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Ingrid Tulp, Chun Chen & Jip Vrooman

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Author(s): Ingrid Tulp, Chun Chen & Jip Vrooman

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Client: Rijkswaterstaat Water, Verkeer en Leefomgeving
Attn.: Charlotte Schmidt

Postbus 2232
3500 GE Utrecht

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Summary

In the Ems-Dollard the turbidity level in the water has increased already from the 1950 onwards, due to the decreased sedimentation capacity of the estuary. This is mainly caused by land reclamation of large parts of the estuary, channel deepening in the Ems river and lack of natural siltation. The aim of this study was to investigate if there are any indications that the nursery function for fish of the Ems-Dollard is in any way hampered by the current conditions with regard to the high silt concentration.

In order to evaluate the potential effect of elevated silt levels on the nursery function, ideally the situation in the Ems-Dollard should be compared to areas similar in all aspects apart from the silt situation. Unfortunately such a situation does not exist, therefore we tried to find **contrasts** both in **time** and **space**. The long time series (the longest going back to 1970) provide the opportunity to compare periods with varying silt concentrations. The time series, however, do not go back to the period before silt levels started to increase, but the levels were still considerably lower in the 1970s as compared to the latest decennia. In our analyses we therefore address changes between the early part of the available time series as compared to the last two decennia. In addition to comparing periods with varying silt levels, we also compare the Ems-Dollard area to surrounding areas, supposedly without elevated silt levels.

To investigate the nursery function of the area, we examined several parameters indicative of the nursery function. Of all potential parameters describing the quality of a nursery; density, growth, survival of juveniles, and emigration, we used existing survey data to analyse **density** (and **trends** therein), and as proxies for growth: **length** and **condition** at the end of the growing season. In order to evaluate whether the situation in (subareas of) the Ems-Dollard is falling behind, comparisons to other areas are needed. Therefore we made comparisons on **three different levels**: 1) within four different **subareas** in the Ems-Dollard, 2) between the Ems-Dollard tidal basin and neighbouring **tidal basins** and 3) (specifically for pelagic species) between the Ems, Elbe and Weser **estuaries**.

In conclusion, our analyses, focussing on trends in time and space, showed no strong difference in the investigated parameters (densities, trends, length, condition) in the Ems-Dollard as compared to other areas that may point at an adverse effect of the higher silt levels. Overall densities of marine juveniles have declined strongly since the 1980s, but that pattern is observed throughout the Wadden Sea (Tulp et al. 2022). The only indication in the trend analyses possibly indicating a worse nursery function in the Ems-Dollard is the pattern reversal in length of plaice at around 1985, with smaller fish after that period in the Ems-Dollard as compared to neighbouring tidal basins. For species that favour siltier situations or the estuarine character of the Ems-Dollard such as sole, flounder and smelt, we found no indications of a deteriorating situation in course of time. This does however not mean that we can exclude such effect, because we lack a good reference situation and the available data are limited.

Comparison of subareas withing the Ems-Dollard (level 1):
The **total density** of 0-group marine juveniles shows a similar trend in all subareas within the Ems-Dollard with a dome shaped pattern in the 1970-1980s and a strong decline thereafter, stabilising at a lower level in recent decades. Absolute densities differ from year to year with no clear area effect. Dab and whiting occur in highest densities in the outer Ems throughout the time series. Smelt and flounder decrease from the Dollard towards the outer Ems along the salinity gradient.
Species-specific **trends** in densities follow the same pattern in all subareas for most species and ages. The hump in the eighties occurs in all subareas and both in 0 and in 1+ group fish. In 1+ group fish **densities** are significantly lower in the outer Ems as compared to the other subareas.

Clear area-specific differences in **length at the end of the growing season** of 0-group fish were found for flounder, with the largest individuals in the outer Ems area and little difference among the other three subareas. 0-group sole is smaller in the outer Ems as compared to the other subareas. In plaice there seems to be an overall downward trend in length, possibly related to warmer

temperatures in later years. For plaice the time series shows that the pattern reversed in the early 1980s: before that period plaice in the Ems-Dollard was larger as compared to the other basins, while after 1980s 0-group plaice was larger in the other two basins. The decrease in mean length at the end of the series in especially the Ems-Dollard could well be caused by the high densities in 2021, causing density dependence and food shortage because of high competition. In flounder the trend in the outer Ems is upwards.

Comparison of the Ems-Dollard to neighbouring tidal basins (level 2):
In comparison to the surrounding tidal basins, the Ems-Dollard has relatively high **densities** of 0-group fish, which is largely due to plaice. In general, the **trends** follow similar patterns in different tidal basins. Plaice, sole and flounder are the dominant species in all basins. Cod is at a very low level throughout the time series, while whiting is increasing without clear differences between tidal basins. The mean **length** at the end of the growing season differs between tidal basins for several species such as plaice, sole and flounder. For most species, the Ems-Dollard does not stand out from other basins in this aspect, apart for plaice and sole for which respectively the average smallest and largest fish occur in the Ems-Dollard. This is not unexpected as sole is known for its preference for siltier conditions.

Overall there are no indications of lower **condition** of 0-group fish in the Ems-Dollard basin in the 3-5 years with available data. Nevertheless there is clear annual variation in condition in plaice and sole, but less in flounder. An additional analysis relating condition to the temperature sum over the entire growing season in the entire DFS set (including Wadden Sea, coastal area and delta, and in all years so not limited to only the three selected tidal basins) showed that the condition of plaice and sole is lower in relatively warm years, while flounder seems to benefit from warm years. The relatively large effect of temperature may be a likely reason for not finding differences in condition caused by other aspects of habitat quality, such as elevated silt levels, between areas in the limited dataset of only the Ems-Dollard and neighbouring basins.

Comparison of the Ems-Dollard to German estuaries (level 3):
Comparing trends across the three estuaries requires caution because there are considerable differences in e.g. water depth and sampling effort. Overall, **densities** are at a similar level in all three estuaries for 0 and 1+ fish. For diadromous and salinity-sensitive species such as smelt and herring, there is a clear cline from brackish to salt water (smelt) or in opposite direction (herring). The comparison between estuaries shows highest densities in the Elbe and lowest in the Ems-Dollard for smelt, but the opposite pattern occurs in herring, with an intermediate position for the Weser in both species. The decline in cod and increase in whiting are observed in all three estuaries. The **trend** in herring is increasing in the Ems-Dollard, but also in the German estuaries. Smelt is quite constant in the Ems-Dollard, but decreasing strongly in the Elbe.

Effects of elevated silt levels can act through different mechanisms. Apart from a direct effect on the fish through hampered oxygen uptake (through clogging or damage to the gills), also indirect effects may occur through reduced food uptake and via cascading foodweb-effects. In our study we investigated parameters such as densities, growth and condition of fish in the Ems estuary, and compared these to other areas, tidal basins and estuaries for which we assume the silt levels are lower. The assumption is that if the aforementioned effects of higher silt concentration would indeed take place, they might be visible in the parameters we investigated. Such comparison based on existing monitoring data is however never ideal, because apart from the difference in turbidity there are many other environmental differences.

In order to actually discern if and which of the potential mechanisms may be at work, additional work is needed. In the concluding chapter we sketch how such approach could be shaped. Roughly two routes can be distinguished:

1. Direct studies of mechanisms at work through dedicated field studies, lab work and modelling studies

Insight into mechanisms is needed to actually gain insight in how high silt levels may affect the functioning of the system for fish. Because many marine juveniles usually mainly inhabit the bottom layer, including other fish guilds such as diadromous species and summer visitors that use the entire water column is recommended. The relatively large-scale sampling we used may be too coarse to capture small-scale variation in silt levels. Therefore we recommend a smaller scaled field study as was carried out in the area in the 1990s. In addition a follow up study of dredging or dumping sites, studying the effect of silt levels on fish performance in the lab and DEB modelling to evaluate conditions for growing may be helpful routes towards a better understanding of the system functioning.

2. Field comparisons on an (inter)estuary scale

Evaluation of the functioning of the Ems estuary for fish, cannot go without comparisons to other more naturally functioning estuaries. Apart from the Elbe, Weser and Jade estuaries, also the Westerschelde is a suitable comparative system: they all flow into the North Sea and share a similar fish fauna. We made a first effort based on existing data collected for different purposes, but current techniques provide much better opportunities. For instance microchemistry analyses of fish otoliths can provide a record of which estuaries a fish visited throughout its life because the chemical profile laid down in the otolith can be linked to the chemical fingerprint of the estuary. Also tracking studies using acoustic transmitters give a more direct record of where fish go in response to their environment. The network in the Ems-Dollard that is part of the project 'Ruim baan voor Vissen' in which tagged flounder and river lamprey will be tracked is promising in that respect.

1 Introduction

1.1 The research question

Because of the high silt levels Rijkswaterstaat is concerned about the functioning of the Ems-Dollard area as a nursery for fish. The concerns are mainly on the central and southern part. Nurseries are areas where juveniles aggregate and where survival and growth are enhanced through good feeding conditions, refuge opportunities and high connectivity with other habitats. After fish have reached a certain size or age, they leave the nursery area and recruit to the (sub)adult populations (Pihl et al. 2002). If functioning of the system is hampered, this may result in worsening living conditions for marine juveniles and eventually a lower recruitment into the adult population. WMR was asked to use existing monitoring data to gain better insight into possible spatial differences in densities and functioning for fish species that use the area as a nursery, both within the Ems area and in comparison to surrounding or comparative areas.

1.2 The Ems estuary

The Ems estuary is one of the major estuaries in the international Wadden Sea. It is located at the border between the north-eastern part of The Netherlands and the north-western part of Germany, at the mouth of the Ems river. Due to human interventions in recent centuries, such as the deepening of waterways and reclamation of salt marshes, more silt enters the system at high tide, while there are fewer areas where the silt can settle (de Jonge et al. 2014; de Jonge and Schuckel 2019). As a result, the water has become more turbid and algae, which are at the base of the food chain, grow more slowly, in turn affecting benthic life and potentially living conditions for fish as well. The elevated silt levels are primarily problematic in the Ems river. Already in the 1950s at the start of the sediment dredging, the silt concentration in the Ems river was several hundred mg/l (de Jonge et al. 2014), which is more than 100 times lower than today. Silt levels increased over the past decennia until ca 2010 after which it stabilised (fig. 1). Both the Netherlands and Germany are working on measures to reduce turbidity. Apart from the silt issue also the river system was under pressure until the 1980s because of major problems with the discharge of industrial and domestic waste water and a lot of organic material, especially from straw cardboard and potato factories.

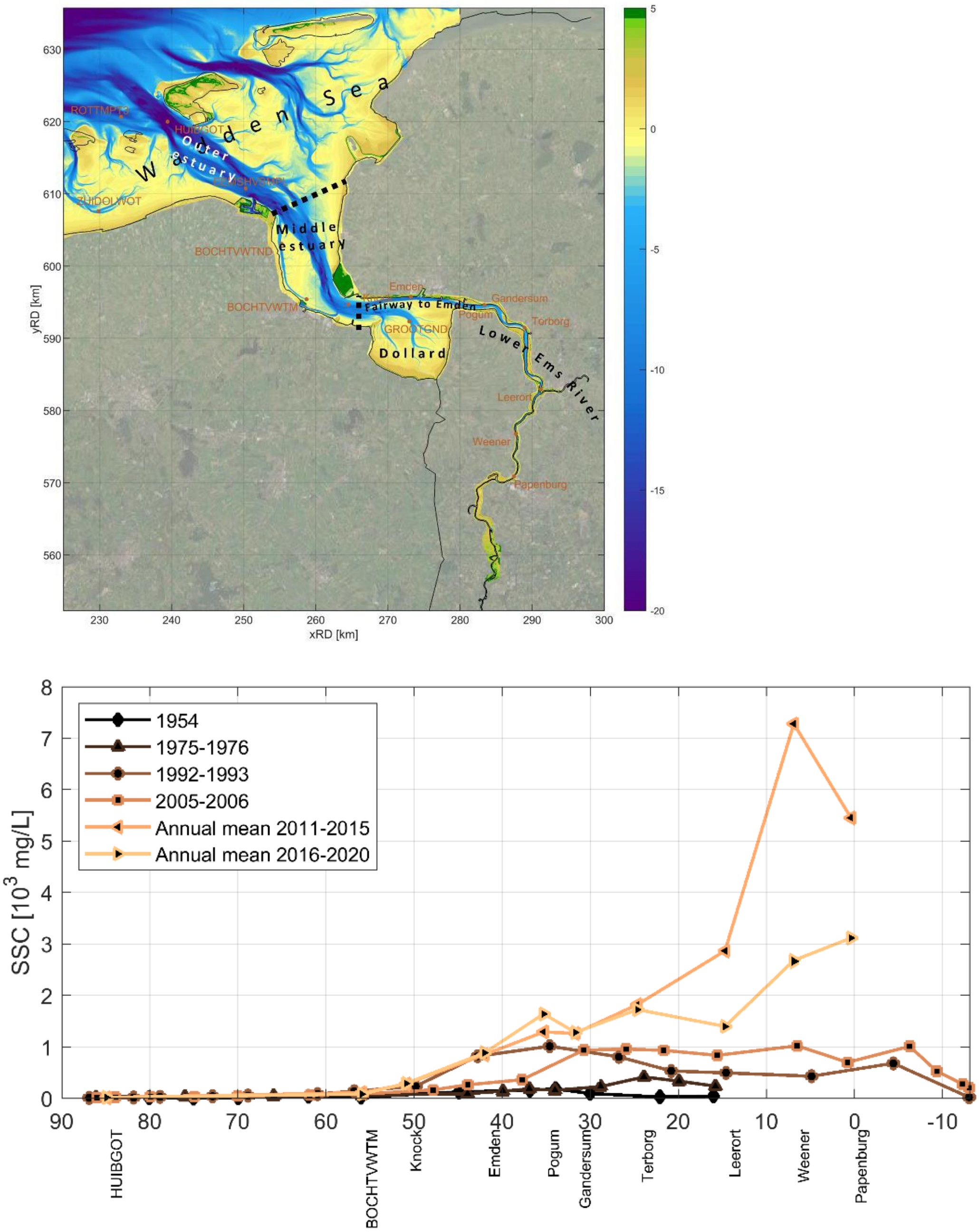

Figure 1. Historical mean SSC (suspended sediment concentration) along the lower Ems River and Ems Estuary (longitudinal distance from Papenburg, see upper map). The average annual mean SSC for periods 2011-2015 and 2016-2020 are from this study. Other historical values are digitized from de Jonge et al. (2014). Reprinted from (Smits and van Maren 2021).

1.3 Potential effect of silt on nursery function

There are several potential mechanisms through which the elevated silt levels and high turbidity may affect the nursery function for fish. Both direct and indirect effects of suspended sediments may act on fish functioning. Fish exposed to elevated levels of suspended sediments may show signs of gill damage following direct contact with sediments in the water (Bruton 1985; Sutherland and Meyer 2007). Gill damage may limit the oxygen uptake capacity of fish and as a consequence affect their growth.

Another mechanism may work through the feeding success, which would be expected to affect visually foraging fish that feed on particles in the water column different from benthic feeders or pelagic filter feeders. In general, pelagic species such as herring and smelt forage by sight and do not rely on filter feeding. If feeding success rate depends on whether the fish are able to (visually) detect food particles (e.g. zooplankton) amidst other floating particles (e.g. silt), then a high concentration of 'disturbing' particles may hamper their food intake rate (Weis and Khan 1991; Shaw and Jenkins 1992; Rowe and Dean 1998; Nurminen et al. 2010; Manning et al. 2013; Chapman et al. 2014; Gayosso-Morales et al. 2019). For larval herring and smelt this relationship has been investigated in several studies (Boehlert and Morgan 1985; Fiksen et al. 1998; Sirois and Dodson 2000; Utne-Palm 2004; Griffin et al. 2012). Utne-Palm (2004) reported higher attack rates by herring in lower turbidity levels (of ca 35 mg/l) as compared to higher levels (80 mg/l). In a mesocosm (outdoor experimental system) study, high silt concentrations (200–400 mg/l of particles <50 μm in size) did not lead to increased mortality of Pacific herring *Clupea pallasi* larvae (Griffin et al. 2012). The turbidity levels in the Ems-Dollard area vary roughly between 500-2000 mg/l at the most turbid sites (Schmidt and Iedema 2019), so are generally higher than the levels used in these studies. How such levels affect older life stages of pelagic fish has not been investigated.

High silt levels may also affect the entire food chain, with less phytoplankton leading to lower food abundance in the higher trophic levels such as zooplankton and benthic invertebrates. Measurements at Heringsplaat in the Dollard have shown a decrease in benthic biomass (Schmidt and Iedema 2019), in the period from the late 1990s, which are thought to be related to the increasing silt levels.
In a recent study in which the diet of herring was studied in the Ems-Dollard area, differences in condition were indeed found for herring in different parts of the Ems-Dollard (Couperus et al. 2022). To find out what mechanism might be causing such patterns and whether the silt levels play a role, additional work is needed.

High turbidity levels can also be beneficial, because fish become less visible to predators. In a model study in the Scheldt estuary, a considerable increase in survival probability of age-0 fish was found in the murkier waters as compared to the open sea (Maes et al. 2005). However, this came at the cost of lower condition. Young herring apparently pay for their migration into safer estuarine water by worse growth opportunities as compared to the open sea.

Lastly high turbidity levels often co-occurs with oxygen deficiency especially in the Ems river (Schmidt and Iedema 2019). A reduction in oxygen concentration affects fish performance negatively because it limits the capacity of circulatory and ventilatory systems to match oxygen demand. Such a constraint affects all higher functions (activity, behaviour, growth, and reproduction). In addition thermal tolerance levels depend on the oxygen concentration (Pörtner et al. 2001), with reduced tolerance for higher temperatures at lower oxygen concentrations.

1.4 The approach

Following the definition by Beck et al. (2001) of a nursery habitat: "an area is a nursery for juveniles of a particular species if its contribution per unit area to the production of individuals that recruit to adult populations is greater, on average, than production from other habitats in which juveniles occur", the ecological processes operating in nursery habitats, as compared with other habitats, must support greater contributions to adult recruitment from any combination of four factors: (1) **density**, (2) **growth**, (3) **survival of juveniles**, and (4) **emigration** to adult habitats. A general null hypothesis is that there is no difference in the nursery value (i.e., production of individuals that recruit to adult populations per unit area of juvenile habitat) of different juvenile habitats for a given species. Evaluating the functioning of a nursery, therefore, always requires comparison to other areas.

In the majority of studies, nursery habitat quality is derived from densities of juveniles relative to another habitat. It is assumed that habitats with higher densities of juveniles are likely to make a greater contribution to the production of adults than habitats with lower densities of juveniles. However, high juvenile densities alone will not suffice, if these individuals never reach adult populations. Density is, as mentioned before, only one of four factors that must be considered to determine whether a habitat serves as a nursery.

To be able to evaluate the nursery function of the Ems estuary we therefore included several analyses at different spatial scales. All of these steps were carried out based on existing monitoring data from different sources. An important parameter to compare was **density** and **trends in densities**. In the survey programs available, densities are measured at the end of the growing season and therefore integrate year class strength and **survival** between the time of settlement in early spring and the end of summer. As **migration** is notoriously difficult to measure in small fish and needs tagging studies, the only other parameters that were available from the monitoring programs were **length** and **condition at the end of the growing season**, both proxies for **growing conditions**. Because marine juveniles have representatives amongst both demersal and pelagic species, we used data from demersal surveys (Demersal Fish Survey (DFS, NL) and Demersal Young Fish Survey (DYFS, DE) aimed at demersal species) as well as stow net surveys (aimed at pelagic species). The availability of data on the different parameters (density, length, condition) differs, which explains why not all analyses could be carried out on all levels.

To investigate the functioning of the (subareas within) the Ems-Dollard area, a set of hypotheses was formulated:

1. Within the Ems-Dollard area (tidal basis numbered 620 in the DFS area coding, fig. 2) densities of marine juveniles differ between subareas (outer Ems, Watum, central Ems, Ems-Dollard, fig. 3) with lower densities in the areas most affected by the higher silt levels.
2. Within the Ems-Dollard trends in marine juveniles densities differ between the subareas, with the trend in the areas most affected by the higher silt levels deviating from the ones in the other subareas
3. Densities and trends of marine juveniles in the Ems differ from those in surrounding tidal basins
4. Densities and trends of marine juvenile pelagic species differ between the Ems-Dollard as compared to German estuaries (Elbe and Weser).
5. The length of marine juveniles (0-group) at the end of the growing season is lower in the subareas most affected by elevated silt levels as compared to other subareas within the Ems-Dollard tidal basin (620)
6. The condition of marine juveniles (0 and 1 group) is lower in the Ems-Dollard area as compared to surrounding tidal basins in the Dutch Wadden Sea.

In order to evaluate the potential effect of elevated silt levels on the nursery function, ideally the situation in the Ems-Dollard should be compared to areas similar in all aspects apart from the silt situation. Unfortunately such a situation does not exist, therefore we tried to find contrasts both in time and space. The long time series (the longest going back to 1970) provide the opportunity to compare periods with varying silt concentrations. The time series, however, do not go back to the period before silt levels started to increase, but the levels were still considerably lower in the 1970s as compared to the latest decennia. In our analyses we will therefore address changes between the early part of the available time series (roughly 1970s) as compared to the last two decennia. In addition to comparing periods with varying silt levels, we also compare the Ems-Dollard area to surrounding areas, supposedly without elevated silt levels. The contrasts we are investigating are presented schematically in figure 4.

The three different scales at which analyses were carried out are presented in figure 3 and 5. For demersal species we compared subareas within the Ems-Dollard (level 1) and between tidal basins (level 2). For pelagic fish we used the comparison at estuary level (level 3). This last comparison cannot be done for demersal species due to the lack of sampling in the DYFS program in the German estuaries.

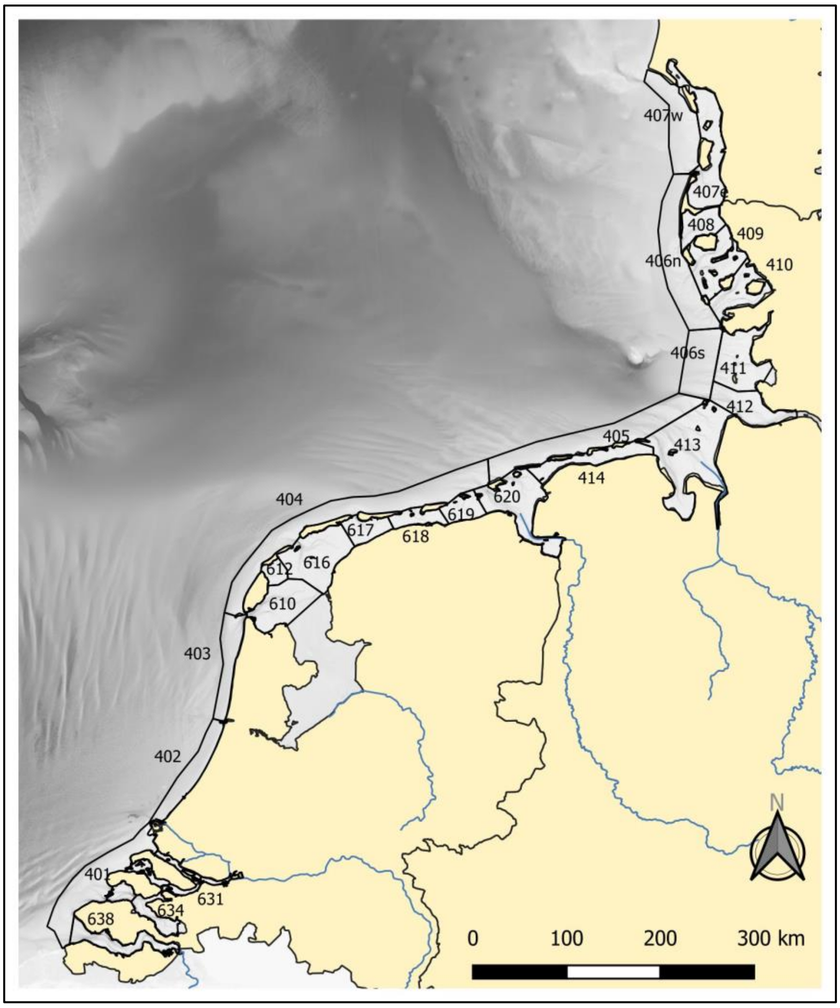

Figure 2. Map of the D(Y)FS tidal basins. 618 = Zoutkamperlaag, 619 = Lauwers/Schild, 620 = Ems-Dollard, 414 = Borkum/Juist.

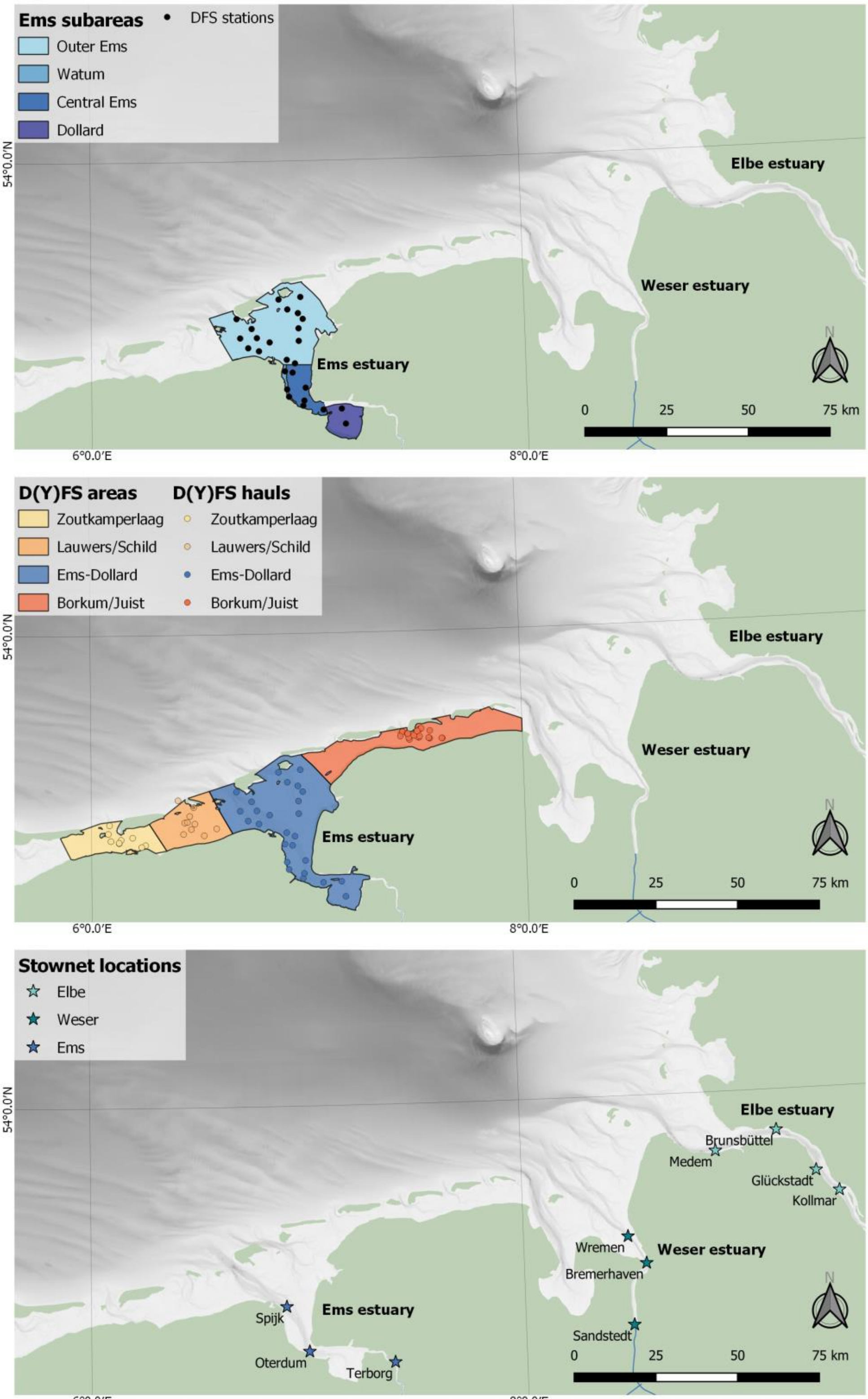

Figure 3. Maps of the study area and different subareas/tidal basins/estuaries that were used in the study. Comparisons are made between level 1) subareas in the Ems-Dollard (outer Ems, central Ems, Watum, Ems-Dollard, upper figure), level 2) between different D(Y)FS areas neighbouring the Ems-Dollard (middle figure) and level 3) between the Ems, Weser and Elbe estuaries (lower figure).

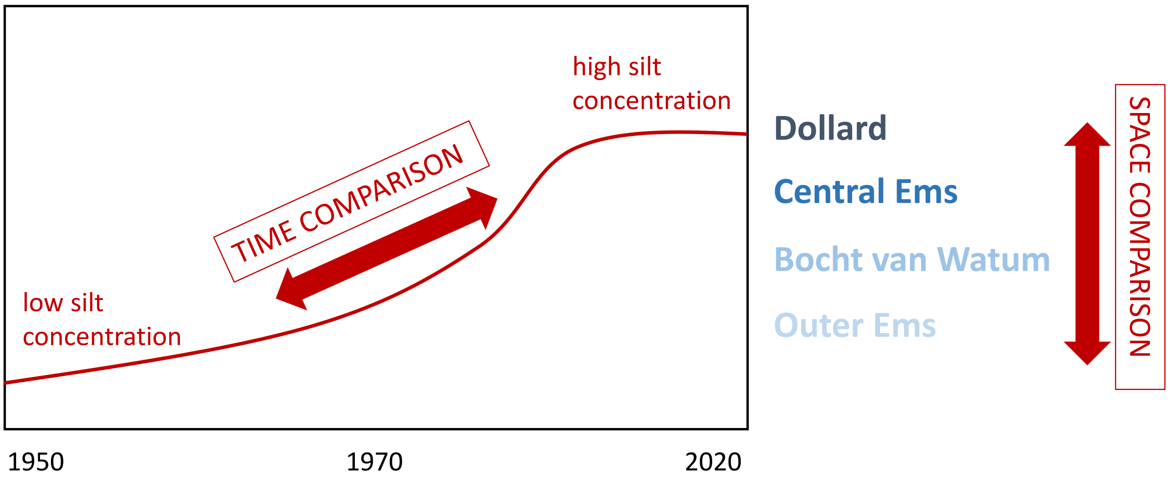

Figure 4. Schematic representation of the comparisons in time and space we carried out to evaluate the functioning of the Ems-Dollard as a nursery function. In time there is a contrast in silt concentrations with increasing levels up to ca 2010 and is space there is a contrast with highest levels in the Ems-Dollard area (and within the Ems-Dollard in the Dollard).

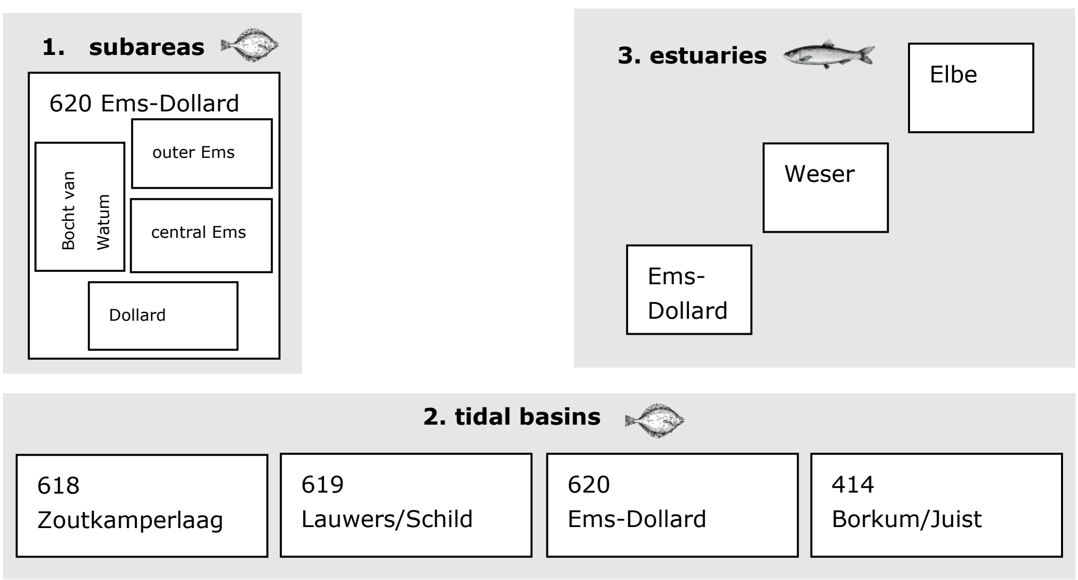

Figure 5. Schedule of comparisons used at three levels. Between subareas within Ems-Dollard, between tidal basins (tidal basins 414, 618, 619, 620) and between the three estuaries. For ***demersal species*** *we compared subareas within the Ems-Dollard and tidal basins. For* ***pelagic species*** *we used the comparison at estuary level.*

2 Methods

2.1 Data

2.1.1 Demersal fish

2.1.1.1 Demersal fish survey (Netherlands)

The Dutch Demersal Fish Survey (DFS) covers coastal waters (up to 25 m depth) from the southern border of the Netherlands to Esbjerg (Denmark), including the Dutch Wadden Sea, the outer part of the Ems-Dollard estuary, the Westerschelde and the Oosterschelde (fig. 3). Sample locations are stratified by depth and area. Approximately 120 hauls are done per year in the Dutch Wadden Sea (including the Ems-Dollard estuary). Sampling is carried out with a 3 m beam trawl rigged with one tickler chain, a bobbin rope, and a fine-meshed cod-end (20 mm stretched). Fishing is restricted to the tidal channels and gullies deeper than 2 m because of the draught of the research vessel. This survey has been carried out in August–October since 1970. Haul duration is 15 min. Fish are sorted and measured to the cm below. In the Wadden Sea, areas are delineated by tidal basin. In this report we use data from tidal basins numbered 618, 619, 620 (Zoutkamperlaag, Lauwers/Schild, Ems-Dollard) (fig. 2, 3). For the condition analyses the whole (Dutch part of the) DFS set was used.

2.1.1.2 Demersal young fish survey (Germany)

The German Demersal Young Fish Survey (DYFS) covers the German North Sea coastal waters and the German Wadden Sea. The number of sampled stations (and areas covered) increased over the years from about 100 stations in early years up to approximately 160 stations at present. A 3 m beam trawl with bobbin rope and a fine-meshed cod-end (20 mm stretched) is deployed. The gear is similar to the DFS gear, except no tickler chain is used. Fishing is restricted to the tidal channels and gullies deeper than 2 m because of the draught of the vessels. This survey has been carried out in August–October since 1977 (in East-Frisia, with different starts in different tidal basins). Haul duration is 15 min. Fish are sorted and measured to the cm below. From this survey we used data from tidal basin numbered 414, the Borkum/Juist/Langeroog tidal basin (fig. 2, 3). Unfortunately in this basin the hauls in the sampling program are all clustered in the gully system south of Langeroog.

2.1.2 Stow net surveys Ems, Elbe and Weser

In all these estuaries commercial stow net vessels are used. These surveys have been carried out since 2007 (Ems and Weser) and 2000 (Elbe). The net, with a fine-mesh tail end (stretched mesh 10-16 mm), passively fishes in the tidal current during subsequent ebb and flood periods. The large vertical net opening catches pelagic fish and some bottom fish (although the latter to a lesser extent than the beam trawl). Despite fishing in one place, hauls give a spatially integrated image, because the water flowing through the net covers a distance of approximately 10 km. The stow net sizes vary by vessel between 90 m² - 130 m² surface opening with a mesh size of 8 - 12 mm in the cod-end. As a rule, the duration of a haul extends over the entire tidal phase (low and high tide phase). The spatially defined catch stations reflect the different estuarine salinity zones from the freshwater section to the polyhaline zone of the outer estuary, where one catch station has been set up in each salinity zone. Only the transitional waters (oligo-, meso- and polyhaline) were included in the analyses. Monitoring takes place twice a year in spring (Apr-May) and autumn (Sep-Oct) and depending on the area each year (Elbe and Ems) or every other year (Weser). Because in this study we are foremost interested in marine juveniles and to harmonise with the other source of information (the demersal fish surveys), we only included the autumn series.

2.1.3 Species

For the analyses we selected only marine juvenile species (following the definition by Elliott & Hemingway (2002)) that spend their first year in the Wadden Sea. The first list contained ten species(groups), but this list was reduced to eight because some species had too few observations to allow for comparisons. The list contains both demersal and pelagic species. In general we used beam trawl surveys for demersal and stow nets for pelagic species. For some species both gears are suitable (cod, whiting, smelt). The two species that were eventually not selected because of too low numbers to allow for meaningful analyses were tub gurnard (*Chelidonichthys lucernus*, rode poon) and sandeels (*Ammodytes* sp, zandspieringen). Flounder and smelt are not considered 'true' marine juvenile species (but rather diadromous species (Elliott and Hemingway 2002)), but since they use the area as a nursery and are important Wadden Sea species, they were included.

Table 1. Species selection for the different surveys

species	scientific name	Dutch name	ages	survey
all marine juveniles			0, 1+	DFS, DYFS
plaice	*Pleuronectes platessa*	schol	0, 1+	DFS, DYFS
sole	*Solea solea*	tong	0, 1+	DFS, DYFS
dab	*Limanda limanda*	schar	0, 1+	DFS, DYFS
flounder	*Platichthys flesus*	bot	0, 1+	DFS, DYFS
cod	*Gadus morhua*	kabeljauw	0, 1+	DFS, DYFS, stow net
whiting	*Merlangius merlangus*	wijting	0, 1+	DFS, DYFS, stow net
smelt	*Osmerus eperlanus*	spiering	0, 1+	DFS, DYFS, stow net
herring	*Clupea harengus*	haring	0, 1+	stow net

The gear used in the DFS survey on board the Stern (photo Ingrid Tulp)

Stow net survey on the Ems (photos by Jörg Scholle)

2.2 Data analysis

2.2.1 Data preparation

Densities from the beam trawl surveys were calculated by dividing the catch by the fished surface area. Before plotting and trend calculations, densities were 4th root transformed to aid visual inspection of the trends. For the subarea trends in the Ems we used five year means, since there are too few data points per subarea per year for meaningful analyses.
Catch per unit effort of the stow net surveys were calculated as: numbers/100 000 m^3 per station. Sampled volumes were based on flow meter measurements.
For the density trend analyses, age classes were separated based on length (table 2), because otolith readings are not available for all species, areas and years. Otoliths are only collected and read for flatfish, and for flounder the readings started later (1989).
For the length at the end of the growing season, the 0-group was defined based on otoliths. This analysis was therefore only done for the flatfish species (plaice, sole, dab, flounder), and only for the Dutch tidal basins (Zoutkamperlaag, Lauwers/Schild & Ems-Dollard).

Table 2. Split lengths to separate 0-group from the older (1+ group fish) (Dankers et al. 1979)

species	split length (cm)
flounder	14
smelt	8
dab	10
plaice	10
sole	10
whiting	17
cod	18
herring	12

2.2.2 Trend calculation: General Additive Models (GAM)

For the standardised trend analyses, we used General Additive Models (GAMs), similar to the method used in the latest Quality Status Report (Tulp et al. 2022). GAMs have the advantage of estimating flexible trends, allowing for trend classification and dealing with missing values, and the use of the data at the observation level so that all individual samples can be used.

Two different response variables were used, depending on species occurrence (expressed as percentage of zero observations, see below). For common species, we modelled **abundance estimates** (catch per unit of effort (CPUE)). For less common species, **the probability of occurrence** was modelled. Abundance estimates were 4th-root transformed and modelled with either a gamma or a Gaussian distribution. Fourth-root transformation is commonly used for this type of data and has the advantage that it improves the interpretation of trend figures and that zero values can be dealt with more easily than when using a log-transformation. Probability of occurrence was modelled with a binomial distribution.

The following cut-off values between the two approaches were applied:

- <30% zero observations => high abundance => abundance modelling
- 30-60% zero observations => intermediate abundance => abundance modelling
- 60-95% zero observations => low abundance => probability of occurrence modelling
- >95% zero observations => rare species => no estimate

Fitted trends were used to compare (sub)areas and to investigate whether (trends in) densities significantly differed between (sub)areas. In the cases of the comparison between subareas in the Ems-Dollard five year means were used, in the comparisons between DFS areas we used the annual values. Models were validated by inspecting the residual patterns. We checked for serial autocorrelation by fitting an AR function. In time series serial autocorrelation often occurs, but since we are dealing here with mainly young of the year fish, this is less likely in our analyses. Because no serious autocorrelation was detected final models were fitted without the AR function. We did not carry out formal tests, but the confidence intervals of the fitted models are used to infer significant differences by visual inspection of the plots (in case of no overlap, values are different). We used a K (number of knots) as 6, the number of knots in which the bias-variance trade-off for the smoother was optimised, where as much variability in the data as possible is explained.

Because of low sample sizes in some subareas within the Ems-Dollard we used five year means to compare the subareas. In those analyses instead of GAMs, Generalised Linear Models (GLMs) were used with five year periods and subareas as factors (see Appendix 2).

2.2.3 Length at end of growing season

In this analyses we investigate the trends in the length at the end of the growing season. Because length at specific ages can change over the years, only fish for which age determination was carried out were used here. For each haul the mean length for 0-group fish at the time of sampling was calculated. Comparisons were made among subareas in the Ems-Dollard area and among surrounding tidal basins (620 to 618, 619). The duration of the growing period is determined by the timing of spawning, which is significantly affected by an increase in winter temperature (SST). We know that over the observation period the spawning window has changed mainly because of an advance of the start (Teal et al. 2008).
The surveys are carried out in September, at the end of the growing season. Because the actual sampling date may vary between years (and especially has shown a cline in the early period of the series), day of the year was included as a covariate in the model explaining length at the end of the growing season. Year and day of year were included as smoothers, and area (either subarea in Ems-Dollard or tidal basin) as a factor.

2.2.4 Condition

For data on fish condition we used length and weight for those fish that were collected during the DFS survey. In every tidal basin usually five individuals of each length class of each flatfish species are collected for otoliths (if available). These individuals are also measured (to the mm) and weighed (to the gram). The subareas within tidal basin 620 hold too few samples to allow an analysis on subarea level. Therefore only a comparison of the entire 620 area to surrounding tidal basins was possible. Unfortunately, only data from the Dutch DFS were available. Apart from the period 2019-2021, some data were available from 1997/1998. As a measure for condition, Fulton's K was calculated as body mass/length^3. We firstly investigated if there were sex differences in condition, and if condition factors were not significantly different the data were pooled for both sexes. Thereafter, a linear model was fitted with tidal basin and year as explanatory variables. To investigate which tidal basins or years differed pairwise, a post-hoc Tukey test was carried out.

The metabolism of ectotherm animals such as fish is influenced by the temperature. Every species and age has an optimal temperature for growth, and usually growth rate increases with temperature until the optimal temperature, which is followed by an abrupt decrease in growth rate. As fish condition is likewise expected to be determined by temperature during the growing season, we also analysed the condition per age group in relation to the temperature sum between the moment of settlement and the day the fish was caught. Growth windows are species-specific and we used 11 March, 17 June and 1 May for the start of the growing season for plaice, sole and flounder respectively (van der Veer et al. 2022). For temperature series we used the daily sea water temperature measurements carried out at the NIOZ jetty (provide by Sonja van Leeuwen, NIOZ). Because the data in the three tidal basins are quite limited for this analysis, we used the entire DFS set covering all DFS-areas (fig. 2). The effect of cumulative temperature on condition was analysed in linear regressions with tidal basin, cumulative temperature and age as predictor variables. To test whether the slope of the relationship with temperature differed between age groups, also the interaction term (temperature x age) was included.

All figures and analyses were produced/carried out in R, maps were prepared in QGIS.
An overview of all analyses carried out and the data series used is presented in table 3.

Table 3. Subsets used for the different analyses.

response variable	data source	areas compared	species/ages	years
densities (trends)	DFS and DYFS	subareas in Ems-Dollard: **outer Ems, Watum, central Ems, Ems-Dollard** (all within 620)	• 0-group and 1+ group plaice, dab, sole, flounder, cod, smelt • all 0-group marine juveniles combined • all 1+ group marine juveniles combined	1970-2021 (Dollard >1985)
	DFS and DYFS	Ems-Dollard with surrounding tidal basins (**Zoutkamperlaag/Lauwers/Schild/Borkum/Juist/Langeroog**)	• 0-group and 1+ group plaice, dab, sole, flounder, cod, smelt • all 0-group marine juveniles combined • all 1+ group marine juveniles combined	1970-2021
	stow net	**Ems** (Spijk, Oterdum, Terborg) with **Elbe** (Medem, Brunsbüttel, Glückstadt, Kollmar) and **Weser** (Wremen, Bremerhaven, Sandstedt)	0-group herring, whiting, cod, smelt	2007-2021
length at end of growing season	DFS and DYFS	subareas in Ems-Dollard: **outer Ems, Watum, central Ems, Ems-Dollard** (all within 620)	0-group plaice, sole, dab, flounder	1970-2021 (shorter series for flounder and dab)
		Ems with surrounding tidal basins (**Ems-Dollard, Zoutkamperlaag, Lauwers/Schild**)	0-group plaice, sole, dab, flounder	1970-2021 (shorter series for flounder and dab)
condition	DFS	Ems with surrounding Dutch tidal basins (620, 618, 619)	0 and 1 group plaice, sole, dab and flounder	1997/1998, 2019-2021
condition~temperature	DFS	all DFS areas (fig. 1)	0, 1 and 2 group plaice, sole and flounder	1994-2021

3 Results

3.1.1 Trends in densities

3.1.1.1 Comparison of subareas within Ems-Dollard (beam trawl data)

Sample sizes per year within the Ems-Dollard are limited (table 4). In recent years sample sizes in the different subareas Outer Ems, Central Ems, Bocht van Watum (fig. 6) and Ems-Dollard were 16, 6, 3 and 2 respectively.

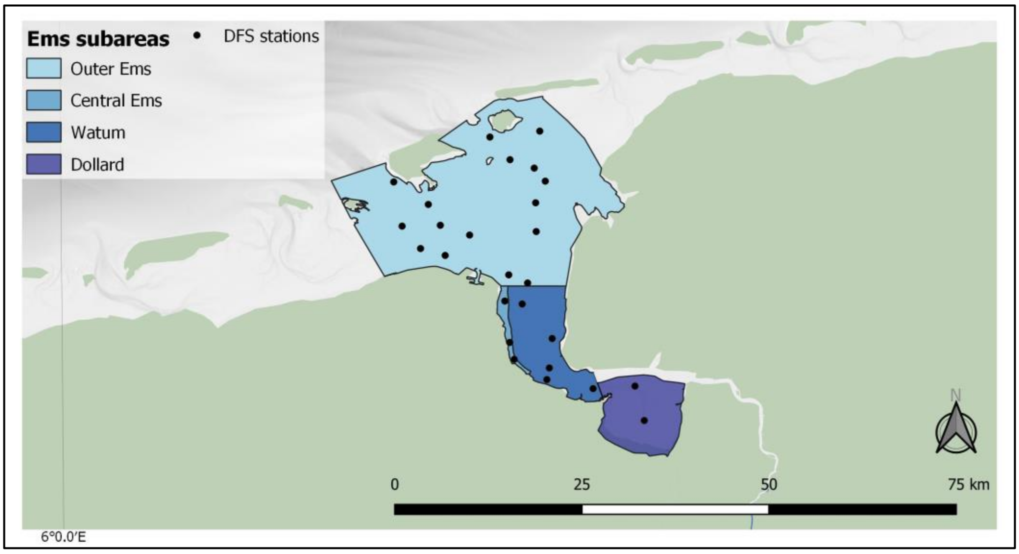

Figure 6. Subareas withing the Ems-Dollard tidal basin that are compared in this paragraph. Dots indicate trawl locations.

Variation in time

In all subareas the total density of 0-group marine juveniles shows a similar trend (fig. 7). Densities differ from year to year with no clear area effect. The increase in the last period in the central Ems area is caused by a very high value in 2021. The hump in the 1970-1980s is visible in all subareas and is primarily caused by the pattern in 1+ group fish. Species-specific trends in densities (fig. 8) follow the same pattern for most species and ages. For the Dollard and Bocht van Watum the pattern is more erratic compared to the other areas, likely due to the low sample size. Of all species flounder is the only one showing stable densities throughout the whole time series. When comparing the early part of the time series to the last decennia it is obvious that overall densities are lower in the last decennia in 0group sole, dab, whiting, cod and smelt and in 1+-group plaice and dab in all subareas.

Variation in space

In 1+ group fish densities are significantly lower in the last decennia in the outer Ems as compared to the other subareas (the confidence intervals do not overlap with the other subareas, fig. 7).
For dab and whiting both age groups occur in highest densities in the outer Ems (fig. 8 and 9), which is in line with the expectation given their more seaward oriented distribution. The opposite pattern holds for both age groups of smelt, sole and flounder; densities decrease from the Dollard towards the outer Ems along the salinity gradient and opposite to the silt gradient. Flounder and smelt are both diadromous species and are attracted towards the fresh water influence of the estuary. For sole this pattern is likely related to their preference for silty conditions. The Dollard has relatively low densities for plaice, whiting and cod and dab is even absent. This is probably related to their preference for sandy substrate. Juvenile dab is nowadays much more a species of the coastal zone than of the Wadden Sea (recently larger individuals have been coming in in winter, though). For plaice the only striking difference between subareas in the recent period is the relatively high value for 0-group plaice

in the central Ems, which was caused by the good 2021 year class. That year class occurred in more areas in the Wadden Sea, but was especially high in this subarea (see also fig. 12).

Table 4. Sample size (number of hauls) for DFS data per subarea in the Ems-Dollard

year	Central Ems	Ems Dollard	Outer Ems	Watum Ems	year	Central Ems	Ems Dollard	Outer Ems	Watum Ems
1970	4	0	12	1	**1996**	7	2	15	1
1971	6	0	14	1	**1997**	6	2	15	1
1972	6	0	13	1	**1998**	8	2	15	1
1973	6	0	16	0	**1999**	8	2	11	1
1974	7	0	14	0	**2000**	7	2	14	2
1975	7	0	14	0	**2001**	7	2	14	3
1976	7	0	14	0	**2002**	7	2	14	3
1977	7	0	14	0	**2003**	7	2	14	3
1978	7	0	14	0	**2004**	6	1	15	3
1979	6	0	12	1	**2005**	6	2	15	3
1980	6	0	14	0	**2006**	9	3	14	3
1981	6	0	14	1	**2007**	6	2	14	3
1982	6	0	14	1	**2008**	5	1	18	3
1983	6	0	14	1	**2009**	4	2	18	3
1984	6	0	14	1	**2010**	5	2	16	3
1985	6	0	13	1	**2011**	6	2	16	2
1986	6	0	14	1	**2012**	4	2	17	4
1987	6	2	14	1	**2013**	6	2	16	4
1988	6	1	14	1	**2014**	6	2	16	3
1989	6	2	14	1	**2015**	5	1	17	2
1990	2	2	15	0	**2016**	5	1	16	3
1991	2	2	18	0	**2017**	5	2	17	3
1992	7	2	18	0	**2018**	4	2	17	3
1993	7	2	16	2	**2019**	6	2	16	3
1994	7	2	15	1	**2020**	5	2	15	3
1995	5	2	14	0	**2021**	5	2	16	3

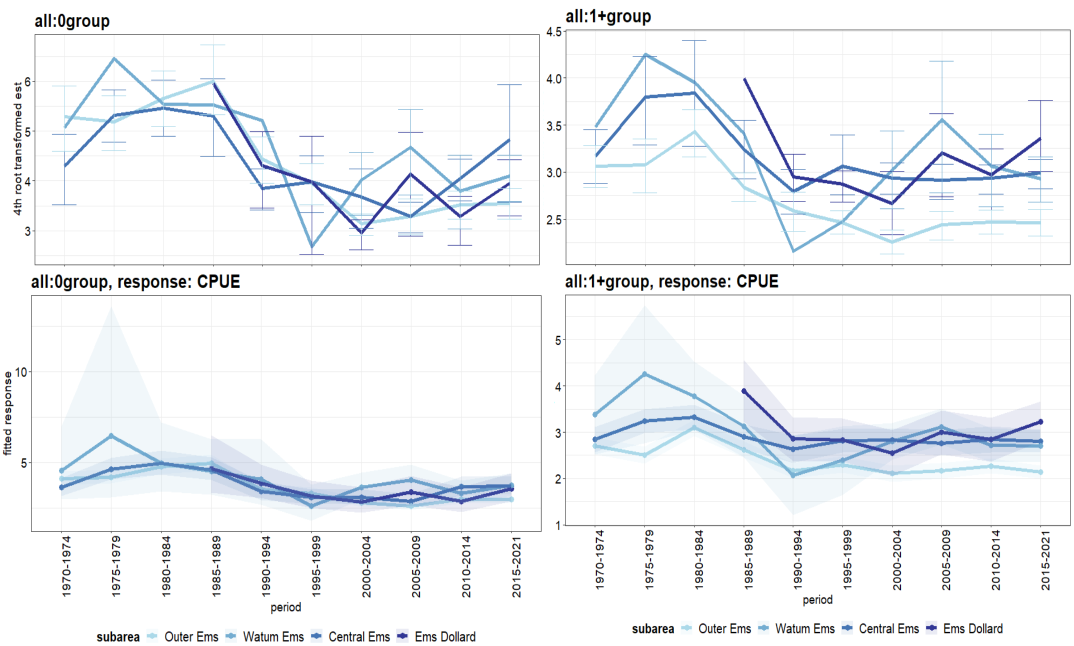

*Figure 7. Trends in **average densities** of all 0-group (upper left) and 1+ group (upper right) marine juveniles per five year period (upper) and result of **modelled trend** (lower) to compare subareas in the Ems-Dollard tidal basin (see fig. 4). The 95% confidence intervals of the rough densities are estimated using bootstrapping. The confidence intervals were not computed when sample size was smaller than five. The confidence intervals of the modelled trends are based on the GAMs.*

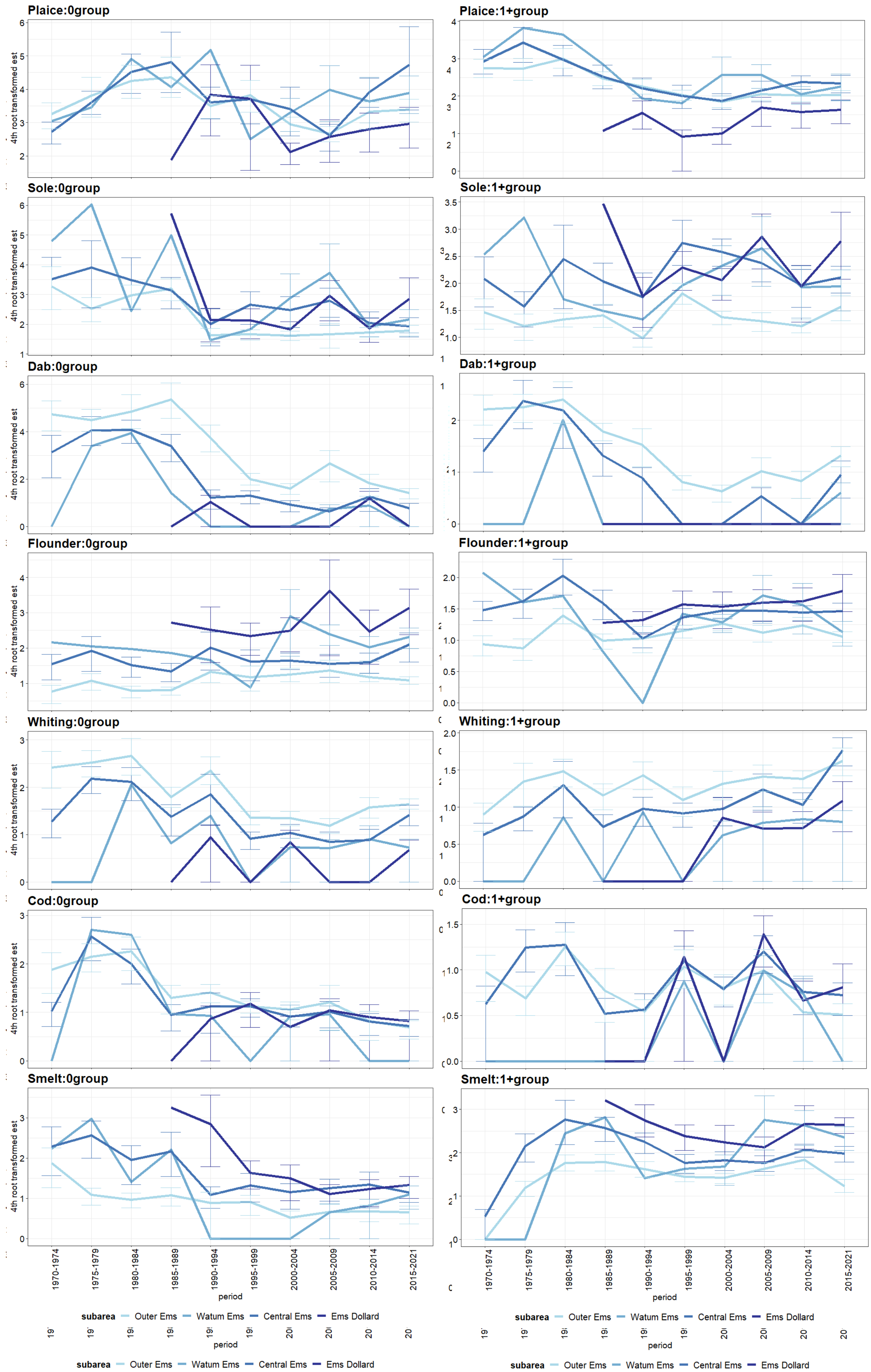

*Figure 8. Trends in **average densities** of 0-group (left) and 1+ group (right) marine juvenile species per five year period. The 95% confidence intervals are estimated using bootstrapping.*

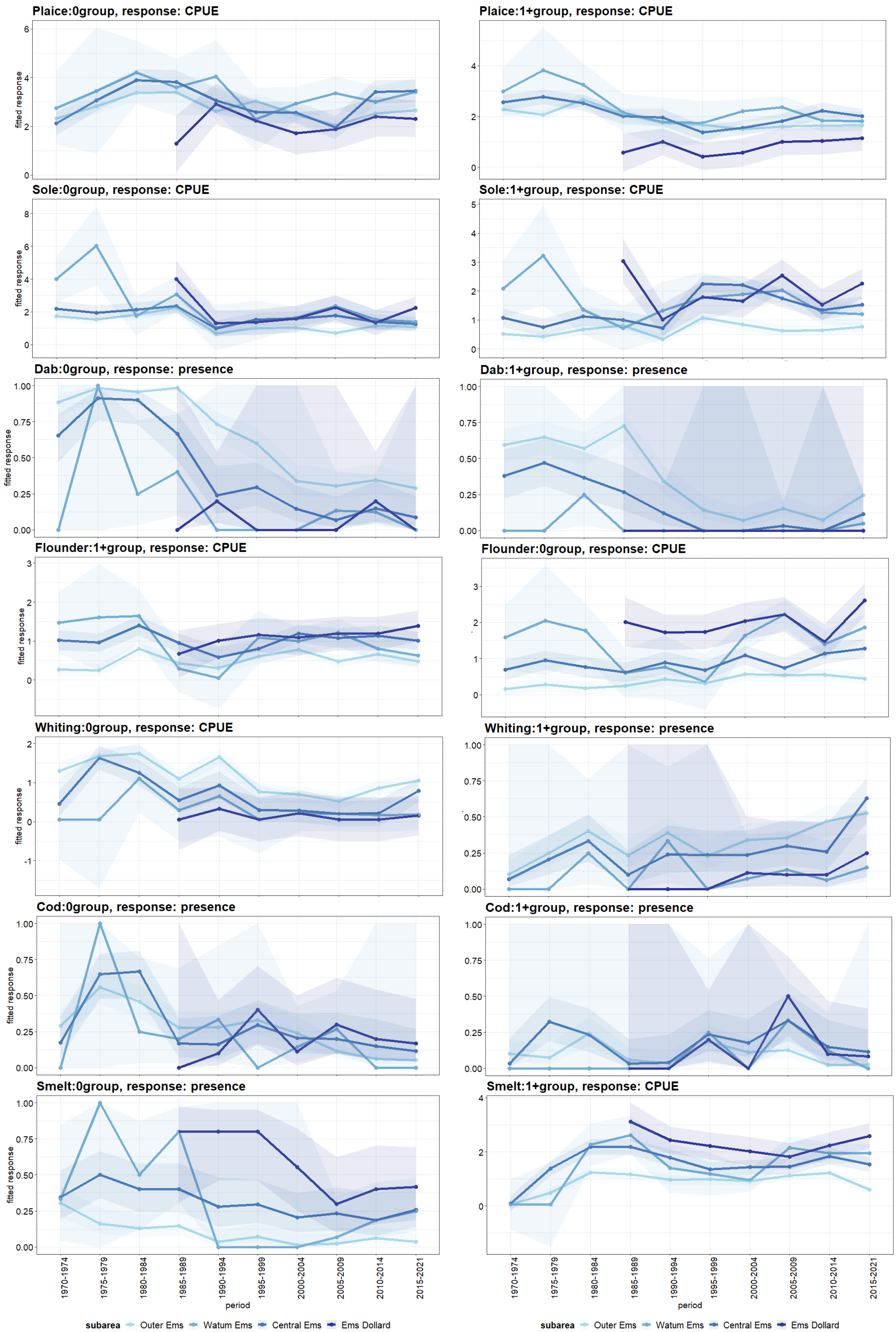

Figure 9. Result of ***modelled trends*** *for 0-group (left) and 1+group (right) marine juveniles to compare subareas in the Ems-Dollard tidal basin. The confidence intervals of the modelled trends are based on the GAMs.*

3.1.1.2 Comparison of Ems-Dollard with neighbouring tidal basins

Variation in time

The comparison of the Ems-Dollard to the neighbouring tidal basins (Zoutkamperlaag, Lauwers/Schild, Borkum/Juist/Langeroog, fig. 10) shows a clear trend over time (fig. 11).

The period in which largest changes occurred in marine juveniles is in the 1970s-1990s. That period was characterised by a dome shaped pattern with a peak in the 1980s with a strong decline thereafter (fig. 11, 12), a pattern that occurred throughout the entire Wadden Sea (Tulp et al. 2022). The decline hit all areas and age groups, but age groups declined consecutively starting with the older fish first (van der Veer et al. 2022). The same pattern is observed in plaice, sole, dab, cod and whiting 0-group. For 1+ group fish the same dome shaped pattern is observed in plaice and dab but not for the other species. After a decrease in that period, 0-group plaice shows some recovery in all areas, but most prominent in the two easternmost areas, Ems-Dollard and Borkum/Juist/Langeroog. Sole clearly shows a different pattern in 0 and 1+ group: 0-group shows a slow decrease, while sole 1+ group is increasing from ca 1990s onwards and especially in the Ems-Dollard, with current densities intermediate from other basins. Cod remains at a very low level, corresponding with the overall low stock size, while whiting is recently increasing without clear differences between tidal basins. Flounder (both age groups) is rather constant or even increasing in the longterm. All age classes of dab are quite rare nowadays and years with zero observations are not uncommon throughout all basins. Since the strong decline in dab after the 1980s, dab has increased in coastal areas and is now considered to be a species of the coastal zone, more than a Wadden Sea species (van der Veer et al. 2022). Smelt 0+ shows an overall slow decline in the Ems-Dollard area but a constant pattern for 1+-group. The strong increase at the start of the series is probably caused by the fact that the two Dollard hauls (with relatively high smelt densities) were only added later (table 4).

Variation in space

For all marine juveniles combined there are few significant differences in densities between the four basins as most confidence intervals overlap (fig. 11). For 0-group fish the first decade shows a higher level in Zoutkamperlaag as compared to the other areas, while from 2000 onwards the level is higher in the Ems-Dollard. For the 1+group Zoutkamperlaag shows most variation, with significantly higher densities until 1990, but significantly lower after 2000. Overall, the Ems-Dollard seems to have an intermediate position among the basins. On a species level, plaice, sole and flounder are the dominant species in all basins (fig. 12 & 13).

The young of the year of plaice show a similar pattern in all basins, but with higher densities in the Ems-Dollard in the second half of the series. The pattern in 1+ group plaice shows less basin-specific differences. For 0-group sole no striking area specific differences occur, while 1+ group sole densities are clearly higher in the Ems-Dollard area. On average the German area has lower densities of sole, which is likely caused by the slightly different gear (no tickler chain in DYFS as compared to the DFS). The pattern in dab is highly uniform between tidal basins with a strong decline from the 1990s onwards. Flounder 0-group has significantly higher densities in Lauwers/Schild basin, while 1+ flounder density is generally highest in the Ems-Dollard basin. 0-group smelt shows no clear differences, but has a more constant occurrence in the Ems-Dollard basin. Strikingly, densities of 1+ smelt are significantly higher in the Borkum/Juist/Langeroog, in the Dutch areas the Ems-Dollard basin holds the highest densities.

Table 5. Sample size for DFS (area 618 Zoutkamperlaag, 619 Lauwers/Schild and 620 Ems-Dollard) and DYFS data (area 414 Borkum/Juist/Langeroog).

year	Borkum/Juist	Zoutkamperlaag	Lauwers/Schild	Ems-Dollard	year	Borkum/Juist	Zoutkamperlaag	Lauwers/Schild	Ems-Dollard
1970	0	10	12	17	**1996**	0	10	9	25
1971	0	8	10	21	**1997**	0	11	9	24
1972	0	10	9	20	**1998**	0	10	10	26
1973	0	9	8	22	**1999**	0	12	10	22
1974	0	10	11	21	**2000**	0	11	10	25
1975	0	9	10	21	**2001**	0	11	10	26
1976	0	10	10	21	**2002**	0	11	9	26
1977	0	10	11	21	**2003**	0	9	9	26
1978	0	10	10	21	**2004**	0	10	8	25
1979	0	9	9	19	**2005**	0	11	9	26
1980	0	10	10	20	**2006**	0	8	8	29
1981	0	10	10	21	**2007**	0	11	8	25
1982	0	10	10	21	**2008**	22	9	9	27
1983	0	10	9	21	**2009**	16	10	8	27
1984	0	10	10	21	**2010**	21	9	6	26
1985	0	10	8	20	**2011**	17	9	7	26
1986	0	10	9	21	**2012**	16	8	10	27
1987	0	10	8	23	**2013**	21	9	10	28
1988	0	9	8	22	**2014**	21	9	11	27
1989	0	10	8	23	**2015**	19	9	11	25
1990	0	10	8	19	**2016**	21	10	10	25
1991	0	10	10	22	**2017**	18	6	10	27
1992	0	6	0	27	**2018**	18	8	9	26
1993	0	11	8	27	**2019**	26	8	7	27
1994	0	10	7	25	**2020**	27	9	10	25
1995	0	10	9	21	**2021**	23	9	10	26

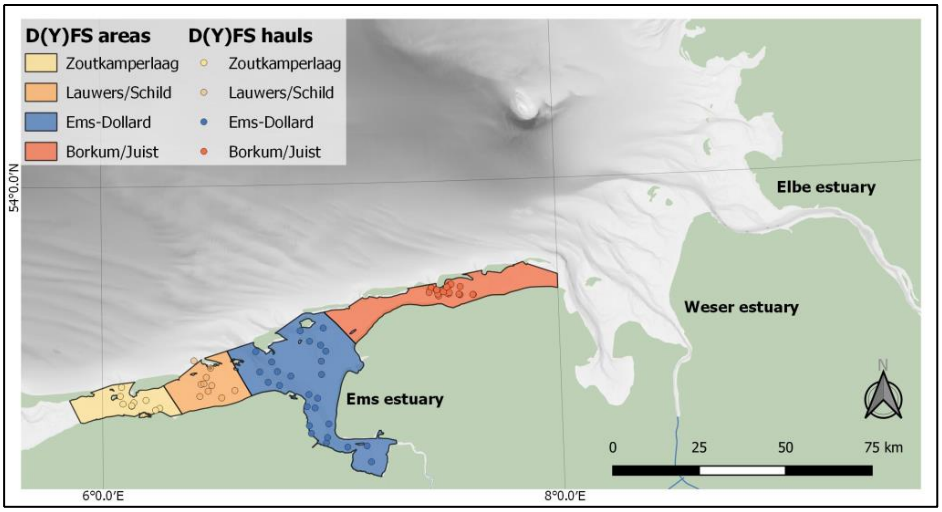

Figure 10. Tidal basins that are compared in this paragraph. Dots indicate trawl locations.

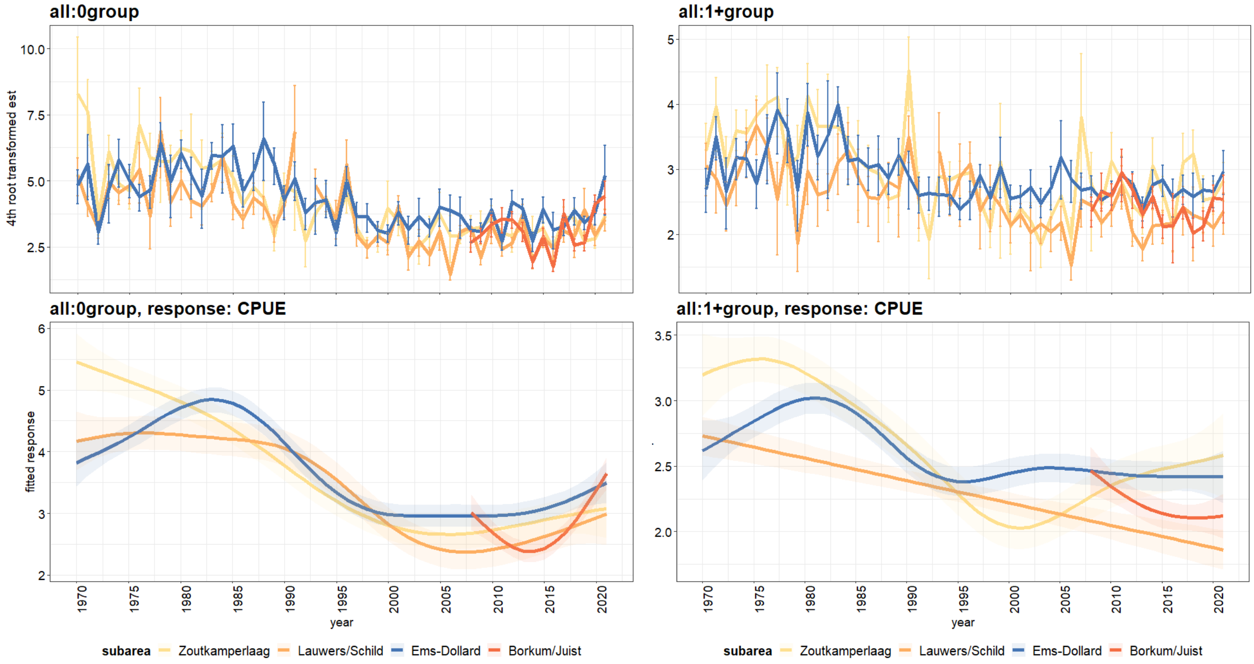

Figure 11. Trends in ***average densities*** *of all 0-group (upper left) and 1+ group (upper right) marine juveniles per five year period (upper) and result of* ***modelled trend*** *to compare (lower) in the Ems-Dollard tidal basin in comparison to neighbouring tidal basins (see fig. 10). The 95% confidence intervals of the rough densities are estimated using bootstrapping. The confidence intervals were not computed when sample size was smaller than five. The confidence intervals of the modelled trends are based on the GAMs.*

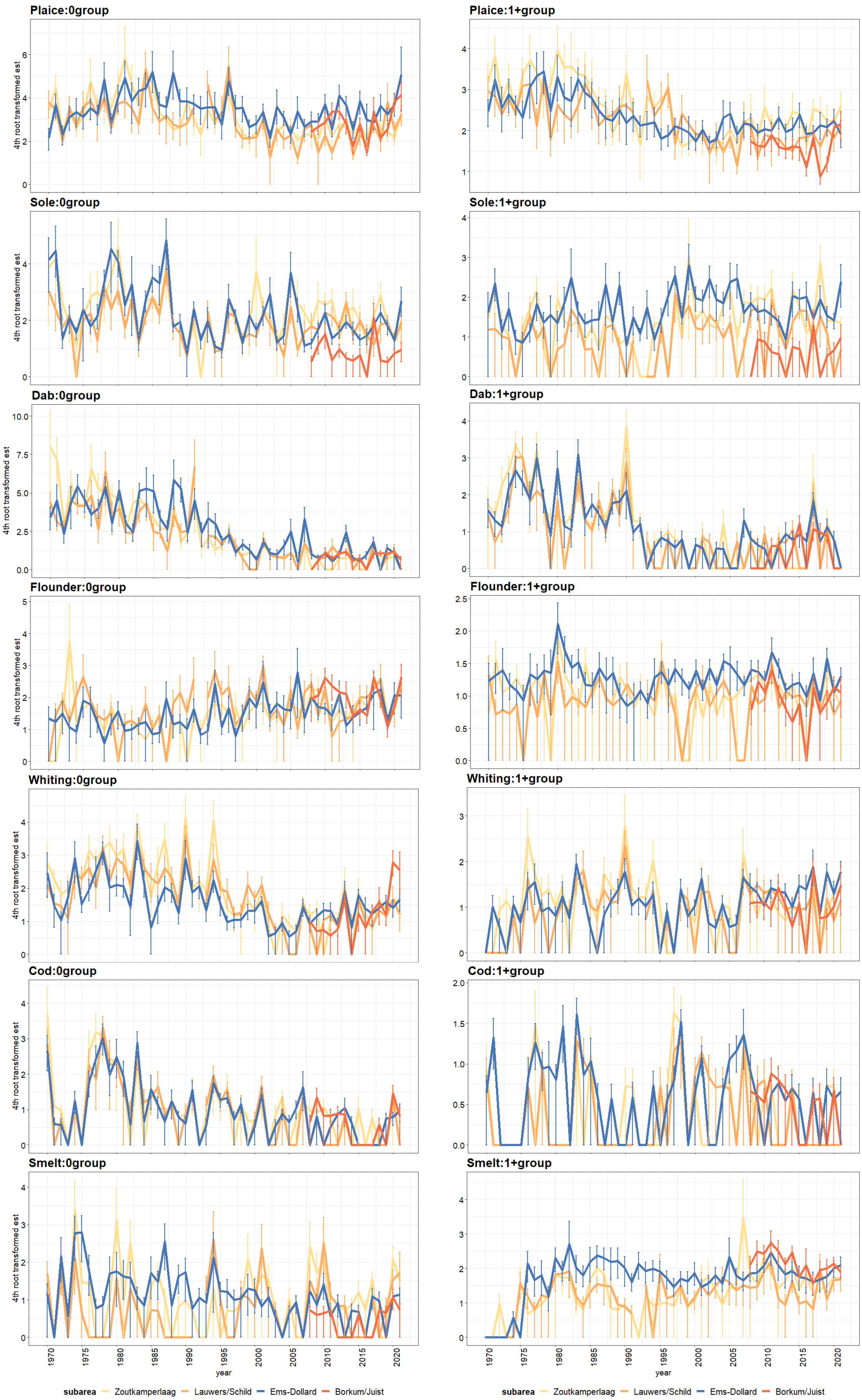

*Figure 12. Trends in **average densities** of 0-group (left) and 1+ group (right) marine juvenile species per five year period. The 95% confidence intervals are estimated using bootstrapping.*

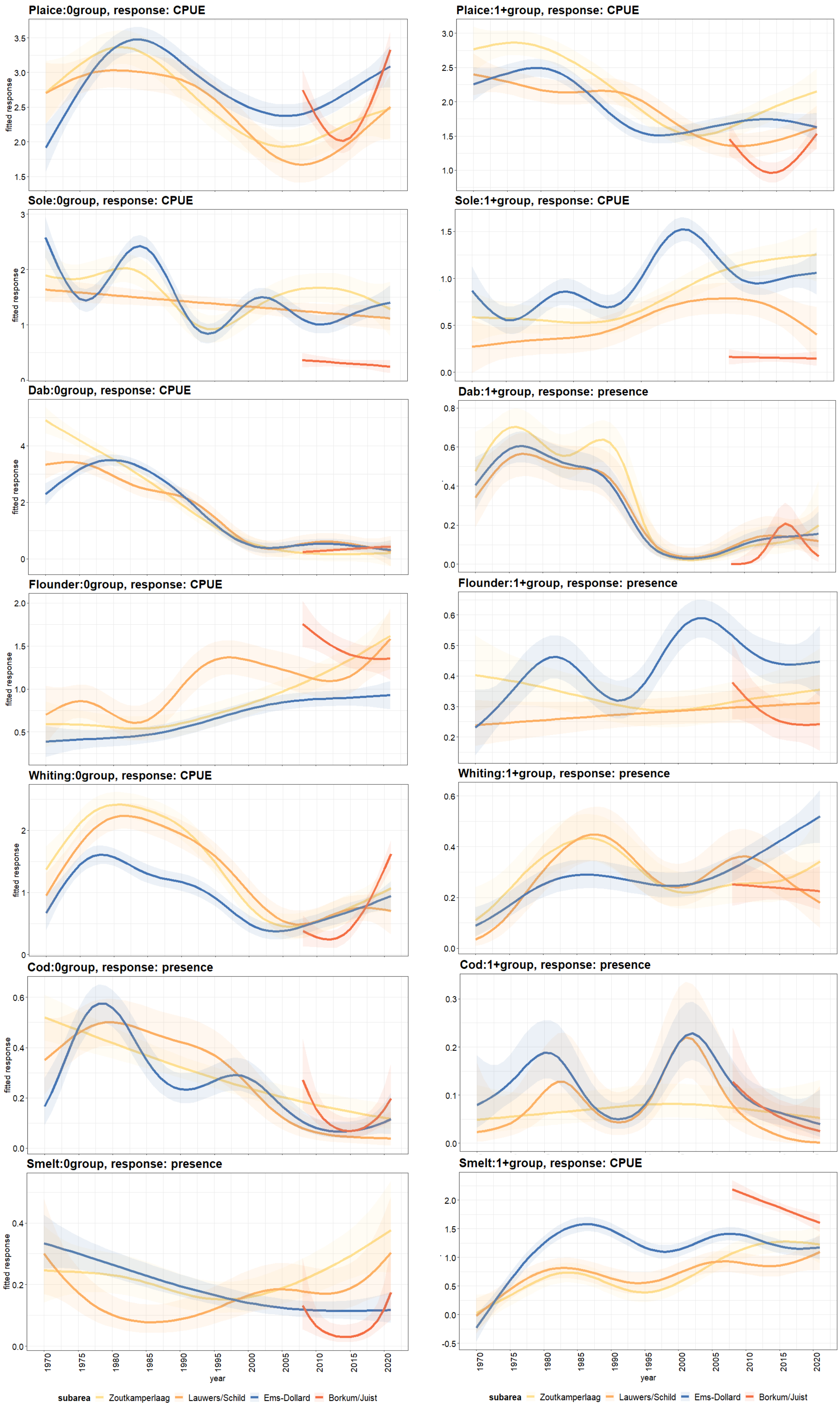

Figure 13. Result of ***modelled trends*** *to compare the Ems-Dollard tidal basin to neighbouring tidal basins. The confidence intervals of the modelled trends are based on the GAMs.*

3.1.1.3 Comparison of Ems-Dollard with estuaries in Germany (stow net)

When comparing the three estuaries based on stow net sampling, it is important to realise that there are considerable differences between them. For instance, the three estuaries differ considerably in depth. Stations in the Ems area are usually shallower than 10 m. The stations in the Weser are deeper than 10 or even 15 m. The depth in Elbe is around 7.5 to 12.5 m. While current surface silt levels are considerably higher in the fresh water sections of the river Ems (>6000 mg/l) as compared to the river Elbe (50 mg/l), silt levels in the Ems-Dollard: e.g. 100-200 mg/l in the Bocht van Watum (Smits and van Maren 2021) are more similar to those in the tidal Elbe section, ca 100 mg/l (Schöl et al. 2007; BioConsult 2020). River runoff conditions are also different (Stanev et al. 2019). Salinity values at the consecutive stations (excluding Kollmar the Elbe) in all three estuaries can be categorised as oligo- (0.5-5 ppt), meso- (5-18 ppt) and polyhaline (18-30 ppt) going from the river towards the estuary (Stanev et al. 2019). Another issue in the comparison are differences in the length of the time series and the interval between sampling years. The Weser stations are only sampled every other year, in the Elbe series there are missing years (table 6). The data from 2011 were collected with a different gear and by a different operator than in other years and may therefore deviate slightly. Comparing trends across the three estuaries therefore requires caution.

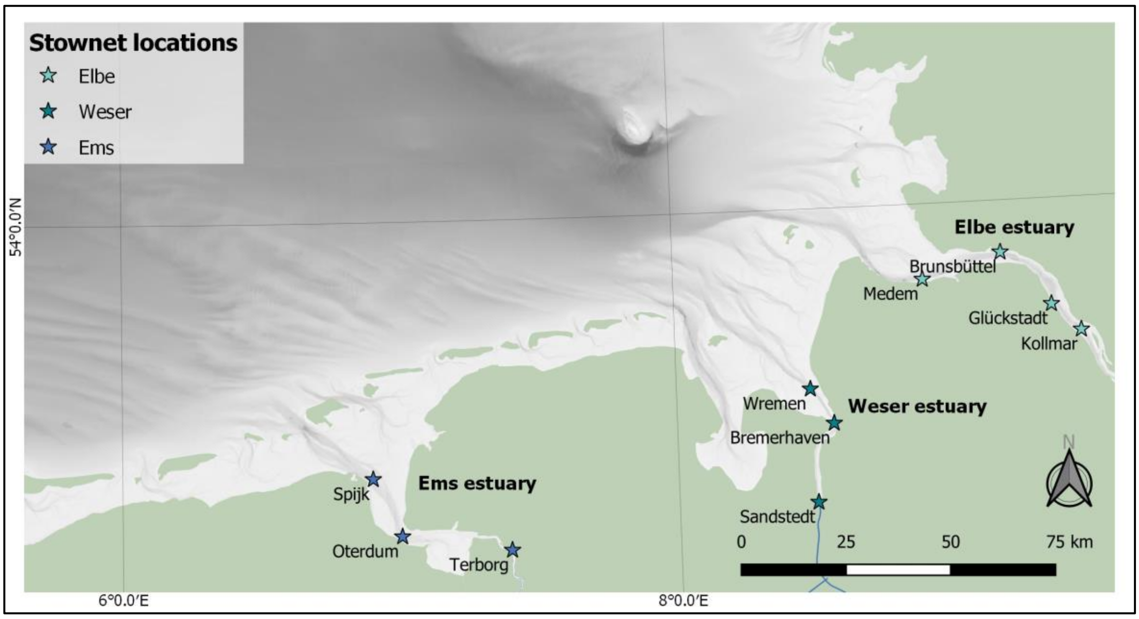

Figure 14. Locations of stow net stations in the three basins that are compared in this paragraph.

Variation in time

As the earliest observations only start in 2000, this series is not long enough to compare periods with varying silt levels. For 0-groups the temporal patterns are clearer than for older fish (fig. 17). The decline in cod is obvious in all series, and the increase in whiting (0-group) is also picked up by all three series (fig. 18). The trend in 0+ herring is increasing in the Ems-Dollard, which also seems to take place in the German estuaries. Smelt is quite constant in the Ems-Dollard, but decreasing in the Elbe, a pattern that also can be seen in the older fish (fig. 18) and previously has been reported (BioConsult 2020). Within the Ems-Dollard time trends for the three stations are similar, apart from the trend in 0-group smelt that shows an opposite pattern in the last five years with an upgoing trend in Spijk and Oterdum, but a declining trend in Terborg (fig. 20). Relative to other years 2011 is characterised by low values for different species, which might be related to the different sampling setup that year.

Table 6. Sample size for stow net data in the three estuaries.

year	Ems	Weser	Elbe	year	Ems	Weser	Elbe
2000	0	0	6	2011	6	6	0
2001	0	0	8	2012	6	0	8
2002	0	0	6	2013	6	6	8
2003	0	0	8	2014	6	0	8
2004	0	0	8	2015	6	6	0
2005	0	0	8	2016	6	0	8
2006	0	0	8	2017	6	6	8
2007	6	6	6	2018	6	0	6
2008	6	0	8	2019	6	6	0
2009	6	6	6	2020	6	0	0
2010	6	0	8	2021	6	6	6

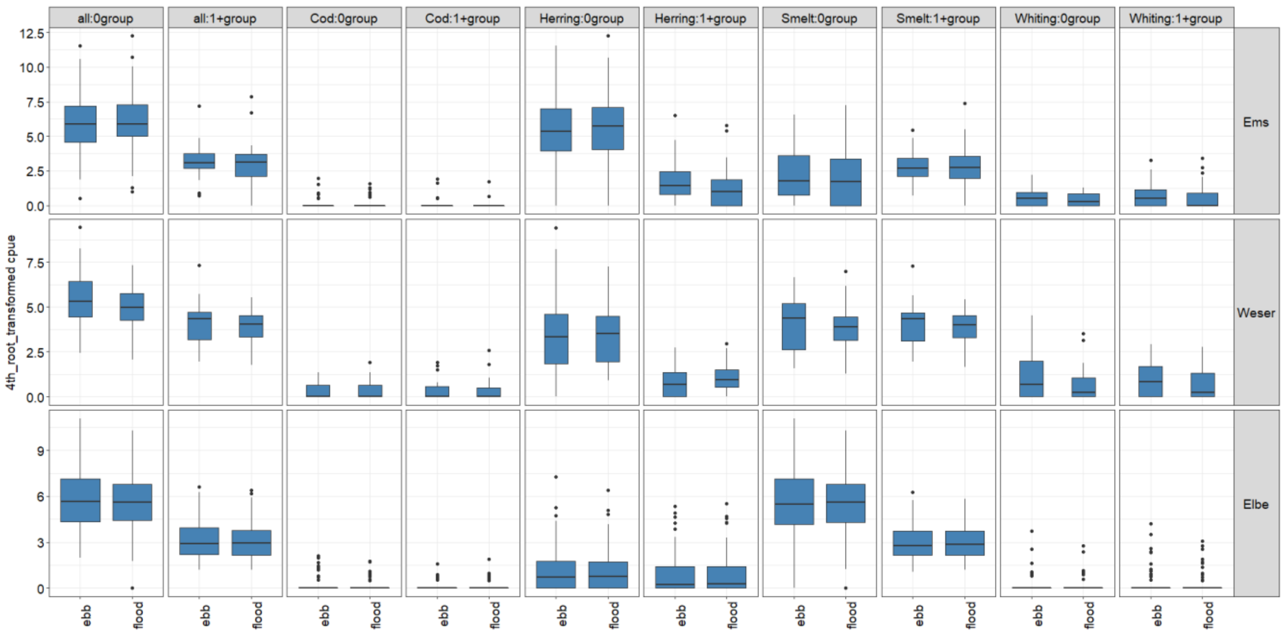

Figure 15. Densities (Catch per unit of effort (CPUE), 4th root transformed) at ebb and flood tides per species, age and estuary.

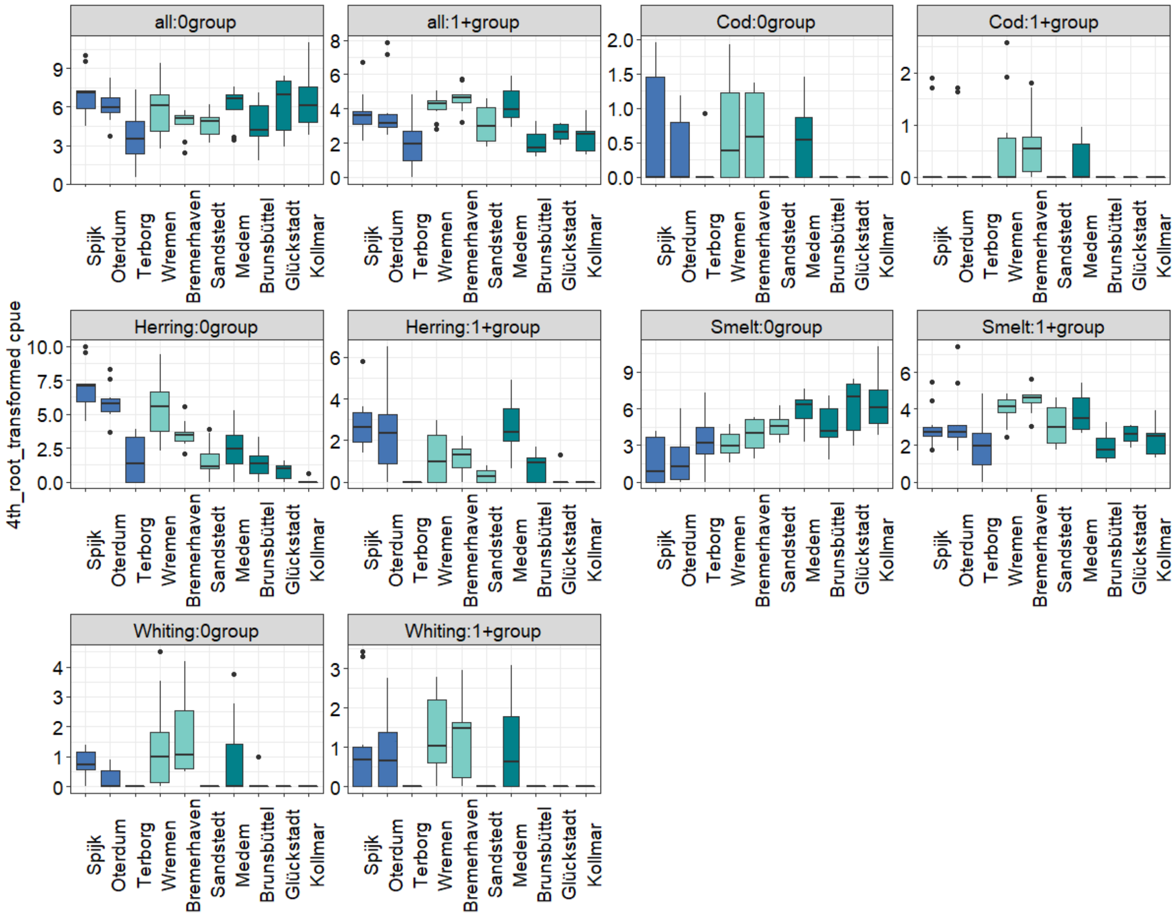

Figure 16. Densities (Catch per unit of effort (CPUE), 4th root transformed) per species, age and catch location within estuary for the five years in which all estuaries were sampled: 2007, 2009, 2013, 2017, 2021.

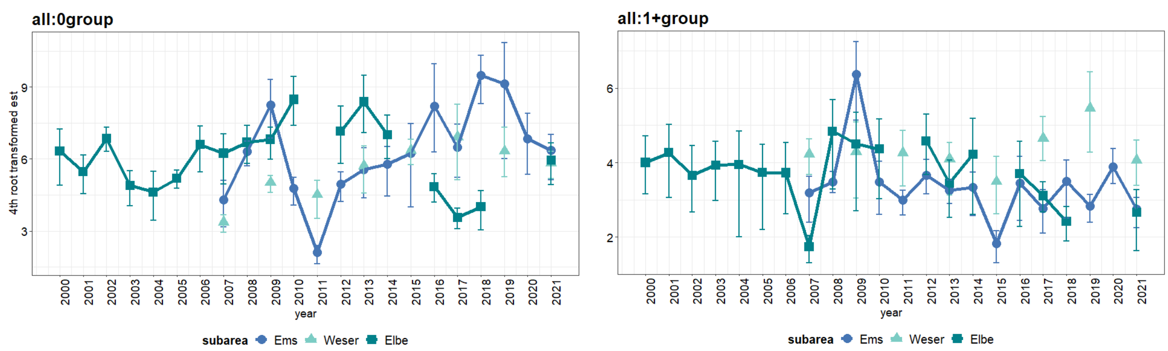

Figure 17. Trends in densities (Catch per unit of effort, CPUE, 4th root transformed, with standard error) for all 0-group (left) and 1+-group (right) in the three estuaries.

Variation in space

The total catch per unit of effort was quite similar between flood and ebb samples (fig. 15). The comparison between estuaries could be done for the five years in which all areas were sampled: 2007, 2009, 2013, 2017 and 2021. Overall densities are at a similar level in all three estuaries for 0 and 1+ fish (fig. 16). For diadromous and salinity-sensitive species such as smelt and herring, there is a clear decline from oligohaline to polyhaline (smelt) or in the opposite direction (herring). The comparison between estuaries shows highest smelt densities in the Elbe and lowest in the Ems-Dollard, but the opposite pattern for herring, notably 0-group (fig. 18). The Weser has an intermediate position in both species.

Zooming in on the individual stations within the Ems-Dollard shows that the decline in the occurrence of species from polyhaline (Spijk) to oligohaline (Terborg) can be seen from Spijk to Terborg for cod, whiting and herring and the reversed pattern for smelt (fig. 19, 20).

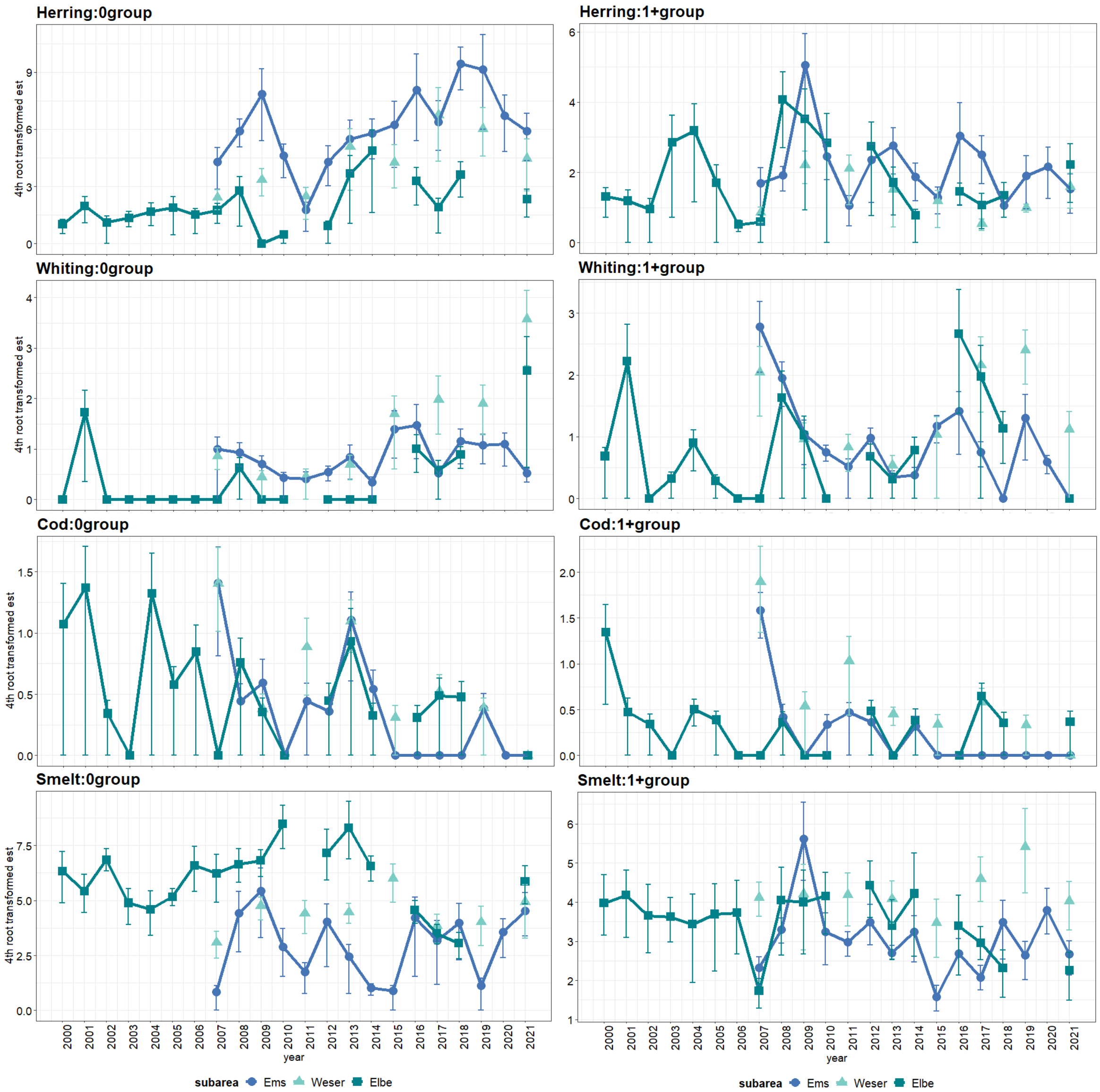

Figure 18. Trends in densities (Catch per unit of effort (CPUE) 4th root transformed) for 0-group (left) and 1+ (right) for herring, whiting, cod and smelt in the three estuaries.

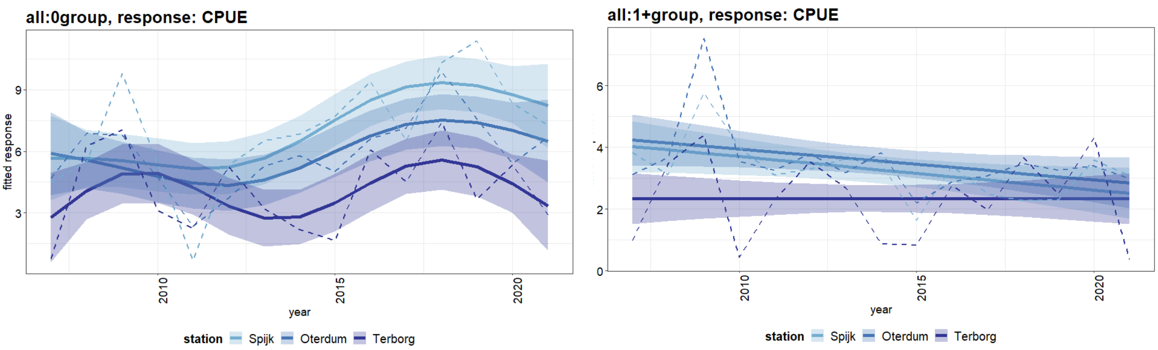

Figure 19. ***Trends in densities*** *(Catch per unit of effort (CPUE) 4th root transformed) (dotted lines with standard deviations) and* ***modelled trends*** *(smooth lines with shaded confidence interval) for 0+ and 1+ group marine juveniles for the three different stations within the Ems-Dollard. The 95% confidence intervals are estimated using bootstrapping, confidence intervals are based on the GAMs.*

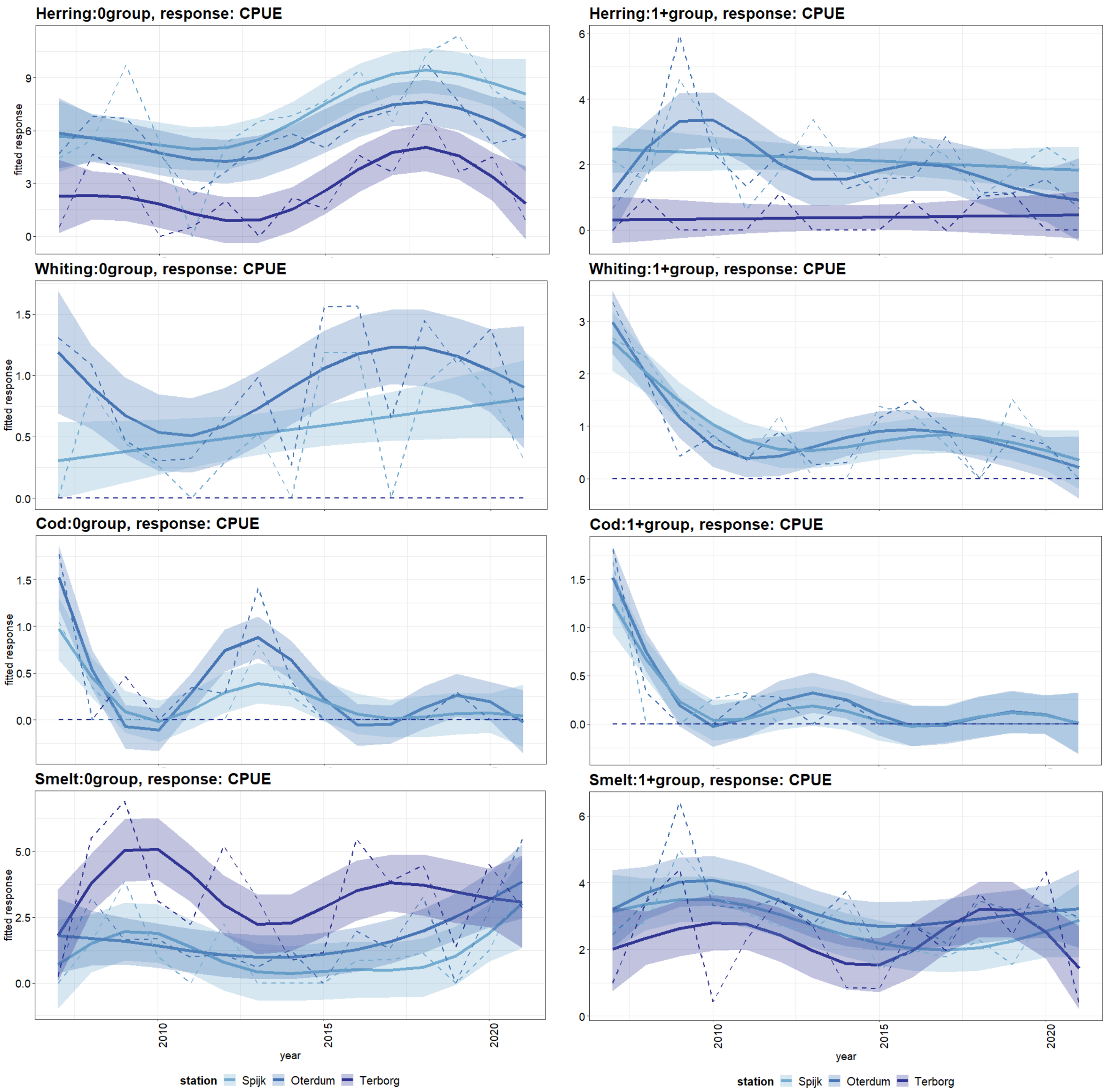

*Figure 20. **Trends in densities** (Catch per unit of effort (CPUE) 4th root transformed) (dotted lines with standard deviations) and **modelled trends** (smooth lines with shaded confidence interval) for 0 (left) and 1+group (right) pelagic marine juvenile species for the three different stations within the Ems-Dollard. The 95% confidence intervals are estimated using bootstrapping, confidence intervals of modelled trends are based on the GAMs. If a species did not occur at a specific station this is indicated by a flat line at 0 (e.g. cod in Terborg).*

3.1.2 Length at end of growing season

3.1.2.1 Comparison of subareas within Ems-Dollard

Variation in time

Mean fish length at age 0 fluctuates throughout the years (fig. 21). Plaice shows a recent overall decrease in mean length since roughly 2005. Although the sampling date advanced since the 1970's (resulting in smaller fish as they have less time to grow, fig. 22), it's been stable since 2005. The pattern is also visible in the predicted mean length, for which the sampling day was included in the model. 0-age plaice in the Ems-Dollard area has become smaller over the recent decades. Sole increased in size since the 1970s, showed a peak in the late 1990s and has been fluctuating around an intermediate length for the last 20 years. For dab data are limited, but the data in the outer Ems indicate that individuals are reaching larger sizes since the 2000's (fig. 22). The relatively short time series for flounder shows strong variation (especially in the Ems-Dollard).

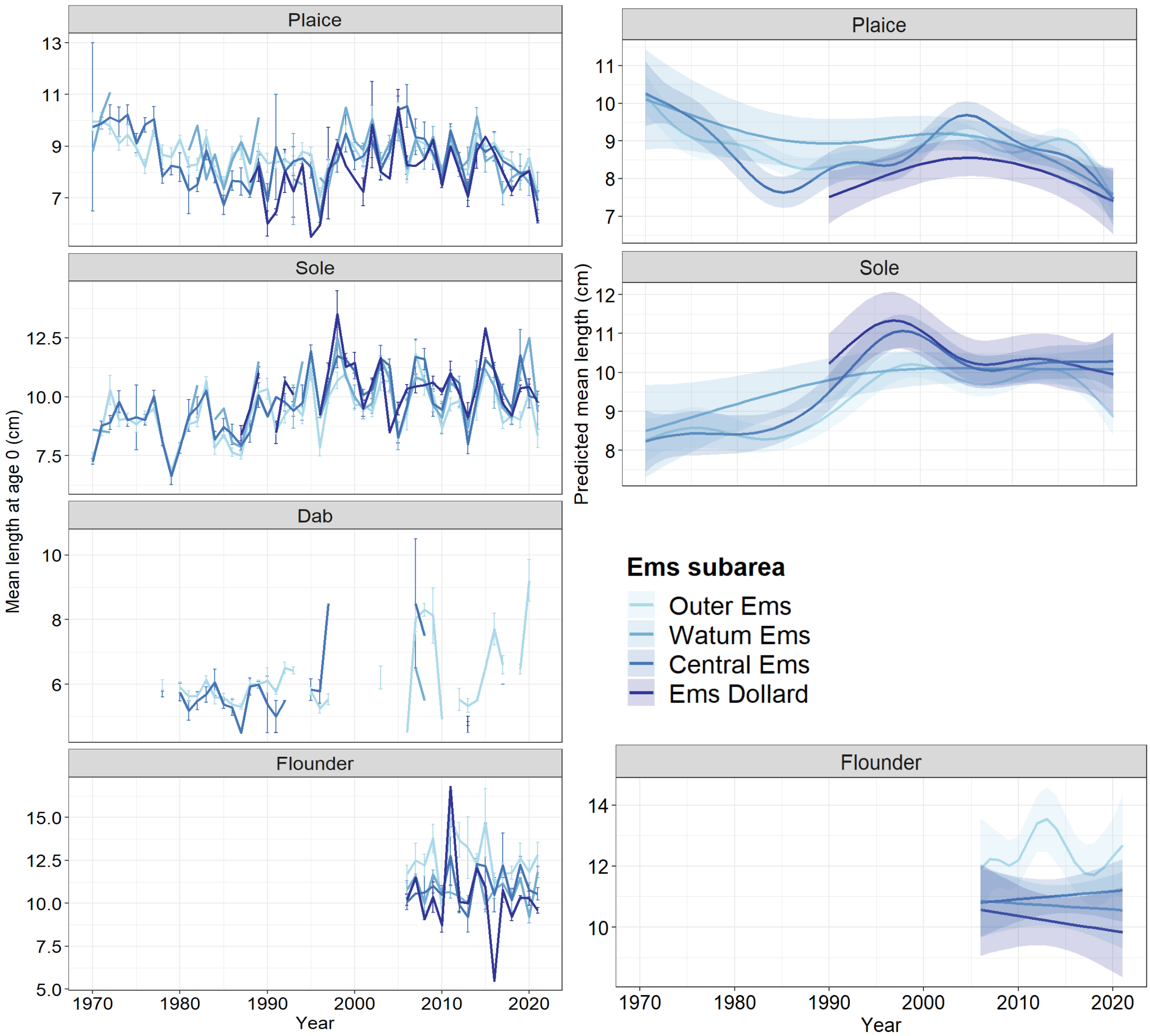

Figure 21. Trends in ***average length*** *at the end of the growing season of 0-group marine juvenile species in the different subareas in the Ems-Dollard area (left) and result from GAM model including sampling date as predictor variable (right). A GAM model could not be fitted for dab because of too limited data.*

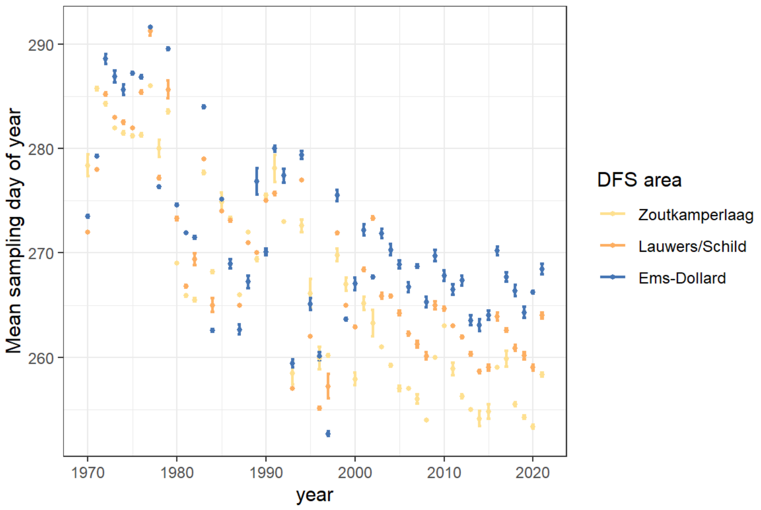

Figure 22. Mean sampling date per year and tidal basin. From 2005 onwards sampling dates are more standardised.

Variation in space

The length at the end of the growing season showed clear area-specific differences for flounder, with the largest individuals found in the outer Ems area and little difference among the other three subareas (fig. 21). The GAMS show overall lower mean length in plaice for the Dollard as compared to the outer area, but these differences are only significant during short periods (e.g. around 1985 and 2005). The downward trend in length for plaice from early 2000 onwards occurs in all subareas. 0-group sole is smaller in the outer Ems and Watum during a short period in the late 90's, but the difference between subareas disappears in more recent years.

3.1.2.2 Comparison of tidal basins

Variation in time

All tidal basins roughly show the same temporal pattern for plaice: 0-group plaice decreased in size until the early 90's, followed by an increase (fig. 23). From the early 2000's 0-group plaice is decreasing in size again. Sole has, on the other hand, increased in size until the early 2000 in all areas, after which it seems to fluctuate at an intermediate length. For dab data are limited, but 0-group dab seems to reach larger sizes since the 2000's. The short series for flounder shows large variation and a decrease in size since 2010 (fig. 23).

Variation in space

Since the mid 80's plaice is smaller in the Ems-Dollard area compared to the other areas (fig. 23). The aforementioned overall decrease in 0-group plaice in recent years seems strongest in the Ems-Dollard area but occurs in the other basins as well. Sole is clearly larger in the Ems-Dollard area than in the other two tidal basins. The temporal pattern is similar between the areas. The increase in size for dab is visible in all tidal basins. Flounder does not show clear differences between the tidal basins (fig. 23).

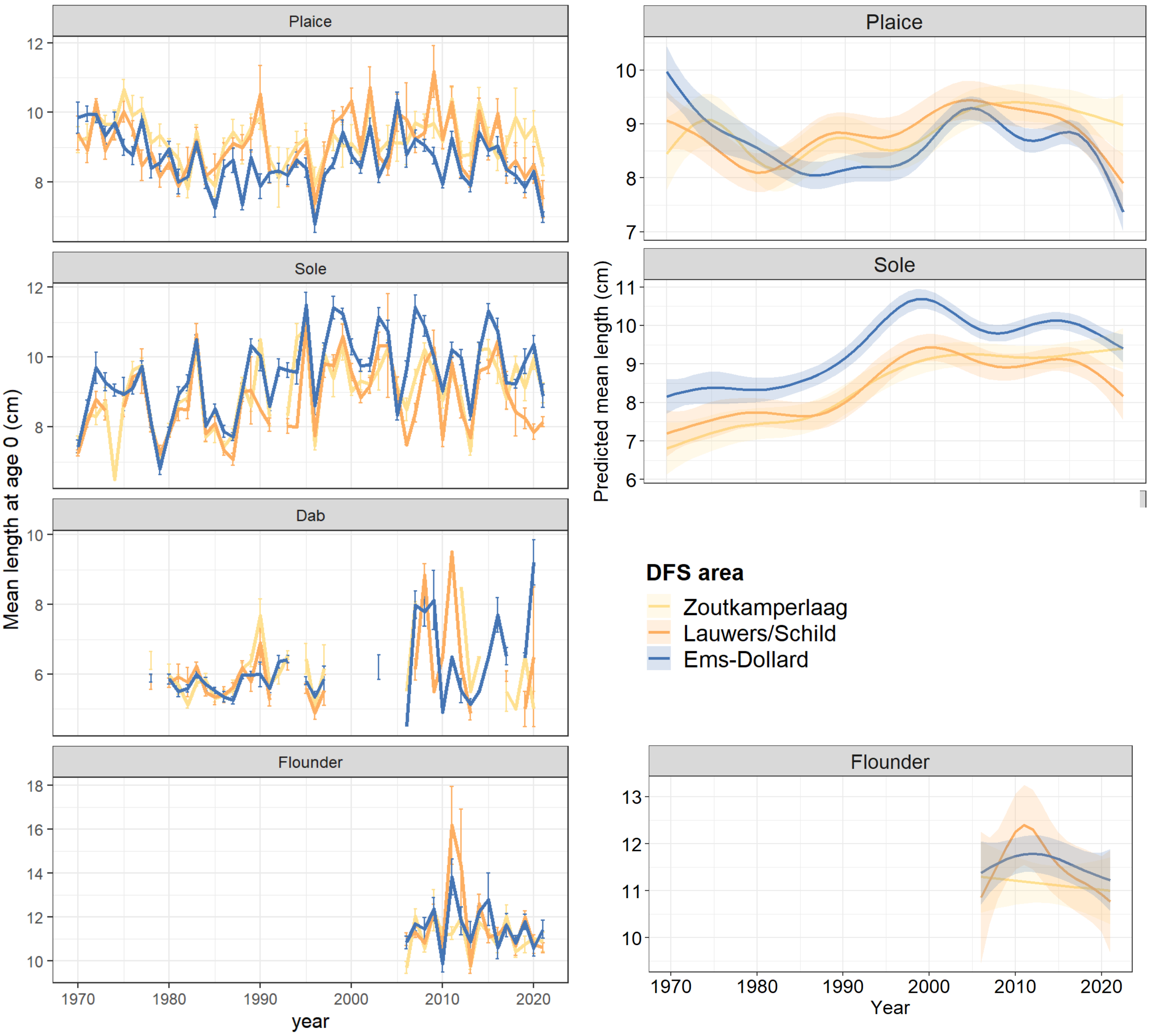

*Figure 23. Trends in **average length** at the end of the growing season of 0-group marine juvenile species in the different tidal basins (left) and result from GAM model including sampling date as predictor variable (right). GAM models could not be fitted for dab because of too few data.*

3.1.3 Condition 0-group fish

3.1.3.1 Comparison of Ems-Dollard with surrounding areas in the Dutch Wadden Sea

The number of years for which data are available in all three areas is limited to 5 (plaice), 4 (sole) and 3 (flounder). Since sample sizes for dab are recently very low, there is no information on dab condition. There is clear interannual variation in condition in plaice and sole, but less in flounder (fig. 24). The statistical analysis showed no effects of year or tidal basin on fish condition in sole and flounder. A significant year effect, but no effect of tidal basin was found for the condition of plaice. A post-hoc Tukey test resulted in a significantly higher condition of plaice in 1997 compared to all other years (apart from 2019) and between 2019 and 2020. An interesting comparison is 2020 and 2021, representing a relatively cool and extremely warm summer. The warm summer resulted in relatively good conditions in sole, but not in plaice or flounder (fig. 24). Overall there are no indications of lower condition of 0-group fish in the Ems-Dollard basin.

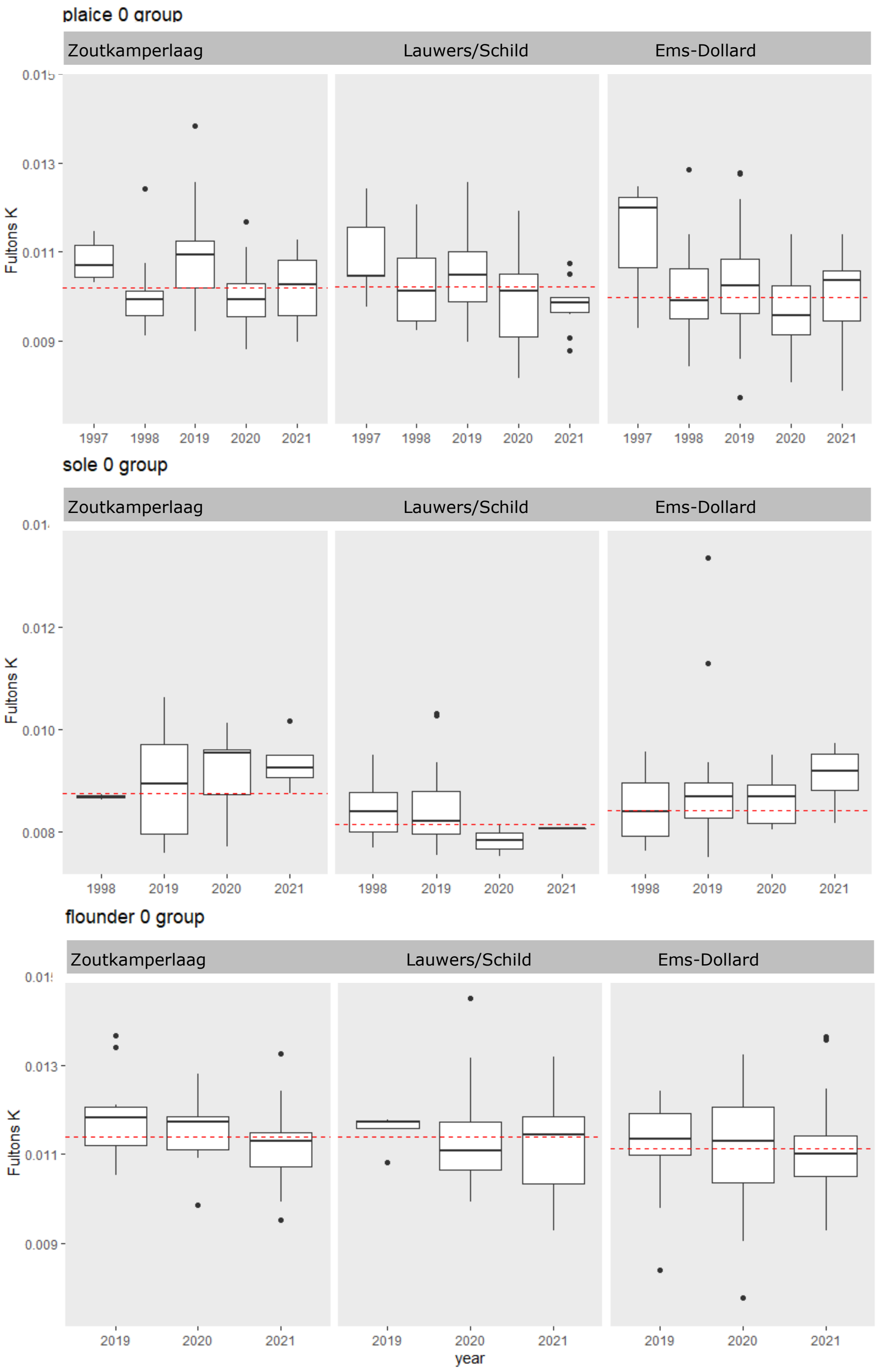

Figure 24. Boxplots of condition index (mean Fulton's K) for 0-group plaice, sole and flounder in the different tidal basins. Data for dab are lacking because the sample size was too low. The red dotted line indicates the basin-specific median value.

3.1.3.2 Condition in relation to temperature

0 and 1 group plaice and sole were in a lower condition at higher temperature sums over the growing season. Thus in overall warmer years they achieved a lower condition (fig. 25 and appendix 2). In contrast, the condition of 0 and 1 group flounder and 1 group dab seems to benefit from higher temperature sums. In all species, the pattern becomes more neutral in age group 2 (which could also partly be due to a lower sample size). In a regression model, cumulative temperature and age were significant ($p<0.05$) predictors in all species (all ages combined). The interaction between age and

cumulative temperature was only significant for sole and dab. This indicates that the slope of the regression line (and therefore the direction of the relationship) is similar for all ages in flounder (positive) and plaice (negative), but depends on the age in sole and dab (e.g. going from negative to positive in sole from 0 to 2 group).

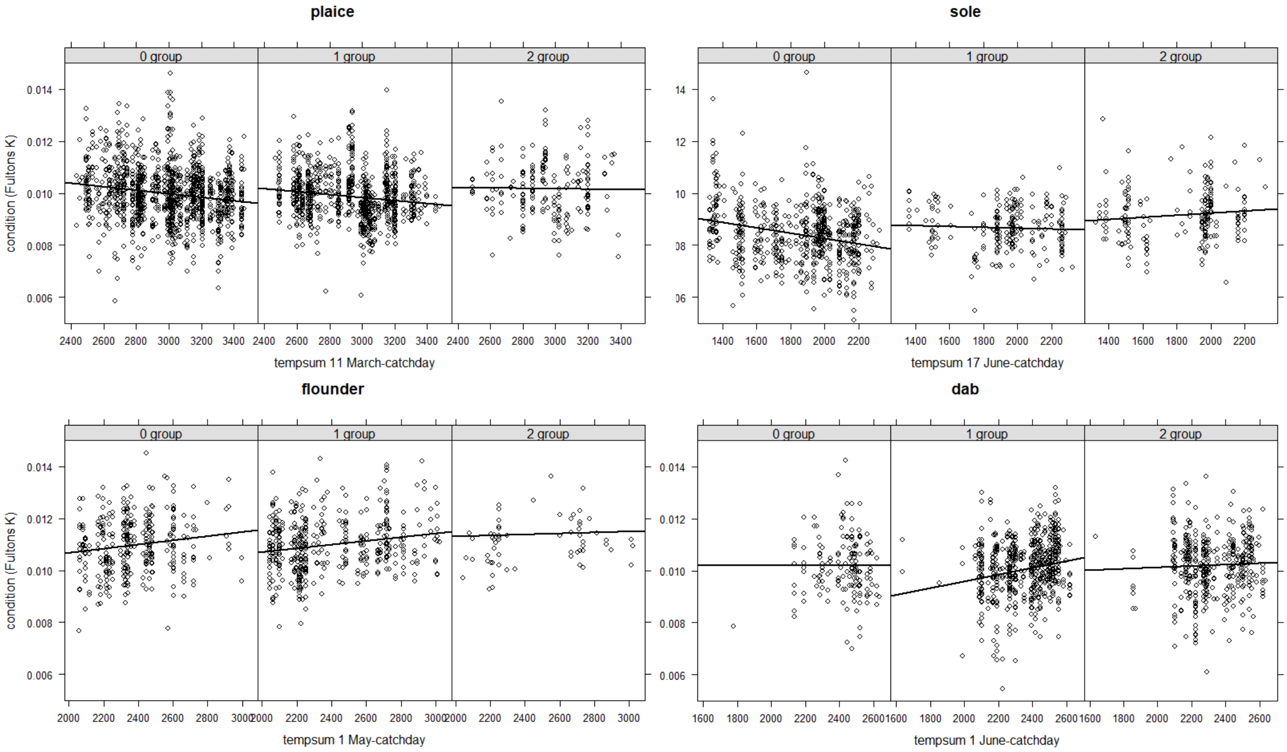

Figure 25. Condition in relation to the temperature during the (species-specific) growth window in three age groups of plaice, sole, dab and flounder over the entire DFS area (see fig. 1). The lines represent linear regressions. The results of the regression analyses are presented in annex 2.

4 Conclusions and discussion

4.1 Conclusions on the nursery function of the Ems-Dollard area

The aim of this study was to investigate if there are any indications that the nursery function for fish of the Ems-Dollard is in any way hampered by the current conditions with regard to the elevated silt levels. Silt concentrations are highest in the Ems river, followed by the Dollard, the central part and are lowest in the outer estuary (Schmidt and Iedema 2019).

To investigate the nursery function of the area we examined several parameters indicative of a nursery function. Of all potential parameters describing the quality of a nursery (density, growth, survival of juveniles, and emigration) we used existing survey data to analyse **density** (and **trends** therein), and as proxies for growth: **length** and **condition** at the end of the growing season. To evaluate whether the situation in (subareas of) the Ems-Dollard is in any way falling behind compared to other (similar) areas, we made comparisons on **three different levels**: 1) within four different **subareas** in the Ems-Dollard, 2) between the Ems-Dollard tidal basin and neighbouring **tidal basins** and 3) (specifically for pelagic species) between the Ems, Elbe and Weser **estuaries**. In the comparison we included both demersal (levels 1 and 2) and pelagic fish species (level 3).

In conclusion, our analyses, focussing on trends in time and space, showed no strong difference in the investigated parameters (densities, trends, length, condition) in the Ems-Dollard as compared to other areas that may point at an adverse effect of the higher silt levels. Overall densities of marine juveniles have declined strongly since the 1980s, but that pattern is observed throughout the Wadden Sea (Tulp et al. 2022). The only indication in the trend analyses possibly indicating a worse nursery function in the Ems-Dollard is the pattern reversal in length of plaice at around 1985, with smaller fish after that period in the Ems-Dollard as compared to neighbouring tidal basins. For species that favour siltier situations or the estuarine character of the Ems-Dollard such as sole, flounder and smelt, we found no indications of a deteriorating situation in course of time.

The available time series start in 1970 or later, a period when silt levels were already increasing for 20 years. Therefore our conclusion does not mean that we can exclude an effect of silt or accompanying problems on any fish species, because we lack a good reference and the available data are limited. In addition there are several other reasons why a clear difference for the areas most affected by higher silt levels on the nursery function do not show up. We will discuss these in paragraph 4.2. Firstly the main findings at the three levels are summarised below.

4.1.1 Subareas within Ems-Dollard

The total density of 0-group marine juveniles shows a similar trend in all subareas within the Ems-Dollard. Absolute densities differ from year to year with no clear area effect. Species-specific trends in densities follow the same pattern in all subareas for most species and ages. Dab and whiting occur in highest densities in the outer estuary. Smelt and flounder decrease from the Dollard towards the outer Ems along the salinity gradient and opposite to the turbidity gradient. In 1+ group fish densities are significantly lower in the outer Ems as compared to the other subareas. The increase from 1970 to the 1980s followed by a decline occurs in all subareas and both in 0 and in 1+ group fish.

Clear area-specific differences in length at the end of the growing season of 0-group fish were found for flounder, with the largest individuals in the outer Ems area and little difference among the other three subareas. 0-group sole is smaller in the outer Ems as compared to the other subareas. In plaice there seems to be an overall downward trend in length, possibly related to warmer temperatures in recent periods.

4.1.2 Tidal basins

In general, the species-specific trends follow similar patterns in different tidal basins. Plaice, sole and flounder are the dominant species in all tidal basins. Cod is at a very low level throughout the time series, while whiting is increasing without clear differences between tidal basins. In comparison to the surrounding tidal basins, the Ems-Dollard has relatively high densities of 0-group fish throughout the series.

The comparison among tidal basins shows differences in mean lengths for plaice, and sole. For sole the growing conditions are apparently best in the Ems-Dollard because the 0-group fish are significantly larger there as compared to the other basins throughout the time series. For plaice the time series shows that the pattern reversed in the early 1980s: before that period plaice in the Ems-Dollard was larger as compared to the other basins, while after 1980s 0-group plaice was larger in the other two basins. The decrease in mean length at the end of the series in especially the Ems-Dollard could well be caused by the high densities in 2021, causing density dependence and food shortage because of high competition (van der Veer et al. 2016). For flounder no significant differences were found.

Overall there are no indications of lower condition of 0-group fish in the Ems-Dollard basin. Nevertheless there is clear annual variation in condition in plaice and sole, but less in flounder. The number of years and number of individuals is, however, too limited to infer strong conclusions. An additional analysis relating condition to the temperature sum over the entire growing season in the entire DFS set showed that the condition of plaice and sole is lower in relatively warm years, while flounder seems to benefit from warm years. We know from other studies (Teal et al. 2012) that temperature has a strong effect on growth conditions and that especially in warm years the food availability becomes limiting to sustain growth under energetically costly warm conditions especially by the end of the season. Every species has an optimal temperature for growth. Physiological performance (such as growth) increases with temperature until a maximum rate is reached (at the optimum temperature), followed by an abrupt decrease to zero. Differences in these optima may explain the species differences. The relatively large effect of temperature may be the reason for not finding differences in condition between areas in the limited dataset of only the Ems-Dollard and neighbouring basins.

4.1.3 Estuaries

Overall, densities are at a similar level in all three estuaries for 0 and 1+ fish. For diadromous and salinity-sensitive species such as smelt and herring, there is a clear decline from brackish to salt water (smelt) or in the opposite direction (herring). The comparison between estuaries shows highest densities in the Elbe and lowest in the Ems-Dollard for smelt, but the opposite pattern occurs in herring, with an intermediate position for the Weser in both species. The decline in cod and increase in whiting are observed in all three estuaries. The trend in herring is increasing in the Ems-Dollard, but also in the German estuaries. Smelt is quite constant in the Ems-Dollard, but decreasing in the Elbe. Comparing trends across the three estuaries requires caution because there are considerable differences in e.g. water depth, river runoff and sampling effort.

4.2 Considerations in the approach

In order to evaluate the quality of (subareas in) the Ems-Dollard for fish, comparisons to reference areas (preferentially without the elevated silt levels, but all other circumstances being equal) are needed. However, the situation in the Ems-Dollard is quite different from any other area in the

Wadden Sea because of its estuarine nature. This means a good reference is lacking. Together with the Westerschelde the Ems is the only open estuary left in the Netherlands. We therefore also included the German estuaries in our analyses. This was, however, only possible for the stow net surveys, since the beam trawl survey (DYFS) does not cover the entire German estuaries, only the seaward parts. In all evaluations involving both Dutch and German beam trawl data (in this case tidal basin 414) we have to take the gear difference into account (tickler chain versus no tickler chain). Especially for the flatfish species a tickler chain usually leads to higher catches.

We used a sampling program that was set up for a different purpose than for area-specific analyses (van Beek 1997). To evaluate patterns within the Ems-Dollard we had to work with rather low sample sizes for especially Bocht van Watum and the Dollard itself. Because each haul measures ca 1200 m, and there are limits to sampling depth of >2 m, there is hardly any space for more hauls in these areas. More specific, smaller-scaled sampling with smaller gear in more specific locations varying in silt content, as carried out in the past, may be a valuable addition (Jager et al. 1993; Jager 2002).

In this study abiotic variables (salinity, turbidity, temperature, current velocity, water depth) were not included because acquiring and collecting such data on haul level form external sources is quite time consuming and often not available or incomplete. Water depth, temperature and water visibility (Secchi depth) are recorded during each haul, but these recordings are incomplete for the earlier part of the series. In this limited desk study abiotics were therefore not included, but also they would show a high correlation with the subarea divisions that were used within the Ems-Dollard. Nevertheless, for comparisons over a larger scale it would be worthwhile to investigate potential effects of these factors on the patterns found.

4.3 Recommendations for further study

In this study we focussed on the nursery function. Because of the limitation of the available data we focussed on demersal species that inhabit the area close to the bottom. Demersal species might not necessarily be species that would be most vulnerable to elevated silt levels. In addition, the nursery function is only one of the functions coastal and estuarine areas have for fish. For some species estuaries form a transition area on annual migrations (diadromous species), others visit the area in summer to feed (seasonal migrants), and other species even reside in the area permanently (resident species). It would be worthwhile to investigate the potential effect of the elevated silt levels on other species in the spectrum and on other functions. Monitoring of fish occurrence does not work for all these species because the probability of catching enough individuals is often too low. Therefore an additional set of techniques is needed.

We see two major routes for future work at different scales:
1. Direct studies of mechanisms at work through dedicated field studies, lab work and modelling studies
2. Field comparisons on an (inter)estuary scale

The situation in the Ems estuary can only be evaluated with the use of good reference areas. In many reports such comparisons are lacking, which may lead to the assumption of causal effects between the elevated silt levels and observed patterns. For instance the general pattern in fish with elevated levels in the 1980s and the decline thereafter is not unique for the Ems-Dollard, but occurred throughout the Wadden Sea (Tulp et al. 2022) and cannot be directly attributed to the silt situation in the Ems-Dollard, as has sometimes been suggested (Schmidt and Iedema 2019). We have made a first attempt by comparing the Ems estuary to other tidal basins and to two German estuaries, the Elbe and Weser, but there are more possibilities.

4.3.1 Mechanisms at work

4.3.1.1 Smaller scaled field study

The relatively large-scale sampling we used may be too coarse to capture small-scale variation in silt levels. Already within the Dollard, silt levels show great variation (e.g. different sampling sites at Heringsplaat, (Schmidt and Iedema 2019)) and the scale of sampling should be at a similar resolution to be able to detect causal relationships. A study setup with small-scale sampling such as carried out in the 1990s might be helpful (Jager et al. 1993; Jager et al. 1995; Jager 2001; Jager 2002).

4.3.1.2 Follow up study of dredging or dumping sites

In order to investigate the effect of dredging or dumping of silt more directly, it would be worthwhile to follow up the development in fish in those specific sites before and after an event. In the Ems-Dollard area there are several dumping and dredging sites (Dankers 2022). Also here a small-scaled sampling design is needed.

4.3.1.3 Study effect of silt concentration in the lab

The problem with this type of comparative studies is that we have to rely on comparisons with areas that hopefully differ in the parameter of interest (in this case silt loading) and not in others. In order to understand how different species are actually responding to different silt concentrations, through which mechanism and at what concentrations problems arise, experiments in a controlled setting can yield valuable new insights. By observing and recording how fish behave and actually being able to measure parameters such as growth or intake rates in response to different silt levels, it is possible to infer a causal relationship and understand the mechanism. Such studies have been carried out for fish larvae, but not for older fish (Utne-Palm 2004). A controlled setup in the lab would be ideal to study this and would yield much more conclusive evidence than any field study could do. From experience we know, however, that such an undertaking requires a careful trajectory with a good preparation and takes substantial amount of time.

4.3.1.4 The difference between realised growth and optimal growth

So far we used the length at the end of the growing season as a measure for habitat quality. The assumption is that fish do not move over large areas and that all growth is realised in the specific area. Fish that lag behind in growth and die are not included in the data collected at the end of the growing season. Measurements at more instances in the season likely gives a better measure of realised growth.

To evaluate whether the length at the end of the growing season deviates from what could be achieved in an ideal situation, an approach using Dynamic Energy Budget (DEB) modelling could be helpful. Based on equal starting lengths of the age 0-group, the annual growth curve can be compared with "optimal" growth curves as predicted by the DEB growth model (Teal et al. 2012). Based on local temperature measurements in every week of the year, we can determine whether growth is slower than expected based on the local temperature. Deviations from the expected (optimal) growth would indicate that food limitation or another limiting factor may play a role. DEB models for plaice and sole are already available, for dab and flounder these would need to be developed based on parameters that are already available. A comparison can then be made in growth and temperature patterns between different locations.

4.3.2 Field comparisons on an (inter-)estuary scale

4.3.2.1 Movement of fish by otolith microchemistry

A well-functioning estuary provides a passage way and living habitat for migratory fish that swim upstream to their spawning locations. To evaluate this function of the Ems and comparable estuaries with an open connection to the North Sea (such as Elbe, Weser, but also the Westerschelde), a technique based on the chemical composition of otoliths is a good tool. In microchemistry analyses, the environmental imprint (consisting of a certain chemical composition) that is laid down along the axis from the core to the edge of otoliths is used to derive in which estuary a fish was born or spent part of its life (Tulp et al. 2013; Randon et al. 2018). That information would be extremely helpful to evaluate which species are actually able to use the Ems as a spawning or migration area and if there is exchange between neighbouring estuaries.

4.3.2.2 Movement of migratory fish by tracking

Within the program 'Ruim baan voor vissen' and 'Eemsvissen in beeld' currently several species (e.g. flounder and river lamprey) are tracked through an acoustic network in the Ems estuary. This program will produce valuable insights in how, where and when different subareas are used. Overlaying the whereabouts of fish with variations in silt concentrations will provide more direct observations on potential preferred or less favourite sites.

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6 Quality Assurance

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

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Annex 1 Number of observations of fish condition per tidal basin

plaice 0-group

	401	402	403	404	405	406	407	610	612	616	617	618	619	620	634	638
1994	0	0	0	0	0	0	0	0	0	20	0	0	0	0	0	0
1995	32	14	8	18	9	15	10	0	0	0	0	0	0	0	0	0
1996	13	4	4	0	0	7	16	0	0	0	0	0	0	0	0	0
1997	0	16	10	6	3	0	0	2	0	1	11	6	5	3	0	0
1998	15	2	6	0	0	0	0	23	19	22	32	17	26	19	0	0
1999	27	33	17	25	0	0	0	0	0	0	0	0	0	0	0	0
2000	38	30	14	26	18	22	31	0	0	0	0	0	0	0	0	0
2001	0	55	35	31	14	22	6	0	0	0	0	0	0	0	0	0
2002	34	27	41	41	38	0	0	0	0	0	0	0	0	0	0	0
2003	49	47	38	29	23	21	13	0	0	0	0	0	0	0	0	0
2004	60	58	26	56	40	46	52	0	0	0	0	0	0	0	0	0
2006	46	49	52	44	27	43	33	0	0	0	0	0	0	0	0	0
2007	48	51	38	43	33	39	34	0	0	0	0	0	0	0	0	0
2008	48	48	39	41	31	21	26	0	0	0	0	0	0	0	0	0
2009	0	20	29	33	25	29	20	0	0	0	0	0	0	0	0	0
2010	50	52	35	38	28	34	25	0	0	0	0	0	0	0	0	0
2011	43	31	25	42	29	24	24	0	0	0	0	0	0	0	0	0
2012	50	46	34	38	34	35	25	0	0	0	0	0	0	0	0	0
2013	50	47	39	38	33	37	22	0	0	0	0	0	0	0	0	0
2014	205	180	130	195	140	100	95	0	0	0	0	0	0	0	0	0
2019	37	39	34	46	33	32	20	18	0	26	30	32	26	33	29	29
2020	34	37	37	46	35	0	0	31	4	35	31	30	26	28	28	1
2021	17	15	11	15	11	13	12	4	2	9	6	9	10	10	11	5
plaice 1 group																
1994	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0
1995	26	2	7	25	26	25	14	0	0	0	0	0	0	0	0	0
1996	37	31	41	42	19	26	4	0	0	0	0	0	0	0	0	0
1997	41	32	26	17	16	0	0	19	0	6	16	13	5	22	0	0
1998	14	13	14	0	0	0	0	26	0	29	2	0	1	0	0	0
1999	24	21	1	1	0	0	0	0	0	0	0	0	0	0	0	0
2000	16	2	0	6	4	18	9	0	0	0	0	0	0	0	0	0
2001	0	0	0	3	0	5	0	0	0	0	0	0	0	0	0	0
2002	19	5	6	0	2	0	0	0	0	0	0	0	0	0	0	0
2003	25	11	8	13	7	8	1	0	0	0	0	0	0	0	0	0
2004	60	72	2	8	24	34	26	0	0	0	0	0	0	0	0	0
2006	9	13	12	7	1	2	1	0	0	0	0	0	0	0	0	0
2007	3	4	1	6	6	13	3	0	0	0	0	0	0	0	0	0
2008	4	18	4	1	1	1	0	0	0	0	0	0	0	0	0	0
2009	0	4	2	7	5	8	4	0	0	0	0	0	0	0	0	0
2010	3	15	8	0	5	7	0	0	0	0	0	0	0	0	0	0
2011	14	25	10	4	16	22	2	0	0	0	0	0	0	0	0	0
2012	5	10	0	1	1	26	5	0	0	0	0	0	0	0	0	0
2013	11	23	2	8	6	11	1	0	0	0	0	0	0	0	0	0
2014	110	160	15	60	55	60	15	0	0	0	0	0	0	0	0	0
2019	28	33	17	3	5	23	22	0	0	3	0	3	4	8	17	12
2020	31	26	12	3	5	0	0	1	0	6	1	1	0	6	6	1
2021	9	7	2	2	3	6	4	3	0	1	2	1	2	7	4	2

sole 0-group

	401	402	403	404	405	406	407	610	612	616	617	618	619	620	634	638
1998	2	0	0	0	0	0	0	24	0	10	10	2	9	21	0	0
1999	4	12	20	18	0	0	0	0	0	0	0	0	0	0	0	0
2000	23	11	6	3	7	12	0	0	0	0	0	0	0	0	0	0
2001	0	28	15	17	5	3	0	0	0	0	0	0	0	0	0	0
2002	10	7	0	31	14	0	0	0	0	0	0	0	0	0	0	0
2003	12	18	8	22	0	2	0	0	0	0	0	0	0	0	0	0
2004	46	26	0	0	4	4	0	0	0	0	0	0	0	0	0	0
2006	9	2	3	26	3	10	0	0	0	0	0	0	0	0	0	0
2007	13	11	20	19	1	13	0	0	0	0	0	0	0	0	0	0
2008	28	15	3	19	6	0	0	0	0	0	0	0	0	0	0	0
2009	0	15	14	19	9	4	0	0	0	0	0	0	0	0	0	0
2010	25	18	26	21	21	1	1	0	0	0	0	0	0	0	0	0
2011	24	23	26	16	2	3	0	0	0	0	0	0	0	0	0	0
2012	31	24	4	20	22	20	2	0	0	0	0	0	0	0	0	0
2013	32	18	29	25	9	10	1	0	0	0	0	0	0	0	0	0
2014	145	140	120	145	110	5	5	0	0	0	0	0	0	0	0	0
2019	35	12	30	25	14	0	0	11	0	27	12	16	14	27	13	23
2020	36	36	28	29	0	0	0	39	1	38	3	8	3	13	12	11
2021	10	6	5	7	4	0	2	8	0	7	4	5	1	11	0	6
sole 1 group																
1998	0	0	0	0	0	0	0	8	0	1	0	0	0	0	0	0
1999	2	1	1	3	0	0	0	0	0	0	0	0	0	0	0	0
2000	6	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
2001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2002	2	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0
2003	2	24	2	8	7	7	1	0	0	0	0	0	0	0	0	0
2004	18	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
2006	25	5	26	11	1	10	0	0	0	0	0	0	0	0	0	0
2007	0	1	0	3	0	4	1	0	0	0	0	0	0	0	0	0
2008	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2009	0	2	0	2	0	3	0	0	0	0	0	0	0	0	0	0
2010	8	39	5	0	1	0	0	0	0	0	0	0	0	0	0	0
2011	31	23	3	1	2	0	0	0	0	0	0	0	0	0	0	0
2012	3	4	1	0	2	0	0	0	0	0	0	0	0	0	0	0
2013	11	2	0	0	0	1	0	0	0	0	0	0	0	0	0	0
2014	170	175	25	10	30	0	0	0	0	0	0	0	0	0	0	0
2019	40	38	11	5	3	4	0	4	0	38	11	5	1	5	36	35
2020	10	9	6	0	0	0	0	1	0	4	2	0	0	2	0	10
2021	10	2	4	2	0	0	0	1	0	1	0	0	0	0	2	8

dab 0-group

	401	402	403	404	405	406	407	610	616	617	618	619	620	634	638
1994	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1995	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1996	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1997	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1998	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1999	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2002	9	0	5	11	1	0	0	0	0	0	0	0	0	0	0
2003	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2004	2	0	0	0	0	2	0	0	0	0	0	0	0	0	0
2006	0	8	4	12	0	1	8	0	0	0	0	0	0	0	0
2007	22	7	2	16	15	16	6	0	0	0	0	0	0	0	0
2008	22	11	1	20	3	5	1	0	0	0	0	0	0	0	0
2009	0	1	2	2	6	3	0	0	0	0	0	0	0	0	0
2010	5	0	9	11	0	1	0	0	0	0	0	0	0	0	0
2011	10	0	3	16	3	0	0	0	0	0	0	0	0	0	0
2012	12	10	11	9	10	12	4	0	0	0	0	0	0	0	0
2013	10	0	4	10	7	2	0	0	0	0	0	0	0	0	0
2014	5	20	5	15	10	0	0	0	0	0	0	0	0	0	0
2019	8	8	11	18	12	11	1	0	0	2	0	0	4	0	0
2020	5	6	12	17	12	0	0	0	0	0	0	0	8	0	1
2021	12	14	5	16	8	10	10	0	0	0	0	0	0	0	0
dab 1 group															
1994	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1995	10	13	1	24	17	15	11	0	0	0	0	0	0	0	0
1996	0	24	17	25	24	18	0	0	0	0	0	0	0	0	0
1997	22	10	18	19	7	0	0	0	0	0	0	0	0	0	0
1998	1	1	4	0	0	0	0	2	1	0	0	0	3	0	0
1999	3	9	0	10	0	0	0	0	0	0	0	0	0	0	0
2000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2001	0	3	1	10	4	2	0	0	0	0	0	0	0	0	0
2002	28	4	6	16	5	0	0	0	0	0	0	0	0	0	0
2003	28	27	9	15	2	5	1	0	0	0	0	0	0	0	0
2004	28	56	16	34	28	18	0	0	0	0	0	0	0	0	0
2006	47	40	19	47	7	3	0	0	0	0	0	0	0	0	0
2007	4	7	3	21	1	3	2	0	0	0	0	0	0	0	0
2008	32	14	4	30	12	2	7	0	0	0	0	0	0	0	0
2009	0	21	12	17	26	21	17	0	0	0	0	0	0	0	0
2010	26	20	27	29	18	6	0	0	0	0	0	0	0	0	0
2011	31	28	14	11	24	17	35	0	0	0	0	0	0	0	0
2012	15	20	19	26	22	17	8	0	0	0	0	0	0	0	0
2013	12	13	5	9	12	20	27	0	0	0	0	0	0	0	0
2014	115	125	65	95	105	100	65	0	0	0	0	0	0	0	0
2019	22	26	15	14	12	20	22	0	0	1	0	0	2	2	0
2020	24	19	18	19	1	0	0	0	0	0	0	0	1	0	0
2021	17	17	16	15	10	16	5	0	0	0	0	0	0	5	0

flounder 0-group

	401	402	403	404	405	406	407	610	612	616	617	618	619	620	634	638
1998	2	0	0	0	0	0	0	24	0	10	10	2	9	21	0	0
1999	4	12	20	18	0	0	0	0	0	0	0	0	0	0	0	0
2000	23	11	6	3	7	12	0	0	0	0	0	0	0	0	0	0
2001	0	28	15	17	5	3	0	0	0	0	0	0	0	0	0	0
2002	10	7	0	31	14	0	0	0	0	0	0	0	0	0	0	0
2003	12	18	8	22	0	2	0	0	0	0	0	0	0	0	0	0
2004	46	26	0	0	4	4	0	0	0	0	0	0	0	0	0	0
2006	9	2	3	26	3	10	0	0	0	0	0	0	0	0	0	0
2007	13	11	20	19	1	13	0	0	0	0	0	0	0	0	0	0
2008	28	15	3	19	6	0	0	0	0	0	0	0	0	0	0	0
2009	0	15	14	19	9	4	0	0	0	0	0	0	0	0	0	0
2010	25	18	26	21	21	1	1	0	0	0	0	0	0	0	0	0
2011	24	23	26	16	2	3	0	0	0	0	0	0	0	0	0	0
2012	31	24	4	20	22	20	2	0	0	0	0	0	0	0	0	0
2013	32	18	29	25	9	10	1	0	0	0	0	0	0	0	0	0
2014	145	140	120	145	110	5	5	0	0	0	0	0	0	0	0	0
2019	35	12	30	25	14	0	0	11	0	27	12	16	14	27	13	23
2020	36	36	28	29	0	0	0	39	1	38	3	8	3	13	12	11
2021	10	6	5	7	4	0	2	8	0	7	4	5	1	11	0	6
flounder 1 group																
1998	0	0	0	0	0	0	0	8	0	1	0	0	0	0	0	0
1999	2	1	1	3	0	0	0	0	0	0	0	0	0	0	0	0
2000	6	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
2001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2002	2	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0
2003	2	24	2	8	7	7	1	0	0	0	0	0	0	0	0	0
2004	18	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
2006	25	5	26	11	1	10	0	0	0	0	0	0	0	0	0	0
2007	0	1	0	3	0	4	1	0	0	0	0	0	0	0	0	0
2008	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2009	0	2	0	2	0	3	0	0	0	0	0	0	0	0	0	0
2010	8	39	5	0	1	0	0	0	0	0	0	0	0	0	0	0
2011	31	23	3	1	2	0	0	0	0	0	0	0	0	0	0	0
2012	3	4	1	0	2	0	0	0	0	0	0	0	0	0	0	0
2013	11	2	0	0	0	1	0	0	0	0	0	0	0	0	0	0
2014	170	175	25	10	30	0	0	0	0	0	0	0	0	0	0	0
2019	40	38	11	5	3	4	0	4	0	38	11	5	1	5	36	35
2020	10	9	6	0	0	0	0	1	0	4	2	0	0	2	0	10
2021	10	2	4	2	0	0	0	1	0	1	0	0	0	0	2	8

Annex 2 Output of statistical analyses

Table A1. Goodness of fit for GAM models on fish densities in the three comparisons

Species	age group	Comparison between	Model	Deviance explained
all	0	Ems subareas	glm(CPUE ~ period*subarea, family=Gamma)	0.205
all	1+	Ems subareas	glm(CPUE ~ period*subarea, family=gaussian)	0.207
Plaice	0	Ems subareas	glm(CPUE ~ period*subarea, family=gaussian)	0.137
Plaice	1+	Ems subareas	glm(CPUE ~ period*subarea, family=gaussian)	0.227
Sole	0	Ems subareas	glm(CPUE ~ period*subarea, family=gaussian)	0.176
Sole	1+	Ems subareas	glm(CPUE ~ period*subarea, family=gaussian)	0.288
Dab	0	Ems subareas	glm(presence ~ period*subarea, family=binomial)	0.391
Dab	1+	Ems subareas	glm(presence ~ period*subarea, family=binomial)	0.278
Flounder	0	Ems subareas	glm(CPUE ~ period*subarea, family=gaussian)	0.313
Flounder	1+	Ems subareas	glm(CPUE ~ period*subarea, family=gaussian)	0.181
Whiting	0	Ems subareas	glm(CPUE ~ period*subarea, family=gaussian)	0.257
Whiting	1+	Ems subareas	glm(presence ~ period*subarea, family=binomial)	0.099
Cod	0	Ems subareas	glm(presence ~ period*subarea, family=binomial)	0.146
Cod	1+	Ems subareas	glm(presence ~ period*subarea, family=binomial)	0.129
Smelt	0	Ems subareas	glm(presence ~ period*subarea, family=binomial)	0.2
Smelt	1+	Ems subareas	glm(CPUE ~ period*subarea, family=gaussian)	0.365
all	0	DFS areas	gam(CPUE ~ subarea + s(year,by=subarea, bs="tp", k=8), family=gaussian, method= "REML")	0.249
all	1+	DFS areas	gam(CPUE ~ subarea + s(year,by=subarea, bs="tp", k=8), family=gaussian, method= "REML")	0.126
Plaice	0	DFS areas	gam(CPUE ~ subarea + s(year,by=subarea, bs="tp", k=8), family=gaussian, method= "REML")	0.119
Plaice	1+	DFS areas	gam(CPUE ~ subarea + s(year,by=subarea, bs="tp", k=8), family=gaussian, method= "REML")	0.167
Sole	0	DFS areas	gam(CPUE ~ subarea + s(year,by=subarea, bs="tp", k=8), family=gaussian, method= "REML")	0.094
Sole	1+	DFS areas	gam(CPUE ~ subarea + s(year,by=subarea, bs="tp", k=8), family=gaussian, method= "REML")	0.111
Dab	0	DFS areas	gam(CPUE ~ subarea + s(year,by=subarea, bs="tp", k=8), family=gaussian, method= "REML")	0.475
Dab	1+	DFS areas	gam(presence~ subarea + s(year,by=subarea, bs="tp", k=8), family=binomial, method= "REML")	0.228
Flounder	0	DFS areas	gam(CPUE ~ subarea + s(year,by=subarea, bs="tp", k=8), family=gaussian, method= "REML")	0.093
Flounder	1+	DFS areas	gam(presence~ subarea + s(year,by=subarea, bs="tp", k=8), family=binomial, method= "REML")	0.034

Whiting	0	DFS areas	gam(CPUE ~ subarea + s(year,by=subarea, bs="tp", k=8), family=gaussian, method= "REML")	0.268
Whiting	1+	DFS areas	gam(presence~ subarea + s(year,by=subarea, bs="tp", k=8), family=binomial, method= "REML")	0.046
Cod	0	DFS areas	gam(presence~ subarea + s(year,by=subarea, bs="tp", k=8), family=binomial, method= "REML")	0.114
Cod	1+	DFS areas	gam(presence~ subarea + s(year,by=subarea, bs="tp", k=8), family=binomial, method= "REML")	0.067
Smelt	0	DFS areas	gam(presence~ subarea + s(year,by=subarea, bs="tp", k=8), family=binomial, method= "REML")	0.064
Smelt	1+	DFS areas	gam(CPUE ~ subarea + s(year,by=subarea, bs="tp", k=8), family=gaussian, method= "REML")	0.192
all	0	Ems estuary	gam(CPUE ~ station + s(year, by=station, k=6), family=gaussian)	0.615
all	1+	Ems estuary	gam(CPUE ~ station + s(year, by=station, k=6), family=gaussian)	0.29
Herring	0	Ems estuary	gam(CPUE ~ station + s(year, by=station, k=6), family=gaussian)	0.748
Herring	1+	Ems estuary	gam(CPUE ~ station + s(year, by=station, k=6), family=gaussian)	0.52
Whiting	0	Ems estuary	gam(CPUE ~ station + s(year, by=station, k=6), family=gaussian)	0.297
Whiting	1+	Ems estuary	gam(CPUE ~ station + s(year, by=station, k=6), family=gaussian)	0.683
Cod	0	Ems estuary	gam(CPUE ~ station + s(year, by=station, k=6), family=gaussian)	0.708
Cod	1+	Ems estuary	gam(CPUE ~ station + s(year, by=station, k=6), family=gaussian)	0.771
Smelt	0	Ems estuary	gam(CPUE ~ station + s(year, by=station, k=6), family=gaussian)	0.542
Smelt	1+	Ems estuary	gam(CPUE ~ station + s(year, by=station, k=6), family=gaussian)	0.392

Table A2. Goodness of fit for GAM models on mean length at the end of the growing seasonat age 0 for the two comparisons.

Species	Comparison	Model	R2-adjusted
Plaice	Between Ems subareas	gam(mean length at age 0 (cm) ~ subarea + s(year, by=subarea, k=10) + s(sampling day of year), family=gaussian)	0.206
Sole	Between Ems subareas	gam(mean length at age 0 (cm) ~ subarea + s(year, by=subarea, k=10) + s(sampling day of year), family=gaussian)	0.316
Flounder	Between Ems subareas	gam(mean length at age 0 (cm) ~ subarea + s(year, by=subarea, k=10) + s(sampling day of year), family=gaussian)	0.134
Plaice	Between DFS areas	gam(mean length at age 0 (cm) ~ DFS area + s(year, by=DFS area, k=10) + s(sampling day of year), family=gaussian)	0.162
Sole	Between DFS areas	gam(mean length at age 0 (cm) ~ DFS area + s(year, by=DFS area, k=10) + s(sampling day of year), family=gaussian)	0.283
Flounder	Between DFS areas	gam(mean length at age 0 (cm) ~ DFS area + s(year, by=DFS area, k=10) + s(sampling day of year), family=gaussian)	0.0296

Table A3. Results of the linear models of the effect of temperature sum over the growing season on fish condition. Analayses were carried out for 0, 1 and 2 year old fish. The sign of the temperature effect (last column) is indicated by colour to illustrate positive and negative effects.

species	response	explanatory variable	factor levels	F-value	p value	coefficient
plaice	condition	tempsum		49.2889	<0.001	**-1.052e-06**
		factor (age)	not shown here	10.7385	<0.001	
			age 1			-8.750e-04
			age 2			-1.661e-03
		factor (area)	not shown here	3.5342	<0.001	
		tempsum*factor(age)		1.7803	ns	
sole	condition	tempsum		26.2190	<0.001	**7.739e-08**
		factor (age)		37.6419	<0.001	
			age 1			-1.982e-04
			age 2			-1.575e-03
		factor (area)	not shown here	4.7751	<0.001	
		tempsum*factor(age)		6.8836	<0.01	
			tempsum*age1			2.862e-07
			tempsum*age2			1.273e-06
dab	condition	tempsum		10.6863	<0.01	**-7.982e-07**
		factor (age)		3.3442	<0.05	
			age 1			-5.447e-03
			age 2			-1.985e-03
		factor (area)	not shown here	2.9749	<0.001	
		tempsum*factor(age)		5.3045	<0.01	
			tempsum*age1			2.173e-06
			tempsum*age2			7.926e-07
flounder	condition	tempsum		21.9378	<0.001	**1.011e-06**
		factor (age)		3.0928	<0.05	
			age 1			-3.100e-04
			age 2			1.244e-03
		factor (area)	not shown here	4.4516	<0.001	
		tempsum*factor(age)		0.4256	ns	

Justification

Report C092/22
Project Number: 4316100300

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

Approved: Dr. L. van Walraven
DLO Onderzoeker

Signature:

Date: 2 januari 2023

Approved: Dr. Ir. T.P. Bult
Director

Signature:

Date: 2 januari 2023

Wageningen Marine Research
T +31 (0)317 48 7000
E: marine-research@wur.nl
www.wur.eu/marine-research

Visitors’ address

- Ankerpark 27 1781 AG Den Helder
- Korringaweg 7, 4401 NT Yerseke
- Haringkade 1, 1976 CP IJmuiden

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