Shifting beach wrack composition in the SW Baltic Sea and its effect on beach use

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ABSTRACT. Beach visitors rate beach quality in large part by its appearance. Removal of natural beach litter (called beach wrack) has, therefore, high priority for beach managers in coastal areas dependent on revenues from tourism. Focusing on the German Baltic Sea coast, the amount of beach wrack has increased by a factor of approximately 3.4 between 1977 and 2012/2013. At the same time, the composition of macrophyte communities underwent a severe change from late successional stages (eelgrass and bladder wrack) toward more ephemeral communities. Correspondingly, the contribution of bladder wrack to seaweed litter alone dropped from 75% in 1977 to 18.1% today, while the contribution of ephemeral and nutrient-opportunistic seaweeds increased by a factor larger than 6.2 to approximately 44%. Such seaweed opportunists could have a higher potential for olfactory nuisance than late successional macrophytes. To test this hypothesis, odors extracted from equal amounts of nutrient-opportunistic and non-opportunistic species that had been partially degraded under equal conditions were compared in a public survey. Participants graded the smell of opportunistic species, in particular Ceramium tenuicorne, consistently as more intense and less pleasant than the odor of non-opportunistic species. The particularly high potential of Ceramium litter and the relatively lower potential of eelgrass litter for deterrence were confirmed in field experiments. We conclude that the documented compositional shift in macrophyte communities at German Baltic Sea coasts since the onset of eutrophication has caused a shift of beach wrack composition toward species with a higher potential for olfactory deterrence, which could explain recent concerns of beach managers about beach wrack despite the limited increase of biomass in the study area.

Key Words: beach management; beach user behavior; beach wrack; coastal eutrophication; nuisance seaweed; seaweed odor

INTRODUCTION

In the Baltic Sea region, as worldwide, coastal tourism and beach recreation provide important employment opportunities and income (Haller et al. 2011; Pendleton 2007). In general, the perception of beach quality by the public is based upon appearance of the water and presence of litter pollution (Vaz et al. 2009, Williams and Barugh 2014). Beach management, therefore, usually gives high priority to the removal of any debris of anthropogenic or natural origin, typically by mechanical grooming, that causes considerable costs. For example, authorities in seaside resorts on the German Baltic Sea coast annually remove 269 kg litter per m of beach, which on average costs 38 € per m (Mossbauer et al. 2012). The annual removal of estimated 100,000 m³ of litter from beaches in Brittany, France, costs between 10 and 150 US$ per m³ (Charlier et al. 2008).¹

Natural beach litter, also referred to as beach wrack, mostly consists of seaweed and sea grass in different stages of decay. Such beach wrack plays a key role in Baltic Sea shoreline ecosystems, providing important resources to organisms (Malm et al. 2004) and stabilizing soft bottom substrates. Frequent removal of such beach wrack by grooming reduces species richness and ecological diversity of sandy coasts and increases the risk of beach erosion (Defeo et al. 2009, Gilburn 2012, Malm et al. 2004, Vanhooren et al. 2011). There are, thus, good arguments for removing beach wrack less frequently.

However, accumulations of drifting macrophytes increasingly cause problems in beach environments worldwide and there is often compelling evidence for a direct connection between this increase and anthropogenic nutrient supply (Schramm and Nienhuis 1996, Smetacek and Zingone 2013, Valiela et al. 1997). Seaweed communities typically respond to eutrophication with shifts toward more nutrient-opportunistic components (Troell et al. 2005), which may result in an increased nuisance potential of beach wrack. Significant changes of macroalgal communities after eutrophication have also been observed and documented at the 402 km long Baltic Sea coast of Schleswig-Holstein (Schramm and Nienhuis 1996, Voigt and Schramm 1991, Weinberger et al. 2020), where 34.8 million of overnight stays and 58.5 million of day visitors generated revenues of 4200 million € in 2019, providing 83,130 persons with a primary income (Ostsee-Holstein-Tourismus e.V. 2020).

Since beach wrack removal is relatively costly and has a significant negative effect on shoreline ecosystems, information on the nuisance potential of beach wrack (and the necessity of its removal) is relevant for sustainable beach management. The aim of this paper is to provide such information, building on three different approaches. First, we investigate if beach wrack in the area underwent significant compositional change toward more ephemeral and nutrient-opportunistic components. Historical records of beach wrack in the Baltic Sea area are very scarce. A first quantitative study was conducted in August 1977 (Grave and Moeller 1982). It was based upon aerial black-and-white photography and detected 900 kg of dry biomass per km of Schleswig-Holstein's Baltic Sea beaches. A repetition of this study in 2012, using exactly the same approach, found 2 833 kg km⁻¹, corresponding to an increase by a factor of 3.15 (Weinberger et al. 2020). An increase in this order of magnitude alone is unlikely

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to explain repeated media coverage and scientific publications (Mossbauer et al. 2012, Weinberger et al. 2020). However, compositional changes of beach wrack probably also occurred in the area, reflecting the documented change in species compositions of macroalgal habitats. We here report the results of an analysis of the recent beach wrack composition on Baltic Sea shores of Schleswig-Holstein and we describe changes since 1977. Second, we extract olfactory compounds from different types of beach wrack and, monitoring their perception in a public survey, we test the hypothesis that nutrient-opportunistic macrophytes have a higher potential for olfactory nuisance than those of later successional stages when they are present at similar density. Degrading beached biomass may release intensely odorous volatile compounds, and anoxic decomposition may even result in the production of toxic volatiles, such as hydrogen sulfide (H₂S), at detrimental concentrations (Tautziède et al. 2009). In addition, repeated coverage by the media (Die Welt 2009, Lübecker Nachrichten 2013, Ostsee-Zeitung 2013, 2015, Schleswiger Zeitung 2015, DeutschlandfunkKultur 2018) suggests that the odor emitted by beach wrack constitutes an important component of its nuisance potential toward beach visitors. Third, we report results of an observational field study of beach visitors’ behavior in response to different beach wrack which we had distributed at the beach.

METHODS

Analysis of beach wrack composition

To determine the quantity and composition of beach wrack along the Baltic Sea coast of the German state Schleswig-Holstein 13 sites were visited in 2012 and 2013 (Table 1). All selected sites were neither subject to beach cleaning, nor protected from waves by artificial infrastructures. Further, they represented the full salinity gradient and were characterized by various types of substratum composition and different main wind exposure directions. All sites were sampled in late summer (all but one in August, Table 1), to allow for a direct comparison with historical data obtained in August 1977 (Grave and Moeller 1982).

For samplings a point in the middle of the drift line marked by presence of beach wrack was selected randomly at each visited site. Two additional points in the drift line were marked in the exact distance of 10 m to the left and the right of the first point.

At each of the three points, the width of the drift line was measured with a measuring tape. Furthermore, the ground cover of beach wrack within a sampling frame (size: 40 cm x 40 cm) was estimated at each point and its thickness was measured at five different positions within the frame. All beach wrack that fell within each frame was collected in plastic bags, transported to the lab, and stored in a freezer. For analysis, all samples were thawed, rinsed with seawater to remove sand, and sorted into phylogenetic groups (Fucus, other Phaeophyta, Zostera, Ulva, other Chlorophyta, Rhodophyta). The sorted material was dried at 70°C to weight constancy and weighed. The biomass density per m of coastline at the sampling sites was calculated by multiplication of biomass present within the frame, 2.5 to extrapolate from the frame size of 0.4 m to 1 m, and the drift line width. To calculate mean densities and compositions of beach wrack at the sampling sites, data obtained at the three sampling points were averaged.

We compared wind intensities and directions in our sampling area in 2012 and 2013 - as well as in the reference period 1977, as wind must be expected to drive wave action and thereby the accumulation of marine biomass on beaches (Fig. S1). Within the two months during and preceding the sampling periods (1st of July and 31st of August) the main wind directions were W and SE in 2012, and W and ENE in 2013 (Fig. S1a). During the same two months in 1977 less wind from W and considerably more wind from N, NE and E was recorded (Fig. S1a). The average wind speed was 6.0 m s⁻¹ in 1977, but only 5.4 m s⁻¹ in 2012 and 5.5 m s⁻¹ in 2013. In particular, wind coming from SW, SE and N to E had higher average speeds in the reference period 1977 than in 2012 and 2013 (Fig. S1b). As a consequence, more air coming from sea (N to E) and less air coming from land (WNW to WSW) crossed the area in 1977 than in the latter two years (Fig. S1c, compare Fig. 2). This probably resulted in more wave impact on surveyed beaches during and immediately prior to the sampling period in 1977 than in 2012/2013.

Sampling of odorants from beach wrack

Six different macrophytes that are relatively frequent components of macroalgal blooms and beach wrack at the 13 sites were selected for extraction of odorous compounds. They represent the three main phylogenetic groups of marine macrophytes, namely Phaeophyta (Fucus vesiculosus and Dictyosiphon

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**Table 1.** Geographic coordinates and sampling dates of sites sampled for the quantification and characterization of beach wrack.

| Nr. | Site          | Geographic coordinates | Sampling dates          |
|-----|---------------|------------------------|-------------------------|
| 1   | Glücksburg    | 54° 50' 20.58" N, 9° 31' 06.53" E | 15.8.12; 18.8.13        |
| 2   | Neukirchen    | 54° 48' 11.91" N, 9° 44' 49.18" E | 15.8.12; 18.8.13        |
| 3   | Wackerballig  | 54° 45' 30.59" N, 9° 52' 43.83" E | 15.8.12; 18.8.13        |
| 4   | Schönhausen   | 54° 37' 51.46" N, 10° 01' 57.50" E | 15.8.12; 21.8.13        |
| 5   | Kiekut        | 54° 26' 53.22" N, 9° 52' 20.19" E | 15.8.12; 21.8.13        |
| 6   | Strande       | 54° 26' 48.52" N, 10° 11' 01.80" E | 15.8.12; 17.8.13        |
| 7   | Mönkeberg     | 54° 21' 09.54" N, 10° 10' 40.06" E | 11.8.12; 14.8.13        |
| 8   | Stein         | 54° 25' 03.76" N, 10° 15' 55.42" E | 16.8.12; 24.9.13        |
| 9   | Brasilien     | 54° 25' 23.36" N, 10° 23' 49.71" E | 11.8.12; 14.8.13        |
| 10  | Holchwitz     | 54° 19' 01.73" N, 10° 40' 42.45" E | 16.8.12; 29.8.13        |
| 11  | Grüner Brink  | 54° 30' 29.94" N, 11° 12' 04.22" E | 14.8.12; 19.8.13        |
| 12  | Kellenhufen   | 54° 11' 31.44" N, 11° 04' 07.98" E | 14.8.12; 29.8.13        |
| 13  | Brodtener Ufer| 53° 59' 32.52" N, 10° 50' 45.48" E | 14.8.12; 29.8.13        |
Assessment of public perception of beach wrack odors

To test our hypothesis that nutrient-opportunistic macrophytes have a higher nuisance potential than those of later successional stages we designed a public survey. The survey consisted of two parts. In the first part, respondents were asked face-to-face about their perception of four different Sniffin’Sticks. Fig. 1 illustrates the test sequence with the four Sniffin’Sticks. All participants started by sniffing the same control stick and were asked to rate its intensity and pleasantness. We used a six-item scale for intensity (1 = no smell to 6 = very strong odor) and a seven-item scale for pleasantness (-3 = very unpleasant to +3 = very pleasant). Subsequently, participants were presented a Sniffin’Stick with odor extracted from brown, green or red seaweed and asked to rate its intensity and pleasantness. After using the control stick again to neutralize any odor, they were presented another Sniffin’Stick with odor extracted from a seaweed of the same phylogenetic group as the first but with an opponent life strategy and again asked to rate intensity and pleasantness. Except for the control stick, participants never received the same Sniffin’Stick twice. Fifty percent of the participants first received odor from an opportunistic and vice versa for the remaining 50%. We distributed the different sequences of the sticks equally across genders. In the second part of the survey, respondents received a clipboard and had to fill out the remaining questions of the survey on their own. This second part of the survey included questions on socio-demographic characteristics.

We conducted the survey in summer 2016 in three places at the German Baltic Sea coast (Kiel, Eckernförde and Schönberg). In Kiel, we approached visitors at a major public festival (“Kiel Week”) and asked them to participate. In Eckernförde and Schönberg, two popular seaside resorts, we asked beach visitors. Table S4 in the appendix provides descriptive statistics of our sample of respondents. Since we found no significant difference between the subsamples in terms of socio-demographic characteristics, we analyzed the three samples jointly. In order to control for differences in the respondents’ overall ability to perceive odor, we normalized the odor intensity ratings. To do this, the rating of the control stick was subtracted from the ratings of the sticks with beach wrack extracts. The resulting normalized intensity ratings - as well as the pleasantness ratings - were tested for absence of statistically significant differences using repeated measures-2-way-ANOVA on ranks. As each participant rated odors of one nutrient-opportunistic and one non-opportunistic beach wrack species that both belonged to the same phylogenetic group, the group (green plants, brown algae or red algae) was used as between-subjects factor, while the life strategy (nutrient-opportunistic or non-opportunistic) was used as within-subjects factor.

Behavioral responses to beach wrack odor

To verify the different nuisance potentials of selected macrophytes, two experiments were conducted at a seaside resort, Eckernförde, that were based upon the manipulation of beach wrack and the subsequent hidden observation of the behavior of beach visitors. Located at the inner parts of a bay, Eckernförde has 4 km of sand beach that are a major source of income to this town of 22 000 inhabitants.

In experiment 1, two neighboring beach sections of (A) 106 m and (B) 30 m length that extended along the coastline southward and northward of the point 54°27.829’N 9°50.516’E were designated as experimental plots. On 17 August 2016, natural beach wrack already present on the site - consisting almost exclusively of eelgrass - was equally distributed with rakes along the drift line of both plots. This resulted in a 20-30 cm broad line of loose lying beach wrack with a mean fresh weight density of 333 g per m. In addition, plot B received 200 g per m of partially degraded Ceramium tenuicorne (for the resulting aspect see Fig.
Southeastern part of the coast. Filamentous red algae (primarily both years, while various algal opportunists dominated in the beaches in the Northwestern coastal sections of the study area in years within the same site. Sea grass and bladder wrack dominated. However, similar species compositions were often found in both composition of beach wrack is geographically highly diverse (Fig. 2, for the detailed data set see Tables S1 to S3 in appendix).

RESULTS

Beach wrack composition

The sampling conducted on Schleswig-Holstein’s Baltic Sea coast in late summer 2012 and late summer 2013 indicates that the composition of beach wrack is geographically highly diverse (Fig. 2, for the detailed data set see Tables S1 to S3 in appendix). However, similar species compositions were often found in both years within the same site. Sea grass and bladder wrack dominated beaches in the Northwestern coastal sections of the study area in both years, while various algal opportunists dominated in the Southeastern part of the coast. Filamentous red algae (primarily of the genus Ceramium, sometimes together with Vertebrata fucoides) and filamentous green algae (primarily of the genus Cladophora) contributed the overwhelming quantity of beach wrack in the South East, while the green algal genus Ulva (represented by Ulva compressa) dominated only one site located in the Kiel Fjord (Mönkeberg). Brown filamentous algae of the genera Pylaiella or Ectocarpus were the dominant beach wrack component at the most southern site (Brodtener Ufer) in 2012, but not in 2013. Additional components representing a wide spectrum of red seaweeds (genera Agarophyton, Delesseria, Cococylus, Ahnfeltia, Fucellaria), brown seaweeds (Chorda, Dictyosiphon) and green seaweeds (Cladophora) were occasionally detected at various sites, but not particularly abundant. The mean quantity of dried beach wrack along the coastline at the 13 visited sites was estimated to be approximately 4.0 kg m⁻¹ in 2012 (Table S1 in appendix) and 2.4 kg m⁻¹ in 2013 (Table S2 in appendix), the average of both years was 3.2 kg m⁻¹ (Table S3 in appendix). Compared to 1977 (Grave and Möller 1982) the mean relative contribution of Fucus to beach wrack was significantly reduced in 2012 and 2013 (Fig. 3).

Fig. 2. Quantity and composition of beach wrack at 13 sites along the Baltic Sea shore of Schleswig-Holstein in the two periods 12.8. to 16.8.2012 (top) and 14.8. to 24.8.2013 (bottom). Blue numbers correspond with site numbers given in Table 1. No beach wrack was detected in 2013 in site 4 (Schönhagen, see also tables S2A and S2B).
Perception of beach wrack odor nuisance potential
Survey respondents (Fig. 4A, Table S5) perceived the odor intensity of surface extracts generated from equal amounts of degrading macrophytes differently. They rated the odors of all three nutrient-opportunistic seaweeds as significantly more intense than odors of the corresponding non-opportunistic seaweeds of the same phylogenetic group. The mean rank difference between opportunists and non-opportunists was 1.03 on a scale ranging from 0 to 3. The odors of the opportunistic species Ceramium tenuicorne and Dictyosiphon foeniculaceus were rated as particularly intense, while extracts of the two non-opportunists Fucus vesiculosus and Zostera marina were rated as the least intense odors. The maximal rank difference (Ceramium vs. Zostera) was 1.66. The intensity also differed significantly between all three phylogenetic groups. The smell of red seaweeds was rated as the most intense and odors emitted by green macrophytes as the least intense. In addition, the pleasantness of odors emitted by opportunistic and non-opportunistic degrading macrophytes was perceived differently: the opportunists’ smell was perceived as significantly less pleasant (Fig. 4B, Table S6). Moreover, the two red seaweeds, Ceramium tenuicorne and Agarophyton vermiculophyllum, emitted more deterrent odors than the two brown seaweeds or the two green macrophytes. On average, odor emitted by the two late successional species Fucus vesiculosus and Zostera marina was rated as neutral (close to zero), but the smell of the opportunistic C. tenuicorne clearly as unpleasant (close to -1).

Experimental verification of nuisance potential
Avoidance of a whole beach section treated with C. tenuicorne at a density of 200 g m$^{-1}$ in addition to eelgrass at 333 g m$^{-1}$ was not observed and the contaminated section was even visited by significantly more persons than the neighboring uncontaminated section, which only harbored 333 g m$^{-1}$ of eelgrass (paired t-test: p = 0.0122; see Fig. 5A). Moreover, the willingness of beach visitors to step over the beach wrack was not significantly reduced when Ceramium was present (Wilcoxon matched pairs signed ranks test: p = 0.8457; Fig. 5B). However, three beach visitors in the section with Ceramium contamination were overheard complaining to each other about the smell of the beach wrack and the readiness of persons to stay in the close vicinity of this beach wrack was significantly reduced (paired t-test: p = 0.0276; Fig. 5C).

In contrast, presence of eelgrass alone had relatively little influence on the behavior of beach visitors (Fig. S4 in appendix). Their readiness to cross this beach wrack even at the highest densities of 2.2 to 15.6 kg m$^{-1}$ was not lower than their readiness to cross a drift line without any biomass (Mann-Whitney test: p = 0.6009, Fig. 6A, see also Fig. S3 in appendix). Only the readiness to stay in the close vicinity of beached eelgrass at such high densities decreased significantly (t-test: p = 0.0071, Fig. 6B), suggesting that C. tenuicorne beach wrack raised avoidance behavior in beach users at a lower concentration than Z. marina beach wrack.
DISCUSSION

Beach wrack producing macrophytes have been abundant habitat formers in Baltic Sea environments even before the onset of industrialization. Eelgrass (Zostera marina) typically formed extended meadows in close vicinity to the shore (Lehmann 1814) and one eelgrass shoot litters 6 to 30 leaves per year (Mateo et al. 2007). Correspondingly, large accumulations of eelgrass litter have already been observed 200 years ago in the region (Lehmann 1814). Another important component of beach litter in Baltic Sea environments is bladder wrack (Fucus vesiculosus), which is buoyant and drifts after detachment over long distances before it finally accumulates onshore (Rothäusler et al. 2015). In 1977 F. vesiculosus contributed 75% of the beach wrack on Schleswig-Holstein's Baltic Sea coast (Grave and Möller 1982).

Increasing amounts of drifting seaweeds are typically observed in coastal regions that are subject to particularly severe eutrophication, such as Brittany (Charlier et al. 2008) or northern central China (Zhou et al. 2015). Furthermore, in many cases the long-term temporal dynamics of macroalgal blooms reflect increases (Schramm and Nienhuis 1996) and decreases (Beusekom et al. 2009) in eutrophication. However, not all marine macrophytes benefit equally from nutrient supply. Ephemeral nutrient-opportunistic species that are capable of rapid nutrient uptake and rapid growth, but largely devoid of stored nutrient resources are typically limited by external nutrient supply. In contrast, slow-growing and long-living perennial macrophytes, such as Zostera or Fucus, that form the late successional stages of macrophyte habitats benefit much less from eutrophication (Bokn et al. 2003, Pedersen and Borum 1997, Pedersen et al. 2010).

This has also been observed and documented at the Baltic Sea coasts, where massive increases of nitrogen and phosphorous input occurred between 1965 and 1985, followed by only partial reductions (Fleming-Lehtinen et al. 2008, Lennartz et al. 2014). Subsequently, the typical late successional vegetation of shallow water was severely reduced in this area, due to increased competition with fast-growing nutrient opportunists: The standing stock of bladder wrack (Fucus vesiculosus) was reduced by 95% (Vogt and Schramm 1991) and local decreases were also reported for eelgrass (Zostera marina) (Messner and von Oertzen 1991). At the same time, various nutrient-opportunistic seaweeds became more abundant and the total standing stock of macrophytes rather increased (Schramm and Nienhuis 1996).

The data presented here hint at considerable variability in the distribution of beach wrack along the Baltic Sea coasts, which was already detected in 1977 (Grave and Möller 1982). However, the average beach wrack quantity detected in late summer in 2012 and 2013 (3.2 kg m⁻¹) corresponds with an increase by a factor of approximately 3.4 since 1977 (0.9375 kg m⁻¹, Grave and Moeller 1982). Our estimate, based upon dry matter determination, is approximately in the same order of magnitude as the estimated increase by a factor of 3.1 that was observed earlier based on aerial photography (Weinberger et al. 2020).

Grave and Möller (1982) provided no information about exact sampling dates and it is for this reason impossible to precisely compare the impact of wind speed and wind direction on quantities of beached biomass in 1977 and 2012/2013. However, altogether a stronger exposure of the studied coastal sections to
northerly onshore winds was observed in July/August 1977 than in July/August 2012/2013 (Fig. S1) and this difference is reflected in a particularly high beach wrack density in coastal sections exposed toward north in 1977 (Grave and Möller 1982), but not in 2012 and 2013 (Fig. 2). These observations confirm that air exposure in July and August correlates to some degree with beach wrack accumulation in August. The higher detected amounts of biomass in 2012/2013 may then not simply be explained with higher coastal wind exposure during these years, given that this exposure was overall higher in 1977 (Fig. S1), and other causes must have brought about the difference.

Evidence for these causes can be found in the fact that the composition of beach wrack in our study area changed much more than the total amount. (Fig. 3, see also Tabs. S1 to S3 in appendix): In 1977 Fucus contributed on average 75% of the beach wrack at 10 sites between Flensburg and Neustadt that were investigated (Grave and Möller 1982), while its contribution in 2012 and 2013 was reduced to 21% and 14%, respectively. As eutrophication has caused a reduction in the depth distribution of Fucus by approximately 50% since 1976/1978 (Schories et al. 2009; Vogt and Schramm 1991), the standing stock of the species has declined drastically (Schories et al. 2009; Vogt and Schramm 1991), and this is clearly reflected in beach wrack compositions. However, although a similar decline in the standing stock has been observed for eelgrass (Schories et al. 2009) this is not reflected in the quantities that are beached in Schleswig-Holstein. Instead, they rather increased by a factor of at least 4 to 5 (1977: less than 0.23 kg per m, 2012: 1.45 kg per m, 2013: 0.96 kg per m). It currently remains unclear whether this reflects (i) a recovery of the standing stock; (ii) a higher turnover rate (e.g., more production and littering of leaves) than in 1977; or rather (iii) an upward movement of eelgrass within the depth gradient due to increased light limitation (Schramm and Nienhuis 1996), which could bring it into the closer vicinity of beaches. Similar to eelgrass, all other macrophytes except of Fucus also increased. As Grave and Möller (1982) did not distinguish between eelgrass and other algae than Fucus, we have no exact information on the relative contribution of both groups in 1977. In 2012/2013, the group of "other algae" was mainly composed of ephemeral and nutrient-opportunistic red and green filamentous macrophytes of the genera Ceramium, Vertebrata and Cladophora. Each of the two groups (red and green filamentous algae) contributed approximately 20% to the total amount of beach wrack (Tabs. S1 to S3 in appendix), which confirms earlier reports of increasing standing stocks of Ceramium tenuecorne in the area (Schramm and Nienhuis 1996). Interestingly, the genus Ulva was much less abundant, although it is by far the most abundant nuisance seaweed on a global scale (Smetacek and Zingone 2013) and ecological impact of Ulva blooms in the region has been observed on a local scale (Steinhagen et al. 2018). Taken together, the total amount of "other algae", consisting primarily of ephemeral species today, increased from less than 0.225 kg per m in 1977 (Grave and Moeller 1982) to 1.4 kg per m in 2012/2013 (Tab S3 in appendix). This hints at an increase by a factor of at least 6.2. However, given that the value observed in 1977 also, and probably mainly, included eelgrass the true increase of opportunistic seaweeds in the region was probably much more drastic.

To test our hypothesis that nutrient-opportunistic macrophytes have a higher nuisance potential than those of later successional stages when they are present at similar density, we extracted the olfacorial compounds of three nutrient-opportunistic and three non-opportunistic species that had been partially degraded under equal conditions. In a survey, we found that people consistently rated the smell of equal amounts of nutrient-opportunistic species, in particular Ceramium tenuecorne, as more intense and less pleasant than the odor of non-opportunistic species. In particular, odors extracted from the two native perennial species F. vesiculosus and Z. marina, that have already contributed large amounts of beach wrack in the area prior to the onset of eutrophication (Lehmann 1814), were mostly perceived as smelling rather faint and as neutral in pleasantness. The decomposition rate of beach-cast seaweeds is species-specific (Mews et al. 2007). Nutrient-opportunists in the Baltic Sea are generally characterized by larger surface/volume-ratios than non-opportunists (Wallentinus 1984) and they can for this reason be expected to degrade more rapidly, which may explain their higher potential for olfactorial nuisance.

The particularly high potential of Ceramium litter and the relatively lower potential of eelgrass litter for deterrence was confirmed in field experiments, observing beach visitors' behavior toward beach wrack of known composition and quantity. In these experiments, we measured the combined effect of beach wrack odor and appearance. Eelgrass alone generated a reduced willingness of beach visitors to linger at the water line only when it was present at relatively high concentrations above 2.2 kg per m. In contrast, only 0.2 kg per m of Ceramium litter mixed with 0.3 kg per m of eelgrass litter was sufficient to cause the same effect. Further, beach visitors were only heard complaining about beach wrack in general and about its odor in particular when Ceramium was present. Based on these observations, and because the odor of Ceramium litter was rated as particularly intense and unpleasant in our survey, we conclude that odor is an important determinant of deterrence by beach wrack, and potentially more important than its appearance.

SPECULATION

Our comparison of beach wrack composition at German Baltic Sea coasts today with the reference study from 1977 suggests a shift toward more nutrient opportunistic species. Such a change would be expected in principle and appears credible despite the limited availability of historical data, because corresponding changes in the composition of algal habitats in the study area are well documented. At the same time our study of olfactorial perception hints at a higher olfactorial nuisance potential of nutrient opportunistic drift seaweed. Thus, the eutrophication of German Baltic Sea coasts has caused a shift of beach wrack composition toward species with a higher potential for olfactorial deterrence, which could explain recent concerns of local coastal managers despite the limited increase of beached biomass in the study area. A significant reduction of Baltic Sea nutrient levels in the years to come might reverse this trend. However, given that eelgrass litter alone had a deterrent effect when it was present at elevated concentrations its removal from beaches may still be necessary even in a less eutrophicated Baltic Sea environment, despite its importance for the ecosystem. Our study was conducted with selected species from the German Baltic Sea coast. Most other sea areas offer different environmental conditions and harbor different algal species inventories. As a consequence, the specific nuisance potential of SW Baltic Sea beach wrack may...
not be identical to beach wrack in other areas. However, we predict a more or less general validity of our observation that beach wrack composed of nutrient opportunistic algal species has a relatively higher nuisance potential than beach wrack composed of late successional macrophytes.

The removed material generally ends up in landfills. To reduce costs for removal opportunities to use the material for energy production, as fertilizer or bio-based compost are discussed (see, e.g., Chubarenko et al. 2021 or Kupczyk et al. 2021).

Responses to this article can be read online at: https://www.ecologyandsociety.org/issues/responses.php/12759

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Data Availability:
The data that support the findings of the olfactory survey described in this study are available on request from the corresponding author, F. W. These data are not publicly available because they contain information that could compromise the privacy of research participants. All other data are included in the paper and its annex. The ethical responsibility of this study - in particular with regard to the handling of personal data - was affirmed by the Central Ethics Committee of Kiel University.

LITERATURE CITED
Bokn, T., C. M. Duarte, M.F. Pedersen, N. Marbà, F. Moy, C. Barrón, E. Bjerkeng, J. Borum, H. Christie, S. Engelbert, F. L. Fotel, E. H. Hoell, R. Karez, K. Kersting, P. Kraufvelin, C. Lindblad, M. Olsen, K. A. Sanderud, U. Sommer, and K. Sörensen. 2003. The response of experimental rocky shore Linblad, M. Olsen, K. A. Sanderud, U. Sommer, and K. Sörensen. 2003. The response of experimental rocky shore

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Data Availability:
The data that support the findings of the olfactory survey described in this study are available on request from the corresponding author, F. W. These data are not publicly available because they contain information that could compromise the privacy of research participants. All other data are included in the paper and its annex. The ethical responsibility of this study - in particular with regard to the handling of personal data - was affirmed by the Central Ethics Committee of Kiel University.

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Table S1A: Dry matter of different macrophytes in beach wrack sampled in August 2012, related to length of beach line [kg m⁻¹]

| Site         | A. Fucus | B. Zostera | C. Ulva | D. other Chlorophyta | E. Rhodophyta | F. other Phaeophyta | Opportunists (sum of C to F) | Total  |
|--------------|----------|------------|---------|----------------------|---------------|---------------------|-----------------------------|--------|
| Glücksburg   | 2.054    | 0.018      | 0       | 0                    | 0.828         | 0                   | 0.828                       | 2.900  |
| Neukirchen   | 0.031    | 0.002      | 0       | 0.005                | 0.022         | 0                   | 0.027                       | 0.060  |
| Wackerballig | 0.376    | 9.621      | 0       | 0.019                | 0             | 0                   | 0.019                       | 10.015 |
| Schönhagen   | 0        | 0.043      | 0       | 0.009                | 0.012         | 0                   | 0.022                       | 0.065  |
| Kiekt        | 3.833    | 0.118      | 0       | 0.092                | 2.190         | 0                   | 2.282                       | 6.233  |
| Strande      | 4.084    | 6.709      | 0       | 7.743                | 0.103         | 0.006               | 7.852                       | 18.645 |
| Mönkeberg    | 0.010    | 0.312      | 0       | 0                    | 0             | 0                   | 0.312                       | 0.322  |
| Stein        | 0.017    | 1.848      | 0       | 0.070                | 0.122         | 0                   | 0.192                       | 2.056  |
| Brasilien    | 0        | 0.006      | 4.6E-06 | 0.006                | 0.330         | 0                   | 0.336                       | 0.342  |
| Hohwacht     | 0.019    | 0.469      | 0       | 1.789                | 6.283         | 0.003               | 8.075                       | 8.563  |
| Grüner Brink | 0.275    | 0.056      | 0       | 0.139                | 0.106         | 0.026               | 0.272                       | 0.602  |
| Kellenhusen  | 0        | 0.009      | 0       | 0.846                | 0.772         | 0                   | 1.619                       | 1.628  |
| Brodten      | 0.001    | 0.022      | 0       | 0.002                | 0.004         | 0.551               | 0.557                       | 0.580  |
| Mean         | 0.823    | 1.455      | 0.024   | 0.825                | 0.829         | 0.045               | 1.722                       | 4.001  |

Table S1B: Relative contribution [%] of different macrophytes to dry weight of beach wrack sampled in August 2012.

| Site         | A. Fucus | B. Zostera | C. Ulva | D. other Chlorophyta | E. Rhodophyta | F. other Phaeophyta | Opportunists (sum of C to F) |
|--------------|----------|------------|---------|----------------------|---------------|---------------------|-----------------------------|
| Glücksburg   | 70.8     | 0.6        | 0       | 0                    | 0.0           | 28.5                | 0.0                         | 28.5   |
| Neukirchen   | 52.2     | 2.6        | 0       | 8.4                  | 36.8          | 0.0                 | 0.0                         | 45.2   |
| Wackerballig | 3.8      | 96.1       | 0       | 0.2                  | 0.0           | 0.0                 | 0.0                         | 0.2    |
| Schönhagen   | 0        | 66.5       | 0       | 14.6                 | 18.9          | 0.0                 | 0.0                         | 33.5   |
| Kiekt        | 61.5     | 1.9        | 0       | 1.5                  | 35.1          | 0.0                 | 0.0                         | 36.6   |
| Strande      | 21.9     | 36.0       | 0       | 41.5                 | 0.6           | 0.0                 | 0.0                         | 42.1   |
| Mönkeberg    | 3.1      | 0.0        | 96.9    | 0.0                  | 0.0           | 0.0                 | 0.0                         | 96.9   |
| Stein        | 0.8      | 89.9       | 0       | 3.4                  | 5.9           | 0.0                 | 0.0                         | 9.3    |
| Brasilien    | 0.0      | 1.9        | 0       | 1.8                  | 96.3          | 0.0                 | 0.0                         | 98.1   |
| Hohwacht     | 0.2      | 5.5        | 0       | 20.9                 | 73.4          | 0.0                 | 0.0                         | 94.3   |
| Grüner Brink | 45.6     | 9.3        | 0       | 23.1                 | 17.7          | 4.3                 | 45.1                        | 49.4   |
| Kellenhusen  | 0.0      | 0.6        | 0       | 52.0                 | 47.4          | 0.0                 | 0.0                         | 99.4   |
| Brodten      | 0.2      | 3.7        | 0       | 0.3                  | 0.7           | 95.0                | 96.1                        | 43.1   |
| Mean         | 20.6     | 36.4       | 0.6     | 20.6                 | 20.7          | 1.1                 | 43.1                        |
**Table S2A:** Dry matter of different macrophytes in beach wrack sampled in August/September 2013, related to length of beach line [kg m\(^{-1}\)]

| Site        | A. Fucus | B. Zostera | C. Ulva | D. other Chlorophyta | E. Rhodophyta | F. other Phaeophyta | Opportunists (sum of C to F) | Total  |
|-------------|----------|------------|---------|----------------------|---------------|---------------------|-----------------------------|--------|
| Glücksburg  | 2.327    | 0          | 0       | 0.024                | 0             | 0                   | 0.024                       | 2.351  |
| Neukirchen  | 0.173    | 0.518      | 0       | 0                    | 0             | 0                   | 0                           | 0.691  |
| Wackerballig| 0        | 5.878      | 0       | 0                    | 0             | 0                   | 0                           | 5.878  |
| Schönhagen  | 0        | 0          | 0       | 0                    | 0             | 0                   | 0                           | 0      |
| Kiekut      | 0.694    | 0.694      | 0       | 0                    | 0             | 0                   | 0                           | 1.387  |
| Strande     | 0.819    | 1.228      | 0       | 0                    | 0             | 0                   | 0                           | 2.046  |
| Mönkeberg   | 0        | 0          | 0.177   | 0                    | 0             | 0                   | 0.177                       | 0.177  |
| Stein       | 0        | 3.295      | 0.069   | 0.035                | 0.069         | 0                   | 0.173                       | 3.468  |
| Brasilien   | 0        | 0          | 0       | 0.319                | 1.275         | 0                   | 1.594                       | 1.594  |
| Hohwacht    | 0.159    | 0          | 0.040   | 0.198                | 1.587         | 0                   | 1.825                       | 1.984  |
| Grüner Brink| 0.212    | 1.062      | 0.159   | 0                    | 3.876         | 0                   | 4.035                       | 5.310  |
| Kellenhusen | 0        | 0          | 0       | 0.645                | 0.215         | 0                   | 0.860                       | 0.860  |
| Brodten     | 0        | 3.295      | 0.069   | 0.035                | 0.069         | 0                   | 0.173                       | 3.468  |

**Mean** | 0.337 | 0.975 | 0.034 | 0.502 | 0.540 | 0 | 1.077 | 2.389

**Table S2B:** Relative contribution [%] of different macrophytes to dry weight of beach wrack sampled in August/September 2013.

| Site        | A. Fucus | B. Zostera | C. Ulva | D. other Chlorophyta | E. Rhodophyta | F. other Phaeophyta | Opportunists (sum of C to F) | Total  |
|-------------|----------|------------|---------|----------------------|---------------|---------------------|-----------------------------|--------|
| Glücksburg  | 99.0     | 0.0        | 0.0     | 1.0                  | 0             | 0                   | 0                           | 1.0    |
| Neukirchen  | 25.0     | 75.0       | 0.0     | 0.0                  | 0             | 0                   | 0                           | 0      |
| Wackerballig| 0.0      | 100.0      | 0.0     | 0.0                  | 0             | 0                   | 0                           | 0      |
| Schönhagen  | 0.0      | 0.0        | 100.0   | 0.0                  | 0             | 0                   | 100.0                       | 100.0  |
| Kiekut      | 50.0     | 50.0       | 0.0     | 0.0                  | 0             | 0                   | 0                           | 0      |
| Strande     | 40.0     | 60.0       | 0.0     | 0.0                  | 0             | 0                   | 0                           | 0      |
| Mönkeberg   | 0.0      | 95.0       | 2.0     | 1.0                  | 2.0           | 0                   | 5.0                         | 5.0    |
| Stein       | 0.0      | 0.0        | 20.0    | 80.0                 | 0             | 0                   | 100.0                       | 100.0  |
| Brasilien   | 0.0      | 0.0        | 0.0     | 20.0                 | 80.0          | 0                   | 92.0                        | 92.0   |
| Hohwacht    | 8.0      | 0.0        | 2.0     | 10.0                 | 80.0          | 0                   | 76.0                        | 76.0   |
| Grüner Brink| 4.0      | 20.0       | 3.0     | 0.0                  | 73.0          | 0                   | 76.0                        | 76.0   |
| Kellenhusen | 0.0      | 0.0        | 0.0     | 75.0                 | 25.0          | 0                   | 100.0                       | 100.0  |
| Brodten     | 0.0      | 0.0        | 0.0     | 100.0                | 0             | 0                   | 100.0                       | 100.0  |

**Mean** | 14.1 | 40.8 | 1.4 | 21.0 | 22.6 | 0.0 | 45.1 |
Table S3A: Mean dry matter of different macrophytes in beach wrack sampled in 2012 and 2013, related to length of beach line [kg m\(^{-1}\)]

| Site         | A. Fucus | B. Zostera | C. Ulva | D. other Chlorophyta | E. Rhodophyta | F. other Phaeophyta | Opportunists (sum of C to F) | Total |
|--------------|----------|------------|---------|----------------------|---------------|---------------------|----------------------------|-------|
| Glücksburg   | 2.191    | 0.009      | 0       | 0.012                | 0.414         | 0                   | 0.426                      | 2.625 |
| Neukirchen   | 0.102    | 0.260      | 0       | 0.003                | 0.011         | 0                   | 0.013                      | 0.375 |
| Wackerballig | 0.188    | 7.749      | 0       | 0.010                | 0             | 0                   | 0.010                      | 7.947 |
| Schönhausen  | 0        | 0.021      | 0       | 0.005                | 0.006         | 0                   | 0.011                      | 0.032 |
| Kiekut       | 2.263    | 0.406      | 0       | 0.046                | 1.095         | 0                   | 1.141                      | 3.810 |
| Strande      | 2.451    | 3.969      | 0       | 3.871                | 0.052         | 0.003               | 3.926                      | 10.346|
| Mönkeberg    | 0.005    | 0          | 0.244   | 0                    | 0             | 0                   | 0.244                      | 0.249 |
| Stein        | 0.000    | 2.571      | 0.035   | 0.052                | 0.096         | 0                   | 0.183                      | 2.762 |
| Brasilien     | 0        | 0.003      | 2.3E-06 | 0.163                | 0.802         | 0                   | 0.965                      | 9.68  |
| Hohwacht     | 0.089    | 0.235      | 0.020   | 0.994                | 3.935         | 0.002               | 4.950                      | 5.274 |
| Grüner Brink | 0.243    | 0.559      | 0.080   | 0.070                | 1.991         | 0.013               | 2.153                      | 2.956 |
| Kellenhusen  | 0        | 0.005      | 0       | 0.746                | 0.494         | 0                   | 1.239                      | 1.244 |
| Brodten      | 0.001    | 0.011      | 0       | 2.656                | 0.002         | 0.276               | 2.933                      | 2.945 |
| Mean         | 0.580    | 1.215      | 0.029   | 0.663                | 0.684         | 0.023               | 1.400                      | 3.195 |

Table S3B: Average contribution [%] of different macrophytes to dry weight of beach wrack sampled in 2012 and 2013.

| Site       | A. Fucus | B. Zostera | C. Ulva | D. other Chlorophyta | E. Rhodophyta | F. other Phaeophyta | Opportunists (sum of C to F) |
|------------|----------|------------|---------|----------------------|---------------|---------------------|----------------------------|
| Glücksburg | 83.4     | 0.3        | 0       | 0.4                  | 15.8          | 0                   | 0.0                        | 16.2 |
| Neukirchen | 27.2     | 69.2       | 0       | 0.7                  | 2.9           | 0                   | 0.0                        | 3.6  |
| Wackerballig | 2.4       | 97.5       | 0       | 0.1                  | 0.0           | 0                   | 0.0                        | 0.1  |
| Schönhausen | 0        | 66.5       | 0       | 14.6                 | 18.9          | 0                   | 0.0                        | 33.5 |
| Kiekut     | 59.4     | 10.6       | 0       | 1.2                  | 28.7          | 0                   | 0.0                        | 29.9 |
| Strande    | 23.7     | 38.4       | 0       | 37.4                 | 0.5           | 0                   | 0.0                        | 37.9 |
| Mönkeberg  | 2.0      | 0          | 98.0    | 0.0                  | 0.0           | 0                   | 0.0                        | 98.0 |
| Stein      | 0.3      | 93.1       | 1.3     | 1.9                  | 3.5           | 0                   | 0.0                        | 6.6  |
| Brasilien  | 0.0      | 0.3        | 0       | 16.8                 | 82.9          | 0                   | 0.0                        | 99.7 |
| Hohwacht   | 1.7      | 4.4        | 0.4     | 18.8                 | 74.6          | 0                   | 0.0                        | 93.9 |
| Grüner Brink | 8.2     | 18.9       | 2.7     | 2.4                  | 67.4          | 0.4                 | 0.0                        | 72.9 |
| Kellenhusen | 0.0     | 0.4        | 0       | 59.9                 | 39.7          | 0                   | 0.0                        | 99.6 |
| Brodten    | 0.0      | 0.4        | 0       | 90.2                 | 0.1           | 9.4                 | 0.0                        | 99.6 |
| Mean       | 18.2     | 38.0       | 0.9     | 20.8                 | 21.4          | 0.7                 | 43.8                       |
Table S4: Distribution of characteristics over samples of respondents in surveys conducted at Kiel, Schönberg, Eckernförde and in total. Absolute numbers are given if not stated otherwise.

| Characteristics       | Value       | Kiel  | Schönberg | Eckernförde | Total\(^a\)           |
|-----------------------|-------------|-------|-----------|-------------|------------------------|
| Sample size           |             | 60    | 61        | 56          | 177                    |
| Gender                | Female      | 35    | 30        | 34          | 99 (55.57%)            |
|                       | Male        | 25    | 31        | 20          | 76 (43.43%)            |
| Age in years          | Average     | 47.53 | 47.36     | 55.94       | 50.27                  |
| Household size        | Average     | 2.25  | 2.74      | 2.34        | 2.45                   |
| Household net income  | Median category\(^b\) | 2500-2599€ | 2600-3599€ | 2500-2599€ | 2500-2599€            |
| School education      | 9 years     | 5     | 5         | 6           | 16 (9.04%)             |
|                       | 10 years    | 12    | 24        | 15          | 51 (28.81%)            |
|                       | 12-13 years | 15    | 17        | 17          | 49 (27.68%)            |
|                       | Graduated in college | 17 | 10        | 14          | 41 (23.16%)            |
|                       | Missing information | 11 | 5         | 4           | 20 (11.29%)            |

\(^a\) If numbers do not sum up to total sample size this is due to missing observations.

\(^b\) A number of participants did not provide information on their household’s net income.
Table S5: Repeated measures-2-way-ANOVA of the normalized and ranked perception of intensity of odor from six decaying macrophytes. Phylogenetic groups (= PG, green plants, brown algae or red algae) were used as between subject factor and life strategy (= LS, opportunistic or non-opportunistic) was used as within subject factor. See also Figure 4A.

| Source             | SS     | df  | MS     | F      | P     |
|--------------------|--------|-----|--------|--------|-------|
| **Between subject effects**                  |
| Intercept          | 2840001| 179 | 15866.0| 3.80   | < 0.0001|
| PG                 | 187523 | 2   | 93761.5| 7.27   | 0.0009 |
| Error              | 2243180| 174 | 12891.8|        |        |
| **Within subject contrasts**                |
| LS                 | 369139 | 1   | 369139.1| 88.44  | < 0.0001|
| PG*LS              | 42493  | 2   | 21246.4| 5.09   | 0.0071 |
| Error (LS)         | 726241 | 174 | 4173.8 |        |        |
Table S6: Repeated measures-2-way-ANOVA of the ranked perception of pleasantness of odor from six decaying macrophytes. Phylogenetic groups (= PG, green plants, brown algae or red algae) were used as between subject factor and life strategy (= LS, opportunistic or non-opportunistic) was used as within subject factor. See also Figure 4B.

| Source          | SS     | Df | MS    | F     | P       |
|-----------------|--------|----|-------|-------|---------|
| Between subject effects |        |    |       |       |         |
| Intercept       | 1982892| 179| 11077.6| 1.82  | < 0.0001|
| PG              | 130216 | 2  | 65108.0| 6.37  | 0.0021  |
| Error           | 1777907| 174| 10217.9|       |         |
| Within subject contrasts |        |    |       |       |         |
| LS              | 73720  | 1  | 73720.1| 12.09 | 0.0006  |
| PG*LS           | 1712   | 2  | 855.9 | 0.14  | 0.8691  |
| Error (LS)      | 1054794| 174| 6097.0|       |         |
Figure S1: Frequency of wind directions (A), average wind speed from different directions (B) and overall air stream from different directions (C), recorded at 54.5272° N 11.0580° E (meteorological station Fehmarn) between 1st of July and 31st of August in the years 1977, 2012 and 2013. Wind direction was recorded in hourly intervals and in increments of 10°. Wind speed was recorded in the same hourly intervals. Air stream is the overall length of the air stream coming from a given direction that passed the area within the recording period and was calculated by multiplication of data shown in A and B. Data kindly provided by Deutscher Wetterdienst.
**Figure S2:** Density of beach wrack (333 g m\(^{-1}\) eelgrass + 200 g m\(^{-1}\) *Ceramium*) tested for effects on beach visitors in field experiment 1.
Figure S3: Minimal (0 g m\(^{-1}\)) and maximal (15600 g m\(^{-1}\)) densities of beach wrack tested for effects on beach visitors in experiment 2.
Figure S4: Effect of *Zostera* beach wrack density on (A.) the frequency of beach visitors crossing the beach wrack and (B.) the frequency of these visitors staying in direct vicinity of the beach wrack for 30 s or more time. Altogether 118 repeated measurements were conducted during two consecutive days in time intervals of 30 min on six different beach sections at Eckernförde and biomass densities were determined in parallel. Lines represent best fitting linear functions (calculated in B. from the logarithmic biomass density and the non-logarithmic effect size and in A. from the double-logarithmic dataset), dotted lines indicate their 95% confidence intervals.