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1. Introduction

Projects leading to potential significant environmental impacts in the EU - and in most of the rest of the world - are legally obliged to provide an Environmental Impact Assessment (EIA) as part of the consenting process in order to describe and assess likely significant impacts the project could have on the environment, species and habitats (Guerra et al, 2015; Morris and Therivel, 2009). The European Habitats Directive requires that assessments are based on best scientific knowledge available and best techniques and methods to estimate the impacts, especially if protected areas are affected by a project. Birds and in particular migrating birds are especially protected by the EU birds directive (Ramirez et al. 2017). Migrating waterbirds are characterized by a flexible use of variable and widespread wintering habitats. Impacts thus necessarily have to be assessed at the appropriate population level. This might be a challenging task as impacts have to be predicted beforehand, and most impact assessments are based on abundance data, which are then related to individual responses to habitat changes or simply disturbance and displacement due to the presence of an activity or structure (Masden and Cook, 2016; Mäkelainen and Lehikoinen, 2021).

Assessments of likely significant impacts thus require a good strategy, sound baseline data, and the right tools to project how impacts on individuals may affect populations or subpopulations in a given area (Gontier et al., 2006). Geographical Information Systems and regression models are commonly used for projections in EIAs (Morris and Therivel, 2009). However, these approaches do not allow realistic estimates of population impacts as they usually do not consider the physiology of the target species nor decisions individual animals inherently make in natural environments such as avoidance, competition, resting, etc. (Brown and Stillman, 2021; Stillman and Goss-Custard, 2010). Hence, EIAs often lack proper tools to provide realistic estimates of projected impacts on animal population parameters in defined space-time.

Individual-based models (IBM), also called agent-based models (Grimm et al., 2006), allow the simulation of individual behavior of one or multiple species in a defined space-time scenario while physiology, dynamic environments and resources are considered simultaneously (Stillman and Goss-Custard, 2010). IBMs have become important tools to simulate individual behavior of animals in different ecosystems. Models have been developed for different taxa such as lizards (Malishev et al., 2018), salps (Groeneveld et al., 2020), harbor porpoises (van Beest et al., 2017) and wolves (Bauduin et al., 2020). Several IBMs were developed for birds, e.g. for waterfowl (Miller et al., 2014), Barnacle Geese (Oudman et al., 2020), Little Owls (Hauenstein et al., 2019), and swans (Wood et al., 2021). The software MORPH (Stillman, 2008) was explicitly developed for coastal bird populations. Although IBMs have the potential to become a standard decision-support tools for EIAs (Wood et al., 2015) there are still few case studies which demonstrate the utility of IBMs for birds in an EIA context such as West et al. (2002) or Warwick-Evans et al. (2018).

The Fehmarn Belt Fixed Link is a major infrastructure project to ease travel between Central Europe and Scandinavia. It is planned as an immersed tunnel of about 18 km length that will connect Germany and Denmark, becoming one of the world's longest road and rail tunnels (Mabit et al., 2013; Pedersen and Brøndum, 2018). An extensive EIA was conducted, and baseline data were gathered between 2008 and 2010 (FEMA 2013, FEBI 2013a, b). Forty-two bird species were analyzed for potential impacts during the construction phase. For only one species, the Common Eider (*Somateria mollissima* L.), a potential negative impact affecting >1% of the biogeographic flyway population (Wetlands International, 2021). was identified caused by a decrease in habitat capacity (FEBI, 2013a). In this context, habitat capacity is a synonym for food abundance and available habitat area. The waters around the islands Fehmarn (Germany) and Lolland (Denmark) have for long been identified as a major wintering area of Common Eider of the Baltic Sea (Bräger & Nehls, 1987). The main food resource for Common Eiders in this area is the Blue Mussel (*Mytilus edulis* L.). Blue Mussels occur in shallow areas of the Fehmarn Belt and west of Fehmarn in high quantities being a dominating species of the benthic communities (Kautsky, 1981; FEMA, 2013). Even though this bivalve is very abundant, severe reductions in habitat capacity could lead to significantly increased mortality, as it has been observed for the Common Eider in the Wadden Sea (Camphuysen et al., 2002; Larsen and Guillemette, 2000). Hence, for the Common Eider, a more detailed assessment of impact on population level was carried out to provide an adequate EIA report.

Dredging works for tunnel construction will produce temporary sediment spills, which potentially affect the Blue Mussel population by temporarily reducing biomasses and thus reducing food availability (FEMA 2013). Further, eiders are predicted to become periodically displaced by construction activities and decreased water transparency. The construction activities may lead to displacement of the birds so that habitat areas are effectively lost; hence habitat capacity will be reduced temporary. Combined with higher food demands at colder water temperatures and shorter daylight periods during winter this could have an impact on the local wintering population, e.g. a strong decrease in body weight during winter could impact breeding success of females in the breeding colonies. However, it is unclear whether the habitat capacity in the Fehmarn Belt would be still sufficient to supply enough food allowing the maximum local abundance estimate for the Common Eider (250,000 birds, FEBI, 2013a) to gain enough weight over the wintering period or if additional mortality would occur Furthermore, estimates of local population numbers are dynamic and can vary considerably between the years. Depending on the season, population estimates varied between 150,000 (autumn) and 325,000 birds (spring) in the larger Fehmarn Belt area (Heinänen et al., 2017).

The major aim of this study is to demonstrate the usefulness of applying an IBM in an EIA. Using the Fehmarn Belt Fixed Link project as a case-study, we predict the impact of tunnel construction work on the population of wintering Common Eider in the Fehmarn Belt. Using the software MORPH (Stillman, 2008), we define two scenarios i.e. with and without the tunnel construction activities in the study area. First, we study the effects of reduced habitat capacity on body weight and its development over a time period of six months (October to March). Second, we analyze whether a theoretical incremental increase in population size would lead to a severe increase in mortality rates, again comparing the two scenarios. Finally, we use this case-study to discuss the application of IBMs for EIAs.

2. Material and Methods

2.1. Study area

Our study area, the Fehmarn Belt, is located in the southwest of the Baltic Sea. It is a strait of about 19 km in width separating Denmark and Germany (Figure 1). The Fehmarn Belt has a maximum water depth of about 40 m. The current in the Fehmarn Belt is affected by the vertical stratification that can de-couple the upper and lower layers. The mean current is outwards towards the North Sea in the upper 15 m and in-wards towards the Baltic Sea below 15 m depth with a mean surface speed of 0.34 m/s. Salt content of the Fehmarn Belt is seasonally influenced by the North Sea and ranges between 7 and 31 PSU. The climate is temperate oceanic with mild summers and cool winters according to Köppen & Geiger (Peel et al., 2007)**,** and has a median annual air temperature of 8.5 °C and 773 mm of mean annual precipitation.

The Fehmarn Belt Fixed Link is an immersed tunnel with a length of 18 km that will connect the two islands Fehmarn (Germany) and Lolland (Denmark) for road and railway traffic (Figure 1). An environmental impact assessment (EIA) was initiated in 2008. For the EIA, extensive monitoring of various animal populations was conducted until late 2010 (FEBI, 2013; FEMA, 2013). The beginning of tunnel construction was further delayed by a complex lawsuit for several years and construction work finally started in 2020 on the Danish side and in 2021 on the German side. Tunnel construction will temporarily reduce the available resting and feeding habitats for eiders and will likely also temporarily reduce Blue Mussel biomass in the Fehmarn Belt. The affected area was conservatively estimated based on the EIA results for the different project pressures. As very low densities of eiders were observed in the area east of Fehmarn, it was decided to not include these cells in the final grid, which defines the study area used by the IBM (Fig. 1).

[FIGURE1]

2.2. Common Eider

The Fehmarn Belt study area serves as an internationally important wintering site for the Common Eider with more than 40% of the biogeographic population using this area during winter (Wetlands International, 2021). During the baseline investigations for the EIA in 2008–2010, population size of wintering Common Eider was estimated based on counts from large scale aerial surveys (Heinänen et al., 2017). Common Eiders are large sea ducks that forage on a large variety of especially benthic prey organisms. However, the species usually specializes on one or few dominant prey species in an area (Leopold et al., 2001). Analyses of the stomach content of Common Eiders sampled in the Fehmarn Belt study area revealed that the species predominantly forage on Blue Mussels of relatively small size (14 mm; FEBI, 2013). The diet of eiders is characterized by a low energy content per unit live mass as prey are swallowed whole and include shells. Consequently, eiders must process a large amount of material to meet their daily energy requirements (Guillemette et al., 1992). This is especially true in winter as low water and food temperature increases the energy demand of diving seabirds. Radio telemetry studies on the foraging ecology in the Fehmarn Belt indicated that Commons Eiders were almost exclusively diurnal foragers. Foraging intensity varied during the winter period indicating that birds had to invest more of the daylight time feeding in mid-winter, when Common Eiders spent up to 60% of daylight hours diving (FEBI, 2013). This period of highest individual food demand coincides with highest Common Eider abundance in the Fehmarn Belt area

2.3. MORPH

We used the software MORPH (Stillman, 2008) to run Individual-based models (IBM) of the Eider population in the Fehmarn belt. IBMs simulate the behavior and body mass development of individual birds given external and internal parameters. External parameters can be environmental or disturbance parameters while internal are related to the physiology of an individual, including feeding habit, energy requirements and behavior. Over a specified time period, in our case mid-October to end of March, birds represented by points are moving over a grid-system of single patches to search for food. In this grid, each patch or cell contains various information about the local environment. The environment can change locally if disturbance is caused by external drivers, i.e. construction work. If birds cannot meet their energy requirements, they starve in the long run. The total number of birds starved is recorded as one important model outcome.

Running MORPH requires an extensive parameterization of the organism's physiology and a model calibration including a sensitivity analysis. This was done for the EIA of the Fehmarn Belt Fixed Link; for details we refer to the specific literature (FEBI, 2013a, 2013b). The parameterization of the IBM included parameters defining the environment across the site, patch-specific conditions, the quantity of food available to the birds and the physiology and behavior of the birds themselves (Table S1). The area considered by the IBM covered 3,856 km² and consisted of 964 contiguous patches of

4 km² (Fig. 1). Areas where no Eiders were observed in very low densities during the EIA, i.e., east of Fehmarn, were excluded from the final IBM grid.

To understand potential environmental impacts, MORPH was run for two different scenarios i.e., a baseline versus tunnel scenario from mid-October to end of March. In the baseline scenario, no construction took place and population development was only influenced by the natural environment. During the winter months water temperature got colder and birds had to consume more food to maintain their energy demand. Furthermore, day length was also reduced during winter months so that there was less time for food uptake. In combination, change in water temperature and reduced time for foraging will create stress impacting the body weight of the Eider population. Blue Mussel biomass was reduced naturally by predators such as starfish and crabs and additionally by sediment spill. In the construction scenario, environment changes in the same way as in the baseline scenario but in addition the available area for food uptake will shrink due to area covered by the construction site and diffuse sediment spill which is mainly assumed to be east-wards (Fig. 1). Given reduced habitat area and food resources for an increasing number of birds, competition was expected to increase, particularly in the winter months, potentially impacting body weight and thus survival.

To implement the food resource, we used an existing species distribution model of Blue Mussel biomass for the area. Based on empirical mussel density data, the estimated Blue Mussel biomass for the Fehmarn Belt study area is calculated as 28,000 t ash-free dry weight (FEMA, 2013). Initial mussel density was based on empirical data collected during the Fehmarn Belt benthic baseline monitoring (FEMA, 2013). The Blue Mussel biomass, measured as ash-free dry weight (g), at each time point was calculated using a biomass-reduction model, excluding bird predation (FEBI, 2013b). While day length was calculated for the Fehmarn Belt, mean daily water temperature was extracted from a dynamic hydrological model of the Fehmarn Belt (FEBI, 2013b). Common Eider population size was set to 250,000 individuals based on the relation of the IBM-area (3,645 km²) to the total area surveyed (4,875 km², > 325,000 individuals, see Heinänen et al., 2017). During winter, blue mussel biomass was reduced, and energy demand of eiders was increased due to lower water temperatures. Thus, eiders had to take up more food to keep up with their energy requirements but had less time for foraging as day length was also reduced during the winter.

Individual behavior is controlled by various model parameters (Table S1). Individuals in MORPH are represented by so called super-individuals. One super-individual was set to equal 1,000 Common Eiders (Table S1). This was done to improve computing time. Common Eider physiology was described using literature data and direct observations of several individuals (FEBI, 2013a, 2013b). In the simulation, birds started with a body weight of 2,150 g and died of starvation when body weight was less than 1,476 g, based on Camphuysen et al. (2002). Model behavior was controlled by the parameters c1 to c5 (Table S1). These control the individual behaviour of the super-individuals and represent foraging efficiency (c1), dominance (c2), day of arrival and departure (c3 and c4) and patch capacity (c5). The values for c1 and c2 were randomly drawn from statistical distributions (c1: Normal distribution $\mu=1$, SD=0.125; c2: Uniform distribution min=0, max=1, see FEBI, 2013b). Birds entered the study area with random starting locations successively between day 1 and 30 (October), stayed within the area until day 153 and then started emigrating from the winter habitat until day 182 (end of March). Between the immigration and emigration phase birds remained in the study area and were not allowed to leave even if experiencing starvation. Super-individuals actively search for food in the neighboring cells and move each day to another nearby cell if food is available. If not, then super-individuals can also migrate larger distances within the grid. The efficiency parameter controls how much food a super-individual can consume during a day. In addition, dominance controls whether an individual can enter a cell when other, potentially more dominant birds are already in a cell and maximum number of birds was not yet reached. Based on expert knowledge, carrying capacity of cells was limited to maximum number of 5,000 birds. For further details on the MORPH software see Stillmann (2008).

2.4. Model evaluation

We aimed to quantify the impact of the reduction of habitat capacity on body weight and mortality rates of Common Eiders by comparing two different scenarios, i.e. a baseline scenario and the tunnel construction scenario. The baseline scenario represents the observed state and thus the expected natural mortality. The effect of the tunnel construction is defined as the difference in mortality between the baseline and tunnel scenario. First, we simulated the reduced habitat area by removing grid cells in the disturbance zone which extends approximately 3 km to each side of the tunnel trench (Figure 1). The disturbance zone includes area lost by construction, areas inaccessible due to traffic caused by construction vessels, as well as area that is affected by sediment spill causing the water to become too muddy for eiders to find food." Then, to simulate an increased population size, we successively increased the number of birds from 250,000, representing the observed population (FEBI, 2013b), by 50,000 birds leading to six different population sizes with a maximum of 500,000 birds. For each of the different population sizes, five simulations were run for each of the two scenarios i.e. with and without tunnel. Maximum likelihood confidence intervals for count data were calculated using a Poisson mean (Patil and Kulkarni, 2012), as the mortality rates cannot reach negative values. The model simulated the wintering period of Common Eider during 1st October to 31st March.

To evaluate the effect of reduced habitat capacity, i.e. the effect of reduced food uptake on mortality rate, we measured the development of body mass over time for each super-individual. The data comprised hourly data for 250 super-individuals across 12 selected dates (every second week) and for five model runs. To test for differences in average body weight for each date we calculated a two-sample independent t-test. The effect of increased competition was simulated with increasing population sizes. We compared the average number of birds predicted to die and between the two scenarios for each different population size. Statistical significance of the differences was assessed with Wilcox-rank sum tests. Outcomes of the scenarios were compared with the original observation data from the EIA.

3. Results

Seasonal changes in predicted Common Eider body mass for the baseline and tunnel scenario for the wintering period are presented in figure 2. The two curves show a similar pattern across time i.e., a slow increase followed by drop in body weight during December to mid of January. For the tunnel scenario, the mean body mass is approximately 50 g less than for the baseline scenario in mid-January. This winter depression is then followed by a constant increase in body mass which, in both cases, reached a final body weight of about 2,400 g on average. The error bars, depicting standard deviations, show a strong overlap throughout the whole time period. Variation in winter was much higher than in autumn but in both scenarios 2,000 g was the lowest standard deviation value reached (Figure 2). Neither of the curves or error bars reached the threshold of 1,476 g thus no mass starvation of ducks was predicted by the model. Comparisons of the average body weights for the two scenarios per time step did not show any significant difference between the means (Appendix S2).

[Figure 2]

The effect of an increase in bird population size on mortality is shown in figure 3. The number of 250,000 birds represents the observed eider abundance in the IBM study area. The difference between baseline and tunnel scenario was an additional mortality of 600 birds on average which is equal to 0.24% of the local abundance. When more than 350,000 birds were assumed in the model, the effects of the tunnel scenario became larger, i.e. significantly more birds starved in the tunnel scenario than under natural conditions. The largest effect of the tunnel construction was observed for the scenario of 500,000 birds in the model with additional mortality of 5,200 birds (1.04 %) while the second largest effect was observed for 350,000 birds with 3,000 predicted additional mortalities (0.84 %) (Table 1).

[Figure 3]

[Table 1]

4. Discussion

4.1. Habitat capacity

We hypothesized that tunnel construction activities within the Fehmarn Belt will have a negative effect on the Blue Mussel abundance and Common Eiders being displaced from suitable habitats due to disturbance or reduced water transparency from sediment spill. Blue Mussel constitutes the main food resource for Common Eiders in the Fehmarn Belt and a strong reduction in food availability or exclusion of birds from foraging grounds could lead to increased mortality. Mass mortality events for Common Eiders due to food shortage were reported from the Dutch Wadden Sea where 21,000 birds died; mainly caused by continuous depletion of bivalve stocks (Camphuysen et al., 2002). Common Eiders therefore need to be assumed to be sensitive against decreasing food stocks. However, there was no significant difference between the baseline and the tunnel scenario with regard to Common Eider body weight. Both scenarios showed a similar development of body weight over time with a clear dip between mid-December and mid-January (Figure 2) due to the increased difficulty (i.e. shorter days, colder water temperatures) to uphold energy demands. No mass mortality event was observed during the simulations in which case the tunnel scenario curve would have neared or declined below 1,426 g. Hence, we conclude that there is no effect due to reduction in food shortage but rather a slight effect of general habitat loss caused by the tunnel construction activities by leading to a predicted additional mortality of 600 birds (0.2% of the model population). However, this would not have a relevant effect on the biogeographic Common Eider population which represents the North Sea and Baltic Sea populations and is estimated as 720,000 individuals (0.08% of the biogeographic population, Wetlands International, 2021) with an apparent declining trend in many areas (Desholm et al., 2002; Ekroos et al., 2012; Öst et al., 2016; Tjørnløv et al. 2019). Furthermore, different to the IBM, where birds are forced to stay within the model area, under natural conditions birds likely will leave the model area before suffering starvation leading to an even further reduced effect.

Similar studies which used individual-based modelling to predict effects of a potential food shortage on population dynamics of wintering birds, e.g. swans (Wood et al., 2021) or Brant Geese (Stillman et al., 2021) included multiple species to simulate resource competition. Although it would be possible to include other species, we solely modelled the development of the Common Eider population given one food resource (Blue Mussel) thus neglecting potential effects of interspecific competition with other seabirds and food resource diversity. The Common Eider is the most abundant (FEBI, 2013a) and largest benthivorous bird species in the Fehmarn Belt consuming more Blue Mussel biomass than all other bird species. Also, the Blue Mussel occurs in large quantities in the Fehmarn Belt. As the wintering population of the Common Eider observed during the EIA consumed approximately 3,000 t ash-free dry weight of Blue Mussel Biomass equaling to 10.7% under baseline conditions. During the construction phase eiders consumed 13.2% Blue Mussel biomass with a reduced blue mussel biomass of 22,800 t. As Blue Mussel is the main food resource constituting more than 72% of the daily energy consumption (FEBI, 2013b), other prey species such as crabs (*Carcinus maenas*), molluscs (e.g. *Hydrobia ulvae, Littorina sp.*) polychaetes (e.g. *Nereis diversicolor*) and fish (e.g. *Gobius sp.*) were considered as negligible. Hence, including other prey or competitor species would make the IBM more complex but would have little effect on the final outcome.

4.2. Population size

We further hypothesized that the number of wintering Common Eiders could increase by several thousand individuals during the construction phase. More individuals would require more food and given the reduced habitat extent caused by disturbance and sediment spill from construction activities these higher numbers would compete for food in a smaller area. For the actual observed Common Eider abundance of 250,000 birds in the study area, the IBM resulted in a difference in mortality of 600 birds between the baseline and tunnel scenario. This equals to 0.2% of the eiders wintering in the area (Table 1). This percentage of additional mortality increases with artificially increased bird numbers in the model up to 1% when doubling the assumed eider abundance in the model area. However, such large population sizes are unlikely to occur in reality as this would require almost 70% of the Baltic, North and Celtic Seas biogeographic Common Eider population (720,000 individuals, Wetlands International, 2021). Several studies using individual-based models tested the increase in population size as one factor that could affect mortality. For example, Stillman et al. (2021) simulated effects of food availability, climate and disturbance on two Arctic goose species, i.e. Black Brant (*Branta bernicla nigricans*) and Cackling Goose (*Branta hutchinsii*) feeding on eelgrass (*Zostera marina*) in Alaska. They found that, given optimal food resources, the area could support twice the population size for both geese species. However, when eelgrass biomass was strongly reduced the total population could not be supported and starvation set in. A strong reduction in food availability would also have negatively impacted the Common Eiders. The simulated reduction in Blue Mussel biomass in our IBM, together with the exclusion of eiders from large areas due to reduced water transparency from sediment spill or disturbance from construction activities, did have no effect on the larger population. We conclude that the current habitat capacity in the Fehmarn Belt is sufficient to support wintering eider and even if substantially higher numbers of birds were using the area, the habitat capacity would not be immediately reached.

Our findings could imply that Baltic eider population is not limited by food supply on their wintering, as the model indicates high resilience against a reduction of their main prey. The Baltic eider population has been found to decrease in many areas (Desholm et al., 2002; Ekroos et al., 2012; Öst et al., 2016; Tjørnløv et al., 2019) and the reasons are not well understood yet. However, some studies indicate that the main reasons are found in the breeding areas (Oest et al., 2015; Morelli et al., 2021; Laursen & Moeller, 2022). The finding of Laursen & Moeller (2022) of increasing body mass in wintering

Baltic eiders in parallel to a decreasing population also point at improving conditions on the wintering grounds when less individuals have access to a constant food resource.

4.3. Temporal and spatial aspects

If there is enough food available why do birds still die in the simulation? There are several reasons why this effect occurs. Due to stochasticity a small number of super-individuals could be inefficient and subdominant, meaning that they cannot take up food and are always last in the queue for food uptake. These individuals would be outcompeted by more efficient and more dominant birds. Furthermore, the spatial distribution of starting locations of super-individuals are randomly scattered across the IBM grid. Thus, even if more birds are present, they could be better distributed across the grid, while low numbers of birds could be aggregated just by chance. This might explain the lower mortality for 300,000 birds in the simulation experiment. Thus, mortality becomes a stochastic effect in the model. Second, the IBM is a locked box, where birds cannot escape for 180 days. Even if there are feeding grounds just outside the IBM grid, birds cannot reach these areas as they are locked inside the model grid where they move within the grid on a daily basis. Using GPS tracking, Common Eiders were observed to travel from the Fehmarn Belt to areas beyond the Island of Langeland, the Kiel Bay west of Fehmarn (FEBI, 2013b). A species distribution model for the Common Eider (FEBI, 2013b) as well as additional observations from regional bird monitoring programs report 77,000 Common Eider at the Baltic Sea coast of Schleswig-Holstein outside the Fehmarn Belt (FEBI, 2013b). But even if Common Eiders would leave the study area of the Fehmarn Belt to find food in the nearby feeding grounds, they might encounter similar situations and subdominant individuals could still be displaced from feeding grounds. Hence, the observed mortality could also reflect natural situations.

When conducting IBM simulations for EIA, such a lack of realism has to be kept in mind when model results are interpreted and communicated to stakeholders (Crooks et al., 2008; Wallentin, 2017). While IBMs often focus more on the temporal aspect than on the spatial aspects (Wallentin, 2017), the question how large a model grid should be is an important decision to be made in the beginning. Other solutions are found in Stillman et al. (2021) who used 11 single sites instead of one large area covering a lagoon complex in Alaska. This has the advantage that the single lagoons can be clearly delineated, while the extent of the whole lagoon complex would be less clear and also include areas which do not belong to the lagoon system. Stillman et al. (2000, 2001) studied effects of habitat loss and shellfishery on Oystercatchers (*Haematopus ostralegus*) in the Exe estuary (UK). Due to the tidal-cycle optimal feeding grounds were dynamically changing effectively impacting the available area within the model extent. These examples show different ways to decide on the extent of the IBM grid. In this study, we decided to set the extent of the IBM according to the expected impact of the tunnel construction within the Fehmarn Belt, i.e. one single area and global dynamic environment. If the area would have been increased beyond the impacted area, there were likely no birds starving as plenty of habitat would be available for the birds to make up the habitat loss by the construction activities. Hence, in order to measure a "signal" using a simulation, and also due to limitations in computation power, model grids cannot be very large. The question on how to choose the correct size for an IBM in the context of an EIA is important, in particular when communicating the outcomes to stakeholders (Wallentin, 2017). Clearly, different settings require different solutions. Hence, we encourage researchers to set up guidelines for practitioners on how to correctly decide on the extent of model grid for IBM.

4.5 IBM as a new tool for EIAs

When EIA require the assessment of complex ecosystems where one or multiple species are simultaneously affected by different processes, using an IBM to compare baseline and impact scenarios with increasing disturbance intensity offer a way forward to understand impacts on species populations caused by e.g. construction processes over large spatial areas. Alternatives to IBM have been discussed by Stillman & Goss-Custard (2010) such as species distribution models (covering mainly regression-based predictive modelling), daily rotation models or spatial depletion models. However, these models do not consider the behavior of the individual, lack complexity or cannot operate over many time steps. As pointed out DeAngelis and Grimm (2019), IBMs will play an increasingly important role when tackling questions with regard to complex ecological systems. In the light of EIAs, properly parametrized IBM, although challenging, replicate empirically observed patterns and provide confidence that such model accounts for the most important processes determining species–habitat interactions. By considering competition of multiple species, different food resources which might change in quantity over the seasons, implementing disturbance factors, reducing available habitat quantity or quality, all happening on a spatially explicit grid where animals can move as their behavior allows them, IBM can be used to study the complex interactions to a degree commonly applied methods cannot handle such complexity. As the EU habitats directive demands that EIAs consider the best available techniques and methods to estimate environmental impacts (Ramirez et al. 2017), IBM have the potential to become a such as best method and standard tool to assess environment impacts on foraging species such migrating water birds as the case-study of the Fehmarn Belt Fixed Link has shown. However, the lack of applications of IBM in the context of EIAs shows that more case-studies could help to verify the usefulness of this method for future construction projects. Setting up guidelines for how to best implement IBMs in EIAs would also be an important step to ensure the success of such a complex methodology.

5. Conclusion

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Strong impacts on wintering Common Eider population by the tunnel construction project in the Fehmarn Belt between Germany and Denmark are not to be expected based on the results of the IBM simulations. The artificial increase of eider numbers assumed in the model indicates that the habitat capacity of the Fehmarn Belt study area is higher than actually used by Common Eiders. Instead, habitat loss during tunnel construction seemed to be more important. We further found that model parameters such as foraging efficiency (c1) and dominance (c2) will cause non-zero mortality rates due to stochasticity effects and that the choice of the model extent will influence the outcomes as well. A large spatial extent of the IBM grid might not lead to any mortality as habitat would be more abundant while being too small more birds could potentially die. The question remains how to correctly size the model extent and justify it in the context of an EIA. This is important when results are interpreted and communicated to stakeholders and decision makers. In conclusion, our study demonstrates that individual-based modelling is a powerful tool to support EIAs when potential impacts of construction sites on bird populations are uncertain. Given the importance of projecting impacts in EIAs, we expect the application of IBMs in environmental management to increase in the future. However, there is a lack of sound guidelines for practitioners to set up IBMs for EIAs. We recommend developing such guidelines for EIA practitioners to best apply individual-based modelling for different scenarios, e.g. different taxa and ecosystems.

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Author contributions

JO: writing – original draft, review & editing, visualization; **RZ**: formal analysis, writing - review & editing; **MD**: writing - review & editing, **RS**: software, writing - review & editing, **GN**: writing - review & editing, conceptualization

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Table 1: Average mortality of Common Eiders given increasing population sizes and affected percentage of the population. 250,000 equals the observed population size of wintering Common Eider in the Fehmarn Belt. The difference between baseline and tunnel scenario is the mortality attributable to the tunnel construction. The effect in percentage relates the effect to the population size. Differences were assessed with a non-parametric Wilcox-test. W and p-value provide test statistic and significance, respectively.

Population Size	Average mortality		Effect	Effect [%]	W	p-value
	Baseline	Tunnel				
250,000	600	1,200	600	0.24	16.0	0.501
300,000	400	800	400	0.13	17.0	0.270
350,000	600	3,600	3,000	0.86	21.0	0.086
400,000	1,400	2,400	1,000	0.25	20.0	0.135
450,000	1,200	3,800	2,600	0.58	24.5	0.013
500,000	2,400	7,600	5,200	1.04	25.0	0.011

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Figure Captions

Figure 1: Tunnel construction area for the Fehmarn Belt Fixed Link between Germany and Denmark crossing the Fehmarn Belt. The polygon grid (3,856m²) was used for the Individual-Based-Modelling of Common Eider.

Figure 2: Development of Common Eider body mass (g) during the wintering period. The two curves represent the baseline and tunnel scenario. Points are averages and error bars represent standard deviations of five model runs. The mortality threshold of 1,496g was not reached. Points and error bars are shifted by five days for clarity.

Figure 3: Number of dead Common Eiders for observed (250,000) and hypothetical higher abundance estimates for baseline and tunnel scenario. Bars represent averages and whiskers represent upper Poisson-based confidence intervals.

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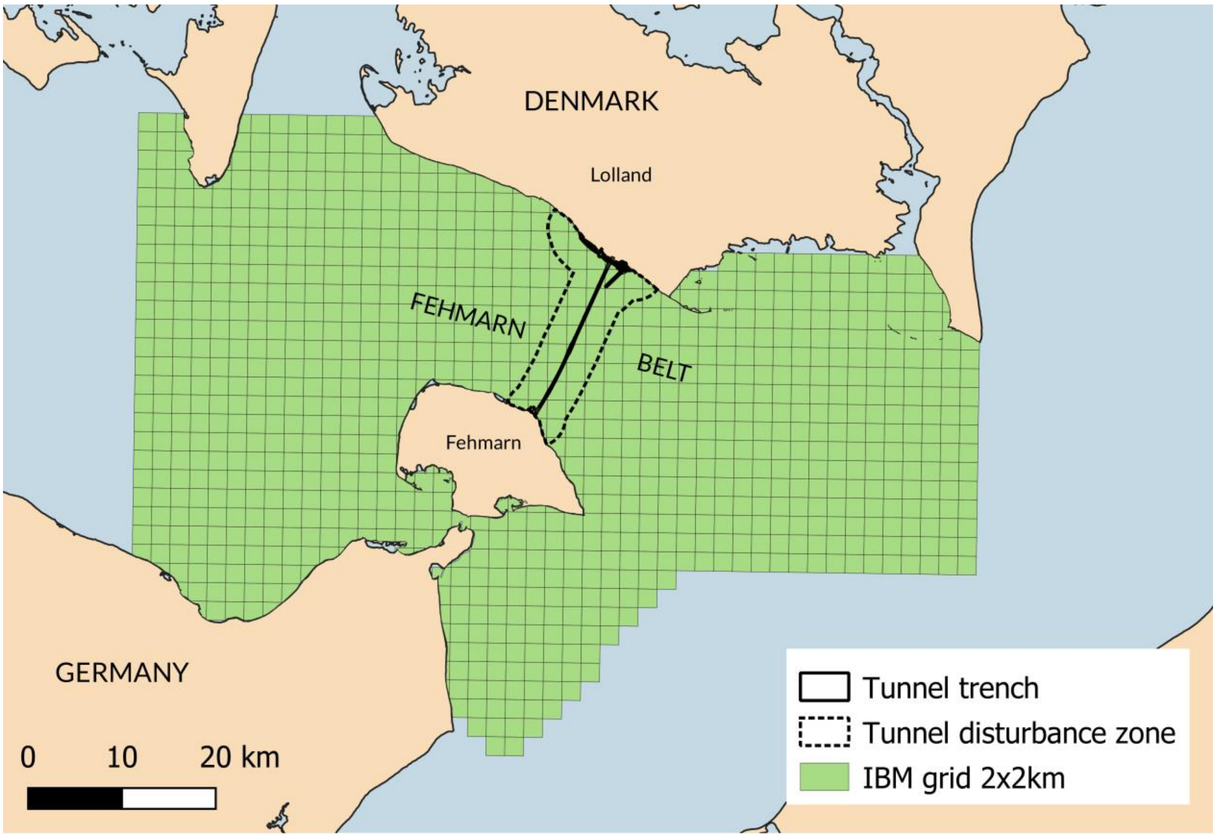

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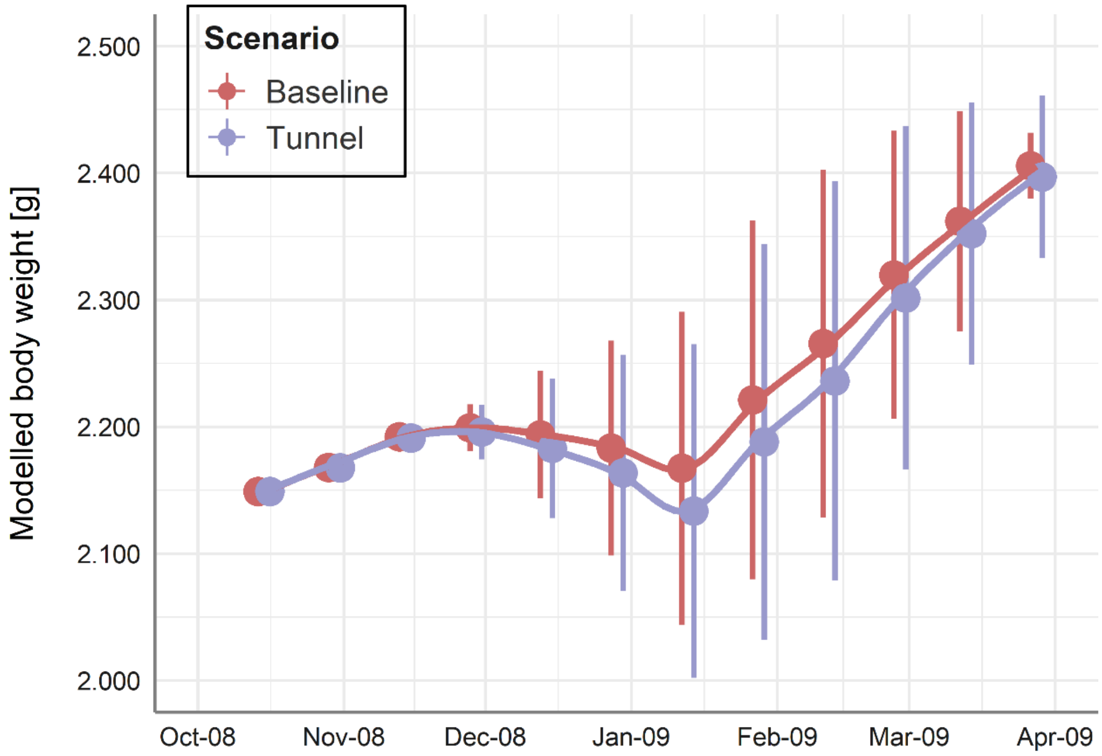

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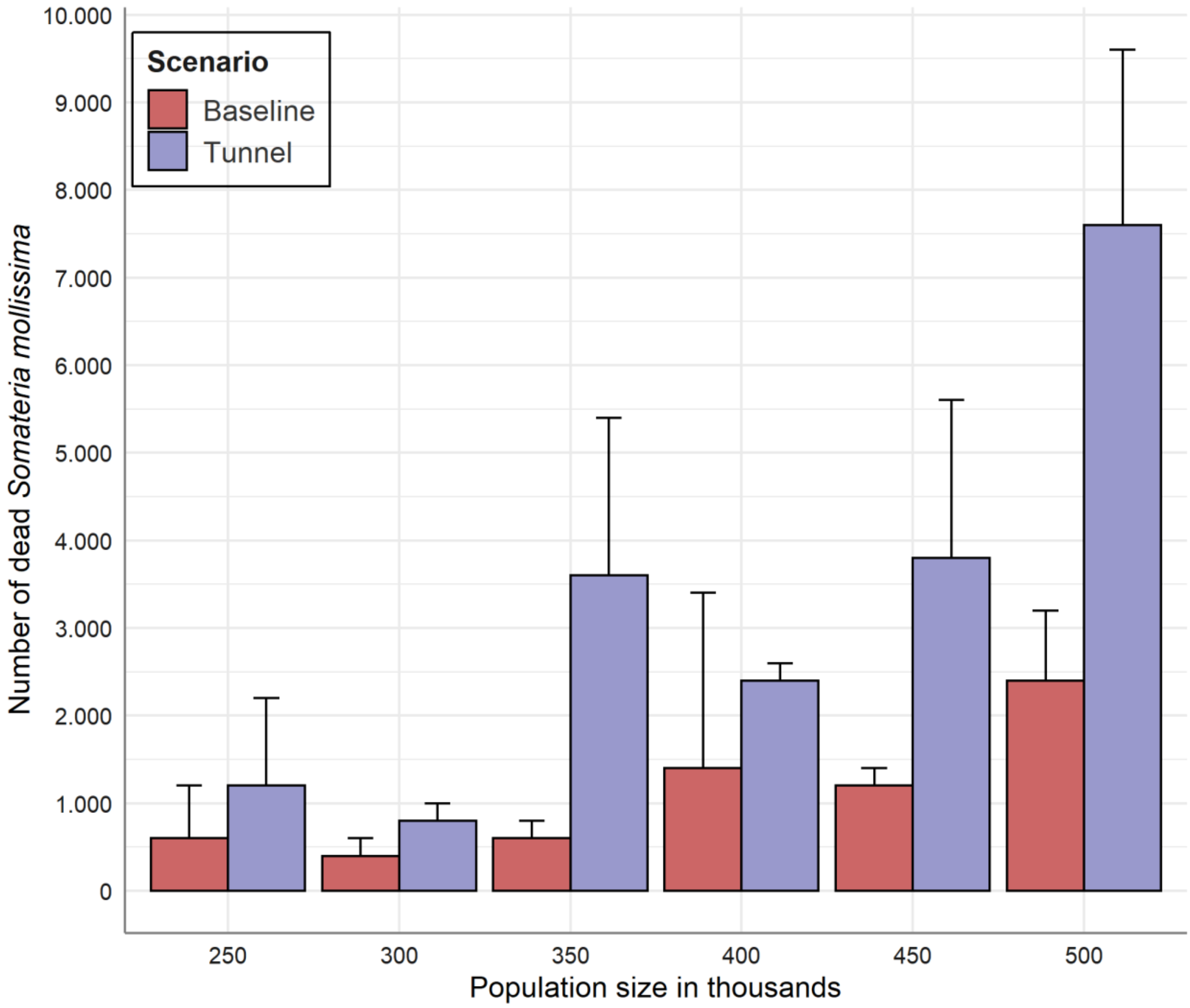

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