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Regime shift and changes in sediment morphology driven by sea level rise affect abundance of migratory waders

Karsten Laursen¹ · Thomas Bregnballe¹ · Romke Kleefstra² · John Frikke³ · Klaus Günther⁴ · Menno Hornman² · Claus L. Pedersen¹ · Jan Blew⁴ · Anders Pape Møller⁵

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Abstract

Regime shifts are likely to have strong impacts on all trophic levels and their interactions. In addition, weather conditions and sea level rise together with tidal currents may change sediment morphology in coastal areas and estuaries. Here, we studied the effects of these drivers of ecosystems on abundance of seven wader species feeding on macrozoobenthos in the German sector of the Wadden Sea. We hypothesized that regime shift caused decreases in wader abundance and that changes in sediment morphology driven by sea level rise and tidal amplitude affected these changes. We analyzed numbers of waders on a short term, 1998–2016, that matched a large-scale geographical study of sediment morphology in the German sector, and at a long term, 1987–2019. Changes in numbers of waders were estimated as slope of coefficients of the trends of wader species numbers in the two periods. The average (se) year of decreases in numbers of waders was initiated for most species and tidal basins in the year 1992 (± 0.4) that followed a regime shift in the Southern North Sea and in the Wadden Sea in 1988–1989. There were no statistical differences between the years when numbers of waders started to decrease between the northern and the southwestern tidal basins of the German sector, indicating that the drives affected both coastal sections simultaneously. Significant relationships were found between slopes of coefficients of wader species and sediment morphology and physical features as sea level rise and tidal amplitude. Relationships were most pronounced for the long term, 1987–2019 compared to the short term, 1998–2016. We conclude that regime shift and changes in sediment morphology driven by sea level rise and sediment change can affect abundance of migratory wader species in large estuaries and shallow coastal waters.

Keywords Climate change · Population development · Sediment morphology · Shorebirds · Tidal amplitude · Wadden Sea

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Zusammenfassung

Meeresspiegelanstieg verursachte tiefgreifende Veränderungen in der Sedimentmorphologie und beeinflusst die Populationsgrößen ziehender Watvögel.

Im Internationalen Wattenmeer finden tiefgreifende Veränderungen statt, welche erhebliche Auswirkungen auf alle trophischen Ebenen und deren Interaktionen haben können. Wetterbedingungen und Meeresspiegelanstieg können in Kombination mit den Gezeitenströmungen die Sedimentmorphologie an den Küsten- und Mündungsgebieten verändern. Wir untersuchten die Auswirkungen dieser ökologischen Treiber auf die Populationsentwicklungen von sieben Watvogelarten innerhalb des deutschen Wattenmeergebiets, welche sich von Macrozoobenthos ernähren. Es wird die Hypothese aufgestellt, dass diese tiefgreifenden Veränderungen zu abnehmenden Trends der Watvogelpopulationen führen; das ist ursächlich durch Änderungen in der Sedimentmorphologie bedingt, welche wiederum durch den Meeresspiegelanstieg und den geänderten Tidenhub verursacht werden. Wir haben einen Kurzzeit-Trend der Watvogelzahlen für die Zeitperiode 1998 bis 2016 analysiert, für welche eine umfangreiche geographische Untersuchung der Sedimentmorphologie im Deutschen Wattenmeer vorlag, sowie einen Langzeittrend von 1987 bis 2019. Für die beiden betrachteten Zeitperioden wurde jeweils die Steigung der Regressionsgraden der Watvogeltrends geschätzt. Im Mittel begannen die abnehmenden Trends für die meisten Watvogelarten im Jahr 1992 (± 0.4), welches auf tiefgreifende Veränderungen in der südlichen Nordsee und im Wattenmeer in den Jahren 1988–1989 folgte. Für die deutschen nördlichen und südlichen Wattengebiete konnte kein statistisch signifikanter Unterschied zwischen den Jahren, in welchen der abnehmende Trend begann, gefunden werden; das weist darauf hin, dass diese Treiber alle Wattenmeergebiete gleichzeitig betreffen. Die Zusammenhänge zwischen den Trends der untersuchten Watvogelarten (hier Steigung der Regressionsgeraden) und der Sedimentation bzw. Erosion sowie Parametern des Meeresspiegelanstiegs und des Tidenhubs sind statistisch signifikant. Die Zusammenhänge sind für den Langzeittrend (1987–2019) stärker ausgeprägt als für den Kurzzeittrend (1998–2016). Somit stellen wir fest, dass die tiefgreifenden Veränderungen vor allem der Sedimentmorphologie, ausgelöst durch Meeresspiegelanstieg und folglich Änderungen in der Sedimentzusammensetzung Auswirkungen auf die Watvogelpopulationen großer Ästuare und flacher Küstengewässer haben kann.

Introduction

Regime shifts in ecosystems are defined as sudden change or changes that affect several trophic levels, leading to rapid ecosystem reorganization. These shifts are generally thought to be driven by external perturbations (e.g., climatic fluctuations, overexploitation, eutrophication and invasive species), but the exact mechanism is often unclear (Andersen et al. 2009). Some regime shifts have strong impact on regional and local weather conditions affecting wind speed and frequency of storms (Hurrell and Trenberth 2010). It is common that a diversity of organisms is affected, positively or negatively by changes in these broad-scale weather patterns. Climate implies diverse patterns of environmental conditions on organisms at all trophic levels and their interactions (Moreno and Møller 2011; Philippart et al. 2017). In the southern North Sea and in the Wadden Sea, regime shifts occurred in the marine ecosystem in 1979 and 1988 (Weijerman et al. 2005). These regime shifts were triggered by shifts in a number of environmental factors including changes in salinity and weather and affected a diverse group of organisms in the ecosystem.

Sediment morphology is a product of wind force, wind direction, water currents, tidal amplitude and sea level rise (Reineck 1983; Benninghoff and Winter 2019). The tidal current plays a major role in sediment transport, and a coastal area like the German Bight with high tidal amplitudes, exposure to high wind force and strong currents is highly dynamic when it comes to the composition of

sediments and the distribution of different sediment types (Oost et al. 2017).

For several waterbird species, population trends differ between different parts of the Wadden Sea. In the southwest and northeast regions (The Netherlands and Denmark), numbers have mostly been stable or increasing, whereas in the central parts in Lower Saxony and Schleswig–Holstein, numbers of waterbirds have tended to decrease (Ens et al. 2009; Laursen et al. 2010; Waser 2018). These differences applied mainly to species that depend on intertidal flats for feeding (Blew et al. 2016; van Roomen et al. 2012). Recent information of morphological changes of the intertidal flats in the German Wadden Sea has been presented by Benninghoff and Winter (2019) giving data on accretion and erosion of the intertidal flats and subtidal deeps.

Here, we assume that the abundance of waders in coastal areas across continents will partially be impacted by sediment and weather conditions. We examine the hypothesis that a regime shift caused by changes in physical features as wind and tidal amplitude would lead to modifications in sediment morphology which would cause changes in habitat quality and thus wader numbers (Laursen et al. 2010). We analyze changes in numbers of birds in relation to the broad-scale pattern of change in sediment morphology and weather conditions. We do so by examining relationships between abundance of waders in the Wadden Sea and prevailing patterns of regime shifts and sediment morphology, relying on

long-term data collected during 1987–2019 (Kleefstra et al. 2021).

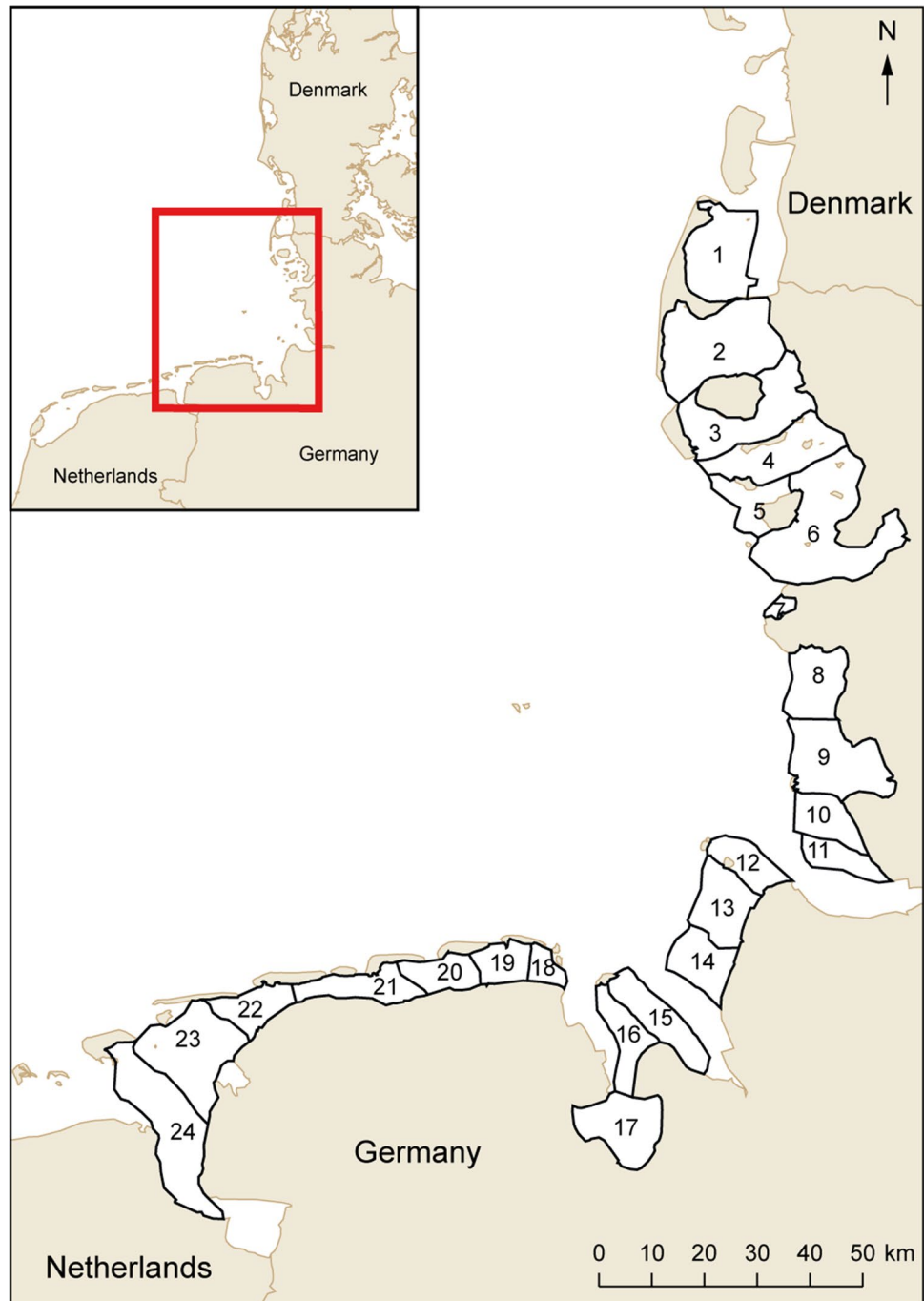
Materials and methods

Wader numbers

Since 1987, waterbird populations were monitored in the Wadden Sea under the Trilateral Monitoring and

Assessment program on a regular and systematic base (van Roomen et al. 2012; Kleefstra et al. 2021). Here, we focused on seven common and widespread wader species that use the intertidal flats for feeding: Eurasian Oystercatcher *Haematopus ostralegus* (Oystercatcher), Pied Avocet *Recurvirostra avosetta* (Avocet), Grey Plover *Pluvialis squatarola*, Dunlin *Calidris alpina*, Bar-tailed Godwit *Limosa lapponica*, Eurasian Curlew *Numenius arquata* (Curlew) and Common Redshank *Tringa totanus* (Redshank). For these species, data were extracted from

Fig. 1 Map showing the German sector of the Wadden. The tidal basins are shown together with basin number. There was no information on sediment morphology for tidal basin no. 7 and 22. Insert is the southeastern part of the North Sea



the Joint Monitoring of Migratory Bird database for 24 tidal basins in the German sector of the Wadden Sea for a short-term period 1998–2016, which coincides with large-scale sediment analyses (Benninghoff and Winter 2019) and a long-term period 1987–2019 (Fig. 1). Sites for the bird count data were combined so they fitted the extent of tidal basins used in the sediment analyses obtained by Benninghoff and Winter (2019). One exception is the tidal basin no. 15, which was analyzed as three tidal basins in the study of Benninghoff and Winter (2019). In the present study, average values of sediment variables were calculated for these three tidal basins and used for tidal basin no. 15.

For tidal basins, trend lines for each species were calculated and the slope coefficient estimated (see ESM, Electronic Supplementary Material). To compare the reliability of slope coefficients average bird numbers were estimated for 1998–2016 and 1987–2019. The long period was included in the analysis since we assume that the short period is a part of a continuum of processes in the environment during more years.

Regime shifts, sea level rise and tidal amplitude

Weijerman et al. (2005) identified regime shifts in 1988 in the southern North Sea and the Wadden Sea. Dippner et al. (2012) identified a biological regime shift in the southern North Sea and the Baltic Sea in 1988/1989. The two analyses confirm that a regime shift in the southern North Sea and the Wadden Sea took place in 1988 or in 1988/1989. In the present study, we identified the effect of a regime shift as a year with maximum number of waders after which the number decrease throughout the period considered. To analyze regime shifts in the German sector we identified for each species of wader and each tidal basin the year with maximum number during the long term, 1987–2019. In some cases, the number of waders did not decrease after the year with maximum number but a second and smaller peak appeared, after which the number decreased throughout the period. In such cases, we took a conservative approach and the year of the second peak were selected. Years with maximum numbers were identified in 107 cases (see ESM).

Information on sea level rise in the German sector of the Wadden Sea was analyzed by Wang et al. (2013) during 1993–2011. Estimates of average sea level rises were from north to south: 6.6 (± 3.2) mm year⁻¹ at southern Sylt, 3.7 (± 2.3) mm year⁻¹ at Cuxhaven and 2.2 (± 2.5) mm year⁻¹ at Norderney. To quantify sea level rise in the German sector, we assign tidal basins no. 1–6, the value 6.6 mm year⁻¹; tidal basins no. 7–13, the value 3.7 mm year⁻¹; and tidal basins no. 13–24, the value 2.2 mm year⁻¹. Information on tidal amplitudes was taken from Postma (1983).

Large-scale data of sediment morphology

Results of temporal changes of tidal flat morphology in the German sector of the Wadden Sea were presented by Benninghoff and Winter (2019), using homogeneous and comparable datasets from tidal basins obtained during 1998–2016. The main source was a set of digital elevation models of tidal surface available in a 50 × 50 m grid. To derive a consistent dataset on a year-to-year basis, data were merged by use of spatio-temporal interpolations. The compilation includes data from shipborne echo sounder, LiDar and profile measurement surveys, with a highly varying density of measuring points (Benninghoff and Winter 2019). Data on sediment morphology were provided by Benninghoff and Winter (pers. comm.). Sediment data were not estimated for tidal basin no. 7 and 22 (Fig. 1).

Statistical methods

Relationships were analyzed using linear ANOVA models with GLM procedure. Slope of coefficients for trends of seven wader species recorded during 1998–2016 as dependent variable were analyzed in relation to ratio of change of intertidal flat areas, intertidal flat erosion or accretion (mm year⁻¹), subtidal deep erosion or accretion (mm year⁻¹), tidal amplitude (m), sea level rise (mm year⁻¹) and cross over effects of ((intertidal flat erosion or accretion, mm year⁻¹) * (sea level rise, mm year⁻¹)) as explanatory variables. Slope of coefficients were standardized for each species to reduce variation and to give the species the same statistical weight. During the standardization, data were rescaled to have a mean of zero and a standard deviation of one (unit variance). SAS Guide 7.1 was used for the statistical analyses (SAS 2017).

Results

Slope coefficient and number of waders

There were significant correlations between number of individual of waders counted in the tidal basins and the slope of coefficients estimated during the short term, 1998–2016 (Spearman correlation Coefficient = 0.9096, $p < 0.0001$, $N = 141$) and the long term, 1987–2019 (Spearman Correlation Coefficient = 0.9923, $p < 0.0001$, $N = 141$).

Short- and long-term numbers of waders

All seven wader species have decreased in numbers in the short term, 1998–2016, in the German sector (see ESM). The average decrease was – 19.1% and the range was

– 2.3% for Curlew and – 28.0% for Redshank. Average slope coefficients of the wader species are shown for the tidal basins (see Fig. 3C). During the long term, 1987–2019, the decrease amounted to – 33.0% on average and the range was – 12.3% for Curlew and –43.8% for Redshank. Comparisons between the northern part (tidal basins no. 1–10) and the southwestern part (tidal basin no. 11–28) showed no statistical differences between the proportions of species for which a decrease was recorded. Data for the tests were pooled for the short and the long terms, and log transformed (Paired *t* test: $t = -0.34$, $p = 0.74$, $df = 13$).

Regime shift

The mean (se) of the year when numbers of individuals started to decrease for each wader species and tidal basin was 1992.3 (± 0.4 , $N = 107$, Table 1). As an example, the development in numbers during 1987–2019 is shown for four wader species in tidal basin no. 10 in the northern and for tidal basin no. 23 in the southwestern parts of the German sector (Fig. 2). There were no significant differences between the northern basins and the southwestern basins

in the average (se) year when decreases started (1991.3 (0.4) versus 1992.5 (0.4), one-way ANOVA: $F = 1.182$, $p = 0.1803$, $df = 106$). In addition, there were no significant differences between the species in the year of the start of the decrease in numbers (one-way ANOVA tests in which species were tested against the years with maximum number of Oystercatcher; for all tests ($p > 0.05$)).

Sediment morphology accretion and erosion

There was a general mean (se) accretion of 9.0 (± 1.1) mm year⁻¹ of the intertidal flats in the German Wadden Sea sector during 1998–2016, with a range of – 3.9–22.4 mm year⁻¹ with the largest values in the central tidal basins (Fig. 3A). All intertidal flats increased in size except for tidal basin no. 1 and no. 12 (ratio of area of intertidal flats in relation to total area of the tidal basin) and the range was – 0.05 – 0.207 (without unit; Fig. 3B). All data shown are from Benninghoff and Winter (2019).

Table 1 The average year of shifts of numbers of individuals for seven wader species in each tidal basins in the German sector of the Wadden Sea during 1987–2019. In the following cases, a year of shift in trends was not recorded: (s) if numbers were stable during the

period; (i) if numbers were increasing during the period without a clear initiation, and (–) if the counted numbers were insufficient during the period

Tidal basin no	Oystercatcher	Avocet	Grey Plover	Dunlin	Bar-tailed Godwit	Curlew	Redshank	Average
1	1987	1997	1992	1987	1987	1987	1987	1987.7
2	1994	1994	1994	1994	1993	i	1994	1993.8
3	1994	1995	1993	1994	1994	s	1994	1994.0
4	1994	–	1993	1990	1989	1989	1992	1991.2
5	1990	1995	1993	1992	1990	s	s	1992.0
6	1993	1991	1994	1992	1989	1994	1994	1992.4
8	1990	2001	1992	1992	1989	1987	–	1991.8
9	1989	1993	1993	1992	1996	1995	1992	1992.9
10	1992	–	–	–	–	–	1992	–
11	1994	–	–	s	–	–	–	–
15	–	i	1991	1991	–	i	1987	1989.7
16	1991	1994	1992	1992	1995	1996	1992	1993.1
17	1996	1991	1992	1992	1990	1988	1987	1990.7
18	1995	1993	1994	1990	2002	1994	1987	1993.6
19	1987	1994	1995	i	1996	1995	1987	1992.3
20	1991	1992	1994	s	i	s	1993	1992.5
21	1987	1992	1994	s	1995	1995	1995	1993.0
22	1992	1993	1994	1993	s	1997	1994	1993.8
23	1992	2001	i	i	1992	i	1995	1995.0
24	1993	1993	1993	s	i	s	1993	1993.0
Average (se)	1991.6 (0.6)	1993.7 (0.9)	1993.1 (0.3)	1991.6 (0.5)	1992.6 (1.1)	1992.5 (1.2)	1991.5 (0.8)	1992.4 (0.3)

In addition, tidal basins no. 12–14 had insufficient count data. See Methods for more information

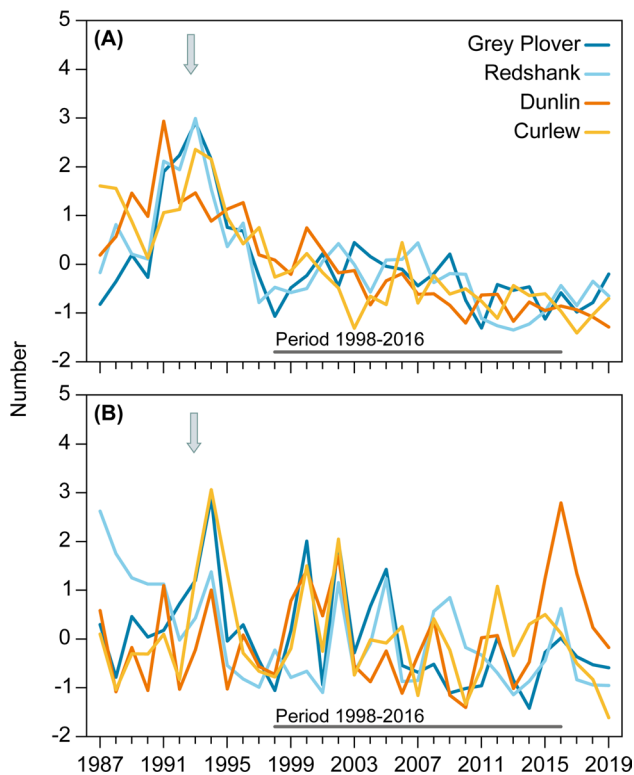


Fig. 2 Numbers (standardized) of individuals of four wader species during 1987–2019 in **A** tidal basin no. 10 and in **B** tidal basin no. 23 in the German sector of the Wadden Sea. Arrows indicate the average year (1992) when wader numbers started to decrease. The short-term period 1998–2016 is indicated. See main text for standardization of numbers

Slope of coefficients, sediment morphology and physical features of tidal basins

The analyses of slopes of coefficients for trends in numbers of individuals of waders during the short term, 1998–2016, show significant relationships with tidal amplitude, sea level rise and changes in sediment morphology such as increase in intertidal area and accretion (Table 2). The levels of statistical significance of some of the relationships were, however, more pronounced during the long term, 1987–2019. Relationships between slope coefficients for Grey Plover and sediment morphology such as vertical changes and area changes of intertidal flats are shown as examples of the results (Fig. 4).

Discussion

Regime shift and changes in sediment morphology driven by sea level rise were identified as factors affecting wader abundance in the German sector of the Wadden Sea, acting in two dimensions, temporal and horizontal.

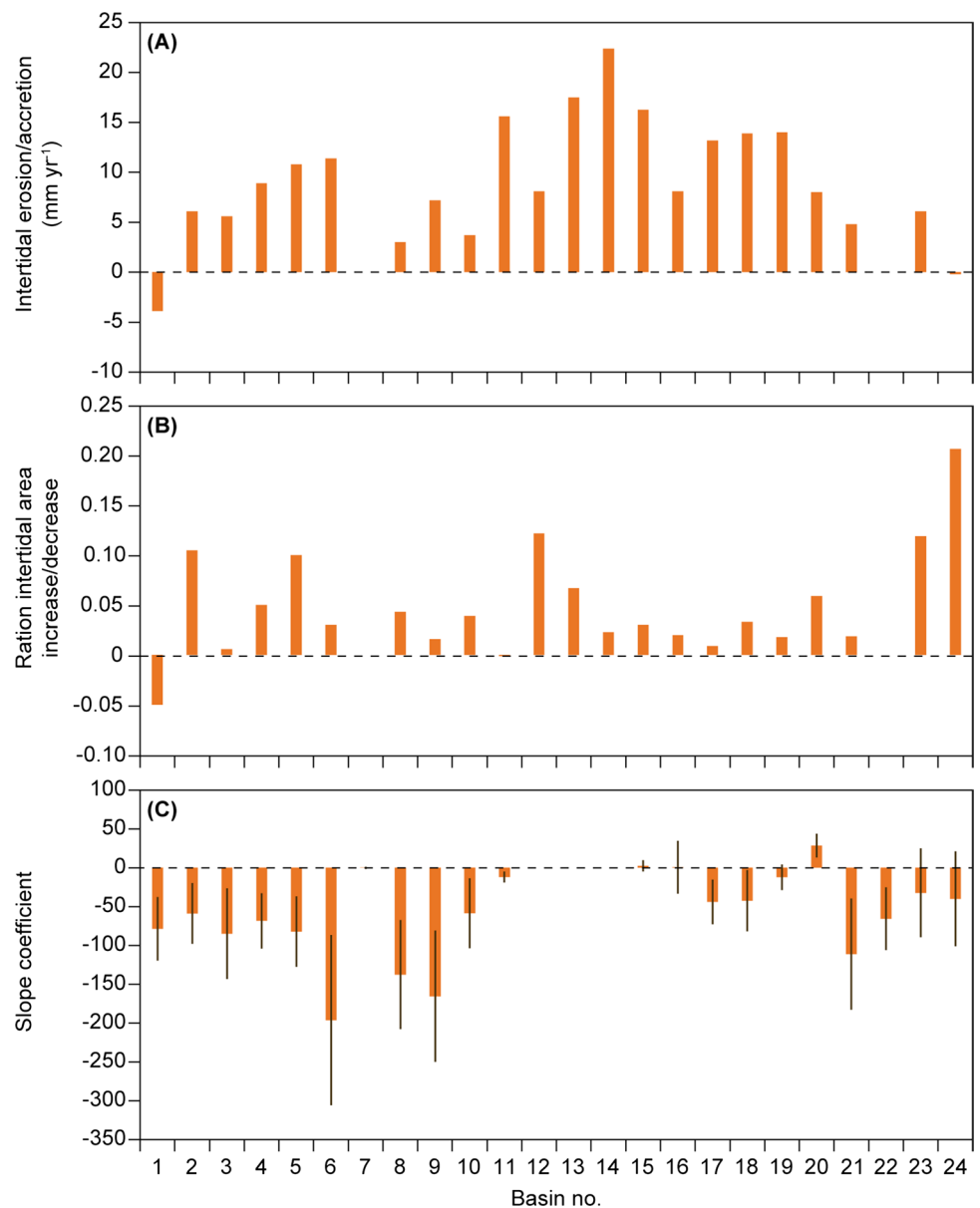
Regime shift

Analysis of climate and biological data reveal that a regime shift took place in the southern North Sea in 1988 (Weijerman et al. 2005) or in 1988/1989 (Dippner et al. (2012)). Regime shift was probably initiated by changes in the northern branch of the Gulf Stream, which reach northwestern Europe and the North Sea. Changes in marine conditions caused changes in temperature and salinity in the North Sea as well as changes in climate and biological processes affecting all trophic levels (Dippner et al. 2012). The year 1989 coincides with the highest water temperature (11.7 °C) so far measured in Mars Diep, The Netherlands since 1880 (Philippart et al. 2017). Compared to the regime shift in 1988/1989, the number of individuals of waders in the German sector started to decrease 3 years later in 1992, which may be attributed to a delayed response of the ecosystem. The wader species are all feeding on the intertidal flats at low water taking macrozoobenthos species as worms, mussels and crustaceans (Horn et al. 2019). Long-term studies in the Wadden Sea show that biomass of macrozoobenthos communities have decreased after 1990, and have stayed at a low level until about 2010 (Drent et al. 2017). However, no macrozoobenthos species important as food for wader species have decreased, except for blue mussels *Mytilus edulis*, which probably can explain the decreasing numbers of Oystercatcher in the Wadden Sea (van Roomen et al. 2012, van de Pol et al. 2014).

Sediment morphology and sea level rise

Abundance of waders in the German sector was connected to changes in sediment morphology. The relative number of individuals of waders estimated as slopes of coefficients increased together with increases in the area of tidal flats, accretion of the flats, tidal amplitude and sea level rise. In addition, we found negative relationships between combined effects of the intertidal flat accretion and sea level rise, indicating a relative decrease in wader numbers in tidal basins with a high increase of sea level. Benninghoff and Winter (2019) gave no information on sediment composition, although they suggested that the sediment in the German sector of the Wadden Sea may had become more muddy in general. The wader species prefer different sediment compositions with some preferring sandy sediments and other preferring muddy sediments or a mixture of sediments (Vanerman et al. 2006). Our results do not provide information of this aspect, and more detailed information of sediment composition and distribution in the Wadden Sea is, therefore, necessary. However, some indications were found in the tidal basins in the southwestern parts (tidal basins no. 23–24; Table 1) where species as Dunlin, Bar-tailed Godwit

Fig. 3 Sediment morphology shown for **A** intertidal flat erosion or accretion (mm year^{-1}), **B** ratio of the intertidal flat area in relation to the total area of the tidal basin and **C** average (se) slope coefficient of wader species in tidal basins the German sector of the Wadden Sea. Data in **(A)** and **(B)** are based on Benninghoff and Winter (2019). There were no or insufficient data for tidal basins no. 7 and 22 (A and B) and no. 12–14 (C)



and Curlew that prefer muddy-sandy mixed sediments (Vanerman et al. 2006, Waser 2018) showed stable or increasing numbers (see Fig. 2B).

Abundance of waders

The seven wader species included in this study occur in the Wadden Sea during the non-breeding season in highly variable numbers. When staging, the waders are living in a complex network of primary producers and benthos species acting as food for higher trophic levels. Moreover, the waders in the Wadden Sea may compete for space and resources (Horn et al. 2019). The seven wader species are all decreasing in numbers in the German sector of the Wadden Sea, but some species as Grey Plover,

Bar-tailed Godwit and Curlew are stable or increasing in numbers in the Danish and the Dutch sectors (Ens et al. 2009; Kleefstra et al. 2021). It raises the question about sediment morphology in the two sectors. In the Dutch sector, studies of sea level rise and sedimentation in six large tidal basins showed that the current sedimentation rate of about 2.5 mm year^{-1} is sufficient to keep up with the extent of sea level rise until 2100 (Wang et al. 2018), whereas the intertidal flats in the smaller basins will mainly reduce in average height (Huisman et al. 2022). This indicates a sedimentation rate $< 8 \text{ mm year}^{-1}$ for the Dutch sector. In the Danish sector, import of fine-grained sediment in three tidal basins showed an accretion of tidal flats of 3.5 mm year^{-1} (Pedersen and Bartholdy 2006). It was estimated that the sedimentation rate will be able to

Table 2 Linear ANOVA models with GLM procedure testing relationships between slope of coefficients of seven wader species recorded in tidal basins in the German sector of the Wadden Sea during 1998–2016 (upper panel) and during 1987–2019 (lower panel) as dependent variables in relation to ratios of changes of intertidal area,

intertidal flat erosion or accretion (mm year^{-1}), subtidal deep erosion or accretion (mm year^{-1}), tidal amplitude (m), sea level rise (mm) and cross over effects of ((intertidal flat erosion or accretion, mm year^{-1}) * (sea level rise, mm)) as explanatory variables

Variables, period 1998–2016	<i>F</i>	<i>df</i>	<i>p</i>	Estimate	SE
Intercept	10.60	1	0.0015	− 3.5003	1.0749
Ratio intertidal area/total basin area, extension/decrease	6.08	1	0.0151	6.1312	2.4870
Intertidal erosion/accretion, mm year^{-1}	2.78	1	0.0982	0.0918	0.0551
Subtidal deep erosion/accretion, mm year^{-1}	4.2	1	0.0284	− 0.0170	0.0077
Tidal amplitude, m	6.24	1	0.0139	0.8471	0.3392
Sea level rise, mm	5.24	1	0.0238	0.2402	0.1049
(Intertidal erosion/accretion, mm year^{-1}) * (Sea level rise, mm year^{-1})	5.13	1	0.0254	− 0.0247	0.0109
Variables, period 1987–2019	<i>F</i>	<i>df</i>	<i>p</i>	Estimate	SE
Intercept	11.56	1	0.0009	− 3.6022	1.0595
Ratio intertidal area/total basin area, extension/decrease	7.79	1	0.0061	6.7714	2.4264
Intertidal erosion/accretion, mm year^{-1}	8.68	1	0.0039	0.1582	0.0537
Subtidal deep erosion/accretion, mm year^{-1}	5.45	1	0.0212	− 0.0171	0.0075
Tidal amplitude, m	3.86	1	0.0519	0.6589	0.3355
Sea level rise, mm	11.13	1	0.0011	0.3418	0.1025
(Intertidal erosion/accretion, mm year^{-1}) * (Sea level rise, mm year^{-1})	13.81	1	0.0003	− 0.0395	0.0106

Figures in bold font are statistically significant. Slope of coefficients are standardized

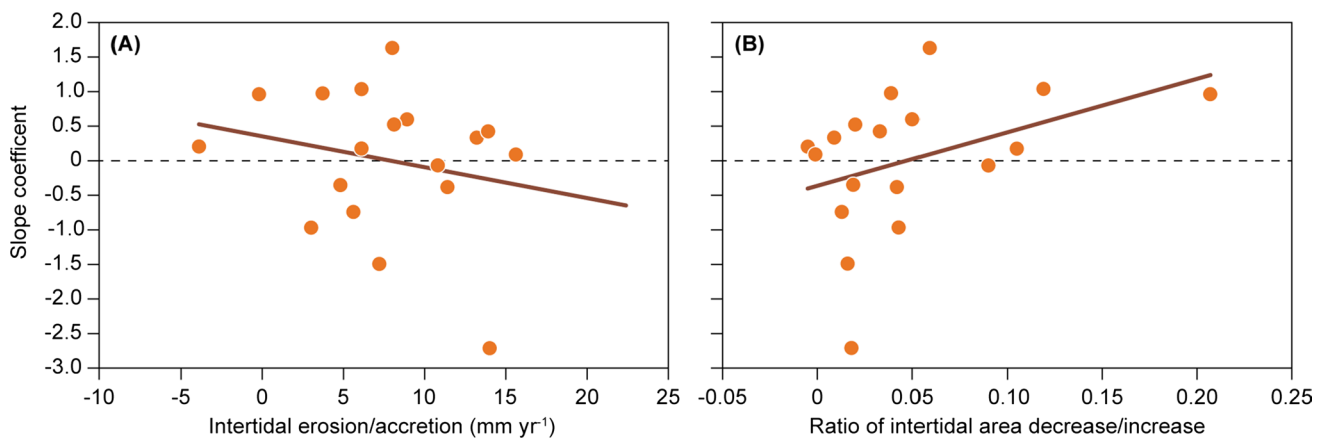


Fig. 4 For Grey Plover relationships between slope of coefficients and **A** intertidal flat erosion or accretion (mm year^{-1}) and **B** ratio of intertidal flat area increase or decrease are shown for tidal basins in

the German sector of the Wadden Sea as examples of the results. A positive slope corresponds to an increase in numbers of individuals. Trend lines are shown for illustration purpose

follow a sea level rise of 0.6–4 mm year^{-1} (Ingvarsen et al. 2006a, b). These scenarios for the Dutch and Danish sectors indicate smaller accretion of the intertidal flats compared to the German sector with a mean accretion of 9.0 mm year^{-1} and up to 22.4 mm year^{-1} (Benninghoff and Winter 2019). This could indicate that modest changes in sediment accretion were related to relatively small changes in wader numbers. However, our results show that the relationships are far more complex. Accretion of the tidal flats

is only one of many parameters that influence numbers of waders, and inclusion of other variables is necessary to analyze changes in wader numbers. An obvious example of how other variables affect wader numbers is given in Fig. 2, showing that in addition to decreasing numbers around 1992, the wader species show synchronous changes in numbers in tidal basin no. 23, i.e., in the southwestern part of the German Wadden Sea (Fig. 2B). This shows that more detailed studies are needed to analyze and describe

these changes and relationships between numbers of waders and sediment and probably other variables as well.

Waders are using tidal areas and estuaries worldwide for feeding during migration and several species depend on these habitat types for building up body stores (Ens et al. 1990; Buehler and Piersma 2008; Rakhimberdiev et al. 2018).

However, changes in the physical structure of the tidal areas and estuaries are seldom considered when analyzing drivers for changes in population size of these species. The results found here suggest that sediment changes may contribute to explain increases and decreases in wader populations. Such knowledge is useful for managers at the local as well as at the regional scale to understand population dynamics, and to identify drivers caused by natural and anthropogenic processes.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10336-023-02056-w>.

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Data availability Data is available at reasonable request.

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