<u>**Final Report**</u>

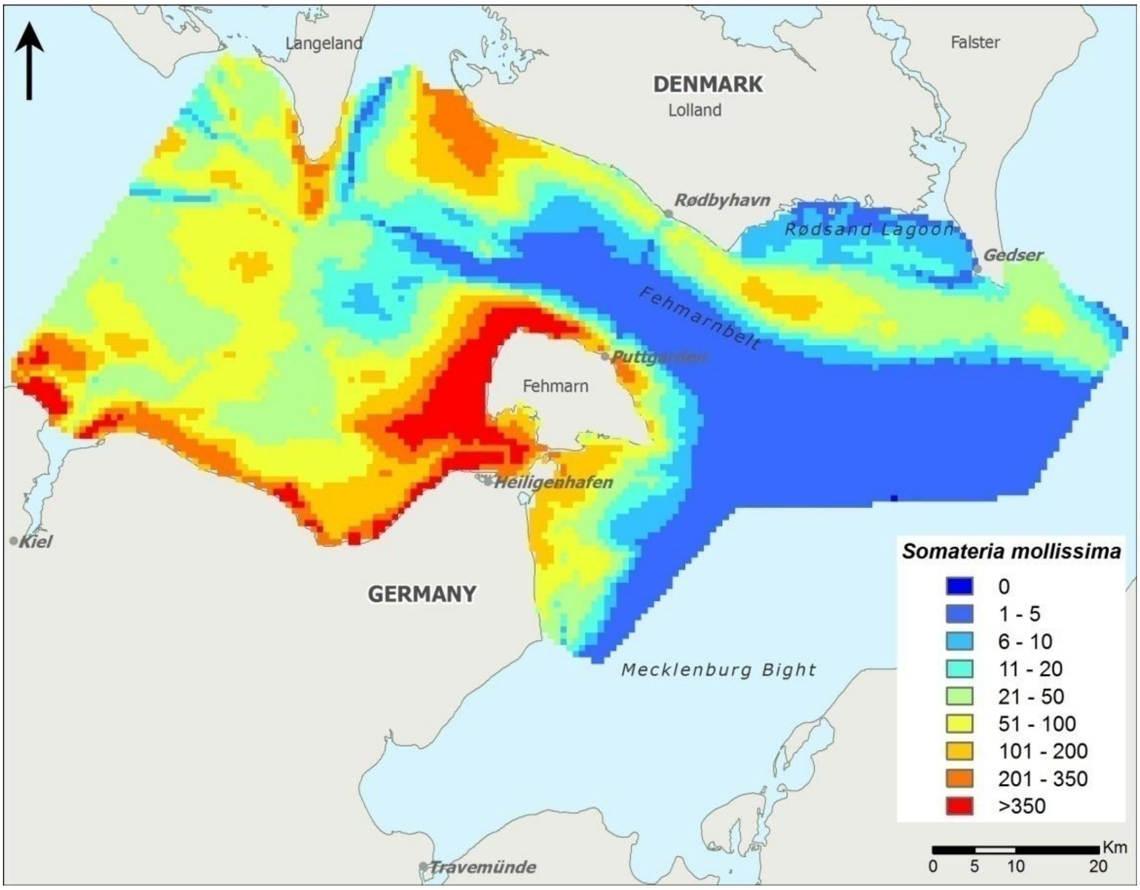
FEHMARNBELT FIXED LINK
BIRD SERVICES (FEBI)

Bird Investigations in Fehmarnbelt - Baseline

Waterbirds in Fehmarnbelt

E3TR0011 Volume II – Appendix VI

Sensitivity testing of individual-based model (IBM) of Common Eiders wintering in the Fehmarnbelt



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Lists of figures and tables are included as the final pages

Note to the reader:
In this report the time for start of construction is artificially set to 1 October 2014 for the tunnel and 1 January 2015 for the bridge alternative. In the Danish EIA (VVM) and the German EIA (UVS/LBP) absolute year references are not used. Instead the time references are relative to start of construction works. In the VVM the same time reference is used for tunnel and bridge, i.e. year 0 corresponds to 2014/start of tunnel construction; year 1 corresponds to 2015/start of bridge construction etc. In the UVS/LBP individual time references are used for tunnel and bridge, i.e. for tunnel construction year 1 is equivalent to 2014 (construction starts 1 October in year 1) and for bridge construction year 1 is equivalent to 2015 (construction starts 1st January).

A. APPENDIX VI

Sensitivity testing of individual-based model (IBM) of Common Eiders wintering in the Fehmarnbelt

After the Common Eider baseline IBM was fully parameterised and calibrated, as presented in chapters 2.3.5 and 5.4.2 of this report, a sensitivity testing of the IBM to variation of input parameter values has been conducted and is reported in this appendix. Sensitivity analysis allows for better understanding of the IBM and how response variables are related to input parameters (Topping et al. 2010, Topping and Petersen 2011).

All variables used in parameterising the baseline IBM (Table 2.22 in this report) were screened and 15 of them were deemed to be relevant for the sensitivity analysis (Table A.1). The sensitivity of the IBM to variation in parameter values was tested by independently varying parameters by ±5, 10, 20 and 40% of their values used in the calibrated baseline model. Two response variables were used to assess the model sensitivity: bird survival and body mass dynamics during wintering season. Although more response variables were possible to use for assessing the model performance, bird survival and biomass were assumed as being the most relevant given the purpose of the IBM modelling in this study.

Table A.1 Parameters defined as relevant in the sensitivity analysis.

No	Parameter	Value	Description
1	Day length	varying	Actual day length in hours for each day in the simulation
2	Water temperature	varying	Sea surface water temperature from FEHY hydrodynamic model for winter 2009/2010
3	Initial mussel density	varying	Modelled mussel biomass converted to a number of 14 mm long mussels
4	Change in mussel density	0.18% / day	Proportional decline due to natural mortality and predation
5	Mussel flesh dry mass	0.01478 g AFDW	Flesh dry mass per 14 mm mussel
6	Number of foragers	250	Number of super-individuals each consisting of 1,000 birds
7	Maximum bird density	5,000 birds/km^2	Maximum number of birds per area unit allowed in the model
8	Underwater time per dive	varying	Underwater time calculated using empirically developed sub-model
9	Travel time per dive	varying	Underwater travel time calculated using swimming speeds
10	Surface time per dive	varying	Surface time calculated using empirically developed sub-model
11	Diet consumption rate	varying	Mussels eaten per second of the bottom time as a function of prey density
12	Component assimilation rate	0.49	The proportion of the total amount of resource component (bivalve flesh dry weight) consumed that is assimilated into the forager's (eider) system
13	Component metabolic rate while feeding	varying	Metabolism of eiders while feeding calculated using sub-model

No	Parameter	Value	Description
14	Component metabolic rate while resting	varying	Metabolism of eiders while resting calculated using sub-model
15	Starvation body mass	1,476 g	Body weight of eider below which a bird would die

Testing model performance by varying each of 15 parameters 8 times would require running 120 different model design combinations. Furthermore, because the IBM design contains a certain level of stochasticity, multiple replicates could be desired for assessing parameter effects.

Simulation of the baseline model was computationally demanding and required approximately 2.5 hours CPU time for a single run. To increase processing time for sensitivity testing, the spatial scale of the model grid has been reduced by increasing cell size from 2x2 km to 4x4 km (Figure A.1), which has reduced number of spatial units (grid cells) from 964 to 256 and CPU time down to 30-40 minutes for a single run. As the rest of the IBM design remained the same, it was assumed that the model of coarser resolution would have the same or very similar sensitivity to variation in parameter values.

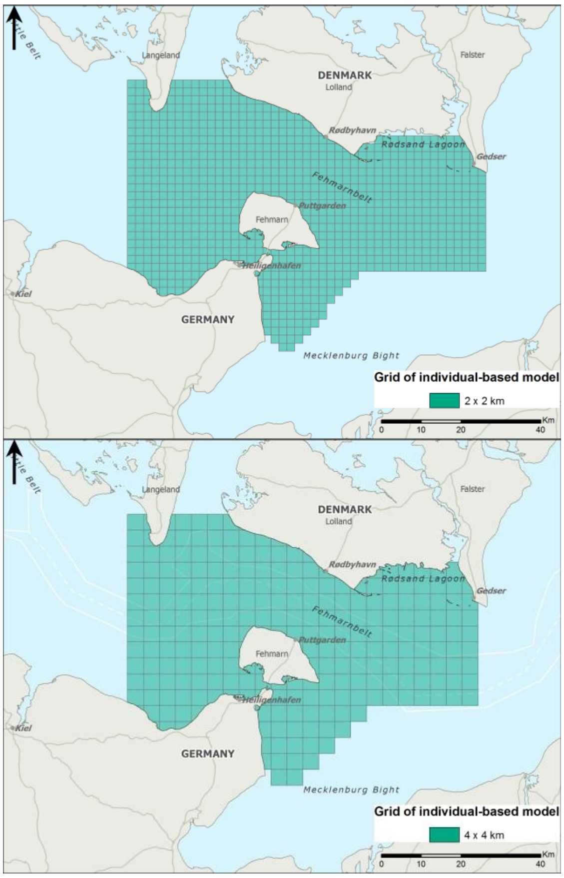


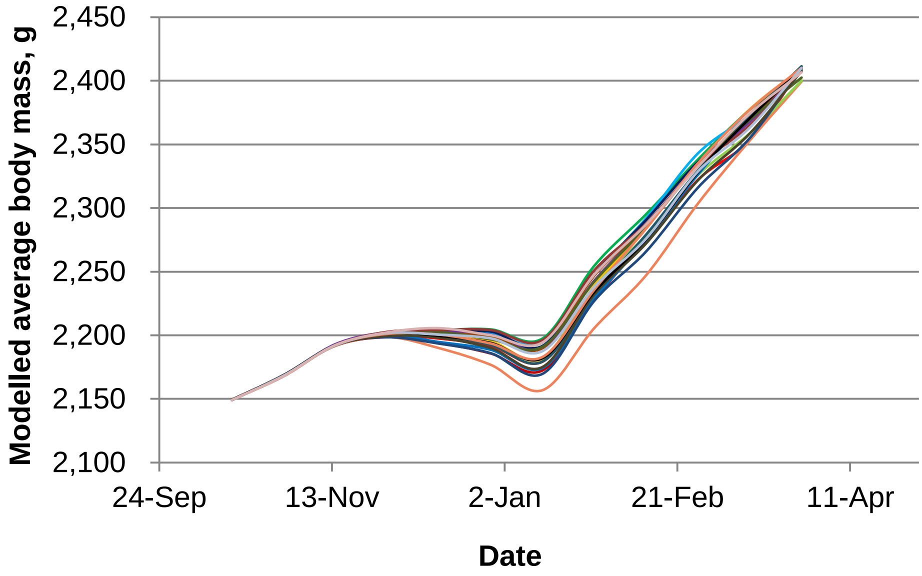
Figure A.1 Maps representing 2x2 km grid used in the baseline IBM (left) and the coarser grid of 4x4 km (right) that was used to test model sensitivity to parameter variations.

Although overall architecture of the coarser-scale model (4x4 km) was identical to the original 2x2 km model (i.e. all input parameter values, sub-models including the amount of available food and number of birds in simulations), we compared results on key response variables (body mass dynamics and bird survival presented below) to make sure that the models had comparable performance. Considering other parameters listed in Table A.1, there is no reason to believe that equations defining them would be solved differently due to altered grid, especially if response variables show similar model performance.

Further, the model stochasticity was tested by replicating the baseline model 20 times and analysing variability of used response variables. Considering bird mortality, in 3 out of 20 simulations one 'super-individual' (consisting of 1000 birds; see model description in chapter 2.3.5 of this report) has died and no mortality was predicted in the remaining 17 simulations. This suggests occasionally low mortality of 0.4% of all birds due to starvation, the result that is similar as obtained in the fine resolution (2x2 km grid) baseline IBM (chapter 5.4.2 of this report). Considering modelled bird body mass dynamics during the winter season, each of the simulations yielded very similar results in terms of absolute values (Figure A.2), the largest difference between separate simulations being 2.2% of the body mass value for a given time step. Body mass dynamics in the original model with 2x2 km grid fell within a range of values of 4x4 km model (Figure A.2), in this way illustrating a very similar model performance and therefore the validity of the approach of using the coarser-scale model for sensitivity testing. Considering rather little variation among repeated simulations, we chose to rely on a single replicate of each unique model combination during the sensitivity testing. This enabled to keep IBM simulations within manageable limits of CPU time ([120 unique model combinations + 20 baseline replicates] x 35 minutes = 82 hours).

Hence, considering the results of repeated baseline simulations, bird mortality below 1% of all birds, and modelled body mass deviation within 1.1% of the average body mass predicted by 20 replicates of the baseline model, should not be considered as differing from the baseline in simulations with modified parameter values.

Also, due to the nature of the model design and the response variables used, substantial positive effects of parameter change might not be detected, as zero mortality indicates the best possible state of this response variable; and body mass development during the winter season would be strictly linear during optimal conditions.



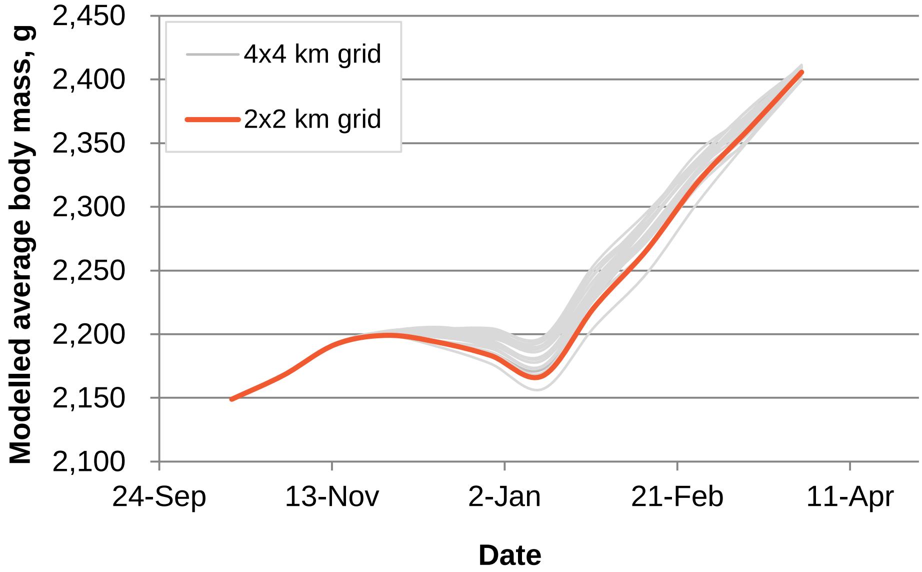


Figure A.2 Modelled body mass of Common Eiders during the wintering season: plotted 20 curves in the upper chart represent results of repeated simulations of the calibrated baseline model. The lower chart represents body mass curve from fine-resolution (2x2 km) model overlaid on curves predicted by the coarser-scale (4x4 km) model.

Parameter 1: Day length
This parameter represents actual day length in the study location at each time step during the IBM simulation period between October 1 and March 31. The importance of this parameter in predicting habitat carrying capacity for Common Eiders lies within the restriction for birds to forage during the daylight hours only.

Analysed response variables appeared to be highly sensitive to variation of the day length: overall bird mortality increased to 17% at day length reduced by 20% and mortality exceeded 90% if day length was 40% shorter (Figure A.3). Similar pattern was reflected in modelled bird body mass: birds were not able to maintain good body condition when day length was reduced by 20% and 40%, but had nearly optimal body mass (following linear increase) when the day length was increased by 10% or more (Figure A.4).

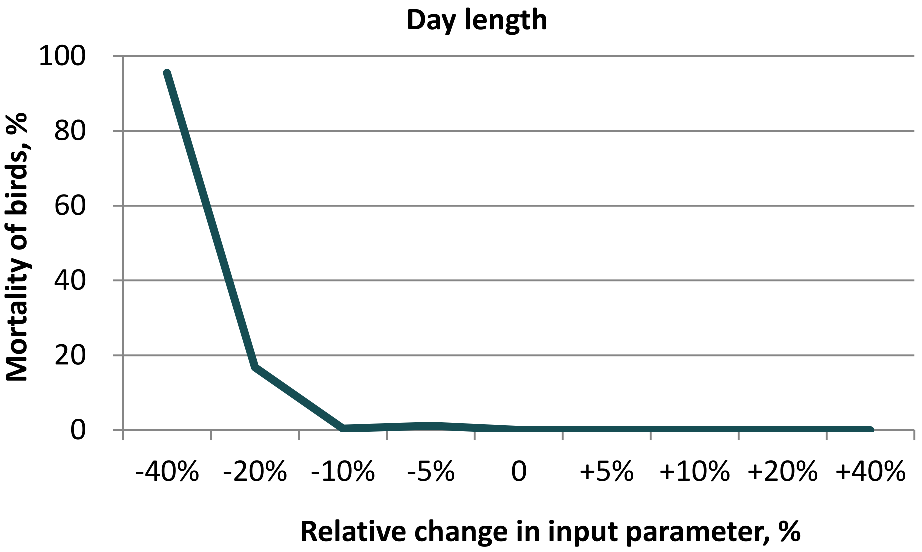


Figure A.3 Changes in predicted mortality of Common Eiders due to starvation in relation to changes in parameter 'day length'.

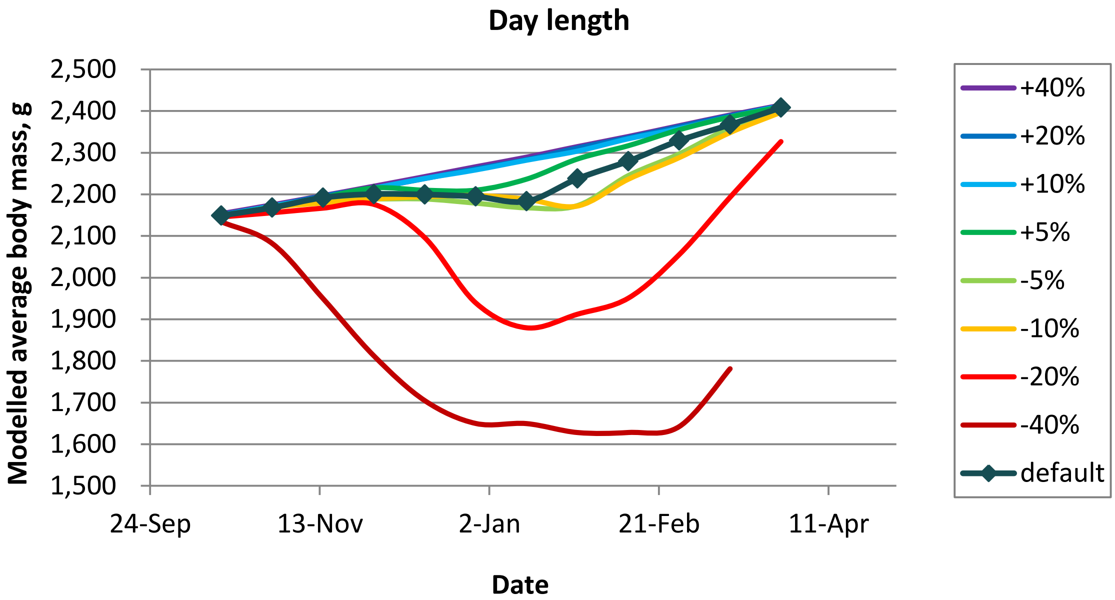


Figure A.4 Effects of changes in parameter 'day length' on modelled seasonal body mass development of Common Eiders.

Parameter 2: Water temperature

This parameter represents mean daily sea surface water temperature in the study area during the period of IBM simulation between October 1 and March 31. Water temperature affects bird metabolism through thermoregulation and in this way may influence their energetic needs and ultimately habitat carrying capacity.

Analysed response variables showed that the model was insensitive to variation of the water temperature within ±40% (Figure A.5, Figure A.6).

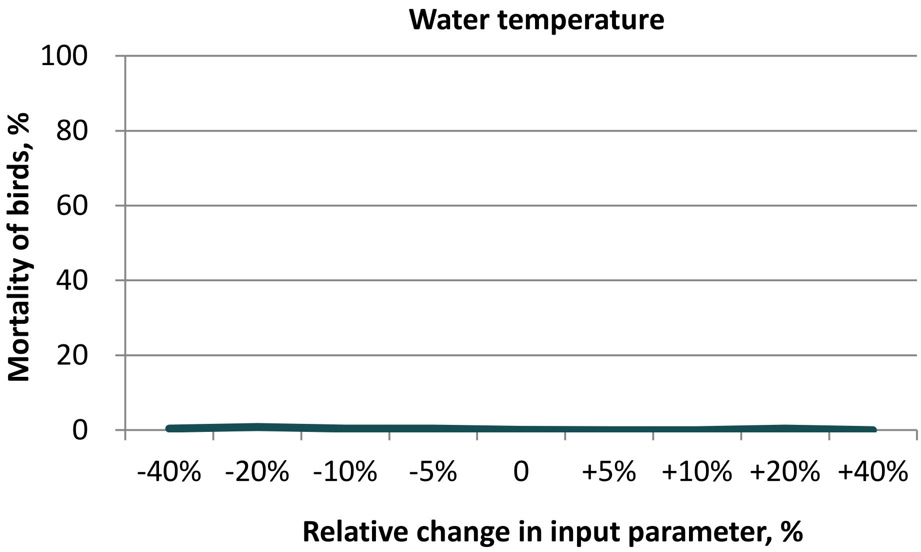


Figure A.5 Changes in predicted mortality of Common Eiders due to starvation in relation to changes in parameter 'water temperature'.

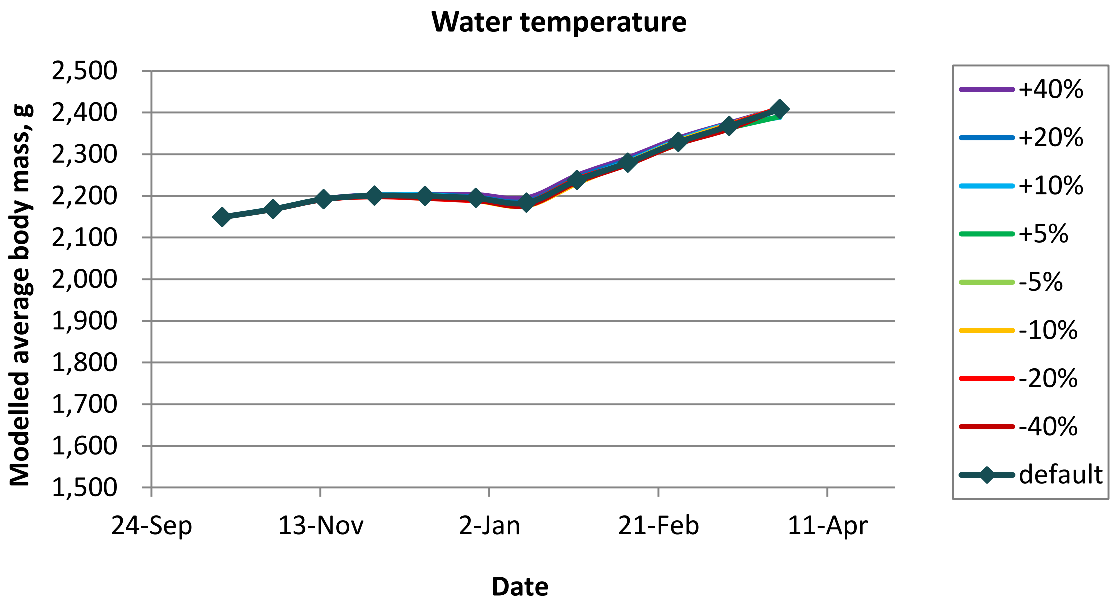


Figure A.6 Effects of changes in parameter 'water temperature' on modelled seasonal body mass development of Common Eiders.

Parameter 3: Initial mussel density
This parameter defines the availability of food resources at the start of the modelling period, which are further consumed during the IBM simulation. Initial mussel density is one of the main factors determining habitat carrying capacity.

Analysed response variables were sensitive to variation of the parameter: bird mortality increased to 10% when initial mussel density was reduced by 40% (Figure A.7). Similarly, the response could be seen in modelled bird body mass: birds had poorer body condition compared to the baseline when initial mussel density was reduced by 20% and 40%, but had higher body mass (approaching linear increase) when the initial mussel density was increased from values used in the baseline model (Figure A.8).

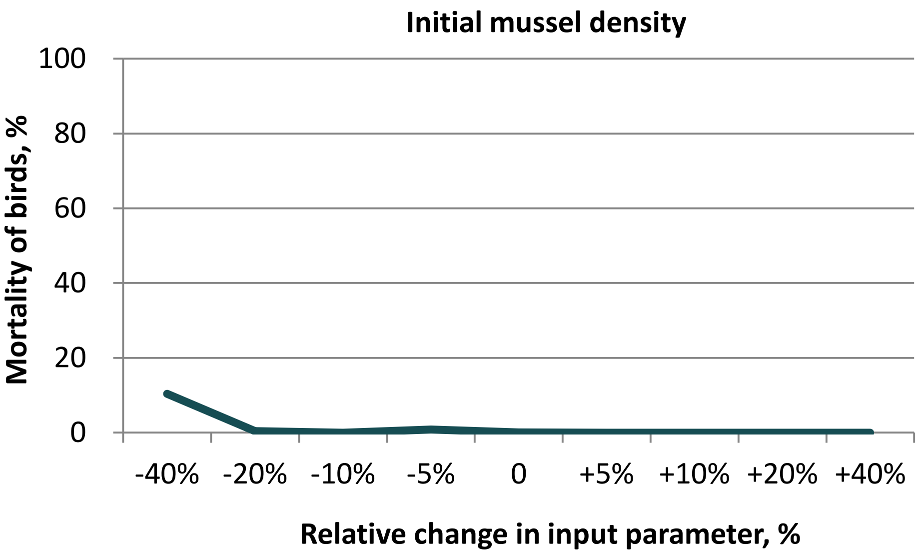


Figure A.7 Changes in predicted mortality of Common Eiders due to starvation in relation to changes in parameter 'initial mussel density'.

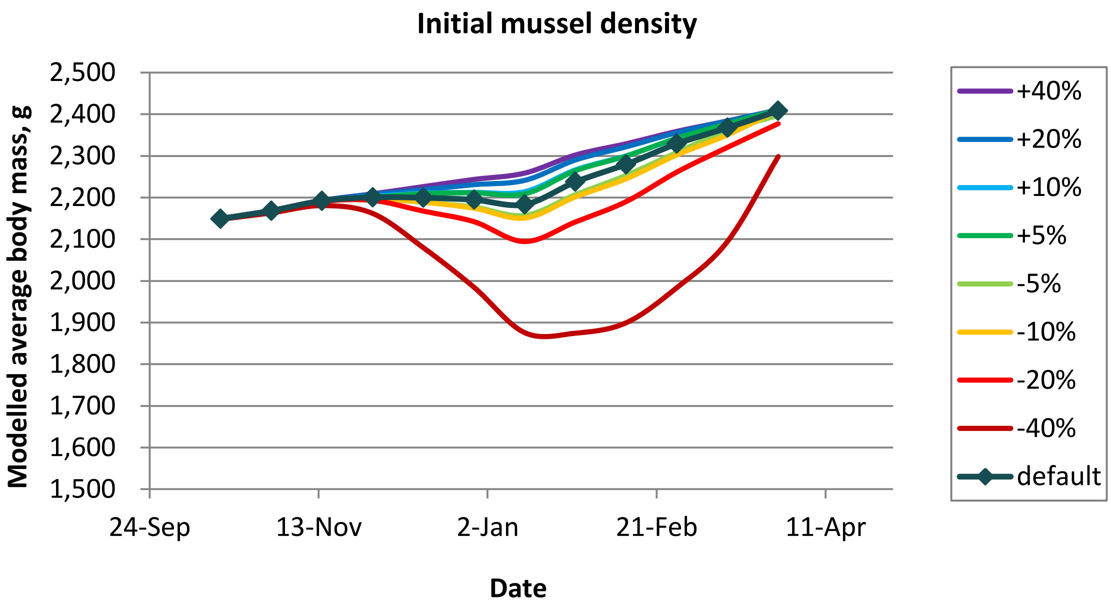


Figure A.8 Effects of changes in parameter 'initial mussel density' on modelled seasonal body mass development of Common Eiders.

Parameter 4: Change in mussel density
This parameter defines the rate at which mussel resources decline due to other reasons than bird consumption during the winter season. Therefore, this parameter may potentially have direct impact on habitat carrying capacity.

Analysed response variables showed that the model was nearly insensitive to variation in mussel density change rate: bird mortality didn't change when the parameter was varied within ±40% (Figure A.9), and predicted bird body mass was slightly higher than that in the baseline when change rate of mussel density was reduced (Figure A.10).

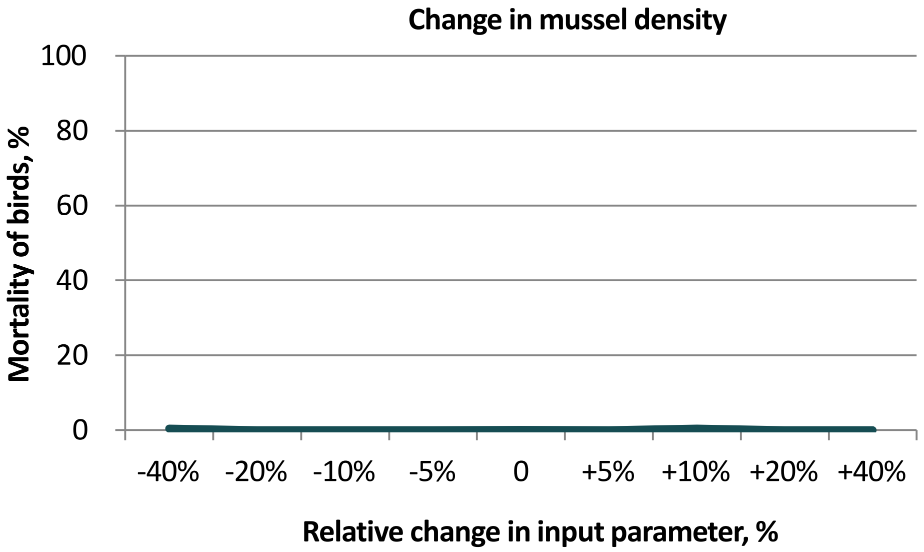


Figure A.9 Changes in predicted mortality of Common Eiders due to starvation in relation to changes in parameter 'change in mussel density'.

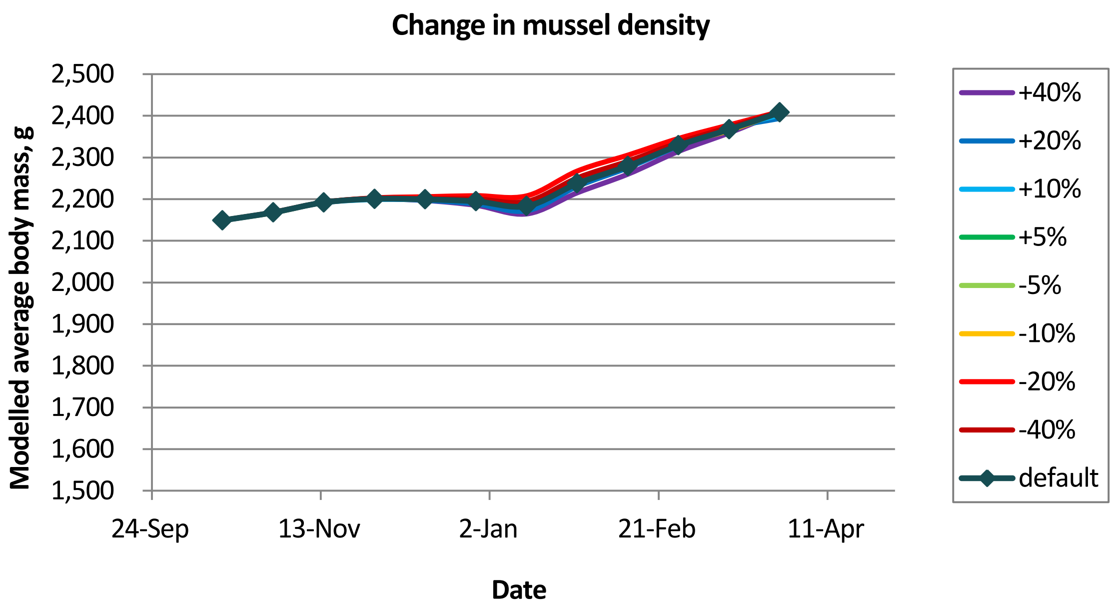


Figure A.10 Effects of changes in parameter 'change in mussel density' on modelled seasonal body mass development of Common Eiders.

Parameter 5: Mussel flesh content

This parameter defines the amount of flesh per size unit of mussels. Mussel flesh content reflects food profitability and is therefore one of the main factors determining habitat carrying capacity.

Analysed response variables were highly sensitive to variation of the parameter: bird mortality increased to 7% when mussel flesh content was reduced by 20% and to 75% when the parameter values were reduced by 40% (Figure A.11). Similarly, modelled bird body mass was highly affected by mussel profitability:

birds had increasingly poorer body condition compared to the baseline when mussel flesh contents were reduced; and body mass approached optimal as the parameter values were increased (Figure A.12).

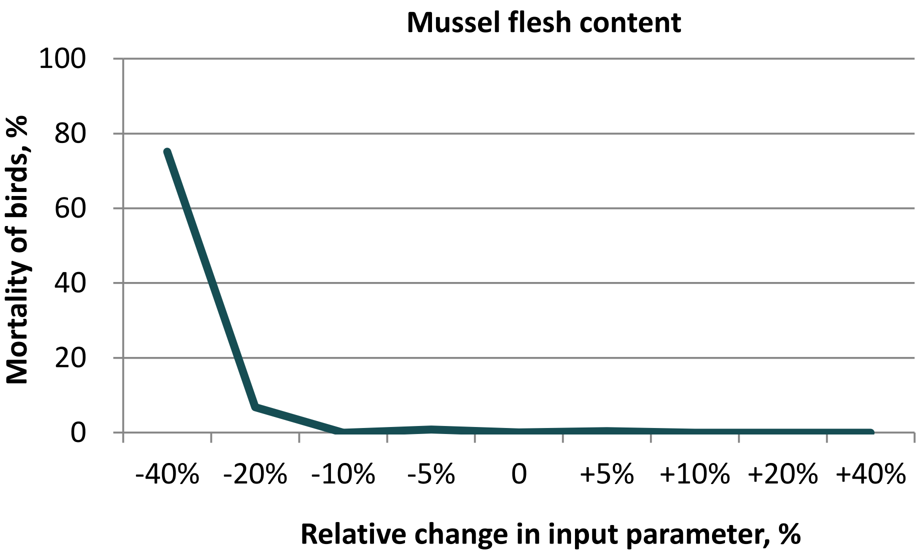


Figure A.11 Changes in predicted mortality of Common Eiders due to starvation in relation to changes in parameter 'mussel flesh content'.

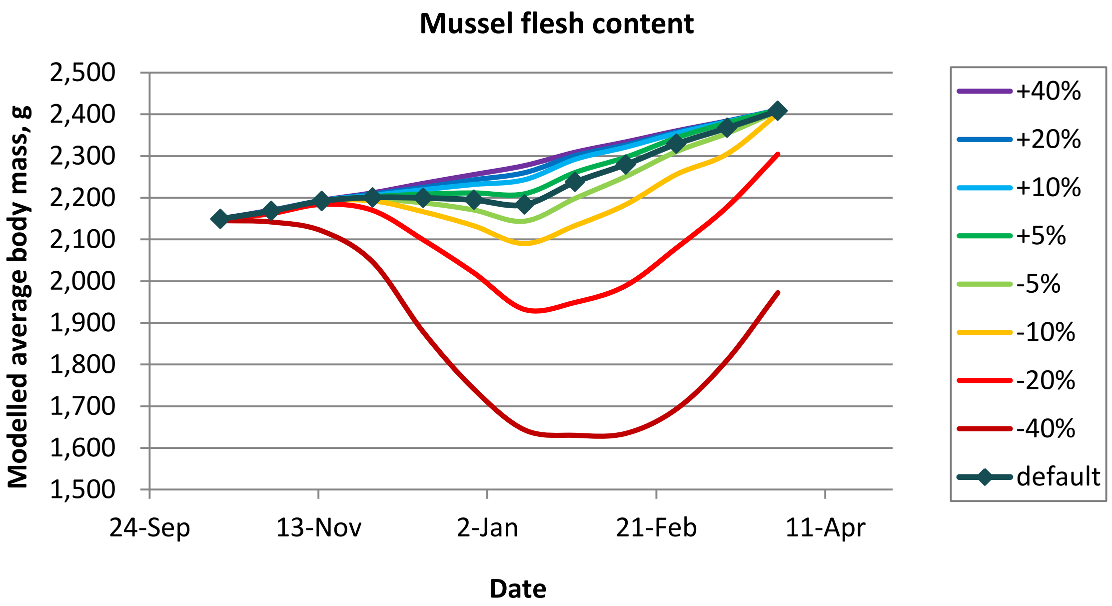


Figure A.12 Effects of changes in parameter 'mussel flesh content' on modelled seasonal body mass development of Common Eiders.

Parameter 6: Number of foragers
This parameter defines the number of birds in the model system and therefore might have a direct impact on habitat carrying capacity.

Analysed response variables showed that the model was nearly insensitive to variation in number of birds in the model system within ±40%: eider mortality was not affected (Figure A.13), and predicted bird body mass was slightly higher than that in the baseline model when number of foragers was reduced (Figure A.14). Even increasing the number of foragers in the model by 100% resulted only in a slight increase in mortality and slight decrease in bird body mass (see chapter 5.4.2 of this report).

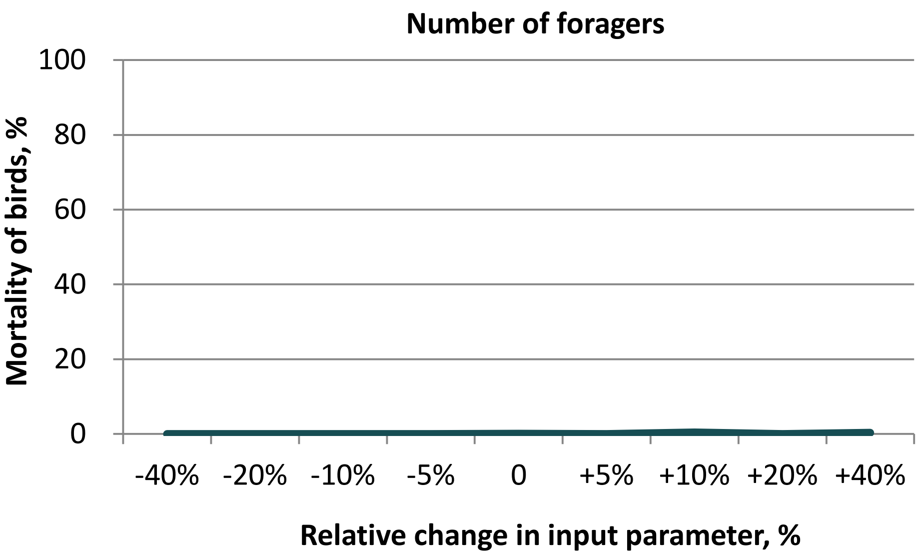


Figure A.13 Changes in predicted mortality of Common Eiders due to starvation in relation to changes in parameter 'number of foragers'.

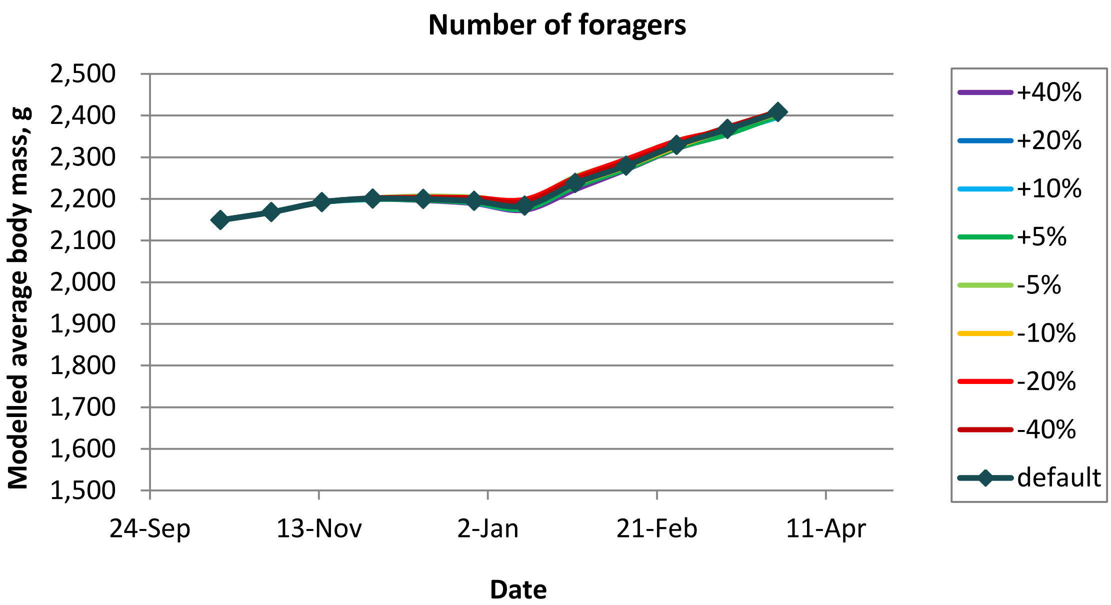


Figure A.14 Effects of changes in parameter 'number of foragers' on modelled seasonal body mass development of Common Eiders.

Parameter 7: Maximum bird density

This parameter defines the maximum number of birds per area unit that is allowed in the model. This parameter could have an influence on habitat carrying capacity if bird distribution is regulated by density dependence of individuals.

Analysed response variables showed that the model was nearly insensitive to variation in maximum bird density within ±40%: eider mortality was not affected at all (Figure A.15), and predicted bird body mass was slightly higher than that in the baseline model when the value of maximum bird density was increased (Figure A.16).

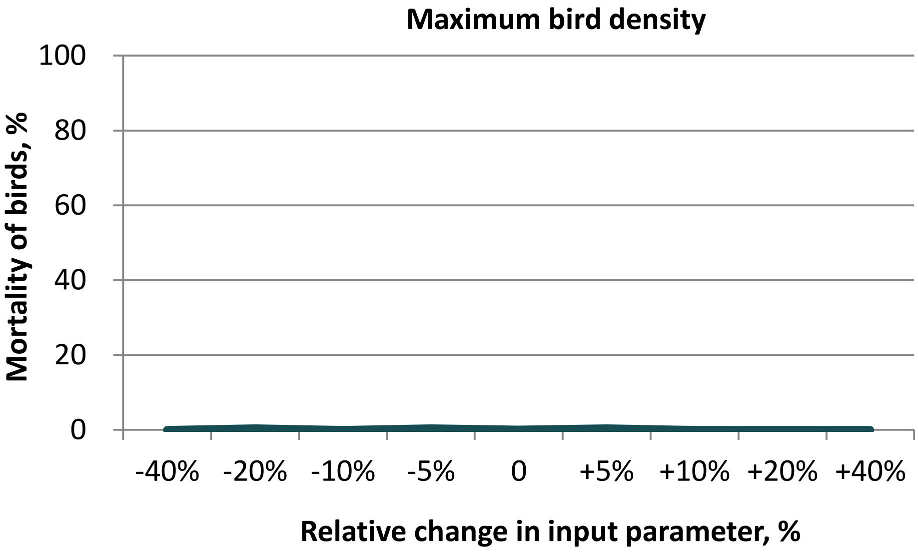


Figure A.15 Changes in predicted mortality of Common Eiders due to starvation in relation to changes in parameter 'maximum bird density'.

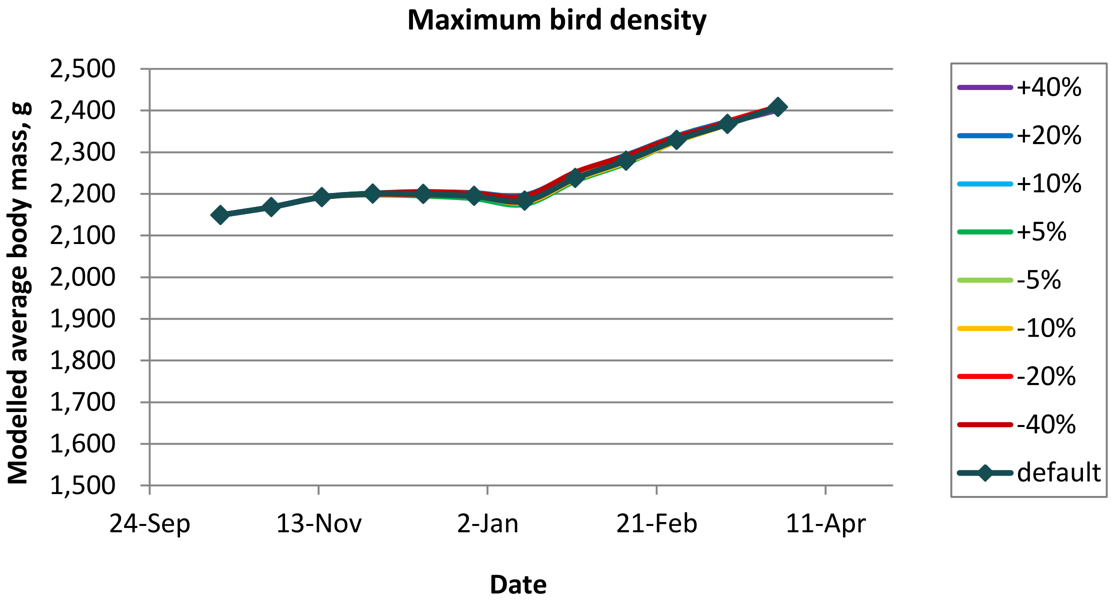


Figure A.16 Effects of changes in parameter 'maximum bird density' on modelled seasonal body mass development of Common Eiders.

Parameter 8: Underwater time per dive

While feeding, Common Eiders dive to the bottom, but birds are physiologically limited by how long they can stay underwater holding their breath. This parameter defines the underwater time per dive. Underwater time could be a restricting factor limiting intake of food and therefore it could be important variable determining habitat carrying capacity.

Analysed response variables were highly sensitive to variation of this parameter: bird mortality increased to 8% when underwater time per dive was reduced by 20% and mortality exceeded 99% when the parameter values were reduced by 40% (Figure A.17). Likewise, modelled bird body mass was highly affected by underwater time: birds had increasingly poorer body condition compared to the baseline when underwater time was reduced; and body mass approached optimal as the parameter values were increased (Figure A.18).

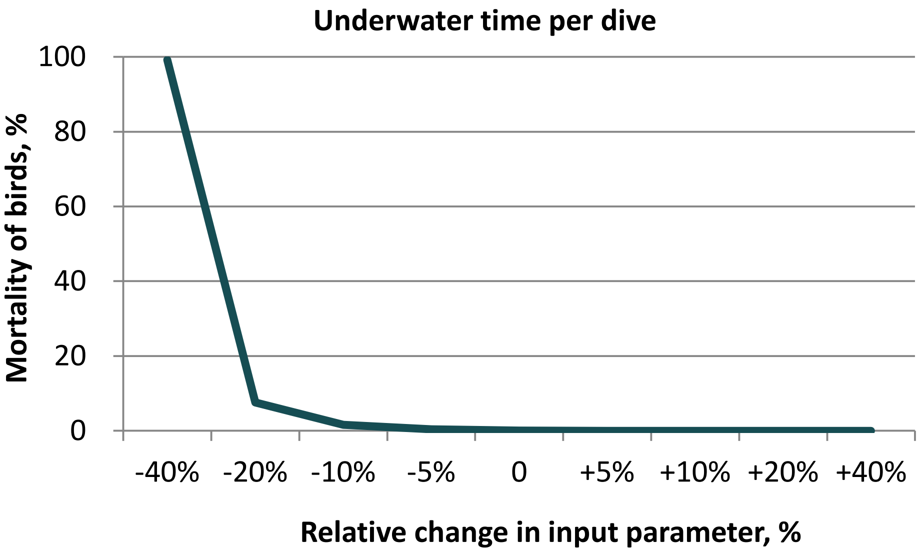


Figure A.17 Changes in predicted mortality of Common Eiders due to starvation in relation to changes in parameter 'underwater time per dive'.

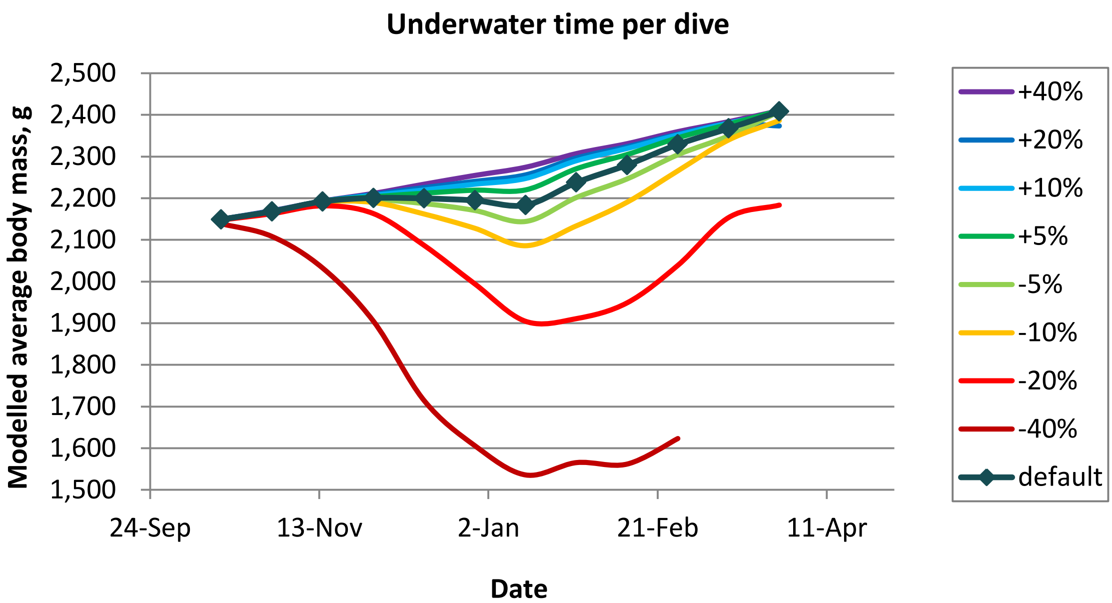


Figure A.18 Effects of changes in parameter 'underwater time per dive' on modelled seasonal body mass development of Common Eiders.

Parameter 9: Underwater travel time per dive

While feeding, Common Eiders dive to the bottom and spend a certain amount of time descending and ascending, which is the non-foraging part of the dive. This parameter defines the underwater travel time per dive, i.e. time needed to get to the food and back to the water surface. Therefore, underwater travel time could be a restricting factor limiting intake of food and subsequently determining habitat carrying capacity.

Analysed response variables were somewhat sensitive to variation of this parameter: bird mortality increased to 5% when underwater travel time per dive was increased by 40% (Figure A.19). Also, modelled bird body mass was affected by underwater travel time: bird body mass was lower compared to the baseline when underwater travel time was increased; and body mass has increased with decreasing parameter values (Figure A.20).

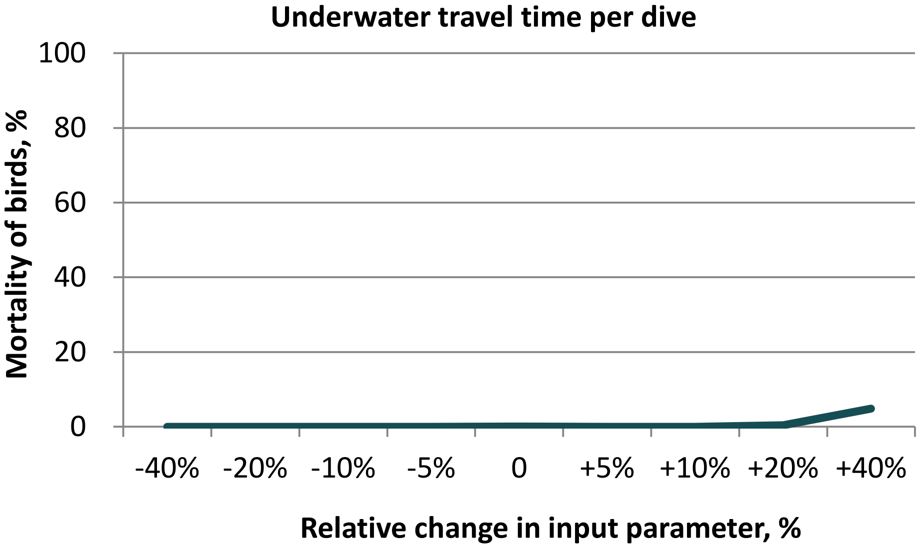


Figure A.19 Changes in predicted mortality of Common Eiders due to starvation in relation to changes in parameter 'underwater time per dive'.

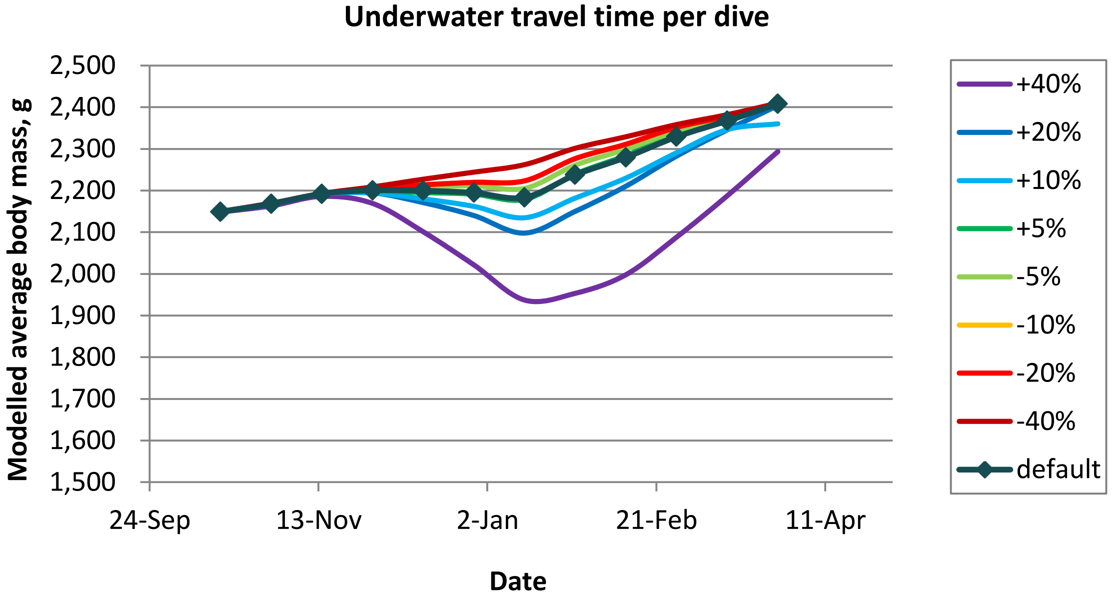


Figure A.20 Effects of changes in parameter 'underwater time per dive' on modelled seasonal body mass development of Common Eiders.

Parameter 10: Surface time between dives
Common Eiders forage in feeding bouts, when birds perform as series of consecutive dives with short surface pauses between them. This parameter defines these surface pauses, which are necessary for replenishing oxygen reserves before the following dive. Surface time between dives could be a restricting factor that limits foraging (i.e. diving) time and therefore this parameter could be important in determining habitat carrying capacity.

Analysed response variables were somewhat sensitive to variation of this parameter: bird mortality increased to 5% when surface time between dives was increased by 40% (Figure A.21). Also, modelled bird body mass was affected by surface time between dives: bird body mass was lower compared to the baseline when surface time increased; and body mass has increased with decreasing parameter values (Figure A.22).

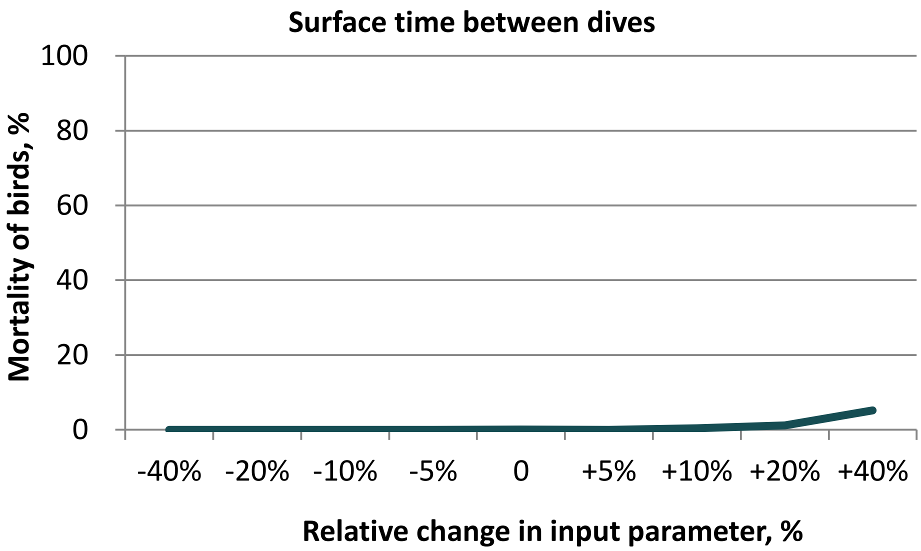


Figure A.21 Changes in predicted mortality of Common Eiders due to starvation in relation to changes in parameter 'surface time between dives'.

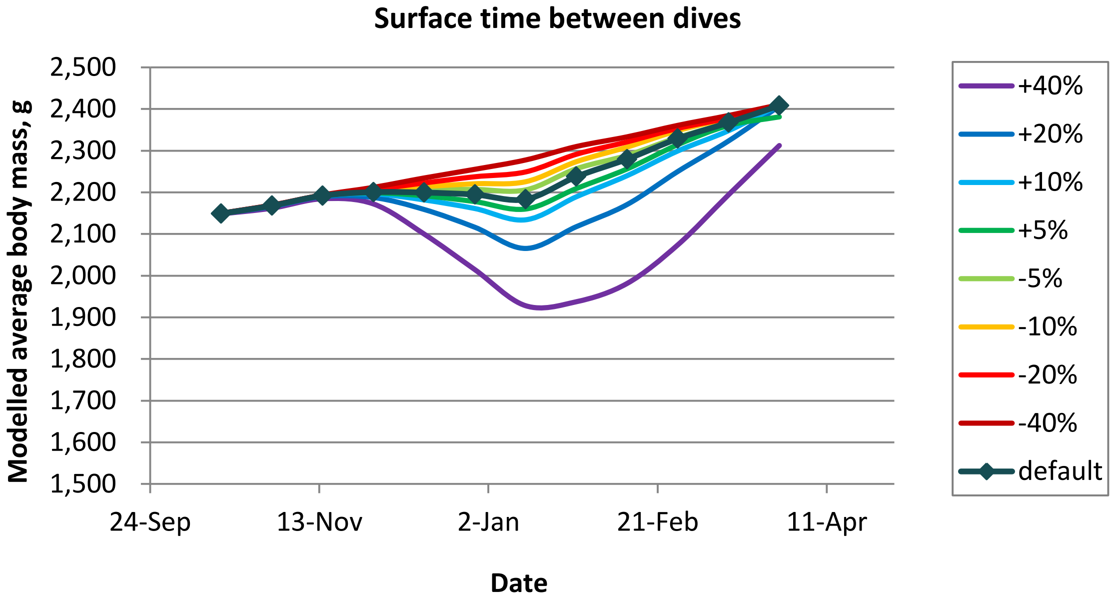


Figure A.22 Effects of changes in parameter 'surface time between dives' on modelled seasonal body mass development of Common Eiders.

Parameter 11: Diet consumption rate

This parameter defines the number of mussels eaten per second of the bottom time as a function of mussel density. This parameter is direct metric describing bird efficiency when foraging and therefore is an important factor in determining habitat carrying capacity.

Analysed response variables indicated that the model was highly sensitive to variation of this parameter: bird mortality increased to 6% when diet consumption rate was decreased by 20% and 63% of all birds were predicted to die when diet consumption rate was decreased by 40% (Figure A.23). Similarly modelled bird body mass was affected: relative to the baseline, bird body mass was decreasing with decreasing diet consumption rate and increasing along with higher parameter values (Figure A.24).

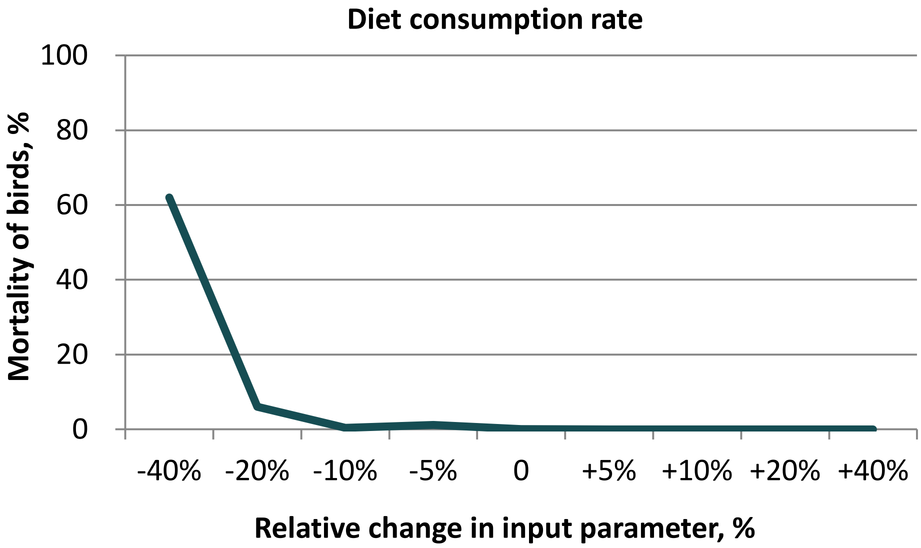


Figure A.23 Changes in predicted mortality of Common Eiders due to starvation in relation to changes in parameter 'diet consumption rate'.

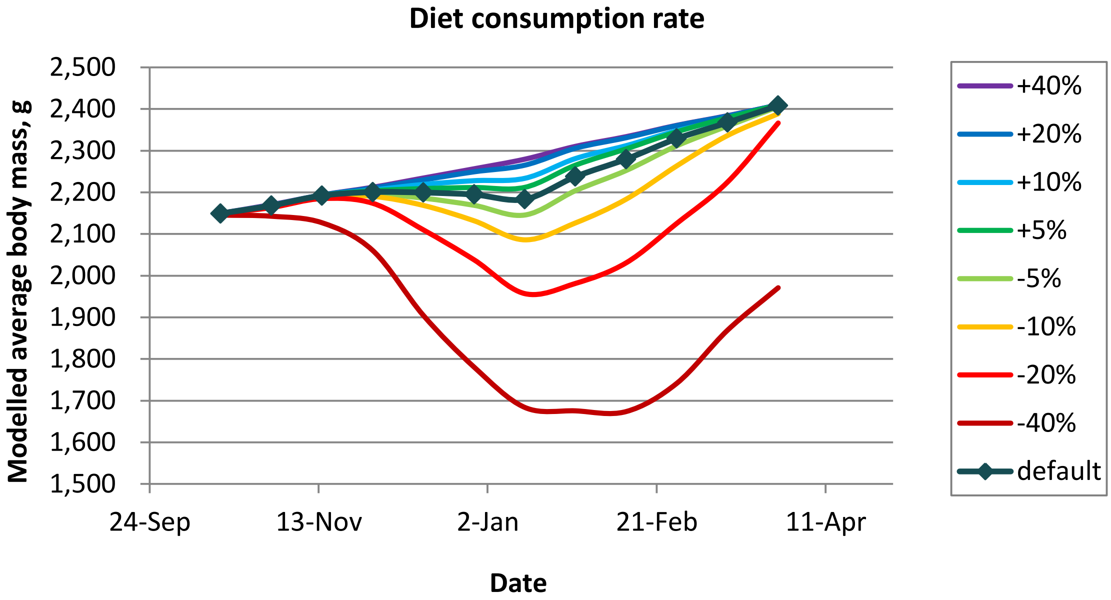


Figure A.24 Effects of changes in parameter 'diet consumption rate' on modelled seasonal body mass development of Common Eiders.

Parameter 12: Component assimilation rate

This parameter defines the proportion of the total amount of the resource component (bivalve flesh dry weight) consumed that is assimilated into the forager's (eider) system. This is another parameter characterising bird foraging efficiency and therefore is an important factor in determining habitat carrying capacity.

Analysed response variables indicated that the model was highly sensitive to variation of this parameter: bird mortality increased to 6% when the component assimilation rate was decreased by 20% and became 70% when the resource assimilation efficiency was decreased by 40% (Figure A.25). Similarly modelled bird body mass was affected: relative to the baseline, bird body mass was decreasing with decreasing component assimilation rate and increasing along with higher parameter values (Figure A.26).

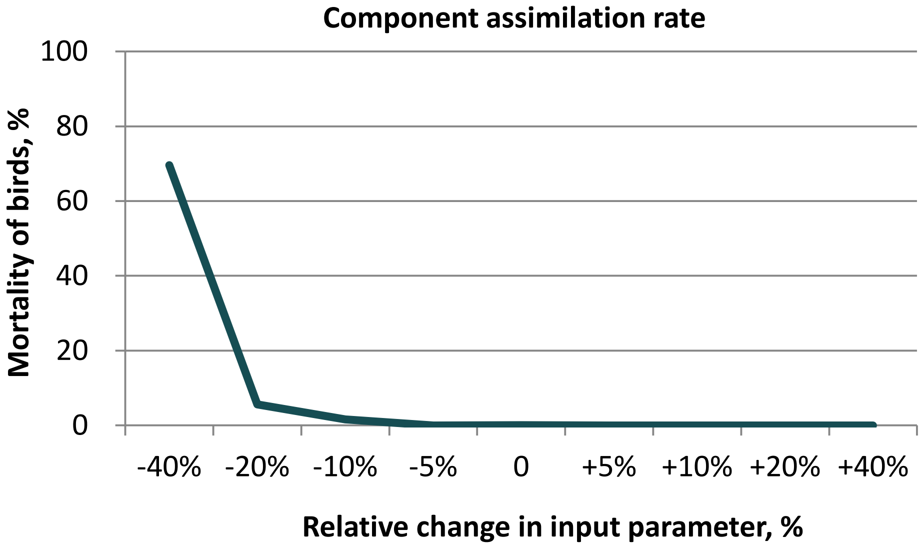


Figure A.25 Changes in predicted mortality of Common Eiders due to starvation in relation to changes in parameter 'component assimilation rate'.

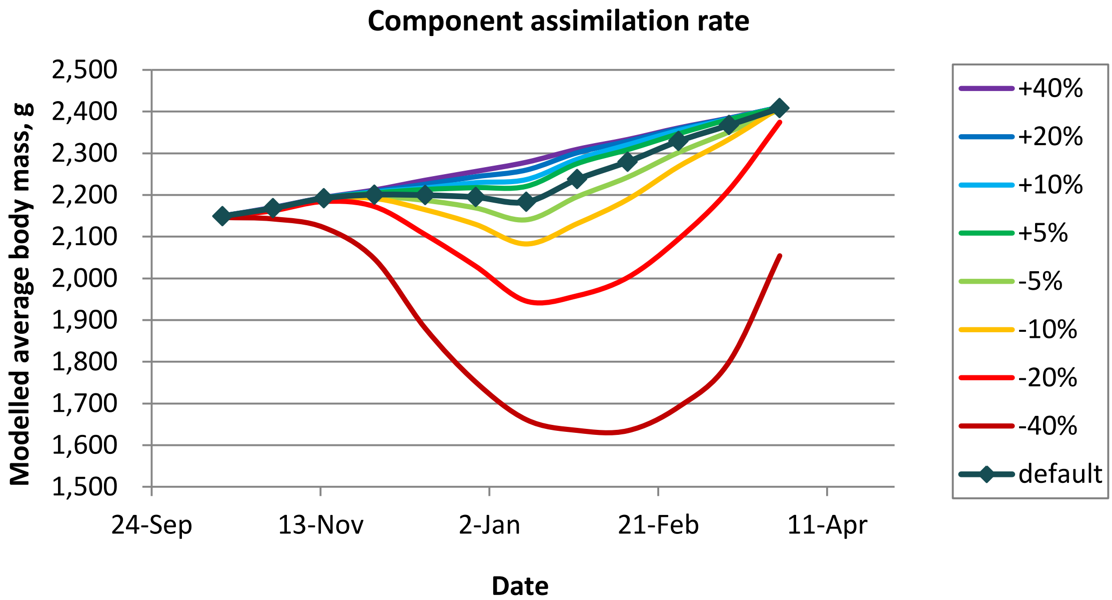


Figure A.26 Effects of changes in parameter 'component assimilation rate' on modelled seasonal body mass development of Common Eiders.

Parameter 13: Component metabolic rate while feeding
This parameter defines the metabolic rate of eiders while feeding. Because this parameter describes how fast birds metabolise consumed food or their body reserves, it may potentially be an important factor when assessing the habitat carrying capacity.

Analysed response variables showed that the model was relatively little sensitive to variation in component metabolic rate while feeding: bird mortality didn't change when the parameter was varied within ±40% (Figure A.27), and predicted bird body mass was followed the direction of change in parameter values, however at low magnitude relative to the baseline (Figure A.28).

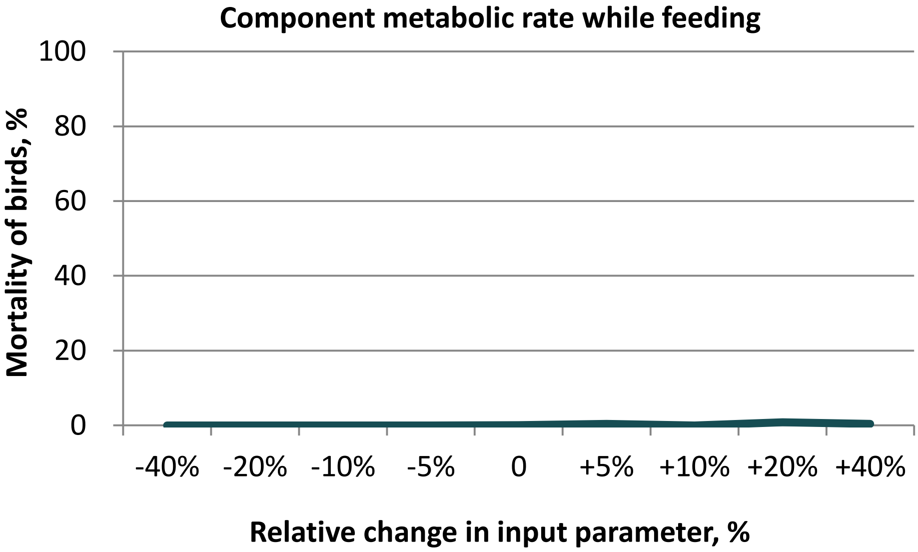


Figure A.27 Changes in predicted mortality of Common Eiders due to starvation in relation to changes in parameter 'component metabolic rate while feeding'.

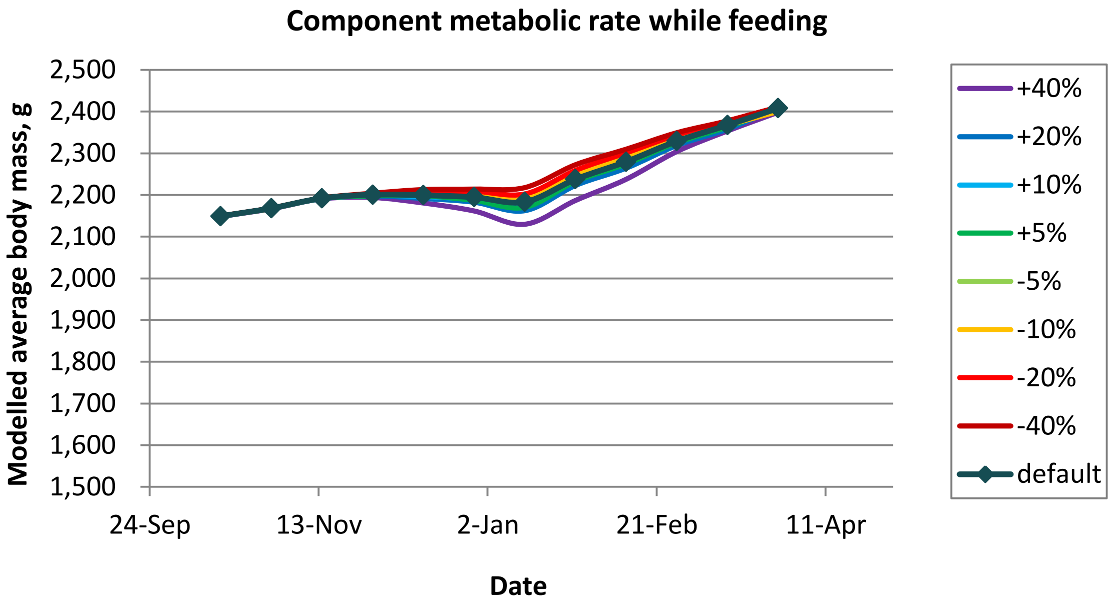


Figure A.28 Effects of changes in parameter 'component metabolic rate while feeding' on modelled seasonal body mass development of Common Eiders.

Parameter 14: Component metabolic rate while resting

This parameter defines the metabolic rate of eiders while they are resting. This parameter describes how fast birds metabolise consumed food or their body reserves and therefore it may potentially be an important factor when assessing the habitat carrying capacity.

Analysed response variables indicated that the model was highly sensitive to variation of this parameter: bird mortality increased to 30% when the component assimilation rate was decreased by 40% (Figure A.29). Also, modelled bird body mass followed the direction of parameter change: increased metabolic rate led to lower body mass and vice versa – modelled body mass was higher than that under the baseline conditions when metabolic rate was decreased (Figure A.30).

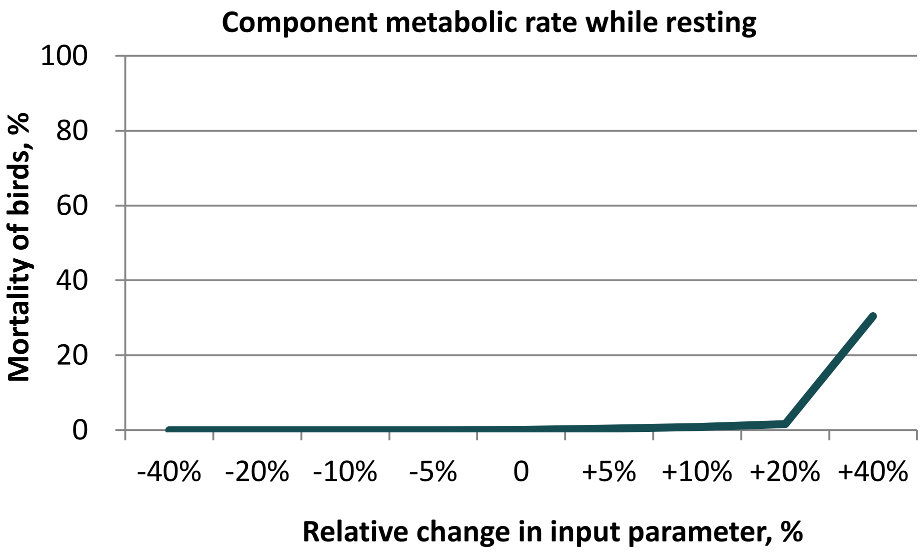


Figure A.29 Changes in predicted mortality of Common Eiders due to starvation in relation to changes in parameter 'component metabolic rate while resting'.

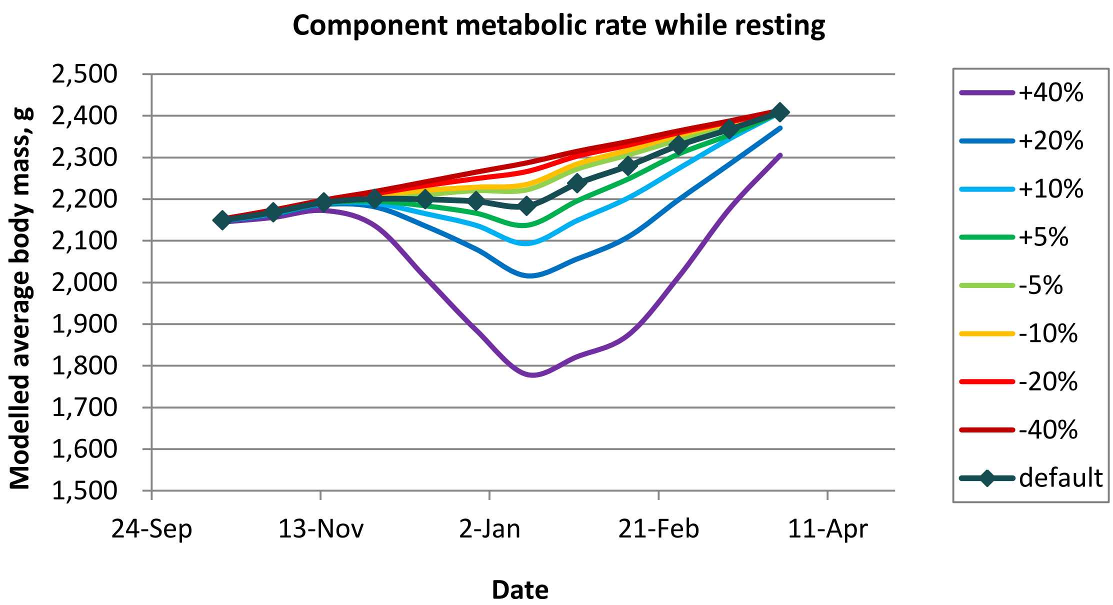


Figure A.30 Effects of changes in parameter 'component metabolic rate while resting' on modelled seasonal body mass development of Common Eiders.

Parameter 15: Starvation body mass
This parameter defines a threshold body weight of an eider below which a model bird would die. Therefore this parameter may potentially be an important factor when assessing the habitat carrying capacity.

Response variable 'mortality of birds' indicated that the model was sensitive to variation of this parameter: bird mortality exceeded 1% when starvation body mass was increased by 10% and 20%, and bird mortality reached 17% when starvation body mass was increased by 40% (Figure A.31).

Dynamics of modelled bird body mass was not assessed in relation to this parameter, as due to applied changes in the model design bird body mass dynamics could not be different from that of the baseline model. Increased mortality due to raised threshold of starvation body mass would have led to an increase of overall average body mass (as birds with the lowest body mass would have died), which could lead to a false interpretation of the results.

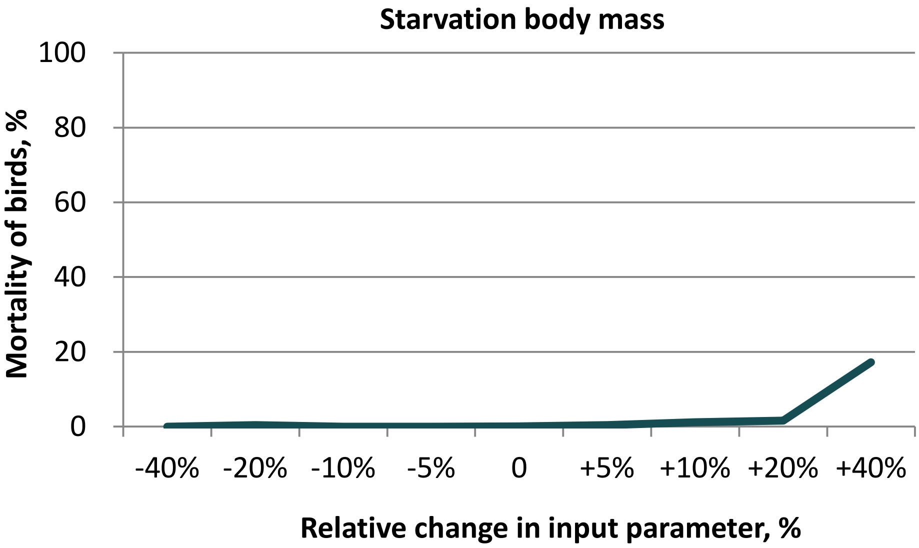


Figure A.31 Changes in predicted mortality of Common Eiders due to starvation in relation to changes in parameter 'starvation body mass.

Summary of sensitivity testing

Sensitivity testing of Common Eider IBM indicated the model is sensitive to 14 out of 15 parameters considering one or both response variables that were tested (Table A.2). This therefore suggests that the calibrated model demonstrates high sensitivity to a broad array of parameters describing the environment, food resources, bird physiology and foraging behaviour. Because such sensitivity testing was not part of the model parameterisation procedure, it provides an assurance that parameter values implemented in the model design are indeed reasonable and realistic. Therefore, the results of sensitivity testing support the assumption that the model could be used as a tool to measure effects of environmental change (chiefly food resources) on the fitness of Common Eiders wintering in the Fehmarnbelt area.

Table A.2 Effects of parameter variation within a range of ±40% on modelled bird mortality and seasonal body mass dynamics. Mortality exceeding 1% of all wintering birds and body mass change by more than 1.1% from that of the baseline were considered as thresholds indicating IBM sensitivity to a given parameter.

No	Parameter	Modelled bird mortality	Body mass dynamics
1	Day length	sensitive	sensitive
2	Water temperature	insensitive	insensitive
3	Initial mussel density	sensitive	sensitive
4	Change in mussel density	insensitive	sensitive
5	Mussel flesh dry mass	sensitive	sensitive
6	Number of foragers	insensitive	sensitive
7	Maximum bird density	insensitive	sensitive
8	Underwater time per dive	sensitive	sensitive
9	Travel time per dive	sensitive	sensitive
10	Surface time per dive	sensitive	sensitive
11	Diet consumption rate	sensitive	sensitive
12	Component assimilation rate	sensitive	sensitive
13	Component metabolic rate while feeding	insensitive	sensitive
14	Component metabolic rate while resting	sensitive	sensitive
15	Starvation body mass	sensitive	insensitive

References

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