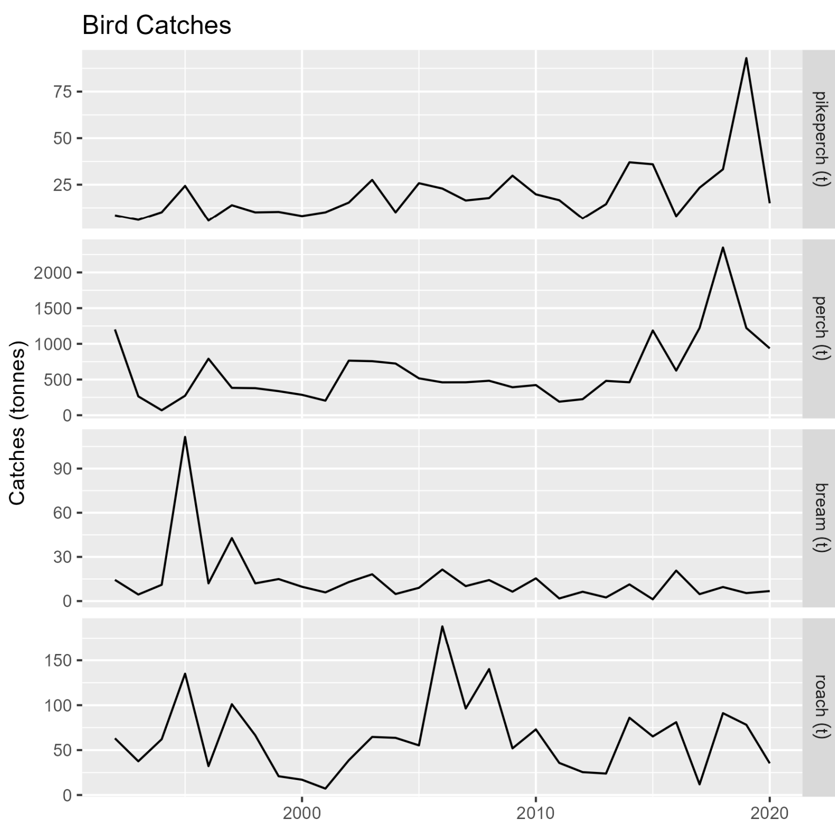

Figure 2-2 *Annual catch estimates (tonnes) by the IJsselmeer/Markermeer bird populations from 1992 to 2020. Due to missing input data in 2021-2022, these years were given the average catch value for the bird populations observed in 2018-2020.*

2.3 Survey

An annual trawl survey in the IJssel/Markermeer provides a fishery-independent perspective of population dynamics by age (Volwater et al. 2023). From this information, stock biomass estimates can be computed (***Figure* 3-2**). Trends in the stock biomass sampled by the survey were used to condition the OM through an age structure provided by the assumed selectivity across ages for the survey (see chapter 3.1.1.1). The trends in survey biomass were used in one of two ways in the OMs, depending on the stock: 1) filtering the selected OM trajectories (pikeperch and perch) and 2) providing the key driver for historical projections (bream and roach, see chapter 4 for details).

In the historical component of each OM, the annual recruitment level is determined by three factors: (i) the projected amount of spawning fish in that year, (ii) the estimated number of recruits per spawning fish (stock-recruit relationship; section 3.1) and (iii) the abundance of age-0 fish in the survey, which served as a proxy for recruitment strength[10] in that year. Changes in abundance of age-0 fish were used to generate a series of recruitment deviates for the stock-recruits relationship in each OM run. The strength of those deviances was considered uncertain and weighted through a prior distribution.

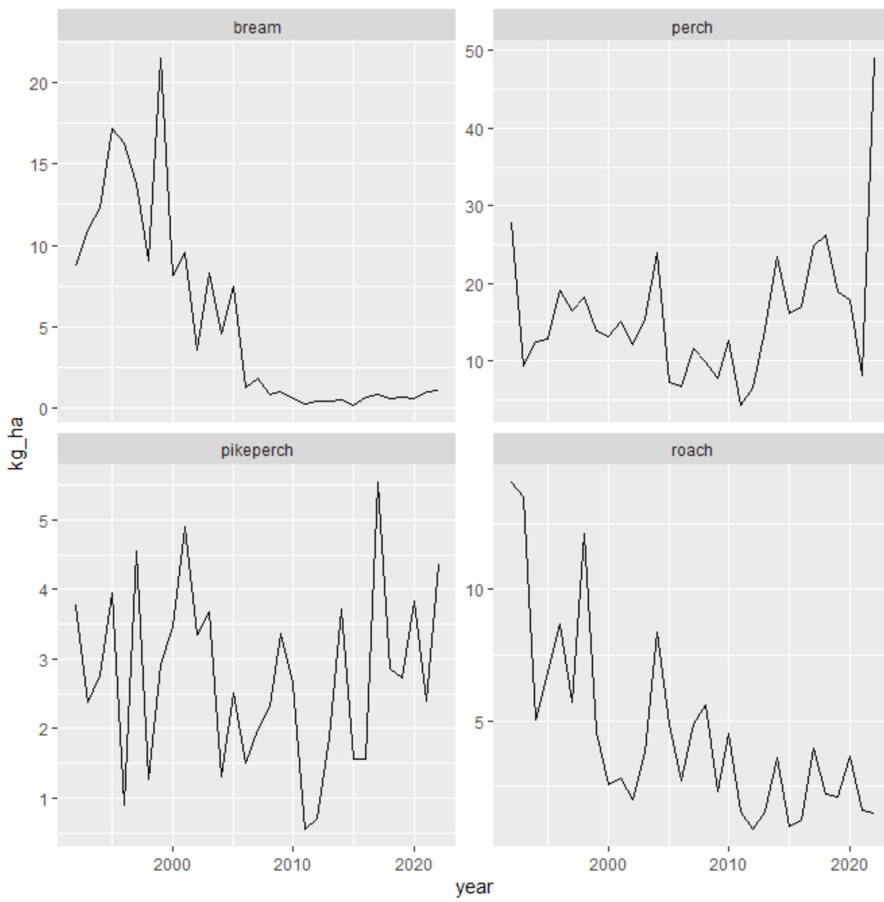

Figure 2-3 *Annual survey biomass indices (kilograms per hectare) for each stock from 1992 to 2020, caught in the beam trawl survey.*

[10] The number of new recruits depends on more than the number of adult fish alone. Many ecological and abiotic factors can also play a role. By taking the amount of age-0 fish in the survey into account, this 'recruitment strength' is accounted for.

2.4 Biology

2.4.1 Growth

Within the OMs for each stock, the lengths for each age group must be estimated. This is achieved by fitting von Bertalanffy curves with length-at-age data from the survey for each species (Figure 2-4). Age observations obtained from the survey are length-stratified, with a target of 20 individuals for each 1 cm length bin. Growth models were fitted for the four stocks using weighted nonlinear least squares, with weights being defined by the number of fish caught in the survey in each length bin. A single model was fitted for the whole time series, as the number of samples precluded estimating changes in time in growth. Model fitting was carried out using the models and algorithms available in the FSA R package (Ogle et al. 2022).

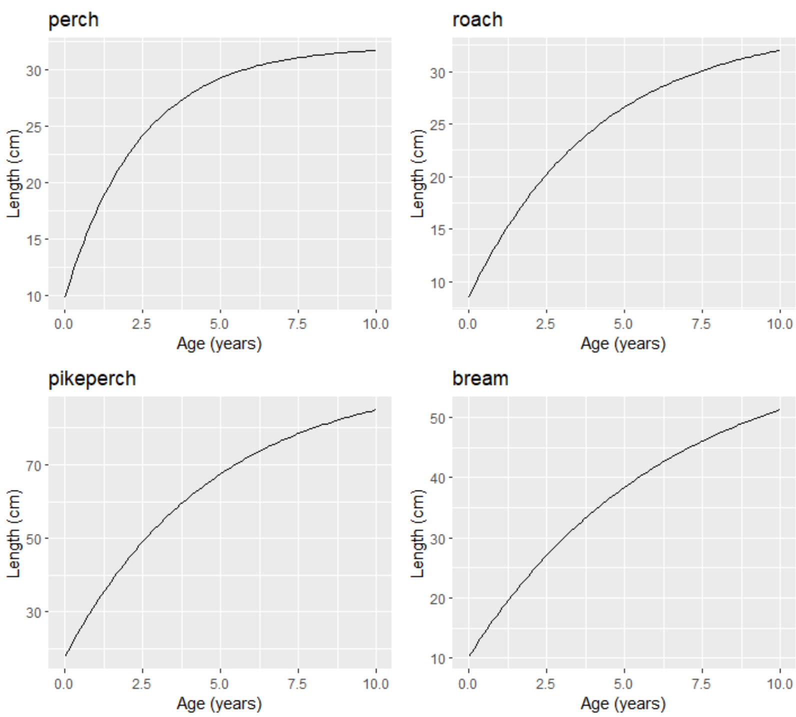

Figure 2-4 *Estimated von Bertalanffy growth curves per stock.*

2.4.2 Maturity, weight at age, natural mortality

Figure 2-5 presents an overview of proportions of mature fish-at-age, weight-at-age and natural mortality-at-age used in the OMs. Bream has the longest period needed to reach maturity while pikeperch displays the highest mean weight-at-age. Natural mortality is assumed to be highest for bream from age 0-1 followed by a decline as the fish mature. All stocks were assumed to show a constant rate of natural mortality by age 3 (Figure 2-5). Appendix 1 provides more information on how this data was derived.

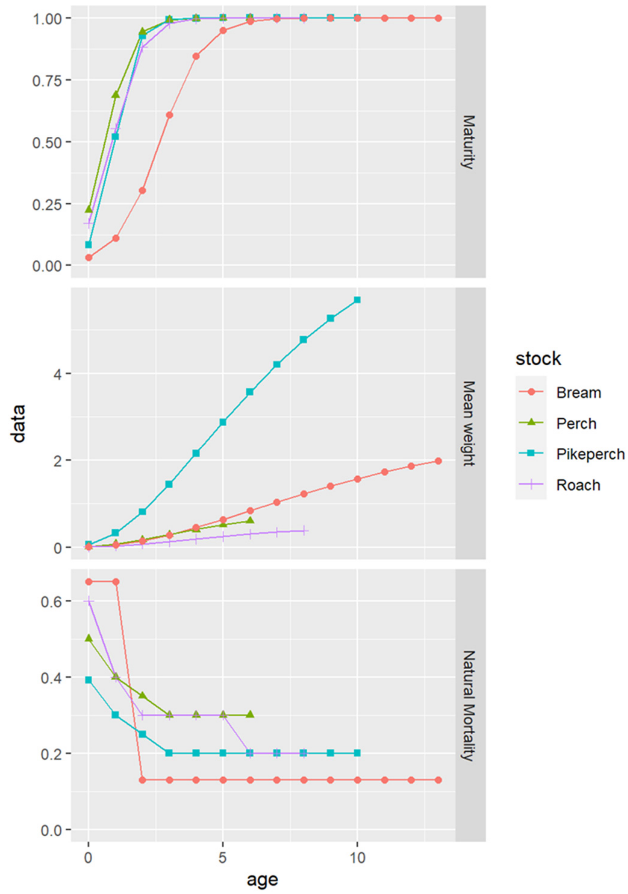

Figure 2-5 *Maturity, weight and natural mortality-at-age used for the OMs for the four stocks assessed in this MSE.*

3 Methods: Operating Models

The operating models (OMs) are the foundation for constructing a simulated environment (Figure 3-1). They create a type of 'virtual stock' with a range of outcomes ('trajectories') based on initial priors on stock characteristics. The model is 'conditioned' with real data by calibrating the parameters of the model based on historical observations such as fisheries catches, or biomass indices taken from surveys. The generated stock trajectories are then filtered with a specific set of selection criteria to ensure realistic and reasonable dynamics. The resulting OM can then be used carry out simulations to test how management procedures (MPs) can affect the future stock dynamics.

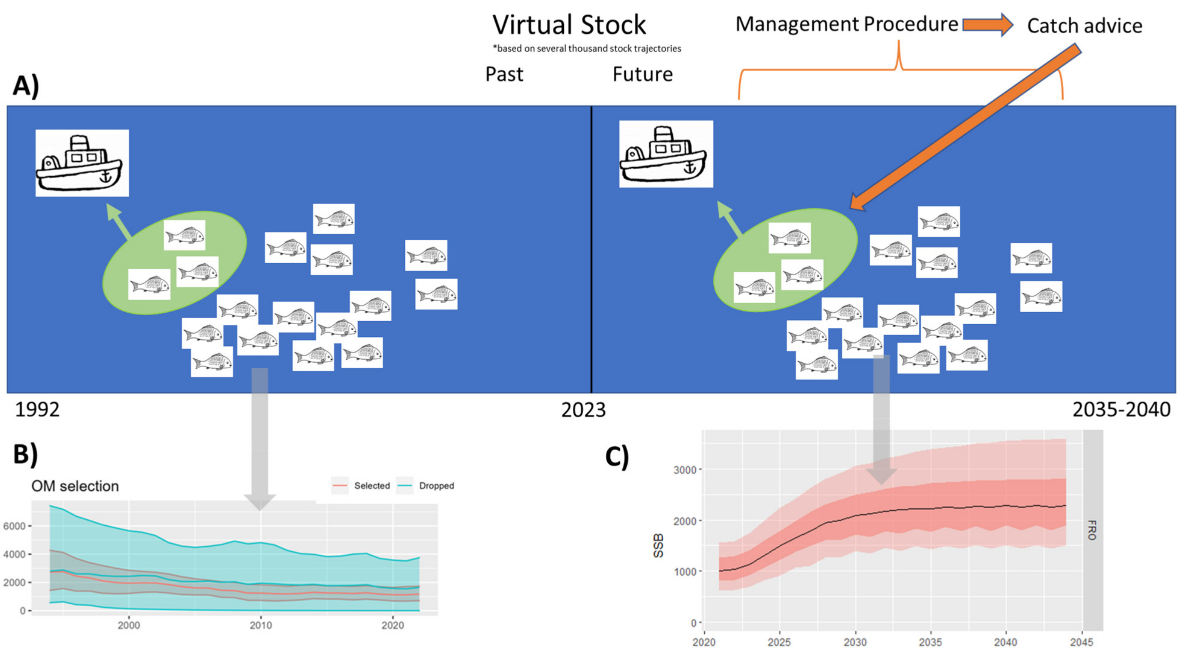

Figure 3-1 (A): *Illustration of historical and future projections generated by the OM. (B): The wide range of possible historical stock trajectories (blue) and selected trajectories (red) from the OM. (C): An example of the range of possible future trajectories with the estimated spawning stock biomass in (SSB), based on projections in which the stock is managed through one of the MPs.*

3.1 The Operating Models

The operating models are age-structured, with recruitment determined by the spawning stock biomass (known as both SSB and B). Population abundances at the start of the time series are at an unknown level of depletion (dep) over their carrying capacity (K) – which is assumed equal to the potential unfished spawning biomass (B0). Abundance-at-age for a given year is given by:

$$N_{a,y} = \begin{cases} \frac{4sR_0B_y}{(B_0(1-s)+B_y)(5B_0-1)} e^{\epsilon_y - \sigma_R^2/2} & \text{if } a = 0 \\ N_{y-1,a-1} e^{-Z_{y-1,a-1}} & \text{if } 1 \leq a \leq x \\ N_{y-1,x-1} e^{-Z_{y-1,x-1}} & \text{if } 1a = x \end{cases}$$

where R_0 is the expected recruitment at virgin biomass levels, B_y is the spawning biomass in year y, s is the steepness of the stock-recruit relationship, B_0 is the unfished spawning biomass, and ϵ_y is the recruitment deviance for year y, $N_{a,y}$ is the number of fish of age a at the start of year y. $Z_{a,y}$ is the total mortality of individuals of age a during year y:

$$Z_{a,y} = M_{a,y} + F_{a,y}$$

$M_{a,y}$and $F_{a,y}$ are the instantaneous rates of natural and fishing mortality at age a and in year y, respectively. Total F is determined by the partial fishing mortalities imposed by individual fisheries:

$$F_{a,y} = \sum_{f=1}^{f=F} E_{f,y}\, S_{f,a,y} \alpha_f B_y^{\beta_f}$$

where $E_{f,y}$ is the effort of fishery f in years y, $S_{a,y}$ is the selectivity of fishery f on age a, B_y is the total biomass in the middle of the period of activity of fishery f, and α and β are the cachability coefficients for fishery f.

Recruitment is predicted through a Beverton and Holt relationship (Methot et al, 2011). Deviances derived from age-0 abundances in the survey are subsequently incorporated to introduce variability to the recruitment estimation.

Catch at age by year (C) is computed as follows:

$$C_{a,y,f} = \frac{F_{a,y,f}}{Z_{a,y,f}} N_{a,y}(1 - e^{-Za,y,f})$$

The yearly time step used in the model refers in fact to the April to March period that matches the timing of the fishery and the implementation of management regulations.

Additionally, an observation error model (OEM) is developed to account for uncertainty in the data (see section 3.1.3). It is used to estimate the accuracy and give indications of uncertainty in both the historical and future projections.

Table 3-1 provides a summary of stock-specific input data used in the OMs.

***Table 3-1** Information on age structure, year span of historical data used, and stock specific information for the IJssel/Markermeer stocks assessed in this MSE.*

Stock	Age Structure *(highest age = plus group)*	Year span	Stock specific information
Pikeperch	0 – 10	1992 – 2022	Intraspecific predation occurs in this species which is accounted for in the OM.
Perch	0 – 9	1992 – 2022	Bird catches are larger for this stock than fisheries catches. Future birds catches of perch are predicted based on future recruitment, based on a relationship established from the historical part of the OM.
Bream	0 – 13	1992 – 2022	High uncertainty in catches between 1992-2005. OM is filtered by upper and lower catch estimates during this period.
Roach	0 – 8	1994 – 2022	High uncertainty in catches between 1992-2008. Fisheries catches from before 2008 not used in OM. High values from the survey data from 1992-1993 were omitted to assist the model in reconciling catch and survey data.

3.1.1 Conditioning

The process by which an operating model makes use of the available data, combined with the chosen priors and assumptions, is termed ‘conditioning’. This approach aims to ensure that the model can effectively explain past observations to provide confidence in future projections. To achieve this, we combined prior distributions for the main population parameters with a set of selection criteria that compare the generated dynamics with observed data. This selection of model trajectories filters unrealistic model outcomes.

The *feasible trajectories* estimator presented by Bentley and Langley (2012) is suited for the construction of the OM’s used in this MSE. This method can be implemented with relative efficiency using the FLR toolset (Kell et al., 2007) while incorporating information with varying levels of complexity and knowledge. The method generates a pool of possible population trajectories by combining priors for population parameters (carrying capacity, initial depletion, and stock-recruit steepness) with the state variables (biomass and population structure) derived from those priors. A hindcast projection is conducted using one or more data sources which reflect changes in the historical population dynamics across the available data collection period. For the IJsselmeer stocks, these primary data sources are: 1) the SSB trends computed from survey, and 2) the total catch series computed from landing data and other supplementary information (i.e. alternative high catch estimates and bird catches). The decision to use a particular data source to infer feasible trajectories for each stock was made based on its capacity to represent historical population dynamics.

A set of MSY and depletion reference points is calculated within each OM using the combination of prior values for carrying capacity/virgin biomass (B_0) and stock-recruitment steepness (h), and the fitted fishery selectivities. A wide set of possible stock trajectories (simulated population dynamics in the historical period) is narrowed down through a stock specific process of selection based on feasibility criteria (Section 3.2.2). The values for variables in the stock trajectories are compared with likelihood functions that reflect how feasible those values are. For example, a population that has collapsed in the past, despite catch and survey data indicating otherwise, is excluded from the set of trajectories. In contrast with the original implementation from Bentley and Langley (2012), the set of trajectories is not dynamic, due to the computational approach of the FLR libraries. Instead, a wide range of possible trajectories is created, then filtered. Selection criteria are applied simultaneously to the initial OM output.

The number of stock trajectory replicates required depends on the acceptance rate that the selection criteria impose. To obtain 500 trajectories in the final OM, a much higher number of initial populations (for example, 10,000) would be required, if only a low percentage of them are accepted. A two-step process was applied, where initial runs with 10,000 to 15,000 iterations would be used to obtain the acceptance rate. This was then used to calculate the necessary number of model runs in order to achieve the required 500+ iterations.

The methodology used for these stocks in previous studies (Tien et al. 2020a, 2020b) has been refined by the addition of extra selection criteria. The code has also been improved in its efficiency and flexibility.

3.1.1.1 Selectivity patterns for the fishery, survey and removals by the birds

The OMs developed for each stock require the calculation of the selectivity at age associated with each 'extraction' method (e.g. survey beam trawl nets, fisheries gillnets). This involves determining the portion of an age group present at a given location that the extractor effectively catches. For example, old fish can swim faster and may thus have a lower chance of being caught in the beam trawl than young fish.

The selectivity-at-age for the bird predation, the commercial fishery and for the scientific survey used in the OMs of the four stocks are presented in ***Figure* 3-2**. The values used in the current the OMs were taken from the previous MSE work (Tien et al. 2020a, 2020b).

For the fishery and the survey, the selectivities were based on the length frequency distribution from the respective data sets (see Appendix 1), as well as expert knowledge on the expected behaviour of the respective gears. The selectivity-at-length was later converted into selectivity-at-age using von Bertalanffy growth curves for each species.

Selectivity of the overall bird population was based on the proportion of removal per bird species and their respective prey length ranges (see Appendix 2). This was used to compute a selectivity at length for all stocks which was then converted into selectivity-at-age (***Figure* 3-2**).

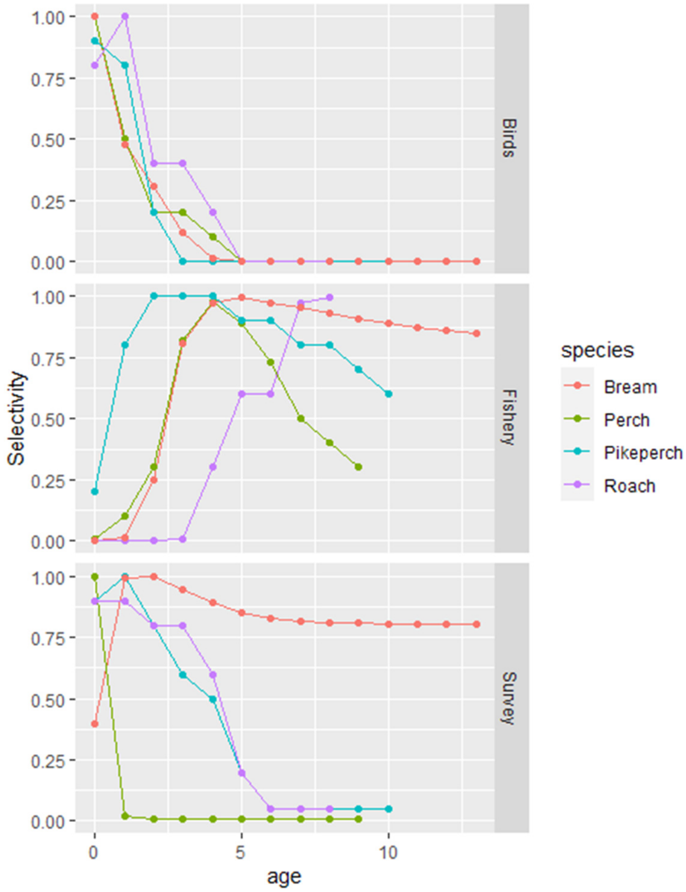

***Figure* 3-2** *Selectivity-at-age for the bird predation, commercial fishery, and the survey, used for the OMs of the four fish stocks.*

3.1.1.2 Priors

Initial priors were constructed for three parameters in the operating models, determining the scale of the stocks, their initial abundance, and their productivity. These parameters are: 1) virgin biomass (B_0; also assumed here to be carrying capacity), 2) the level of depletion of the stock at the start of the selected data period (dep), and 3) the steepness of the stock-recruitment relationship (h). The range of values and the type of distribution used for each stock are given in **Table 3-2**.

Priors for virgin biomass were set to follow either uniform or inverse beta distributions, depending on the stock. The lower bounds of the distributions were informed by an analysis on historical maximum densities of fish encountered during the open water survey (Tien et al., 2020a). Upper bounds were set to a large multiple of the lower bounds (e.g. 10 times). Depletion at the start of the time period (1992) was modelled as a uniform prior, ranging between 20 and 80%. The priors for steepness in the stock-recruitment relationship were set as bounded beta distributions. Bounds were set according the life-history of each species, drawing from the correlations in the *FishLife* database (Thorson, Cope, and Patrick 2014).

Table 3-2 *Prior distributions for virgin biomass (B0; also assumed to be carrying capacity), initial depletion from fishing (dep), and steepness of the stock recruitment relationship (h) used in the conditioning of operating models for the four stocks. U refers to a uniform distribution, while B denotes a beta distribution, unbounded or bounded (constrained) to certain limits.*

Stock	$B0$	dep	h
Pikeperch	U(1500, 15000)	U(0.2, 0.8)	B(1.91, 1.28), bound to 0.55-0.85
Perch	B(2,2) * 55500	U(0.4, 0.8)	U(0.4, 0.8)
Bream	B(2,2) * 62000	U(0.2, 0.8)	B(1.91, 1.28), bound to 0.55-0.85
Roach	B(2,2) * 14400	U(0.2, 0.8)	B(1.91, 1.28), bound to 0.55-0.85

3.1.2 Model validation

Model validation is the determination of the degree to which a model or a simulation are accurate representations of the real world, as inferred through the available data and knowledge. To that aim, the distribution at age and length of the catches generated by OMs were assessed by comparing annual percentages of landings at age from 2017 to 2020 to the modelled percentages of catches at age. Validation plots of this metric for all four stocks can be found in Appendix 3. It can be observed that the observed and modelled distribution exemplify good agreement.

3.1.3 Observation Error Model (OEM)

In the MSE simulation process, stock observations are generated from the OM in a way that mimics those that are routinely obtained from fishery independent and fishery dependent data. The collection of all data and information is replicated as close as possible, including any potential source of uncertainty. This step in the management process is termed Observation Error Model (OEM). In the current analysis, the OEM is used to obtain observations from the two main sources of data on the IJsselmeer stocks: landings from the commercial fleets and the survey.

For each simulation time step, stock abundance is calculated given fishing mortality, natural mortality, and recruitment. Thereafter, an observation of the catch at age from the aggregated commercial fleet is computed, based on their calculated selectivity, with lognormal error added as LN(0, 0.20). For the survey, abundances at age (I_ay) are generated as:

$$I_{a,y} = N_{a,y} \cdot S_a \cdot q$$

where $N_{a,y}$ is the stock abundance at age per year in the OM, S_a is the selectivity at age for the survey, and q is the catchability coefficient for the survey, computed during the OM conditioning process for each simulation iteration. Error is added with a lognormal distribution for approximately a 30% CV, LN(0, 0.3).

4 Results: Operating Models

The following sections describe the historical stock developments obtained from the operating models (OMs). These estimates offer insights into uncertainties and stock productivity levels serving as important background information for the interpretation of future predictions. It is important to recognize that it is not the aim (or the capability) of these OMs to estimate the past development to the highest precision, but rather to serve as vital input to simulation testing of management procedures (MPs; chapters 5 and 6). Accurate historical estimates rely on the quality of data provided, which is limited in the case of these stocks. It is therefore recommended to exercise caution when interpreting the information presented in the following section as the results do not intend to achieve the level of precision found in robust stock assessments that benefit from comprehensive data.

The chapter is organized by fish stock featuring subsections detailing OM projection methodology, trajectory selection, prior and posterior parameters and stock status. Descriptions of OM projection methods for bream and roach are more detailed as their initial projection deviates from the methodology used for pikeperch and perch.

4.1 Pikeperch

4.1.1 OM projection method

The historical projection of the pikeperch OM is largely driven by gillnet catches (**Figure 2-1**), with bird predation (**Figure 2-2**) making minor contribution to the historical population dynamics.

4.1.2 Selection of feasible trajectories

Four specific selection criteria were applied to the pikeperch population simulation runs (also see Figure A5.1 in Appendix 5), after the population was projected from its initial depleted status by extracting the total reported catch:

1. **Catch**: Annual catch is on target, with a 1% error allowance from total catch records.
2. **Survey biomass:** Changes in biomass of ages 0 to 3 matches those in survey (***Figure 2-3***) with less than a 10% deviation in the yearly rates of change.
3. **Maximum harvest rate:** Annual harvest rate (catch/biomass), defined as total catch over the biomass available to the fleets given their selectivity, falls between 0 and 0.80.
4. **Limit effort change:** Effective effort or partial fishing mortality increases to a maximum of 400% from one year to the next.

*Refer to Appendix 5 for definitions and additional details on each selection criterion.

The application of these selection criteria to the base case OM, leads to a 6% overall acceptance rate. Of the selected trajectories, a random pool of 500 iterations were used within the pikeperch OM. The change in biomass reported by the survey is the dominant factor selecting less than 20% of initial population trajectories incorporated into the OM (Figure A5.2 in Appendix 5).

4.1.3 Prior vs posterior parameters

From the wide priors initially assigned to the three main unknown parameters - virgin biomass (carrying capacity; $\boldsymbol{B0}$), depletion ($\boldsymbol{dep}$), and stock-recruit steepness ($\boldsymbol{h}$) - the procedure narrows down the range of feasible values for the first two (**Figure 4-1**). The OM conditioning accepted around 6% of the proposed prior combinations. Several proposed populations could not explain the observed catches (figure A5.1 in Appendix 5) or could do so only by imposing unrealistic harvest rates, greater than 80%, which were then filtered out. The most selective criterion was the agreement with annual biomass trends detected by the trawl survey (Figure A5.1 in Appendix 5).

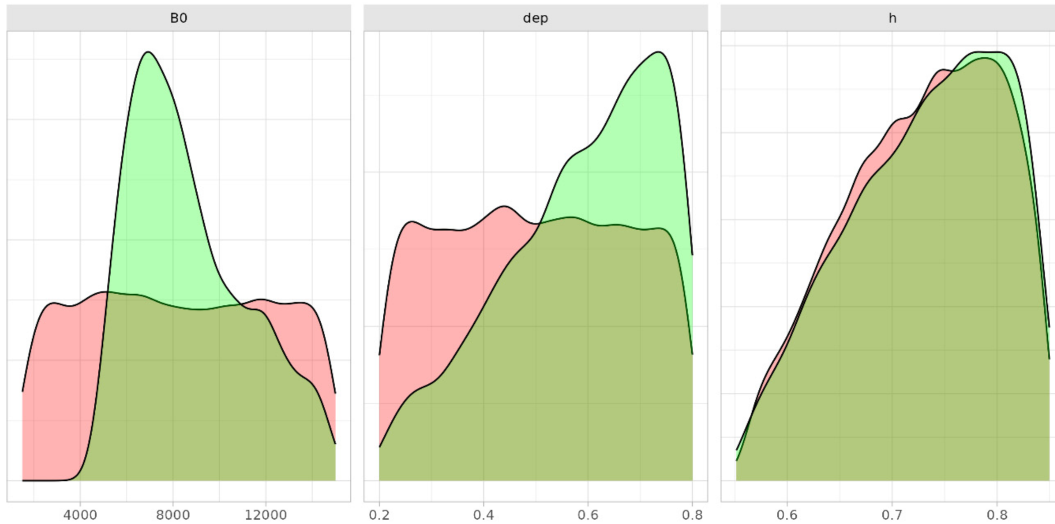

Figure 4-1 *Pikeperch. Comparison of the prior (red) and posterior (green) probability distributions for the three main population parameters (virgin biomass, B0, initial depletion level, dep, and stock-recruitment steepness, h, for pikeperch.*

4.1.4 OM trajectories and stock status

A summary of results for the candidate base case OM for pikeperch is presented in **Figure 4-2**. The open-water survey suggests that large recruitment events have taken place in recent years. Whether future recruitment variability remains as high as that apparent in the last decade will also be an important factor determining the effect of applying the MP in the short term. The possible ability of MPs to benefit from those larger reproductive rates, and to respond to subsequent drops, will be an important robustness test for this stock.

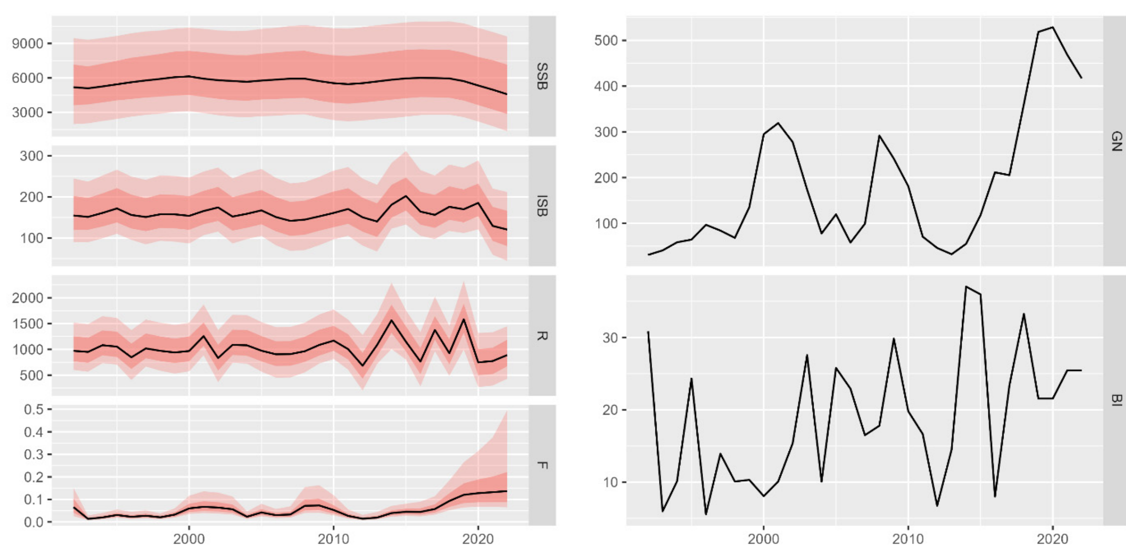

Figure 4-2 *Pikeperch. Time series of population dynamics: spawning biomass (SSB; tonnes), immature biomass (ISB; tonnes), recruitment (R; thousands), and fishing mortality (F; proportion year⁻); and catches (tonnes) by gillnets (GN) and birds (BI) for the conditioned pikeperch base case operating model. F concerns mortality by both the fisheries and the birds.*

The model presents considerable uncertainty in current stock status, although recent increases in catches can only be explained by a significant increase in fishing mortality. This is likely to affect the decisions that any MP will take in the short term. MP performance evaluation should be more robust to this uncertainty in the medium and long term (Figure Figure 4-3).

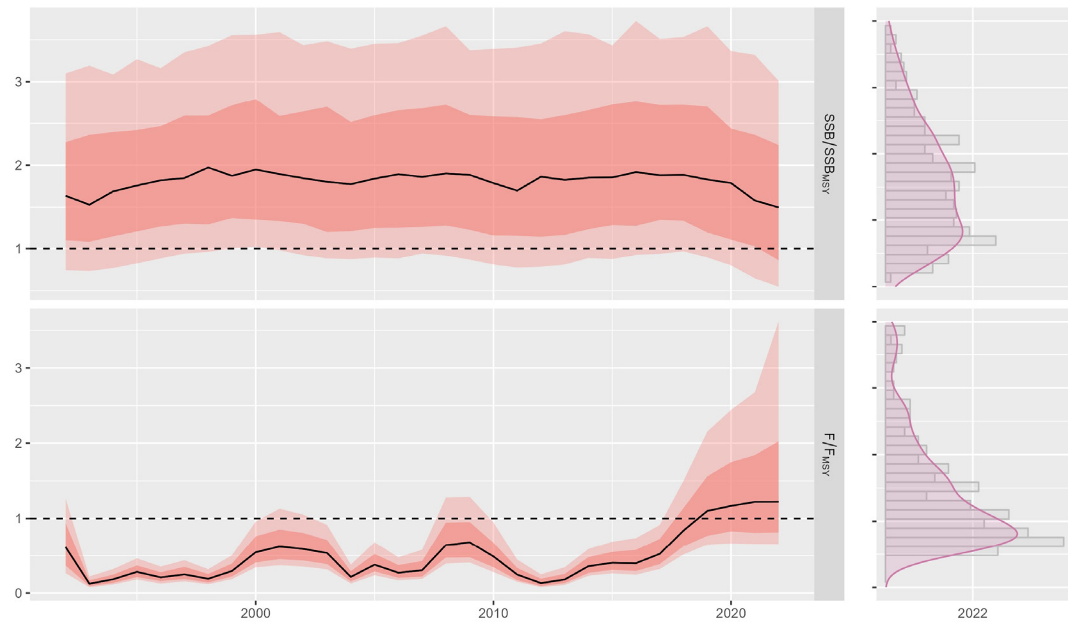

Figure 4-3 *Pikeperch. Historical trajectories of SSB/SSB$_{MSY}$ and F/F$_{MSY}$ (concerning both the fisheries and the birds) in the pikeperch OM (left panels) and data distribution from the 2022 simulations (right panels). F concerns mortality by both the fisheries and the birds.*

4.1.5 Alternative operating models

Three alternative operating models have been tested for pikeperch. They incorporate other population processes that have been raised as credible hypothesis and can then be used for robustness tests of the tuned MPs (i.e. those on which the candidate MPs are tested to understand their robustness to these alternative OM dynamics). Pikeperch was chosen for this exercise as some of the scenarios on natural mortality are only relevant to this stock. Figure 4-4 presents the base case run together with those of the three following alternatives:

- Variable age 0 M. Natural mortality of age 0 individuals was linked to recruitment strength, as determined by the age 0 in the open water survey. This reflects a process of density dependence, apparent in the weak cohort signal between ages 0 and 1 for pikeperch in the survey data (Tien et al. 2023).
- Decrease in productivity. Primary productivity in the IJsselmeer has decreased over the last 2 or 3 decades, as nutrient inflow has been substantially curtailed (de Leeuw et al. 2023). An annual decrease of around 3% has been applied to the virgin biomass of the pikeperch stock to account for lower B0 values
- Senescence M. Natural mortality in the last two ages in the model (9 and 10+) is increased from 0.20 to 0.25 and 0.30, to reflect a possible onset of senescence. The abundance of larger pikeperch was a problematic issue in previous simulations (Tien et al. 2020a). This uncertainty is induced by the limited sampling of old individuals, which could be explained by both their absence from the lake or the inability of both fleets and survey to catch them.

The alternative conditioned models present a range of alternative hypotheses on the stock dynamics, that will provide useful when carrying out robustness test of candidate MPs (see section 6.1). The incorporation of early-life density dependence (Variable age 0 M) does not appear to have a large effect in the range of population trajectories the OM algorithm selects (top row). In contrast, the other two hypothesis do alter the view on stock productivity and stock status. Future trends in productivity may be considered when evaluating MPs under the relevant alternative OM. However, as no reliable predictions exist regarding future changes in productivity, this has not been conducted at this stage. Changes to future lake productivity are expected to be smaller than those of the past decades, as influx of nutrients to the system has already decreased markedly since the 1980s (de Leeuw et al., 2003). The impact of any future changes in the time span of applying an MP (maximum of 5-6 years) are likely to be smaller than the variability in other environmental and ecosystem factors over the same time period.

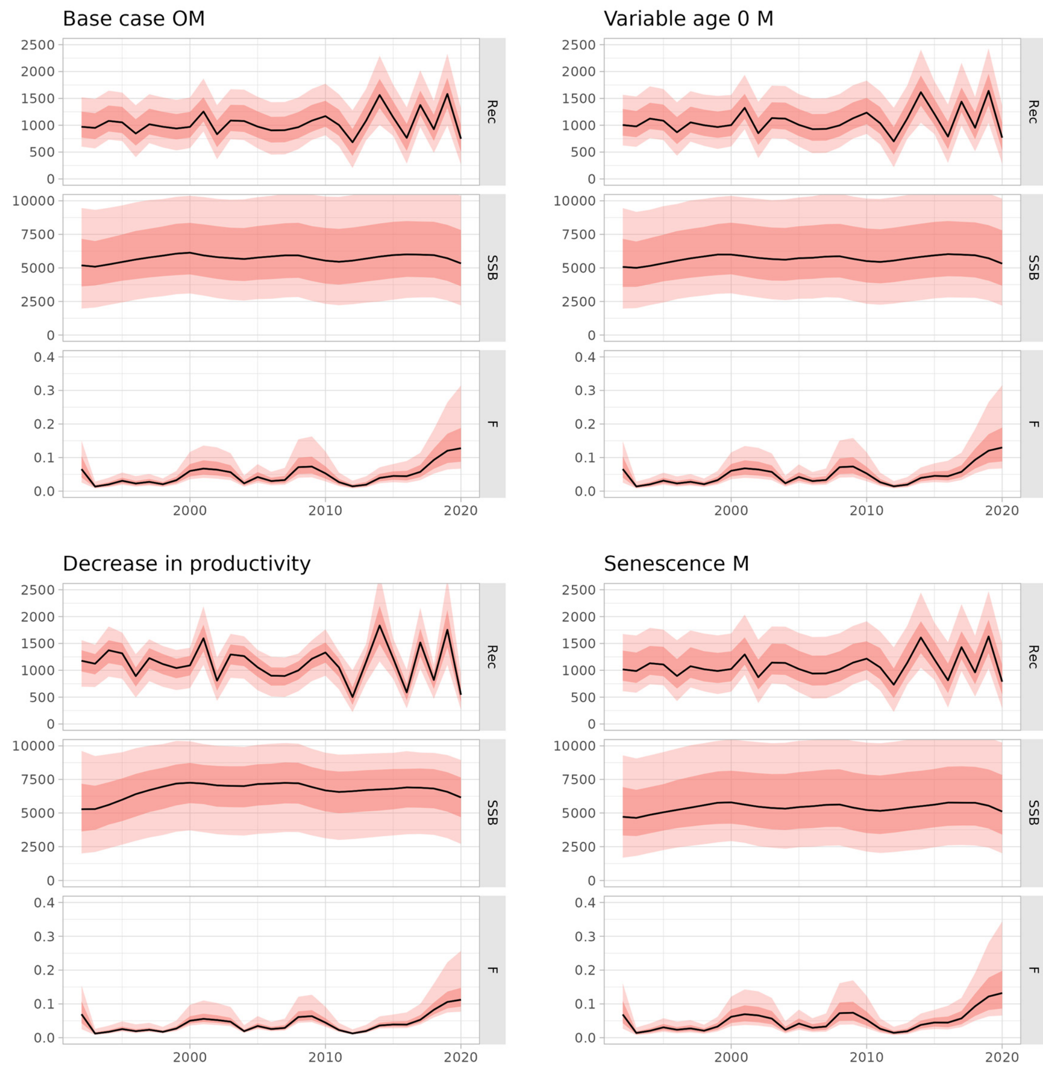

Figure 4-4 *Pikeperch. Comparison of the time series of population dynamics (recruitment, spawning biomass, and fishing mortality) for the four conditioned pikeperch base case operating models.*

4.2 Perch

4.2.1 OM projection method

The OM for perch used historical catch data from the fishery (**Figure 2-1**) together with the estimated bird catch (**Figure 2-2**) to compute historical stock trajectories stock over the 1992–2022 period.

4.2.2 Selection of feasible trajectories

Compared to the other stocks, the perch OM exhibited a lower sensitivity to depletion when applying selection criteria. To arrive at the final selection of trajectories, a broader range of criteria were used. A total of seven selection criteria were used to select feasible trajectories for perch:

1. **Catch**: Annual catch is on target, with a maximum 5% error allowance from total catch records (see Appendix 5 Figure A5.3 "Catch")
2. **Survey biomass:** Year-to-year variation in the survey biomass index for ages 0 to 3 (Figure 2-3) and the corresponding biomass generated in the OM should not deviate by more than 1 for more than 8 years throughout the historical time series. This threshold was selected to prevent excessive filtering of trajectories (see Appendix 5 Figure A5.3 "Biomass"). The direction of change between the yearly biomass (log values) over the ages 0 to 3 in the survey from the OM should not differ.
3. **Biomass trend 1992-2005:** The time series is divided into two periods: a) 1992-2005, associated with a decline in biomass and b) 2005-2020, associated with an increase in biomass. Only iterations matching the decrease over the period 1992-2005 are retained (see Appendix 5 Figure A5.3 "Biomass trend 1992:2005").
4. **Maximum harvest rate**: The harvest rate (Catch/Biomass) was limited to 0.6 in any year of the historical period or to be lower than 0.002 for a maximum of 10 years in any iteration to ensure that all accepted runs corresponded to a minimal level of exploitation (**Minimum harvest rate**). This resulted in two selection criteria (see Appendix 5 Figure A5.3 "Maximum harvest rate" and Figure A5.4, "Minimum harvest rate")
5. **Limit effort change:** Any iteration exhibiting an annual rate of change in effort which was over four times the level of the previous year, was discarded (see Appendix 5 Figure A5.4 "Limit effort change").
6. **Index age 2:** Interannual variations in numbers at age 2 in the official survey match those in OM. This criteria works in a similar manner as criteria 3 but while criteria 3 aims at making sure that the biomass trend in the OM reflects the survey, this criteria aims at making sure the year-class strength dynamics in the OM matches with the survey. Age 2 was chosen because that is the last age for which the survey is considered meaningful (older ages are not caught) and an age that starts being significantly caught by the fishery.
7. **Feasible Fbars:** Model runs requiring unrealistic levels of fishing mortality, F greater than 4, to explain catches, where eliminated (see Appendix 5 Figure A5.4 "Feasible Fbars").

*Refer to Appendix 5 for definitions and additional details on each selection criterion.

Criteria 3 for the first period (imposing a decreasing trend between 1992 and 2005) proved to be the most selective for the perch OM, as it resulted in discarding 57% of the iterations (see Appendix 5 Figure A5.5). The combination of all criteria selected 735 iterations out of the 5000 initial ones (15% acceptance) of which 500 were randomly selected to form the base OM.

4.2.3 Prior vs posterior parameters

Figure 4-5 shows that the data and model structure can narrow the possible values for virgin biomass, while the spread for both steepness and depletion remain similar to the priors. Uncertainty in initial depletion will translate into large uncertainty in stock status at the start of the simulation.

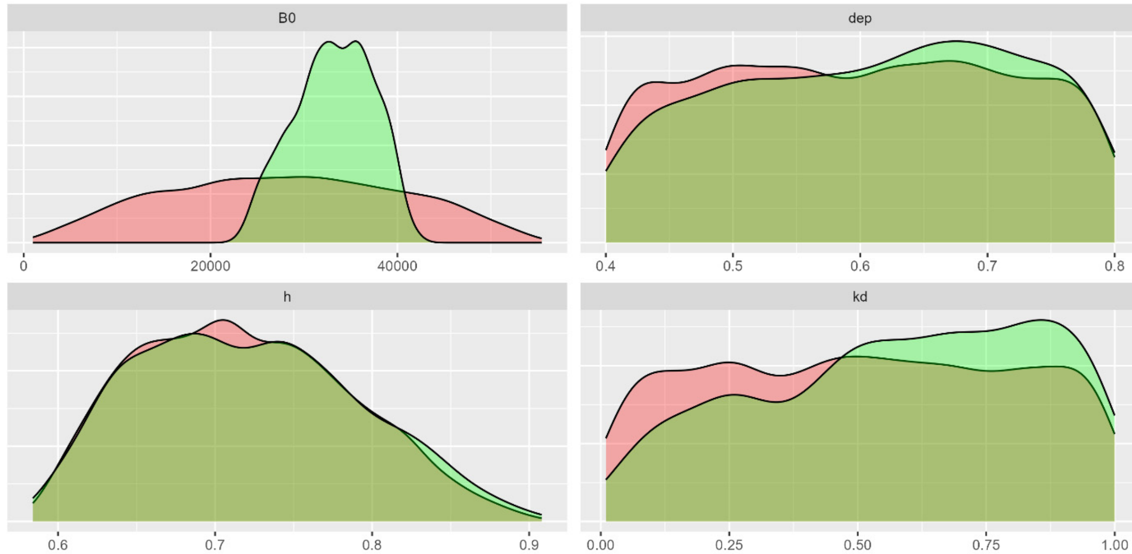

Figure 4-5 *Perch. Comparison of the prior (red) and posterior (green) probability distributions for model parameters: virgin biomass (B0), initial depletion level (dep), stock-recruitment steepness (h) and deviance weighting factor (kd), for perch.*

4.2.4 OM trajectories and stock status

Data input from fishery catch data shows a slight increase in catches in the last decade. However, gillnet catches are minor in comparison to the catches taken by birds. Bird catches have been estimated to have increased in the last decade with a high level in 2018. Current estimates for 2020 indicate bird catches to be at least 15 times higher than the catches from gillnetters. Avian predation is disproportionally more important as a data source for the perch OM compared to other stocks.

Historical projections of SSB show a slight downtrend with an uncertainty envelop for the whole projection period (**Figure 4-6**). Recruitment is fluctuating without any specific trend, and the fishing mortality (which is representative for both the commercial fishing and the birds) has increased markedly from the early 2010’s until 2018, fluctuating at high level after that.

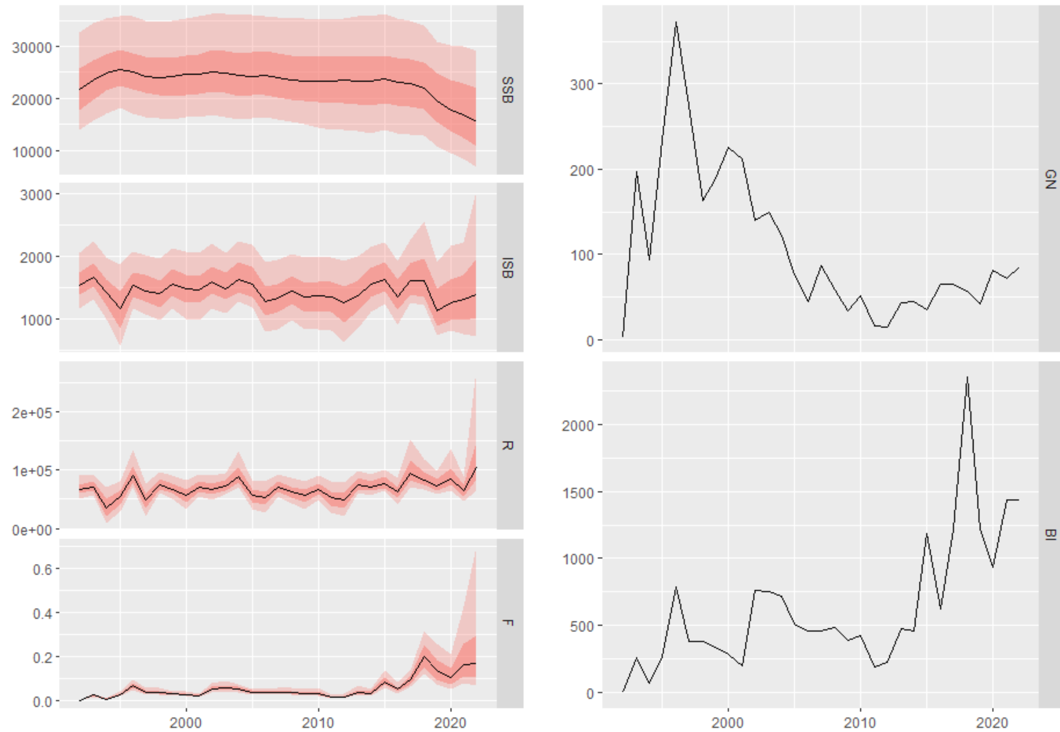

Figure 4-6 *Perch. Time series of population dynamics: spawning biomass (SSB; tonnes), immature biomass (ISB; tonnes), recruitment (R; thousands), and fishing mortality (F; proportion year^{-1}); and catches (tonnes) by gillnets (GN) and birds (BI) for the conditioned perch operating model. F concerns mortality by both the fisheries and the birds.*

The OM shows that the spawning stock biomass in relation to MSY reference point (SSB/SSB_{MSY}) has been above 1 for most of the historical period but has decreased since 2010 (**Figure 4-7**). At the start of the simulation period, the central value is still above 1, but a high proportion of the iterations are below 1. In general, there is a large uncertainty in the perch OM, with the 90% envelop spreading from SSB/SSB_{MSY} = 0.5 to nearly SSB/SSB_{MSY}=2.

The ratio for the fishing pressure and its reference (F/F_{MSY}) shows an increase in the recent decade, from a level well below 1 to levels above 1 in 2018. In the most recent years, there is a slight decrease in fishing pressure. In the last year (2022), the central value is around 0.75 (Figure 4-7).

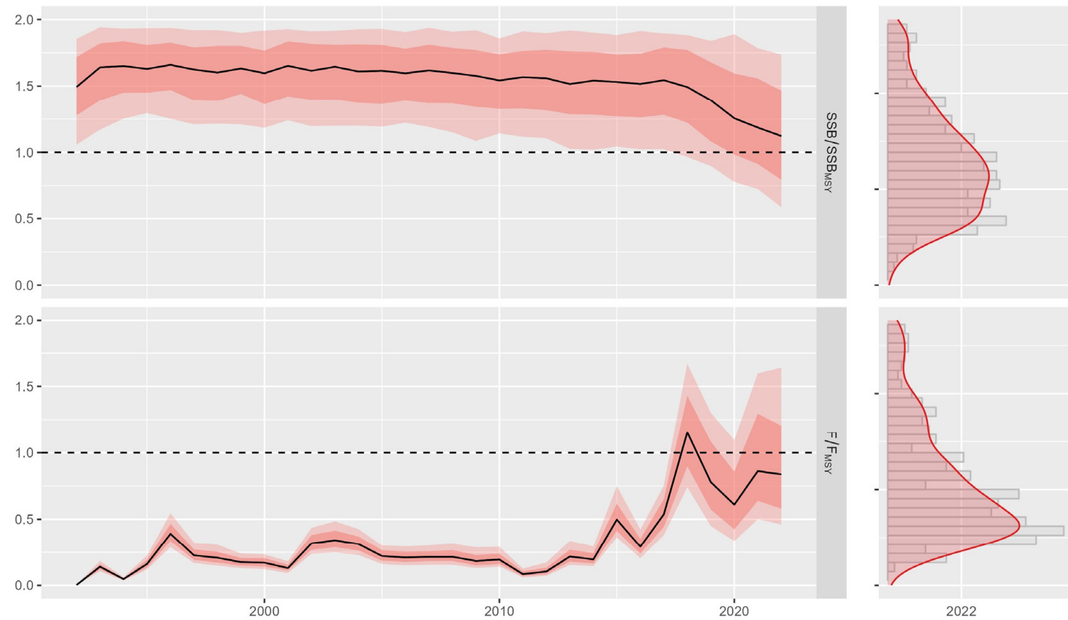

Figure 4-7 *Perch. Historical trajectories of SSB/SSB_{MSY} and F/F_{MSY} in the perch OM (left panels) and data distribution from the 2022 simulations (right panels). The distribution of SSB/SSB_{MSY} trajectories displays a notably uniform pattern across the range of potential outcomes, resulting in a 'flat' appearance. F concerns mortality by both the fisheries and the birds.*

4.3 Bream

4.3.1 OM projection method

The OM uses an annual rate of change from the stock biomass survey index for its historical projections. After initializing the population[11], the stock was projected forward until the final data year (2022) by imposing an annual rate of change in stock biomass equal to the annual rate of change in the biomass index from the survey. A LOESS (locally weighted smoothing) smoother was first applied to the survey index to filter out the short-term variation and keep only the longer term trend (Figure 4-8).

Recruitment deviances were based on the survey index at age 0 (Figure 4-9). For bream, there is overall a decreasing trend in the age 0 index from the survey. This trend is more likely to be the consequence of overall decrease in stock size, rather than of having predominantly positive recruitment deviation at the start of the period and negative deviations at the end. In the OM, the link between spawning stock size and the subsequent number of offspring is accounted for in the stock-recruitment model. The decrease in stock size used to condition the OM already generates recruitment that have a downwards trend over time. The recruitment deviances concern the stochasticity introduced to the stock-recruitment model. These recruitment deviances were generated based on the differences between annual age-0 index values and a LOESS smoother of the index.

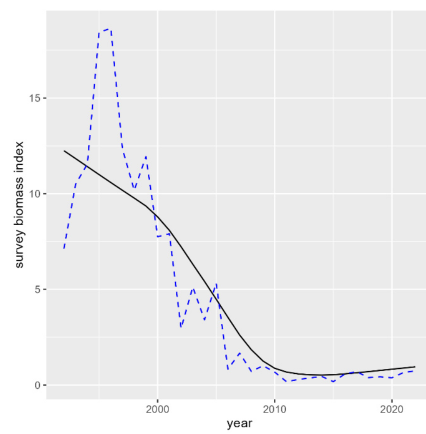

Figure 4-8 *Bream. Biomass index from the survey and LOESS smoother used to project the bream OM over the historical period.*

[11] I.e., creating a stock at the start of the data period, 1992, for each value of virgin biomass and depletion levels

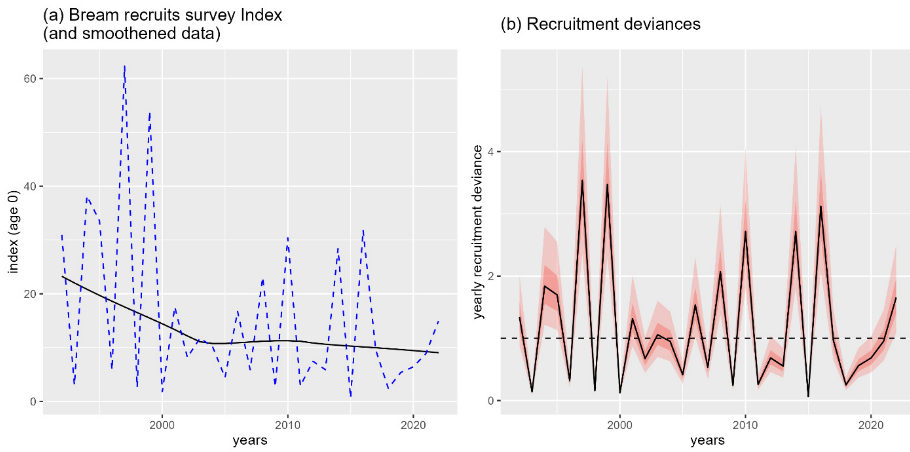

Figure 4-9 *Bream. Age-0 index from the survey for bream (and smoother, panel (a)) and historical recruitment deviances generates based on the differences between yearly index and smoother (panel (b)).*

4.3.2 Selection of feasible trajectories

The iterations in the OM that have plausible trajectories were selected based on several criteria (see Figure A5.6 in Appendix 5):

1. **Catch**: The modelled catches should agree with the catch data available. The catch information for bream prior to 2005 is very uncertain, as there was no good report of the catches from the seine fishery. Rather than catch data, there are two available scenarios for that time period (a Cmax and a Cmin scenario). The selection of feasible trajectories, based on criteria related to the catch, was therefore conducted separately for two time periods: 1998 to 2002 for the period with the two catch scenarios and from 2015 to 2022 for the recent period with accurate data. For the 1998-2002 period:
    a. the annual catch should never be lower than the Cmin values
    b. the annual catch should on average be lower than 1.5 times the Cmax value

    and for the period 2015-2022 :

    c. the catch should be on average at least the reported catch, but not more than twice the reported catch.
2. **Survey biomass:** Trend in the stock biomass should be close to the trend in the biomass index from the survey (R^2 of the linear regression of OM vs. survey biomass of at least 0.5).
3. **Maximum harvest rate:** The harvest rate (catch/stock biomass) should not be higher than 80% for more than 3 year over the OM projection period.
4. **Limit effort change:** Fishing effort cannot increase by more than 4 times from one year to the next.

*Refer to Appendix 5 for definitions and additional details on each selection criterion.

The most selective criteria were the combination of the catch related criteria (1.), which when applied jointly, selected just under 20% of the iterations (see Appendix 5 Figure A5.7). The combination of all criteria selected 1,521 iterations (15.2% acceptance rate).

4.3.3 Prior vs posterior parameters

Figure 4-10 shows the distribution of the priors (values for the initial 10,000 iterations) and posteriors (values of the 1,521 iterations remaining after selection of plausible trajectories) for the population dynamic parameters. The prior for virgin biomass, B0, had a wide distribution, ranging from very small values up to 60,000 t. This parameter is strongly revised for (posterior have a much narrower distribution than priors) by the selection of feasible trajectories, with a mode of the posterior distribution close to 37,000 t, and all values lower than 20 000t being removed from the OM. The posterior distribution for the initial depletion rate is also narrower than the prior, with a mode at 0.50 and values lower than 0.25 and higher than 0.70 being removed. For steepness (h), high values - between 0.70 and 0.85- were selected. The distribution of the parameter limiting recruitment variability was less revised by the feasible trajectory selection than the other parameters.

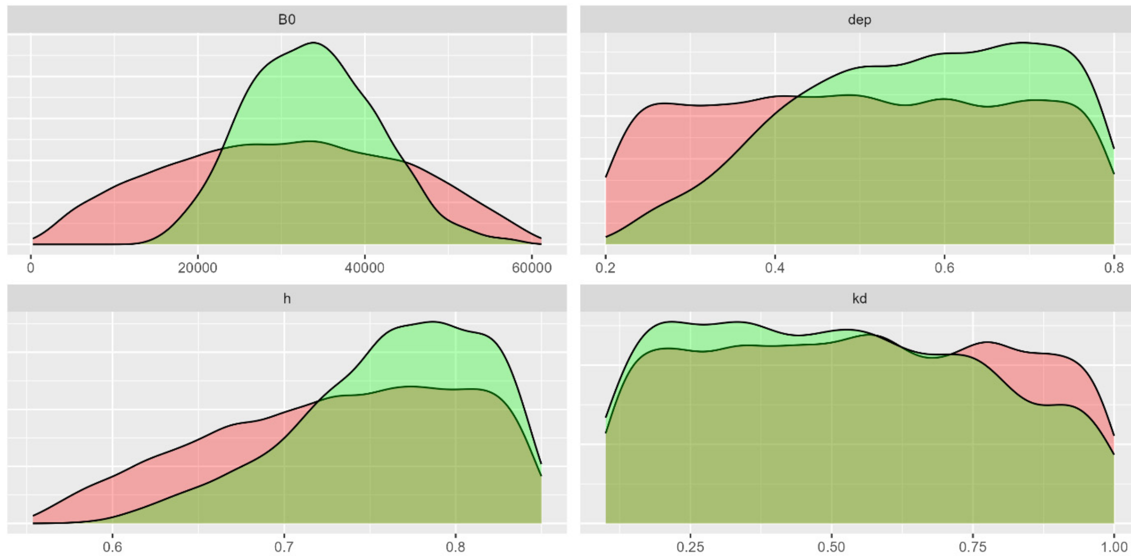

Figure 4-10 *Bream. Comparison of the prior (red) and posterior (green) probability distributions for model parameters: virgin biomass (B0), initial depletion level (dep), stock-recruitment steepness (h) and deviance weighting factor (kd), for bream.*

4.3.4 OM trajectories and stock status

From the 1990's onward, the OM for bream suggests consistent declines in biomass, recruitment and fisheries catches. This also holds true for bird catches although their impact is notably less substantial compared to gillnet catches (Figure 4-11).

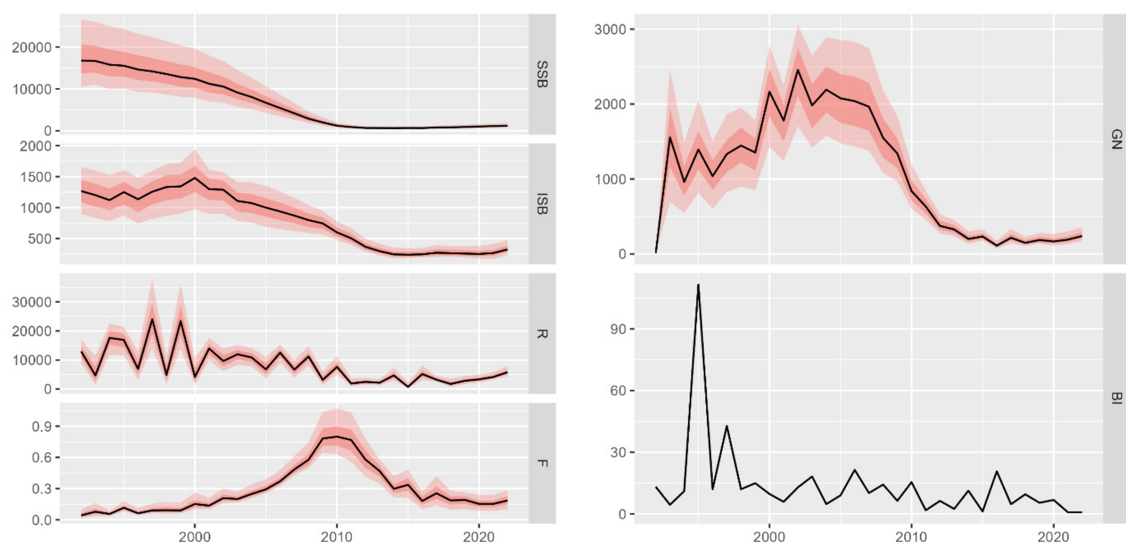

Figure 4-11 *Bream. Time series of population dynamics: spawning biomass (SSB; tonnes), immature biomass (ISB; tonnes), recruitment (R; thousands), and fishing mortality (F; proportion year*$^{-1}$*); and catches (tonnes) by gillnets (GN) and birds (BI) for the conditioned bream OM. F concerns mortality by both the fisheries and the birds.*

The OM for bream shows a stock that decreases from biomass levels above SSB_{MSY} at the start of the period to levels far below SSB_{MSY}, close to 0, by 2010 (Figure 4-12). The status estimated at the present time, is that of a severely depleted stock, with stock biomass at 2.5% to 7.5% of SSB_{MSY}. The level of exploitation increased from F well below F_{MSY} at the beginning of the time series to F up to 9 times F_{MSY} between 2007 and 2010. F subsequently decreased but remained well above F_{MSY}. The starting conditions for the projections correspond to F/ F_{MSY} in 2022 between 0.7 and 4.0 (Figure 4-12).

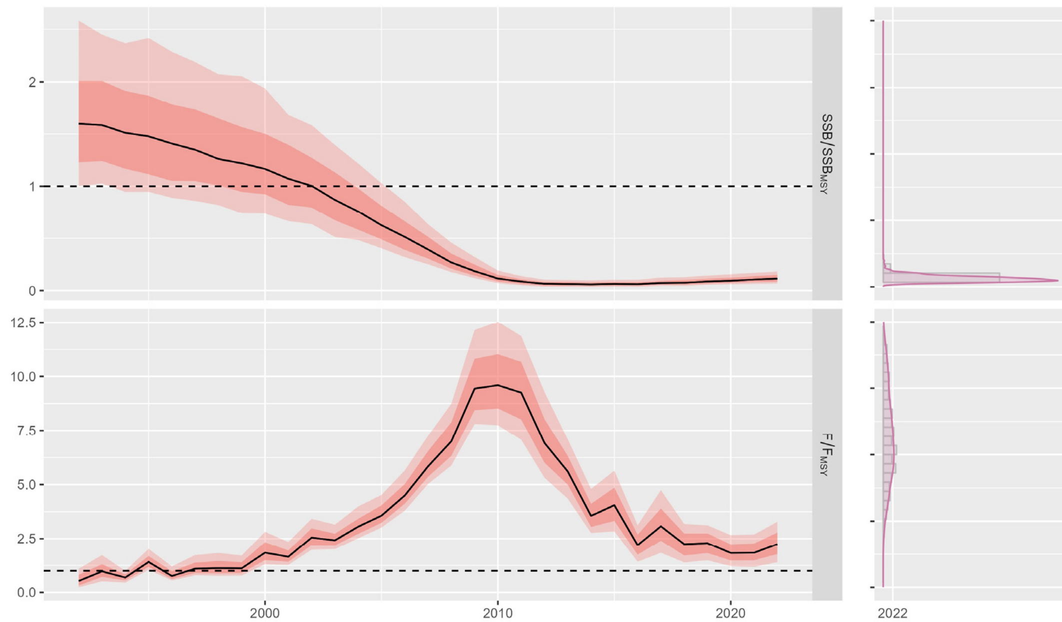

Figure 4-12 *Bream. Historical trajectories of SSB/SSB_{MSY} and F/F_{MSY} in the bream OM (left panels) and data distribution from the 2022 simulations (right panels). F concerns mortality by both the fisheries and the birds.*

4.4 Roach

4.4.1 OM projection method

The simulations initialize the population in 1994 and projects the stock to 2022 by imposing an annual rate of change in the adult stock biomass equal to the annual rate of change in the adult biomass index from the survey. To filter out the short-term variation and keep only the longer term trend, a LOESS (locally weighted smoothing) smoother was applied to the survey data (Figure 4-13) to obtain the yearly trend used in the simulations.

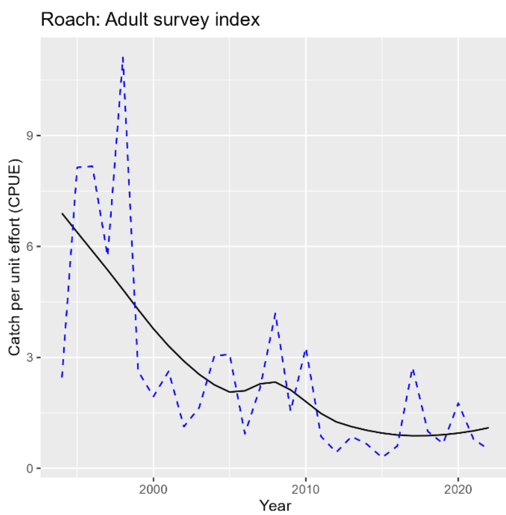

Figure 4-13 *Roach. Adult survey index for roach. A LOESS smoother with a 0.75 span (black solid line) was used to infer long term trends(a). The proportional annual rate of change from the smoothened data (b). A value below 1 reflects a relative decrease while a value above 1 shows an increase in the biomass trend.*

4.4.2 Selection of feasible trajectories

The projected populations in the roach OM exhibited heightened sensitivity to depletion compared to the other stocks assessed in this MSE. The survey biomass criterion, for example, filtered out any possible OM trajectories when used in conjunction with any other criteria with many of the selected iterations leading to an unrealistic population extinction prior to 2022 (unrealistic clearly as catch and survey data show that this is not the case) (see Figure A5.8 in Appendix 5). Selection criteria for this stock were therefore limited to:

1. **Catch:** Mean catches in the projections were permitted to fluctuate within a range of 20 % lower to 2 times higher than the recorded catches measured in the period 2008 – 2022. This is due to high uncertainty in catches prior to 2008. Prior to 2008, catches were excluded from consideration within this specific criterion.
2. **Maximum harvest rate:** Iterations projected in the OM could not exhibit an annual harvest rate (catch/biomass) greater than 1 (restricting unrealistically high F projections).
3. **Limit effort change:** The effective effort increase in the projections was capped at 25 times of the previous year's level. This is to avoid the abundance trend being followed by increases in effort and fishing mortality that could not be explained when the virgin biomass prior had generated a very low value.

*Refer to Appendix 5 for definitions and additional details on each selection criterion.

The catch criteria (criterion 1) was the most selective (under 20% acceptance rate) of the three criteria used (see Appendix 5 Figure A5.9). However, the combination of two or three criteria had the effect of retaining only a low number of samples. Applying all criteria yielded only 313 iterations for stock trajectories (1.2 % acceptance rate). With the limited number of selected iterations (below 500), all were used as stock trajectories in the roach OM.

4.4.3 Prior vs posterior parameters

The distribution of priors for virgin biomass (B0; range = 95 – 14,365 t), initial depletion rate (dep; range = 0.20- 0.79), and steepness of the stock-recruitment model (h; range = 0.55 - 0.85) were defined using 25,000 iterations (***Figure 4-14***). The posterior distribution for B0 narrowed to between 3,000 to 9,000 t. In comparison, posterior distributions for steepness and depletion showed a relatively wide distributions with the latter peaking at 0.57.

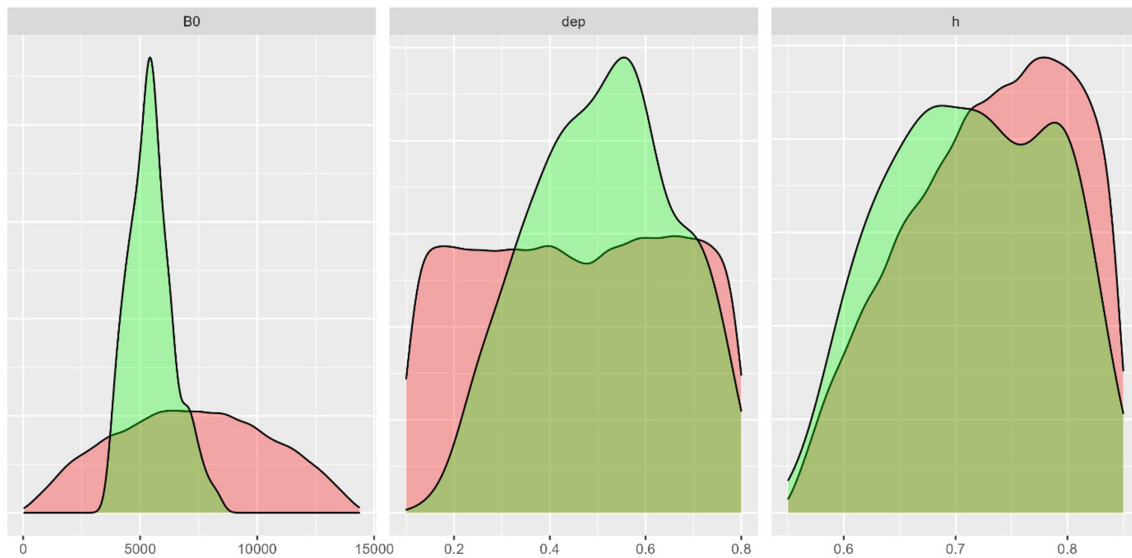

Figure 4-14 *Roach. Prior (red) and posterior (green) probabilities for operating model parameters: virgin biomass ('B0'; a), initial depletion ('dep'; b) and steepness for the stock recruitment relationship ('h'; c) for the roach stock.*

4.4.4 OM trajectories and stock status

Similar to bream, the IJsselmeer roach stock shows decreasing trends for biomass and recruitment since the 1990's. However, the trends for roach are comparatively less steep (Figure 4-15). An additional layer of noise was introduced to address uncertainty in catch data to allow for variability in the modelled trajectories. This variability is apparent in the gillnet catch data shown in Figure 4-15 (top right). Historical projections of SSB and ISB (immature stock biomass) reflect a downward trend in stock biomass evidenced in the survey index (Figure 4-13).

Figure 4-15 *Roach. Time series of population dynamics for roach: spawning biomass (SSB; tonnes), immature biomass (ISB; tonnes), recruitment (R; thousands), and fishing mortality (F; proportion year^{-1}); and catches (tonnes) by gillnets (GN) and birds (BI) for the conditioned roach operating model. F concerns mortality by both the fisheries and the birds.*

The roach OM suggests a decline in stock biomass from the start of the projections commencing above SSB_{MSY} at the start of the simulations. Biomass trajectories trend fall below SSB_{MSY} relatively early in the time series. The model estimates that SSB has been below SSB_{MSY} since the late 1990s/early 2000s. There is, however, considerable uncertainty persisting throughout the projection period for both relative biomass and fishing mortality (Figure 4-16). Fishing mortality has been estimated to have been above F_{MSY} shortly after the start of the simulations reaching its peak values in 2018 and subsequently declining from that point onward (Figure 4-16).

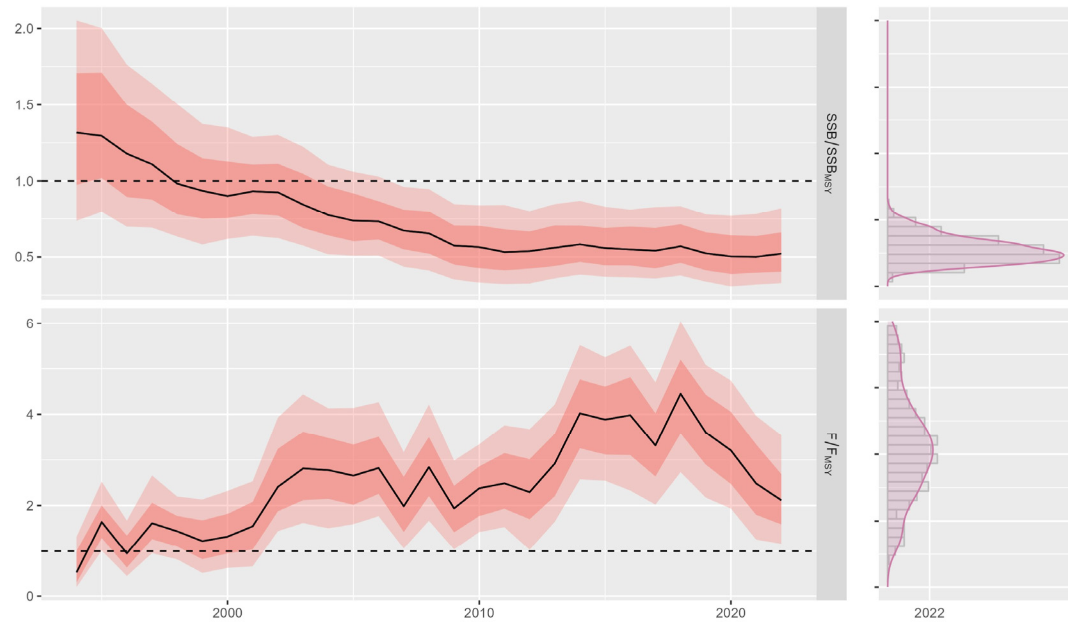

Figure 4-16 *Roach. Historical trajectories of SSB/SSBMSY and F/FMSY in the roach OM (left panels) and data distribution from the 2022 simulations (right panels). F concerns mortality by both the fisheries and the birds*

4.5 Differences between previous and current OMs

The current OMs incorporate a particular difference in methodology from the previous MSE (Tien et al. 2020a): the biomass trend in the survey (kg/ha) has been added as selection criterion, to select feasible trajectories. These changes in the methodology lead to population trajectories that differ from the previous analysis for pikeperch and perch (**Figure 4-2** and**Figure 4-6**, to be compared with Figures B.5.4 and B.5.10 from Tien et al. 2020a). The current method makes full use of the information that can be derived from the survey, as both recruitment deviances and biomass are determined by it. In addition to survey biomass, the current MSE incorporates stricter and more numerous selection criteria for feasible trajectories compared to the previous analysis (see Appendix 5 for a description of selection criteria). For bream and roach the OM trends remain similar to those in Tien et al. (2020b).

5 Methods: Management Procedures

Management procedures consist of at least two components: (1) a stock-size indicator (model- or data-based), and (2) a harvest control rule that provides a management quantity (here a TAC), based on the stock-size indicator and a series of reference levels. In the previous report outlining the exploration of appropriate MPs (Mosqueira et al., 2023), several options were investigated, using a range of different stock-size indicators: length-based indicators, length-based assessment, or survey indices. In this work, two types of MP are used, both using a survey index, as the length-based methods were found to have a too high uncertainty in earlier studies (Mosqueira et al., 2023).

5.1 Stock-size indicator

The two MPs tested use a biomass index derived from the beam trawl survey as a stock-size indicator. This biomass index is based on the average across all sampling stations for the weight of all fish caught per unit of surface trawled (expressed as kg per hectare). In absence of a stock assessment, this is the main index available to follow the developments of the stocks.

In the MSE framework, the survey is modelled as abundance-at-age indices. This is done to consider the age-related difference in catchability of the survey and generate a survey index that is representative of the part of the stock actually sampled. The stock-size indicator that is used in the simulations to inform the harvest control rules, is obtained by multiplying the modelled survey abundances-at-age (generated by the OEM; section 3.1.3) by the corresponding weights-at-age and taking the sum across ages.

When testing the model for each stock, small discrepancies emerged between the OM and the empirical data for the survey index in biomass during the historical period (Figure 5-1). The OM models the survey as an abundance-at-age index and takes into account the selectivity of the survey. A biomass index is constructed by multiplying the index at age by the corresponding stock weight at age and summing across all ages resulting in an index that differed from the survey data in certain years likely due to the assumption about the stock weight-at-age. However, for the simulations, it is important that the index used in the MP in the first years to be identical to the real index, otherwise the first TACs set in reality would differ from those set in the simulations. For each stock, the modelled index at age for the historical period was therefore rescaled so that the yearly biomass values correspond to the real survey biomass index. This issue has no impact on the construction of the OM itself.

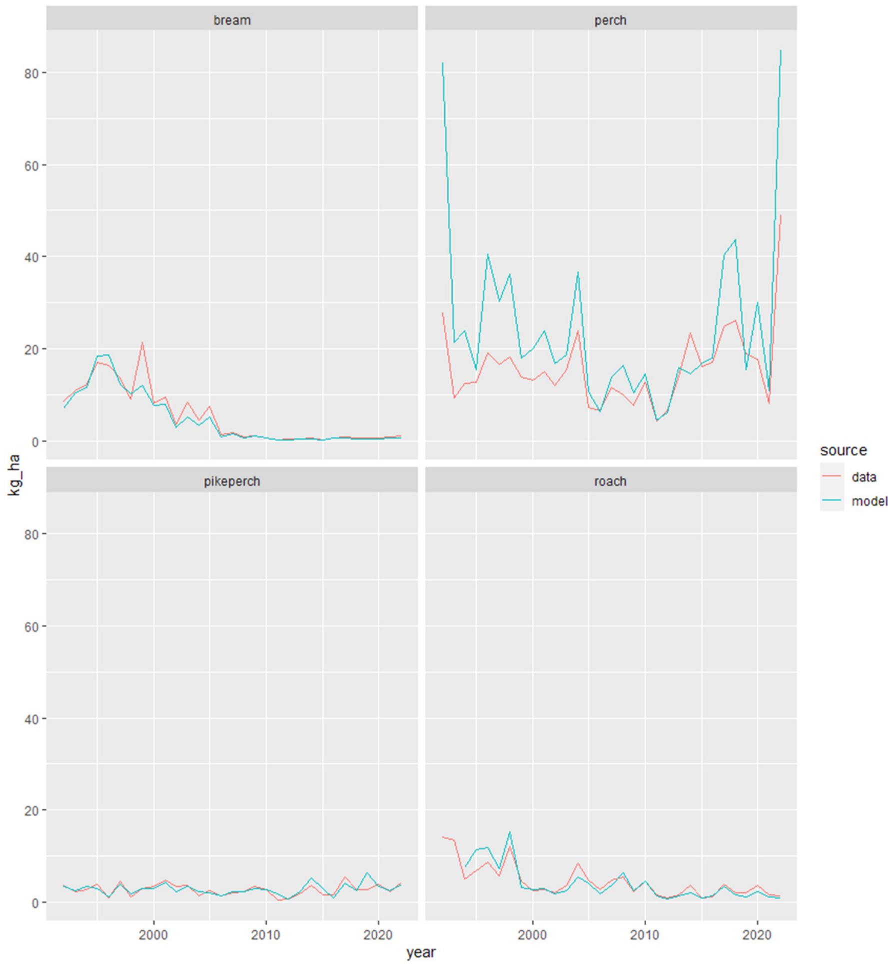

Figure 5-1 *Comparison of the biomass index from the survey (data) and from the OM (model) for the four stocks. The survey index is a direct estimation of the average biomass of fish per hectare, while the OM represents the survey based on the abundances-at-age from the survey and an assumption on the mean weight-at-age.*

5.2 Harvest control rules (HCRs)

The following harvest control rules were chosen as they are both designed to use a survey index as stock-size indicator. Both HCRs differ in the way the index is used:

1. Constant harvest rate HCR: the survey index is multiplied by a constant factor to obtain the TAC.
2. CPUE-based HCR: the annual change in the TAC compared to the previous year is calculated based on the recent trend and value of the survey index.

5.2.1 Constant harvest rate HCR

The harvest rate - ratio of the total catch over the stock biomass - is a measure of fishing pressure frequently used in stock assessment models and management rules. It provides an alternative to instantaneous fishing mortality to measure the level of exploitation of a stock (i.e. how much of the stock biomass is fished each year).

For most of the data-rich stocks such as those managed by ICES, the TAC is determined by an HCR that applies a constant "target" fishing mortality, often set to F_{MSY}. However, in some regions like Iceland, management rules use a target *harvest rate* (catch/stock biomass) instead of a target fishing mortality. Recently, ICES extended this concept allowing a similar type of management for stocks without a formal stock assessment but benefiting from yearly surveys. Such HCR involves using the ratio of total catch to a *relative* stock-size indicator. This concept is now used to give advice for data limited stocks at ICES.

The approach using a target relative harvest rate (named CHR for "constant harvest rate") has been proposed and tested by Fischer et al. (2022). In the CHR rule, the TAC for the upcoming year is defined as:

$$\text{TAC}_{y+1} = I_{last\ 3\ years} * H_{target} * \text{BSG}$$

with

$$\text{BSG} = min(1, \frac{I_{last\ 3\ years}}{I_{trigger}})$$

The TAC for the coming year is defined as the product of the average survey index over the recent (last three) years, $I_{last\ 3\ years}$, and the target harvest rate value, H_{target}. In addition, a biomass safeguard (BSG) is applied to protect the stock when its biomass decreases below a given threshold. The BSG reduces the target harvest rate when the biomass index falls below a trigger value, $I_{trigger}$. The BSG essentially imposes a 'hockey-stick' functional form on the HCR (**Figure 5-2**), similar to the ICES MSY advice rule.

The two control parameters in the HCR, H_{target} and $I_{trigger}$, can be defined empirically from the data:

- The parameter $I_{trigger}$ represents the lowest survey biomass that should be observed if the stock is exploited consistently at an exploitation level corresponding to MSY, considering the natural range of variations in the stock. The proxy proposed by Fischer et al. (2022) for $I_{trigger}$ is the lowest observed stock index, multiplied by an arbitrary factor of 1.4 in the absence of better knowledge. However, other approaches have also been used at ICES in cases where the index time series contained very low values.
- The reference level for harvest rate, H_{target}, can be defined by computing the past relative harvest rate values (catch over biomass index) and taking the mean over time periods where the stock was considered exploited at below MSY. A reference level can also be chosen based on the perception of various stakeholders regarding a specific period when catch and catch rates both appear to be reasonable and stable.

In the context of this MSE, the value of $I_{trigger}$ is set, based on specific considerations for each stock, and the value of H_{target} is obtained by tuning (see section 5.3.2).

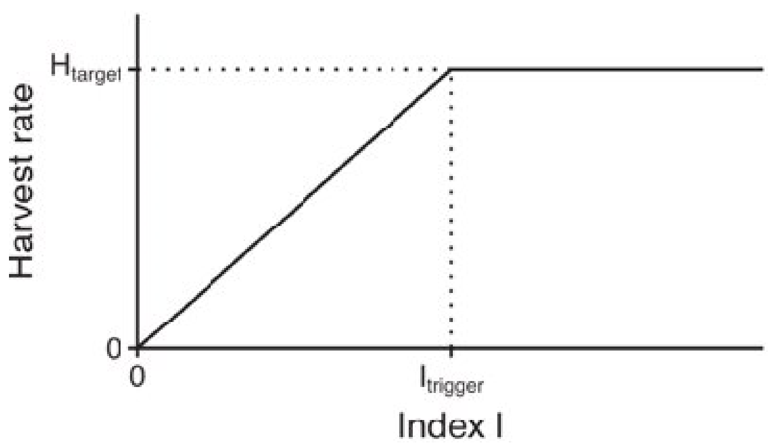

Figure 5-2 *Hockey-stick principle of the constant harvest rate control rule (CHR).* H_{target} *represents a sustainable level of fishing and* $I_{trigger}$ *indicates the biomass level that triggers the initiation of the harvest control rule to reduce fishing intensity.*

5.2.2 CPUE-based HCR

The CPUE rule (ITOC 2018) bases the decision of future TAC on the recent trend in a stock-size index, combined with the distance between the current index value and a target CPUE value (**Figure 5-3**). It was originally developed for application on commercial CPUE indices in tuna fisheries. The index used here, however, is the survey biomass index, as in the previous HCR. Future TAC is calculated as a proportion, TAC_{mult}, of the current TAC, which is defined as

$$TAC_{mult} = 1 + k_a Sl + k_b D$$

Where Sl is the slope of the survey biomass index (in log) over the last 5 years, D is the difference between the average of the index value over the last 3 years and the target value for the index. This rule reacts to both the recent trends in the stock and to the state of the stock compared to a target stock size. An increasing stock will lead to an increasing TAC. Likewise, a positive distance (stock above the target) will lead to an increase in the TAC. The parameters k_a and k_b control the reactiveness of the TAC changes to the slope and distance to the target respectively and their relative value also determine whether the rule will tend to react more to the recent stock trends or the distance to the target stock size.

High values for the parameters k_a and k_b lead to a MP that will react quickly to the changes in the index which potentially lead to a better management performance. However, this also means that the MP is more sensitive to any measurement error (i.e. imprecision) in the index, which on the contrary may deteriorate the MP performance. For this MSE, the parameters k_a and k_b were assigned a value of 0.2 which is relatively low, but in line with the choices made for other MSEs (Brunel and Mosqueira, 2023). This choice is motivated by the fact that the index used is based on a survey, and therefore can be assumed to have some level of imprecision, and by the fact that the survey for most stocks is mainly representative of the younger age-classes and not of the exploitable stock, which should ideally be used in the CPUE rule. The target index value was obtained by tuning.

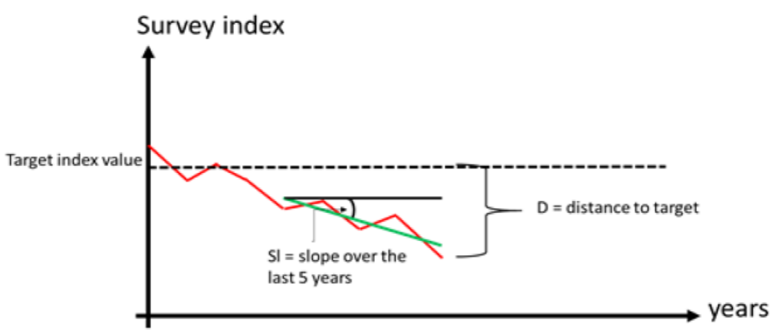

Figure 5-3 *The CPUE rule is based on responding to both the recent (five years) slope in the survey index (SI) and the distance to the target index value (D).*

5.2.3 TAC stabilizer

As requested by the ministry (Chapter 1.3.3), the MPs were implemented using a TAC stabilizer to avoid large changes in the TAC from year to year. Once the TAC corresponding to the HCR was calculated, a maximum TAC change of 20% compared to the previous TAC (upwards and downwards) was applied. This did not apply in the first year of implementation of the MPs, for which any value for the TAC change was allowed.

5.3 Evaluation and tuning of the management procedures

5.3.1 Performance statistics

The performance of management procedures is evaluated based on several metrics related to both stock conservation and productivity and the corresponding reference values. These quantities are determined by the management objectives and interest of all stakeholders (Punt et al. 2014). A series of performance statistics that provide a precise quantification of those objectives need to be defined beforehand. For this, the existing set of performance statistics from the previous analysis (Tien et al, 2020a, 2020b) was reviewed and deemed suitable for the updated MSE, together with an additional statistic regarding the spawner biomass at B_{MSY}. The following list presents the six performance statistics used to assess each MP. The name for each statistic employed in different output tables and plots can be found in parenthesis.

1) Fishing mortality (F) relative to the fishing mortality at F_{MSY} (F/F_{MSY}).
2) Spawning stock biomass (SSB or B for short usage) relative to the spawner biomass at B_{MSY} (SSB/SSB_{MSY} or B/B_{MSY}).
3) Spawning biomass relative to B_{lim}, defined as 10% of virgin biomass (B/B_{lim}).
4) Catch of the commercial fleet (‘Mean catch’).
5) Fish biomass available to birds (‘Bird Food’) relative to biomass available in a reference year.
6) Biomass-weighted mean length (‘BWML’) relative to the last year of the historical trajectories.

These performance statistics are computed for one or more time periods (e.g. short, medium, long term), as averages across years to avoid the effect of process variability in their estimates (

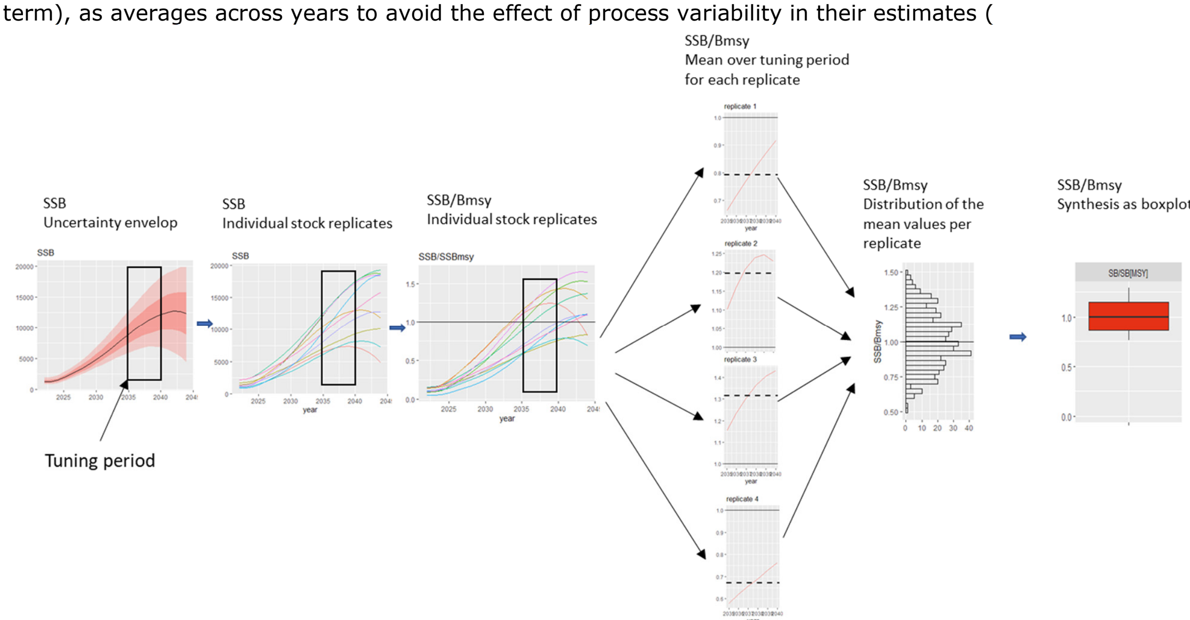

Figure 5-4). Calculations are carried out separately for each stock. Further details on the performance statistics can be found in Appendix 4.

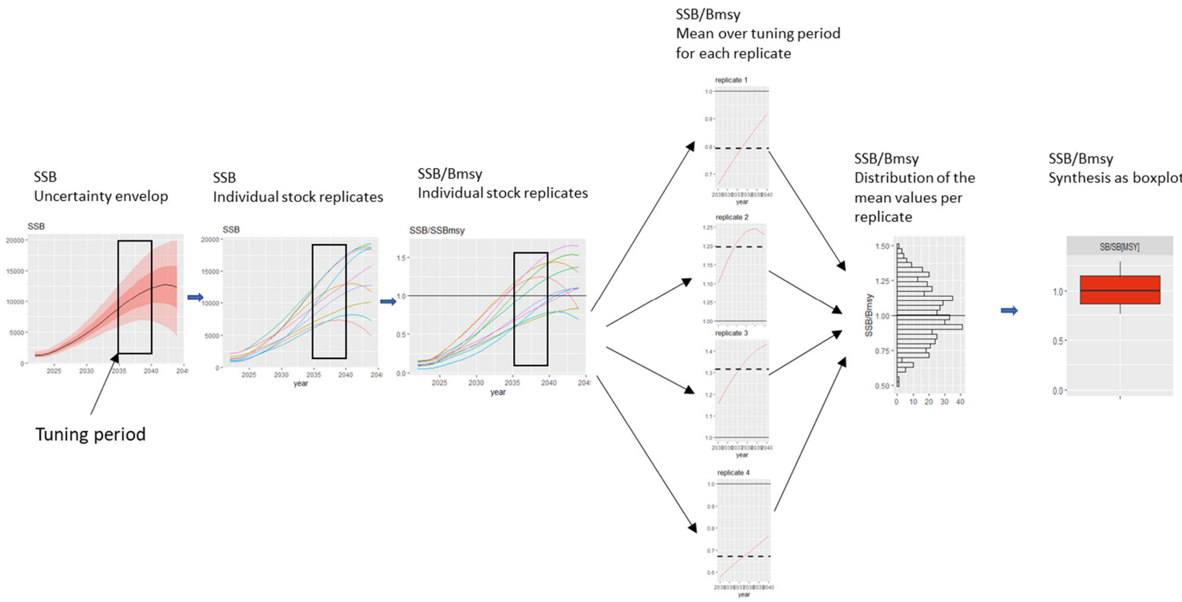

Figure 5-4 *Computation of performance statistics: each simulation run contains 500 stock replicates. For each replicate, the performance statistics (here SSB/B_{MSY}) are calculated using the mean SSB of the replicate over the tuning period (black rectangle) and divided by the specific reference value (B_{MSY}) of the replicate. The statistical distribution of the 500 resulting SSB/B_{MSY} values can then be represented by a box plot. In this example the median of the distribution (black line) is at 1, corresponding to a situation in which the probability of being at or above B_{MSY} is 50%.*

5.3.2 Tuning management procedures

The candidate management procedures have control parameters which impact the overall performance of the MP (see Section 5.2 on HCR). These control parameters can be automatically adjusted so that the management procedures meet the objectives set by the managers. The process first involves choosing a tuning period (time horizon by which the management objective should be met) and choosing a specific tuning criteria (observing a given outcome with a given probability) based on the set of specific 'performance statistics' described above. The value of the MP parameter is obtained by iteratively testing different values for the control parameter that is deemed to be the most appropriate, until the resulting management procedure meets the tuning objectives. This process is called "tuning".

Tuning was carried out three times, for three different management objectives for the CHR MP and the CPUE-based MP, resulting in a total of six MPs per stocks. The management objectives chosen (see chapter 1.3.3) were to achieve over the medium to long term (years 2035 to 2040):

1) a 50% probability of having a stock size at or above the biomass level necessary to deliver in the long term the Maximum Sustainable Yield ($\boldsymbol{B_{msy}}$; *denoted as* '_**B**' *below*)

2) a 50% probability of being simultaneously at an exploitation level or below the fishing mortality associated with Maximum Sustainable Yield ($\boldsymbol{F_{msy}}$*; denoted as* '_**F**' *below*)

3) the two previous objectives simultaneously (***both****; denoted as* '_**both**' *below*).

Thus, there are six MPs (HCR + tuning objective) that are compared; '**CHR_B'**, **CPUE_B**', '**CHR_F**', '**CPUE_F**', '**CHR_both**', '**CPUE_both**'.

The tuning criteria are calculated by first calculating the performance statistics for each stock replicate and then taking the mean across all replicates. For example, when tuning for 50% probability of being above B_{MSY}, the probability is first calculated for each stock replicate as the number of years in the tuning period for which B>B_{MSY}, divided by six (the total number of years in the tuning period). Then the mean of the values of the 500 replicates is calculated, and the tuning iteratively adjusts the control parameter of the MP until this mean is equal to 50%.

6 Results: Management Procedures

The performance of the tested MPs is summarized using a standard series of figures:

- Boxplots compare the MP performance in the 2035-2040 tuning period, for all six performance statistics.
- Time series plots are presented with the top panel showing the yearly values in the historical period, and each of the bottom panels displaying the projection period (2023-2044), for a selection of performance statistics (B/B_{MSY} and Fishery catches).
- In Appendix 6 additional information is given: the time series for F/F_{MSY}, trade-off plots between performance statistics and tables with the parameter values of the performance statistics (corresponding to the boxplots). For an explanation of how to read the boxplots and time series, see Figure 1-2.

6.1 Pikeperch

Configuration of the MPs
Each of the two MP types have been tuned for a single parameter, deemed to be more responsive (

Table *6-1*). For CHR MP this is the target harvest rate, while the survey index value at which the HCR starts decreasing catches, $I_{trigger}$, was set following the standard formulation in ICES, at 1.4 times the minimum survey index value observed in the past. For the CPUE MP, again the target level was selected as the tuneable parameter, while the responsiveness arguments, k_a and k_b, were kept at the standard value of 0.2.

Table 6-1 *Pikeperch. Management procedure parameters obtained after tuning, and fixed parameters for pikeperch.*

MP	Tuning Objective	Target Parameter Tuned	Fixed parameters
CHR	$p(B \geq B_{MSY})=50\%$	harvest rate = 103.1	$I_{trigger}= 0.767$
CHR	$p(F \leq F_{MSY})=50\%$	harvest rate = 96.9	$I_{trigger} = 0.767$
CHR	*both*	harvest rate = 90.6	$I_{trigger} = 0.767$
CPUE	$p(B \geq B_{MSY})=50\%$	index value = 2.99	$k_a = k_b =0.2$
CPUE	$p(F \leq F_{MSY})=50\%$	index value = 2.48	$k_a = k_b =0.2$
CPUE	*both*	index value = 3.07	$k_a = k_b =0.2$

Tuning of both MPs was carried out for a primary performance objective of obtaining a 50% probability over the 2035-2040 period, and for the three performance statistics (Section 5.3.2): the probability of spawning biomass being equal or above the B_{MSY} reference point, that of the fishing mortality being equal or below the F_{MSY} value, and that of both the previous being true.

Performance of the MPs
The performance indicators for the tuned MPs for pikeperch are shown in **Figure 6-1**. For all MPs, the tuning objectives are achieved: for CHR_B and CPUE_B, the mean of B/B_{MSY} is at 1, for CHR_F and CPUE_F, the mean of F/F_{MSY} is at 1, and for CHR_both and CPUE_both, the mean of B/B_{MSY} at 1 (while F/F_{MSY} is always lower than 1). Note that the black line on **Figure 6-1** shows the median of the distribution, which differs from the mean, and is therefore not always exactly on 1.

All three management objectives combined with the two MPs led to a convergence of the tuning process. Tuning for both F and B at MSY levels returns MPs which are closer to those obtained from tuning for B at MSY level only, as seen by comparing the corresponding distributions in the top row of **Figure 6-1** (see CPUE_B vs. CPUE_both, for example). The CPUE MP appears to perform more poorly when tuned for F/F_{MSY}, with a large uncertainty and expected levels of biomass that are too low (for example with very high risks of $B<B_{lim}$ for CPUE_F). This might be due to the initial stock status being close to that achieved by tuning for the MSY biomass level, compared to what is needed to reach F_{MSY}. The stock status indicators appear to show that the CHR MP could be expected to maintain the stock at the target biomass levels for any of the tuning objectives. The risk of biomass falling below the B_{lim} level is in some cases slightly higher than 10% for the CHR MPs: 12% when tuned for biomass (CHR_B), and 14% when tuned for fishing mortality (CHR_F) (see Table A6.1 in Appendix 6). Both MP types differ in the level of expected catches they report under the simulation conditions. The CHR MP appears to be able to provide higher catches and with less variability in 2035-2040. The path this MP takes to achieved the tuning objectives is based on changing stock abundance by a small rate. In contrast, the CPUE-based MP takes initial larger catches to bring the stock to a level that then requires a substantial reduction to achieve the targets. The difference in behaviour must be related in a large part to their different speed of reaction to stock changes, which is faster in the case of CHR MP. No differences can be observed in the expected changes to the abundance of large fish, as measured by the BWML indicator.

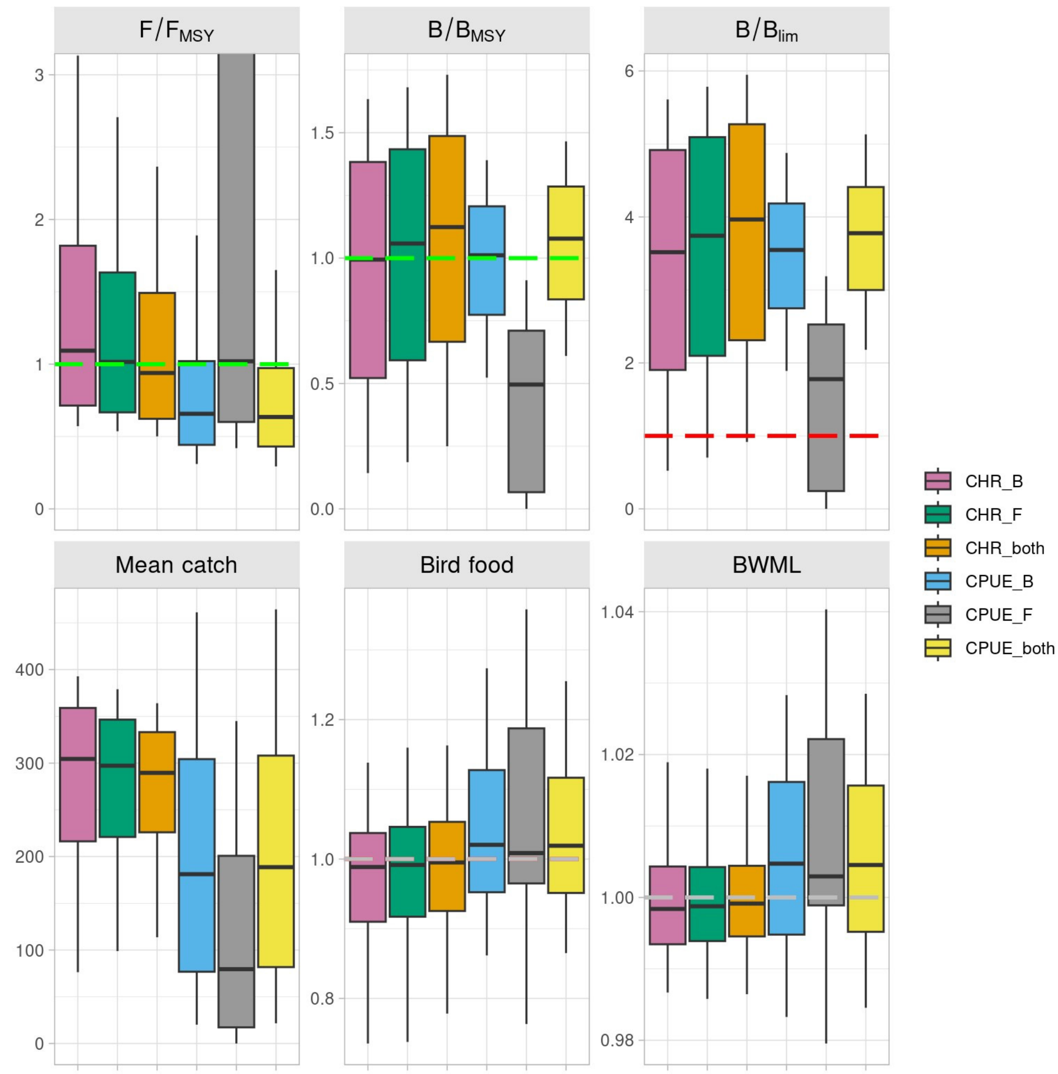

Figure 6-1 *Pikeperch. Boxplots of the performance for all management procedures applied along six statistics: fishing mortality relative to F_{MSY} (F/F_{MSY}), spawning stock biomass relative to B_{MSY} (B/B_{MSY}) and to B_{lim} (B/B_{lim}), mean catch of the fishing fleet (Mean catch), stock biomass available for the birds (Bird food) and biomass-weighted mean length (BWML). Dashed horizontal lines represent the various target values (green) or lower limits (red) or reference values (grey). F concerns mortality by both the fisheries and the birds.*

Stock and catch trajectories

The pikeperch OM suggests the population is likely above B_{MSY} levels (Figure 6-2). Most population trajectories, therefore, would undergo a slight decline to reach B_{MSY} during the 2035-2040 tuning period to maximize fisheries yield at a sustainable rate (Figure 6-2). The CPUE MP achieves this by increasing the fisheries catches for most trajectories before 2035-2040. This, however, results in lower catches during the tuning period compared to both the CHR MP projections and the current catches (Figure 6-3). The CHR MP adopts a more stable approach resulting in reduced fluctuations in catches (Figure 6-3). Higher catches in the tuning period presented by the CHR MP compared to the CPUE MP, involves a trade-off that leads to lower initial catches from the first year of the projections (Table A6.1 in Appendix 6).

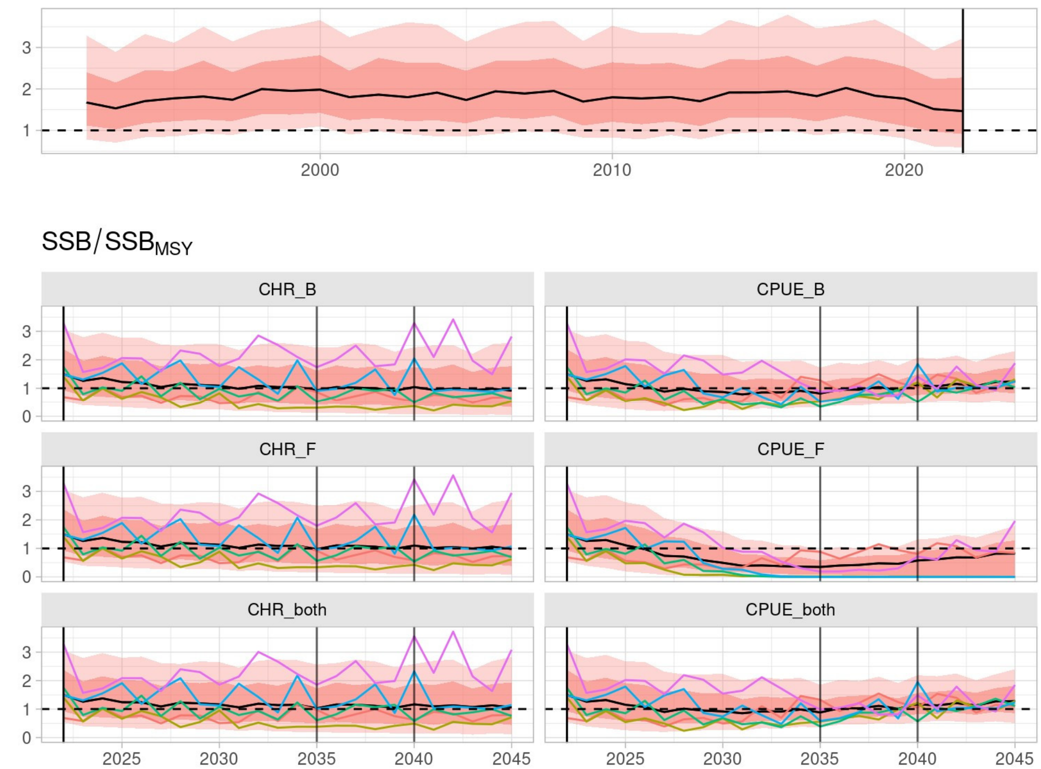

Figure 6-2 *Pikeperch. Time series of the SSB/SSB$_{MSY}$ indicator for the historical period (top panel) and for all management procedures applied for the future projection period (2023-2045; bottom panels). The five coloured lines represent the individual trajectories for five different iterations. (note: shorter name 'B/B$_{MSY}$' is used in the text)*

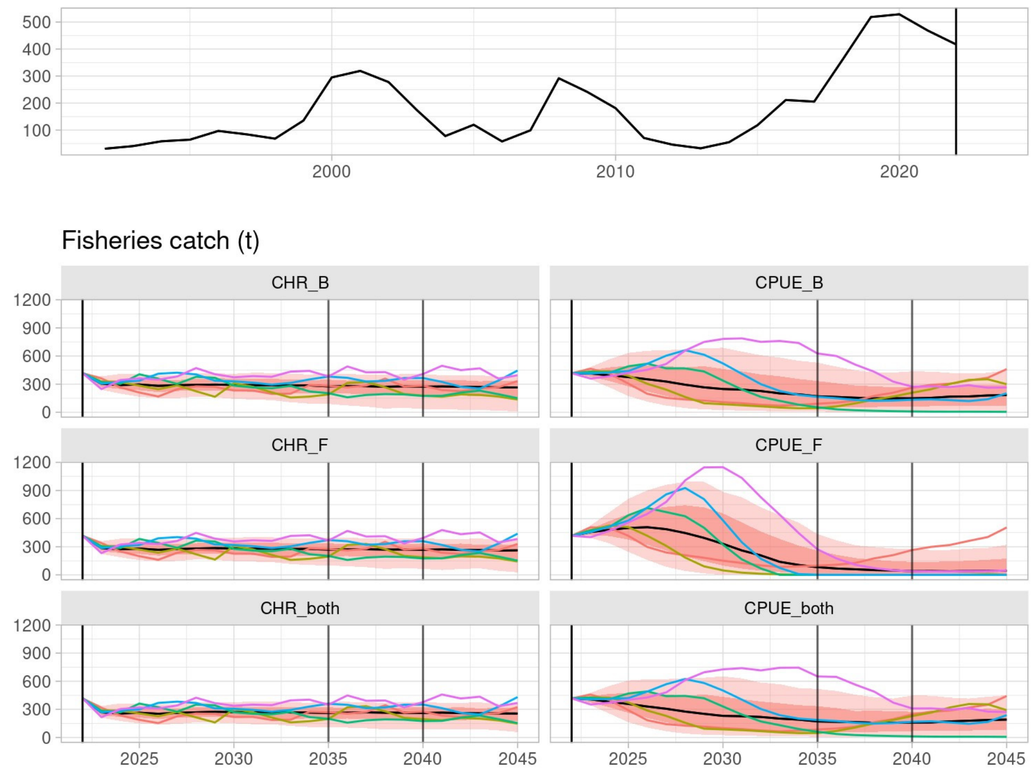

Figure 6-3 *Pikeperch. Time series of the catches from the commercial fishery for the historical period (top panel) and for all management procedures applied for the future projection period (2023-2045; bottom panels). The five coloured lines represent the individual trajectories for five different iterations.*

Robustness tests
The performance of the CHR MP, tuned for either F_{MSY} and B_{MSY}, was evaluated against a set of alternative OMs for the pikeperch stock (see section 4.1.5). These OMs reflect a series of alternative assumptions about past and future biology that have been identified as most relevant and of interest: variable natural mortality of age 0 fish ('Variable age 0 M'), an increase in natural mortality at older ages due to senescence (higher mortality at older ages, 'Higher M'), and changes in carrying capacity over the conditioning period (1992-2022) due to decreased productivity in the lake ('*Change in K*').

The ability of the tuned MPs to perform under the three alternative OMs was evaluated using the CHR_both MP as an example. The value of three performance statistics was compared over the tuning period (2035-2040). The results (*Table 6-2*) indicate that the MP performance would only be minimally affected due to the differences in biology between the base case and alternative OMs.

Table 6-2 Pikeperch. Median values of the B_{MSY} and F_{MSY} performance statistics, and mean probability of falling below B_{lim} (Pblim), obtained when applying the CHR_both tuned management procedure for pikeperch on three alternative OMs: variable M at age 0, higher M on older ages due to senescence, and changes in carrying capacity (K) due to decreasing productivity. Values are compared with those obtained when MPs are run on the base case OM.

Performance statistic	Base case	Variable age 0 M	Higher M	Change in K
B_{MSY}	1.12	0.98	0.98	0.88
F_{MSY}	0.94	1.10	1.02	1.00
Pblim	10.5%	12.9%	13.3%	7.5%

6.2 Perch

Configuration of the MPs

For the CHR MP, the trigger survey index value ($I_{trigger}$) used was 10.72 which is the 25% quantile of the historical survey biomass values. The default value used at ICES is 1.4 times the lowest survey value. However in cases where the index has some very low values (as it is the case for perch), this default approach would lead to very low $I_{trigger}$ values, that would not be a suitable trigger point in the harvest control rule, as it would result in a MP that reduces fishing when the stock is already at low levels. Using the 25% quantile of the distribution is an ad hoc solution used at ICES in such cases. Tuning this MP for the three criteria leads to target harvest rate values ranging from 94.4 to 96.9 (***Table 6-3***).

As for other stocks, the control parameters for the CPUE MPs were set at 0.2. The target survey index values obtained by tuning the MPs ranges from 11.4 to 13.0.

Table 6-3 *Perch. Management procedure parameters obtained after tuning, and fixed parameters.*

MP	Tuning Objective	Target Parameter Tuned	Fixed parameters
CHR	p(B≥B_{MSY})=50%	harvest rate = 87.6	Itrigger= 10.72
CHR	p(F≤F_{MSY})=50%	harvest rate = 96.9	Itrigger= 10.72
CHR	*Both*	harvest rate = 84.4	Itrigger= 10.72
CPUE	p(B≥B_{MSY})=50%	index value = 11.4	ka=kb=0.2
CPUE	p(F≤F_{MSY})=50%	index value = 12.5	ka=kb=0.2
CPUE	*both*	index value = 13.0	ka=kb=0.2

Performance of the MPs

The performance indicators for the tuned MPs for perch are shown in **Figure 6-4**. For all MPs, the tuning objectives are achieved: for CHR_B and CPUE_B, the mean of B/B_{MSY} is at 1, for CHR_F and CPUE_F, the mean of F/F_{MSY} is at 1, and for CHR_both and CPUE_both, the mean of B/B_{MSY} is at 1 (while F/F_{MSY} is always lower than 1). Note that the black line on **Figure 6-4** shows the median of the distribution, which differs from the mean, and is therefore not always exactly on 1.

For perch, there is a wide range of uncertainty in the biomass-related performance indicators (B/B_{MSY} and B/B_{lim}). This mainly derived from the uncertainty in the starting conditions (OM values in 2022) which are relatively large. All MPs lead to 50% probability or more of being above B_{MSY} in the tuning period (except CHR_F), but given the variability in the OM, this also corresponds to a non-negligible risk for the stock to also be below B_{lim} in the tuning period. For the three tuned CHR MPs, the probability of being below B_{lim} is above 23% (see Table A6.2 in Appendix 6). For the CPUE MP, the probability of being below B_{lim} is at or under 10%, with the CPUE_both MP showing the lowest value at 6.2% (Table A6.2 in Appendix 6). Overall, the CPUE MPs lead to higher biomass (for the same tuning criteria) and smaller uncertainty than the CHR MPs for perch.

All perch MPs display high uncertainty when tuned with the F/F_{MSY} objective (**Figure 6-4**) which is partly due to the variability in the starting conditions, but also influenced by the effect of the MP. For example, the application of the CHR MPs to perch results in substantially increased uncertainty in relative fishing mortality (F/F_{MSY}) for the initial years of the projections, but the variation narrows as it reaches the tuning period 2035-2040 (Figure A6.4 in Appendix 6). For the CPUE MPs, the range of variation in F/F_{MSY} increases over time and is particularly large during the tuning period (Figure A6.4 in Appendix 6).

As most stock trajectories for the perch OM suggest that it is currently above B_{MSY}, its associated MPs bring the stock down to B_{MSY} levels in future projections by increasing catches. Implementing the tuned MPs would lead to an initial (first year) increase in perch catches for the CHR MPs by a factor of 25 and a factor of 2.5 for the CPUE MPs[12] (**Figure 6-6** and Table A6.2 in Appendix 6). There are differences in

[12] Change in median catch in the OM, from 2022 to 2023

the mean catch in 2035-2040 between the two MP types, with median values around 1100 tonnes for all CHR MPs, while values vary between 1478 and 2151 for the CPUE MPs. Uncertainty in these catches is, however, quite large for the CPUE MPs, ranging from around 500 to just under 5000 tonnes.

The biomass of perch available for the birds in the tuning period is similar to the current value for the CHR MPs, but 5% to 10% lower for the CPUE MPs, with a large uncertainty. The mean length of perch in 2035-2040 is only marginally different from the current values, but there is also a large uncertainty for the CPUE MPs.

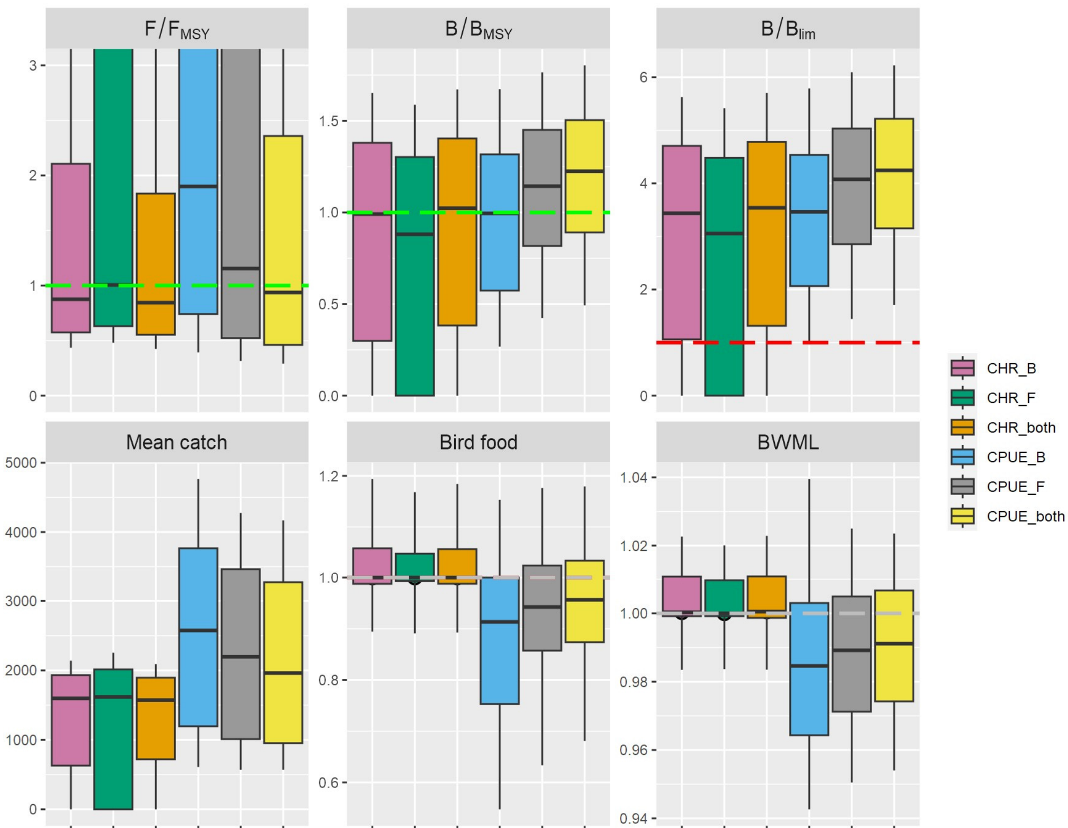

Figure 6-4 *Perch. Boxplots of the performance for all management procedures applied along six statistics: fishing mortality relative to F_{MSY} (F/F_{MSY}), spawning stock biomass relative to B_{MSY} (B/B_{MSY}) and to Bl_{im} (B/B_{lim}), mean catch of the fishing fleet (Mean catch), stock biomass available for the birds (Bird food) and biomass-weighted mean length (BWML). Dashed horizontal lines represent the various target values (green) or lower limits (red) or reference values (grey). F concerns mortality by both the fisheries and the birds.*

Stock and catch trajectories

The two MP types lead to different stock trajectories (**Figure 6-6** for biomass and **Figure 6-6** for catch). For the CHR MP, due to a sharp initial increase in the catches, the perch stock quickly decreases and the median SSB reaches levels below B_{MSY} in 2024. In the second part of the simulations, the MPs lead to a recovery in SSB to above B_{MSY} levels. Due to this initial rise in the catches with the CHR MP, a high proportion of the stock replicates (those starting the simulation with a low stock status) even collapse within the first years of the implementation of this MP.

With the CPUE MP, the catch increases progressively and the stock remains stable well above B_{MSY} for the first part of the simulation period. For part of the stock replicates (that were identified as having a number of successive good recruitments at the start of the simulation period), the CPUE MPs lead to a continued increase in the catches. Eventually, for these replicates, the stock cannot sustain the level of catch advised and it collapses, most of the time around 2035 to 2040. This tends to happen more frequently as the simulation time progresses, and ultimately results in a median stock biomass declining strongly in the years after 2040.

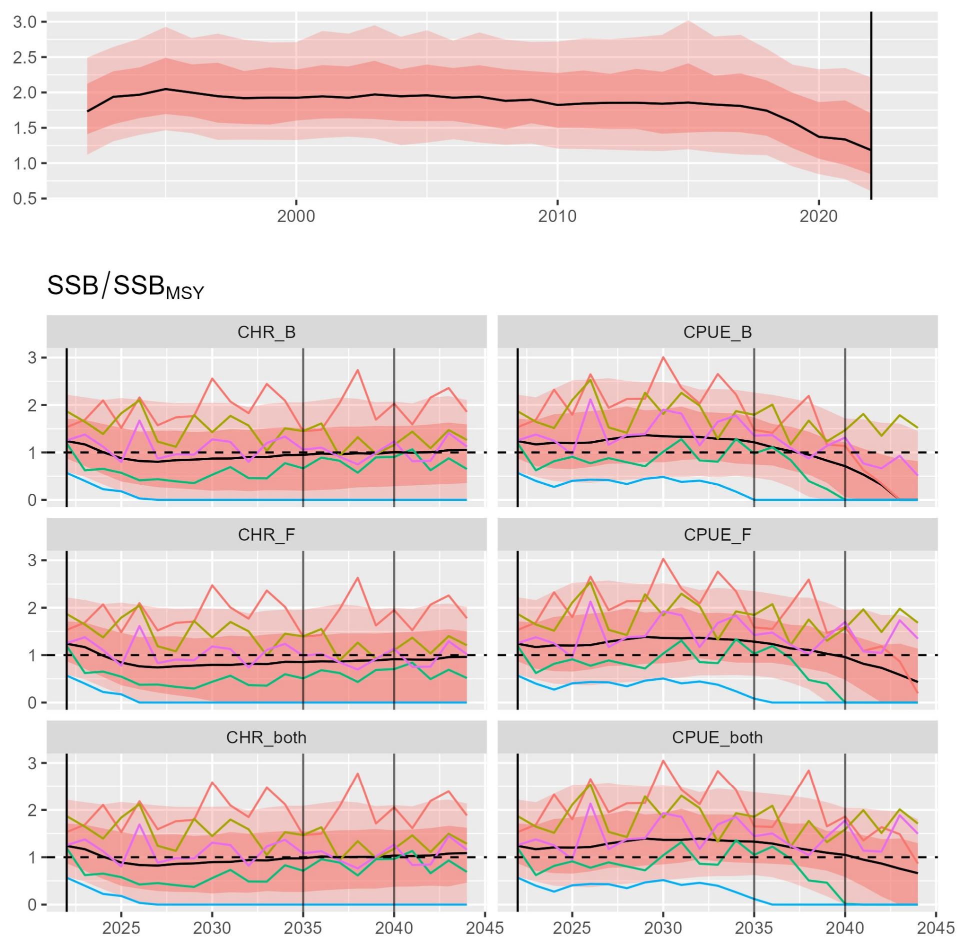

Figure 6-5 *Perch. Time series of the SSB/SSB$_{MSY}$ indicator for the historical period (top panel) and for all management procedures applied for the future projection period (2023-2045; bottom panels). The five colored lines represent the individual trajectories for five different iterations. (note: shorter name 'B/B$_{MSY}$' is used in the text).*

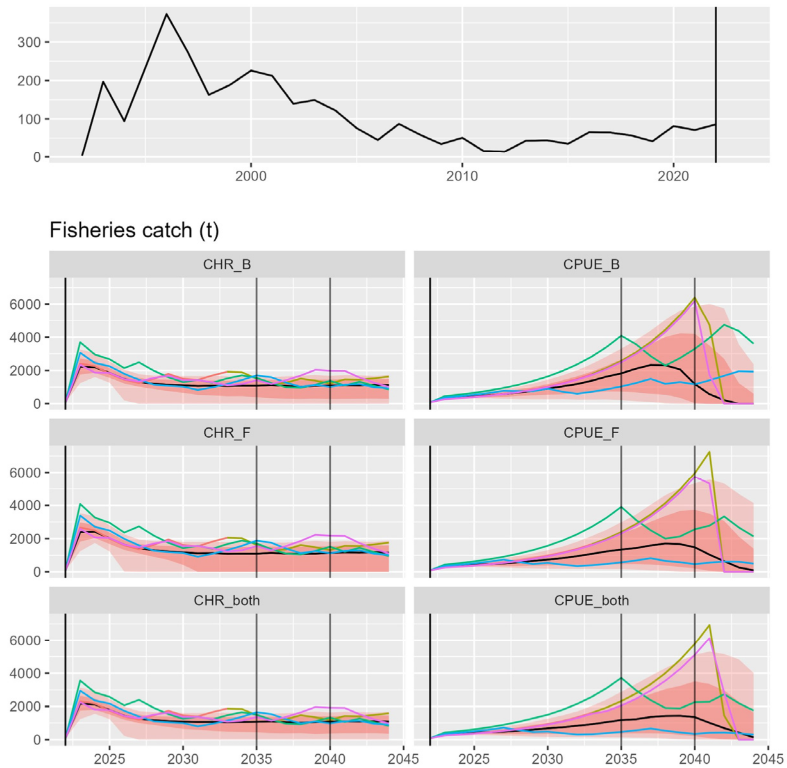

Figure 6-6 *Perch. Time series of the catches from the commercial fishery for the historical period (top panel) and for all management procedures applied for the future projection period (2023-2045; bottom panels). The five colored lines represent the individual trajectories for five different iterations.*

6.3 Bream

Configuration of the MPs

For the CHR MPs, both of the approaches used for pikeperch (section 6.1) and perch (6.2) led to quite low $I_{trigger}$ values for bream, as the indices for bream have been at very low levels. Therefore, the trigger survey index value ($I_{trigger}$) used was the survey index value for the year 2000. Based on the OM, 2000 was one of the last years where the stock biomass was above B_{MSY} (**Figure 4-12**). Using this value as the trigger point in the harvest control rule means that until the stock recovers to the levels corresponding to MSY, the exploitation level will be reduced compared to the target harvest rate value. This is, therefore, a way to ensure that the MP leads to a recovery of the stock. Tuning this MP for the three management objectives leads to target harvest rate values ranging from 367 to 559 (***Table 6-4***).

As for other stocks, the control parameters for the CPUE MPs were set at 0.2. The target survey index values obtained by tuning the MPs ranges from 1.72 to 2.28.

Table 6-4 *Bream. Management procedure parameters obtained after tuning, and fixed parameters.*

MP	Tuning Objective	Target Parameter Tuned	Fixed parameters
CHR	$p(B \geq B_{MSY})=50\%$	harvest rate = 381.3	$I_{trigger}$= 8.13
CHR	$p(F \leq F_{MSY})=50\%$	harvest rate = 559.4	$I_{trigger}$= 8.13
CHR	*both*	harvest rate = 367.2	$I_{trigger}$= 8.13
CPUE	$p(B \geq B_{MSY})=50\%$	index value = 2.27	$k_a=k_b$=0.2
CPUE	$p(F \leq F_{MSY})=50\%$	index value = 1.72	$k_a=k_b$=0.2
CPUE	*both*	index value = 2.28	$k_a=k_b$=0.2

Performance of the MPs

The performance indicators for the tuned MPs for bream are shown in **Figure 6-7**. For all MPs, the tuning objectives are achieved : for CHR_B and CPUE_B, the mean of B/B_{MSY} is at 1, for CHR_F and CPUE_F, the mean of F/F_{MSY} is at 1, and for CHR_both and CPUE_both, the mean of B/B_{MSY} at 1 (while F/F_{MSY} is always lower than 1). Note that the black line on **Figure 6-7** shows the median of the distribution differs from the mean, and is therefore not always exactly on 1.

Except for the CPUE_F MP, all other the tuned MPs, lead to a low risk of being outside safe biological limits during the tuning period (2035-2040), with all MPs having a probability of $B<B_{lim}$ of 0% (Table A6.3 in Appendix 6). For the CPUE_F MP, the risk is larger than 10% (12.6%).

The choice of the management objective used for tuning has a large impact on the MP performance. Aiming for 50% chance of being below F_{MSY}, leads to higher fishing mortality, lower stock size, and higher catches than aiming for 50% chance of being above B_{MSY} (or both criteria combined). Aiming for F_{MSY}, combined with the choice of the CPUE MP leads to the lowest stock size, and higher risk to be below B_{lim} (12.6%).

The type of MP used leads to large differences in performance. The CHR MP leads to higher catches and higher average fishing mortality in the tuning period compared to the CPUE MP (for the same tuning criteria). There is also less uncertainty in the mean catch for the CHR MP than for the CPUE MP. There is however little difference in stock size between most of the MPs with the exception of tuning for F_{MSY} which typically leads to lower stock size (see B/B_{lim} in **Figure 6-7**).

Implementing the CHR MP implies a strong reduction in the catch in the first year of implementation (73% to 82%[13], Table A6.3 in Appendix 6). The initial reduction in catches is smaller for the CPUE MP (less than 26%).

[13] Change in median catch in the OM, from 2022 to 2023

For all MPs, the stock biomass available for the birds increases between the start of the simulation and the tuning period, but by a small percentage (4% to 6% depending on the MP). The mean length also increases but only by 1% to 2%.

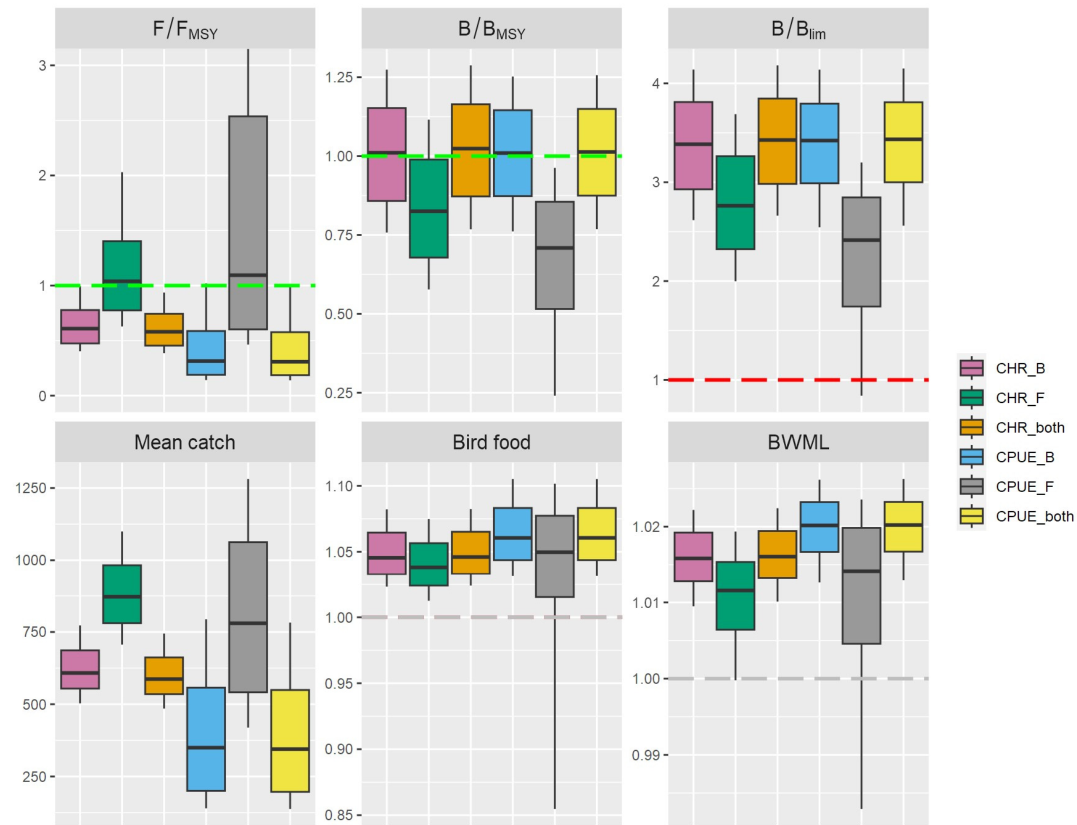

Figure 6-7 *Bream. Boxplots of the performance for all management procedures applied along six statistics: fishing mortality relative to F_{MSY} (F/F_{MSY}), spawning stock biomass relative to B_{MSY} (B/B_{MSY}) and to B_{lim} (B/B_{lim}), mean catch of the fishing fleet (Mean catch), stock biomass available for the birds (Bird food) and biomass-weighted mean length (BWML). Dashed horizontal lines represent the various target values (green) or lower limits (red) or reference values (grey). F concerns mortality by both the fisheries and the birds.*

Stock and catch trajectories

All MPs result in trajectories with a recovery of the stock (**Figure 6-8**). The MPs tuned for B_{MSY} and 'both' B_{MSY} and F_{MSY}, lead to SSB reaching levels above B_{MSY} during the tuning period. However, while the increase in SSB continues after the tuning period for the CPUE MPs, it levels off or decreases slightly for the CHR MPs (**Figure 6-8**). When tuning for F_{MSY}, the SSB does not recover to above B_{MSY} for most of the stock replicates and SSB declines for both MP types after the tuning period.

Both CHR and CPUE MPs result in an initial reduction in the catch for bream (**Figure 6-9**). For the CHR MPs, this reduction occurs in the first year, and the catches increase in the subsequent years. The CPUE MPs reduce the catch progressively until around 2030 after which the catches start to increase, but to lower levels than with the CHR MP for the tuning period.

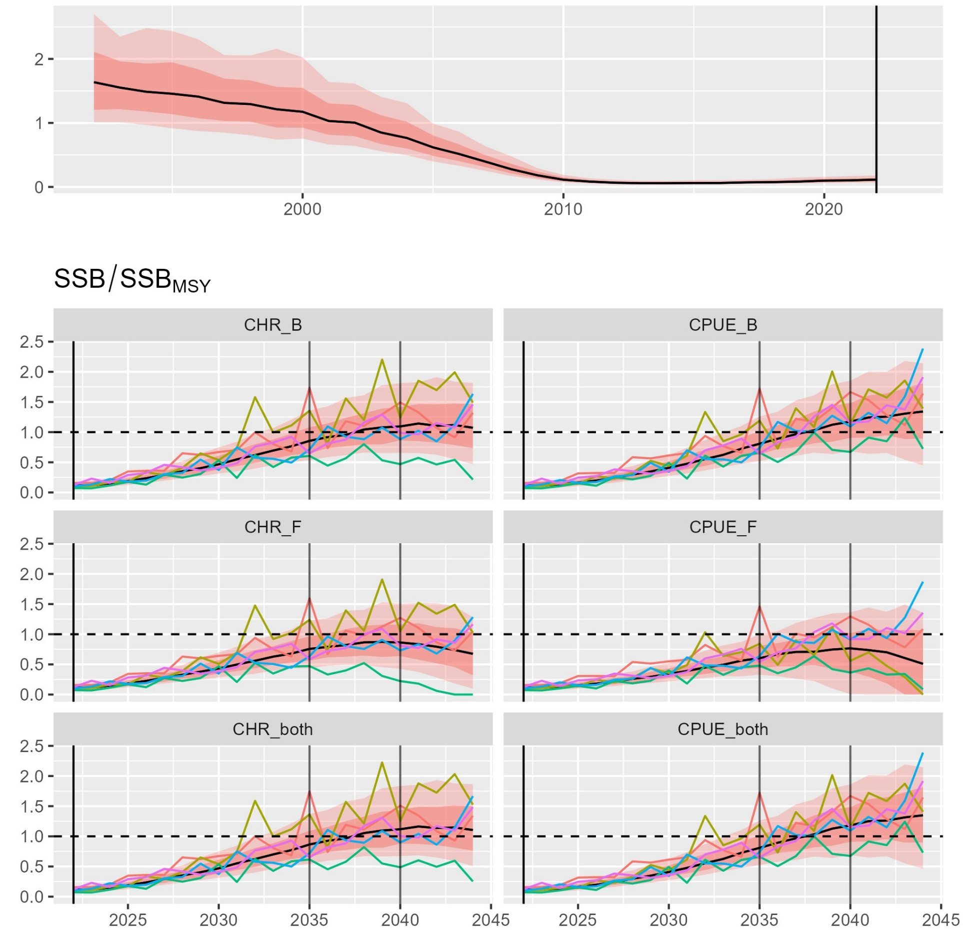

Figure 6-8 *Bream. Time series of the SSB/SSB$_{MSY}$ indicator for the historical period (top panel) and for all management procedures applied for the future projection period (2023-2045; bottom panels)Perch. The five colored lines represent the individual trajectories for five different iterations. (note: shorter name 'B/B$_{MSY}$' is used in the text)*

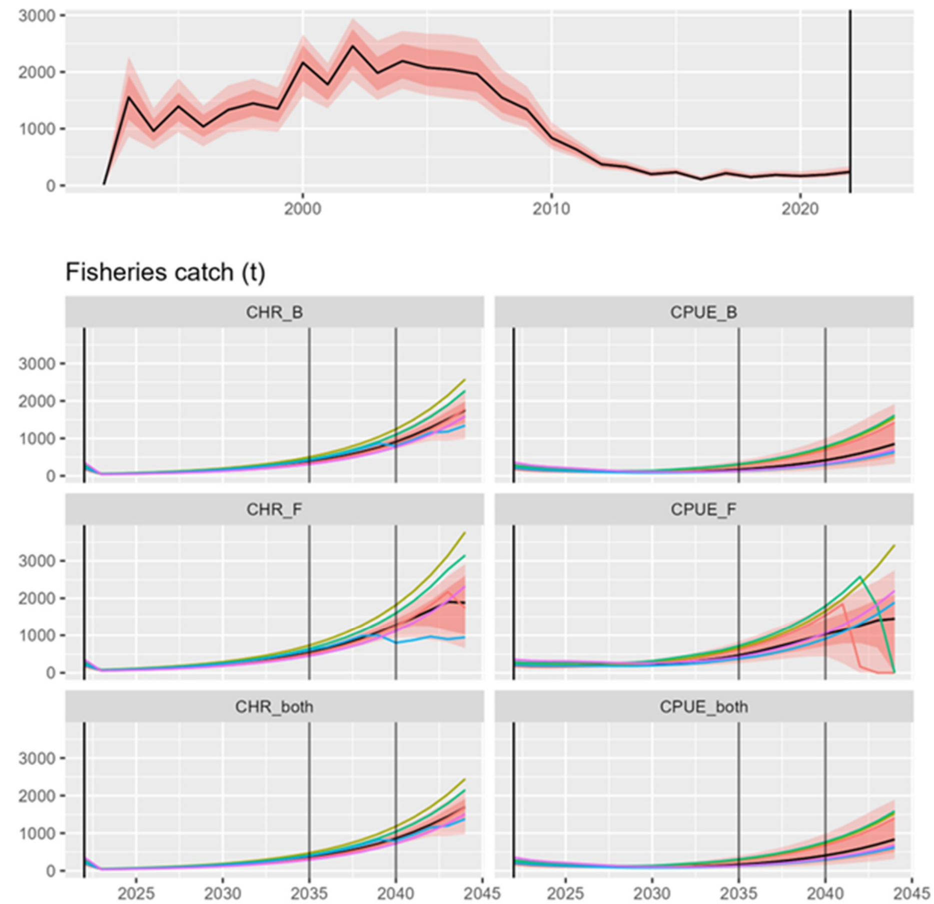

Figure 6-9 *Bream. Time series of the catches from the commercial fishery for the historical period (top panel) and for all management procedures applied for the future projection period (2023-2045; bottom panels). The five colored lines represent the individual trajectories for five different iterations.*

6.4 Roach

Configuration of the MPs

Similar to bream, the method used to determine the trigger survey index value $I_{trigger}$ for pikeperch and perch resulted in values that were too low for the CHR harvest control rule to be effectively applied to roach. This may be attributed to the biomass levels for bream and roach which have estimated by their respective OMs to be under B_{MSY} levels for a substantial portion of the recorded dataset. The CHR MPs used for roach, thus, applied an $I_{trigger}$ value corresponding to the survey index value recorded in the year 1999, marking the final year where the stock biomass was above B_{MSY} (**Figure 4-16**). Using this value as the trigger point in the harvest control rule is a strategic choice aimed at ensuring that the MP effectively guides the stock towards recovery. Tuning this MP with the three defined strategies (B_{MSY}, F_{MSY}, both) leads to target harvest rate values ranging from 84.4 to 114.8 (***Table 6-5***)

As for all species, the control parameters for the CPUE MPs were set at 0.2. The target survey index values obtained by tuning the MPs ranges from 1.24 to 1.47.

Table 6-5 *Roach. Management procedure parameters obtained after tuning, and fixed parameters.*

MP	Tuning Objective	Target Parameter Tuned	Fixed parameters
CHR	*p(B≥B_{MSY})=50%*	harvest rate = 84.4	$I_{trigger}$= 4.54
CHR	*p(F≤F_{MSY})=50%*	harvest rate = 114.8	$I_{trigger}$= 4.54
CHR	*both*	harvest rate = 84.4	$I_{trigger}$= 4.54
CPUE	*p(B≥B_{MSY})=50%*	index value = 2.1	k_a=k_b=0.2
CPUE	*p(F≤F_{MSY})=50%*	index value = 1.8	k_a=k_b=0.2
CPUE	*both*	index value = 2.1	k_a=k_b=0.2

Performance of the MPs

The performance statistics for the tuned MPs for roach are shown in **Figure 6-10**. Across all MPs, the tuning objectives were successfully met. These results are supported with the mean value when tuning for B/B_{MSY} being 1 for CHR_B and CPUE_B when tuning for the MSY biomass objective, and with the mean value when tuning for F/F_{MSY} being 1 for CHR_F when tuning for the MSY fishing pressure objective. When tuning for B/B_{MSY}, the mean CHR_F, CPUE_F and are lower than 1, while CHR_B, CPUE_B, CHR_both and CPUE_both are all lower than 1 when tuning for F/F_{MSY}. Note that the black line on **Figure 6-10** shows the median of the distribution differs from the mean, and is therefore not always exactly on 1.

For roach, 4 out of 6 tuned MPs display a relatively low risk (<10%) of falling outside of safe biological limits (B<B_{lim}) during the tuning period (2035-2040). CPUE_F exhibits the highest risk of B falling under B_{lim} with a 11.6% risk (Table A6.4 in Appendix 6). It is worth noting that the risk associated with CHR MP's (7.8-10.8%) were generally lower than that showed by CPUE MPs (9.2-11.6%; Table A6.4 in Appendix 6).

The choice of the management objective used for tuning has a sizable impact on the MP performance. Similar to bream, targeting a 50% chance of being below F_{MSY}, leads to higher fishing mortality, lower stock size, and higher catches compared to aiming for a 50% chance of being above B_{MSY} or aiming to achieve both F_{MSY} and B_{MSY} combined. The F_{MSY} objective used with the CPUE MP leads to the lowest stock size, and highest risk of population depletion for roach.

The CHR MP leads to higher catches compared to the CPUE MP (for a same tuning criterion). Like bream, there is less uncertainty for the mean catch for the CHR MP compared to the CPUE MP. Between MP types (CHR vs. CPUE) stock size is not markedly different.

The CHR MP is linked to a strong reduction in the catch in the first year of implementation (32% to 50%[14]; Table A6.4 in Appendix 6). Catches for the CPUE MP decrease by only 2% in the first year but show a progressive decline in the following years (Table A6.4 in Appendix 6).

For all MPs, the stock biomass available for the birds increases between the start of the simulation and the tuning period, but only by a small percentage (1% to 3% depending on the MP). The mean length also increases but at a maximum of 1 % when using the CPUE MP.

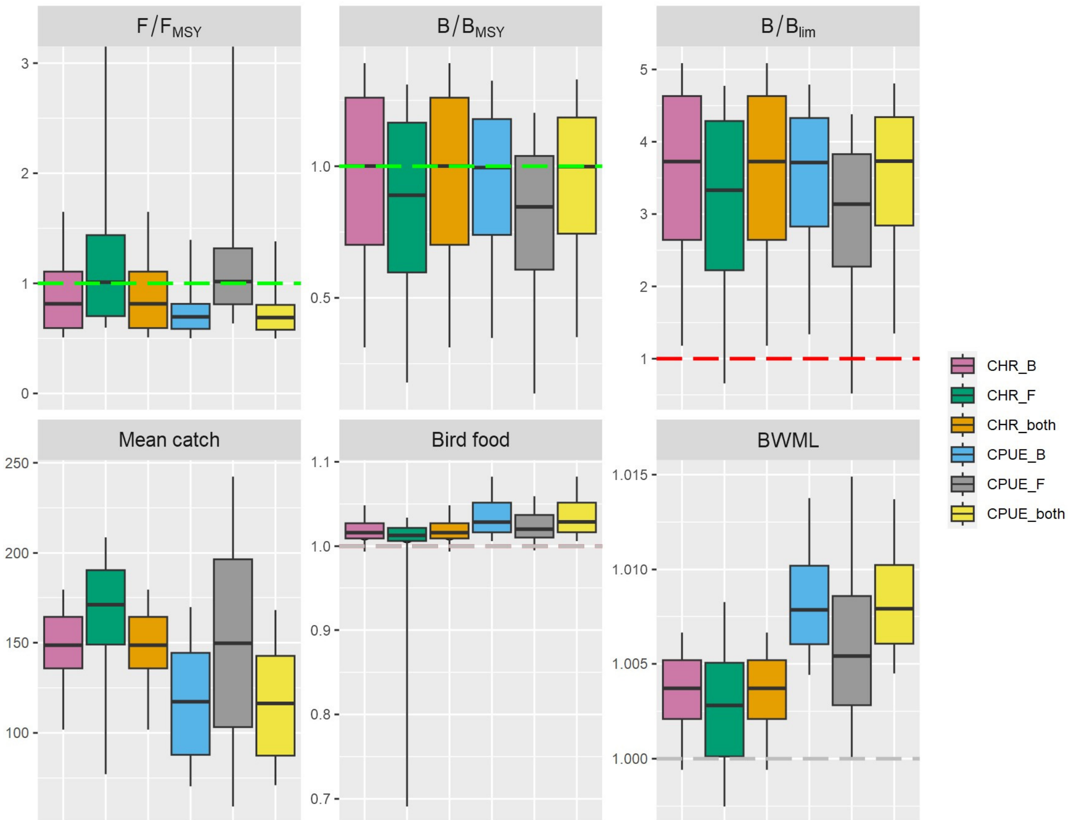

Figure 6-10 *Roach. Boxplots of the performance for all management procedures applied along six statistics: fishing mortality relative to F_{MSY} (F/F_{MSY}), spawning stock biomass relative to B_{MSY} (B/B_{MSY}) and to B_{lim} (B/B_{lim}), mean catch of the fishing fleet (Mean catch), stock biomass available for the birds (Bird food) and biomass-weighted mean length (BWML). Dashed horizontal lines represent the various target values (green) or lower limits (red) or reference values (grey). F concerns mortality by both the fisheries and the birds.*

Stock and catch trajectories

The MPs for roach collectively suggest a recovery in spawning stock biomass (SSB) by the 2035-2040 target period (**Figure 6-11**). Most trajectories for MPs tuned to optimize for B_{MSY} and F_{MSY} (and the combination of both) lead to SSB reaching levels at or near B_{MSY} during the tuning period. The CPUE MPs tuned for B_{MSY} and both (B_{MSY} and F_{MSY}) display an upward trajectory in SSB after the tuning period. As with bream, most trajectories for MPs tuned for F_{MSY} do not depict SSB recovering to levels above B_{MSY}. However, in contrast to bream, trajectories for both MPs types remain relatively stable after the tuning period.

[14] Change in median catch in the OM, from 2022 to 2023

Both MP exhibit reductions in the catch during a certain period (**Figure 6-12**). For the CHR MPs, this reduction occurs in the first year with catches increasing in the subsequent years. The CPUE MPs reduce the catch progressively until after the tuning period when catches begin to increase slightly. Catches for the CHR MPs are consistently higher than for the CPUE MPs over the tuning period.

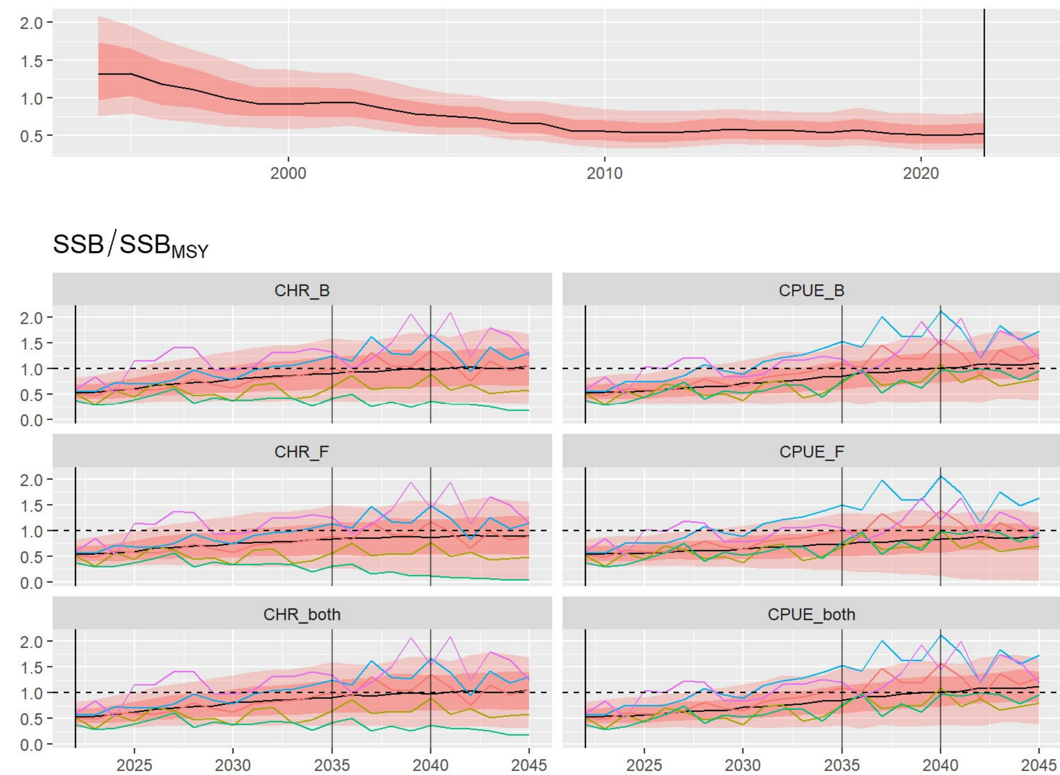

Figure 6-11 *Roach. Time series of the SSB/SSB$_{MSY}$ indicator for the historical period (top panel) and for all management procedures applied for the future projection period (2023-2045; bottom panels). The five colored lines represent the individual trajectories for five different iterations. (note: shorter name 'B/B$_{MSY}$' is used in the text)*

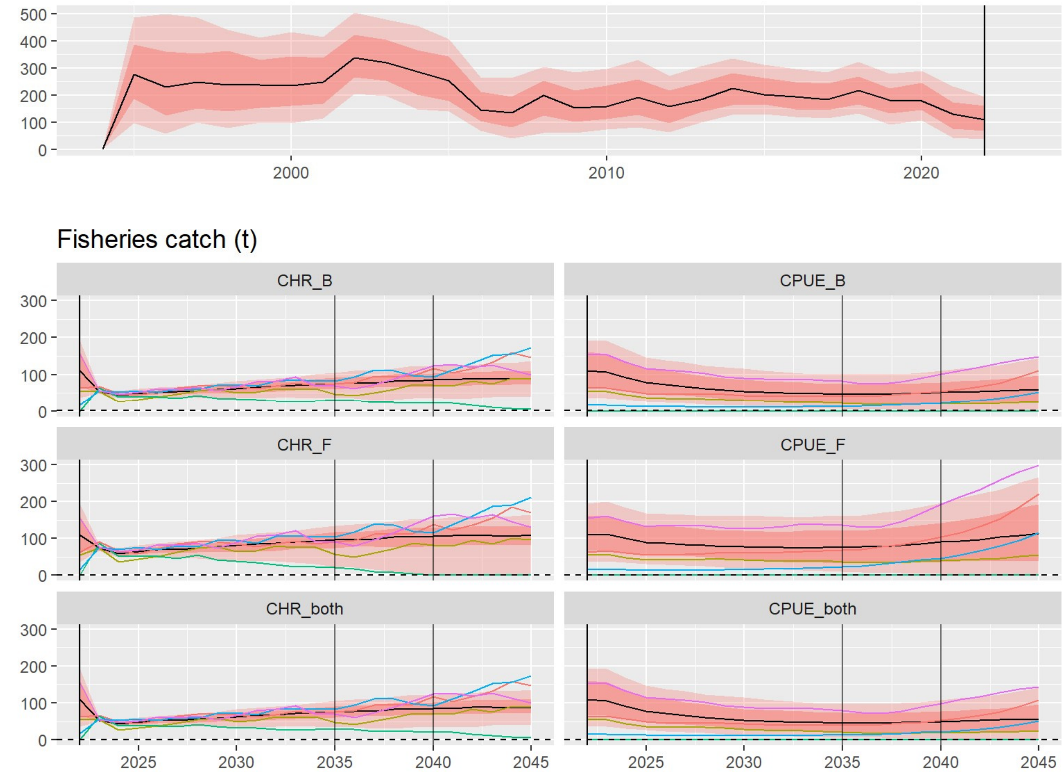

Figure 6-12 *Roach. Time series of the catches from the commercial fishery for the historical period (top panel) and for all management procedures applied for the future projection period (2023-2045; bottom panels). The five colored lines represent the individual trajectories for five different iterations.*

7 Discussion and conclusions

The following discusses key insights and interpretations derived from the results presented in the previous chapter (MP results). It is important to note that the results from these MSEs originate from scenario-based simulations that incorporate predictive elements from empirical data. These results should be viewed primarily as tools for guiding management decisions rather than precise qualifications of stock status or precise predictions of future stock and catch trajectories. The intention is to provide structured frameworks for implementing and adjusting management strategies based on the most reliable scientific information available.

Among the six combinations of MPs (CHR or CPUE; *see Section 5.2*), and tuning strategies (B_{MSY}, F_{MSY}, or both; see Section 5.3.2), this analysis attempts to highlight the options associated with the highest/lowest risk levels together with maintaining sustainable future stock populations as well as trade-offs linked to catches, stock biomass and conservation strategies.

7.1 Pikeperch

Both candidate MP types set up for pikeperch could be tuned to achieve the various management objectives. Aiming for a 50% probability of reaching those objectives in the set time frame (2035-2040) might lead to a risk of biomass falling below the limit biomass reference point B_{lim} that is higher than the chosen level of 10% in some cases. The performance levels obtained from both MP types differ in a few elements, notably on the level and variability of catches that could be obtained under the simulated scenarios (**Figure 6-1**). The risk of overfishing (i.e. B falling below B_{lim}) is higher than desired for the CHR MP if set to achieve either the B_{MSY} or F_{MSY} objectives (14% and 12% respectively), while if set to achieve both simultaneously (CHR_both) it decreases to around 10%. These risks are calculated to be lower for the CPUE MPs, but at the cost of lower and more variable catches. The CPUE MP does not appear to be a viable option when set to achieve the F_{MSY} objective. Although it could be tuned to the F_{MSY} probability of 50%, the risk of depletion and expected biomass level are both outside of the accepted bounds. Setting the CHR MP to achieve both F_{MSY} and B_{MSY} levels provide similar catch levels as tuning for either of them separately but leads to less catch variability, a lower risk of biomass falling below B_{lim}, and a higher mean biomass over B_{MSY}.

No major differences are found across MPs in the returned values for both ecosystem-related performance statistics, the relative biomass of older fish (BWML) and the availability of bird food (**Figure 6-1**). Changes in BWML could be expected over a longer period for a relatively long-lived species such as pikeperch, though it is not evident within the projection period (2023-2044) of the current MPs.

7.2 Perch

For perch, all available CHR MP options result in risk levels surpassing 10% indicating that this MP is not considered precautionary for this stock (risk of stock depletion deemed excessively high). The CPUE MP applied to perch achieves acceptable risk levels, at or under 10%. Therefore, it is recommended to refrain from using the CHR MP and instead to consider the CPUE MP variations presented for perch. Among those, two slightly different management options are available: CPUE_F and CPUE_both, which result in lower catches, or the CPUE_B, that leads to higher catches, but at a lower stock biomass level and a risk to fall below B_{lim} that slightly exceeds 10%.

While leading to an acceptable risk of falling below B_{lim} in the tuning period 2035-2040, the CPUE MP sets the stock on a declining trajectory (starting during the tuning period), and the risk to fall below B_{lim} increases quickly beyond 2040 (**Figure 6-5**). When choosing to implement one of the CPUE MPs presented here, it is therefore advisable to periodically conduct a new MSE (at least once before 2035) to update the parameters to be used in the CPUE MP and make sure the implementation of this MP continues to be precautionary in the medium term.

The relatively high risk of falling below B_{lim} for this stock is due to the large uncertainty in the starting conditions of the future projection, with stock replicates starting at 0.5 B_{MSY} and others up to 2 times B_{MSY}. The stock replicates starting with a low biomass will have a higher chance to be under B_{lim} in the tuning period. Contrary to the other stocks, the feasible trajectory approach for perch did not lead to a strong selection of the initial depletion parameter (see **Figure 4-5**). In other words, during the OM construction process, the data used to select the feasible trajectories does not provide enough information to narrow the range of the possible initial depletion states to compare to the initial assumption. As a consequence, there is also a large range of stock status at the start of the projection period. The reason of this particularity in the perch OM is not clear, but it could be related to the selectivity curve of the survey which implies that the historical survey information is mainly informative on the biomass of juveniles. The survey might thus be too specific to a small portion of the population to be really useful in the feasible trajectory process.

Another difficulty in managing perch comes from the fact that the survey biomass is mainly representative of the younger fraction of the stock. Although information on recruitment can be relevant to manage stocks, management should ideally be based primarily on the exploitable and spawning biomass.

Finally, the by-catch of perch in the fyke fishery targeting eel were not considered in this analysis. Although this time series is too uncertain to use in the OM (see Appendix 1), it could have been used as a robustness test in order to test the influence of this by-catch on the MPs. In principle, these by-catches could have been included as a third fleet when building the OM, and taken into account in the simulation when testing the MPs. However, the catches from the fykes are mainly age 0 (appendix 2 in Tien et al., 2023), while the gillnet fishery starts targeting perch at age 2 and 3. Also, the volume of the catches is small in comparison to the catches by the birds (3% on average), which also predate on the younger age classes. Therefore, not including the catches in the fykes is not likely to have a noticeable impact on the OM, and the tuned MPs presented above can be considered robust to the non-inclusion of this data source.

7.3 Bream

For bream, all the MPs presented lead to acceptable probabilities of falling below safe biological limits (risk of $B<B_{lim}$ lower than 10%) in 2035-2040. The CHR MP implies a strong initial reduction of the catches and lower catches in the short term, but leads to a slightly faster recovery, and higher catches in 2035-2040. The CPUE MP brings the catch downwards progressively and therefore results in higher catches in the short-term, but as recovery in SSB is slower, catches during the tuning period (2035-2040) are markedly lower that with the CHR MP. There is also more uncertainty about the future level of the catches with the CPUE MP.

The choice of the tuning criteria also has a strong impact. Aiming at exploiting the stock at F_{MSY} over 2035-2040 does not allow the stock to recover to level above B_{MSY}. It leads to higher catches, but sets the stock on a declining trajectory beyond the tuning period (after 2040). Aiming at exploiting the stock at levels above B_{MSY} represents an option to rebuild the stock to higher level, around B_{MSY}, which means that it would set the stock on a correct path to obtain the highest possible yields in the longer term.

A limitation of the approach for this stock is that the model does not explicitly represent the two fleets fishing for bream. The modelled fishing fleet is a combination of the gillnet and seine fisheries. It implies that simulations are conducted assuming that the two fleet will have the same contribution to the total catch in the future as they had in the recent years. If management decisions lead to disproportionate changes in the efforts of the two fleets, the future exploitation pattern (selectivity-at-age) for the combined fishery might differ from the one assumed in this study, which would warrant updating the model.

7.4 Roach

Four out of six MPs for roach are expected to operate within safe biological limits (risk of $B<B_{lim}$ under 10%) during the tuning period of 2035-2040. The CPUE MP tuned for F_{MSY} (CPUE_F) is considered the riskiest objective, with a 11.6% probability of B falling under B_{lim}.

In terms of balancing the risk of bringing the stock under safe biological limits while maintaining high catches during 2035-2040, the CHR MPs generally outperform the CPUE MPs (**Figure 6-10**). However, achieving these safe biological limits with CHR MPs involves a reduction in catch during the first year of its implementation. This strategy contrasts with the more gradual decline in catches observed when implementing the CPUE MP (**Figure 6-12**).

When considering tuning objectives within the two MP types for roach, optimizing for F_{MSY} is linked to a higher risk of stock depletion, compared to tuning for B_{MSY} and both (B_{MSY} and F_{MSY}), accompanied by the trade-off of achieving higher catches (**Figure 6-10**). It is important to note that tuning for B_{MSY} or both B_{MSY} and F_{MSY}, while more conservative in the short and medium term, is expected to yield higher catches in the long-term (after 2040) as the stock rebuilds.

The roach stock shows similarities to bream in terms of its decline in stock status (albeit less severe for roach) observed over previous decades as well as high uncertainty in historical catches. The OM used for roach exemplifies the common discrepancies between survey and catch data, contributing to high uncertainty in the OM (Tien et al., 2020b).

7.5 Conclusions

This analysis shows the stock-specific nature of management outcomes across the six combinations for MP and tuning objective (CHR_B, CHR_F, CHR_both, CPUE_B, CPUE_F, CPUE_both) for pikeperch, perch, bream and roach in the IJsselmeer/Markermeer complex. The following insights emerge from the findings:

Comparing tuning objectives (B_{MSY}, F_{MSY}, both)

- For populations that are below B_{MSY} at the start of the simulations (i.e., 2023 in the OM), tuning for B_{MSY} (CHR_B and CPUE_B) is generally more conservative and entails lower risk compared to tuning for F_{MSY} (CHR_F and CPUE_F) as it allows the population to recover to healthy levels. This is evident with the MP projections for bream and roach.
- For populations above B_{MSY} at the start of the simulations, tuning for F_{MSY} (CHR_F and CPUE_F) is found to be more conservative, preventing a population from declining towards unhealthy levels. However, this distinction is less apparent in the pikeperch and perch MP results due to uncertainty within their respective OMs.
- Tuning for B_{MSY} and F_{MSY} simultaneously ('both' objective) is the least risky tuning objective for all stocks with respect to keeping populations above B_{lim} but it often results in lower catches in 2035-2040.

Best performing management procedures and catch strategies

- Regarding the balance between projected catches and sustainable biomass levels, the CHR MP outperforms the CPUE MP for all stocks except for perch (albeit with high uncertainty for pikeperch). CPUE_F presents the riskiest MP/tuning combination for all stocks, except for perch where CHR_F is associated with potentially high population depletion.
- Unlike the other stocks, perch populations are projected to achieve higher catches with lower risk levels during the tuning period when implementing a CPUE MP compared to a CHR MP, which results in an excessively high biological risk for perch.

- An important point of distinction between the two tested MP types is the approach used to adjust the catches to achieve B_{MSY} or F_{MSY} during the tuning period:
    - The CHR MP involves a change in the catches in the first year of implementation of the MP, but relatively stable catches thereafter. For bream and roach, which need to recover from low initial stock levels, this is characterized by an abrupt decline in the catches and low catches in the short term, but higher catches in the longer term due to the faster recovery of the stocks.
    - On the other hand the CPUE MP employs a more gradual decrease in annual catches, and therefore higher catches in the short term. However, this approach is often associated with a higher risk to the stock populations during the tuning period (2035-2040) leading to lower catches in the longer-term.

Indicators for bird populations and fish length

- The statistic for fish biomass available for birds ('Bird food'; Section 5.3.1) was only informative for bream and roach showing an average increase of ~5% and ~3% respectfully when the CPUE MP was implemented.
- Similarly, the fish length statistic: biomass weighted mean length ('BWML'; section 5.3.1), could only provide meaningful insight for bream and roach, with only minor differences linked to CPUE_F and CPUE_both (~2% for bream; <1% for roach). This implies that only a slight shift in fish length is expected to occur during the tuning period using these MPs and only for bream or roach.
- The lack of noticeable effects for perch and pikeperch in these parameters may be attributed to the need to 'fish down' their populations to B_{MSY} levels in the MP.
- The availability of fish in sizes consumed for bird population is a management objective, but it is highly dependent of the strength of recruitment, which is known to be highly variable. The actual consumption of any of the four fish species by the bird population is also highly dependent on their availability, and even on the changes in abundance of other stocks, such as smelt.

Robustness tests

- Alternative OMs for pikeperch were used to test the robustness of the base-case OM by investigating the potential impacts of variability in key ecological parameters on population dynamics.
- Historical projections suggest that decreased productivity and increased senescence (natural mortality in older ages) have a greater potential to affect population dynamics compared to density dependent changes in recruitment strength.
- Nevertheless, results from the MPs incorporating the alternative OMs were similar to those of the base-case OM. It is expected that the time frame of future MP application will exhibit relatively small changes in the lake productivity compared to past observations due to the reduced influx of land-based nutrients.

The OM and MP results derived from this MSE are grounded in a simplified virtual system, offering practical insights for fisheries management. It is essential to understand that ecosystems are dynamic and that predictive outcomes at the current juncture are subject to changes in future re-analyses, influenced by evolving natural and anthropogenic drivers. Additionally, less predictable ecological features such as fish behaviour and movement may pose challenges or be impossible to fully incorporate into these analyses, potentially resulting in disparities between predicted and realized outcomes.

The MPs presented in this study were tested under a range of assumptions regarding stock and fishery dynamics for the future years. In the event of exceptional circumstances that lead to reality diverging from these assumptions, the stocks may be pushed beyond the boundaries of the simulation envelop. Applying the MPs in such instances may no longer be optimal, or even precautionary. Examples could include unusually high or low recruitment of a magnitude that has not been observed in the past, deviations in future bird catches, or any recurrent difference between the advised TAC and the effective landings. Any of these circumstances would imply that the actual performance of the MPs would deviate from the evaluation presented in this analysis, and that the main management objectives would likely not be met. Regular assessments are, therefore crucial to ensure that the reality does not deviate substantially from the assumptions made in the simulations. This can be accomplished by: (i) comparing future values of the survey index with the simulated values from this MSE, (ii) comparing future bird populations and catch estimates with the assumptions used in this work, and (iii) by monitoring the differences between the landings and the TACs. Furthermore, the availability, and sufficient quality, of the survey is essential for the application of the MPs.

Quality Assurance

Wageningen Marine Research utilises an ISO 9001:2015 certified quality management system. The organisation has been certified since 27 February 2001. The certification was issued by DNV.

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Note: also contains literature discussed in the following appendices.

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Justification

Report C005/24
Project Number: 4318100385

The scientific quality of this report has been peer reviewed by a colleague scientist and a member of the Management Team of Wageningen Marine Research

Approved: B.J.P Bergès
Researcher

Signature: 

Date: 28 February 2024

Approved: Dr. A.M. Mouissie
Business Manager Projects

Signature: 

Date: 28 February 2024

Appendix 1: Survey and fisheries data

For an overview of all data sources, see Appendix 1 of Volwater et al. (2023), and for an explanation of raising these data see Appendix 2 of Volwater et al. (2023). Here, a short overview is given of the data used in the MSE's and an extensive explanation is given is methodology diverged from Volwater et al. (2023).

Survey and biological data

Standard surveys and market sampling

The most important survey is the beam trawl survey and takes place yearly with 25 hauls in IJsselmeer and 20 hauls in Markermeer. It started in 1966 and was standardized in 1989. Up until 2012, the survey took place with a different but similar gear type; the 'grote kuil', which used a wooden frame (7.4 meter wide) instead of the metal frame of the beam trawl (4 meter wide). There are some uncertainties concerning the exact relationship between the catch success in the two gear types (see Appendix 5 in Volwater et al. 2023). The other standard survey takes place simultaneously with the beam trawl using an electric beam trawl; catches from this survey were used to collect biological samples, together with those from the beam trawl. Another source of biological samples is the market sampling. These biological samples were used for the age and maturity keys as described below, while for the weigh-at-length key a standard key as used at WMR was used (van Keeken et al. 2022)

The following raised data are used:

1. Catch success (number and biomass per fished hectare) per length/age of the beam trawl survey
2. Age-length key for the market sampling (yearly and over all years)
3. Maturity key per length/age, over both survey and market sampling

A-toomkuil survey

Data from a new survey in the lake complex was used to determine the selectivity of the beam trawl survey. This 'A-toomkuil' survey is currently under development (three years of testing a standard methodology, School et al. 2022) and has a higher selectivity-at-age for many ages than the beam trawl. It was therefor was used to help estimate the selectivity of the beam trawl, by comparing the length-frequency distribution in the two gears per year.

Literature

Information on natural mortality-at-age was gathered in literature for pikeperch (Heikinheimo et al. 2014, Vainikka & Hyvärinen, 2012 and Heikinheimo et al. 2015), perch (Pauly, 1980, Willemsen, 1977 and Schoenebeck and Brown, 2011), bream (Lammens et al. 2002, Sloof and De Zwart 1983 and Ding et al., 2019) and roach (Otjacques et al. 2015, Kirjasniemi, M., & Valtonen, 1997 and Peltonen et al. 1999)

Fisheries data

Length distribution of catch

Two different market sampling regimes have been used in the past, with their own methodology and thus their own data raising; the historic market sampling (1992-2010) and the present-day market sampling (2016-now).

- LF of landings: historic market sampling. In the historic market sampling up to 2010, only landings were sampled, and only of pikeperch and perch. The sampling was quarter-stratified and samples were bought at the auction. However, the sampling is not well balanced; the number of samples per quarter differ between years. Also, in many years only information on yearly landings is available (and not per quarter): thus, estimating the length distribution by weighing the importance of every quarter is not feasible. Therefore, the assumption was made that the sum of samples within a season is a representative sample of the length distribution of that season.

- LF of total catch: present-day market sampling. In the present-day market sampling, the total catch is sampled on board of vessels that fish with gill nets and seine. The length distribution of the total catch is estimated for the seasons in which the total catch has been sampled in the market sampling: season 2016/2017 and onwards. For the methodology of the data raising and the underlying assumptions, see chapter 5 of Tien et al. (2022) . Here, only the results are shown per data raising step.

101mm gill net fisheries

The length distribution per quarter (step a.) and the proportion landing per quarter (step b.) for the 101 mm gill net catches of most seasons are shown in appendix 3 of Tien et al. (2022) Based on these data the length distribution of the 101 mm gill net catches per season is estimated (step c, Figure A1.1)

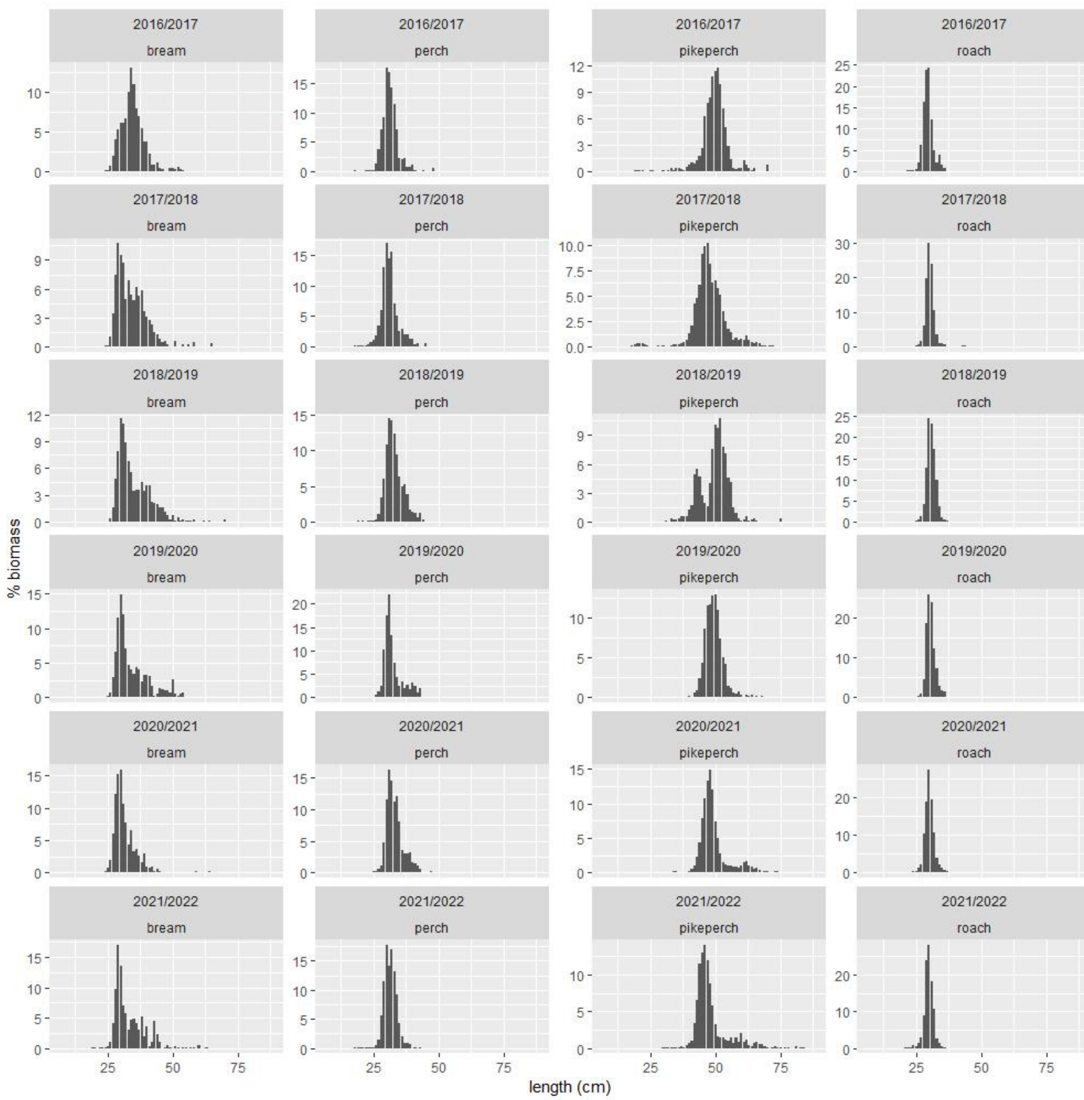


Figure A1.1 *Estimated length-biomass distribution of the 101mm gill net fisheries, per season.*

Gill net fisheries with large mesh sizes

For the gill net fisheries with large mesh sizes, the length distribution over all trips of the market sampling (all quarters and seasons) is used (Figure A1.2).

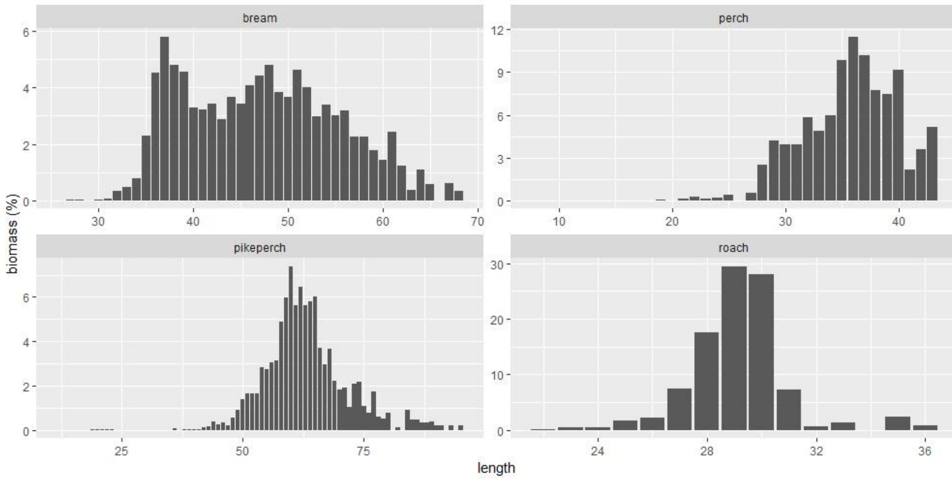


Figure A1.2 *Estimated length-biomass distribution (%) of the gill net fisheries with large mesh sizes, over all sampled trips in the market sampling. This distribution is assumed to be representative for every season.*

Seine fisheries on bream

For the seine fisheries in season 2016/2017, 2017/2018 and 2019/2020 the length distribution over all trips in the market sampling is used ('all' in Figure A1.3). In the other seasons the length distribution of the trips in that particular season are used (Figure A1.3)

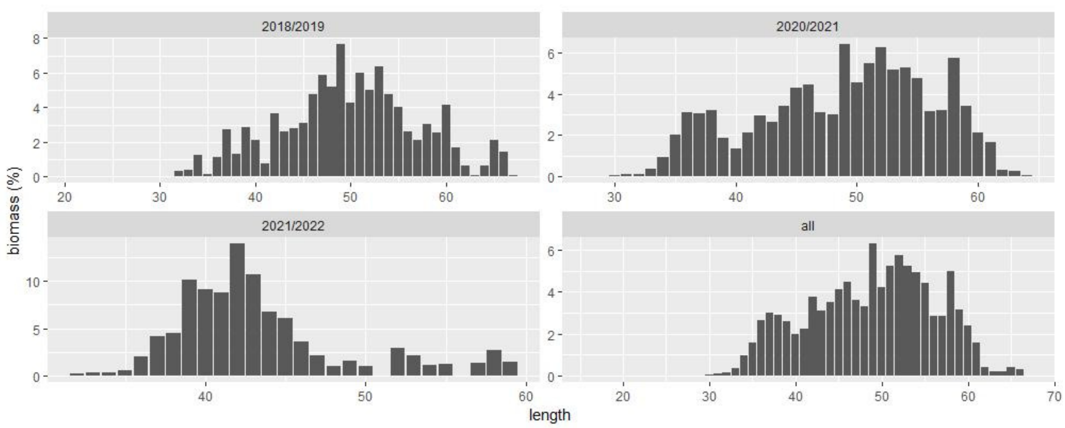


Figure A1.3 *Estimated length-biomass distribution of bream in the seine fisheries, per season (2018/2019, 2020/2021 and 2021/2022) and over all trips in the market sampling ('all').*

Total fisheries

The length distribution of the catches of all fisheries on a stock are estimated based on the estimated length distribution per métier as shown above, where the importance of every métier in a season is determined by the proportion landings of that métier (Figure A1.4). This leads to the estimated length distribution of the entire catch as in Figure A1.5.

Figure A1.4 *Division of landings (%) over the three métiers, per season, as registered in the logbooks.*

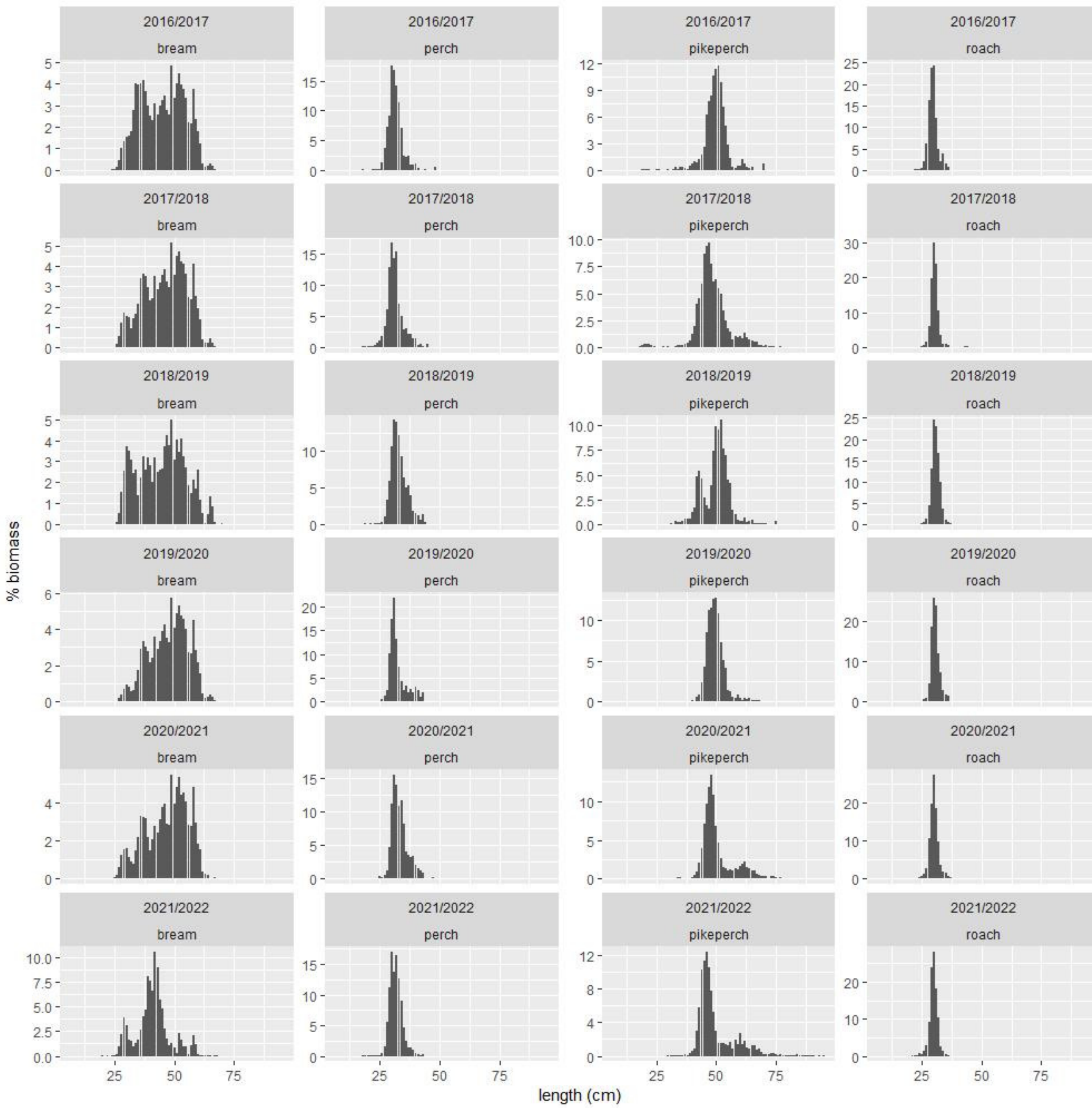


Figure A1.5 *Estimated length-biomass distribution (%) of the total fisheries, per season.*

Division of catch into landings and discards

For the seasons 1992/1993 to 2009/2010 only length distributions of the landings of pikeperch and perch are available. For the seasons 2016/2017 onwards, the LF distributions of the catches of all stocks are available. In order to divide these modern LF's into landings and discards, the following methodology was used.

Information on the ultimate purpose of each fish in the modern catch (discard or landing) is available from 2019/2020 onwards. For bream in the seine fisheries, all fish were landed. For bream and roach in the gill net fisheries, partial discarding took mainly place for fish <28 cm. However, the proportion of discarding of these size classes followed no clear pattern and differed between months, fishermen and seasons. Also the contribution of these size classes to the catch length distribution (in % biomass) is low. Therefor it was assumed that all catches of bream and roach are landed.

For perch, the division into landings and discards followed the minimum landing size (MLS) well: perch up to 22 cm were mostly discarded, and from 22 cm onwards were mostly landed. Therefor the MLS

(22 cm) was used to divide the catch of perch into landings and discards. For pikeperch, individuals just below MLS (1-2 cm below 42 cm) were often landed; roughly 50% of these length classes were landed. Therefor it was assumed that pikeperch is landed from 41 cm onwards.

These two cut-off lengths (22 cm for perch and 41 cm for pikeperch) were used to divide the estimated LF of their present-day catch (Figure A1.5) into discards and landings. Subsequently, this division is also used to estimate the ratio between landings and discards. On average, for every kg of landed pikeperch, 0.03 kg is discarded and for every kg of landed perch 0.004 kg is discarded.

Total catch

Landings time series
For an explanation of the methodology of the raising of the yearly landings; see appendix 2 of Volwater et al. (2023). Here, the methodology was slightly adapted, in order to raise from yearly landings to landings per season. From the season 2000/2001 onwards[15] landings per week are available, as reported in the PO-dataset and logbooks; these can thus be raised to seasonal landings without any assumptions. However, for the previous seasons only yearly landings are available (as in the PVIS-dataset). In order to estimate the landings per season for this period, the average division of yearly landings between the two seasons (January-March and July-December) was estimated in the adjacent years with PO-data; 2000-2010 (Table A1.1). With these divisions, the landings of 1992-2000 are split into seasonal landings for the seasons 1992/1993 – 1999/2000. Subsequently, data are raised using the same methodology as in Volwater et al (2023), where the source with the highest seasonal estimates is chosen. This lead to the following choices: PVIS for 1992-2006, PO for 2007-2016 and 2021-2022 and logbooks for 2017-2020. And a second scenario for bream including the estimate by the seine fisherman to the PVIS time series.

Table A1.1. *Fraction of yearly landings, caught in January-March, as registered in the PO-dataset, averaged over the fractions of 2000-2010.*

	Fraction in January-March
Perch	0.34
Pikeperch	0.17
Roach	0.65
Bream	0.60

Discards
For all four stocks, the discards are in the gill nets and seine assumed to be negligible; see above (“Division of catch into landings and discards”). However, the discards in the fykes (targeting eel) are estimated to be a substantial part of the catch, most notably for perch (Tien et al 2023, chapter 3.2). Because the available information on fyke discards, however, is not enough to raise reliable time series of the discards, these data are not included in the OM. Their impact on the MPs was however considered for the stock with the highest fyke discard estimates; perch, as discussed in chapter 7.2.

For a detailed explanation of the calculation of the discards in fykes, see chapter Tien et al. (2023). Here, an update of the calculations is given, using the method as described in appendix 1 of Tien et al. (2023); the ‘alternative method’. When publishing Tien et al. (2023), not all necessary data were yet available; the survey data and the total landings of eel of 2022 were not available and as a proxy the data from 2021 were used. Here the 2022 data are used (table A1.2 and A1.3). Moreover, data are here raised per fishing season instead of year. Since the vast majority of eel is caught during spring and summer (i.e., starting in the second season of that year), all landings of a year x are assumed to be caught in season year (x) / year (x+1).

[15] 2008/2009 for roach

Table A1.2. *Amount of eel caught (kg) in 2021 and 2022.*

Gear type	2021	2022
‘schietfuik’	110980	125852
’grote fuik’	168878	150377
Total	279858	276229

Table A1.3. *catch success (kg/ha) of 0+ fish in the beam trawl survey.*

Species	2021	2022
Pikeperch	0.44	2.37
Perch	6.65	46.99
Roach	0.11	0.45
Bream	0.08	0.22

In addition to the 2022 data, data from a fieldtrip sampling ‘grote fuiken’ in December are now available. However, the catch composition of this eel fishing trip was deemed unrepresentative for the eel fyke fisheries in December: the fishing exercise (with 8 nets of ‘grote fuiken’) took place under bad weather conditions and only one eel was caught. While bad weather conditions are not rare in December, experts in the field mentioned that the extremely low catch in this trip is not representable for fishing in December. While this first December fieldtrip was a good exploration, future investigation should include more fieldtrips in December, to get a better and more representative idea of the fyke discards for this month. For now, since most of the eel landings are caught during spring and summer (96% in 2022), the ratio of discards:eel was based on the fieldtrips as described in Tien et al. (2023).

The catch success of 0+ fish in 2022 in the beam trawl survey was higher than the proxy used in Tien et al. (2023) (Table A1.3), while the total amount of caught eel was more or less the same (Table A1.2). Thus, the estimated total amount of discard and mortality in fykes for all the other seasons (Figure A1.6) became considerably lower, than calculated in Tien et al. (2023).

The method to calculate the fyke discards is sensitive as only two reference seasons were used to create a time series of 30 seasons. Tien et al. (2023) used two different methods based on different assumptions and the outcome of these methods were considerably different. Moreover, the updated calculations (using beam trawl survey data of 2022 instead of 2021) changed the outcomes considerably. While the data give an indication of the discard mortality in fykes, the time series itself is too sensitive for (even small) changes in assumptions and parameters.

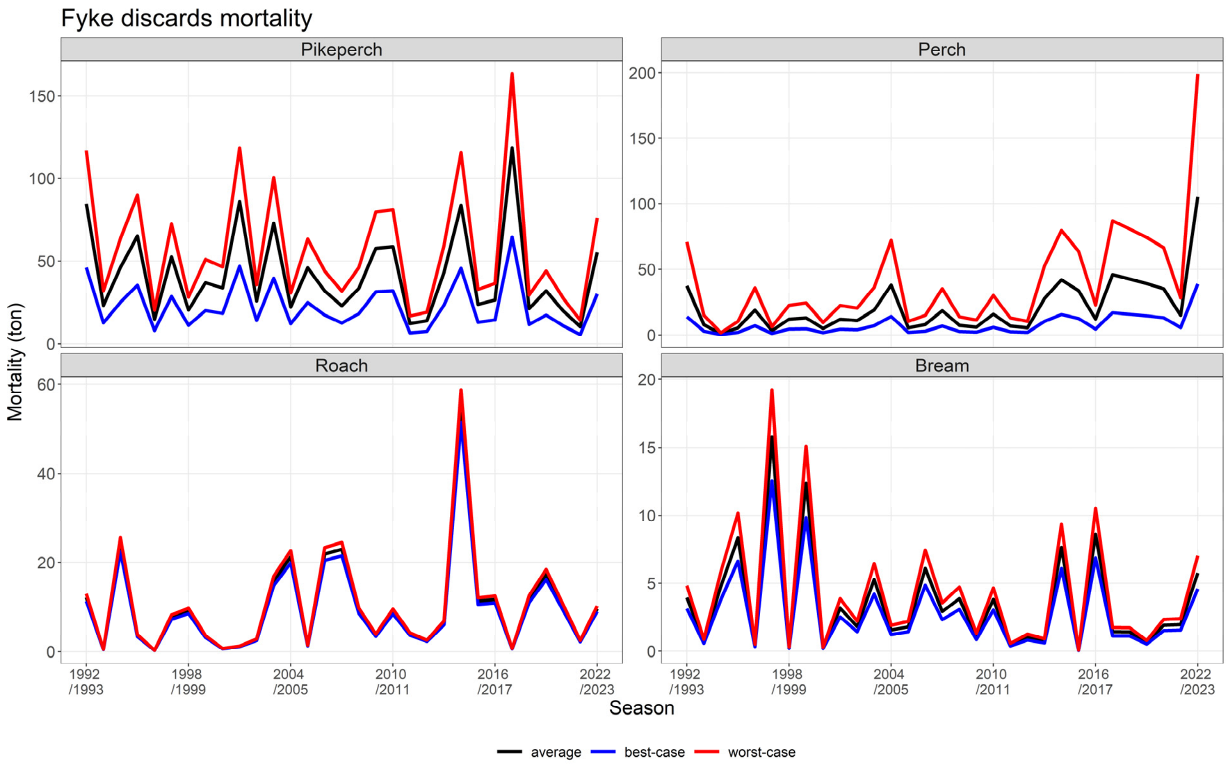


Figure A1.6. *Discard mortality of each species (pikeperch, perch, roach and bream) in weights (ton ; 1000 kg) for the seasons 1992/1993-2022/2023. Blue colour represents best-case scenario, red the worst-case scenario and black is the average of the two scenarios.*

Appendix 2: Bird predation and food reservation Natura2000

Bird predation

For a detailed explanation of the methodology of estimating the amount of fish extraction by bird predation; see appendix 4 of Tien et al. (2020a). This appendix summarizes the methodology and the differences with the method of Tien et al (2020a).
The following three steps were made:

1. Calculating the daily energy requirement (kJ) for each bird species.
2. Calculating the bird numbers foraging in the IJsselmeer and Markermeer.
3. Calculating the proportion pikeperch, pike, roach and bream in the diet of each piscivorous bird species.

(1). The daily energy requirement was calculated for each piscivorous bird species (unit in kJ). The daily energy requirement for chicks was also included for common tern (*Sterna hirundo*) and cormorant (*Phalacrocorax carbo)*.
(2). The seasonal average of piscivorous birds of each species around lake IJsselmeer and Markermeer were calculated from monthly aerial counts (SOVON.nl). The seasonal average was based on counts of twelfth sequential months, each season starting from July and ends next year June. An aerial correction was applied on the seasonal averages for each bird species, as the areal counts do not completely cover lake IJsselmeer and Markermeer (Table A1.2 and Tien et al. 2020a). For all bird species the aerial counts were used for the seasonal average bird numbers, except for common tern and black tern (*Chlidnias niger*). The seasonal averages of the common tern were based on breeding pairs. Two assumptions were made for common tern estimates: (1) each breeding pair raised one chick and this chick will forage as an adult for two more months in lake IJsselmeer and lake Markermeer. (2) Common tern breeding pairs will stay from 15 of April till 31 of august around lake IJsselmeer and lake Markermeer (4.5 months).
Black tern estimates in the SOVON dataset are expressed in seasonal maximum instead of seasonal average. However, there is a strong correlation between seasonal maximum and seasonal average (3:1), which make it possible to calculate the seasonal average (van der Winden et al. 2022). As the Sovon estimates of black tern is based on nest counts (not aerial counts), no areal correction was necessary.
(3). Proportion of each fish in the diet of piscivorous bird species is based on (i) the minimum and maximum length of prey that a piscivorous bird species is preying on and (ii) the fish species composition. The minimum and maximum prey length of each bird species is summarized in Table A2.1**.** Composition of fish was calculated from the yearly beam trawl survey of lake IJsselmeer and lake Markermeer. The prey composition of each bird species was calculated separately, as each bird species have different range of prey lengths (e.g. cormorant could have a different prey composition as other birds species each season, because they are able to forage on bigger fish).
Mous (2000) assumed that the catch composition of the beam trawl survey underestimates the relative density of smelt (*Osmerus eperlanus*) in the lakes by a factor of 5. Therefore, to estimate the species composition in the lakes and the diet of birds, the catch success (kg/ha) of smelt in the beam trawl survey was multiplied with 5, while that of the other species was not. On the other hand, stomach analyses showed the diet of cormorant consist only of a small fraction of smelt, therefore the original catch success of smelt (before the factor 5 is applied for the other bird species) will be divided by 2 for cormorant. Moreover it is assumed black tern will only forage on smelt (de Leeuw & van Donk, 2020). These corrected estimated diets fit considerably well with the diet of the piscivorous bird species, based on stomach content analysis (De Leeuw & van Donk, 2020).

After the diet composition for each season and each bird species is estimated, the total amount of energy each piscivorous bird species needs from each fish species (Kj) was converted to weight (gram), based on a species specific energetic value (Schreckenbach et al. 2001; Table A2.2.

Table A2.1. *Minimum and maximum prey length for each piscivorous bird species. The prey size range are based on the ranges mentioned in de Leeuw & van Donk (2020). Prey length of European herring gull is mentioned in Spaans (1971) and prey size of red-breasted merganser is mentioned in Feltham (1990). As no prey size is mentioned for little gull, it is assumed little gull forage on the same prey lengths as common gull.*

Species	Minimum prey length (cm)	Maximum prey length (cm)
Cormorant	2	30
Common merganser	7	18
Great crested grebe	2	18
Black tern	3	11
Smew	3	11
Common gull	3	11
Common tern	3	12
Black-headed gull	2	18
Red-breasted merganser	5	12
European herring gull	5	15
Little gull	2	11

Table A2.2*. Fish species specific energetic values (KJ/g).*

Species	Energetic value (KJ/g)
Pikeperch	5.40
Perch	4.84
Roach	5.08
Bream	5.23

Tien et al. (2020a) included 7 piscivorous birds: cormorant, grebe (*Podiceps cristatus)*, smew (*Mergellus albellus)*, common merganser (*Mergus merganser)*, common tern, black tern and black-headed gull (*Chroicocephalus ridibundus)*. Current method included four extra piscivorous bird species for the calculations, to gain a more accurate number of the total predation of birds on fish in lake IJsselmeer and Markermeer. The following four piscivorous bird species were included: European herring gull (*Larus* argentatus), common gull (*Larus canus*), little gull (*Hydrocoloeus minutus*) and red-breasted merganser *(Mergus serrator*) (Table A2.3). Average weight of an individual for each species was derived from literature (van Donk et al., 2019; Feltham 1990). Basal Metalic Rate (BMR) was calculated from weight, using the formula as described in de Leeuw & van Donk (2020). The correction factor from BMR to FMR (Field Metabolic Rate) was different for different bird species, depending on the season the species is visiting lake IJsselmeer and Markermeer: summer (correction of 3) or winter (correction of 4). Seasonal averages of European herring gull, common gull and red-breasted merganser are estimates from SOVON.nl, while seasonal average estimates of little gull is derived of van Rijn & van Eerden (2021). It is assumed European herring gull, common tern and red-breasted merganser in lake IJsselmeer and Markermeer are 100% piscivorous, while the diet of little gull consist of 50% fish and 50% insects (mostly Chironomidae) (van Rijn & van Eerden, 2021).

Table A2.3. *weight, BMR, correction factor to FMR and digestion efficiency to calculate the daily energy requirement of an individual of each bird species. Aerial correction to calculate the bird numbers is the same for lake IJsselmeer and lake Markermeer. Parameters for the other piscivorous bird species are the same parameters as in table B2.1, de Leeuw and van Donk (2020).*

Species	Weight (gr)	BMR (kJ/day)	Correction	Digestion efficiency	Daily energy requirement (kJ/day)	Aerial correction
European herring gull	960	317	3	0.8	1190	1.5
Common gull	390	167	3	0.8	627	1.5
Little gull	100	63	3	0.8	238	1.5
Red-breasted merganser	1000	327	4	0.8	1634	3

According to the method pikeperch, perch, roach and bream were mostly predated by cormorant (Figure A2.1). Perch is the fish most eaten by birds; the last ten seasons on average 890 ton of perch is eaten, with a peak of 2349 ton in the season of 2018-2019. In that particular season perch was by far the most caught species in the beam survey (Rijssel et al., 2022), which explains the high estimates of consumed perch here. In the last 10 seasons an average of 53 ton of roach were eaten by piscivorous birds. The average amount of pikeperch eaten by birds, was 28 ton in the last 10 seasons. Of the four species, bream was least predated, with an average of 7 ton in the last 10 seasons.

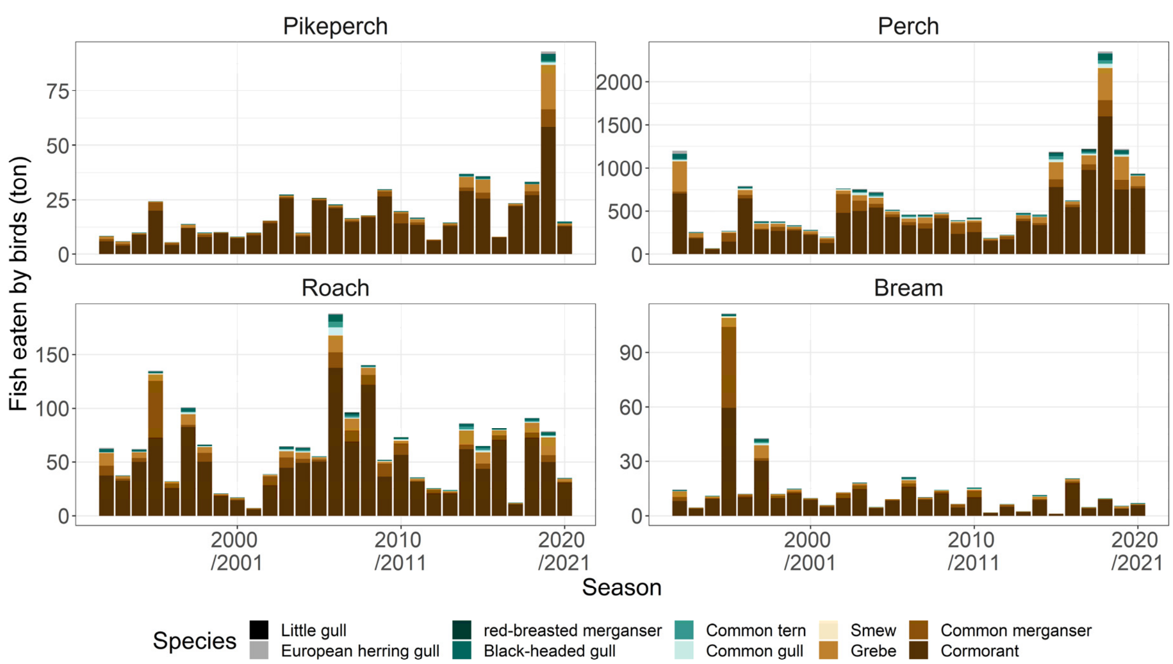


Figure A2.1. *Predation by birds on each species (pikeperch; perch; roach and bream) in weights (ton; 1000kg).*

Food reservation for Natura2000

According to the Natura2000 conservation objectives ('Natura2000 doelaantallen'), for certain bird species on average a number of individuals has to be present in the IJsselmeer and/or Markermeer for multiple years in a row (Table A2.4). The ministry of LNV has incorporated food reservation for these target number of birds as one of the management objectives for the HCRs of pikeperch, perch, roach and bream. Consequently, the estimated future amount of fish in a stock (in the suitable length range) is used as one of the status indicators in the projections; Fish biomass available to birds ('Bird Food', section 5.3.1 and Appendix 4). In order to estimate how this amount of fish biomass relates to the food requirements stemming from the Natura2000 bird targets, this biomass estimate is compared to the biomass of fish in a reference year: a past year in which the number of birds best approach the target amount of birds. This reference year is here recalculated, based on the newest data and estimates. The season is picked from the last 10 seasons, as seasons further in the past are deemed less representable for future seasons. For a detailed explanation of the method, see de Leeuw & van Donk (2020).

Table A2.4 *Overview of the Natura2000 conservation objectives (on average, a specific number of birds has to be present in lake IJsselmeer and/or Markermeer for multiple years in a row) for each lake and each species. Targets are seasonal averages, with the exception of black tern (seasonal maximum) (www.natura2000.nl).*

	IJsselmeer		*Markermeer*	
Bird species	Natura2000 Targets	Breeding pairs	Natura2000 Targets	Breeding pairs
Cormorant	8100	8000*	2600	8000*
Grebe	2200		170	
Smew	180		80	
Common merganser	1850		40	
Common tern		3300		630
Black tern	73200			
Little gull	85			

* IJsselmeer and Markermeer combined

None of the previous seasons meets the Natura2000 conservation objectives (Table A2.5). The season of 2016-2017 comes closest as only breeding pairs of cormorant, breeding pairs of common tern and numbers of black terns targets were not achieved. As it is assumed the diet of black tern consist of 100% smelt, no food reservation has to be taken into account for this bird in the management of the fisheries on pikeperch, perch, roach and bream. The target amount breeding pairs of common tern is not met, but 916 breeding pairs were found around the Markermeer, meaning in total (IJsselmeer + Markermeer) the Natura2000 target would have been achieved. Therefore no extra food has to be reserved for the common tern breeding pairs. Only the cormorant breeding pairs target were not achieved, but this Natura2000 target has never achieved in history according to our calculations. In conclusion, the season that best reflects the N2000 targets for bird numbers is 2016/2017. The estimated bird vulnerable biomass of fish in that season is used for comparison in the bird food status indicator. Ideally even more fish has to be reserved, to include the cormorant breeding pair target. Also, this reference point is estimated with very large (especially ecological) assumptions and does not reflect a true 'target' biomass but merely a rough estimate; reaching a higher bird vulnerable biomass per stock will ensure higher chances of having enough food for the Natura2000 protected bird species in place.

Table A2.5. *Calculated number of birds and the target numbers of Natura2000 (seasonal average). Only natura2000 bird species are included. In green is the natura2000 targets achieved, after the calculation and correction factors for the aerial counts, to prevent an underestimation. IJM = IJsselmeer; MM = Markermeer; Comb. = IJsselmeer and Markermeer combined.*

Bird species	Lake	2011/ 2012	2012/ 2013	2013/ 2014	2014/ 2015	2015/ 2016	2016/ 2017	2017/ 2018	2018/ 2019	2019/ 2020	2020/ 2021	Targets Natura2000
Cormorant	IJM	10428	11838	7972	10221	7898	11695	10419	11061	7336	9822	**8100**
	MM	3301	3350	3002	3607	2345	3310	2496	2118	1113	1073	**2600**
Cormorant (breeding)	Comb.	5211	6615	4196	5110	3246	4862	4510	4575	2945	3101	**8000**
Grebe	IJM	4962	2337	2433	3270	3582	5238	5259	3663	4251	5688	**2200**
	MM	333	220	334	624	694	870	475	511	481	274	**170**
Smew	IJM	417	312	24	57	141	369	276	84	36	66	**180**
	MM	39	165	24	15	76	118	93	19	15	7	**80**
Common merganser	IJM	2487	3879	1017	741	1095	2916	2193	1251	1116	816	**1850**
	MM	79	93	127	102	82	138	105	64	96	45	**40**
Common tern (breeding)	IJM	5178	3957	5309	4652	3831	2515	2861	2343	841	1172	**3300**
	MM	352	190	166	375	475	915	1980	1825	1030	1422	**630**
Little gull	IJM	162	249	135	159	72	199	153	57	82	NA	**85**
Black tern*	IJM	15000	12880	22000	19000	6500	5500	16000	10000	7000	10	**73200**

** For black tern the natura 2000 target is a seasonal maximum. Also, black tern is assumed to not depend on these four fish species as food and thus should play no role in shaping the management of these stocks.*

Appendix 3: Landings at age versus modelled catches at age

This appendix contains the OM validation plots comparing modelled and observed landing composition. Catches-at-age estimated by the OM show a larger proportion of individuals of older ages than what is generally observed across all stocks. The selectivity at age for the gillnetting fleets has been calculated from the distribution at length in the landings and the computed age-length key. Selectivity has been chosen to decrease rapidly with age but never to reach a zero value. Although catches of old fish in this gear are uncommon, they have been recorded. The effect of this assumption is more clearly noticeable in the case of pikeperch. The large proportion in the observed catches for age-2 fish is diminished in the OM-generated catch-at-age.

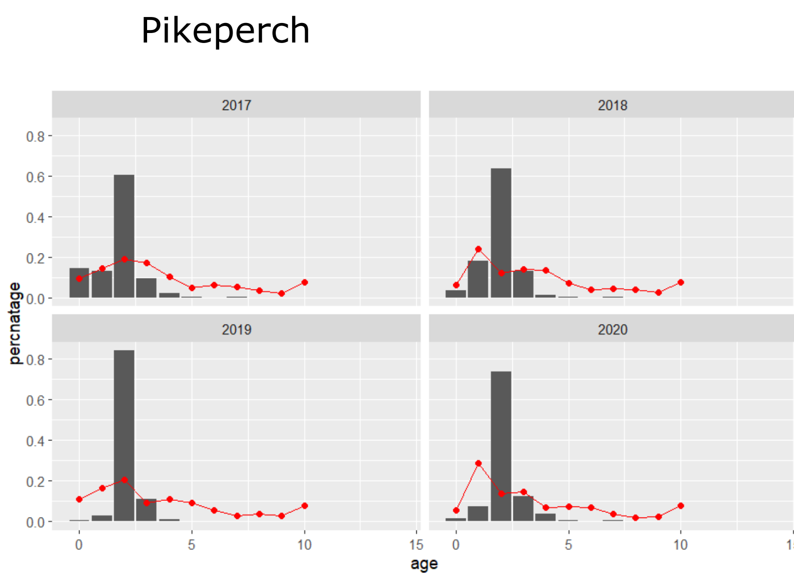


Figure A3.1 *Modelled catches at age (red) compared with landings at age caught from the fishery (grey bars) for pikeperch.*

Perch

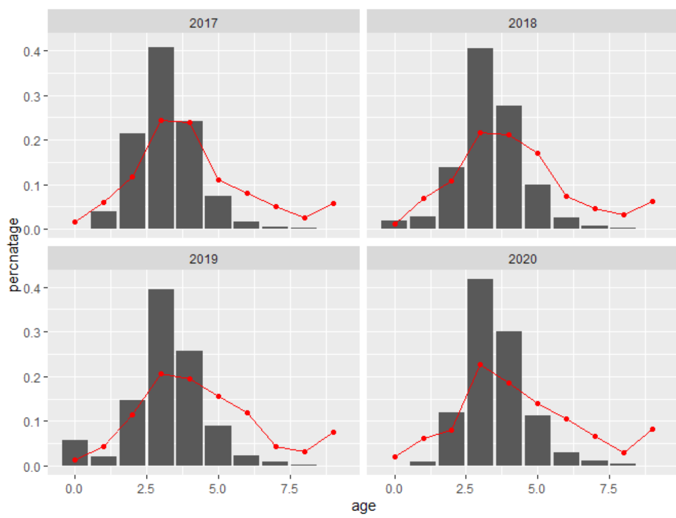


Figure A3.2 *Modelled catches at age (red) compared with landings at age caught from the fishery (grey bars) for perch.*

Bream

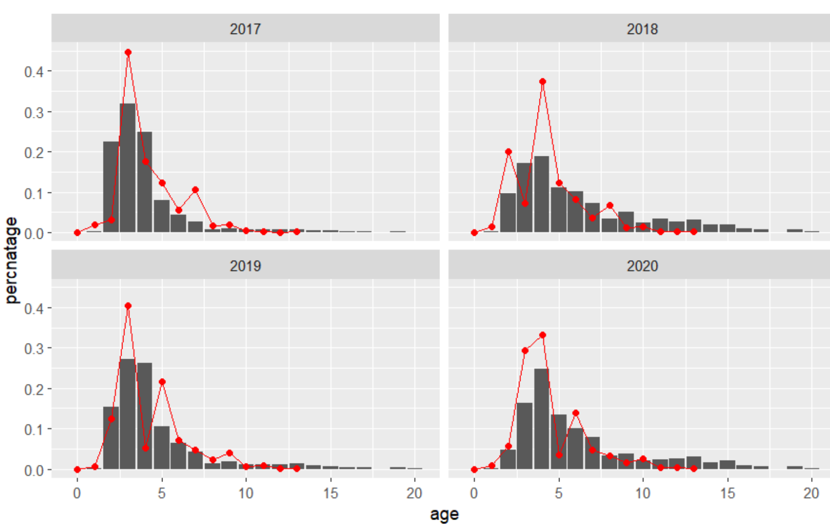


Figure A3.3 *Modelled catches at age (red) compared with landings at age caught from the fishery (grey bars) for bream.*

Roach

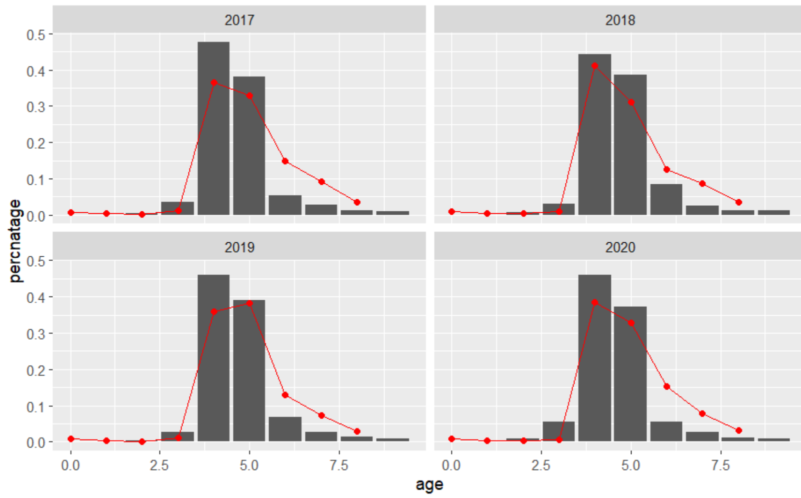


Figure A3.4 *Modelled catches at age (red) compared with landings at age caught from the fishery (grey bars) for perch.*

Appendix 4: Performance statistics

To evaluate the ability of a management procedure at achieving the required management objectives and also to monitor the results of its application on other quantities of interest, a series of five performance statistics were defined. Each statistic is calculated on quantities derived over the tuning period (2035-2040) from the OM projected under each MP,.

1. F/F_{MSY}: Fishing mortality (F) relative to F_{MSY}

This performance statistics is computed as mean over the tuning period of the annual values of the ratio F/F_{MSY}, where F is mean of the yearly fishing mortality across a range of fully selected ages[16], and F_{MSY}, the fishing mortality that would lead to a maximum sustainable yield.

2. B/B_{MSY}: Spawning stock biomass (B) relative to B_{MSY}

This performance statistics is computed as mean over the tuning period of the annual values of the ratio of the spawning stock biomass (B) relative to the spawning stock biomass capable of producing maximum sustainable yield (B_{MSY}).

3. B/B_{lim}: Spawning stock biomass (B) relative to B_{lim}

This performance statistics is computed as mean over the tuning period of the annual values of the ratio of the spawning stock biomass (B) relative to the limit reference point, B_{lim}, which in this case is being set at 10% of carrying capacity. This B_{lim}, which ICES defines as a "Limit reference point for Spawning Stock biomass (SSB)", is considered a biomass level that should be avoided with a large probability, as recruitment can be expected to be impaired below this point.

4. Mean catch: Average catch over the tuning period.

Mean catches projected by the MPs during annual fishing seasons by the fishing fleets over the tuning period.

5. Bird Food: Fish biomass available to birds ('Bird Food')

Mean of the biomass of fish available as prey for birds (typically smaller fish) over the tuning period, relative to the value in the reference year. This reference year is the year that is estimated to have neared the aspired bird populations; season 2016/2017 (see Appendix 2) .

6. BWML: Biomass Weighted Mean Length

This indicator represents the mean length of individual fish in the population and is one of the indicators used to describe good environmental status under the Marine Strategy Framework Directive. The indicator is computed as:

$$\frac{\sum_{l=min}^{l=max} l \cdot n_l \cdot w_l}{\sum_{l=min}^{l=max} n_l \cdot w_l}$$

where l is length of fish, in cm, while n_l and w_l are the abundances and weights at length, respectively. As the operating models are age-based, abundances at length for this indicator are being computed from the application of an observed age-length key and the modelled abundances at age.

This MSE presented the relative change (relative to the BWML in the last year of the historical trajectories; $BWML_{2022}$) , with values higher than 1 signaling an increasing mean length in the stock and values less than 1 signaling a decreasing mean length.

[16] The ages that have the highest chance of being caught by the fishery

Appendix 5 Supplementary OM information

Description of selection criteria used for feasible trajectories

The following describes the general categories used for the step-wise selection procedure to define more realistic historical stock trajectories within each OM. Each criterion is tailored to the unique characteristics of each stock. Specifics details for stock-specific criteria are provided in the "Selection of feasible trajectories" section for each stock in Chapter 4.

- **Catch**: Annual catches within projected OMs are filtered to allow a level of error when compared to observed catches.
- **Survey biomass**: The biomass index derived from the annual trawl survey in the IJssel/Markermeer is used to filter the trajectories which match the trends observed in the survey with some error allowed.
- **Maximum harvest rate**: An upper limit is set to the annual 'harvest rate', defined as total catch over the available biomass (the fraction of the stock biomass available to the fishery given their selectivity) to filter out trajectories displaying unrealistically high fishing rates within OMs.
- **Limit effort change**: A putative effort series ('effective effort'), derived from the partial fishing mortality, is used in the projection.The annual change in these values are given an upper limit to ensure more realistic proportional changes in year to year fishing effort.

Additional trajectory selection criteria were applied specifically for perch.

- **Biomass trend 1992-2005**: Two periods were defined in the perch timeseries to account for directional changes in the survey biomass trend.
- **Minimum harvest rate**: In addition to maximum harvest rate limit (catch/biomass), the selection of the perch OM also featured lower limits to annual harvest rates. This limited the acceptance excessive biomass values.
- **Index age 2**: The biomass index for perch is thought to be a more reliable indicator for age 2 compared to ages 0-1. Therefore, trajectories in the perch OM were filtered to match patterns seen in the age 2 biomass index from the survey.
- **Feasible Fbars**: Upper limits to fishing mortality (F) were used for trajectory selection in the perch OM.

OM selection plots for feasible trajectories

Pikeperch

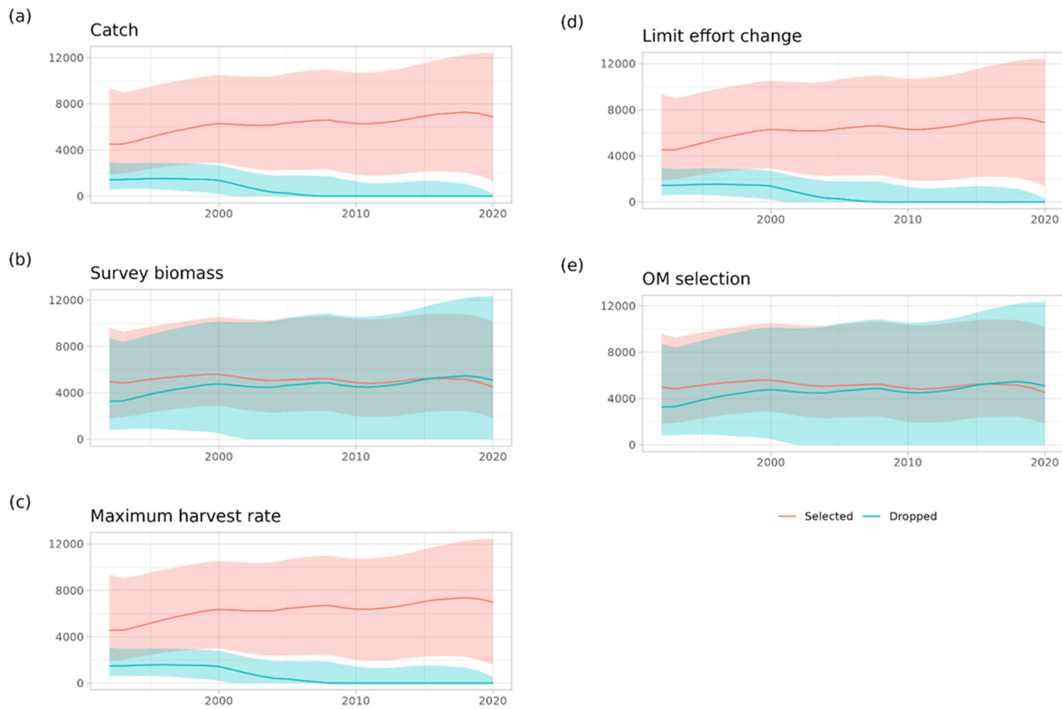


Figure A5.1 *Selection of population trajectories by each of the selection criteria (a-d) and overall OM selection (e), for pikeperch.*

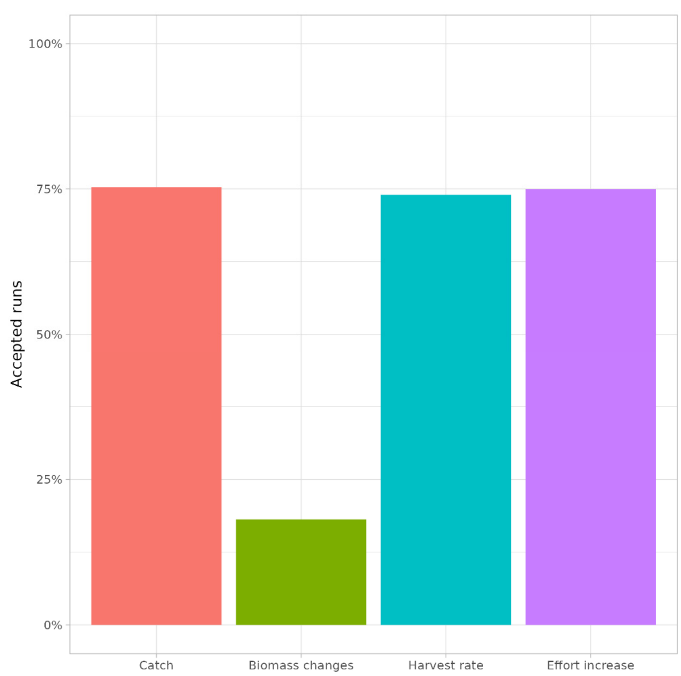


Figure A5.2 *Proportion of the iterations with plausible trajectories for each selection criterion, for pikeperch*

Perch

Figure A5.3 *Selection of possible population trajectories (as SSB) for each of the eight selection criteria, plus random draw of 800 runs (1 of 2) , for perch.*

Figure A5.4 Selection of possible population trajectories (as SSB) for each of the eight selection criteria, plus random draw of 800 runs (2 of 2) , for perch. Plots show the median (line) and the 80% quantiles.

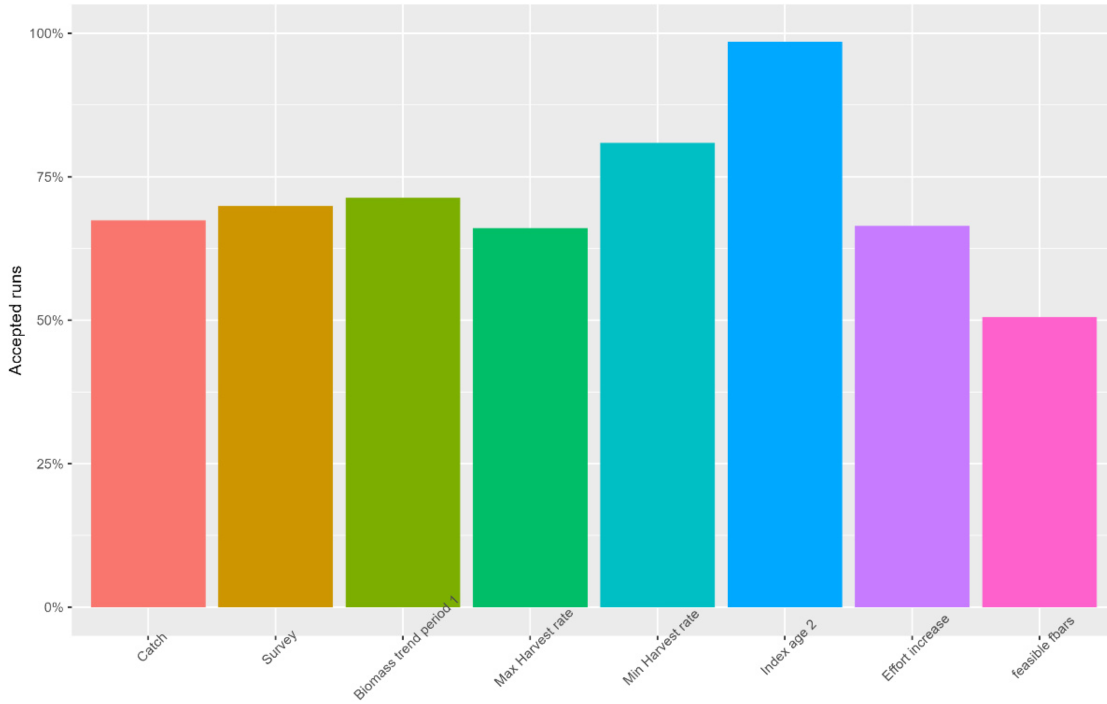


Figure A5.5 *Proportion of the iterations with plausible trajectories for each selection criterion, for perch.*

Bream

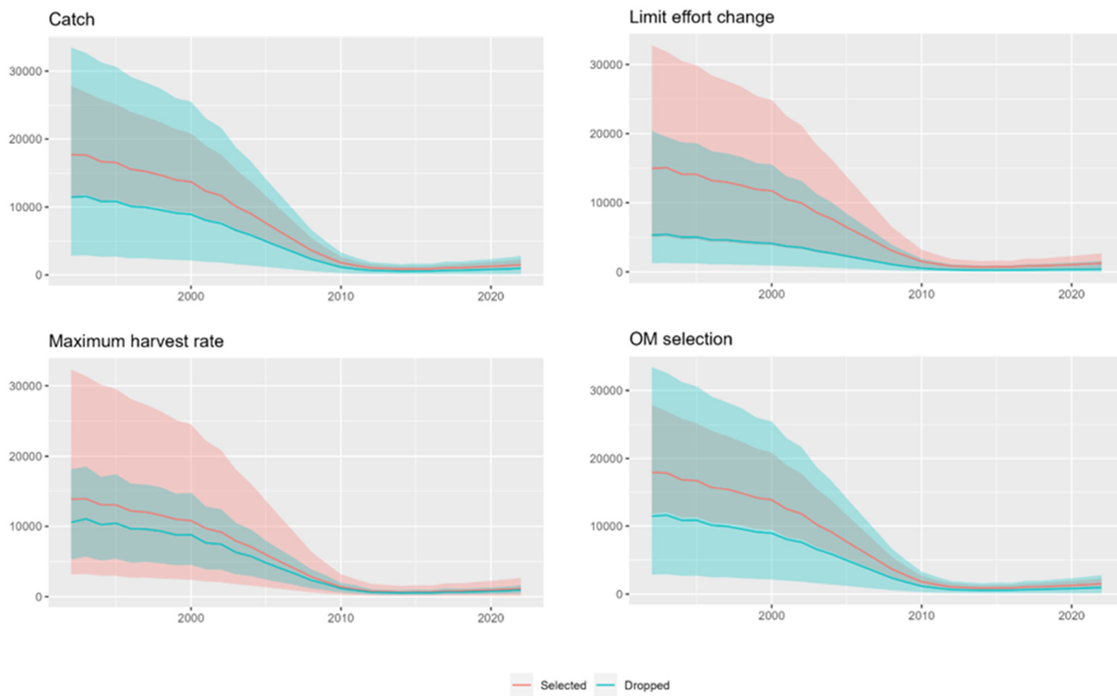


Figure A5.6 *Selection of population trajectories by each of the selection criteria and overall OM selection, for bream.*

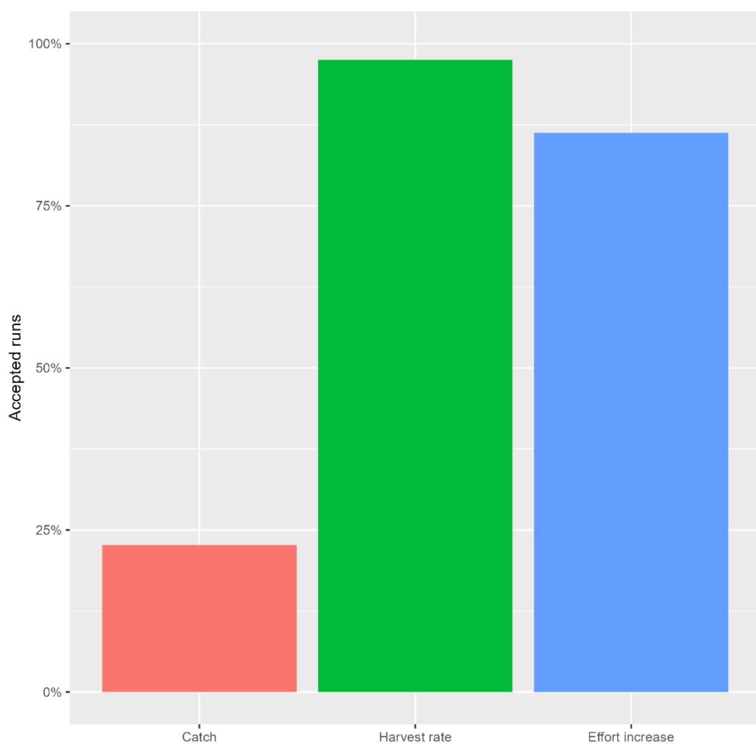


Figure A5.7 *Proportion of the iterations with plausible trajectories for each selection criterion, for bream (criteria on survey trend is not shown as all iterations passed that test)*

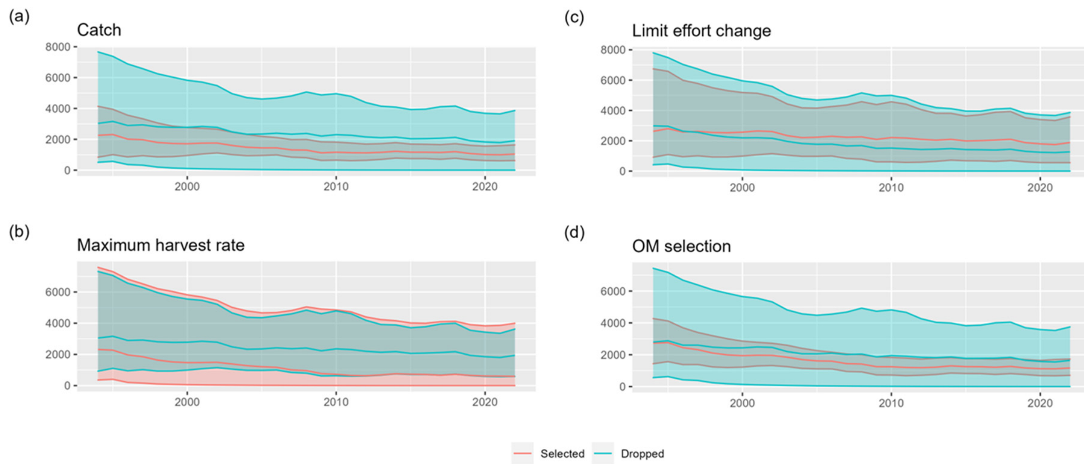


Figure A5.8 *Selection of population trajectories by each of the selection criteria (a-c) and overall OM selection (d), for roach.*

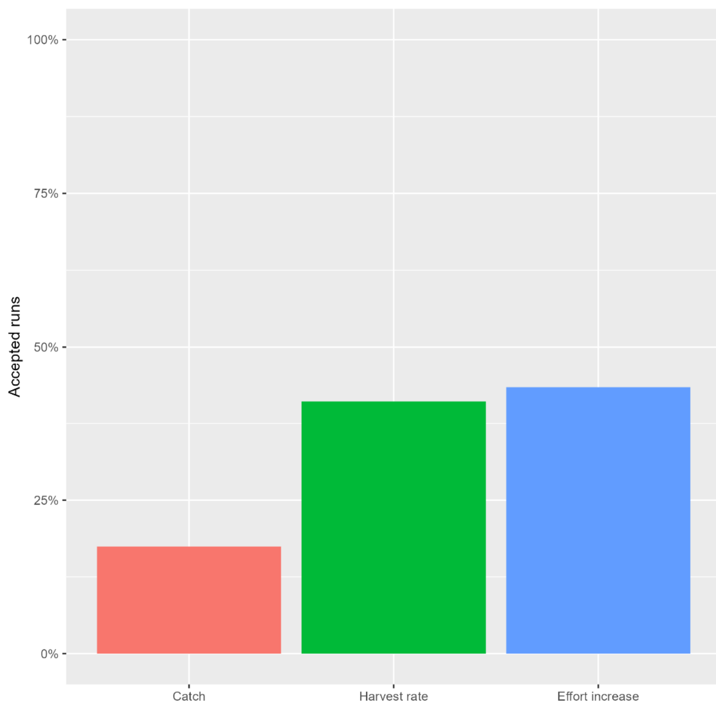


Figure A5.9 *Proportion of the iterations with plausible trajectories for each selection criterion, for roach (criteria on survey trend is not shown as all iterations passed that test)*

Appendix 6: Supplementary MP information

This appendix contains the figures and tables regarding extra results from the tested management procedures.

MP Figures: Trade-off and fishing pressure plots

Pikeperch

Pikeperch MP: Expected catches versus performance indicators

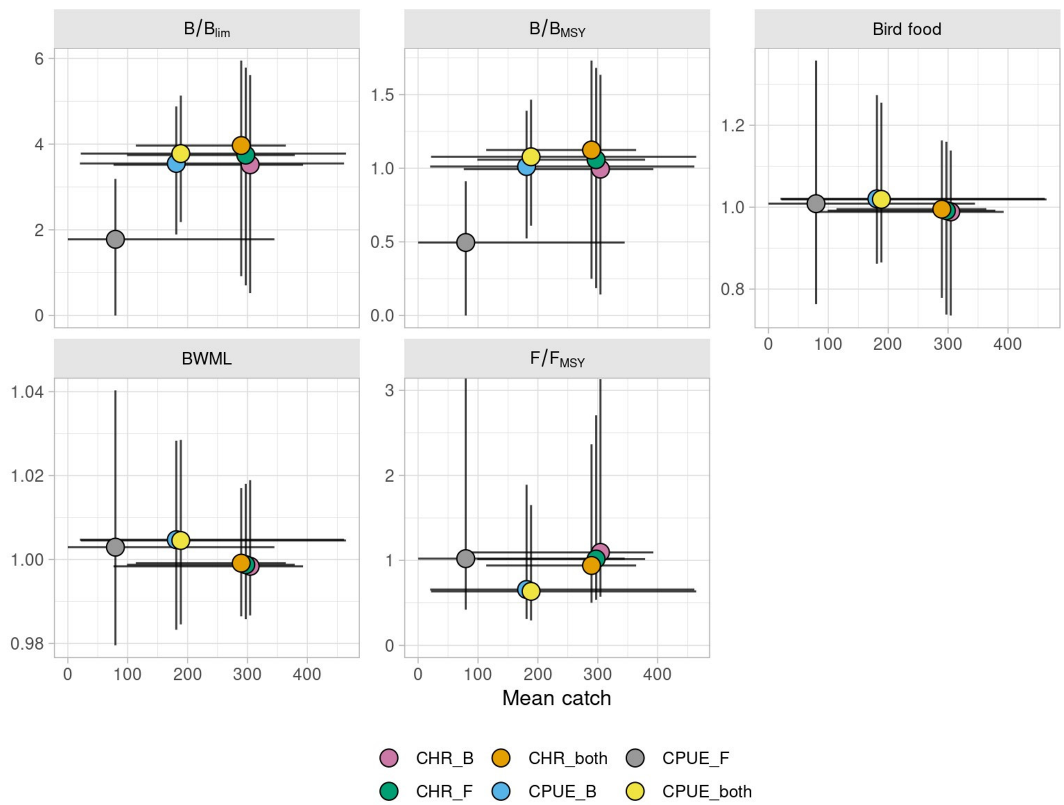


Figure A6.1 *Trade-offs between catch and the five other performance indicators for all management procedures applied to the pikeperch stock OM: stock biomass over B_{lim} (B/B_{lim}), spawning stock biomass relative to SSB_{MSY} (B/B_{MSY}), stock biomass available for the birds relative to sitiation in reference year (bird food), biomass-weighted mean length relative to situation in 2022 (BWML) and fishing mortality over F_{MSY} (F/F_{MSY}).*

Pikeperch MP: Fishing Pressure

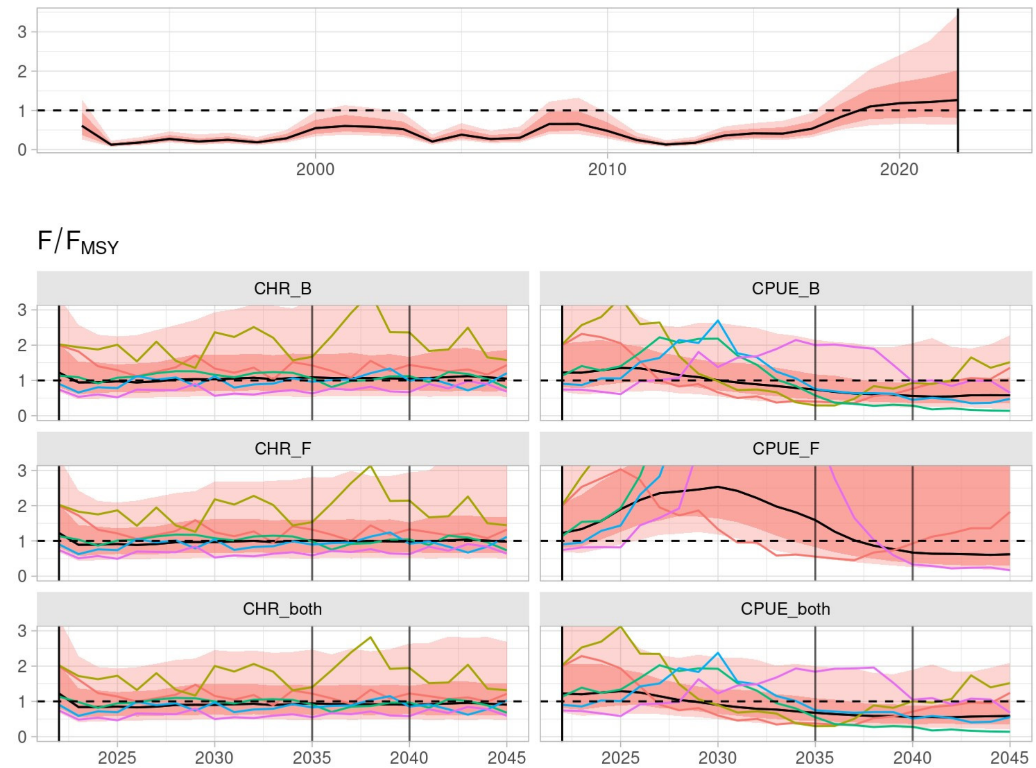


Figure A6.2 *Time series of the F/ F_{MSY} indicator for the historical period (top panel), and for all management procedures applied for the future projection period (2023-2045; bottom panels). The five colored lines represent the individual trajectories for five different iterations. F concerns mortality by both the fisheries and the birds.*

Perch

Perch MP: Expected catches versus performance indicators

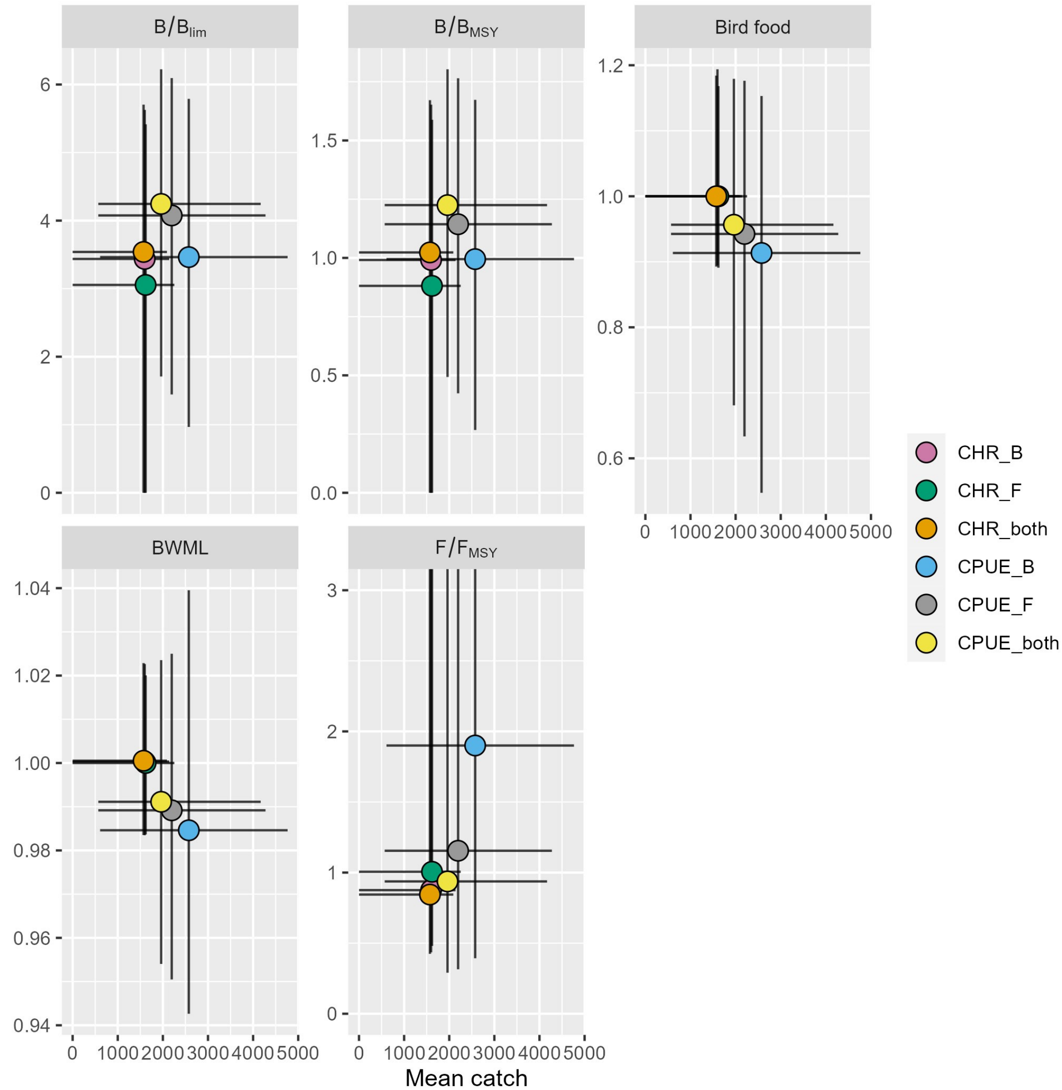


Figure A6.3 *Trade-offs between catch and the five other performance indicators for all management procedures applied to the perch stock OM: stock biomass over B_{lim} (B/B_{lim}), spawning stock biomass relative to SSB_{MSY} (B/B_{MSY}), stock biomass available for the birds relative to situation in reference year (bird food), biomass-weighted mean length relative to situation in 2022 (BWML) and fishing mortality over F_{MSY} (F/F_{MSY}).*

Perch MP: Fishing Pressure

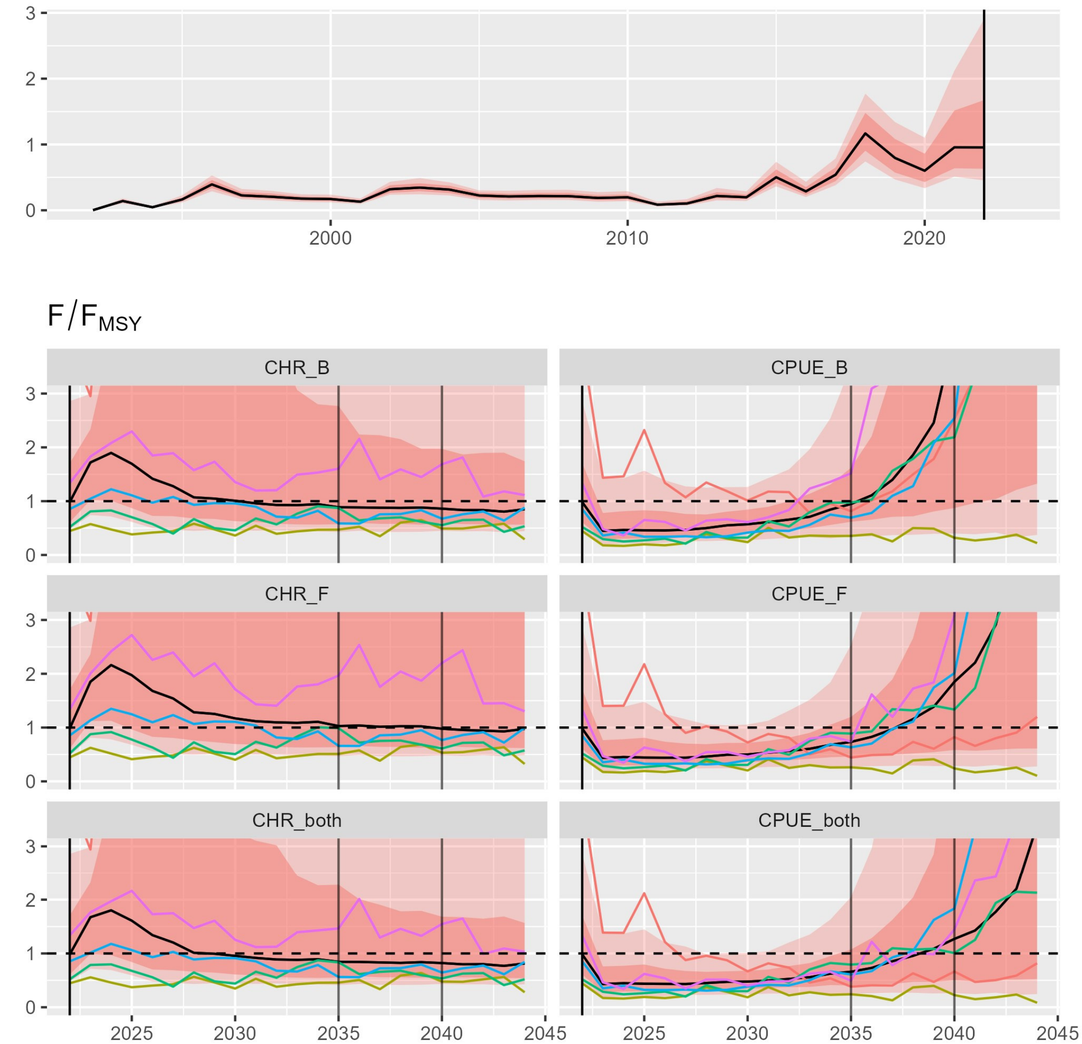


Figure A6.4 *Time series of the F/ F_{MSY} indicator for the historical period (top panel), and for all management procedures applied for the future projection period (2023-2045; bottom panels). The five colored lines represent the individual trajectories for five different iterations F concerns mortality by both the fisheries and the birds.*

Bream

Bream MP: Expected catches versus performance indicators

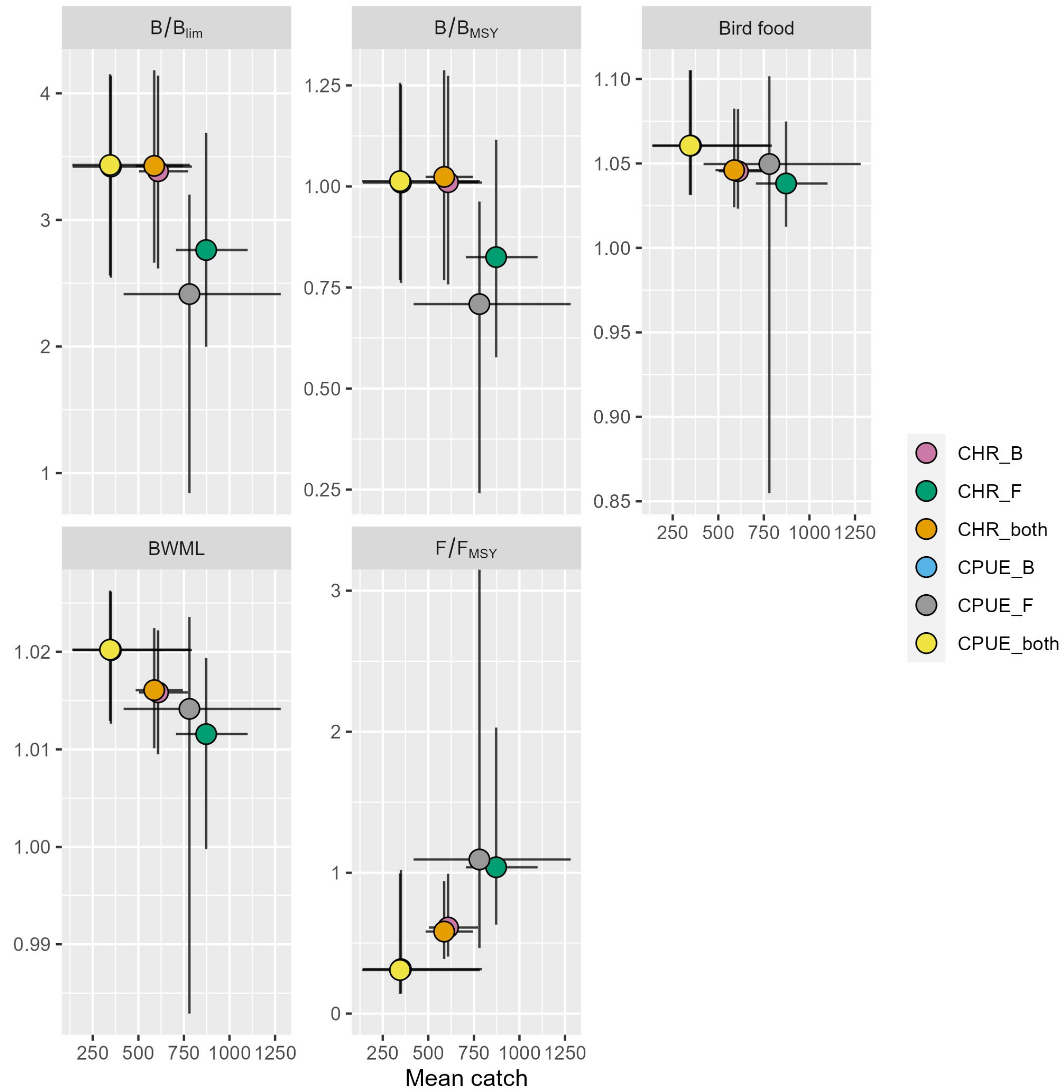
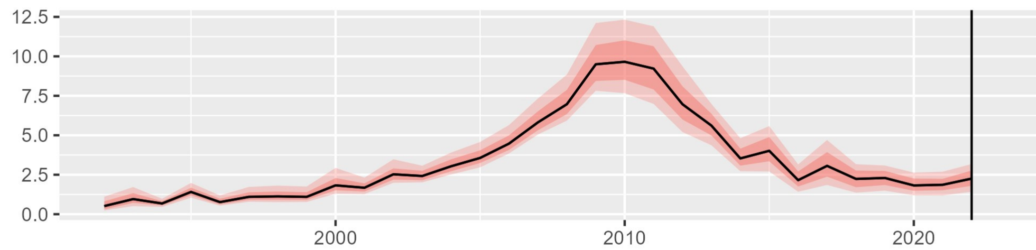


Figure A6.5 *Trade-offs between catch and the five other performance indicators for all management procedures applied to the bream stock OM: stock biomass over B_{lim} (B/B_{lim}), spawning stock biomass relative to SSB_{MSY} (B/B_{MSY}), stock biomass available for the birds relative to sitiation in reference year (bird food), biomass-weighted mean length relative to situation in 2022 (BWML) and fishing mortality over F_{MSY} (F/F_{MSY}).*

Bream MP: Fishing Pressure (F)



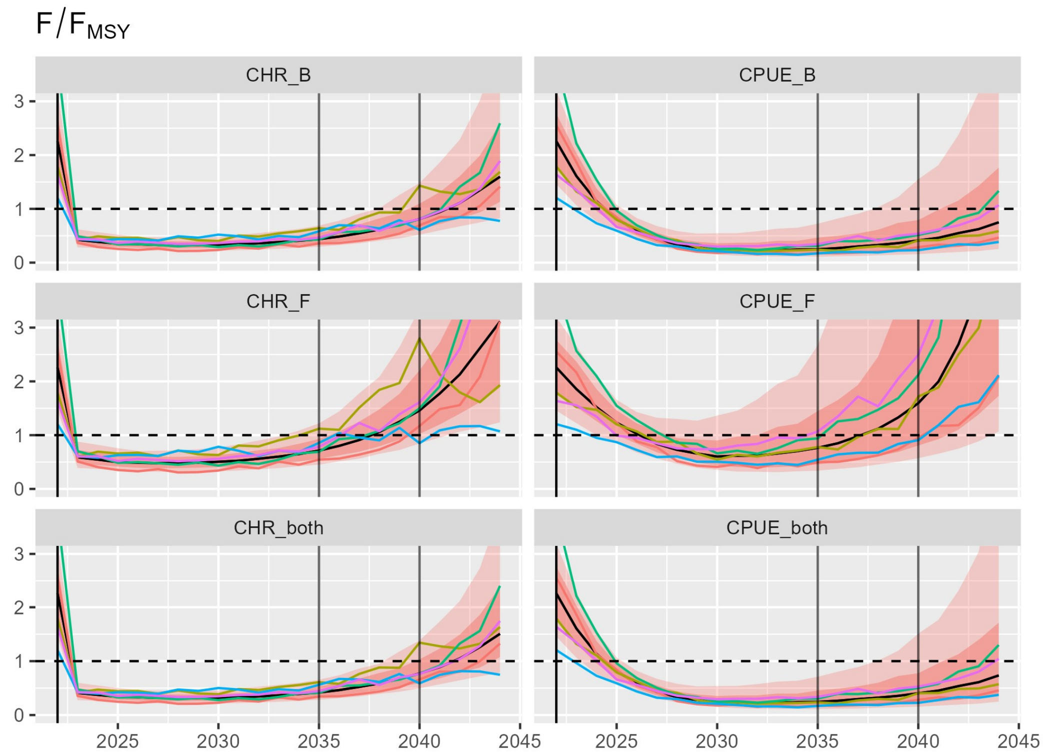


Figure A6.6 *Time series of the F/F_{MSY} indicator for the historical period (top panel), and for all management procedures applied for the future projection period (2023-2045; bottom panels). The five colored lines represent the individual trajectories for five different iterations. F concerns mortality by both the fisheries and the birds.*

Roach

Roach MP: Expected catches versus performance indicators

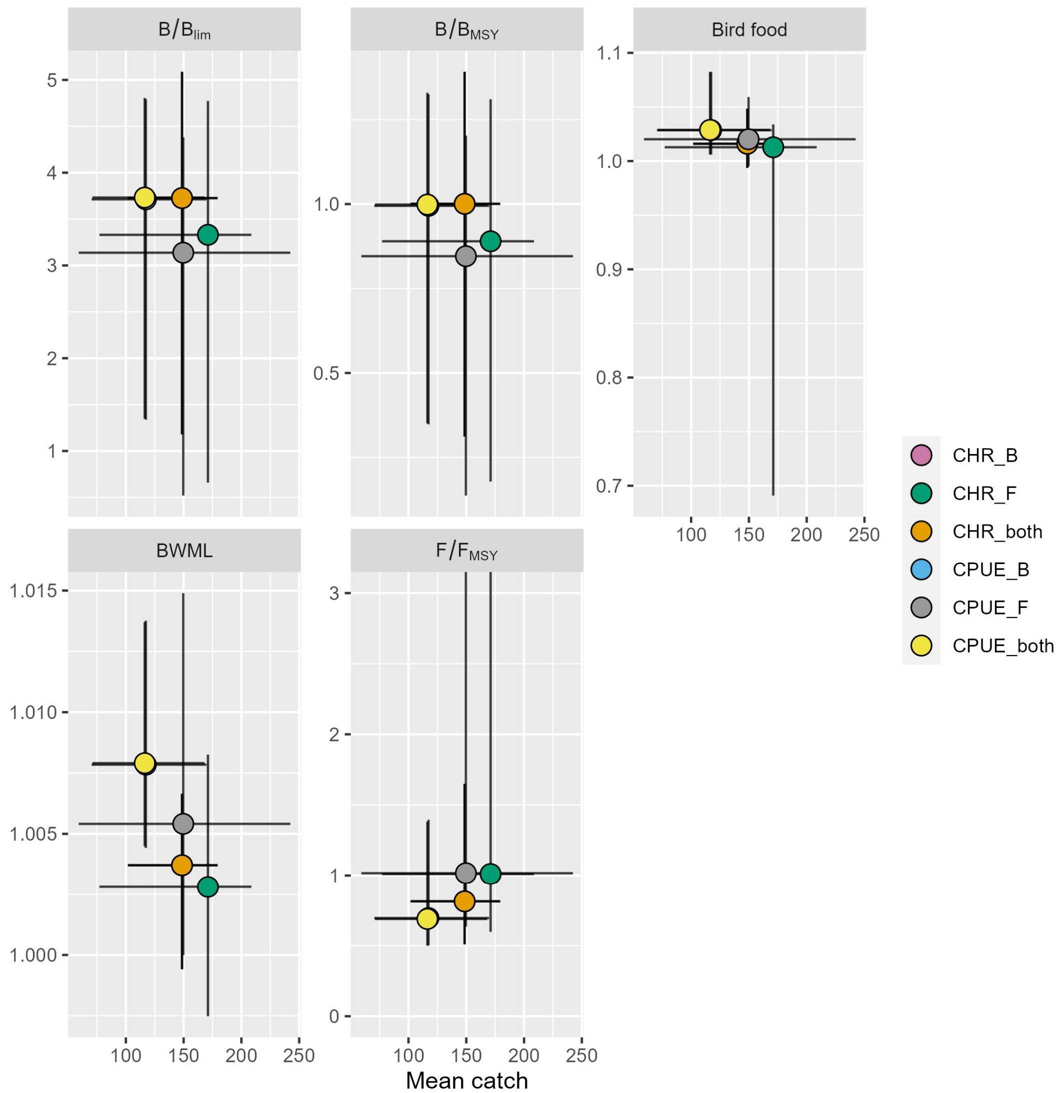


Figure A6.7 *Trade-offs between catch and the five other performance indicators for all management procedures applied to the roach stock OM: stock biomass over B_{lim} (B/B_{lim}), spawning stock biomass relative to SSB_{MSY} (B/B_{MSY}), stock biomass available for the birds relative to situation in reference year (bird food), biomass-weighted mean length relative to situation in 2022 (BWML) and fishing mortality over F_{MSY} (F/F_{MSY}).*

Roach MP: Fishing Pressure (F)

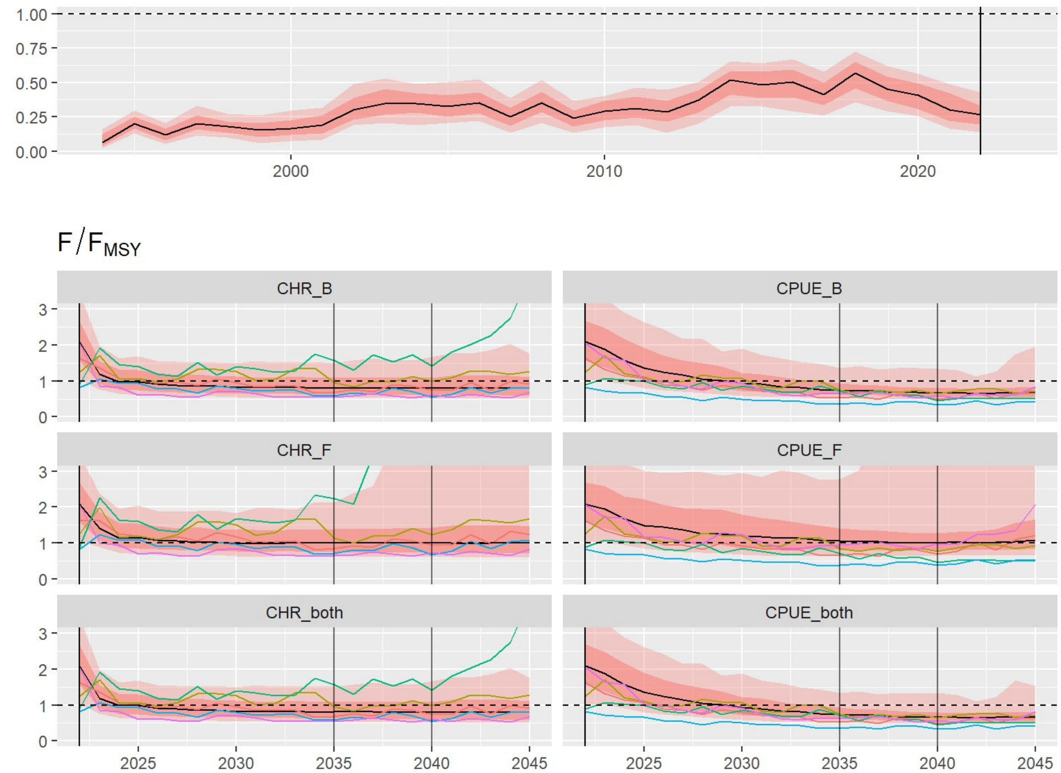


Figure A6.8 *Time series of the F/F_{MSY} indicator for the historical period (top panel), and for all management procedures applied for the future projection period (2023-2045; bottom panels). The five colored lines represent the individual trajectories for five different iterations. F concerns mortality by both the fisheries and the birds.*

MP Tables: Performance statistics[17]

Pikeperch

Table A6.1. *Performance for the two management procedures (CHR and CPUE) tuned to reach objectives for B/B_{lim} (B), F/ F_{MSY} (F) and combined objectives (both) for the period 2035-2040, for pikeperch. Columns represent data for various performance statistics: B/B_{MSY}, B/B_{lim}, probability of being below B_{lim} (P(B<B_{lim}), BWML (relative to $BWML_{2022}$), Bird food (relative to Bird $food_{ref}$), F/F_{MSY}, Mean Catch and percentage change in catches from 2022 to 2023 (see 5.3.1 for details). Data represents the median and 80% credible intervals (0.10 and 0.90 quantiles) for each statistic.*

MP	Performance Statistics							
	B/B_{MSY}	**B/B_{lim}**	**P(B<B_{lim})**	**BWML**	**Bird food**	**F/F_{MSY}**	**Mean Catch**	**Change in catches in 1st year (median)***
CHR_B	0.99 (0.1-1.6)	3.5 (0.5-5.6)	14.4%	1.00 (0.99-1.02)	0.99 (0.74-1.14)	1.09 (0.6-2.9)	304 (76-393)	-26.0%
CHR_F	1.06 (0.2-1.7)	3.7 (0.7-5.8)	12.3%	1.00 (0.99-1.02)	0.99 (0.74-1.16)	1.02 (0.5-2.7)	297 (99-379)	-30.5%
CHR_both	1.12 (0.25-1.7)	4.0 (0.9-6.0)	10.7%	1.00 (0.99-1.02)	1.00 (0.78-1.16)	0.94 (0.5-2.4)	289 (114-364)	-35.0%
CPUE_B	1.00 (0.5-1.4)	3.5 (1.9-4.9)	6.3%	1.00 (0.98-1.03)	1.02 (0.86-1.27)	0.66 (0.3-1.9)	181 (21-461)	+0.3%
CPUE_F	0.50 (0.0-0.9)	1.8 (0.0-3.2)	36.0%	1.00 (0.98-1.04)	1.01 (0.76-1.36)	1.02 (0.4-3.0)	79 (0-345)	-10.0%
CPUE_both	1.08 (0.6-1.5)	3.8 (2.2-5.1)	5.5%	1.08 (0.98-1.03)	1.02 (0.9-1.3)	0.64 (0.3-1.7)	189 (21-464)	+1.2%

Perch

Table A6.2. *Performance for the two management procedures (CHR and CPUE) tuned to reach objectives for B/B_{lim} (B), F/ F_{MSY} (F) and combined objectives (both) for the period 2035-2040, for perch. Columns represent data for various performance statistics: B/B_{MSY}, B/B_{lim}, probability of being below B_{lim} (P(B<B_{lim}), BWML (relative to $BWML_{2022}$), Bird food (relative to Bird $food_{ref}$), F/F_{MSY}, Mean Catch and percentage change in the catches from 2022 to 2023 (see 5.3.1 for details). Data represents the median and 80% credible intervals (0.10 and 0.90 quantiles) for each statistic.*

MP	Performance Statistics							
	B/B_{MSY}	**B/B_{lim}**	**P(B<B_{lim})**	**BWML**	**Bird food**	**F/F_{MSY}**	**Mean Catch**	**Change in catches in 1st year (median)**
CHR_B	0.99 (0.0-2)	3.44 (0.0-6)	24.8 %	1 (1.0-1)	1 (0.9-1)	0.88 (0.4-3)	1597.40 (0.0-2140)	2500%
CHR_F	0.88 (0.0-2)	3.05 (0.0-5)	29.8 %	1 (1.0-1)	1 (0.9-1)	1.01 (0.5-3)	1617.68 (0.0-2254)	2692%
CHR_both	1.02 (0.0-2)	3.54 (0.0-6)	23 %	1 (1.0-1)	1 (0.9-1)	0.84 (0.4-3)	1572.24 (0.0-2090)	2432%
CPUE_B	0.99 (0.3-2)	3.46 (1.0-6)	10.8 %	0.98 (0.9-1)	0.91 (0.6-1)	1.90 (0.4-3)	2574.69 (609.1-4765)	274%
CPUE_F	1.14 (0.4-2)	4.08 (1.4-6)	7.6 %	0.99 (0.9-1)	0.94 (0.6-1)	1.15 (0.3-3)	2196.32 (569.0-4275)	251%
CPUE_both	1.22 (0.5-2)	4.25 (1.7-6)	6.2 %	0.99 (0.9-1)	0.96 (0.7-1)	0.94 (0.3-3)	1962.07 (569.4-4168)	241%

[17] Though it is mathematically possible for F/FMSY to reach higher values, this is unrealistic for the IJssel/Markermeer and therefore constrained in to an upper limit of 3 in our analysis.

Bream

Table A6.3. Performance for the two management procedures (CHR and CPUE) tuned to reach objectives for B/B_{lim} (B), F/F_{MSY} (F) and combined objectives (both) for the period 2035-2040, for bream. Columns represent data for various performance statistics: B/B_{MSY}, B/B_{lim}, probability of being below B_{lim} ($P(B<B_{lim})$), BWML (relative to $BWML_{2022}$), Bird food (relative to Bird $food_{ref}$), F/F_{MSY}, Mean Catch and percentage change in catches from 2022 to 2023 (see 5.3.1 for details). Data represents the median and 80% credible intervals (0.10 and 0.90 quantiles) for each statistic.

MP	Performance Statistics							
	B/B_{MSY}	**B/B_{lim}**	**$P(B<B_{lim})$**	**BWML**	**Bird food**	**F/F_{MSY}**	**Mean Catch**	**Change catches in 1st year (median)**
CHR_B	1.01 (0.8-1.3)	3.38 (2.6-4.1)	0 %	1.02 (1.0-1.0)	1.05 (1.0-1.1)	0.61 (0.4-1.0)	608 (503-773)	-82 %
CHR_F	0.83 (0.6-1.1)	2.76 (2.0-3.7)	0 %	1.01 (1.0-1.0)	1.04 (1.0-1.1)	1.04 (0.6-2.0)	872 (706-1099)	-73 %
CHR_both	1.02 (0.8-1.3)	3.43 (2.7-4.2)	0 %	1.02 (1.0-1.0)	1.05 (1.0-1.1)	0.58 (0.4-0.9)	587 (485-744)	-82 %
CPUE_B	1.01 (0.8-1.2)	3.42 (2.5-4.1)	0 %	1.02 (1.0-1.0)	1.06 (1.0-1.1)	0.31 (0.1-1.0)	350 (140-794)	-26 %
CPUE_F	0.71 (0.2-1.0)	2.41 (0.8-3.2)	12.6 %	1.01 (1.0-1.0)	1.05 (0.8-1.1)	1.09 (0.5-3.0)	780 (419-1281)	-15 %
CPUE_both	1.01 (0.8-1.3)	3.43 (2.6-4.2)	0 %	1.02 (1.0-1.0)	1.06 (1.0-1.1)	0.31 (0.1-1.0)	345 (138-783)	-25.8 %

Roach

Table A6.4. Performance for the two management procedures (CHR and CPUE) tuned to reach objectives for B/B_{lim} (B), F/F_{MSY} (F) and combined objectives (both) for the period 2035-2040, for roach. Columns represent data for various performance statistics: B/B_{MSY}, B/B_{lim}, probability of being below B_{lim} ($P(B<B_{lim})$), BWML (relative to $BWML_{2022}$), Bird food (relative to Bird $food_{ref}$), F/F_{MSY}, Mean Catch and percentage change in catches from 2022 to 2023 (see 5.3.1 for details). Data represents the median and 80% credible intervals (0.10 and 0.90 quantiles) for each statistic.

MP	Performance Statistics							
	B/B_{MSY}	**B/B_{lim}**	**$P(B<B_{lim})$**	**BWML**	**Bird food**	**F/F_{MSY}**	**Mean Catch**	**Change in catches in 1st year (median)**
CHR_B	1.00 (0.31-1.4)	3.7 (1.2-5.0)	7.8 %	1.00 (1.00-1.01)	1.02 (1.00-1.09)	0.81 (0.50-2.0)	149 (102-175)	-50 %
CHR_F	0.87 (0.17-1.3)	3.3 (0.7-5.0)	10.8 %	1.00 (1.00-1.01)	1.01 (0.70-1.03)	1.02 (0.60-3.0)	171 (77-209)	-32 %
CHR_both	0.99 (0.31-1.4)	3.7 (1.2-5.0)	7.8 %	1.00 (1.00-1.01)	1.02 (1.00-1.04)	0.82 (0.50-2.0)	149 (102-179)	-50 %
CPUE_B	0.99 (0.34-1.3)	3.7 (1.3-4.8)	9.4 %	1.01 (1.00-1.01)	1.03 (1.00-1.08)	0.67 (0.50-1.0)	117 (70-170)	-2 %
CPUE_F	0.85 (0.13-1.2)	3.1 (0.5-4.0)	11.6 %	1.01 (1.00-1.01)	1.02 (0.95-1.05)	1.00 (0.61-3.0)	150 (59-242)	-2 %
CPUE_both	1.00 (0.35-1.3)	3.7 (1.4-5.0)	9.2 %	1.01 (1.00-1.01)	1.03 (1.00-1.08)	0.66 (0.50-1.0)	116 (71-168)	-2 %

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