# Appendix

# Contents

## A) Size based model

To model the large marine ecosystems we use a framework of size spectrum models (Hartvig *et al.* 2011) . Size spectrum models are based on individual level processes and book keep the energy flows from these processes. Furthermore, the models used are dynamic, making them a suitable candidate for strategic management evaluations of fishing (Andersen and Pedersen 2010; Jacobsen *et al.* 2014; Andersen *et al.* 2015). The models are based on the size spectrum, $N(w,W_\infty)$, of each species, *i*. $w$ is the individual weight and $W_\infty$ is the asymptotic weight (Andersen and Beyer 2006). We use two central assumptions: 1) that weight, asymptotic weight and growth rate are central in describing individuals. 2) food preference is determined by individual weight and prey vulnerability. For full description of the model framework and standard parameters see Jacobsen et al (2014). The main equations and changes to the framework there are presented below and parameters in table A1.

The equation used to describe the dynamics of a system is the McKendrick-Von Foerster conservation equation

$$\frac{\partial N_i}{\partial t} + \frac{\partial g_i(w)\,N_i(w)}{\partial w} = -\mu_i N_i$$

Where $N_i$ is the size spectrum of species *i*, $g$ is the growth rate, $\mu$ mortality and $w$ is the individual weight. Mortality and growth rates are dynamically calculated from sub-models that take available food and predators into account.

The equation is supplemented by a boundary condition at $w_0$

$$g(w_0)N_i(w_0) = R_i$$

where $R_i$ is recruitment into the population provided by mature individuals.

The fish size spectrum is supplemented by a resource spectrum, $N_R$, which represents food outside the fish community (i.e. invertebrates). The total number of individuals is therefore the community spectrum

$$N_C = \sum_i N_i(w) + N_R(w)$$

When the size spectrum is known it is possible to calculate the biomass, which is most conveniently described in log classes. The species cohort biomasses are calculated as

$$B_{\log,i}(w) = \int_{W_{\infty,i}}^{w_0} N_i(w)w\, dw$$

Growth in the model depends on a combination of the prey present in the community $N_C$, a log based preference where large eats small and a species specific search rate. This combination provides the encounter of prey, $E(w)$.

$$E_i(w) = \gamma_i w^q \sum_j v_j \int_0^{W_{\infty,j}} N_j(w)\phi\left(\frac{w_{prey}}{w}\right) w\, dw_{prey}$$

$\gamma_i$ is search rate of predator $i$, $v_i$ the vulnerability, $\phi$ is the size based preference function, $j$ is the prey species, and $q$ is the exponent of the search rate.

The uptake is limited by a functional response

$$f_i(w) = \frac{E_i(w)}{E_i(w) + h_i\, w^n}$$

$f(w)$ is a dimensionless number between 0 and 1 and determines satiation of an individual (Andersen and Ursin 1977), referred to as the feeding level. $h_i w^n$ is the maximum consumption rate. In the models presented here $h$ is a species specific parameter that effectively controls the time scale, i.e. weight at age. We use the von Bertalanffy growth rate ($K$) to calculate the species specific $h$ (see Appendix B). Mortality of prey is directly proportional to feeding of predators to keep internal consistency. In the model formulations used here predation is slightly altered compared to previous versions of the models, as we allow a metric of vulnerability to predation (high for fast growing species, and low for slow growing species). Predation mortality is calculated as

$$\mu_{prey,i} = v_i \int_{w_0}^{W_{\infty,i}} \phi(w_p/w)\big(1 - f(w)\big)\gamma w^q \sum_i N_i(w)\, dw$$

The energy an individual has available is divided between growth and reproduction. When an individual is fully mature all energy is directed at spawning rather than growth. The natural mortality is supplementeted for all sizes and species with a background mortality of 0.15 yr$^{-1}$.

Recruitment into the population, $R_i$, depends on the energy directed towards reproduction and a reproductive efficiency, $\epsilon$. Furthermore recruitment is regulated by a Beverton-Holt (Beverton and Holt 1957) like stock-recruitment relationship

$$R_i = R_{\text{max},i} \frac{R_{p,i}}{R_{p,i} + R_{max,i}}$$

57 Where $R_{\text{max}.i}$ is the maximum recruitment (eggs yr$^{-1}$) and $R_{p.i}$ is the physiological recruitment; the total
58 number of eggs produced. Here we use $R_{max.i}$ to calibrate the relative biomasses between species in the
59 models.

60 Organisms that are not included in the size based model, such as non-commercial species and invertebrates
61 are included in the model as a background spectrum that feeds small to intermediate sized fish. The
62 background spectrum acts as the primary food item in the juvenile stages. The dynamics of the background
63 spectrum are modelled as a semi-chemostat and ranges 0.001 to 20 g

$$\frac{dN_R(w)}{dt} = r_0 w^{p-1}\left[\kappa_{pp}w^{-\lambda} - N_R(w)\right] - \mu_p(w)N_R(w)$$

64 Where $r_0$ is the growth rate, $\kappa_{PP}$ the carrying capacity and $\lambda$ the slope of the background spectrum. The
65 carrying capacity of the background spectrum is used to control the total biomass in the large marine
66 ecosystem, as explained in the calibration section below.

67 **Table A1: List of parameters. *see appendix B.**

| Parameter | | Definition | Value |
|---|---|---|---|
| | $\beta$ | Preferred predator prey ratio | 100 |
| | $\sigma$ | Width of selection curve | 1.3 |
| | $q$ | Search volume exponent | 0.8 |
| | $n$ | Maximum consumption exponent | 0.75 |
| | $\eta_m$ | Size at 50% maturation relative to $W_\infty$ | 0.25 |
| | $\epsilon$ | Reproductive efficiency | 0.1* |
| | $\alpha$ | Assimilation efficiency | 0.6 |
| | $K_s$ | Standard metabolism prefactor | 0.8$h_i$ |
| | $p$ | Standard metabolism exponent | 0.75 |
| | $\lambda$ | Background spectrum exponent | 2.05 |
| | $r_0$ | Background spectrum growth rate | 4 g$^{1-p}$ yr$^{-1}$ |
| | $\eta_F$ | Size at 50% trawl selectivity relative to $W_\infty$ | 0.1 |

68

69 **B) Calibration procedure**
70 The calibration is performed in 7 steps:

71    1) Initiate parameters using $W_\infty$ from all species in the considered LMEs. For temperate systems see
72        general metabolic parameterization in Jacobsen *et al.* (2014) or the trait-based model in mizer R
73        package (Scott *et al.* 2014). The initial $R_{\max}$ values are calculated from equilibrium theory (see e.g.
74        Andersen *et al.* (2016)).
75    2) Calculate average biomass and fishing mortality for each species included during the time period
76        1992-2002.
77    3) Calibrate the carrying capacity of the background spectrum, $\kappa_R$ using least sum of squares, such
78        that the modelled spawner biomass distribution is in the same order of magnitude as the observed
79        distribution.
80    4) Add specific species characteristics: species specific maximum uptake rate is calculated as

$$h_i = \frac{3K_i}{\alpha} W_{\infty.i}^{1/3}$$

81        where $K_i$ is the von Bertalanffy growth rate. The *h* parameter sets the time scale of each species,
82        and therefore simulates slow growing versus fast growing species. Similarly, we scale search rate
83        with vulnerability, $v_i$. Vulnerability is calculated such that slow growing species have a *v < 1* and fast
84        growing species have *v > 1*:

$$v_i = \frac{n}{\sum_n h}\, h_i,$$

85        where *n* is the number of species.

86    5) Calibrate the maximum recruitment $R_{\max.i}$. This parameter determines the relative biomasses of
87        species and is calibrated by minimizing the least sum of squares between observed and estimated
88        biomasses.
89    6) Investigate if the physiological reproduction $R_{p.i}$ is much higher than the recruitment, $R_i$ (ratio
90        $\approx 100$ for a species with $W_\infty = 1500,$ but depending on asymptotic size and fishing mortality, see
91        Andersen and Beyer (2015)). High $\frac{R_p}{R}$ indicates that the carrying capacity of that species is
92        controlled by the external parameter $R_{\max.i}$, rather than by emergent competition and predation.
93        Large species often required higher density dependence than smaller ones. If $\frac{R_p}{R}$ is very high the
94        efficiency of reproduction $\epsilon$ can be lowered, to ensure that the species is not overly competitive
95        and resistant to fishing pressure. Standard value of $\epsilon$ is 0.1, but can be lowered by up to a factor of
96        50. Lowering of $\epsilon$ is biologically means higher egg mortality rate or wasteful energy invested in
97        gonads. If $R_p/R = 1$ there is that species is in the linear part of the stock-recruitment relationship
98        (i.e. no density dependence by the stock-recruitment relationship.). In the calibrations presented
99        here the values for $\epsilon$ are 0.005, 0.01, 0.05, 0.1 and 0.005 for the North Sea, Baltic Sea, Barents Sea,
100       NEUSCS and Benguela Current, respectively.
101   7) Verify the models using the "Pope method" (Pope *et al.* 2006). The method involves comparing
102       model output with the estimated values: species biomass distributions, natural mortality, growth,
103       vulnerability to fishing, and catch. Natural mortality is often given in stock assessments, and here
104       we compare it at size at maturation (Figure D7-D12). We compare growth of individual species with
105       von Bertalanffy growth. In the model it depends both on the *h* parameter, but also on available
106       prey. Whether fishing mortality works correctly can be seen if the fishing mortality required to
107       reach maximum sustainable yield, $F_{MSY}$ is in the correct range as the one used in the assessment.
108       This is subject to some bias, as many estimated $F_{MSY}$ seem to be routinely set $\approx 0.2$ year[-1] (Mangel
109       *et al.* 2010), and does not account for changes in the surrounding community.
110   8) Run the model with the fishing mortalities from the assessments and compare with observations
111       (figure C1-C6).

112 Competitive exclusion may occur in systems where species with similar asymptotic size have vastly
113 different growth rates in step 4. If that is the case it can become necessary to perform step 5 first, and then
114 reiterating step 4-5.

115 If verification (step 7) fails one must consider the reasons. Do some species have unnaturally high fishing
116 mortality and slow growth? Is the assumption of everyone eats everything (in the suitable size) violated in
117 that particular system, and is it therefore necessary to create a food web of preferences (as in Blanchard *et*
118 *al.* (2014), Hartvig *et al.* (2011))?. It is also important to acknowledge that empirical rates (such as natural
119 mortality) often have large uncertainty (Pascual and Iribarne 1993; Gislason *et al.* 2010), and that could
120 potentially cause a discrepancy between modeled and observed values. In situations where calibrations fail
121 it is therefore relevant to ask 1) are the input parameters (e.g. $W_\infty$ and $K$, and parameters estimated based
122 on size) correct and realistic?, 2) are empirical values correct? 3) are the assumptions provided by the size
123 spectrum model violated?
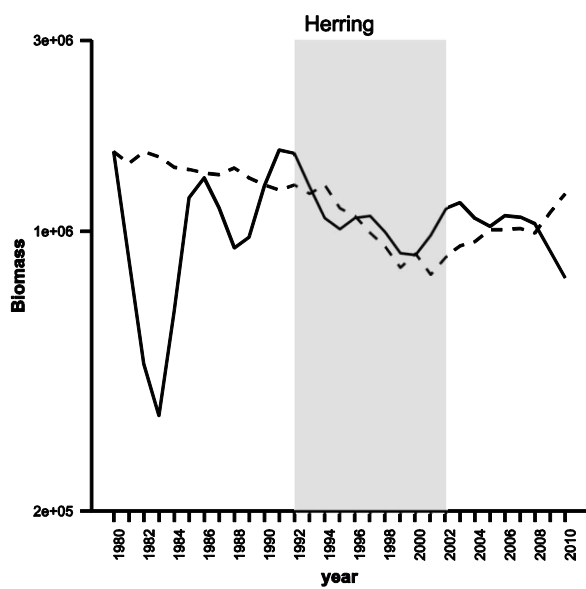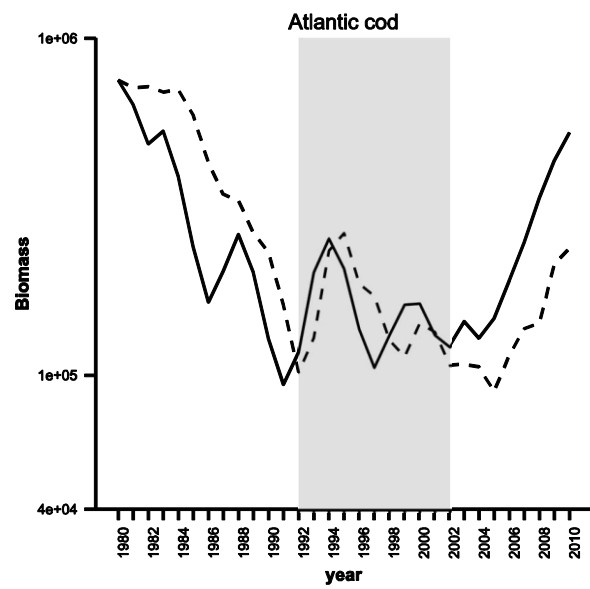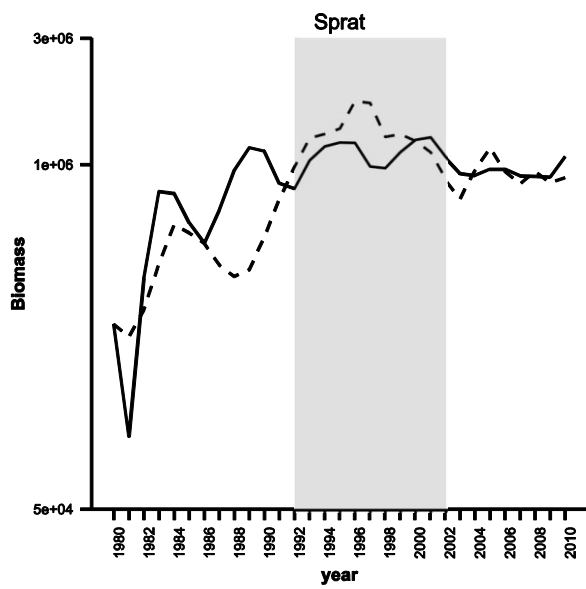
124 **C) Temporal spawner biomasses**
125 The calibrations for the large marine ecosystems are performed using the average biomass distributions
126 and fishing mortalities. To check how the models perform outside those fishing mortalities we provide the
127 temporal evolution of spawning biomass (Figure C1-C7). Generally, the models perform well with accurate
128 description of the dynamics.
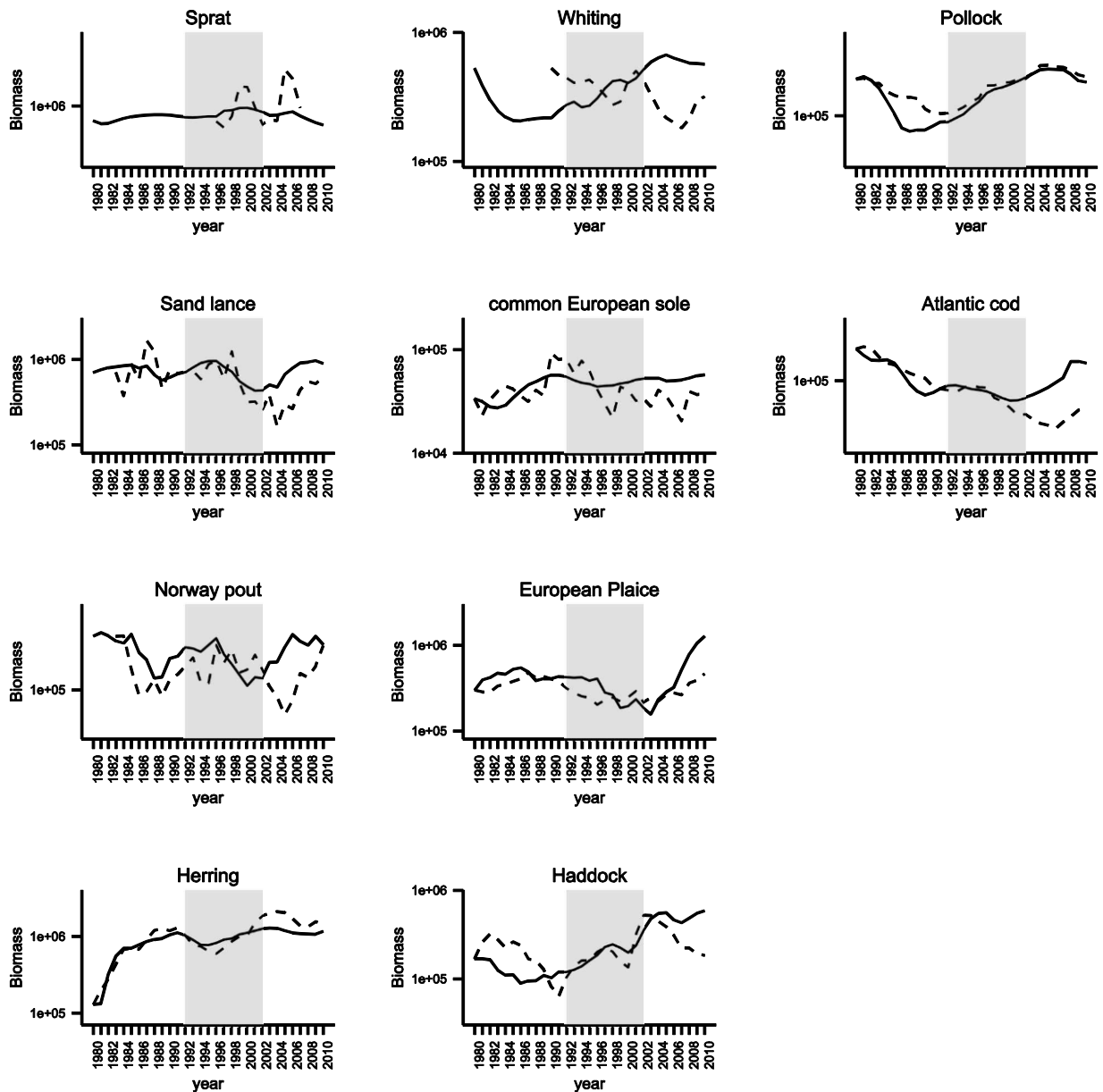
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130    Figure C1: Temporal spawner biomass (metric tons) from the North Sea. Full line is SSB from assessment,
131    dotted line is simulated SSB. Gray area is the time period where the models are calibrated by using average
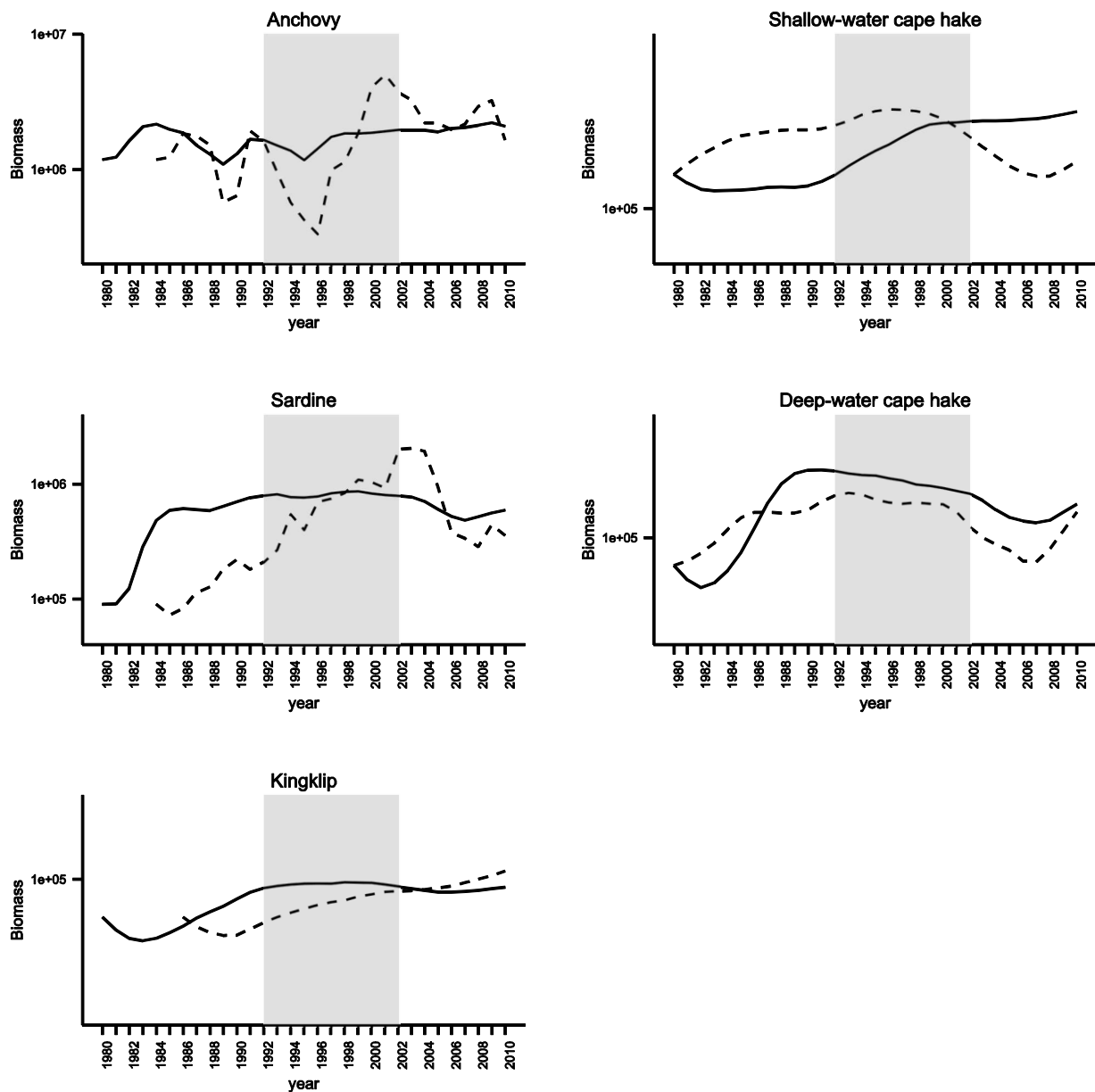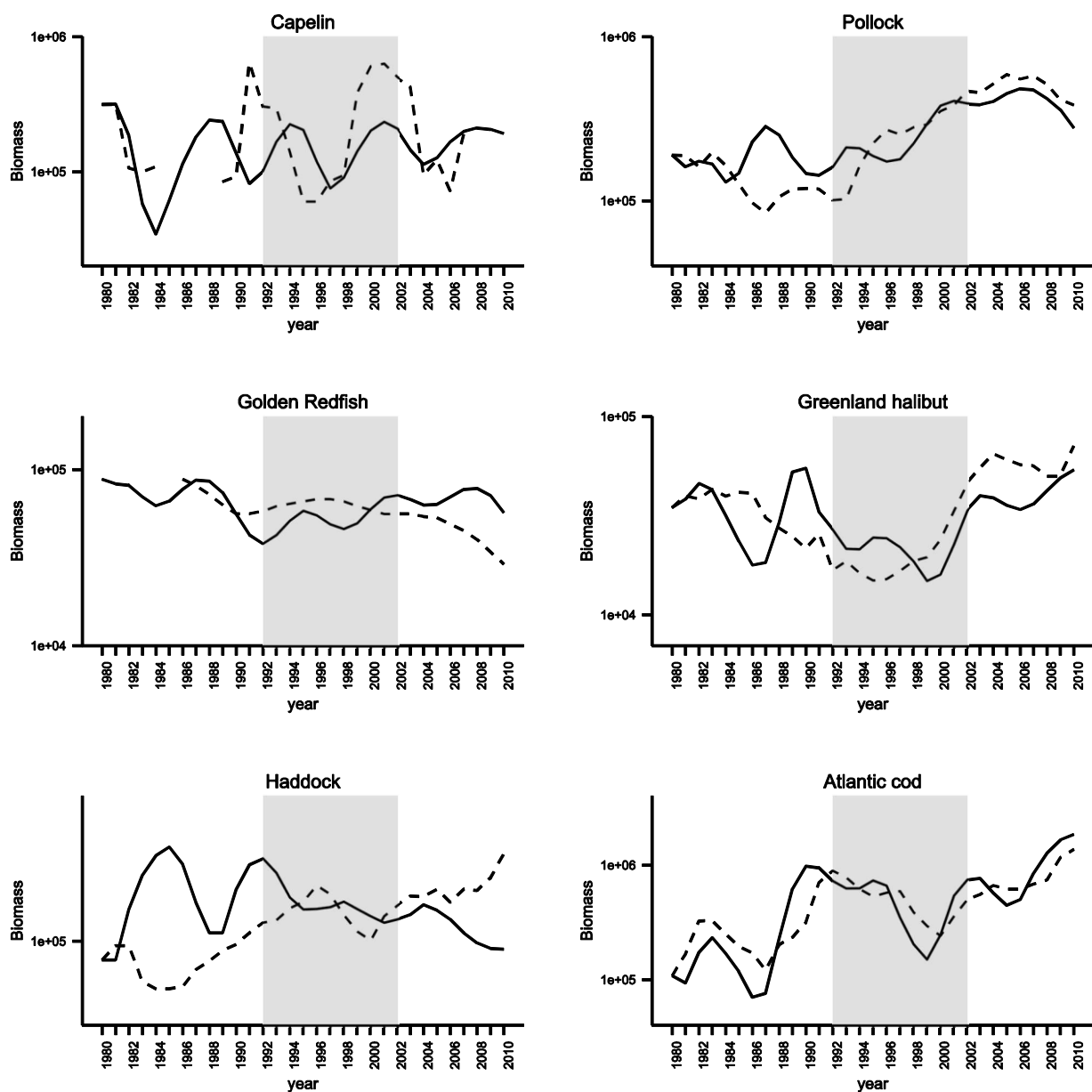132    spawner biomass and fishing mortality.

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134

Figure C2: Temporal spawner biomass (metric tons) from the Baltic Sea. Full line is SSB from assessment, dotted line is simulated SSB. Gray area is the time period where the models are calibrated by using average spawner biomass and fishing mortality.

138
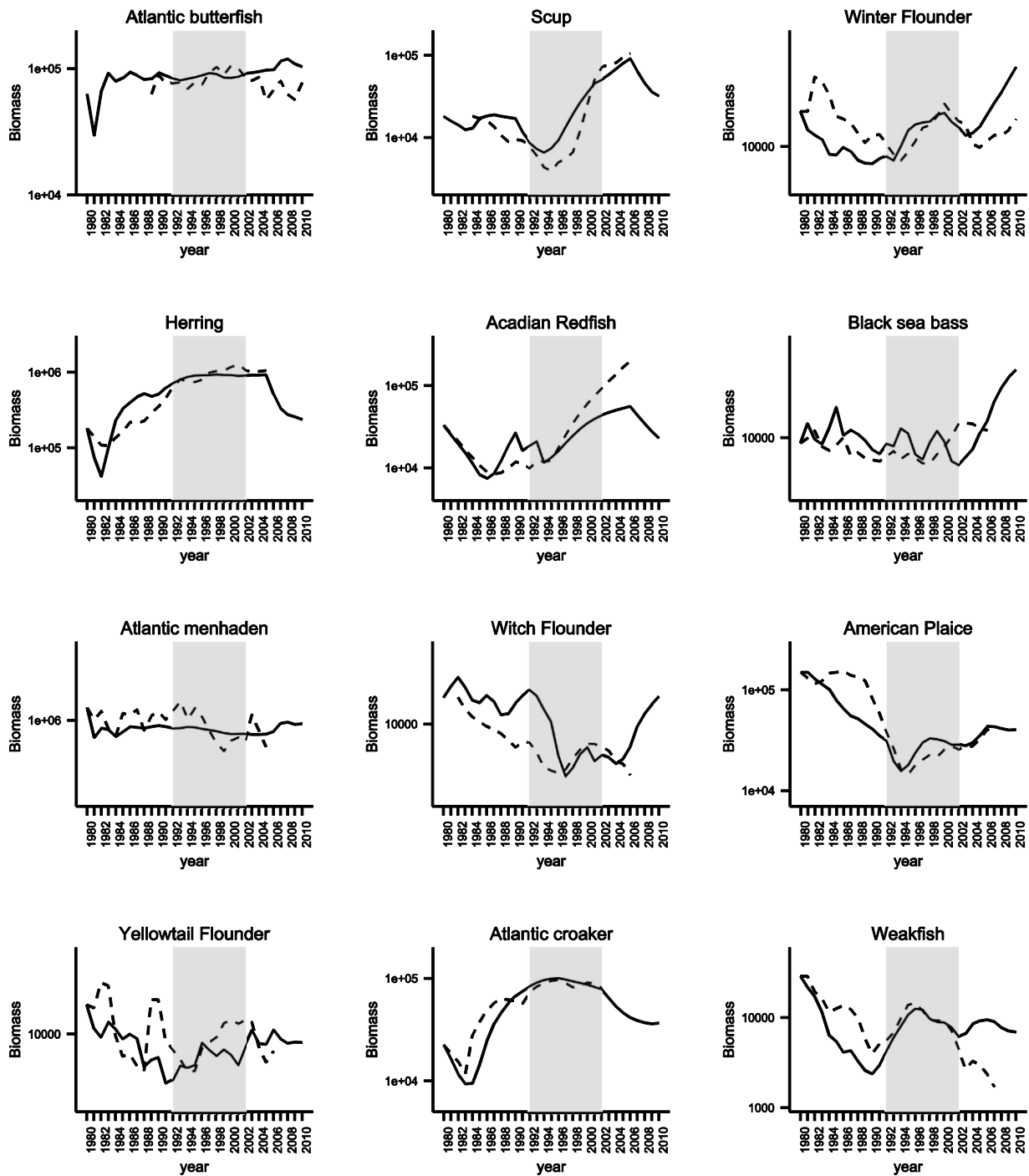
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Figure C3: Temporal spawner biomass (metric tons) from the Benguela Current. Full line is SSB from
assessment, dotted line is simulated SSB. Grey area is the time period where the models are calibrated by
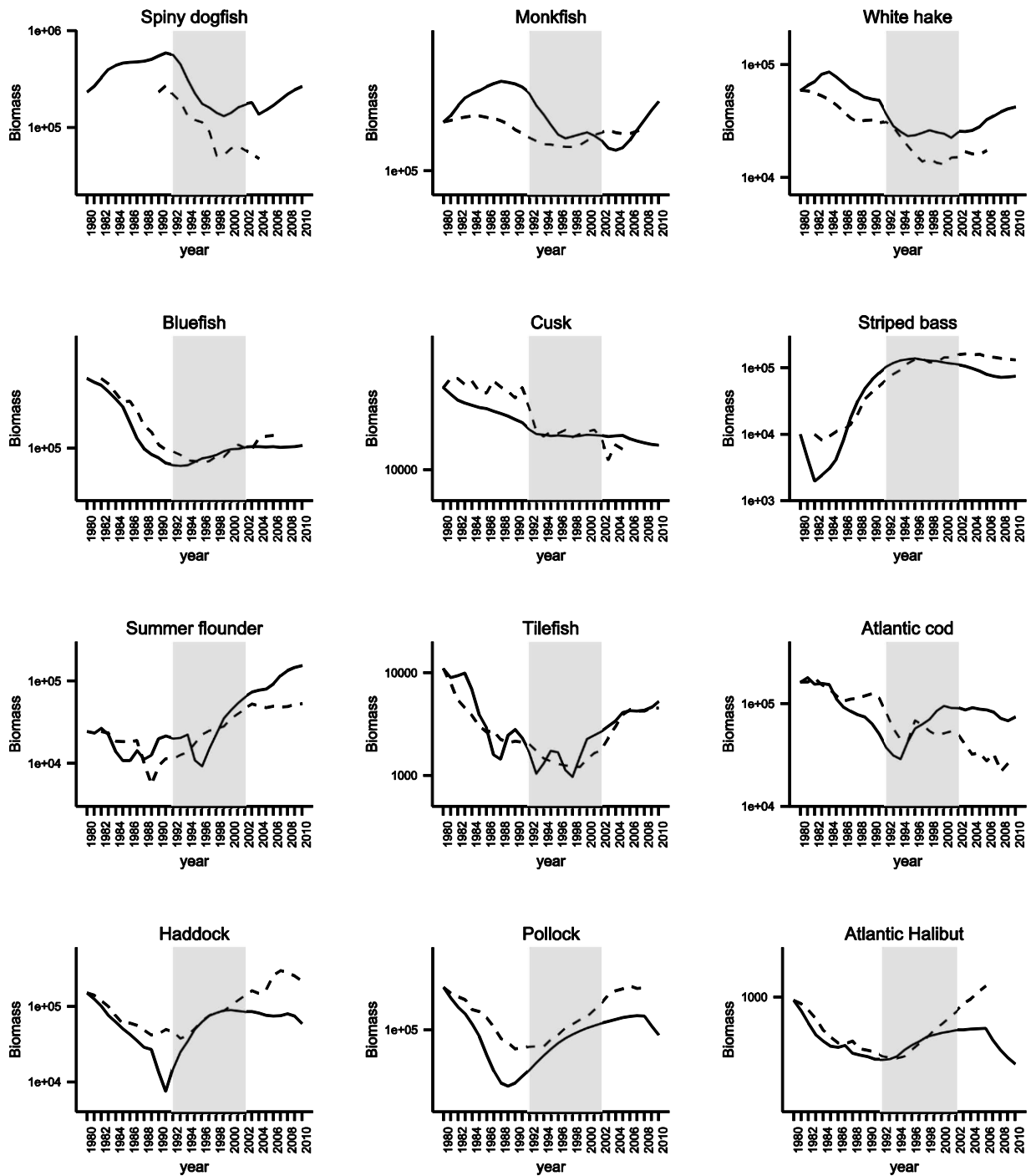using average spawner biomass and fishing mortality.

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144

Figure C4: Temporal spawner biomass (metric tons) from the Barents Sea. Full line is SSB from assessment, dotted line is simulated SSB. Grey area is the time period where the models are calibrated by using average spawner biomass and fishing mortality.

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Figure C5: Temporal spawner biomass (metric tons) from the North East US Continental Shelf (see
remaining species In Figure A6). Full line is SSB from assessment, dotted line is simulated SSB. Grey area is
the time period where the models are calibrated by using average spawner biomass and fishing mortality.

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Figure C6: Temporal spawner biomass (metric tons) from the North East US Continental Shelf. Full line is
SSB from assessment, dotted line is simulated SSB. Grey area is the time period where the models are
calibrated by using average spawner biomass and fishing mortality.

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## D) Calibration verification

The calibrations are verified by looking at the emerging spawner biomasses (when SSB is unavailable total biomass is used), rates (growth, mortality, $F_{MSY}$), and catch distributions. Additionally, we check that the amount of recruitment control is not too high (Rp>>R) and that the systems converge to equilibrium without competitive exclusion.

The catches are generally overestimated in the size based models, but it appears to be constant (Figure D1-7). A similar problem was reported in a recent study (Spence *et al.* 2015) where they calibrated to catches and underestimated spawner biomass.

167
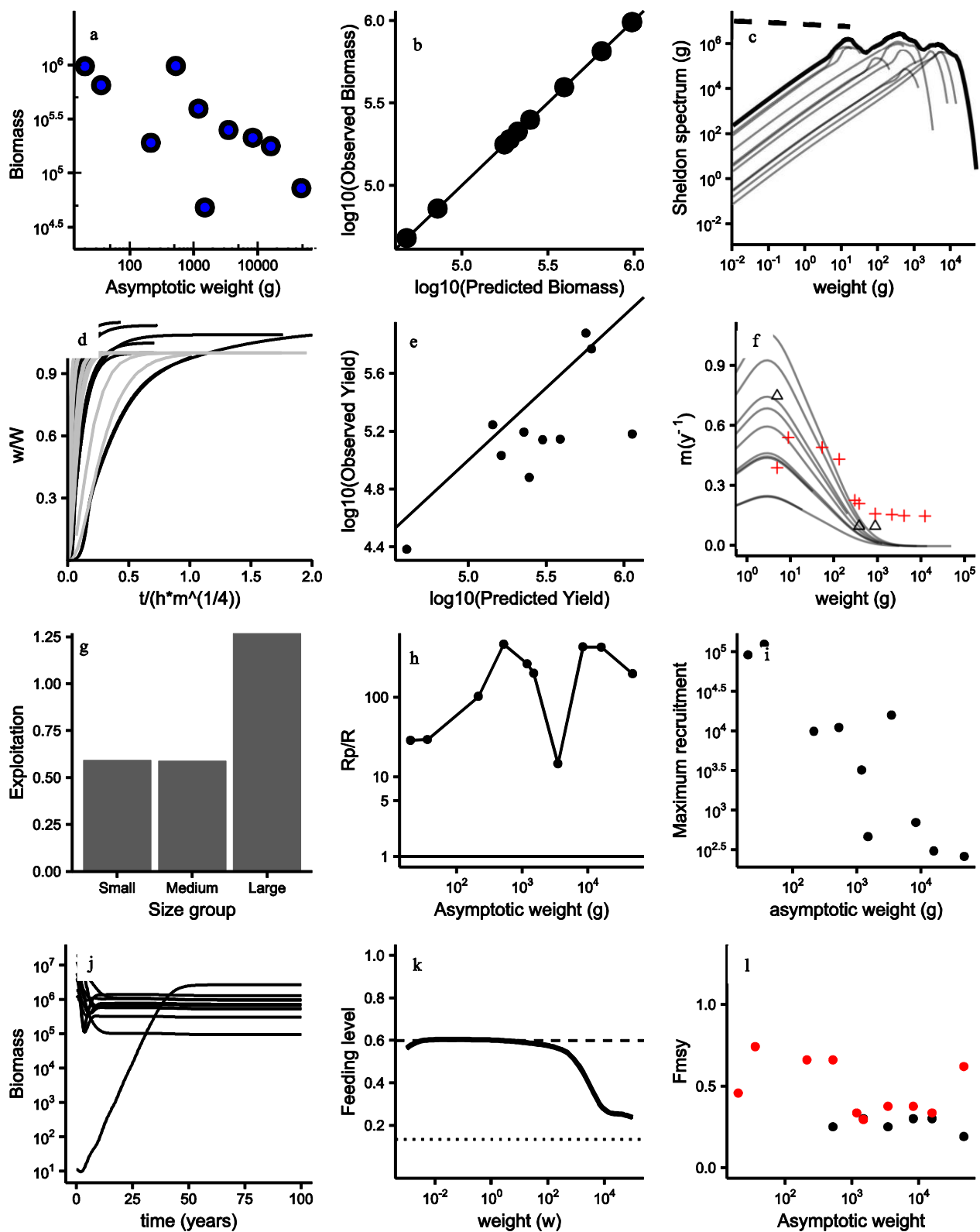
Figure D1: North Sea calibration verification under equilibrium. A) Biomass distribution as a function of asymptotic size (blue dots simulated, black dots from assessment), B) Predicted (simulated) vs observed (assessment) biomass, topleft number indicates $r^2$. Black line is a straight line with slope = 1 and intercept = 0. C) The emerging Sheldon spectrum, D) Growth rates of individual species, black is the emerging

growth from the model, grey is Von Bertalanffy growth. E) Predicted vs observed catch, F) Natural
mortality, triangles are from the assessments, red crosses is total mortality at size at maturation, lines is
mortality at size. G) Size specific ecosystem exploitation  based on asymptotic size. Exploitation is defined
as catch divided by total biomass. H) Physiological reproduction, Rp, divided by reproduction R. If Rp/R = 1
the population is not regulated by the stock recruitment relationship. If Rp/R >> 1 the stock recruitment
relationship controls the population. I) $R_{\max}$ as a function of asymptotic size. J) Temporal biomass
evolution that ensures the community goes to equilibrium. K) Feeding level as a function of individual size.
L) Fmsy as a function of asymptotic size. Red is simulated values, black is from assessments (not often
available).
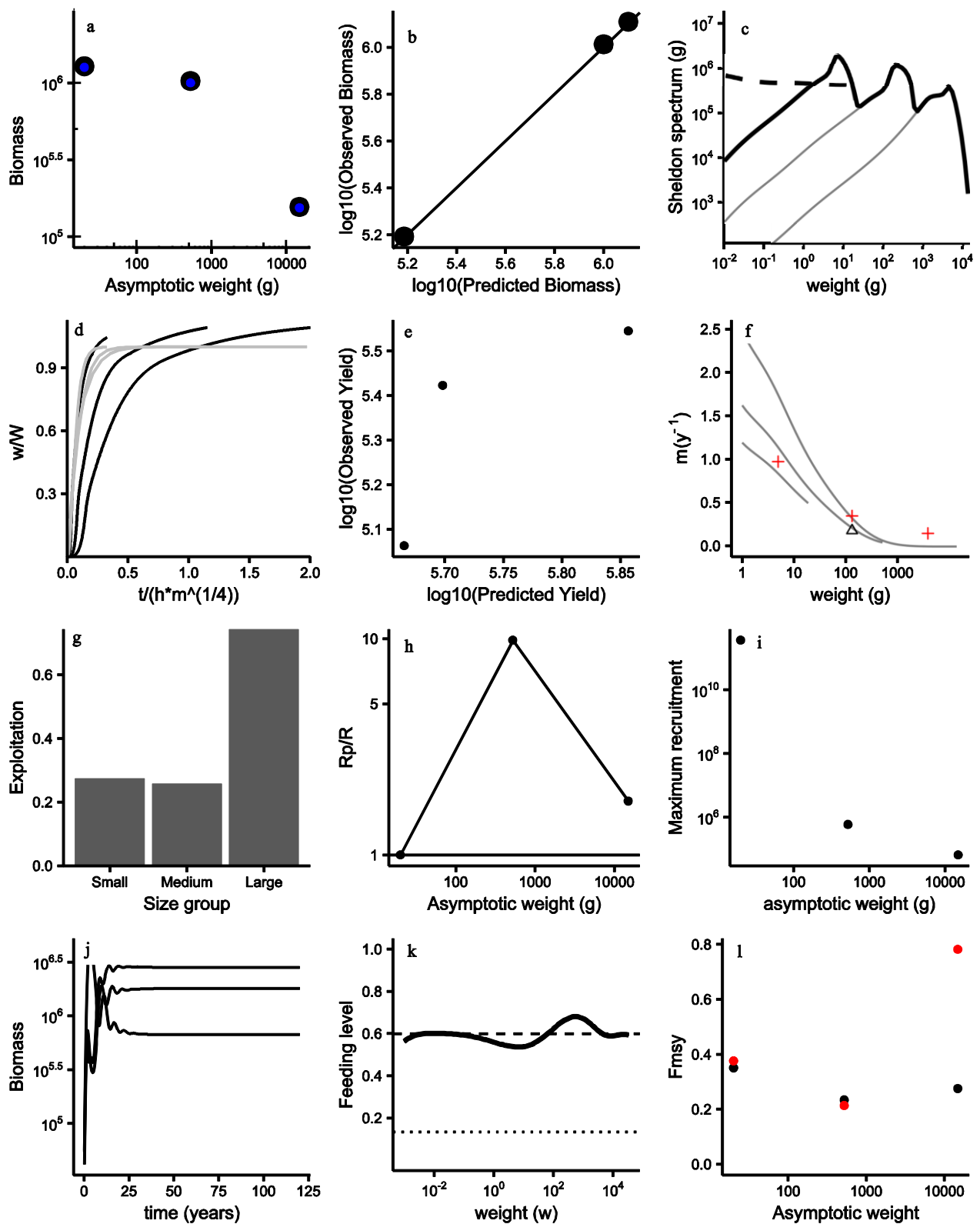
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183    Figure D2: Baltic Sea Calibration. A-L) see figure D1 caption.
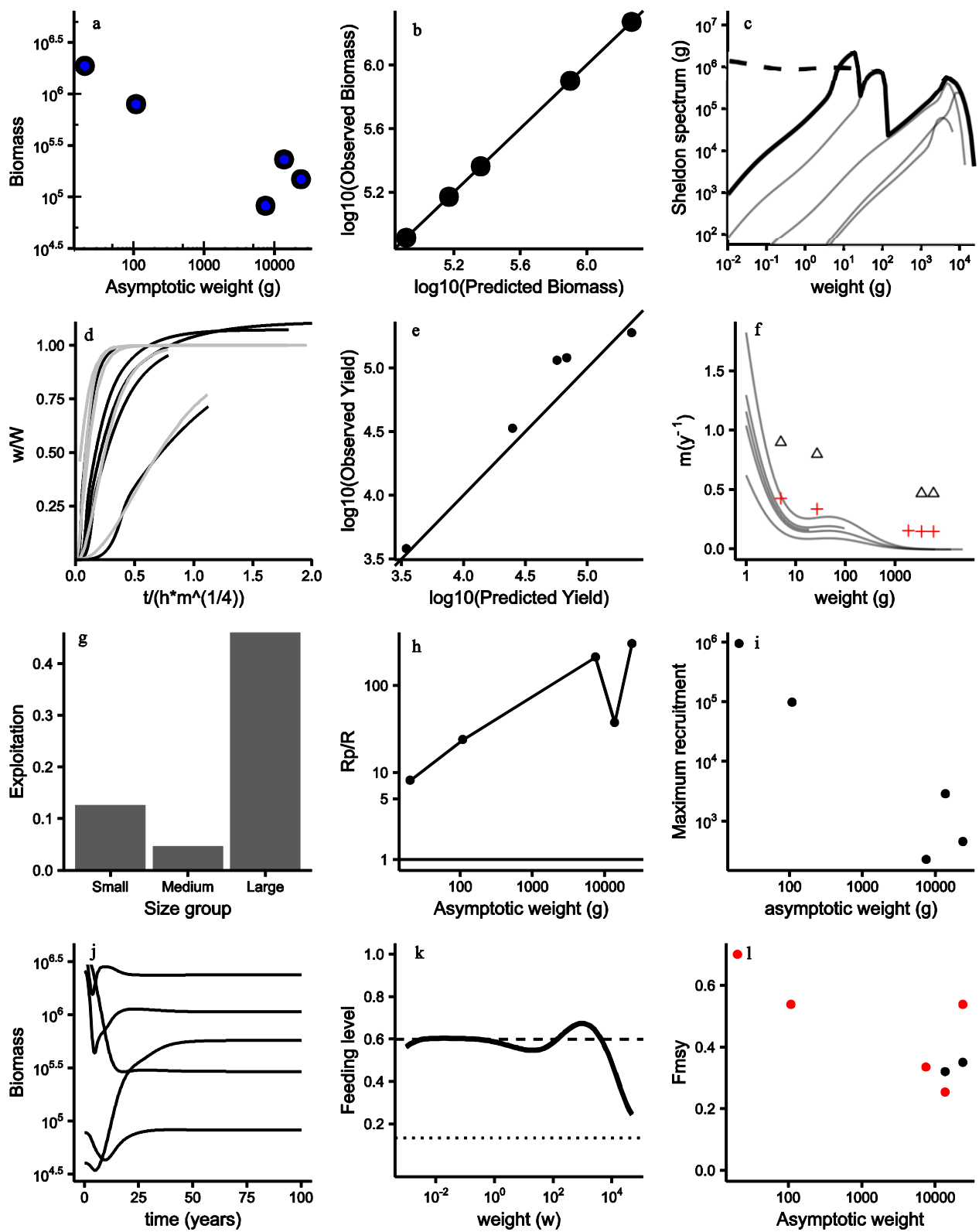
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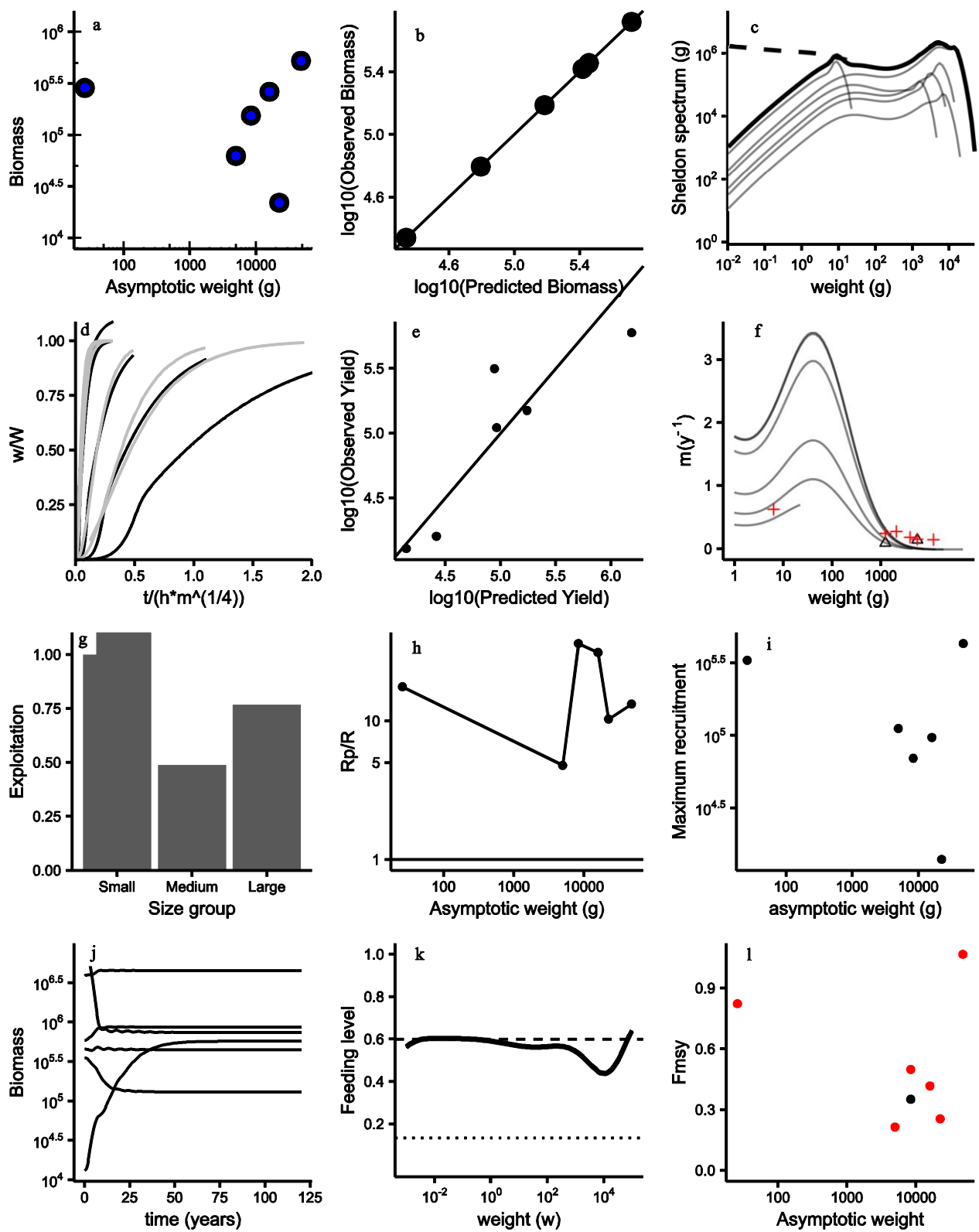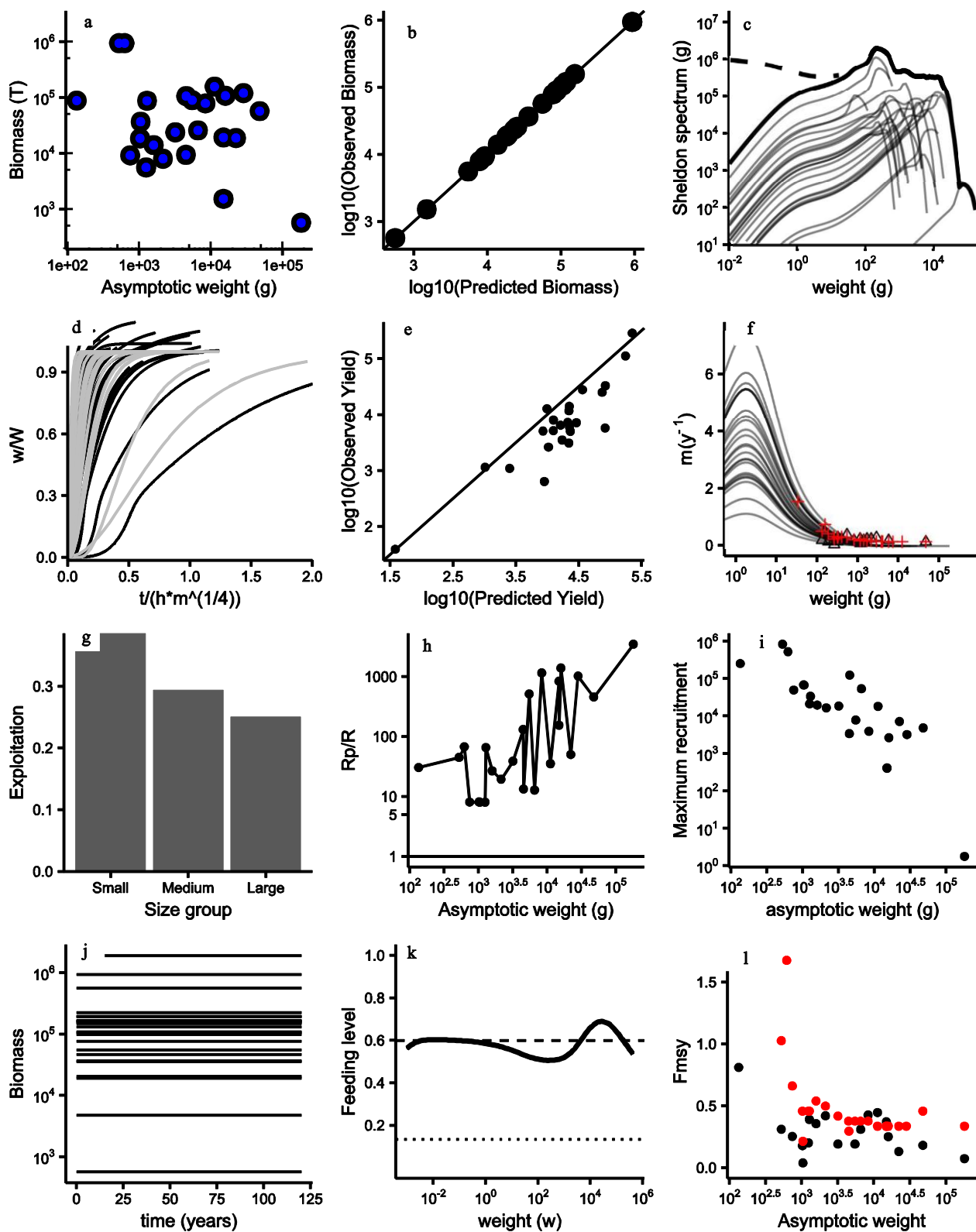185 Figure D3: Benguela Current calibration. A-L) see figureD1 caption.

Figure D4: Barents Sea calibration. A-L) see figure D1 caption.

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191    Figure D5: North East US Continental Shelf calibration. A-L) see figure D1 caption.

## E) Bioeconomic model

We use the economic model from Andersen *et al.* (2015). The price function is based on size based landings from 2006-2010 from the Danish Ministry of Food Agriculture and Fisheries. The parameter *a* is adjusted such that the North Sea fishery becomes marginally profitable in the equilibrium calibration (Profit/cost ≈ 1) (Figure E1). The parameters in the model are $b = 0.4^{1-b}/g$, $c = 0.41$ and $a_p = 0.073$.
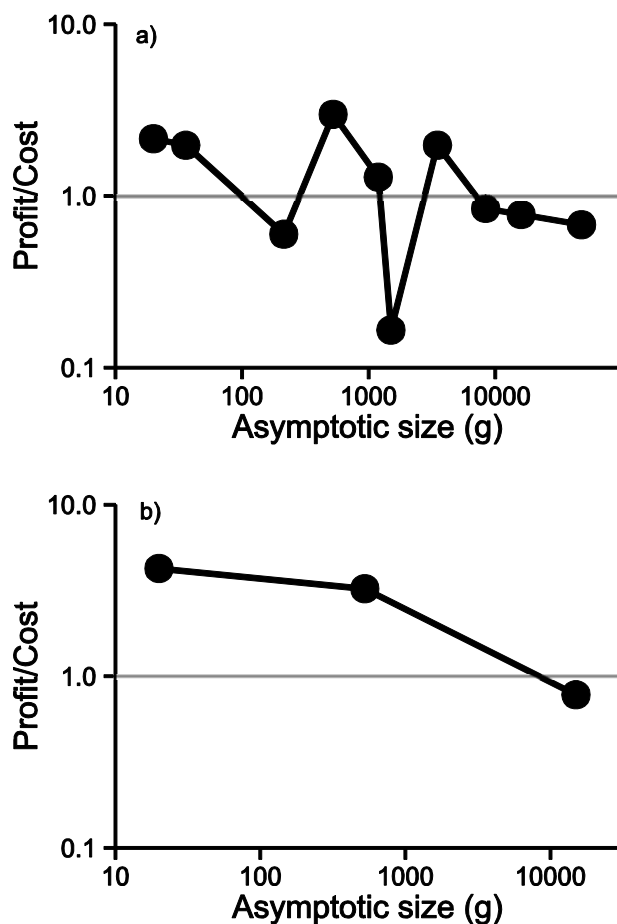


Figure E1: The profit divided by the cost as a function of asymptotic weight under the equilibrium calibrations. A) The North Sea, B) The Baltic Sea.

## F) Species specific information

Table F1: Species information used in the models. *As the Baltic Sea only has three species Herring is represented in the "Medium" fleet.

| Common name | Large marine ecosystem | $W_\infty$(g) | k (yr$^{-1}$) | Fleet |
|---|---|---|---|---|
| Sprat | Baltic | 20 | 0.70 | Small |
| Herring | Baltic | 525 | 0.32 | Medium* |
| Cod | Baltic | 15000 | 0.16 | Large |
| Sprat | North Sea | 20 | 0.68 | Small |
| Sand eel | North Sea | 36 | 1 | Small |
| Norway pout | North Sea | 214 | 0.849 | Small |
| Herring | North Sea | 525 | 0.849 | Small |
| Whiting | North Sea | 1192 | 0.323 | Small |
| European Sole | North Sea | 1500 | 0.284 | Medium |
| Plaice | North Sea | 3500 | 0.120 | Medium |
| Haddock | North Sea | 8400 | 0.271 | Medium |
| Pollock | North Sea | 16000 | 0.175 | Large |
| Cod | North Sea | 48000 | 0.216 | Large |
| Capelin | Barents Sea | 26 | 0.35 | Small |
| Golden redfish | Barents Sea | 5000 | 0.09 | Medium |
| Haddock | Barents Sea | 8400 | 0.234 | Medium |
| Pollock | Barents Sea | 16000 | 0.164 | Large |
| Halibut | Barents Sea | 22500 | 0.0847 | Large |
| Cod | Barents Sea | 48000 | 0.13 | Large |
| Anchovy | Benguela Current | 20 | 0.79 | Small |
| Sardine | Benguela Current | 108 | 0.51 | Small |
| Kingklip | Benguela Current | 7500 | 0.1 | Medium |
| Shallow water cape hake | Benguela Current | 13732 | 0.049 | Large |

| | | | | |
|---|---|---|---|---|
| Deep water cape hake | Benguela Current | 23914 | 0.11 | Large |
| Butterfish | NEUSCS | 135 | 0.8 | Small |
| Herring | NEUSCS | 525 | 0.34 | Small |
| Atlantic menhaden | NEUSCS | 625 | 0.6 | Small |
| Yellowtail Flounder | NEUSCS | 750 | 0.3 | Small |
| Scup | NEUSCS | 1030 | 0.2 | Small |
| Acadian Redfish | NEUSCS | 1050 | 0.1 | Small |
| Witch Flounder | NEUSCS | 1250 | 0.2 | Small |
| Croaker | NEUSCS | 1290 | 0.2 | Small |
| Winter Flounder | NEUSCS | 1592.163 | 0.27 | Medium |
| Black sea bass | NEUSCS | 2150 | 0.27 | Medium |
| American Plaice | NEUSCS | 3200 | 0.2 | Medium |
| Weakfish | NEUSCS | 4500 | 0.3 | Medium |
| Spiny dogfish | NEUSCS | 4550 | 0.09 | Medium |
| Bluefish | NEUSCS | 5513.68 | 0.28 | Medium |
| Summer flounder | NEUSCS | 6630.548 | 0.14 | Medium |
| Haddock | NEUSCS | 8400 | 0.33 | Medium |
| Monkfish | NEUSCS | 11300 | 0.1 | Large |
| Cusk | NEUSCS | 15000 | 0.13 | Large |
| Tilefish | NEUSCS | 15000 | 0.2 | Large |
| Pollock | NEUSCS | 16000 | 0.17 | Large |
| White hake | NEUSCS | 22373 | 0.0815 | Large |
| Striped bass | NEUSCS | 28500 | 0.12 | Large |
| Cod | NEUSCS | 48000 | 0.15 | Large |
| Halibut | NEUSCS | 181914.5 | 0.07 | Large |

209

## G) Sensitivity of ecological indicator

We investigate the sensitivity of $I$ by iteratively changing the parameter $\tau$. We compare $I$ by looking at the distance to the frontier rather than the value. Measuring the distance is more important than the real value as this determines how much a fishery would need to change to move towards the efficiency frontier. The distance is measured by fishing at single species $F_{MSY}$ and comparing that with the frontier (Figure G1). High values of $\tau$ cause an increase in the steepness of I compared to lower values. Generally the relative distance to the frontier is largely independent of the $\tau$ value. The shape of the efficiency frontier also does not change much with changing values of $\tau$.
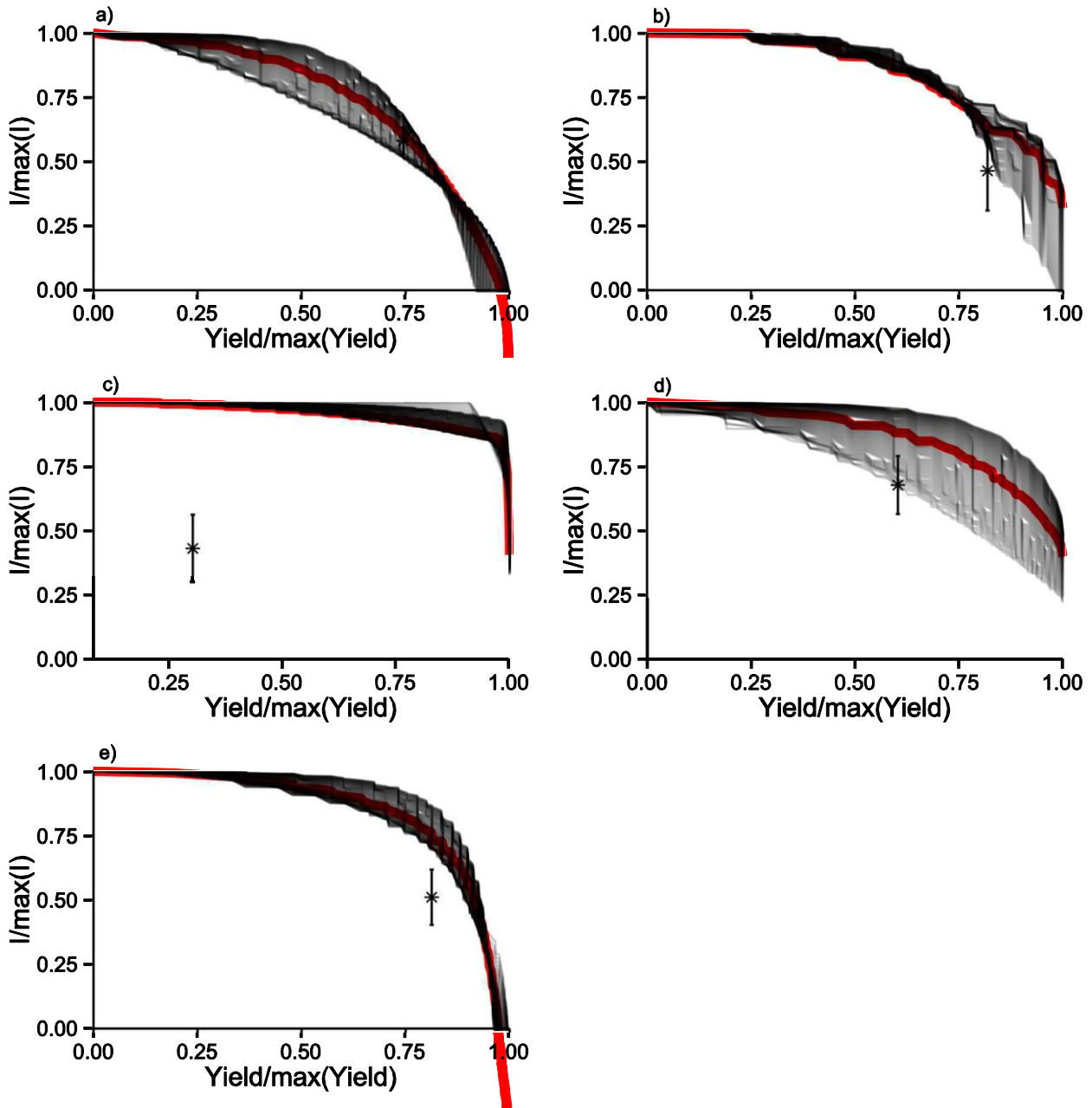


Figure G1: Sensitivity of the yield-ecology efficiency frontiers to changes in $\tau$ (both axes scaled to 1). A) North Sea, B) Baltic Sea, C) Benguela Current, D) Barents Sea, E) North East US Continental Shelf. Red line denotes tau = 100 (as in main text), grey lines denote values of $\tau$ between 1.1 and 10000. The star denotes fishing at $F_{MSY}$ with $\tau = 100$ and the error bar is the standard deviation of scaled I in the remaining runs.

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