Rostocker Meeresbiologische Beiträge Heft 31, 2021 Seite 56–107

# Ecological aspects of sustainable beach wrack management

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# 1 Introduction

Sandy coastlines and their associated dune systems are fragile environments which are faced by many threats and require conservation so that these areas could function ecologically and provide most for the species that rely on this ecosystem. Marine sandy beaches are also highly attractive to humans and the use of coastal areas has increased marginally in the last century, causing also intensified management of these sensitive areas. "Appropriate management and successful conservation can only be achieved if the complex ecology of sandy beach ecosystems is understood" (McLachlan & Defeo, 2018).

This report No 3.3 is the main output of the project CONTRA (2019–2021), which was fulfilled within the Interreg Baltic Sea Region Programme. The report was prepared within the Work Package 3 "Sustainability and ecological assessment" by experts from the CONTRA project partners. It represents the results obtained in the studied managed and unmanaged sandy beaches located in Germany, Denmark, Russia, Sweden, Estonia, and Poland. For more detailed overview on beach wrack ecology-related research carried out under the CONTRA project please see the respective CONTRA report Möller et al., 2021.

The report covers main ecological aspects related to beach wrack ecology and beach management with focus on sandy beaches. The managed beaches had to fill the following criterias: 1) used for recreational purposes, 2) with dominance of sandy sediments, and 3) from where beach wrack is removed on regular basis. The ecological aspects of beach wrack are described in chapter 3, including the seasonality in amounts and composition of beach wrack in selected managed and unmanaged beaches and fate of beach wrack on the natural beaches, shoreline residence time, aeolian dispersal and decomposition. We also highlight the presence of litter on the beaches and in the beach wrack. Different aspects of beach management such as noise pollution, disturbing wildlife, mechanical disturbance, compacting effects, and potential other effects related to beach cleaning are overviewed in chapter 4. In chapter 5 we slightly touch the theme of ecosystem services of managed sandy beaches and in which aspects the CONTRA case-studies relate to those. Suggestions for sustainable beach management based on research carried out under the CONTRA project are presented in chapter 6.

# 2 Study area

As an almost landlocked inland shallow sea, the Baltic Sea is exposed to particularly high loads of nutrients due to the many rivers flowing into it and the low exchange with other seas. Due to the increasing human settlement (on present day over 85 million people) of the catchment areas, this influence has increased over the centuries. Consequently, the Baltic Sea is facing several challenges that affect its ecosystem functioning, e.g. eutrophication, hazardous substances, non-indigenous species, seabed loss and disturbance, overfishing etc. Reducing eutrophication of the Baltic Sea is continuously one of the biggest challenges, it is being estimated that over 97 % of the Baltic Sea area suffers from eutrophication due to past and present excessive inputs of nitrogen and phosphorus. There has been decrease in the inputs of nitrogen and phosphorus to the Baltic Sea sub-basins over the years, but agriculture still plays the key role in nutrient pollution (Feistel et al., 2018, HELCOM, 2018a). Contamination with hazardous substances is another great concern – thousands of environmentally hazardous substances have been identified as potentially occurring in the Baltic Sea and up to one fifth of those is being monitored regularly. Among others, the contamination levels of mercury, polybrominated diphenyl ethers (PBDEs), and the radioactive isotope cesium-137 are particularly high (HELCOM, 2018b).

The focus within the CONTRA project is given to sandy beaches, which are already managed in touristic purposes and where by removing the beach wrack it would be possible to contribute into reducing the nutrient pollution. Overall, the total coastline length of the Baltic Sea is about 8000 km and it is highly heterogeneous, the most distinctive is the difference between north and south – the coasts of Sweden and Finland are highly fretted and generally

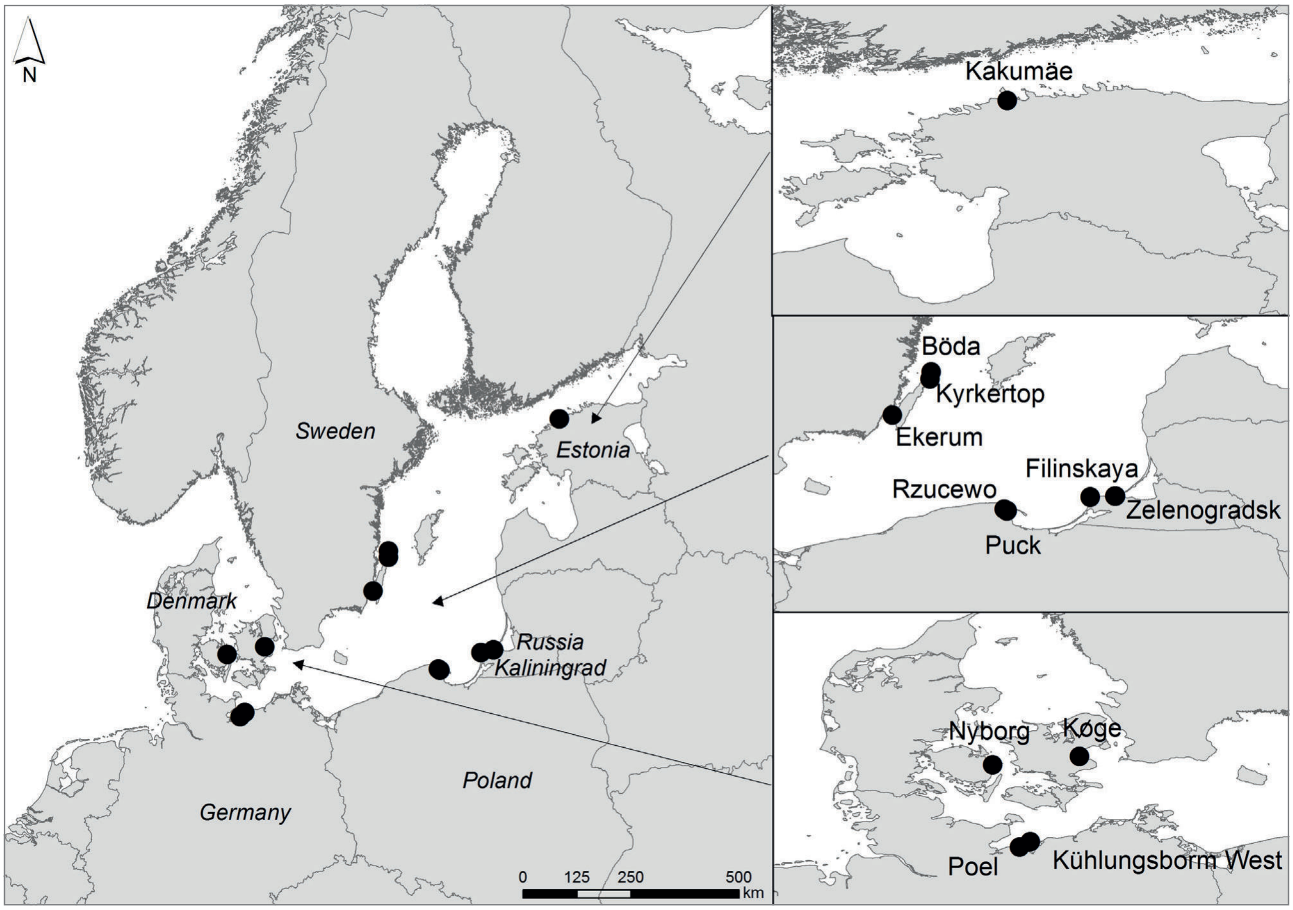



**Figure 2.1**. Map of the studied beaches.

rocky, whereas those of the southern Baltic are flat and rather featureless. The main coastal features in the Baltic Sea region are however sand or gravel spits with diversified dunes, cliffs cut in a variety of sediments and low-lying areas such as lagoons, wetlands and salt marshes (Łabuz, 2015). Within the CONTRA project different studies were carried out on the sandy beaches of the Baltic Sea within six countries: Denmark, Sweden, Germany, Poland, Russia (Kaliningrad) and Estonia. In every country at least one managed and one unmanaged beach was chosen for the comparison and to better highlight the impact of beach wrack removal on the ecosystem. In total, fieldwork was carried out in 23 beaches (beach areas) out of which 12 were managed and 11 represent the natural conditions (→ Figure 2.1).

On the countries level the share of sandy beaches and their management is very different (→ Table 2.1). The management of sandy beaches is of highest rate in Poland and Sweden, where about 25 % and 35 % of all sandy beach ecosystems are managed. However, this information on country level is in some cases very general or missing. For example for Denmark the share of managed beaches is currently not fully known and thus even rough estimations are hard to give. The total length of Danish coastline is about 8700 km and about 1800 km of it is protected by dikes or other permanent technical installations already (Danish Ministry of the Environment, 2005). Most of Danish coastline is sandy or covered with saltmarshes. Overall in Denmark there are 174 Blue Flag Beaches, which are either managed or monitored in regular basis. The total number of managed beaches is probably higher in Denmark.

**Table 2.1.** Indicative share of sandy beaches and the share of managed beaches per country. Managed beach hereby is considered as a beach, where beach wrack removal is a common practice. Information of managed beaches is very rough and based on various sources including personal communication with representatives from local municipalities.

| Country | Total coastline, km | Sandy beaches, km | Managed beaches, km | Managed beaches, number |
|---|---|---|---|---|
| **Estonia** | 3780 | around 600 km | about 20 | about 20 |
| **Russia (Kaliningrad)** | 145 | most of 145 km | a few (varies from year to year) | a few (varies from year to year) |
| **Poland** | 528 | around 465 km | about 120 | about 120 |
| **Germany** | 2582 | around 1692 km | about 53 | about 24 |
| **Denmark** | 8750 | sandy beaches and saltmarshes prevail | at least 1800 km (coastal protection) | over 174* |
| **Sweden** | 3218 | around 350 km | about 100 | about 25 |

# **3** Ecological aspects of beach wrack around the Baltic Sea

Sandy shores consist of three units – surf zones, beaches and dunes and this geomorphic system is also known as littoral active zone. Together beaches and dunes act as a protective buffer against storms and sea-level rise. The most characteristic feature of sandy shores is of course sand and its movement – wave- and wind-induced sand can be transported from up to 20 m depth from the seabed to the landward edge of the active dunes. As overviewed e.g. in McLachlan & Defeo (2018), two ecologically distinct systems are found in sandy shores – 1) a marine beach/surf zone ecosystem that is inhabited by marine biota and which is strongly affected by wave energy and 2) a terrestrial dune system that is inhabited by terrestrial plants and animals and is strongly influenced by wind energy. These systems are influenced by another in both directions.

In sheltered bays the openings of burrows may easily indicate the presence of infauna, however in exposed sandy beaches that are open to wave action the sand is in constant movement and the animals living in this area also need to be highly mobile in order to not to be swept away in the sea. Looking at a 2 m height these kinds of sandy beaches seem to be poor of life and they have been also described as marine deserts. Yet, when looked closer these beaches are also full of life, both microscopic and macroscopic. As in general beach sands have low organic contents, this environment depends largely on carryon from seawater. Input of dissolved organic matter depends on primary production level in the adjacent seawater and is carried into the interstitial system by water filtration. Particulate organic matter inputs include larger beach wrack quantities washed ashore which is then e.g. consumed by marine and terrestrial macrofauna and will enter the beach system and becomes available for animals living in the spaces between individual sand grains in the soil or aquatic sediments (for more detailed overview see e.g. McLachlan & Defeo, 2018).

In this chapter we provide a generalized overview of various ecological aspects related to sandy beach ecosystems including beach wrack amounts, beach-wrack associated species composition, seasonality, residence and decomposition, aeolian dispersal, nutrients, hazardous substances and litter. For methodology and more detailed information about the studies carried out under the CONTRA project please see the respective CONTRA-report Möller et al. (2021).

### 3.1 Beach wrack landings

Information regarding beach wrack landings across the Baltic Sea both on local and large scale is scarce. However, research carried out under the CONTRA project has given important baseline information for different areas and forms a solid base for further investigations. Based on primary predictive models, hot-spot areas of beach wrack accumulation (production up to 4000 g per m² per month) were noted in the Kattegat area, west and east coast of Sweden, all along the southern coast of Finland, west coast of Estonia and in Gdansk Bay (→ Figure 3.1.1, Kotta et al., 2020). Production hotspots were sporadically found also on the east coast of Finland, reaching the northernmost parts of the Bothnian Bay as well as on the shores of St. Petersburg. The remaining areas of the Baltic Sea were characterized by lower beach-cast production potential (approximately 0–1000 g per m² per month) (Kotta et al., 2020).

Beach wrack landings are highly seasonal – the largest amounts of beach wrack commonly reach the beaches in autumn at the end of vegetative season with autumn storms (→ Figure 3.1.2). However, it must be noted that the end of 2019 and winter 2020 were extremely warm and stormy and no ice or snow-cover formed during that period, this should be considered when interpreting the results presented here.

In our study from April 2019 to August 2020 the largest amounts were noted in Køge and Nyborg beaches, Denmark, where the beach wrack amount per 100 m long beach section were estimated as high as 140 m³ (Køge, unmanaged), 124 m³ (Nyborg, unmanaged) and 87 m³ (Køge, managed) (→ Figure 3.1.2). In Rzuzewo, Poland the highest beach wrack accumulation was recorded in spring

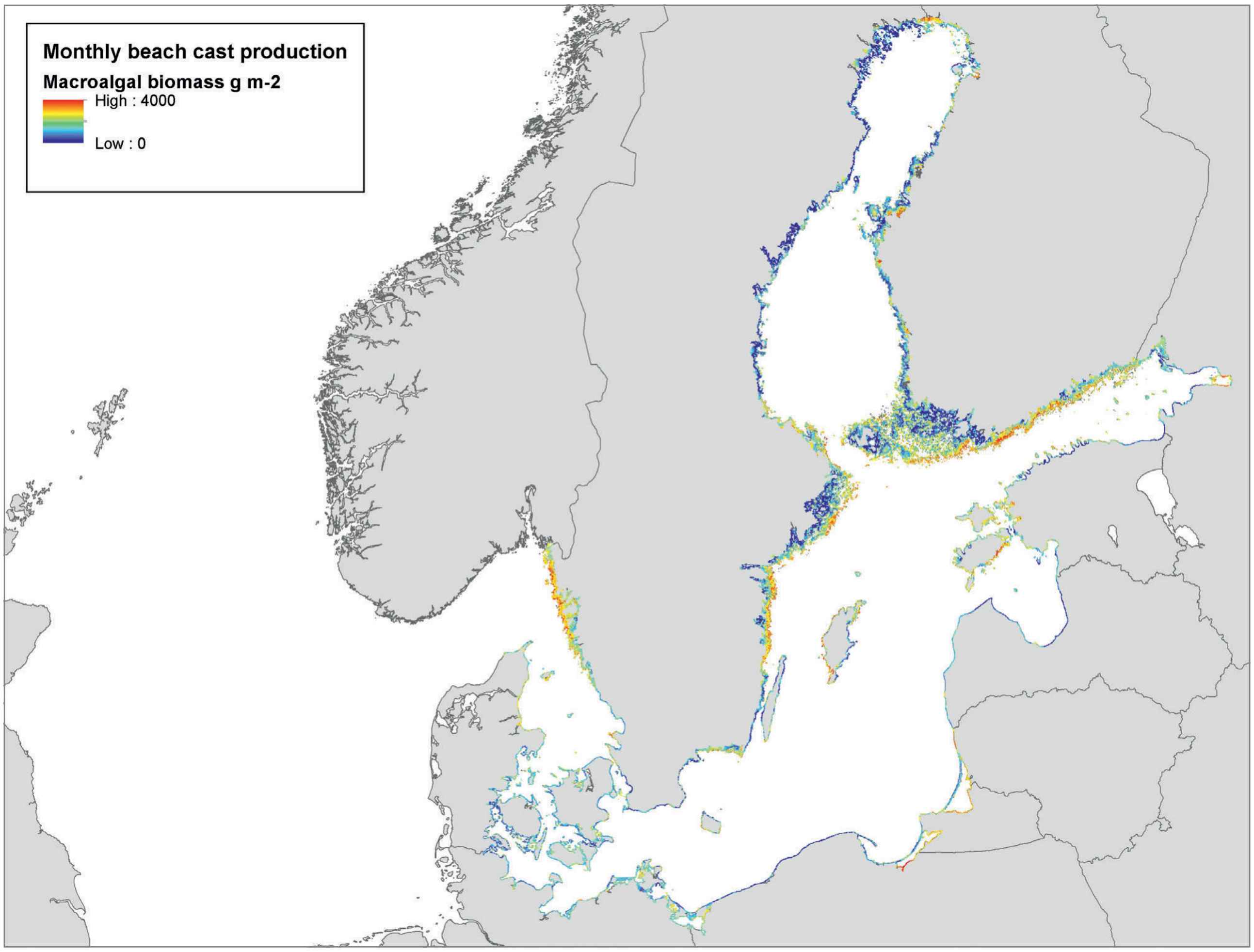



**Figure 3.1.1.** Monthly beach-cast production in [g m-2 dry weight] potential across the Baltic Sea in late autumn (October) (redrawn from Kotta et al., 2020).

2019 with the estimated amount for about 208 m³. In other areas the respective landings were usually less than 30 m³ of beach wrack per 100 m long beach section. Also in some beaches the beach wrack amounts were negligible throughout the year, e.g. Kühlungsborn West in Germany (the largest amount of beach wrack was determined once in early June 2019 with over 20 m³, otherwise the amounts stayed below 1 m³) and Puck beach in Poland.

The beach cast on the beach usually consists of several wrack lines depending mostly on the water level changes and wave activities (→ Figure 3.1.3, → 3.1.4, CONTRA-report Möller et al., 2021). It is common, that part of the algae biomass remains in the water. New wrack is usually the freshest algae near to the water as of old wrack line consists of already partly degraded and drier material. The exact beach wrack placement, it's amounts and residence time are important factors when it comes to e.g. estimating the emission of green house gases and leakage of nutrients and hazardous substances back to the water environment as these processes depend highly on the moisture content (e.g. Liu et al., 2019, see also → section 3.7 Hazardous substances).

In occasions when there are storms with parallel high tides and the water level reaches up to the foredune the beach wrack is placed far behind the usual wrack lines. When this happens, a clear distinction between old and new wrack is impossible. → Figure 3.1.4 shows the same beach at low water level and during a storm event which spreads the beach wrack all over the beach.

## 3.2 Beach wrack composition

The Baltic Sea offers habitat for about 530 macrophytes and algal species, for about 1900 invertebrate species, for about 240 fish species and 5 mammal species (HELCOM, 2012). However, finding all 530 algal species in one beach of the Baltic Sea is not possible as the beach wrack composition is most dependent on nearby prevailing marine benthic habitat types and dominating algae

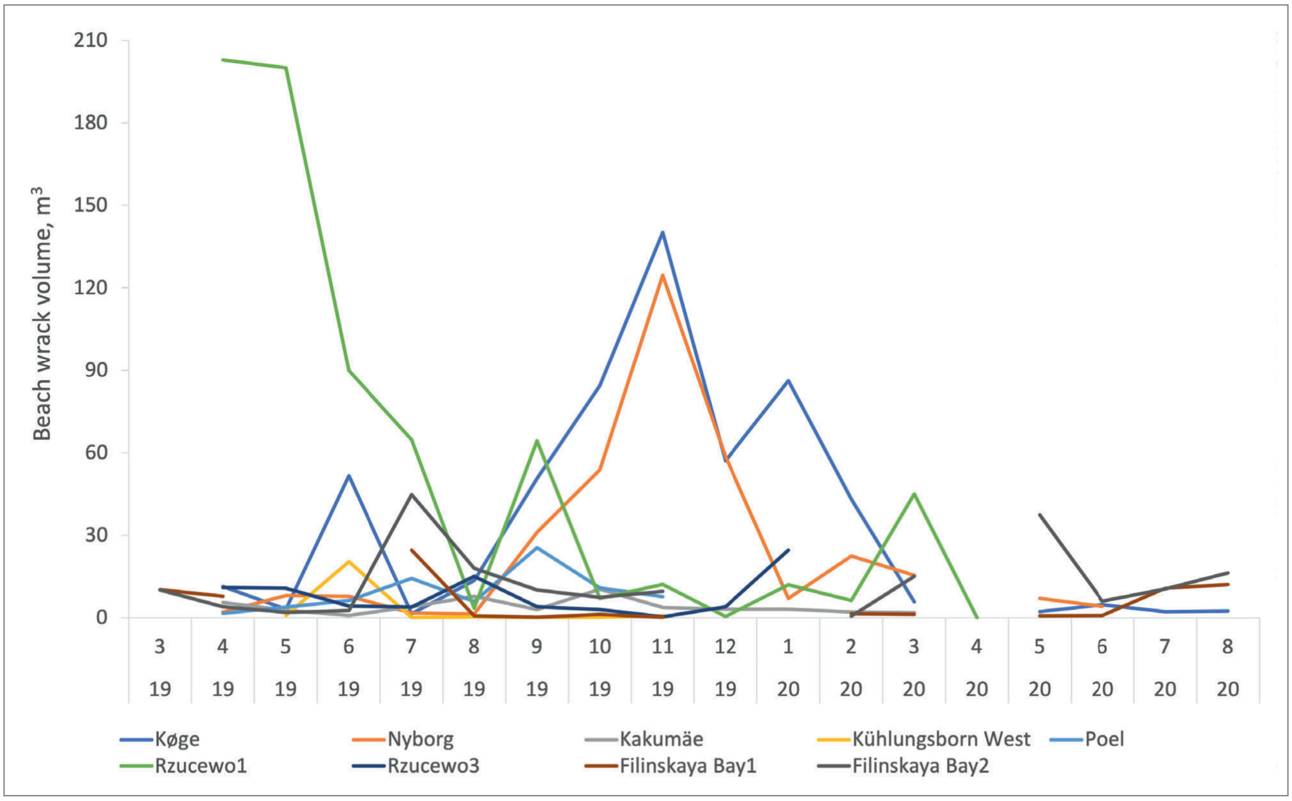



**Figure 3.1.2.** Beach wrack amounts (wet material, volume, m³) in studied unmanaged beaches in the period from April 2019-August 2020. The amounts are presented per a 100 m long beach section.

and macrophytes (e.g. Torn et al., 2015). But with greater storms and intensified water activity the material can be carried to the beaches also from rather remote areas. In general terms, compliance between beach wrack accumulation and submerged vegetation is hydrodynamically possible in case the alongshore currents are weak and the material on the beach originates from the adjacent sea areas. Higher wave events have a significant effect on the thickness and the amount of the beach wrack, no significant influence on the species number has been noted (Suursaar et al., 2014).

Based on estimations from studied beaches on a yearly basis, the main components of beach wrack were angiosperms and red algal species (→ Figure 3.2.1). In sheltered bays there is often an increased proportion of terrestrial plant material, unidentified or rotten wrack, and fauna. In the western Baltic Sea region angiosperms like eelgrass dominate the biomass, while dominance of red and brown algae (Rhodophyceae and Phaeophyceae) was observed within the eastern regions of the Baltic Sea (→ Figure 3.2.1).

Seasonality and species composition of beach wrack are closely related to the species annual life cycle. For example, eelgrass *Zostera marina* was found in particularly high biomasses within the autumn, reflecting the autumn storms where it is ripped off extensively and flushed on land.

More detailed beach wrack analysis was conducted at the beaches of Russia, Estonia and Poland. On the beaches of Kaliningrad Oblast, Russia in total 14 taxa of macroalgae and seagrasses were registered. Excluding the sand (which was on average 39 % of wet weight of beach wrack samples), the biomass of macroalgae was on average 95 %. Beach wrack with *Furcellaria lumbricalis* often contained some number of epiphytic organisms (*Mytilus edulis, Amphibalanus improvisus*, Bryozoa).The biomass of *Mytilus edulis* was comparable to that of algae occasionally. Old beach wrack sometimes contained large numbers of larvae and imago of Diptera in the summer period, but their biomass was not significant.

In Kakumäe beach in a one year period in total 131 taxa were described within the beach wrack, including 74 faunal and 57 floral species. In terms of origin, land-based fauna and sea-based flora dominated the beach wrack (40 and 39 taxa, respectively). In total 34 marine faunal species and remains of 18 terrestrial floral species were determined. In addition to the natural part of the beach wrack it can also contain artificial items such as litter (for more details see → chapter 3.8).

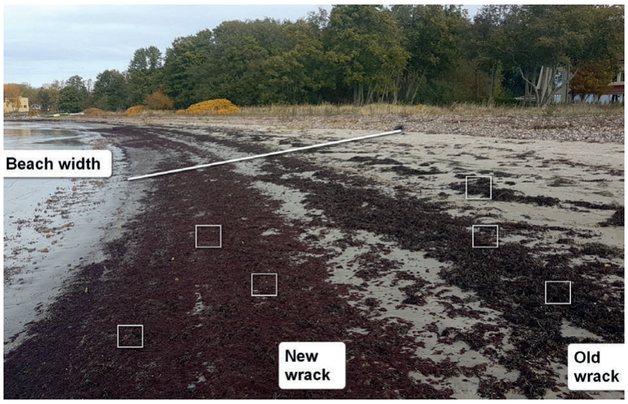



**Figure 3.1.3.** Beach wrack lines on the beach. Squares indicate the sampling methodology for species composition, 3 replicative samples (20 x 20 cm) were collected both from new and old wrack line. Beach wrack coverage and volume were estimated from the water's edge to the back of the beach (beach width) along the length of the 100 m long sample unit (Kakumäe beach, 15 Oct 2019, T. Möller).

**Figure 3.1.4.** Beach wrack lines at the beach "Am schwarzen Busch" in Poel, Germany. The upper picture illustrates very low water levels during Summer in July, second picture shows the same section during an autumn storm event in October. In the second picture much of the beach wrack is floating in the shallow water, being washed ashore and carted off in an almost minutely repeated manner (Poel beach, 01 July 2019 & 14 Oct 2019, P-K. Schätzle).

In Kakumäe Bay, Estonia, altogether 40 different terrestrial macrofauna taxa were found inhabiting the older beach wrack. Overall, representatives of Mollusca and Arthropoda were found in the samples. The molluscs were represented by species of the family Planorbidae (ramshorn snails), which are typical aquatic inhabitants among aquatic pulmonate gastropod molluscs, all other species were representatives of the phylum Arthropoda – crustaceans, arachnids and insects. Among these some species are most typical to this biota, e.g. springtails (Cl. Entognatha, Subcl. Collembola), *Saldula pallipes* (a species of shore bug in the family Saldidae), some species from genus *Sigara* (a genus of water boatmen in the family Corixidae), genus *Cercyon* with species *C. sylvestris, C. haemorrhoidalis, C. marinus, C. littoralis* (belongs to water scavenger beetles Hydrophilidae). Among Diptera many larval stages of the gnatmidge (Nematocera) and flie (Brachycera) species were found. Chironomidae can be found in almost any aquatic or semiaquatic habitat, many species in the genus are marine and are found in the intertidal zone of seashores. The share of occasional guests in beach wrack was also quite high which may be also related to the presence of terrestrial vegetation in old wrack line. Some beetle species that accidentally entered this habitat are for example ladybirds *Semiadalia notate, Coccinella septempunctata, Psyllobora vigintiduopunctata*, death-watch beetle *Ernobius abietinus*, barley flea beetle *Phyllotreta vittula*, weevil *Ceutorhynchus pallidactylus* and pea leaf weevil *Sitona lineatus*. Other occasional guests were: Psocoptera, Aphidodea, Homoptera and Neuroptera (*Chrysoperla carnea, Hemerobius lutenscens*).

Dominant floral species in beach wrack in Puck Bay (Poland) were *Zostera marina, Potamogeton pectinatus* and *Pylaiella* sp. In Rzucewo (Poland), beach wrack was dominated by *Potamogeton pectinatus, Zostera marina* and land plants (the stations are located close to overgrown dunes).

The marine macrofaunal composition was studied in more detail at two beaches of Poland: the Puck beach represents the managed and Rzucewo represents the unmanaged beach (see also CONTRA-report Möller et al., 2021). In both managed and unmanaged areas a total of 21 species or taxa belonging to the macrofauna were found, as well as epiphytic organisms *Amphibalanus improvisus* barnacles and 3 taxa that belong to the meiofauna – Nematoda, Turbellaria and Collembola. There were 20 taxa in total recorded in the unmanaged area, 7 of them were considered constant, although only 3 – Oligochaeta, Hydrobidae, Chironomidae – can be considered as dominant taxa in the overall abundance of the site's community. *Marenzellaria viridis, Limecola balthica* and *Gammarus* spp were constant species at the unmanaged site with relatively high abundance compared to the other taxa. In terms of biomass, representatives of Bivalvia and Gastropoda were dominant, due to the weighting of these individuals with shells.

In the case of meiofauna (organisms that can pass through a 1 mm mesh but will be retained by a 32

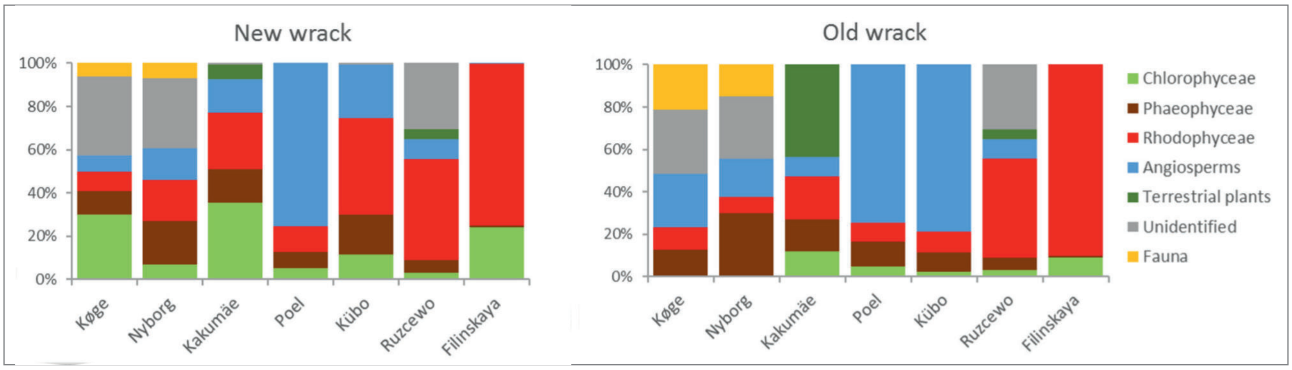



**Figure 3.2.1.** The average proportion of species composition within the wrack at unmanaged beaches within the study period April 2019–August 2020.

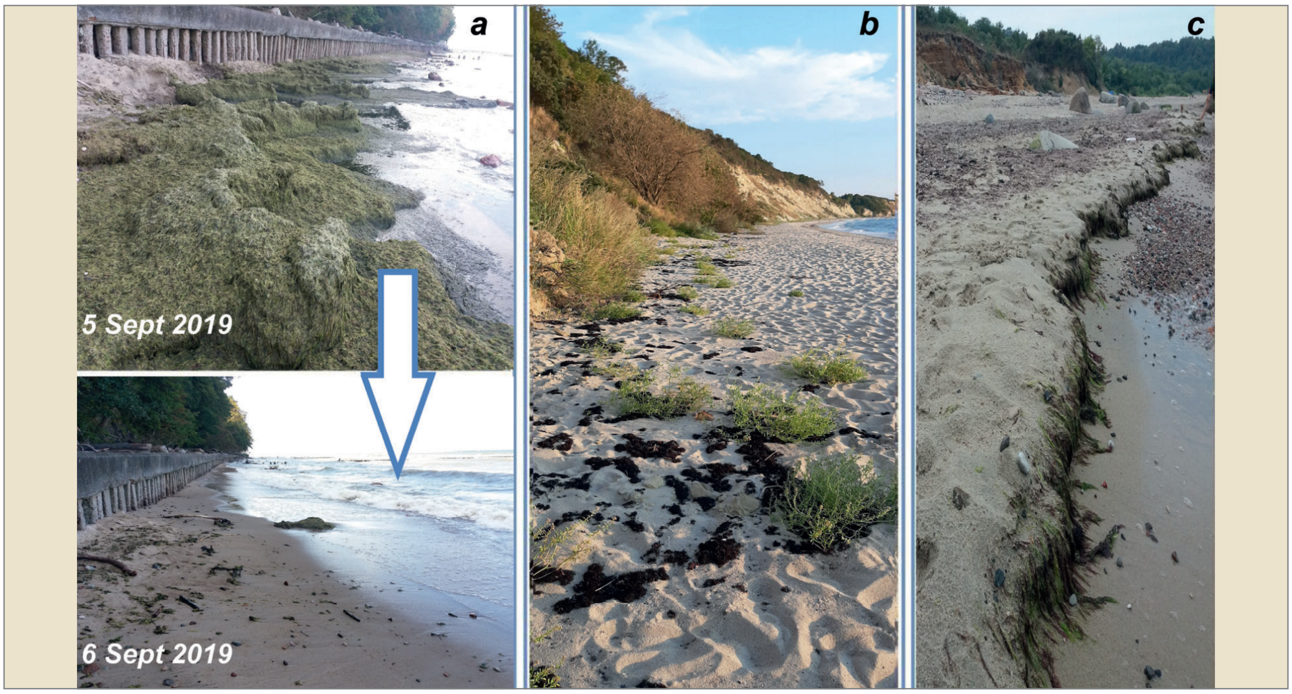



**Figure 3.3.1.** Beach wrack can undergo different transformation ways: flushing back to the sea (a), disperse inland the beach by wind and waves (b), covering under the thickness of sand (c) (J. Gorbunova).

µm mesh) fifteen higher taxa of meiofauna (one represented by larval stage – Copepoda *nauplii*) were recorded at both study areas in Poland. The most common taxa were Nematoda, Harpacticoida and Oligochaeta which were abundant at both sites, while Gastrotricha and Turbellaria were relatively abundant only at the managed beach in Puck. Generally the higher meiofauna densities were observed at the managed beach, however, during the winter months, January and February, higher total meiofauna abundance was found on the unmanaged beach, most likely indicating greater food availability from decaying organic debris. Additionally more favorable oxygen conditions may occur during the winter due to low water temperatures limiting the rate of decomposition and increasing the solubility of gases in water.

## 3.3 Residence time

Regrading beach wrack, besides the amount also residence time is an important factor for the terrestrial ecosystems functioning, resource characteristics, and management options. Variability in wrack supply on sandy beaches can be explained through interactions between wave exposure, hydrodynamic factors, coastal topography and seasonality (Barreiro et al., 2011, Suursaar et al., 2014).

Once on the beach, the beach wrack can either accumulate on the beach for a long time, it can be washed back to the sea or is covered with (thick) sand or small pebbles (potentially followed by flushing to the sea). Furthermore, dispersal by currents along the coastline and by wind to the inland occurs often in parallel. (→ Figure 3.3.1, → 3.3.2).

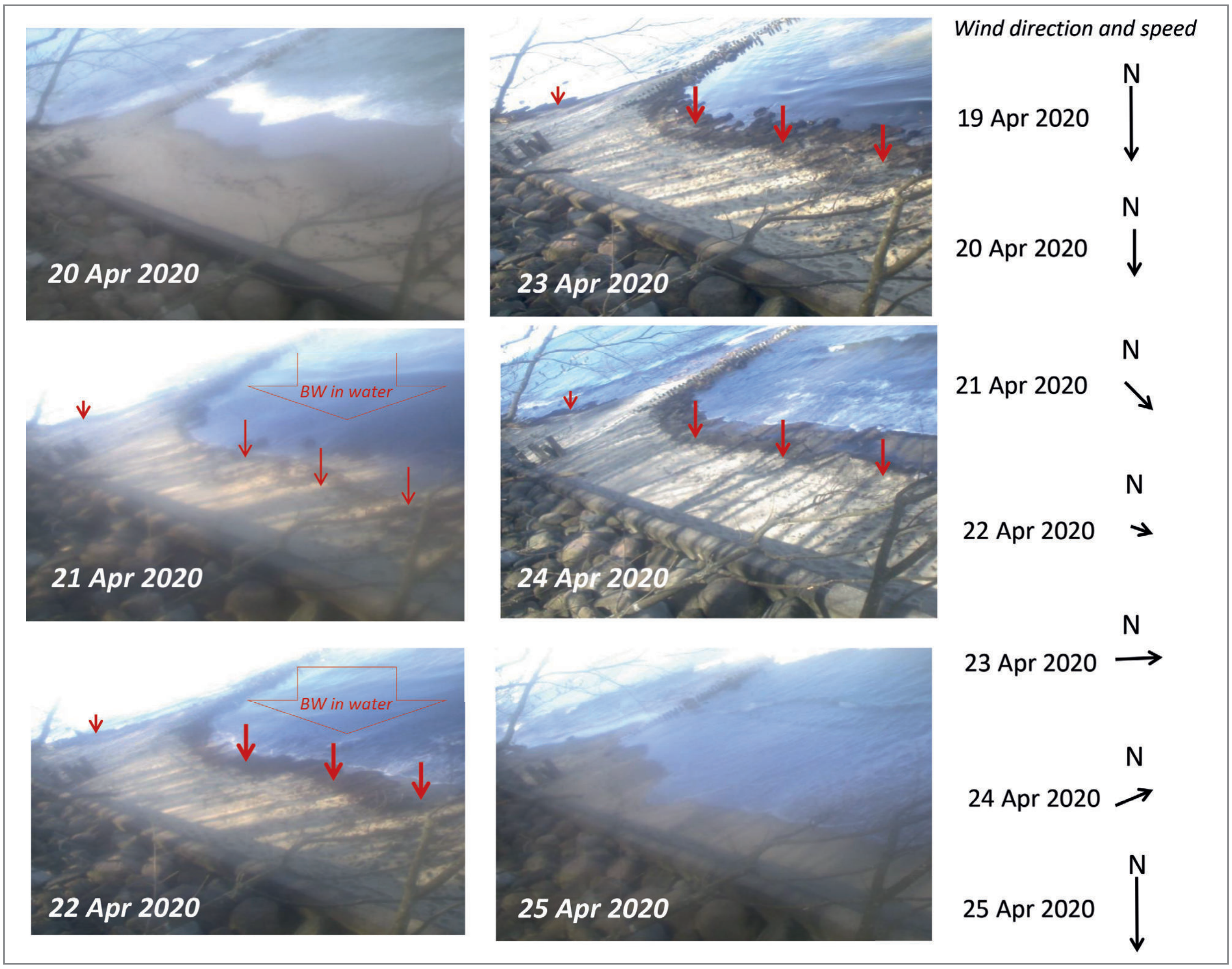



**Figure 3.3.2.** A typical example of beach wrack cast ashore and flushing due to the wind conditions (the western part of the Otradnoye beach, Russia, northern exposure of the coastline). The arrows indicate the direction and strength of the wind (the weather station is located at a distance of 5 km https://rp5.ru).

Our CONTRA studies confirmed that beach wrack residence time varies greatly between different beaches of the Baltic Sea. For example, a long-term presence of wrack is typical for Kakumäe beach (Estonia), which is a sheltered and shallow bay exposed to northern and northwestern winds. Wrack remained on the beach the whole time during the study period (336 days) in the unmanaged area and it was until being removed during the cleaning in the managed area (up to 214 days) (→ Figure 3.3.3). At the same time, beach wrack residence time was short at Otradnoye beach (Russia). The residence time ranged from 1 to 25 days and in average was less than 6 days (→ Figure 3.3.2, → 3.3.4). This short residence time is typical for most of the beaches of the Kaliningrad Oblast (Russia), which are all considered exposed beaches. In conclusion, beach wrack residence variations are related to hydrodynamic conditions, benthic habitats and characteristics of the coastline.

Consequently for planning management activities, it is necessary to consider peculiarities of the wrack residence time, thus short residence time can be a limiting factor for economically sufficient beach wrack harvesting. To improve efficiency, one solution could be the use of webcam observations on the potentially profitable seashore to coordinate the removal activities. At beaches with a long-term wrack residence, beach wrack is important for terrestrial ecosystems as well and all these different ecological aspects must be considered in planning management activities.

## 3.4 Decomposition of beach wrack

### 3.4.1 Natural decomposition of beach wrack in sheltered bays

As already mentioned in the previous sections, the effects of wind and storm waves differentiate input loads of beach wrack to beaches. On some occasions the beach wrack deposits cover beaches

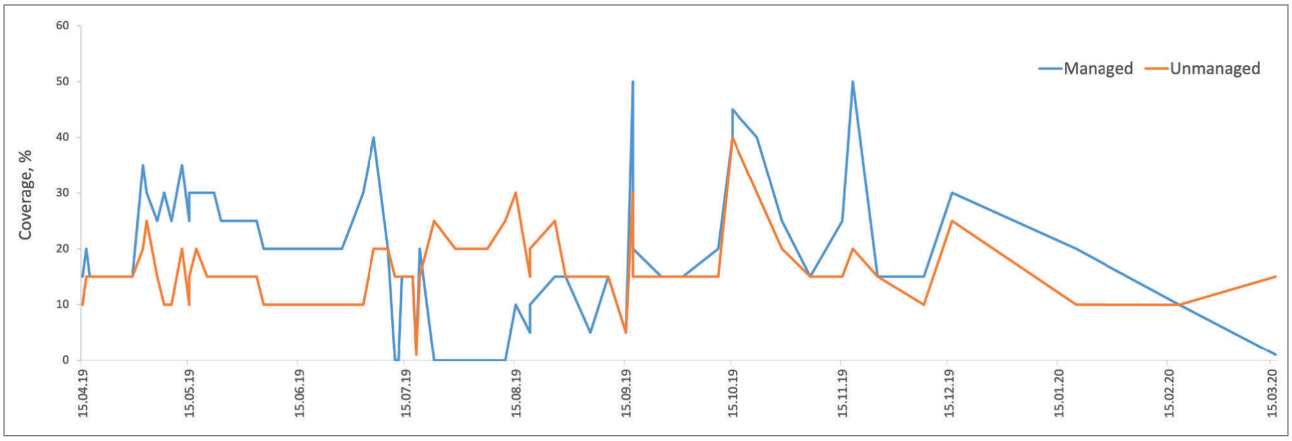



**Figure 3.3.3.** Beach wrack coverage (April 2019–March 2020) in Kakumäe Beach (Estonia) both in the unmanaged and managed area (100m long beach section). In 2019 the first beach wrack cleaning activity in managed beach section took place in the middle of June and overall there were 3–4 cleaning efforts.

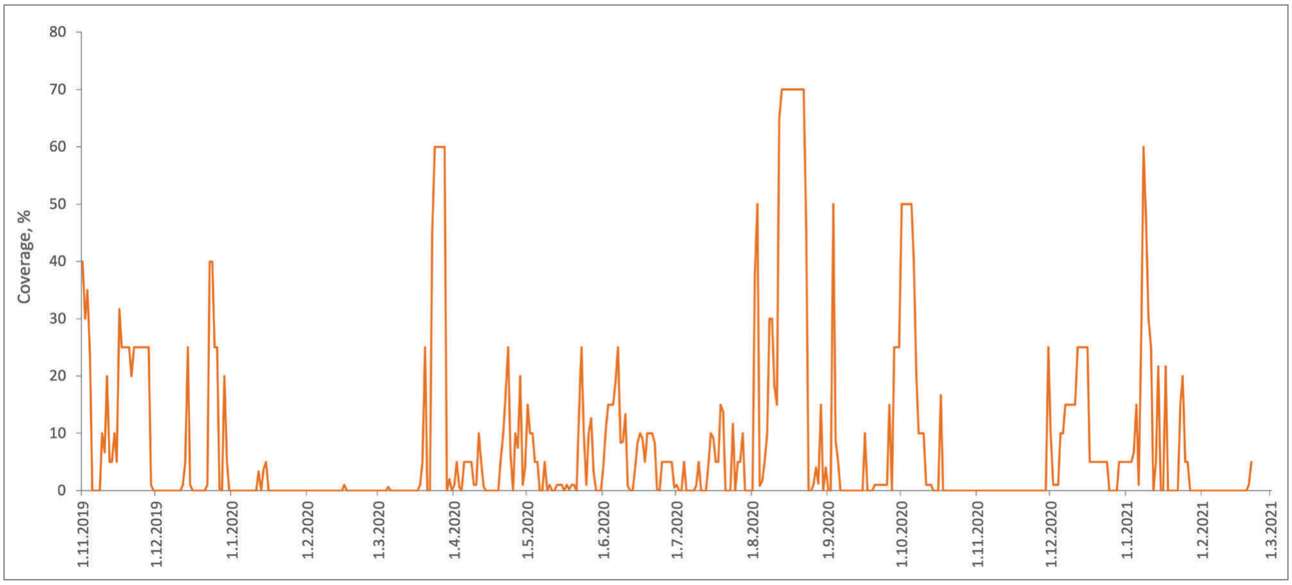



**Figure 3.3.4.** Beach wrack coverage (November 2019-February 2021) in Otradnoye Beach (Russia) (40 m long beach section, unmanaged).

in more than 1 m thick layer, providing important ecological and biogeochemical implications for the coastal ecosystem. Beach wrack contributes to coastal protection by reducing erosion of the coast from both the force of the sea and from sea-level rise caused by global warming, recycles nutrients to the coastal environment and dune vegetation, while providing habitats and food sources for marine and terrestrial biodiversity (Crawley et al., 2009; Mellbrand et al., 2011).

Within the CONTRA project a sheltered beach in western Öland, Sweden – Rälla beach – was studied in the means of natural decomposition process. The beach was mainly covered by decomposing algae (→ Figure 3.4.1, → 3.4.2). The most common species of macroalgae and seagrass that could be found within the beach wrack were: *Fucus vesiculosus, Fucus serratus, Furcellaria lumbricalis, Vertebrata fucoides, Ceramium tenuicorne, Rhodomela confervoides* and *Zostera marina*. The beach wrack deposits were mostly transported to the beach during winter storms. The Rälla beach was temporarily flooded by brackish seawater from the Baltic resulting in a relatively high concentration of salt in the soil, which also affects the composition of plant species. However, due to increased composition processes of beach wrack the soil is enriched with nutrients stimulating growth of vegetation that has high nutrient demand.

The areas closest to the sea were not colonized by plants and were only covered by layers of algae debris in different decomposition stages (→ Figure 3.4.3). It must be noted that this vegetation survey was carried out by the end of August 2020, and thus some of the species with earlier growth had already disappeared. The vegetation

**Figure 3.4.1.** Rälla beach in March 2020 (29 March 2020, Sachpazidou Varvara).

**Figure 3.4.3.** The established vegetation on Rälla beach (Photo by Varvara Sachpazidou).

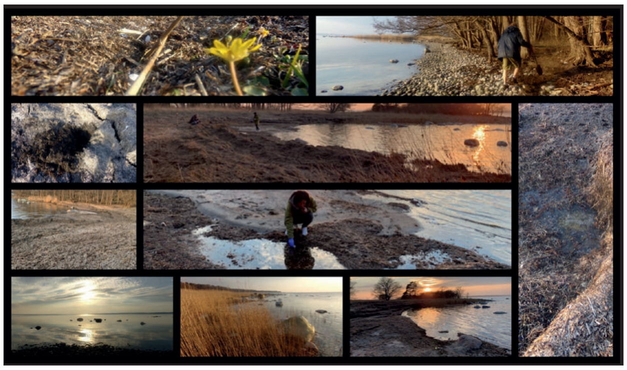


**Figure 3.4.2.** Rälla beach in July 2020 (5 July 2020, Sachpazidou Varvara).

study did not include grass and *Carex* species, neither mosses nor algae.

The lower parts of the vegetated area of the beach were mainly covered by monocultures of *Atriplex littoralis* and *Chenopodium album* (→ Table 3.4.1). In the upper zones of the beach the substrate consisted of a more decomposed organic soil substrate and the species diversity was a bit higher. Here *Urtica dioica* was abundant, but also *Calystegia sepium, Lamium purpureum* and *Galeopsis tetrahit* were found. Also single species of *Achillea millefolium* and *Scorzoneroides autumnalis* and some individuals of *Salix repens* were recorded. In more moist parts *Phragmites australis* was abundant. At the edge of the forest Rälla Tall, in areas that normally were not flooded, adult species of *Quescus robur* and *Alnus glutinosa* were common, as well as some individuals of *Salix caprea*. Due to very robust and cosmopolitic species list we conclude that Rälla's vegetation is adapted to grow in extreme weather conditions and reflects the high nutrient supply within the beach area.

The amount of wrack accumulating on the Rälla beach varied across sites and seasons during the year 2020. We estimate that it will take a long time for this beach wrack landings to disappear and it must be pointed out, that it is a recurring phenomenon in recent years with increasing rates of

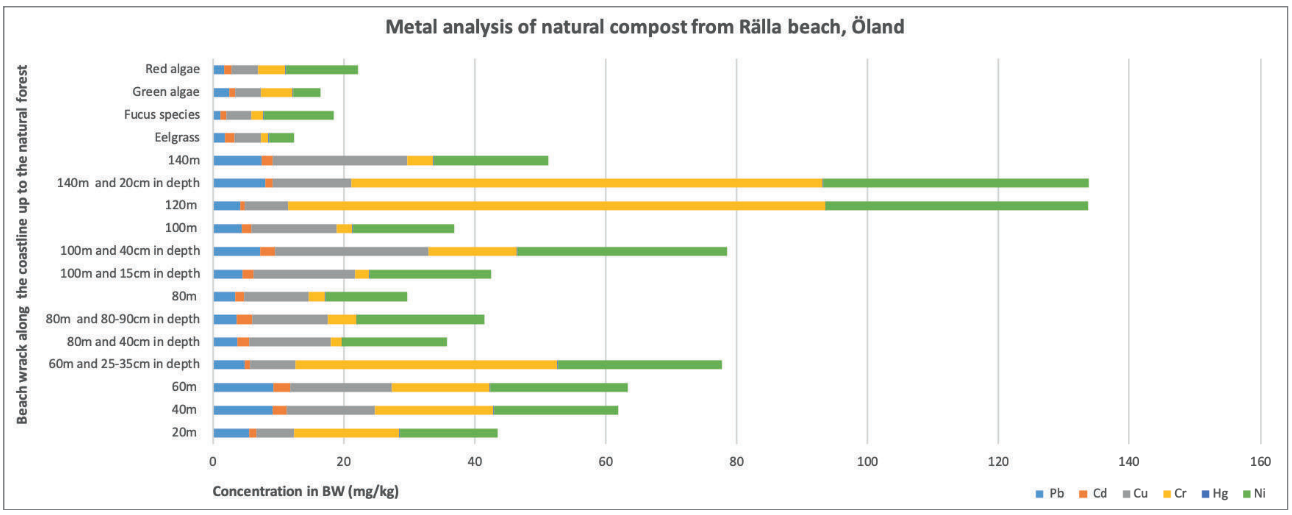



**Figure 3.4.4.** Heavy metal (Pb, Cd, Cu, Cr, Hg, Ni) distribution from the coastline up to the forest in Rälla beach (Öland, Sweden).

**Table 3.4.1.** List of species growing on the beach wrack piles in Öland, Sweden. The abundance was estimated accordingly: 1 – rare, 2 – frequent, 3 – abundant. Information regarding habitat and flowering is adapted from the University and Jepson Herbaria of the University of California database https://ucjeps.berkeley.edu/ (visited 03 May 2021).

| Species | Abundance | Habitat | Flowering time |
|---|---|---|---|
| *Atriplex littoralis* | 3 | Sandy seashores, beach wrack piles | July–September |
| *Chenopodium album* | 3 | Waste grounds, roadsides | June–September |
| *Alnus glutinosa* | 2 | Seashores, nutrient-rich grounds, moist broadleaf woods | April |
| *Lamium purpureum* | 2 | Beach wrack piles, waste grounds, roadsides | May–October |
| *Phragmites australis* | 2 | Ditches, disturbed sites | April–October |
| *Quercus robur* | 2 | Mixed forests | June |
| *Achillea millefolium* | 1 | Meadows, waste grounds, shores | July–October |
| *Calystegia sepium* | 1 | Woodland borders, open floodplain areas along aquatic environments, waste grounds | May–August |
| *Galeopsis tetrahit* | 1 | Waste grounds, rocky outcrops | July–September |
| *Rumex crispus* | 1 | Shores, fields, waste grounds, roadsides | July–August |
| *Rumex maritimus* | 1 | Shores, muddy aquatic grounds, woodlands | June–September |
| *Scorzoneroides autumnalis* | 1 | Shores, rocky outcrops, roadsides, waste grounds | July–October |
| *Salix caprea* | 1 | Damp and rich coniferous forests, broadleaf woods, shores, roadsides | April–May |
| *Salix repens* | 1 | Sandy shores, sandy pine woodland | May |
| *Sporgularia marina* | 1 | Coastal beaches, wetlands | June–August |
| *Tripleurospermum maritimum* | 1 | Seashores, beach wrack piles, roadsides, waste grounds | June–September |
| *Urtica dioica* | 1 | Roadsides, waste grounds, shores, stream sides, broad-leaved forests | July–September |

intensity. Ekerum´s inland forest which is extended to the Baltic Sea, forms in combination with strong winds, excess humidity, forest species communities and water regime, the Rälla beach and is subsequently a part of the coastal area. Therefore, Ekerum's upland forest community include the beach forest sandy soil "Rälla".

The depth profile of the Rälla beach wrack layer can reach 2 to 3 meters as the landing process has continued over 20 years. To determine the accuracy of the quantification of beach wrack and the relationship between depth and cover classes with biomass, compost/soil samples were taken along a 20 m transect from the coastline up to the natural forest (→ Figures 3.4.4). Evaluation of the samples was performed with regards to metal concentration (→ Figure 3.4.4, see → subchapter 3.7 and CONTRA-report Möller et al., 2021 for more details), moisture and organic content. Zinc concentration varied inbetween 115–290 mg/kg with lowest values observed near the waterline and highest values at 140 m from the water edge. Organic content showed the smallest variance, the observed values were inbetween 95–99 % and moisture content decreased gradually with increasing distance from the waterline (80 % of moisture content was noted near the waterline, 25 % was observed at 120 m distance from the waterline). The analysis package was perfomed regarding Swedish legislation for compost. Based on the determined levels of heavy metals, the compost material in Rälla beach is suitable for use in growing edible crops.

### 3.4.2 Decomposition rate

Residence time and decomposition rate are strongly related and must be considered in beach wrack management activities. Marine macrophytes directly enhance abundances of sandy beach fauna through provision of food and habitat and therefore the residence time i.e. time for degradation process on the beaches is most important for the local faunal assemblage (e.g. Ince et al., 2007).

Under the CONTRA project the decomposition experiments were performed with species, which are characteristic of the study area. In Poland, wrack deposits on the Rzucewo beach are composed almost exclusively of the eelgrass *Zostera marina* and the filamentous algae *Pilayella* sp. or *Ectocarpus* sp., which are difficult to distinguish in the wrack. In Estonia, Kõiguste bay, both higher plants and perennial algae accompanied with filamentous algae were found in beach wrack. While the Baltic Sea hosts both attached and loose-lying form of *Furcellaria lumbricalis*, the attached form was used in this experiment.

Significant weight loss occurred within the first month when 14 to 85 % of initial dry weight was lost (→ Figures 3.4.5, → 3.4.6). After four months and more the changes in the remaining biomass were minor. Rapid decline of biomass of filamentous species during the first months was followed by a decrease of more than 90 %. More surprisingly, *F. lumbricalis* showed considerably high decomposition rate despite of relative sturdy thalli. In Estonia, *F. vesiculosus* was the most resistant to decay. *F. vesiculosus* lost 60 % of initial biomass during the year, while *F. lumbricalis* lost 99 % and *M. spicatum* lost 98 % (→ Figures 3.4.7, → 3.4.8).

In addition to morphological differences, the degradation time of different species was significantly affected by the placement of wrack on the shore. In general, degradation was faster in water compared to the placement of wrack above the sediment or buried in the sand (→ Figures 3.4.5, → 3.4.6). The decline of plant material buried in sand in driftline was faster compared to wrack buried in the sand near dunes. While the degradation of *Z. marina* submerged in water was similar to the degradation rate of filamentous algae, the species showed significantly higher resistance when was buried in the sand (→ Figure 3.4.5).

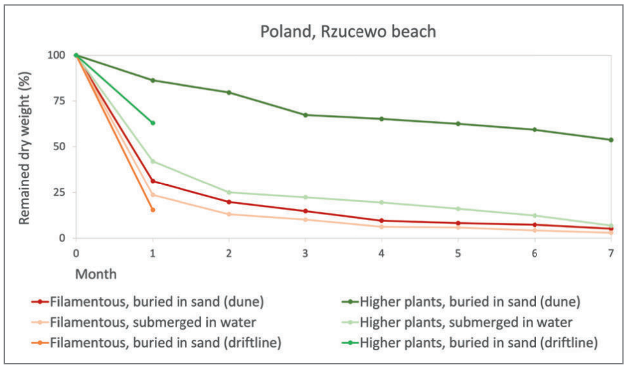



**Figure 3.4.5.** The average proportion of the remained initial dry weight of filamentous algae (*Pylaiella littoralis* and/or *Ectocarpus confervoides*) and higher plants (eelgrass *Zostera marina*) from July 2019 to February 2020.

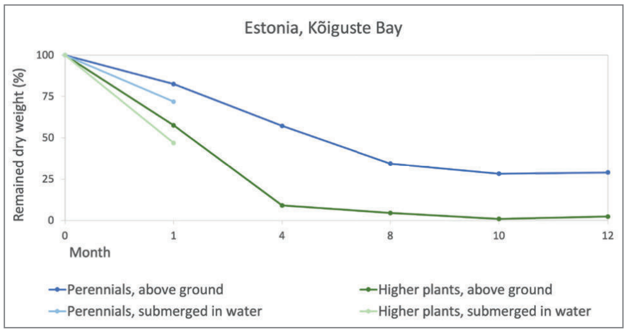



**Figure 3.4.6.** The average proportion of remained initial dry weight of perennials (mainly *Fucus vesiculosus* and *Furcellaria lumbrialis*) and higher plants (mainly *Myriophyllum spicatum*) from August 2019 to July 2020.

The mass loss of beach wrack in wet low-beach is considered predominantly affected by beach fauna, followed by loss from leaching while in the dry high-beach microbial respiration has higher importance (Jędrzejczak, 2002b). The study carried out in Germany refers that in a one-year period the eelgrass that is buried under sand shows very little signs of degradation. Similarly, previous studies have shown that degradation is greater on the surface compared to the buried organic material (e.g. Hackney, 1987).

The Baltic Sea is seasonally varying system, thus characterized by strong fluctuation in temperature, light and hydrodynamic conditions. The degradation of beach wrack is therefore strongly influenced by climatic and site-specific conditions. Consumption of beach wrack by grazers depends on the edibility of the wrack and the environmental conditions that affect both consumers and consumed materials. Both low and high temperatures drastically reduced the consumption of algal material. Decomposition of algae enhanced the consumption by microorganism, with maximum rates

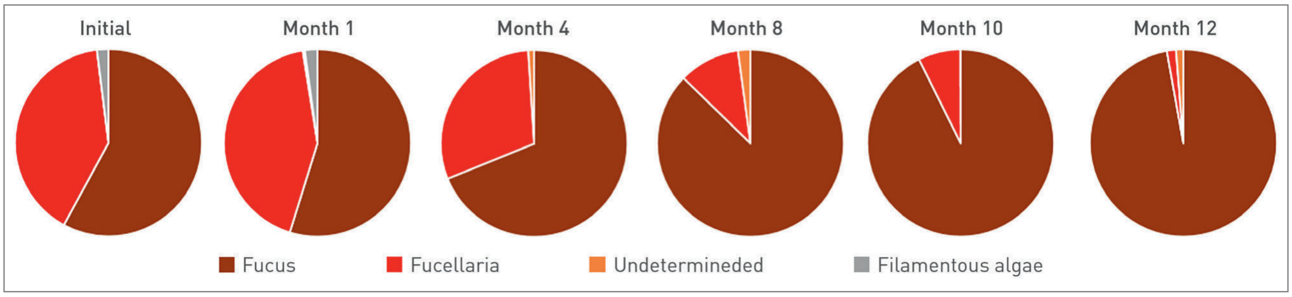



**Figure 3.4.7.** The average proportion of species groups in beach wrack (initially dominated by perennials *Fucus vesiculosus* and *Furcellaria lumbricalis*) used in degradation experiment carried out in Estonia.

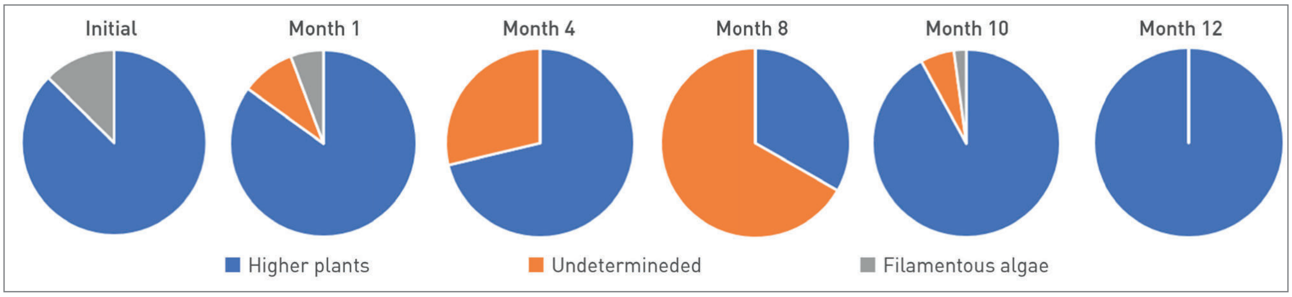



**Figure 3.4.8.** The average proportion of species groups in beach wrack (dominated by higher plant *Myriophyllum spicatum*) used in degradation experiment carried out in Estonia.

obtained when algae decayed in a wet environment (Lastra et al., 2015).

To summarize – the algal degradation process is more rapid in the water than in the coastal environment. It must be taken into account, that hereby the lower temperatures (experiments started in late summer) affect the long-term low degradation level, however it is noteworthy that most of the mass loss of different species took place within 4 months being the most significant for filamentous species.

### 3.4.3 Greenhouse gases emissions

The decaying beach wrack may contribute substantially to global greenhouse gas emissions (this report, Liu et al., 2019). E.g. beach wrack composed by *Zostera nigricaulis* and *Amphibolis antarctica* can be substantial source of $CO_2$, but not $CH_4$, during the decomposing process. In Liu et al., (2019) the observed biomass loss with coinciding $CO_2$ emissions followed a double exponential model (R2 > 0.92). The initial flux rate is usually high, most likely due to rapid leaching of labile compounds, followed by a decrease and stabilizing at < 3 μmol $g^{-1}$ $d^{-1}$ during the remaining decomposing period. Additionally, beach wrack can be cast high up on beaches and remain dry – in this case the seagrass-dominated beach wrack had 72 % lower emissions than wrack that was subjected to repeated wetting in the intertidal zone (Liu et al., 2019). This implies that relocation of seagrass wrack by coastal resource managers (e.g. from water's edge to drier dune areas) could help to reduce atmospheric $CO_2$ emissions. However, if the located wrack is accumulated in large piles, $CO_2$ emissions may be stimulated, since rainfall and high temperatures in summer may stimulate the degradation of this material (see below the → case in Køge, Denmark). On a global scale, it is estimated that the annual $CO_2$-C flux from seagrass ranges between 1.31 and 19.04 Tg C $yr^{-1}$, which is equivalent to annual emissions of 0.63–9.19 million Chinese citizens (→ Figure 3.4.9, Liu et al., 2019).

The green-house gas $CH_4$ has a 25 times greater green-house warming potential than $CO_2$ and in coastal ecosystems its emission depends on salinity level (0–35 psu) with the most intense $CH_4$ emission production at intermediate salinity levels (9–18 psu) (Misson et al., 2021). The $CO_2$ and $CH_4$ emissions in beach wrack are also dependent on species composition, water body residence time, wave action and residence time of beach wrack on the sand. For instance, annual and opportunistic species of macroalgae degrade faster than perennial macrophytes. A longer residence time and presence of macrophytes in the water body allows a higher rate of degradation compared to the beach wrack deposited in the sand. Intense wave action contributes to the fragmentation of the macrophytes tissues, which accelerate the rates of

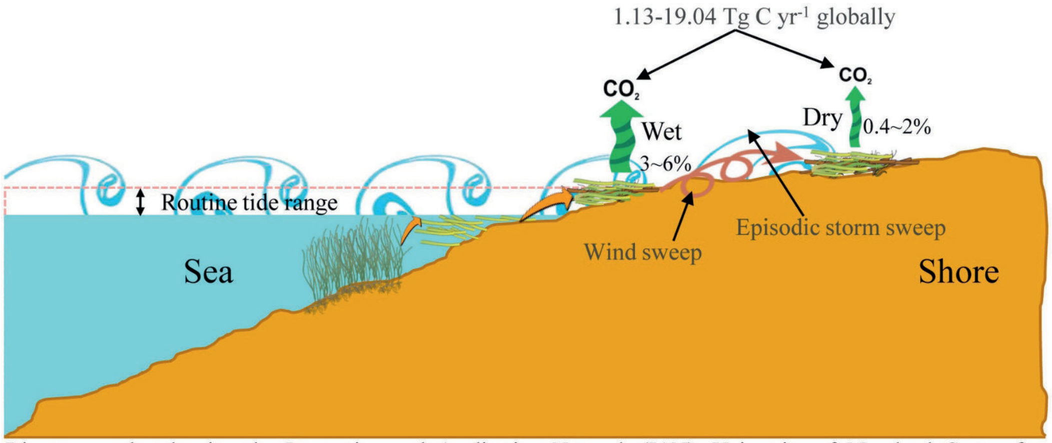


Diagram produced using the Integration and Application Network (IAN), University of Maryland Center for Environmental Science, Cambridge, Maryland

**Figure 3.4.9.** The schematic figure of green hose gases emission from the beach wrack (redrawn from Liu et al., 2019).

degradation and green-house gases emission.

In the Baltic Sea region the studies on green-house gases emission from beach wrack are currently rare. Under the CONTRA project these measurements were carried out monthly from July 2020 to January 2021 in a beach in Køge, Denmark. The efflux is expressed as mmol per m² per day. In Køge, beach wrack composes mainly of the eelgrass *Zostera marina* and the filamentous annual brown algae *Pylaiella* sp. and *Ectocarpus* sp. and the perennial brown algae *Fucus vesiculosus*.

Temporal variation and temperature-dependent emission of $CO_2$ is noted from the results (→ Figure 3.4.10). The high summer temperatures of 20 °C corresponds with high $CO_2$ emissions in August for especially Køge unmanaged beach. Measurements of lower emissions in January is in correspondence to lower temperatures. The $CO_2$ emission reached the highest rates in August in the new wrack and sand (9346–6722 mmol $m^{-2}$ $d^{-1}$) in Køge unmanaged beach, followed by the pile of beach wrack (7131 mmol $m^{-2}$ $d^{-1}$) in September on the managed beach. The air temperature was 20 °C and 15 °C for August and September, respectively.

The pile of beach wrack from the Køge managed site showed emission of $CO_2$. The pile was compiled in the back of the managed beach after cleaning in the summer months. Missing values corresponds to lacking of either new or old beach wrack or non-detectable emissions from the data points. Emission rates of $CO_2$ were generally higher ranging from 331 to 9346 mmol $m^{-2}$ $d^{-1}$ for all measured sites, i.e., new wrack, old wrack, sand and water than $CH_4$ (-3–109 mmol $m^{-2}$ $d^{-1}$) (→ Figure 3.4.10). $CH_4$ and $CO_2$ showed temporal variation and temperature-dependent emissions. The emission of $CH_4$ was higher in summer months compared to the winter months. The $CH_4$ emission reached the highest rates in September in the water (109 mmol $m^{-2}$ $d^{-1}$) in Køge managed beach, followed by new wrack emission rates in August in both managed and unmanaged beach (70–75 mmol $m^{-2}$ $d^{-1}$) (→ Figure 3.4.10). Emissions of $CH_4$ in the water was always higher compared with the emissions from sand, new wrack and old wrack which was either not detectable or very low. The emissions of $CH_4$ were in general higher for the managed site in comparison with the

**Table 3.4.2.** Estimated total emission in $CO_2$ equivalents (tons) for 7 months measures of the green-house gases $CO_2$ and $CH_4$ in Køge managed and unmanaged beaches.

| Køge Managed Beach | $CO_2$ equivalents (tons) |
|---|---|
| Sand | 10.5 |
| Water | 14.3 |
| New wrack | 6.7 |
| Old wrack | 0.4 |
| Pile | 12.0 |
| Total | 43.9 |
| **Køge Unmanaged Beach** | |
| Sand | 2.1 |
| Water | 7.7 |
| New wrack | 9.7 |
| Old wrack | 2.7 |
| Total | 22.2 |

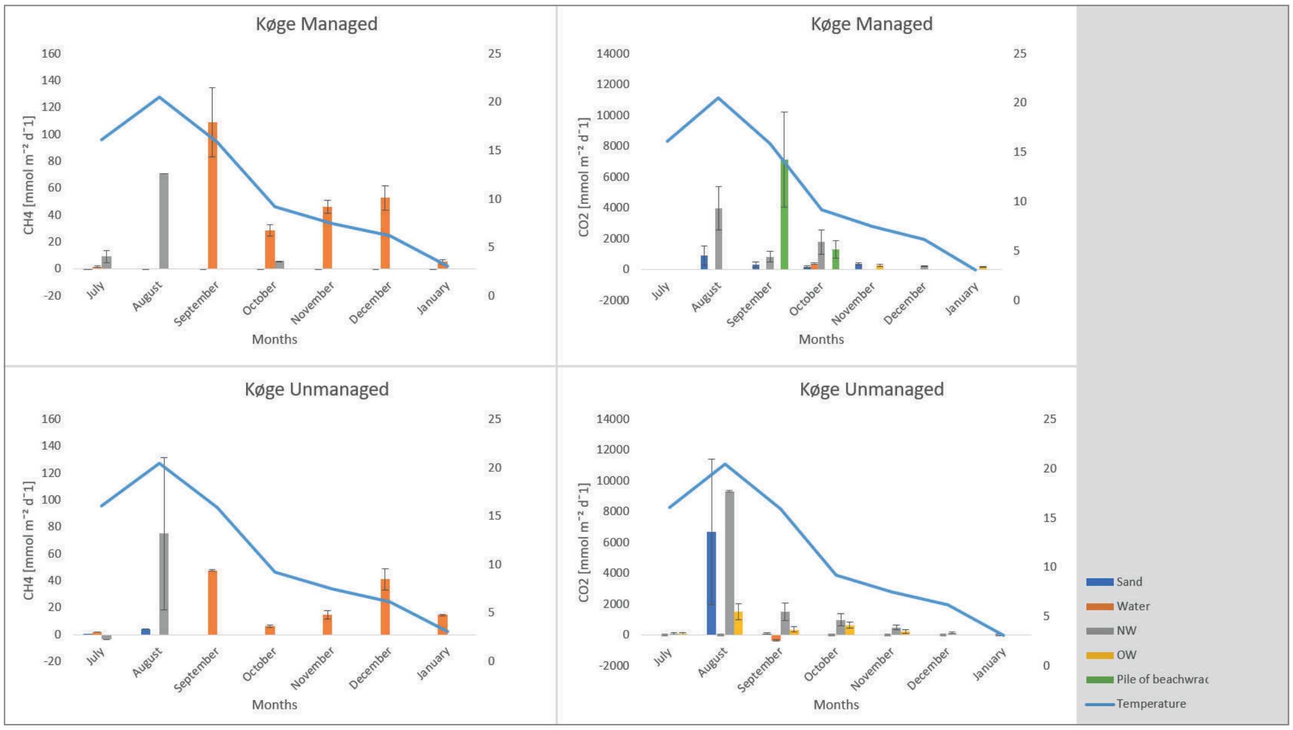



**Figure 3.4.10.** Monthly GHG emissions from July 2020 to January 2021 in the sand, new beach wrack (NW), old beach wrack (OW) and water in Køge (Denmark) managed and unmanaged beaches. The full line represents the average air temperature for the sampling day.

unmanaged site, especially for the water emission measurements. Uptake of $CH_4$ was observed only once during the sampling period (July sampling) for the new wrack on the unmanaged beach.

To make a conservative assessment of total green-house gases emissions, we converted $CH_4$ emissions to $CO_2$ equivalents based on 25-factor green-house warming potential and summed with the $CO_2$ missions and finally transformed the emissions to the corresponding area size of each beach and measured locations (new wrack, old wrack, sand, water). Køge managed beach has a total emission of 44 tons, with the largest contribution of water, sand and pile of accumulated beach wrack (~280 m³) (→ Table 3.4.2). The cleaning of the beach by tractors removing beach wrack by pushing it back to the water can explain the high emissions both in the water and in the sand. The tractors activity mixes the beach wrack in the sand causing higher fragmentation of the material, degradation and thus green-house gas emissions. This sand mixing effect is not observed in the unmanaged beach. In the unmanaged beach the newly deposited beach wrack had the highest emission which is explained by the level of moisture in the material (→ Table 3.4.2). For more precise calculations, a higher resolution of coverage areas of new wrack, old wrack, and also presence of macrophyte material in the water are needed.

The green house gas emission from the beach wrack is an important research field that needs more focus. This information is most valuable for developing present-day coastal carbon budgets to better understand and map changes in coastal development, beach management, general eutrophication, wrack accumulation, and climate, and the relationships between those. As Liu et al., 2019 proved, the location of the beach wrack with regard to moisture content is important as it is possible to reduce atmospheric $CO_2$ emissions e.g. by relocating beach wrack from water's edge to drier dune areas. At present day, relocating and piling up the beach wrack is a common practice in some beaches along the Baltic Sea. However, our study has shown that this material should not be compiled in large piles, since weather conditions such as rain and temperature may trigger organic degradation. Therefore, the relocation of beach wrack to drier dune areas in the Baltic Sea should consider this effect in the future management of beach wrack. More detailed studies regarding the emissions of green-house gases in different amounts of such beach wrack relocations are needed. The management practices, for example, the use of tractors and the transport of beach wrack back to the water may in some cases not be optimal when green-house emissions are considered.

**Figure 3.5.1.** Dense vegetation of the back of the beach accumulate some amount of beach wrack (photo: Julia Gorbunova).

**Figure 3.5.2.** The beach wrack in the vegetation of the back of the beach in the Filinskaya bay, 08.02.2020 (photo: Julia Gorbunova).

## 3.5 Aeolian dispersal

Many studies show the important role of marine beach wrack for beach ecosystem functioning (e.g. Polis & Hurd, 1996, Ince et al., 2007, Barreiro et al., 2013). The aeolian dispersal of sand and beached organic material is the most crucial process in the formation of dunes. The biomass thrown ashore is a pivotal fertilizer for dune vegetation in the process of coastal dune formation (Walter, 1975). Accumulated beach wrack nearest to the sea influences the sand transport rate for a limited time and is readily removed by storm waves, whereas the uppermost wrack line lasts longer, traps more sand, influences the sediment budget of the existing foredune more directly, and forms the basis of the new foredune crest (Nordstrom et al., 2011).

However, only a part of the beach wrack that reaches the shoreline is included into the food web of the dune ecosystem. For some of the Baltic beaches the residence time of wrack on the shore is often limited to a few days (→ see 3.3 "Residence time"). In exposed areas it is common that most of the wrack deposited on the beaches is flushed back to the sea and does not reach the vegetated beach zone (→ Figure 3.5.1, → 3.5.2).

The aeolian dispersal, accompanied with wave dispersal, of the beach brack was investigated at respective sites in Germany, Estonia and Russia. The research included an estimation of the amount of beach wrack that has been accumulated in "trap – beach wrack catcher" – this means a survey sites in thickets of beach vegetation with an area of 1 m². The observed amount of beach wrack in the vegetation was from 0 to 200 g/m². The largest amount (100–200 g/m²) was found in February and March 2020 in Filinskaya Bay, Russia. This is most likely associated with storms, when wind and waves throw algae inland the beach. The winter of 2019/2020 was mild – there was no stable snow cover, there was no fast ice along the coast. Filinskaya Bay belongs to one of the sites in the Kaliningrad Oblast where beach wrack is washed ashore often due to the closeness of a perennial algae growth in the area of Cape Taran (Volodina & Gerb, 2013) and hydrodynamic conditions. The beach in the bay is gentle and does not have a dune. The vegetation zone is in the back of the beach at a 25–45 m distance from the sea line. The gathering of wrack was carried out completely from the same area of vegetation thickets with an area of 1 m² from September 06, 2019 to August 25, 2020, with a frequency of 1–2 times a month. A total of 380 g/m² (dry algae weight) of algae was harvested during this period, which can be conditionally considered an annual input of beach wrack into the vegetation thickets in this area.

The species composition of algae found in the beach vegetation zone was limited to 5 species at the studied sites, namely eelgrass *Zostera marina, Furcellaria lumbricalis, Fucus vesiculosus, Cladophora* sp., *Vertebrata fucoides*.

At the island of Poel beach (Germany) the main species, both in the new wrack from forebeach and in the wrack from the vegetation zone, was *Zostera marina*. Similarly, *Furcellaria lumbricalis* dominated throughout the year in the wrack in the vegetation zone of the beach in Filinskaya Bay, Russia. Also, in the dense vegetation, a relatively large amount of *Fucus vesiculosus* was found, up to 15 % of the total weight of the wrack. At the same time, the share of *F. vesiculosus* is very small in the new wrack located near the water line, less than 1 %, as well as *Z. marina*. The growth of *F. vesiculosus* and *Z. marina* has not been registered at present within the Russian sector of the southeastern part of the Baltic Sea and, presumably, they are brought in small amounts by currents from the surrounding marine areas (Volodyina & Gerb, 2013).

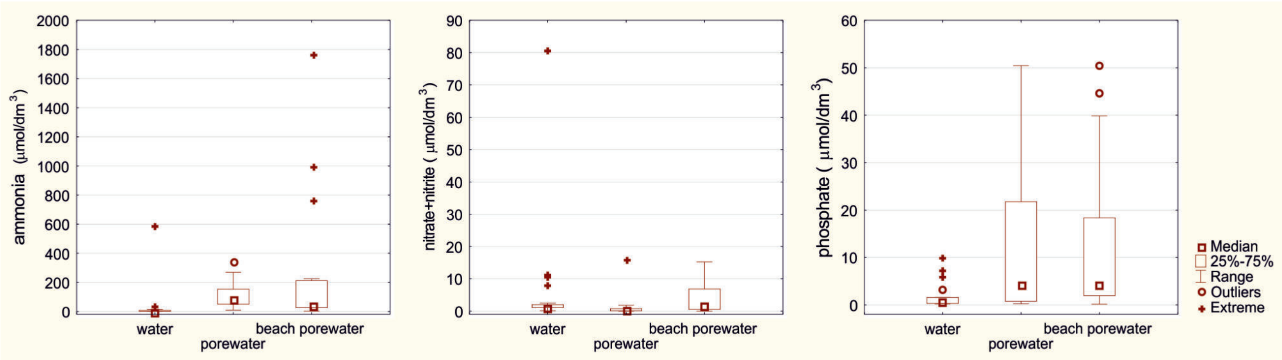



**Figure 3.6.1.** Phosphate, nitrate+nitrite and ammonia concentrations variability in surface water, sediment pore water and pore water from beach (from under the detritus) from April (2019) to November (2019) (values for 3 sampling sites).

In the light of the studies carried out, different species of algae are subject to varying degrees of aeolian and wave dispersal across the beach. It can be assumed that *F. lumbricalis*, having a branchy structure of the thallus, dries up and becomes "fluffy" and is more easily carried by the wind. *F. vesiculosus* is also branched and has air bladders. When dry, these algae and *Z. marina* usually do not stick together. The relationship between the structure of the thallus of algae and their susceptibility to being washed ashore was also noted by other authors (Orr et al., 2005). At beaches with intermediate and high exposure to wave action, wrack was dominated by algae with air bladders in their structure (e.g. *Fucus* sp.), a factor which, by increasing buoyancy, might assist in them drifting ashore (Barreiro et al., 2011). At the same time, filamentous algae (e.g. *Cladophora* sp., Ulva sp., *Vertebrata* sp.), when dried, strongly stick together, forming dense mats along the coastline or at a short distance from where they were casted by waves. Also these species degrade more rapidly (→ see 3.4.2 "Decomposition rate"). These algae were rarely found in the vegetated zone of the beach.
However, a detailed understanding of the mechanisms and quantification of aeolian (and wave) dispersal of beach wrack in the beaches requires additional scientific research.

## 3.6 Nutrient availability

Drifting algal mats have recently become a problem in shallow, eutrophic seas worldwide. On the one hand, the excess organic matter washed ashore or deposited on the seabed enhances the growth rates of suspension feeders, while on the other hand it can create local hypoxia events that are followed by changes in zoobenthos abundance, species composition and food web. Marine plant detritus plays an important role in the global carbon cycle and exceeds three-fold the amount of carbon stored in living marine plants. Coastal marine waters are the key areas of plant detritus production and storage. Owing to their permeability, sandy shores have been shown to be very efficient converters of organic matter. To understand the importance of sandy shores in the turnover of organic matter, it is necessary to have a knowledge of detritus production and its biomass (Kotwicki et al., 2005).
One of the important factors which was measured during the sampling campaign under the CONTRA project was the redox (oxidation-reduction) potential. Redox reactions are essential to major element cycling, to many sorption processes, to trace element mobility and toxicity, thus to most remediation schemes, and to the life of flora and fauna itself. Results of the *in situ* measurements in surface and sediment pore waters showed significant oxygen depletion in the warm period and lower annual oxygen levels in the area impacted by algae. Moreover, the results of the measurements indicated that oxygen consumption during algae decomposition influenced an area wider than just that covered with algae wrack, resulting in oxygen depletion in pore waters.
Nutrients were analyzed from surface and sediment pore waters collected in the surf zone and from sediments, sampled from the beach beneath the beach wrack and in two areas in Poland at respective managed (Puck Municipal Beach) and unmanaged beaches (Rzucewo). The amount of beach wrack on the city beach inside the Puck Bay was much lower compared to the unmanaged beach.
Nutrients concentrations were highly variable in all type of studied waters with no clear spatial and temporal trends. In pore water taken from under the detritus at the beach, nutrient concentration was in most cases greater than in the water column and comparable or greater (nitrate+nitrite) to the

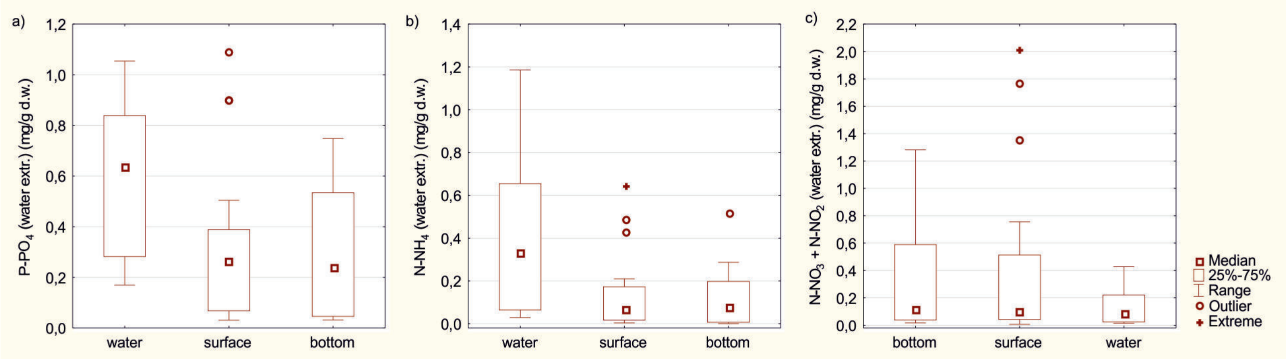



**Figure 3.6.2.** Variability of water extractable forms of phosphorus and nitrogen in beach wrack sampled from surface water and two layers of sediment beaches.

values observed in porewater (→ Figure 3.6.1). Variability (RSD) of total carbon (Ctot), nitrogen (Ntot) and phosphorus (Ptot) concentrations in beach-wrack collected from surface water and two layers of beach sediment (surface and subsurface) in the investigated areas between April and November 2019 varied from 29 % to 52 % (→ Table 3.6.1). This indicates a potential varying degree of mineralization, and/or different beach wrack composition. Molar C:N:P ratios in beach wrack suggest that in managed beach the wrack is mineralized to a lesser extent than in unmanaged beach.

Labile phosphorus and nitrogen (water extracted) showed signifficant differences between wrack collected from water and the beach (ANOVA K-W test). In case of $P\text{-}PO_4^{3-}$ (p=0.02) and $N\text{-}NH_4^+$ (p=0.02). Those species reached lower concentrations in detritus collected from the beach in comparison to the detritus collected from the water column (→ Figure 3.6.2 a,b). In the case of the sum of $N\text{-}NO_3^-$ i $N\text{-}NO_2^-$ differences were not signifficant (p=0.76), although in beach wrack collected on the beach concentration were frequently a lot higher than those collected in surface water (→ Figure 3.6.2 c). Observed variability of labile species of N and P reflects nitrification and release of phosphate and ammonia during decomposition of detritus after deposition to the beaches.
Rough estimation show, that in beach wrack accumulated along 100 m of the coast (mean dry wet of beach wrack) at unmanaged stations in Ruzcewo in Poland, the weight of total phosphorus ranged from 18 to 36 kg (→ Figure 3.6.3). Taking to account, the total phosphorus concentration (median) in algae samples classified as living, it can

**Table 3.6.1.** Statistical outcome of carbon (Ctot), nitrogen (Ntot) and phosphorus (Ptot) in wrack sampled from water column and two layers of sediment beaches in studied managed and unmanaged beaches in Poland, data since April do November 2019).

| | wrack origin | N | Mean±S.D. (mg/g d.w) | Min. | Max. | RDS (%) |
|---|---|---|---|---|---|---|
| **Ctot** | water | 15 | 261±98 | 76.6 | 385 | 38 |
| | beach surface | 17 | 298±124 | 45.3 | 445 | 41 |
| | beach bottom | 11 | 237±123 | 78.2 | 429 | 52 |
| **Ntot** | water | 15 | 18.5±6.49 | 5.55 | 28.8 | 35 |
| | beach surface | 17 | 19.9±6.85 | 4.52 | 31.0 | 35 |
| | beach bottom | 11 | 18.5±7.18 | 6.57 | 32.1 | 39 |
| **Ptot** | water | 15 | 1.93±0.55 | 0.82 | 3.11 | 29 |
| | beach surface | 17 | 1.60±0.62 | 0.66 | 2.99 | 39 |
| | beach bottom | 11 | 1.26±0.42 | 0.44 | 2.12 | 33 |

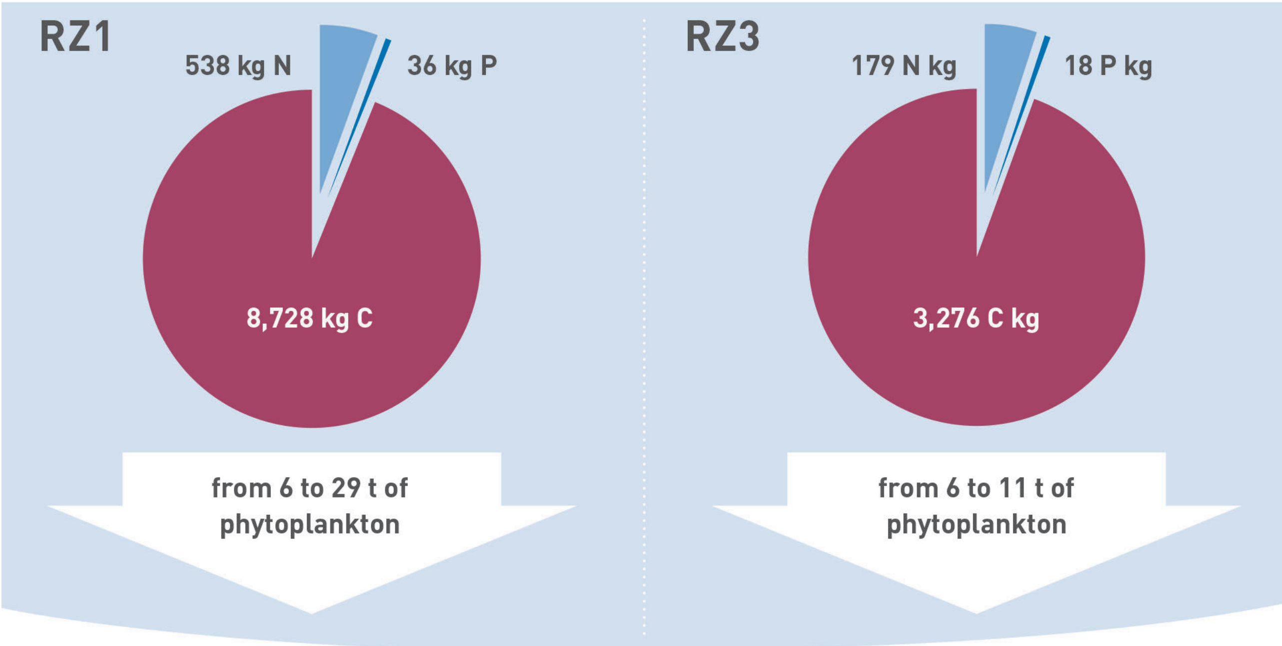



**Figure 3.6.3.** Mean load (kg) of phosphorus, nitrogen and carbon accumulated in beach wrack (dry weight, kg) at 100 m of unmanaged coast (Ruzcewo beach, Poland, stations Rz1 and Rz3) and potential production of phytoplankton biomass (assumes total decomposition of beach wrack and P limitation).

be roughly calculated, that such a load delivered to the sea water is responsible for the production of 6 to 29 tonnes of phytoplankton biomass (→ Figure 3.6.3).

## 3.7 Hazardous substances

Along most of the coast, the beach wrack on the beaches does not unduly affect the people who live closeby. However, in certain areas, a proportion of the wrack moving onshore is permanently trapped and may create problems not only for inhabitants of those areas and local authorities, who are responsible to maintain the beaches, but also for the local beach ecosystem. Beached seagrasses and algae release a number of constituents during decomposition and thus alter the coastal biogeochemical cycles and organisms. This includes nutrients and dissolved organic carbon, which will affect flora and microbial activity, and heavy metals (in polluted systems) – which creates risk for biota. Also, emission of volatile components from decaying plant material might constitute a risk for human health ($H_2S$, Hg0, $^{137}CS$), as well as for the climate (methane $CH_4$). In the presented study beach wrack sediments and water were investigated on the presence of heavy metals, methylmercury, nutrients, bisphenol A (BPA), nonylphenols (NP), octylphenols (OP), polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCB) (for further details see CONTRA-report Möller et al., 2021).

### 3.7.1 Heavy metals

Heavy metals are natural elements of Earth's crust, but their discharge to the environment due to anthropogenic activity overwhelms their natural concentrations. The most toxic heavy metals that pollute Baltic Sea include mercury (Hg), cadmium (Cd), arsenic (As), and lead (Pb) (Szefer, 2002). Heavy metals can be toxic even at very low concentrations since they tend to accumulate in marine organisms and biomagnify along the trophic chain. In consequence, they can pose a threat to final consumers – humans (Zaborska et al., 2019).

Our investigations under the CONTRA project within beaches of Poland revealed that the concentration of heavy metals in sediments does not exceed the thresholds values given according to Polish laws (Journal of Laws 2002 ) and HELCOM core indicator. However, in case of zinc (Zn) one magnitude higher concentration was observed in the beach wrack in the unmanaged beach in comparison to sediments (→ Figure 3.7.1). Also chromium (Cr) concentrations need further investigations. The observed difference between Cr levels in sand from the managed (Puck) and unmanaged beach (Rzucewo1, Rzucewo3), as well as sediments from both areas are significant (→ Figure 3.7.2). Measured values indicate that an intake of Cr from the sediments by algae may occur in the heavily overgrown Rzucewo site, and afterwards the element can be transferred to the beach sand due to algae decomposition.

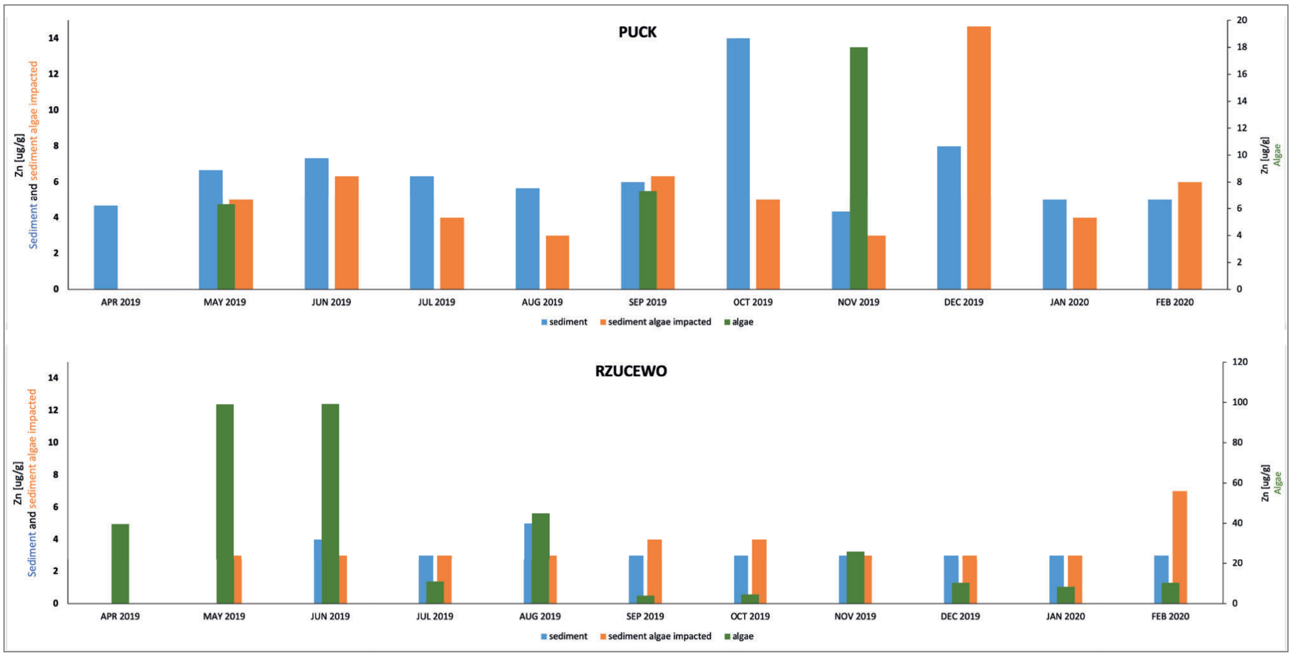



**Figure 3.7.1.** Zinc concentrations from in situ measurements in sediments with and without the impact of algae in managed (PUCK) and unmanaged beach (RZUCEWO).

Although the data for chromium are only available for one sampling campaign (Poland, July 2019), the preliminary results suggest that beach wrack can be a source of metals for the coastal environment.

*Mercury*

Anthropogenic mercury (Hg) remains a problem in the aquatic environment, and, based on the sedimentary records in the Baltic Sea, it exceeds Hg coming from natural sources (i.e. hydrothermal processes and rock weathering) on average on a factor of 5). Recently emission of Hg to the environment has substantially decreased (HELCOM and SYKE 2008) resulting also in noticeable decrease of Hg concentration in macrophyta in Polish coastal zone of the southern Baltic Sea. However, in parallel, intense growth of some macrophytobenthos in many areas of the sea bottom has been observed, which is stimulated by an improvement of environmental conditions and lengthening of the growth season. This leads to rapid inclusion of Hg from the water column (which is introduced from both natural and anthropogenic terrestrial sources) and from sediments (which was deposited in the past, and can be considered retarded anthropogenic emission).

In many areas of the Baltic Sea, due to the pattern of currents and shape of the coastline, large quantities of macrophytobenthos gather in the coastal zone, or end up as beach cast. During the summer season in the Gulf of Gdańsk, on 1 km of beach the amount of beached seagrass and algae wrack ranges from several dozens up to 800 tons (Filipkowska et al., 2008, Weinberger et al., 2020). Considering median Hg concentration: 7.6 ng $g^{-1}$ dw (dry weight), it has been calculated that 1 km long beach segment may receive 6 g of Hg per season. About 39 % of the Polish coast is estimated as accumulative zone (Dubrawski et al., 2008) indicating that about 200 km of coastline favors phytobenthos accumulation. During summer season, beach wrack on Polish beaches alone may contain 0.05 to 1.2 kg of Hg (Bełdowska et al., 2015). Recent study performed within the CONTRA project in the Bay of Puck (sheltered part of Gdańsk Bay), indicate that the concentration of Hg in managed beach (Puck), where live algae occurs were clearly lower, than those collected in the unmanaged site, where decomposing wrack was collected (Rzucewo) (→ Figure 3.7.3). However, concentration of Hg in live algae was similar in the unmanaged and managed site. This indicates, that although biological material from the bay accumulates Hg at the same rate and is characterized with the same Hg concentration in both sites, accumulation does not stop on landing. Decomposing beach wrack in unmanaged site is rich in organic matter and continuously builds up Hg concentration. This is probably caused by excellent sorption capabilities of decaying plant and algae material. It may capture mercury from coastal water, acting as a filter for surf water. Another explanation is Hg capture from

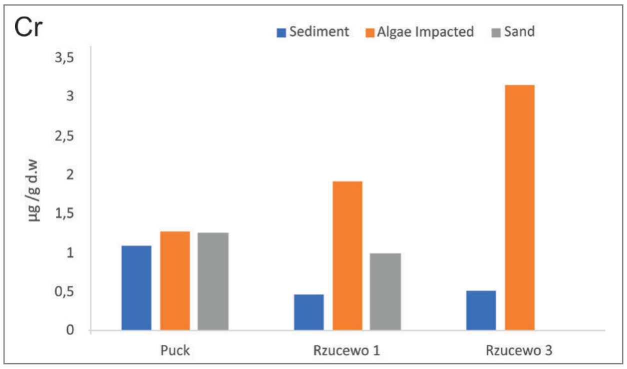



**Figure 3.7.2.** Chromium concentrations in sediments with and without beach wrack (impact of algae) in managed (PUCK) and unmanaged beach (RZUCEWO) in July 2019.

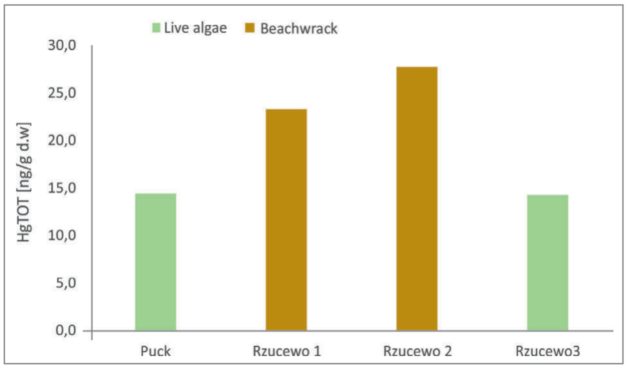



**Figure 3.7.3.** Total mercury concentration in live algae at managed site (P1), decaying beachcast at unmanaged site (Rz1, Rz2) and live algae at unmanaged site (Rz3).

atmosphere, where it originates in low emission from local sources. This means, that unmanaged beaches may not only transfer Hg from beachcast via accumulation in live algae and subsequent release, but additionally enhance Hg flux to the beach from local sources.

*Methyl mercury*

Methylmercury (MeHg) is the most toxic and dangerous form of mercury occurring in the environment. MeHg is highly bioaccumulative in organisms and undergoes biomagnification via the food chain. The environmental conditions promoting methylation processes and production of MeHg are anoxic conditions, presence of high contents of organic matter, and the presence of the specific microorganisms. All of those conditions are present in the beach wrack. However, results from the measurements of MeHg in sediments and sand do not give a definite answer if the beach wrack promotes the production of MeHg. For unmanaged beach (Rzucewo, Poland) in June 2019, the highest concentration of MeHg, 20 pg $g^{-1}$ dw (dry weight) was measured in algae impacted beach sand in comparison to the not impacted site (8 pg $g^{-1}$ dw) and sediments collected from water (5 pg $g^{-1}$ dw). However, in July 2019 the highest concentration was in sediments collected from water (45 pg $g^{-1}$ dw) in comparison to algae impacted beach sand (6 pg $g^{-1}$ dw) and not impacted sand (<LOD). In case of the managed beach in Puck, both in June and July 2019, MeHg was detected only in sediments at low concentration (8–10 pg $g^{-1}$ dw), and in the sand from beach concentration was below the detection limit (<LOD).

## 3.7.2 Organic contaminants

Organic pollutants persist in the environment, are toxic, bioaccumulate in biota, undergo biomagnification along the trophic chain and can be transported over long distances. In this study, polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs) as well as endocrine disrupting compounds (EDCs) like bisphenol A (2,2-bis-(4-hydroxyphenyl) propane – BPA), and alkylphenols: 4-nonylphenol (4-NP) and 4-*tert*-octylphenol (4-t-OP) were selected as representative persistent organic contaminants (POPS).

Seven PCBs and sixteen PAHs were analysed in sediments (1 m depth), beach sand and algae samples collected in July 2019 from beaches in Poland. In case of Σ7 PCBs concentration levels ranging from <LOQ (1.1 ng $g^{-1}$, dw (dry weight)) to 81.8 ng $g^{-1}$ dw in algae and beach wrack and from 2.3 to 17.0 ng $g^{-1}$ dw (dry weight) in sediments and beach sand (→ Figure 3.7.4). Investigation of Σ16 PAH showed concentration levels from 1237 to 21708 ng $g^{-1}$ dw in algae and beach wrack and from 128 to 2590 ng $g^{-1}$ dw in sediments and beach sand (→ Figure 3.7.4). For both groups of contaminants highest concentration was detected in algae and beach wrack samples from unmanaged station. In the case of sediments and sands samples, the highest concentration was detected in no impacted sand in comparison to impacted for PCBs and no differences were observed for PAHs.

Results of PCBs and PAHs show that beach wrack is able to accumulate those contaminants. On the other hand, comparision of impacted and not impacted regions suggest that beach wrack probably adsorbs PAHs and PCBs from the beach and their concentration is lower in impacted regions. The fate of PCBs and PAHs in the investigated region is more complicated than suspected and should be investigated in future.

Bisphenol A (BPA), and 4-nonylphenol (4-NP) were

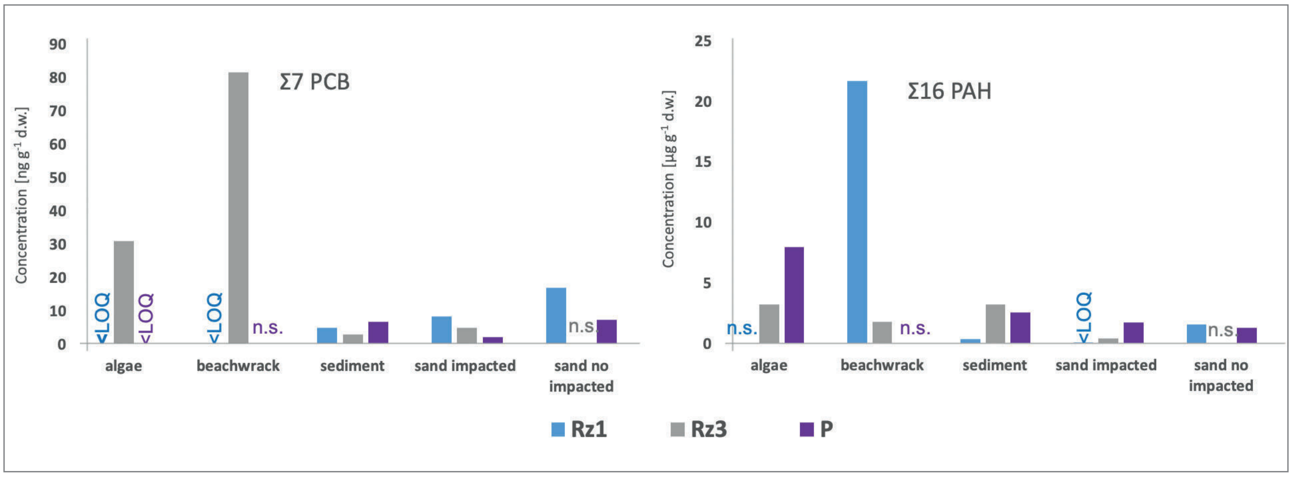



**Figure 3.7.4.** Concentrations of Σ7 PCBs and Σ16 PAHs in July 2019 in unmanaged beach of Rzucewo (Rz1, Rz3) and managed Puck beach (P). n.s.- no sample, <LOQ – below limit of quantification. Sediment indicates the sand samples collected from 1m water depth and sand (impacted/no impacted) indicates the sand collected from beach area.

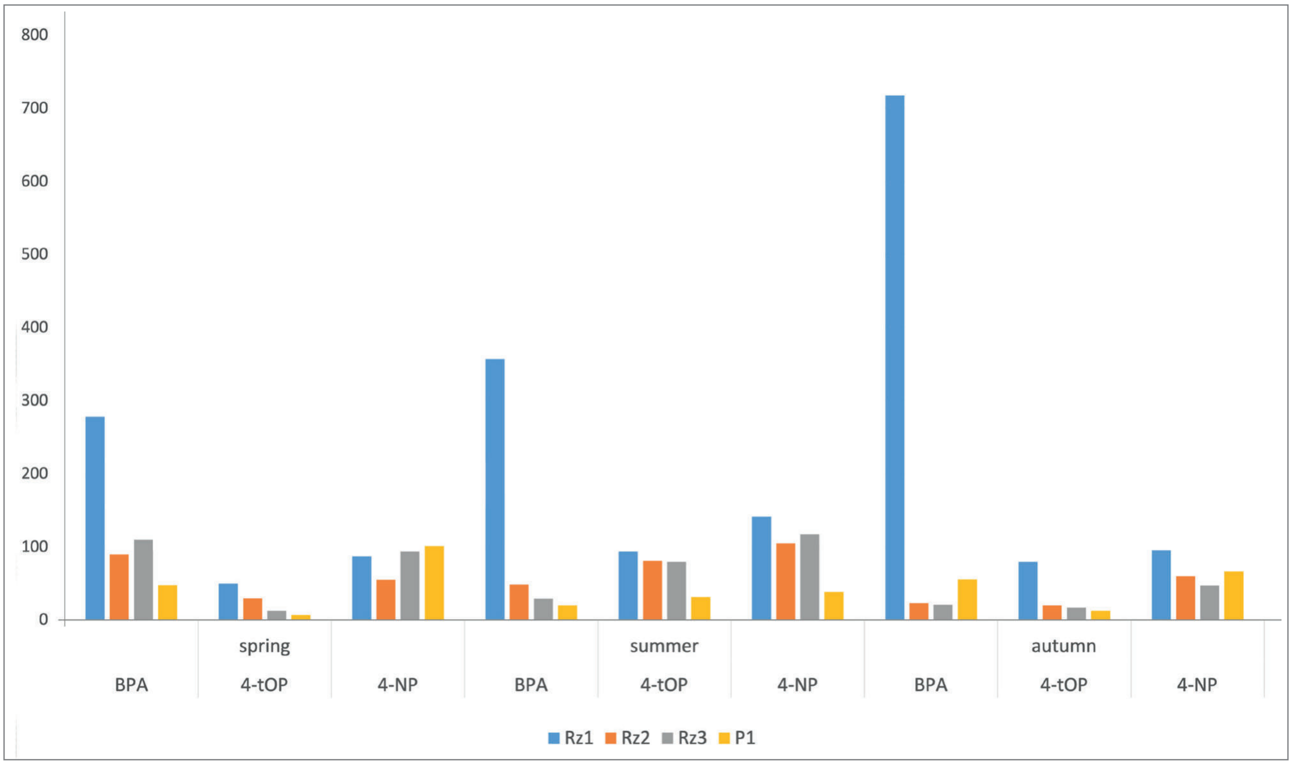



**Figure 3.7.5.** Concentrations of bisphenol A (BPA), 4-tert-octylphenol (4-t-OP) and 4-nonylphenol (4-NP) ng.g-1 dw depending on from season and station.

identified in all samples and the 4-tert-octylphenol was present in 80 % of samples. The highest concentrations were observed for BPA and then for 4-NP. The maximum average concentrations were recorded for unmanaged beach (Rzucewo, station Rz1: BPA 450.7, 4-t-OP 74.1 and 4-NP 107.8 ng g dw) and the lowest for managed beach (Puck, reference station P1: 40.6; 16.6; 68.5 ng g dw respectively). Variability of concentration depended on station and season (→ Figure 3.7.5). Our research indicate that the microalgae may have potential to accumulate bisphenol A, 4-tert-octylphenol and 4-nonylphenol and may result in the pollution of beaches exposed to dead plants or the transfer of dangerous compounds up the food chain.

Based on the obtained results, we can confirm that the beach wrack can release the contaminants accumulated by algae during their lifetime from seawater and sediments. Moreover, mercury studies indicate that beach wrack deposited on beaches continues to accumulate dissolved substances from seawater. Contaminants are being released to the coastal zone during decomposition of organic matter, partly to groundwaters, which are returning to the sea, and partly to atmosphere via volatiles. Moreover, presence of large quantities of organic matter, and the fact, that contaminants were already absorbed by marine plants and algae, results in enhanced bioavailability of contaminants, as compared to seawater where they came from. The process itself is cyclic – contaminants are being removed from seawater and sediments by marine plants and algae, in areas located at considerable distance from the coastal zone. In case of the Puck Bay, this included the entire bay and Gulf of Gdańsk. Then the algae is washed ashore in several locations, building up the metal and organic contaminants pool in these spots. During decomposition, bioavailable forms of contaminants are released to the coastal zone, where biota can absorb it and transfer them to the foodchain. Breaking this link, by removal of beach wrack after deposition, can result in the depuration of the ecosystem.

### 3.8 Human-produced litter

Marine litter is defined as any persistent, manufactured, or processed solid material discarded, disposed of or abandoned in the marine and coastal environment. Litter consists of items that have been made or used by people and deliberately discarded or unintentionally lost into the sea or on beaches, including such materials transported into the marine environment from land by rivers, draining or sewage systems, or winds. Marine litter can be found in all marine compartments (beaches, sea surface and water column, seafloor, ingested by biota) both in remote areas and close to populated areas (Galgani et al., 2013).

Presence of litter in the marine environment and beaches is a globally raising concern. Within beaches the litter directly affects the beach ecosystem and also brings more responsibilities to municipalities and authorities in order to keep the beaches and thus marine environment clean. Beach litter, especially the one of plastic, is stated as environmentally, economically, and psychologically negative and the most positive aspect regarding beach litter is the lack of it (e.g. Galgani et al., 2019; Wyles et al., 2016). One item of 'beach litter' is defined as any discarded item found on the beach over 2.5 cm in length (namely macro litter, including cigarette remains). Beach litter can be both – either marine origin, that is carried to the beach via currents/water or land-based origin e.g. left to the beach by visitors or carried through e.g. winds. Also from the beaches the litter can e.g. move either into the water environment, move inland, and also be ingested by birds and animals. Nevertheless, it is easier for people to remove the litter from the beaches than from other marine compartments.

The amount of beach litter varies greatly across the globe, but present studies confirm that all coastal regions, both in remote areas and close to populated areas, are affected by litter somehow. E.g. in the Mediterranean Sea region the values of litter can be over 6000 items (in size >2.5 cm) per 100 m long beach section (Vlacogianni et al., 2019). However, across Europe, the presence of litter on average is generally lower: in 2015 and 2016, the average beach litter quantity was estimated to 150 litter items per 100 m long beach section, with different averages in different regions: 40 items per 100 m around the Baltic Sea; 106 items per 100 m around the Black Sea; 233 items per 100 m around the North-East Atlantic and the North Sea and 274 items per 100 m around the Mediterranean Sea (van Loon et al., 2020). The Baltic Sea region is currently regarded as the cleanest area in Europe in the means of beach litter, nevertheless, the average amounts of litter items per 100 m of beach section are estimated to 50–300 (HELCOM, 2018ab). When looking closer, then within the Baltic Sea region the average number of beach litter items has been estimated to about 280 litter items per 100 m on urban beaches and up to 47 items per 100 m of shoreline on natural beaches (HELCOM, 2018).

Presence of litter within the beach wrack that is removed is one aspect that needs to be studied locally when searching or choosing for further beach wrack processing options. In the beaches the litter can be removed separately or together with beach wrack. There is also great variety in litter items when it comes to e.g. material, hazardousness, size, origin, and the presence of litter just makes the beach wrack a more complicated raw material for further processing (GESAMP, 2016; Veiga et al., 2016). When big and visible litter items can be removed easily by hand-picking, then the smaller items that are entangled or buried into the beached algal material are harder, if not impossible, to sight and remove. Microlitter (litter items in size < 5 mm) and nanolitter (generally litter items in size < 0.001 mm) surveys within the beach wrack need a more specific approach.

In the CONTRA project litter was mapped in 18 beaches that were visited monthly in a one-year period (CONTRA-report Möller et al., 2021). In total 2289 litter items were removed from the study

**Table 3.8.1.** The share of litter materials in studied managed and unmanaged beaches.

| | Managed beach | | Unmanaged beach | |
|---|---|---|---|---|
| **Material** | No of items | % | No of items | % |
| Artificial polymer materials | 957 | 72.17 | 695 | 72.17 |
| Chemicals | 3 | 0.23 | 1 | 0.10 |
| Glass/ceramics | 116 | 8.75 | 94 | 9.76 |
| Metal | 99 | 7.47 | 31 | 3.22 |
| Food waste | 2 | 0.15 | 8 | 0.83 |
| Undefined | 4 | 0.30 | 7 | 0.73 |
| Paper/carbord | 61 | 4.60 | 40 | 4.15 |
| Rubber | 21 | 1.58 | 23 | 2.39 |
| Cloth/textile | 25 | 1.89 | 34 | 3.53 |
| Processed/worked wood | 38 | 2.87 | 30 | 3.12 |

areas in period April 2019–March 2020. 1326 litter items originated from managed beach sections and 963 from unmanaged beach sections.

Throughout the study period, most of the litter items were collected from the chosen beaches in Estonia and Poland where the record „catches" were 127 and 116 respectively, with both records originating from managed beach sections. In other studied beaches in Denmark, Sweden, Germany and Kaliningrad the number of found litter items remained mostly under 20 items per 100 m of beach section. The threshold value of 20 litter items per 100 m long beach section is also agreed on to represent the good environmental status regarding beach litter (van Loon et al., 2020).

Most of the litter found on the European beaches is plastic-based (Addamo et al., 2017), our studies within the CONTRA project confirmed the previous findings – both in managed and unmanaged beaches the share of plastic among other litter materials was 72 % (→ Table 3.8.1). For other materials, there was little difference between managed and unmanaged beaches.

Most common findings within the CONTRA project were cigarette remains, plastic pieces, food containers and candy wrappers, plastic bags, plastic bottle caps, glass fragments, glass bottles and jars, plastic rope (pieces), plastic foam sponge, metal caps and pull tabs (→ Table 3.8.2). Out of different 82 litter categories under UNEP 56 categories were recorded in the studied beaches. The findings were in accordance with earlier similar studies (e.g. Addamo et al., 2017) showing that most of the litter found on the public beaches is related to simple leisure activities and originate from land-based sources. Numerous cigarette remains in unmanaged beaches are mostly explained by findings in Kakumäe unmanaged beach – the beach is located within the city and is a popular place all year round. Other studied unmanaged beaches are located further away from populated areas and the share of cigarette remains in those beaches was considerably lower. Based solely on observations the size of litter items was in most cases below 10 cm. Presence of large and heavy objects of size > 1 m (e.g. tyre, mattress, wooden pallet) was observed in few times. The amount of litter varied greatly among months, especially in the managed beaches of Estonia and Poland. However, no specific pattern can be brought out here at present (CONTRA-report Möller et al., 2021).

Our findings indicated that most of the litter items found on the beaches were related to beach wrack – in total 45 % of litter were found together with old wrack (within old wrack line), 26 % was found together with new wrack (new wrack line) and 29 % of litter was found from the rest of the beach area. There were variations between beaches but the general pattern indicates that litter and beach wrack do move together and similarly, especially in the unmanaged beaches.

Another topic is microlitter pollution at the beaches. Within the CONTRA project we did not specially investigate meso- and microlitter, but it was

**Table 3.8.2.** Most common litter items in studied managed and unmanaged beaches.

| **Managed beach** | | **Unmanaged beach** | |
|---|---|---|---|
| Litter item | % | Litter item | % |
| Cigarette remains | 31.38 | Plastic (other) | 18.92 |
| Plastic (other) | 16.18 | Cigarette remains | 15.89 |
| Food containers, candy wrappers | 5.78 | Food containers, candy wrappers | 8.11 |
| Glass bottles and jars | 5.45 | Plastic bottle caps and lids | 7.78 |
| Metal bottle caps, lids and pull-tabs | 4.46 | Plastic bags | 7.68 |
| Plastic bags | 4.46 | Glass or ceramic fragments | 5.95 |
| Glass or ceramic fragments | 3.96 | Foam sponge | 4.97 |
| Plastic rope | 2.89 | Plastic rope | 3.35 |
| Plastic bottle caps and lids | 2.81 | Glass bottles and jars | 3.24 |
| Paper (other) | 2.73 | Wood (other) | 2.81 |

determined from the biomass samples collected from Kakumäe beach, Estonia and Filinskaya Bay, Kaliningrad Oblast, Russia. Mesolitter is litter items in size of 5–25 mm length or diameter and microlitter is in size < 5 mm. In Kakumäe beach, out of 129 analysed biomass samples 55 (in total 43 %) contained some piece of still visible microlitter piece/item in a size range of 1–5 mm. In the Filinskaya Bay out of 109 processed samples, 28 % contained mesolitter. 77 % of the findings were pieces of polyethylene. Based on findings from Filinskaya Bay, it was estimated that on average 1 $m^3$ of beach wrack contained about 0.06 $m^3$ of polyethylene.

When the beach wrack is removed for beach cleaning purposes, it is also removed together with sand (see → chapter 4 "Mechanical disturbance"). Recent studies on the microlitter pollution in the Baltic Sea beach sediment indicated another problem. Based on a survey carried out in the 12 beaches in southern Baltic Sea (Polish coast) the amount of microplastic varied between 76 and 295 items per kg dry sediment. Fibres and plastic fragments were the dominant microplastic types (Urban-Malinga et al., 2020). The amount of nanoplastic in the Baltic Sea sandy beaches is currently not known. Consequently, based on the share of plastic pollution and microplastic at the beaches it cannot be advised to use beach wrack directly for soil improvement on the agricultural fields as microplastic pollution on agricultural fields is a growing concern (Nizzetto et al., 2016; Henseler et al., 2019; Gavigan et al., 2020). The consequences of microplastic pollution in the agricultural fields for sustainability and security of food production are currently unknown.

With globally raising marine pollution, littering of dunes is another aspect that has not gained much attention previously (Šilc et al., 2018, Concalves et al., 2019), but amount of litter has been shown to increase along the sea-inland gradient with foredunes and pineforests having the highest litter coverage with main litter material plastic, polystyrene and glass (Šilc et al., 2018). At the same time dunes are often very fragile to mechanical disturbance (both by foot and machines). Thus in beach management and cleaning it is important to have a wider view on the whole beach ecosystem and prevent the beach littering in the first place and also prevent the moving of beach litter towards inland and marine environment.

The amount of litter on the beach ecosystems and both within the beach wrack and sediments should be monitored on a local basis and taken into account when searching for further use possibilities of removed beach wrack – in other words: among other aspects the amount and nature of litter significantly affects the treatment options and possible further use of beach wrack.

# 4 Disturbance on sandy beach ecology due to beach management activities

The ever-increasing human activities on the beach and developments in the surrounding area have led to the endangerment and often destruction of the typical flora and fauna in recent decades and even centuries (Davenport & Davenport, 2006). In addition to littering, humans are taking up more and more space and thus becoming the strongest competitor for the natural flora and fauna of the beach ecosystem. Thus, it is difficult to find a sandy beach especially on the southern part of the Baltic Sea coast that is not and has not been influenced by humans.

Furthermore, due to the high interest for clean beaches, the beaches are increasingly being cleaned to remove nuisance biomass and waste. The frequency and type of cleaning activities are adapted to local and weather conditions as well as the expected amounts of beach wrack (→ chapter 3.1). As beach cleaning is carried out in highly human colonized and thus frequented areas, the human impact is probably particularly high here. There are mainly two types of beach cleaning procedures: mechanical and manual. Mechanical beach cleaning is defined as litter and/or organic material removal based on the work of automatic machines that rake or sieve the most superficial layer of sand. Manual cleaning involves people picking up litter by hand only or/and using hand-held rakes to collect beach wrack – this interferes less with nature, but is also carried out less because of the personal costs.

Earlier studies have presented that managed beaches are wider than the natural ones, have much less vegetation, lower biodiversity, fewer „natural" dunes and much flatter topographic features than unmanaged beaches (overviewed e.g. in Schumacher, 2008; Dugan & Hubbard, 2010). Many of the beaches are also flushed with sand manually during the autumn-spring months, or the sand is moved from one place to another with machines, in order to provide tourists with a wide beach during the summer season. Thus very popular beaches are heavily modified in their ecosystem characteristics for many decades.

As beach wrack accumulates on the beach, it contributes to the reduction of wave energy and currents in the shallow water/swash zone, serves as trap and stabilizes the sediments in front of the beach (→ section 3.1). This could reduce sand loss and erosion already at the swash zone. Despite this potential importance for coastal protection, international studies on beach wrack composition and quantities under seasonal and spatial aspects are surprisingly scarce for the Baltic Sea coast (CONTRA-report Möller et al., 2021). Accordingly, the coastal protective effect for impact on hydrodynamic features of the shore line has not yet been studied as well.

On the other hand, in the case of larger quantities of beach landings, removal could decrease potential higher nutrients and pollutants release at the beach, which could possibly return to the water and thus maintain eutrophication and/or pollution of the Baltic Sea (→ chapter 3.7). Furthermore, the parallel removal of litter is better for wildlife (→ chapter 3.8). However, what it ultimately means for the ecosystem to specifically remove biomass for the purpose of Baltic Sea remediation is not known so far.

Consequently, a lot of far-reaching impacts of human activity on the beach ecosystem are assumed, but there is a lack of sufficient ecological studies for the Baltic Sea coast, which explicitly deal with this complex topic. Consequently, a comparative study in six different countries and corresponding study sites was initiated under the CONTRA project.

## 4.1 Mechanical disturbance

Due to frequent and regular traffic (e.g. cleaning, backfill), beaches are transformed more and more into larger areas of sand, while smaller sand hills and newly formed dunes are flattened (Schumacher, 2008). For mechanical cleaning

**Figure 4.1.1.** Beach wrack removal in Germany (Island of Poel) using heavy machinery (Photos: J.Hofmann).

heavy vehicles such as e.g. tractors pulled sieving machines are used commonly (→ Figure 4.1.1). It can easily be imagined that this may lead to compaction of the sediments/soils, for instance by the sheer weight of the machinery exerting enormous pressure on upper beach layers (Gheskiere et al., 2005). On the one hand, the sediment is compacted, especially in the sensitive swash area, where the beach wrack is preferably removed. On the other hand, the sediments are constantly redeposited by the insertion of rakes to a depth of up to 30 cm. While there are no studies that focus specifically on the mechanical impact of beach cleaning vehicles, evidence for the disturbance of beach ecosystems through recreational driving with off-road vehicles on beaches is well established (Houser et al., 2013). Sand-dwelling microorganisms and invertebrates were hampered e.g. in the construction of new living tubes and/or existing ones were destroyed. They are therefore no longer able to live in the swash area as a habitat or, if possible, have to retreat to not disturbed sections of the beach. This in turn affects the abundance and biodiversity of the species that feed on the inhabitants of the beach wrack infauna by depriving them of their food source (Defeo et al., 2009, → chapter 3.2).
In addition, the presence of the machines and corresponding noise/scare effect can disturb the presence and/or behavior of wildlife like birds even if it is only for a short time.
Dugan et al., (2003) found that the "cleaned" areas of a beach had significantly lower rates of plant survival and reproduction after germination than the "not cleaned" areas of the same beach. As vegetation abundance decreases and the height and presence of dunes decreases, sand transport patterns change in ways that promote the extent of flattened topography. Dunes, beach wrack and vegetation act as barriers that slow down the wind-triggered movement of sand. The disappearance of these features may prevent the formation of future dunes. As beaches become flatter and wider, the abundance and diversity of vegetation decreases further, as vegetation requires stable sand dunes to take root and grow. In this way, mechanical beach cleaning triggers a positive feedback loop that reinforces the flattening and widening of beaches and the loss of vegetation abundance and diversity. Using beach wrack as compost layer to build up dunes or sand catching fences, as shown in case study 4 within the CONTRA (CONTRA-report Chubarenko et al., 2021), for example, could counteract this effect.
One important aspect regarding mechanical disturbance due to beach wrack removal is also the removal of sand from the beach ecosystems. In our study all biomass samples of beach wrack were collected by hand and no special treatment (e.g. shaking off the sand) was applied. Analysis of biomass samples collected from Kakumäe beach (Estonia) showed that the sand proportion in total dry weight of removed beach wrack can be as high as 97 % with an average of 58 %. On average, the share of sand in new wrack was 62 % (±26) and in the old wrack it was 54 % (±33). In our study it equaled to on average of 2.5 kg of sand (dry weight) per 1 m² that was removed together with beach wrack from new wrack line and to 4.1 kg of sand on average per old wrack line. The maximum values reached up to 22 kg of sand removal per m², these high values were observed in thickest lines of old and new wrack (17 and 12 cm, respectively). The smallest amounts of sand were removed together with old wrack at winter period, where the old and relatively dry wrack consisted mostly of the remnants of reed *Phragmites australis*.

## 4.2 Sand compaction

Sand compaction and its potentially negative


**Figure 4.3.1.** Four study sites for wildlife observations off the German Western Baltic Sea coast.

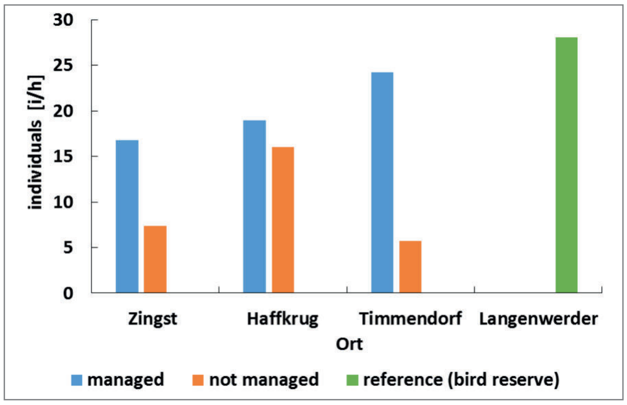



**Figure 4.3.2.** Bird individuals per hour [i/h] and beach area within 1–4 days (n=1–4) in July and August 2020. (Germany).

impact on beach ecosystems was discussed in a comprehensive review of Speybroeck et al., (2006): they highlighted this as a well-known side-effect of beach stabilization measures such as beach nourishment. While findings from this review may certainly be applicable in a broader scope, research specifically focusing on compaction issues related to mechanical beach wrack removal are scarce.
Therefore, the compaction of sand was investigated during the CONTRA project by several bulk density measurements at respective sites in Denmark, Germany, Russia and Estonia (for more details see CONTRA-report Möller et al., 2021).
Our investigations showed the strongest compaction in the swash area decreasing in comparison to the lanes of the machines and the "undisturbed areas" in front of the dunes. However, in the swash zone the sand was also permanently compacted by moisture and wave motion. In addition, it is likely that not only sheer weight of the machinery contributed to the sediment compaction, but also the walking of people. This so-called footfall load has also been investigated and indicated significant compaction of the sand and lower biodiversity of the infauna (Schumacher, 2008).
In the back area of the beach, the sand was much more loosely bedded, thus it depended on where exactly the sample was taken and some of the sand was churned up again at the edge of the tyre print lane. Furthermore, on the Island of Poel (Germany), the vehicles also drove along the "unmanaged areas" to support the cleaning procedure. As this is a common practice, these beaches were included in the investigations, but also complicate the evaluation of the data.
Despite these many impacts on the interpretation, our results indicate that there were differences between undisturbed areas and traveled tracks, even if they are only slight. It can give a small indication of the trend to be expected. Further studies would hence be required and should include a more detailed comparison with natural and undisturbed beaches. It is very likely that temporary structures for instance from burrowing invertebrates may nevertheless be destroyed by over-drive of heavy machinery and the use of deep sediment penetrating forks in beach cleaning. Moreover, numerous studies on the environmental impact of beach nourishment, have brought the evidence that compaction negatively affects the diversity of beach inhabiting invertebrates (Speybroeck et al., 2006).

## 4.3 Effect on biodiversity

Besides the before-mentioned disturbances related to the use of heavy machinery in beach cleaning, the removal of beach wrack itself has the potential to affect beach biodiversity as well. According to various studies summarized in a review by Defeo et al. (2008), the beach wrack cover of the beach and the abundance of shorebirds were positively correlated. In addition, the general loss of dune vegetation contributes to an increased nestling mortality of dune nesting bird species (Watson et al., 1996). Nests are likely to be abandoned with a higher frequency due to disturbance caused by the vehicles, on areas lacking protective vegetation, which in turn increases the risk for nestling predation. There is little controversy about the significant contribution of driving on beaches to the decline of dune breeding bird populations observed in coastal areas heavily affected by tourism, for instance in Australia, Great Britain, and South Africa (Watson et al., 1996, Weston et al, 2014). In fact, on beaches with beach cleaning, there is hardly any breeding activity at all. As stated by Defeo et al. (2008) it is clear that a ban on the use of off-road vehicles

**Table 4.3.1.** Overview of all birds observed in 2020, shown as individual number [i], study day (n=1–4) per beach section. ZIN= Zingst (22.-25.07.), HFK= Haffkrug (17./23.8.), TM= Timmendorf (25.08.-29.08.), LAN= Island of Langenwerder (25./29.8.) (Germany); man. = managed; unman. = unmanaged; ref.= reference; X = occurrence of a species on the respective beach section; – = species not observed. Grey marked bars indicate synanthropic/"culture follower" species (according to Janke & Kremer 1993).

| family | species | ZIN man. n=4 | i | ZIN unman. n=4 | i | HFK man. n=1 | i | HFK unman. n=1 | i | TM man. n=2 | i | TM unman. n=2 | i | LAN ref. n=2 | i |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Anatidae | *Anas platyrhynchos* | - | 0 | - | 0 | - | 0 | - | 0 | - | 0 | X | 1 | X | 18 |
| Charadriidae | *Charadrius hiaticula* | - | 0 | - | 0 | - | 0 | - | 0 | - | 0 | - | 0 | X | 8 |
| Columbidae | *Columba palumbus* | - | 0 | - | 0 | X | 2 | X | 7 | - | 0 | - | 0 | - | 0 |
| Corvidae | *Corvus corone cornix* | X | 4 | X | 21 | X | 3 | - | 0 | - | 0 | - | 0 | - | 0 |
| | *Corvus corone* | - | 0 | - | 0 | X | 8 | X | 4 | - | 0 | - | 0 | - | 0 |
| Haematopodidae | *Haematopus ostralegus* | - | 0 | - | 0 | - | 0 | - | 0 | - | 0 | - | 0 | X | 3 |
| Hirundinidae | *Delichon urbicum* | - | 0 | - | 0 | - | 0 | - | 0 | X | 4 | - | 0 | - | 0 |
| | Sterna sp. | - | 0 | - | 0 | - | 0 | - | 0 | - | 0 | - | 0 | X | 2 |
| Larinae | *Larus ridibundus* | X | 112 | X | 44 | X | 22 | X | 18 | X | 6 | X | 1 | X | 18 |
| | *Larus argentatus* | X | 24 | X | 9 | X | 3 | X | 3 | X | 21 | X | 7 | X | 6 |
| | *Larus canus* | X | 5 | - | 0 | - | 0 | - | 0 | - | 0 | - | 0 | - | 0 |
| Motacillidae | *Motacilla alba* | X | 33 | X | 2 | - | 0 | - | 0 | - | 0 | X | 6 | - | 0 |
| Phalacrocoracidae | *Phalacrocorax carbo* | - | 0 | - | 0 | - | 0 | - | 0 | - | 0 | - | 0 | X | 1 |
| Scolopacidae | *Calidris alpina* | - | 0 | - | 0 | - | 0 | - | 0 | - | 0 | - | 0 | X | 50 |
| | *Gallinago gallinago* | - | 0 | - | 0 | - | 0 | - | 0 | - | 0 | - | 0 | X | 5 |
| | *Numenius arquata* | - | 0 | - | 0 | - | 0 | - | 0 | - | 0 | - | 0 | X | 5 |
| | *Calidris canutus* | - | 0 | - | 0 | - | 0 | - | 0 | - | 0 | - | 0 | X | 9 |

on beaches would have had a positive effect on the coastal bird populations of the corresponding beaches. However whether this will be enough to bring the sensitive shorebird species back remains questionable due to the increasing human presence.

Animal communities inhabiting sandy beaches rely heavily on seaborne inputs of carbon and organic materials since *in situ* productivity is very low (Brown & McLachlan, 1990). Beach wrack, thereby, constitutes the major allochthonous subsidy for these ecosystems. Hence, its frequent removal can affect the productivity and standing crop of primary and secondary consumers in beach inhabiting communities. Indeed, numerous studies found that the removal of beach wrack led to a decrease in diversity, abundance, total biomass of beach inhabiting meio- and macrofauna e.g. macro invertebrates (→ chapter 3.2), indicating the existence of bottom-up effects. Consequently, macrofaunal species at higher trophic levels including shore birds may hence be negatively affected as well (Orr, 2013). Dugan et al. (2003) concluded that the recovery of beach ecosystems from disturbances such as beach wrack removal towards an ecological status similar to undisturbed conditions might take years. A modelling study by Orr (2013) indicated that shore bird populations on western Scottish beaches may need up to 20 years to recover from a decline caused by beach wrack harvesting.

Within the CONTRA four study areas on the Baltic Sea coast of Mecklenburg-Vorpommern and Schleswig-Holstein (Germany) were chosen for the investigation of the impacts on birds: Zingst, Haffkrug and the Island of Poel (Timmendorf) including the nearby Island of Langenwerder, a bird sanctuary, as a reference area for natural conditions (→ Figure 4.3.1).

The beach wrack coverage/amounts were not necessarily correlated with the presence of birds that could feed on beach wrack fauna (for more details CONTRA-report Möller et al., 2021). With a total of 416 individuals counted, the share of cultural followers/synanthropic species amounted to 85 % of all observed birds (i=495), which prefer likely other food sources. The cultural followers dominated with 89 % (i=416) at the managed and unmanaged sites (→ Table 4.3.1). Whereas individuals of other sensitive shorebird species (i=79), susceptible to disturbance and dependent on beach wrack infauna, as well as species assessed as vulnerable in the Red List, have only been observed in the reference area.

This trend towards reflecting more natural conditions for the wildlife in areas without human influence is also confirmed by the presence of individuals per site (→ Figure 4.3.2) or biodiversity values (→ Figure 4.3.3). The highest bird individual presence with 28.1 [i/h] and biodiversity with 1.9 [H'] was determined in total in the reference area. The lower biodiversity values at the managed and unmanaged beach sections were correlated with the dominance of two Larinea species *L. ridbundus* and *L. argentatus*. However, the lowest values were

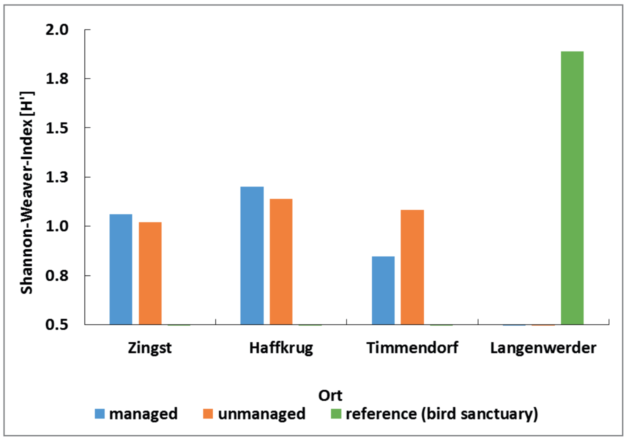



**Figure 4.3.3.** Biodiversity at the different sites at German beaches according to Shannon-Weaver indices; managed in total (H=1.3), unmanaged in total (H'=1.4) and reference area (H'=1.9).

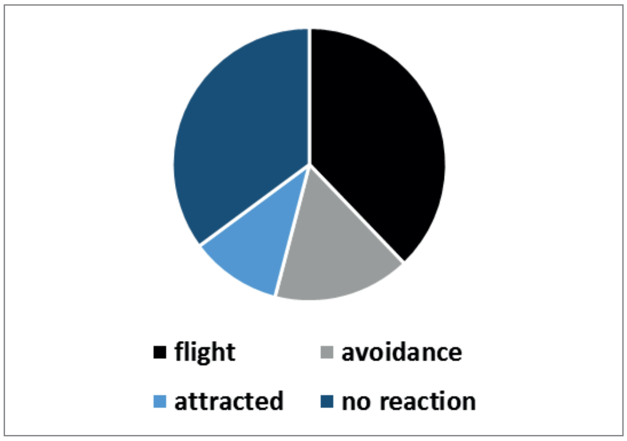



**Figure 4.3.4.** Reactions per individual (i=37) exposed to cleaning activities (n=4) regardless of vehicle type, site and study time (Germany). Only *Larus ridbundus* (i=24) and *Larus argentatus* (i=13) were considered as these were present at all sites.

counted at the unmanaged sites with 8.2 [i/h] and 1.4 [H'] in total. This could be explained by a certain attraction effect when foraging on managed beaches. Sometimes, the beach wrack was also dumped in large piles at the border of unmanaged areas, which made it additionally attractive for the birds to forage.

Consequently, birds as "cultural followers" of the managed and unmanaged sites were optimally adapted in their feeding and distancing behavior to the anthropogenic impact (→ Figure 4.3.4). More than one third of the individuals observed showed no response to mechanical activities. For some species/individuals, it was observed that they were attracted by the cleaning. Flying hunting birds such as swallows *Delichon urbica* (Hirundinidae) or ground-feeding birds like wagtails (*Motacilla* sp.) benefited from the beach cleaning and flew/walked after the machines.

The results of Denmark, Russia and Estonia are similar to our German investigations (see CONTRA-report Möller et al., 2021). In conclusion, especially for these cultural followers/synanthropic species we assume that beach wrack with the respective infauna is a less attractive food source as organic residues from human food that is far richer in fat and protein and thus higher in calorific content. In addition, for the birds this food is far easier to access e.g. from rubbish bins, which are mainly found in managed areas, as tourist numbers are also likely to be higher here.

Our findings within CONTRA also indicate the lower species richness and lower abundance of macrofauna in the managed beaches (20 vs 16 taxa, CONTRA-report Möller et al., 2021), which subsequently supports our bird observations. The macrofaunal composition was studied in more detail at two beaches of Poland: Puck represents the managed and Rzucewo the unmanaged site. The total macrofaunal abundance in the unmanaged area was almost double the values recorded at the managed station. Consequently, the unmanaged region had higher biodiversity, more taxa than the managed region. The biomass of *Hediste diversicolor* (Polychaeta) (absolutely dominant) and the bivalve representatives *Limecola balthica* and *Mya arenaria* in the unmanaged region was significantly higher than in the managed one. This results from the availability of a large amount of organic matter, which in this case provides an excellent food source as well as a possible breeding site. On the other hand, increased organic matter may cause temporary oxygen deficiency, hence the higher abundance of macrofauna in the unmanaged region is mainly due to the presence of opportunistic species that are adapted to live in adverse environmental conditions. Examples of such species, in addition to *H. diversicolor* and *L. balthica*, are insect larvae of Chironomidae and benthic Oligochaetes. The observed seasonal changes reflect the natural life cycle of individual macrobenthic components, with peaks in abundance in late spring and fall, which was observed for both areas. See CONTRA-report Möller et al., 2021 for more details.

## 4.4 Noise and scare effect

As already mentioned, the birds as "cultural followers" of the managed and unmanaged sites were optimally adapted in their feeding and distancing behavior to the anthropogenic impact (→ Figure

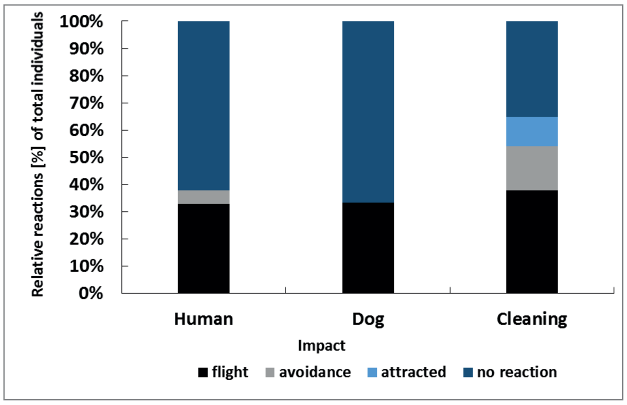



**Figure 4.4.1.** Responses of bird individuals (i=201) exposed to the three different effects: human(s)/walkers (i=122), dog(s) (i=42) and cleaning activities (i=37) for all study days (n=1–4) and beach sections studied (n=7, Germany).

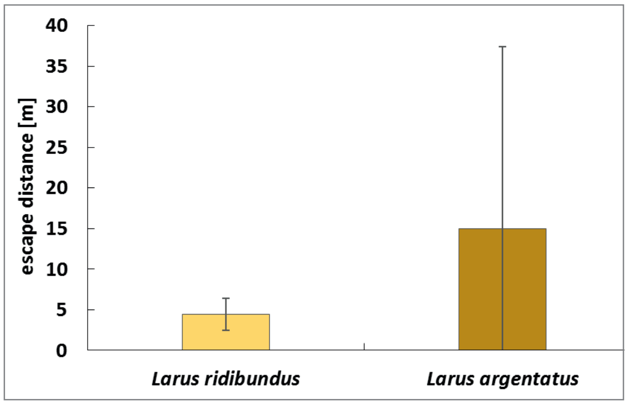



**Figure 4.4.2.** Mean distances [m] to German cleaning vehicles leading to escape for individuals (i=37) of the *Larus ridibundus* (i=24) and *Larus argentatus* (i=13).

4.3.4, → Figure 4..4.1). The mean escape distances of the individuals to the beach cleaning activities were determined to be 4.4 m for *L. ridibundus* (i=24) and 15 m for *L. argentatus* (i=13) (→ Figure 4.4.2). Escape reactions are associated with energy expenditure for the individual and can thus lead to reduced fitness, e.g. due to time lost during feeding or regeneration. It is therefore essential to adapt the behavior in order not to lose energy unnecessarily through avoidable escape reactions ("habituation"). Accordingly, for those birds that do not experience any negative consequences from machine beach cleaning (injury or death from the machine), the escape distance decrease. Furthermore, some species/individuals were attracted by the cleaning. According to Becker-Carus (2004), birds can learn through operant conditioning. In this case, the birds learned that food is increasingly available during beach cleaning (=positive consequence). This positively reinforced the behavior of staying near the cleaning vehicles or follow their tracks in the sand. However, noise is known qualitatively and quantitatively to affect wildlife in manifold ways. Those can include physical damage to ears, fright, flight responses, avoidance responses, altered behavior with regard to foraging, decreased ability to hear predators, all of which can negatively affect fitness and survival (Ortega, 2012). The most commonly observed response to noise is avoidance. To our knowledge, the specific effect of noise pollution from beach cleaning machinery has not been studied so far and neither how this effect relates to those from other potential sources of noise on managed beaches such as visiting tourists or nearby roads.

Our results show that besides the presence of humans, beach cleaning activities can have a direct, short-term influence on bird behavior (→ Figure 4.4.1). However, the vehicles also represent a multisensory stimulus, which means that different and complex senses of the birds were affected, e.g. the visual sense. The machines emit a certain level of sound but also the sound quantity is important, which was not possible to determine with our measuring technique. However, our studies showed that after subtracting the ambient noise, the additional noise pollution caused by the vehicles in Denmark, Germany, Russia and Estonia was between 10 up to 30 dB at the closest distance to the machines. Nevertheless, the sound pressure level is a technical and not a psychoacoustic quantity. A conclusion from sound pressure level to the perceived sensation of loudness is only possible to a very limited extent. In general, an increase or decrease in the sound pressure level tends to produce a louder or quieter perceived sound event. Above a loudness level difference of 10 dB is perceived as a doubling of loudness. However, due to the determination via diverse mobile phone microphone recordings, the short measurement duration and a non-standardised measurement technique, these data should only be understood as an approximate estimate.

# **5** Ecosystems services related to sandy beaches and their management

Ecosystems services are most broadly described as the benefits that people obtain from ecosystems (Burkhard et al., 2010, 2012). The assessment and mapping of ecosystem services has become an important and necessary task both in scientific research and for decision-making in policy (Müller et al., 2020). The assessment scheme is integrative and by applying the concept it is possible to pinpoint several current environmental and also societal challenges and problems.

The maintenance of ecosystem services is a priority target of the conservation of ecosystems. The main goal of valuating ecosystem services is to demonstrate the importance of a full qualitative and quantitative range of benefits that humans gain from nature and the consequences that we face in case of not protecting nature. Whether ecosystem services should be monetarized or not is highly debated (e.g. Costanza et al., 1997; Ahtiainen & Öhman, 2014). Many ecosystem goods do not have a market price or the price does not represent the total value. Therefore two concepts have been developed and can be used: 1) willingness to pay (WTP) and willingness to accept compensation (WTA), with the former being more commonly used. WTP measures the amount of money a person is willing to pay to obtain the ecosystem in a good status close to natural conditions and less impacted by humans, i.e. it measures the economic benefits from the good. WTA is the amount of money a person is willing to accept to change these ecosystem goods in a more affected status, i.e. it measures the economic losses of forgoing the good (overviewed e.g. in Ahtiainen & Öhman, 2014). Our aim within this report is to raise awareness of the multi-functionality of sandy beach ecosystems and changes that are caused by beach management. Hereby the aim is not to put a price-tag on nature features, but to use the ecosystem services valuation system in decision making to help to estimate the consequences of change and whom and how these changes affect most. Applying the ecosystem services concept in beach management strategies can guide us for a better understanding of beach ecosystems in general and for more sustainable nature conservation (Müller et al., 2020).

## 5.1 Various aspects and parameters of ecosystem services

Ecosystem services are divided into three different group based on whether they are provisioning, regulating or cultural services. Taking intergrity as a separate class was proposed and introduced by Müller (2005), including abiotic heterogeneity, biodiversity, biotic water flows, metabolic efficiency, energy capture, reduction of nutrient loss, storage capacity; hereby these are included under regulating and maintenance (→ Table 5.1.1). Sandy shores provide a wide range of ecosystem services, e.g. sediment storage and transport, wave dissipation and associated buffering against extreme weather events (storms), maintenance of biodiversity and genetic resources, scenic views and recreational opportunities, facilitation of functional links between terrestrial and marine environments in the coastal zone (Defeo, et al., 2009). The list and short description of ecosystem services we tackled under the CONTRA project are summarized in → table 5.1.1. In order to gain an overall better understanding of beach wrack management related ecosystem services, we present four different scenarios. All four of the scenarios were based on beach management in managed and unmanaged beaches as well as and presence-absence of beach wrack residuals (see text box for descriptions).

In total a group of 30 experts from 7 countries around the Baltic Sea was involved in the ecosystem services valuation process: Russia (8), Sweden (7), Estonia (4), Germany (3), Lithuania (3), Poland (3), Denmark (2). 17 experts were joined with the CONTRA project while 13 experts were not related to this project directly. Experts outside the

CONTRA were asked to participate based on personal contacts. Based on self-assessment the expert-group involved in evaluating ecosystems services regarding general beach management aspects had diverse background. Most expertise was noted in beach ecology followed by ecosystem services and cultural aspects and beach management (→ Figure 5.1.1).

For the question how important is the respective ecosystem service relatively for the total provision at a Baltic sandy beach, each expert was asked to score the baseline scenario according to 5 categories (1, 2, 4, 8 – accordingly: no/low importance, moderate importance, high importance, very high importance). In order to answer how the ecosystem services are affected by the change from the

**Table 5.1.1.** Overview of the values related to the ecosystems services on sandy beaches, based on the publication of Esther Robbe "An impact assessment of beach wrack and litter on beach ecosystem services to support coastal zone management at the Baltic Sea"" (In preparation).

| | | Ecosystem Services (ES) | Description |
|---|---|---|---|
| Provisioning | 1 | Wild plants for materials (further processing) | Beach wrack for further processing, e.g. eelgrass for insulating material (construction) or stuffing material (pillows, mattress), use of beach wrack within dune restoration. Also raw material in industry (eg cosmetics etc). |
| | 2 | Food | Beached algae and mussels for food (eg Ulva sp, Fucus sp, Rangia sp), also as raw material in food industry. |
| | 3 | Biomass as energy source | Beach wrack or other organic material for energy conversion |
| | 4 | Extraction of minerals (sand, nutrients) | Sand used for further use (construction industry), and direct application of BW to fields without further processing to utilize the nutrients and sand content (for nutrient enrichment, loosen the soil). |
| | 5 | Timber/ Driftwood | Driftwood used for further processing (handicrafts) |
| | 6 | Natural Ornaments | Collection of natural ornaments (e.g. seashells) washed ashore |
| Regulating and Maintenance | 1 | Sediment storage and transport | Beaches as sand storage and transport for natural coastal dynamics |
| | 2 | Coastal Protection/ Flood control | Attenuation of wave energy and flood prevention, e.g. inclination of beach, beach width, beach wrack. |
| | 3 | Biodiversity and habitats | Habitat and food base for several microorganisms and animals, thus including further food for higher animals (e.g. birds) and nursery ground (e.g. flies). Presence/absence of selected species. |
| | 4 | Pest and disease control | Sand and beach wrack as provider of habitat for native pest and control agents |
| | 5 | Water purification | Regulation of the chemical condition of salt waters by living processes (incl. algae, seagrass), e.g. to combat eutrophication |
| | 6 | Groundwater regulation | Groundwater regulation and maintaining water cycle (e.g. water storage and buffer) |
| | 7 | Carbon sequestration/ storage | Regulation of chemical composition of atmosphere and oceans by sequestration of carbon. Enhancing terrestrial sequestration. Including the mitigation of green house gases. |
| | 8 | Nutrient regulation | The capacity of an ecosystem to store and recycle nutrients, e.g. N, P (for beach soil and dune vegetation) |
| | 9 | Dispersal of seeds | Dispersal of seeds and the reproduction of lots of plants (resuspension by beach wrack, coastal dynamics) |

| | | Ecosystem Services (ES) | Description |
|---|---|---|---|
| Cultural | 1 | Recreation and tourism (active) | Beach as recreational, touristic area (hiking, swimming sun bathing) and sports spots |
| | 2 | Recreation and health (observational) | Beach for wildlife watching and nature observation |
| | 3 | Knowledge systems | Beach ecosystem as a site to educate about nature conservation and human-nature conflicts, and as research topic (science) |
| | 4 | Culture and heritage | Beaches and their ecosystems as part of local identity and cultural heritage (historically important) |
| | 5 | Regional identity | Elements or processes of ecosystems that contribute to a person's individual identity (sense of belonging) or strengthen people's group identity. |
| | 6 | Landscape aesthetics | Inspirational experiences at beaches and their ecosystems for enjoyment of nature (natural beauty) |
| | 7 | Natural heritage | The existence value of nature and species themselves, beyond economic or human benefits |

baseline scenario to scenario 1, 2 and 3, each expert had to score each scenario (1 to 3) between -3 to +3 (high decrease, medium decrease, low decrease, no impact, low increase, medium increase, high increase). Hence, this score shows the relative change or impact of each scenario compared to the baseline scenario.

The average scores given for ecosystem services indicated that when it comes to provisioning services, sandy beaches with minimal beach wrack and without management were evaluated to provide the least – that goes for e.g. food, biomass

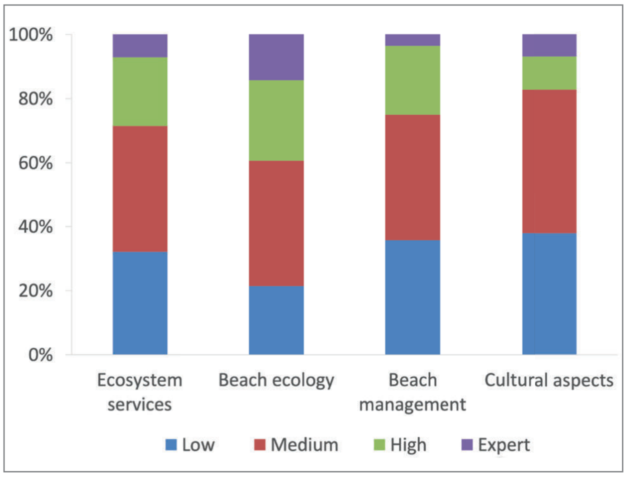



**Figure 5.1.1.** Level of expertise based on self-estimation in different ecosystem services related aspects regarding beach management. Low, medium, high and expert indicate the expertise level on a given thematics. Figure summarizes information from 30 experts.

as energy resource, extraction of minerals etc. Regulating and maintenance related services were estimated a little higher by highlighting most sediment transport, coastal protection and biodiversity. On the other hand the highest importance was given to cultural aspects, especially those related to recreation and tourism, landscape aesthetics and natural heritage (→ Figure 5.1.2).

The management of these natural sandy beaches (scenario 1) which are mostly devoid of beach wrack was evaluated to harm almost every ecosystem service assessed. Positive aspects of such management orientation were noted only in improving coastal protection and recreation (tourism) activities (→ Figure 5.1.4).

Regarding the baseline scenario the overall relative change in ecosystem services, where the landings of beach wrack are medium to high and no management activities exist, (scenario 2) was estimated as positive by most of the experts (→ Table 5.1.2). The presence of beach wrack was considered as a promoter of all ecosystem services except with small negative effect on the extraction of minerals and strong negative effect on tourism-related recreational activities (→ Figure 5.1.5). An increase in biodiversity and habitats and natural heritage in such ecosystems was most significant.

As for scenario 3 – sandy beach with medium to high beach wrack landings and with management the opinions on the effect of ecosystems services were most diverse (→ Table 5.1.2). Those who evaluated the increase in ecosystem services with

**Baseline scenario:**

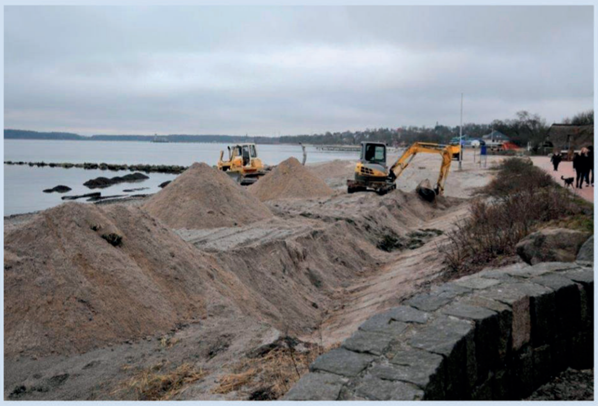
**Sandy beach with no or small beach wrack landings and without any management.**

Naturally sandy beaches where the amounts of beach wrack remain negligible, however, small amounts of algae and other drifting materials (wood, marine litter etc.) will reach the beaches. No beach management activities that encompass machinery take place on the beach.

**Scenario 2:**

**Sandy beach with medium to high beach wrack landings and without management.**

Naturally sandy beaches where the amounts of beach wrack landings are medium to high. No beach management activities that encompass machinery take place on the beach.



**Scenario 1:**

**Sandy beach with no or small beach wrack landings and with management.**

Managed sandy beaches where the amounts of beach wrack remain negligible, however small amounts of algae and other drifting materials (wood, marine litter etc.) will reach the beaches. Beaches are managed mainly for coastal protection reasons (sand addition, beach nourishment, dune restoration).

**Scenario 3:**

**Sandy beach with medium to high beach wrack landings and with management.**

Naturally sandy beaches where the amounts of beach wrack landings are medium to high. Beaches are managed mainly for aesthetical reasons (e.g. beach wrack removal), but also some coastal protection measures may apply (sand addition, beach nourishment, dune restoration).

Photos: scenario 3 - © Tiina Paalme
scenario 1 – © Timmermans, W., de Jong, F., Stelljes, N., Sterr, H., Martinez, G., Harsema, H. 2019. Urban Climate Adaption. Innova Ezine. www.urbanclimateadaptation.net/ezine3-2018/

higher scores were those experts who also witness more of the suffocative nature of beach wrack in their nearby regions. Not surpisingly the strongest positive impact of beach wrack management was seen regarding the active recreation and tourism-related services (→ Figure 5.1.6). A slight increase was also noted in positive aspects of knowledge systems, culture and heritage and regional identity emphasizing that managed beaches have become a part of local culture (see CONTRA-reports of Hofmann et al., 2021ab). The evaluation also indicated a small positive change in scenario 3 due to management activities in provisioning services (e.g. increase in using wild plants for materials (further processing) or biomass as energy resource).

**Table 5.1.2.** The overall estimation on respective change in ecosystems services related to beach wrack amounts and management activities on sandy beaches compared to the baseline scenario (natural sandy beach with no or small amount of algae and no management) based on experts scoring. % shows the share of the experts who evaluated the given scenarios either to have a positive or negative impact on the sandy beach ecosystem compared to the baseline scenario.

| | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|
| | No or small amounts of beach wrack | Medium to high loads of beach wrack | Medium to high loads of beach wrack |
| | Managed | Unmanaged | Managed |
| Positive impact | 40 % | 83 % | 53 % |
| Negative impact | 60 % | 17 % | 47 % |

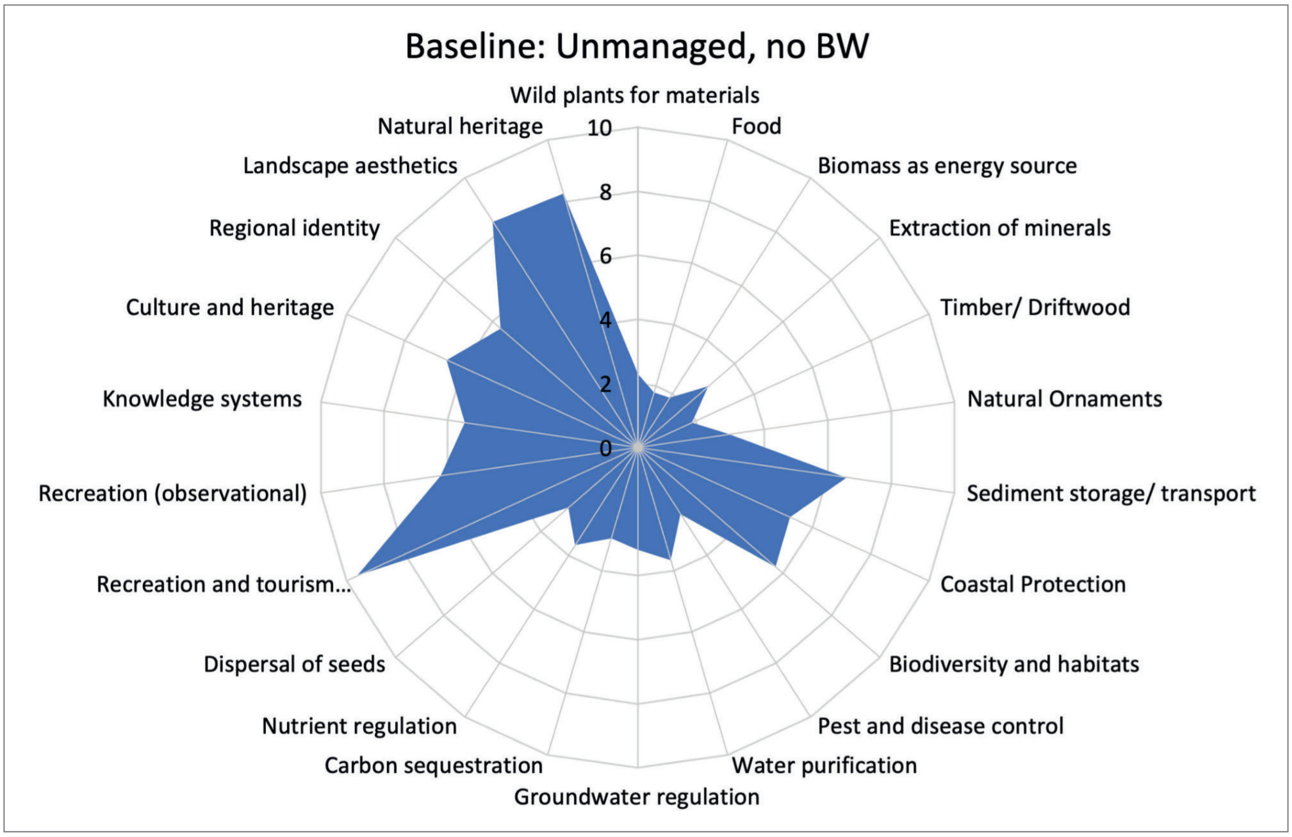



**Figure 5.1.2.** The relative importance (%) of ecosystem services provided by sandy beaches where the beach wrack landings are missing or minimal and no management activities exist (baseline scenario, averaged based on scoring). Numbers indicate the importance of a given service (%) (n=30).

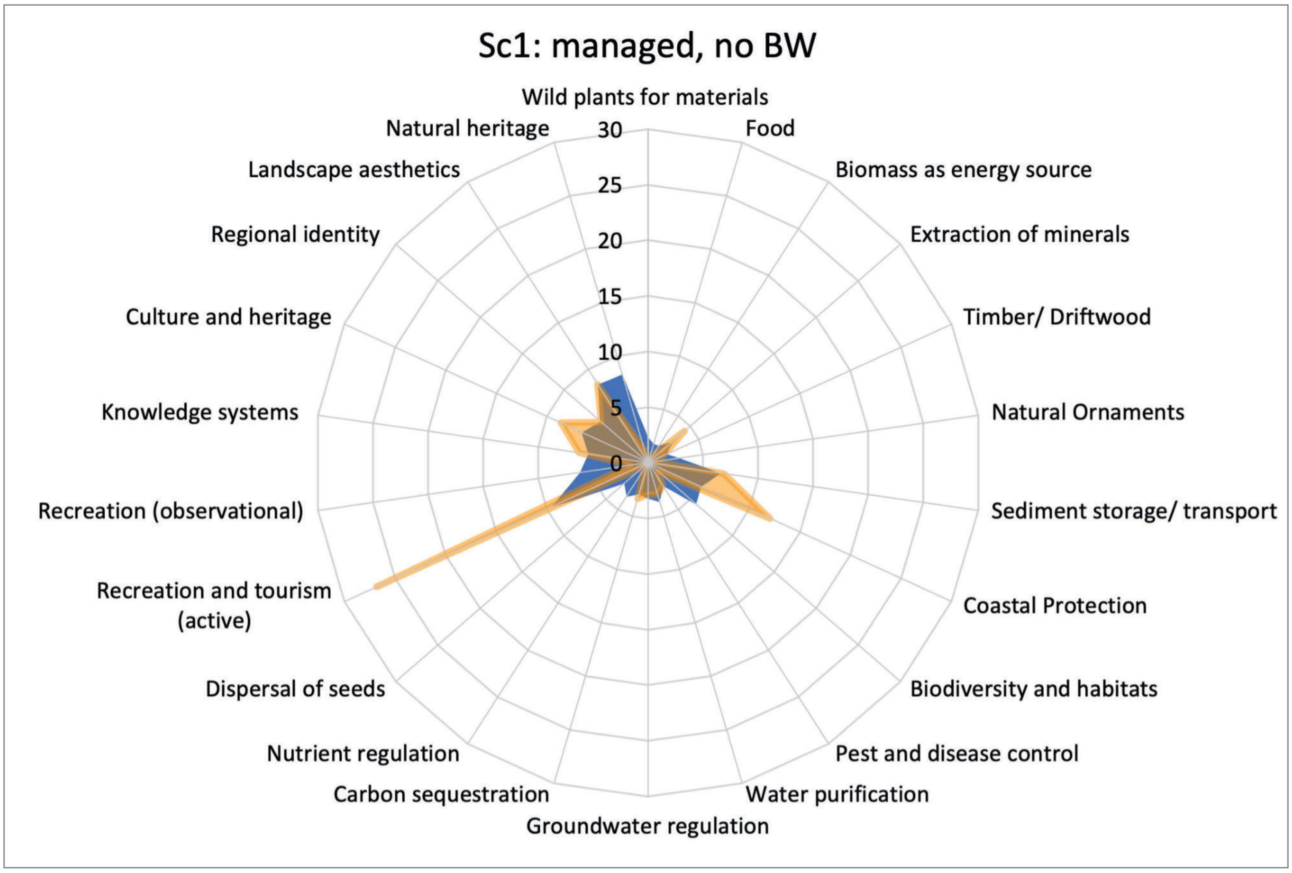



**Figure 5.1.3.** The relative importance (%) of ecosystem services provided by sandy beaches where the landings are missing or minimal and management activities exist (yellow) regarding the baseline scenario (blue) (n=30).

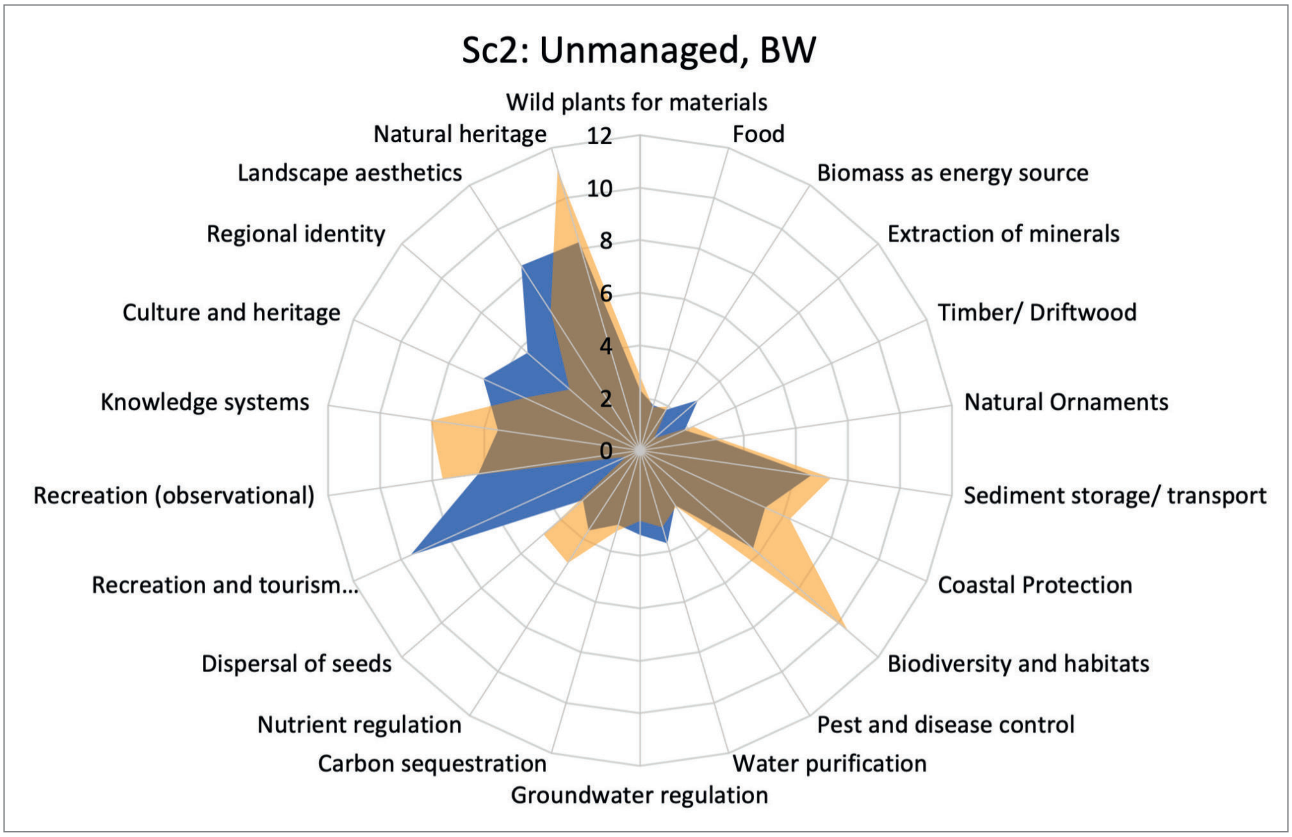



**Figure 5.1.4.** The relative importance (%) of ecosystem services provided by sandy beaches where the landings of beach wrack are medium to high and no management activities exist (yellow) regarding the baseline scenario (blue) (n=30).

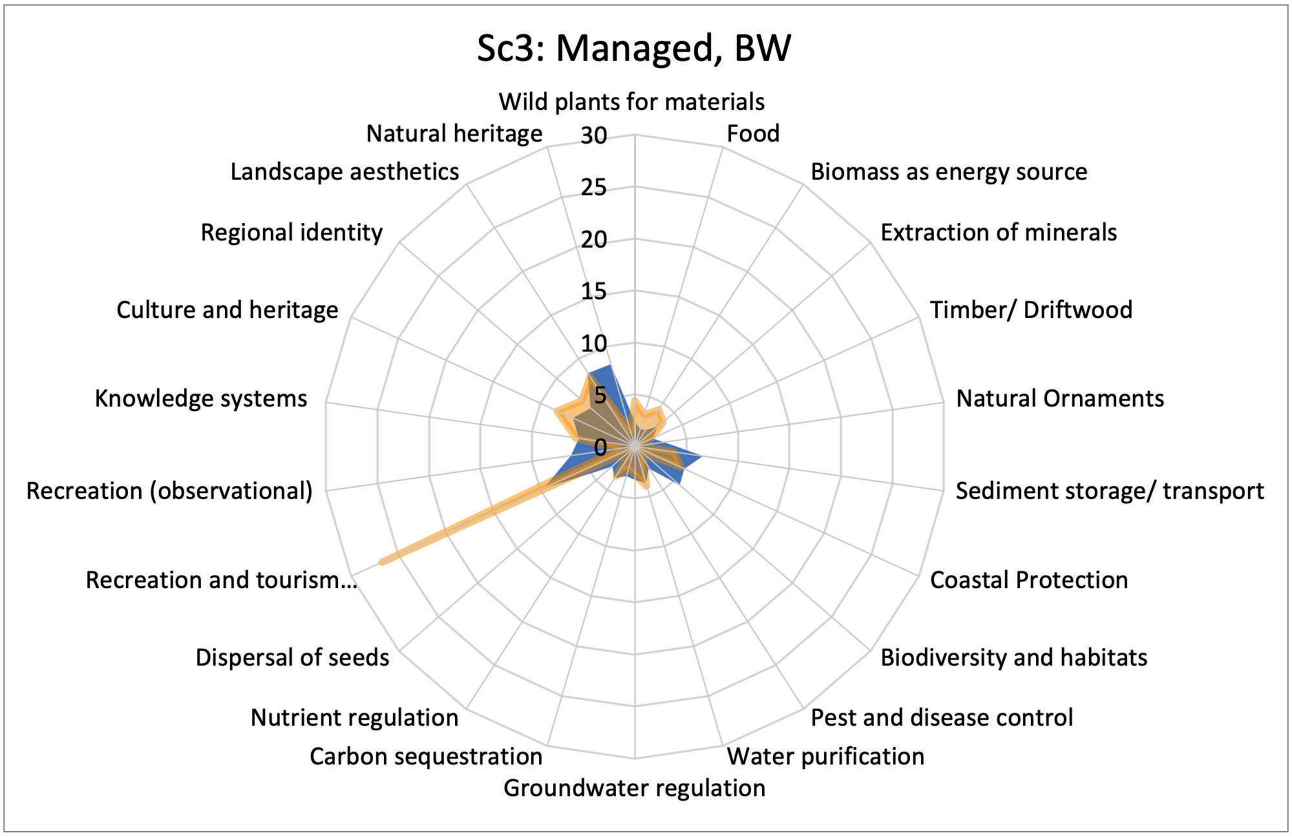



**Figure 5.1.5.** The relative importance (%) of ecosystem services provided by sandy beaches where the landings of beach wrack are medium to high and management activities exist (yellow) regarding the baseline scenario (blue) (n=30).

## 5.2 Ecosystem services in the light of the CONTRA case studies

The possibility of the overall increase of benefits that can be gained from already managed beaches has been one of the driving forces of the CONTRA project from the start. Hereby the aim has been also not to further harm or negatively impact any of the natural sandy beach ecosystem feature. Within the CONTRA project 7 case-studies were described in more detail and 2 more were shortly overviewed in order to cover a wider perspective of beach wrack uses (→ Table 5.2.1). All the case-studies except for one worked with the raw material that was collected from already managed sandy beaches: in the case of Estonian experience (production of furcellaran), the raw material was either trawled directly from the sea or collected from various types of beaches along the coastline after storm events. In addition, the case-study EELGRASS (1a) was performed separately – as hereby the main focus was the pure material collection (*Zostera marina*) from the beaches mostly by hand. For a more detailed overview of different approaches of beach wrack collection and treatment see the CONTRA report Chubarenko et al., 2021.

In → Table 5.2.2 we summarized the relative effect of the case-study based management effort on ecosystems services that are provided by managed sandy beaches. As mentioned earlier, the typical managed beach with removed beach wrack was seen as strongly biased towards only one ecosystem service "tourism-oriented recreation activities" (→ Figure 5.1.5, → Table 5.2.2). However, with a proper and targeted beach wrack management it is possible to gain more value from different ecosystems services (→ Table 5.2.2). For example 6 out of 9 approaches presented in the CONTRA report of Chubarenko et al., (2021) were estimated to contribute into a better use of provisioning services. Hence, beach wrack was used as raw material for soil/compost production (e.g. Wrack4Soil, EELGRASS, FERTIWRACK), or used to meet the special interests in food industry (furcellaran production from the red algae *F. lumbricalis*) or as an energy resource (BWC, ALREA). FERTIWRACK was geared on nutrient cycling as the main aim was the production of beach wrack compost – this can be done e.g. by using reed bed treatment and thus having more control over the decomposition process at the beach and thus causing less harm for

**Table 5.2.1.** Overview of the case-studies addressed under the CONTRA project. For further details see CONTRA reports Chubarenko et al., 2021 and Almquist et al., 2021 (economical aspects).

| Case study nr | Name | Abbrevation | Area | Country |
|---|---|---|---|---|
| 1 | Beach wrack-based soil production | Wrack4Soil | Bad Doberan/ Poel | Germany |
| 1a | Collection of pure eelgrass | EELGRASS | Bad Doberan/ Poel | Germany |
| 2 | Bio-coal from beach wrack | BWC | Island Rügen | Germany |
| 3 | Beach wrack as a compost material in landfill bio-covers | Wracover | Koge Bay | Denmark |
| 4 | Beach wrack applicability for dune restoration measures | Wrack4Coast | Kaliningrad Oblast | Russia |
| 5 | Beach wrack thermal recovery and relevant analytical performances | ALREA | Kalmar | Sweden |
| 6a | Nutrient and pollutant flux to coastal zone originating from decaying beach wrack on beaches | WAIT | Puck Bay | Poland |
| 6b | Beach wrack treatment in a reed bed system | FERTIWRACK | Swarzewo | Poland |
| Estonian experience | Production of furcellaran both from trawled and beached algae *Furcellaria lumbricalis* | ESTAGAR | Saaremaa | Estonia |

the environment in general. The nutrients that are removed together with beach wrack were available for terrestrial plants within the reed bed and thus the leakage back to the marine environment was also smaller. Furthermore, due to the biocovering within the Wracover study it was possible to mitigate methane emissions. In addition – native beach plants were planted the top of the biocover and this kind of activities also contribute into increasing local biodiversity and habitats and also landscape aesthetics. The case study BWC was estimated to contribute partly to carbon neutral solutions – by removing the beach wrack and using this as an alternative source of energy (instead of burning fuel or wood).

The case study Wrack4Coast investigated dune restoration possibilities and thus improving natural coastal protection. These kinds of activities are mainly regarded as restoring the natural environment and thus showing the highest increase in ecosystems services such as e.g. for biodiversity and habitats, sediment storage and transport regulation was estimated.

Responsible beach management with minimal ecosystem harm and proper recycling of beach wrack after removal can significantly enhance regional identity perception e.g. the locals (municipality) produce something useful from beach wrack which is usually regarded as a nuisance/waste. Consequently, the image-building of municipality's/company's activities might further increase the self-pride perception of the local community. In times of increasing awareness of climate change and environmental protection issues it may make a tourist beach/region more attractive for a specific target group of tourist (tourist with focus/preferences on environmental sustainability).

**Table 5.2.2.** The relative importance (RI) of ecosystems services in managed beaches with medium to high loads of beach wrack (scenario 3) with a general indication of how the further treatment of beach wrack can contribute to the importance of various ecosystem services. Stars (*) are indicative, respectively: * small increase in ES, ** medium increase in ES, *** a significant increase in ES.

| Ecosystem Services (ES) | Managed beach with beach wrack, RI (%) | Wrack4Soil | EELGRASS | BWC | Wracover | Wrack4Coast | ALREA | WAIT | FERTIWRACK | ESTAGAR |
|---|---|---|---|---|---|---|---|---|---|---|
| Wild plants for materials (further processing) | 4.4 | *** | *** | | | | | | * | * |
| Food | 3.1 | | | | | | | | | * |
| Biomass as energy source | 4.2 | | | *** | | | *** | | * | |
| Extraction of minerals (sand, nutrients) | 3.6 | | | | | | | | | |
| Timber/ Driftwood | 1.7 | | | | | | | | | |
| Natural Ornaments | 0.6 | | | | | | | | | |
| Sediment storage and transport | 3.8 | | | | | ** | | | | |
| Coastal Protection/ Flood control | 4.9 | | | | | *** | | | * | |
| Biodiversity and habitats | 0.9 | | | | * | *** | | | ** | |
| Pest and disease control | 1.5 | | | | | | | | * | |
| Water purification | 4.0 | | | | | * | | * | * | |
| Groundwater regulation | 2.7 | | | | | * | | | | |
| Carbon sequestrian/storage | 2.2 | * | * | * | ** | ** | | | | |
| Nutrient regulation | 3.4 | * | * | | * | ** | | * | ** | |
| Dispersal of seeds | 0.6 | | | | * | * | | | * | |
| Recreation and tourism (active) | 26.7 | | | | | * | | | | |
| Recreation and health (observational) | 1.7 | | | | | ** | | | ** | |
| Knowledge systems | 5.7 | | | | * | * | | *** | * | |
| Culture and heritage | 8.2 | | | | | * | | | | * |
| Regional identity | 6.7 | * | * | | * | * | | | | * |
| Landscape aesthetics | 8.0 | | | | * | * | | | * | |
| Natural heritage | 1.5 | | | | | * | | | | |

# **6** Summary and recommendations

Tourism-oriented beach management is not an easy task as there are several aspects that need to be taken into account, just to name a few: bathing water quality, local waste management, beach cleaning procedures, safety, specific beach ecosystem characteristics, environmental status, beach infrastucture (shops, parking space etc.), spatio-temporal variability in beach use etc. For the municipalities one source of information is e.g. the Blue Flag Program (www.blueflag.global). This program started in 1987 in France and for now it is established as a worldwide programme promoting sound environmental education and sustainable management of beaches, marinas and boating operators. In total the program is followed in 47 countries covering over 4600 different sites. Consequently, the iconic Blue Flag is a globally well-known voluntary award. In order to qualify for the Blue Flag, a series of strict environmental, educational, safety, and accessibility criteria must be met and continuously maintained. Regarding countries who participated in the CONTRA project the number of Blue Flag beaches at the Baltic Sea is as follows: Denmark 174, Germany 44, Poland 25, Sweden 7, Estonia 3 and Russia (Kaliningrad) 2.

The amount of beach wrack is certainly one of the central questions in beach management perfomance. Regarding the presence of beach wrack the Blue Flag Program (www.blueflag.global/) suggests under the environmental management section as follows: "Algal vegetation or natural debris must be left on the beach (criteria 16)". *„Algal vegetation is generally accepted as referring to seaweed. Seaweed and other vegetation/natural debris are natural components of both freshwater and marine ecosystems. These ecosystems must be considered as living and natural environments and not only as a recreational asset to be kept tidy. Thus, the management of seaweed or other vegetation/natural detritus on the shore should be sensitive to both visitor needs and biodiversity. Natural disposal by tides and waves at the beach is accepted, as long as it does not create a nuisance.*" The acceptance level is highly dependent on the general knowledge of beach ecosystems functioning. Both CONTRA-reports of Hofmann et al., (2021ab) provide more detailed overview of the public acceptance tolerance regarding the amount of beach wrack on the beaches both in touristic high- and low season.

In this chapter we present some suggestions/aspects that should be taken into account in beach management planning and organizing from the environmental point of view. As there is great variability in beaches ecosystems and beach uses across the Baltic Sea region, then it is always advisable for municipalities to invest in the research of local beach ecosystem functioning before introducing/updating the respective beach management activities. Beach management should among other things include the fact that for some beaches the wrack can be an important feature for coastal protection e.g. as wave inhibitor or significant source of nutrients for dune vegetation. However, for some beaches, seasonal beach clean-up planning can help partially avoid conflicts of interest between environmental issues and tourism industry. It is most important to keep in mind that beach wrack is a natural part of beach ecosystems and if it has not turned into an excessive nuisance, less management of beach wrack provides more values for the local environment.

### Accumulation of beach wrack

In the Baltic Sea, beach wrack accumulation is most intensive in the late autumn, winter and early spring seasons, and considerably lower in summer. The beach wrack accumulation pattern is related to increased storm activity in the autumn-winter period and natural cycle of seagrass/macroalgae growth. Species composition of the beach wrack varies over different seasons.

### Amounts of beach wrack

The amounts of beach wrack that land on different regions of the Baltic Sea coastal areas vary significantly. Thus it is difficult to give ubiquitious suggestions, different strategies can be applied based on beach wrack amounts and residence time.

However, it could be helpful to agree upon a maximum amount of beach wrack on the beaches that is acceptable to the wider public and does not need removing. For example, there is no need for beach wrack removal if the new wrack (wrack deposited near waterline) covers the beach less than e.g. 10 % (see CONTRA-report Hoffmann et al., 2021b) and for old wrack these % can be a bit higher depending on the actual volume of the beach wrack.

### Beach wrack species composition

The interest in blue economy is growing and thus there is also growing interest in pure algal material, e.g. with focus on one concrete species or algal group (see CONTRA-report Chubarenko et al., 2021 about collecting eelgrass *Zostera marina* and red algae *Furcellaria lumbricalis*). The proportion of filamentous algae increases up to 85–90 % in new wrack near water line in summer. Beach wrack, which consists of filamentous macroalgae, has a rather dense, consolidated structure as the algae are sticked together. Thus the aeolian dispersal of such a wrack is lower and its significance for the fertilisation of the terrestrial beach vegetation is reduced. Hence, filamentous algae are only found very rarely in the vegetation zone of the dunes or inland. At the same time the degradation rate of filamentous algae both in the swash zone and in the water is much quicker when compared to perennial algae or seagrass.

However, it is recommended that more attention is paid to the species composition of beach wrack over the course of the year. Hence, giving more focus to the species that dominate in beach wrack does not need to serve only the interests of manufacturing enterprises – it can also be useful information regarding nature tourism, education and general knowledge increase in the understanding of beach ecosystems.

### Residence time

It is recommended to take into account the peculiarities of the wrack residence time on respective beaches to plan management activities. Short residence time can be a limiting factor when the aim is a long lasting beach wrack removal (e.g. beaches in Kaliningrad). To improve efficiency, it is necessary to apply special measures in such conditions. For example, a possible optimization solution could be use of webcam observations on potentially profitable seashore to coordinate the harvesting activities. At the same time, for beaches with a naturally long-term wrack residence time (e.g. sheltered beaches in Estonia and Sweden), it might be an important component of the terrestrial ecosystems, for example, as a source of nutrients or food for beach flora/fauna. In conclusion, the combination of the three factors residence time, amounts and composition of beach wrack must be taken into account during planning management and local conservational needs.

### Hazardous substances

In certain areas, a proportion of the wrack moving onshore is permanently trapped. This creates problems not only for inhabitants of those areas and local authorities, who are responsible to maintain the beaches, but also for the local beach ecosystem. Research under the CONTRA project proved that the beach wrack can release contaminants accumulated by algae during their lifetime from seawater and sediments. Moreover, mercury studies indicated that beach wrack deposited on beaches continues to accumulate dissolved substances from seawater. Contaminants are being released to the coastal zone during decomposition of organic matter, partly to groundwaters, which are returning to the sea, and partly to the atmosphere via volatiles. Moreover, the presence of large quantities of organic matter, and the fact, that contaminants were already absorbed by marine plants and algae, results in enhanced bioavailability of contaminants, as compared to seawater where they came from. The process itself is cyclic – contaminants are being removed from seawater and sediments by marine plants and algae, in areas located at considerable distance from the coastal zone. In the case of the Puck Bay (Poland), this included the entire bay and Gulf of Gdańsk. Then they are washed ashore in several locations, building up the metal and organic contaminants pool in these spots. During decomposition, bioavailable forms of contaminants are released to the coastal zone, where biota can absorb those and transfer them to the foodchain. Breaking this link, by removal of beachcast after deposition, can result in the depuration of the ecosystem. However, this accumulation of hazardous substances seems to be strongly dependent on the areas and species composition/amounts of macroalgae and needs further research.

### Litter on the beaches

Based on a survey described in the CONTRA-report of Hofmann et al., (2021a), one third of the municipalities (8 out of 23) had no information regarding the amount and kind of litter within the beach cast. This indicates clearly that on the municipality level the information regarding different aspects of beach management is often lacking. However, the amount of litter both within the organic biomass and sediment should be monitored on a local basis and taken into account when searching for further use possibilities of removed beach wrack – in other words: among other aspects the amount and nature of litter significantly affect the treatment options and possible further use of beach wrack.

From the beaches the litter can be removed separately or together with beach wrack. Most of the litter on the beaches originates from land-based activities, but the general marine pollution cannot be ignored here and litter may be carried to the beach from adjacent areas as well. There is also great variety in litter items regarding e.g. material, hazardousness, size, origin. Consequently, the presence of litter just makes the beach wrack a more complicated material for futher processing. When big and visible litter items can be removed easily by hand-picking, then the smaller items that are entangled or buried into the beached algal material are harder, if not impossible, to find and remove. Microlitter (litter items in size < 5 mm) and nanolitter (generally litter items in size < 0.001 mm) surveys within the beach wrack need more specific approach.

Microplastic pollution is raising public concern globally and the presence of it within beach sand and beach wrack limits the direct use of removed beach wrack. For example, it is not advisable to use it in agricultural lands as fertilizer as the consequences of microplastic pollution in the agricultural fields for sustainability and security of food production are currently unknown. This thematic is rather new and might become a relevant topic for agricultural environmental policies in the future (Henseler et al., 2019).

Littering of dunes is another aspect that needs more attention. For example, in the Mediterranean region a clear increase of litter cover along the sea-inland gradient has been described with foredunes and pine forests having the highest cover of litter (Šilc et al., 2018) of which most frequent were plastic, polystyrene and glass. At the same time dunes are often very fragile to mechanical disturbance (both by foot and machines). In conclusion, in beach management and cleaning it is important to have a wider view on the whole beach ecosystem and prevent beach littering in the first place and also prevent the moving of beach litter (back) towards inland and marine environment.

### Management period

Common practice is that beaches are managed in the touristic high-season from May to August and left untouched for the rest of the year. However, based on a survey carried out within 43 municipalities, the active beach management in some regions takes place all year around (CONTRA-report Hofmann et al., 2021a). E.g. there are some regions in Sweden, which especially suffer from extreme loads of beach wrack (mainly filamentous algae) and remove wrack mostly in November-December and April-May as the removal needs low water levels in a shallow bay. Hence, extra removal activities after storms with large amounts of wrack landings were performed additionally. It has been suggested that in areas, where the water quality on a local level is problematic, it is possible to improve the water quality with a more targeted beach management (CONTRA-report Chubarenko et al., 2021).

As for the regions where beach wrack landings in the low tourism season are less annoying and the recreational beach activities (e.g. walking, nature observations etc) are not severely affected, it is not advisable to carry out cleaning activities during the full year. Thus cleaning should therefore be limited to the time when there is really an increased demand for it. However, in these regions, it is suggested additionally to invest into activities related to raising public awareness regarding the importance of beach wrack as a natural part of beach ecosystems.

### Management disturbance on beach ecology

Managed beaches are wider than the natural ones, have much less vegetation, lower biodiversity, fewer „natural" dunes and much flatter topographic features than unmanaged beaches. According to various studies summarized in a review by Defeo et al., (2009), the beach wrack cover of the beach and the abundance of shorebirds were positively correlated. In addition, the general loss of dune vegetation contributes to increased nestling mortality of dune nesting bird species (Watson et al., 1996). In our studies the absence of beach cleaning was not associated with a significant increase in biodiversity of bird species and numbers of individuals on unmanaged beaches. Both managed and unmanaged beaches in Germany were dominated by two species of seagulls which are possibly more attracted to organic residues from human food compared to infauna within beach wrack. Hence, the highest bird individual presence was determined in total in the reference area (bird sanctuary) that reflected the "real" natural situation (higher biodiversity and possibly less sand compaction). In already heavily impacted sand beaches in Germany the anthropogenic effects such as landscape change/development and massive human presence already lead to a flora and fauna reduction in biodiversity and beach cleaning deepens the effect.

The birds as "cultural followers" (e.g. seagulls) of the managed and unmanaged sites were optimally adapted in their feeding and distancing behavior to the anthropogenic impact. One third of the individuals observed showed no response while 13 % of the birds were attracted to mechanical cleaning. At the same time, over half of the birds avoided or flew away during the cleaning activities.

Animal communities inhabiting sandy beaches rely heavily on seaborne inputs of carbon and organic materials since *in situ* productivity is very low (Brown & McLachlan, 1990). Beach wrack, thereby, constitutes the major allochthonous subsidy for these ecosystems. Hence, its frequent removal can affect the productivity and standing crop of primary and secondary consumers in beach inhabiting communities. Indeed, numerous studies found that the removal of beach wrack led to a decrease in diversity, abundance, total biomass of beach inhabiting macrofauna. Based on our findings within the CONTRA, the total macrofaunal abundance in the unmanaged area was almost double the values recorded at the managed site. The unmanaged region had higher biodiversity, more taxa than the managed region. Due to the negative impact of the removal of beach wrack on local biodiversity, there is a necessity to consider if the beach wrack can be partly left untouched.

On the other hand, increased organic matter may cause temporary oxygen deficiency in deeper layers under thicker beach wrack biomass and/or sediments, hence the higher abundance of macro- and meiofauna in the unmanaged region is mainly due to the presence of opportunistic species that are adapted to live in adverse environmental conditions. The fact of less oxygen in pore waters directly affects the abundance of meiofauna, the organisms that live in the spaces between sand grains. It was shown that meiofauna, living in pore waters with lower oxygenation than the water column, are more sensitive to environmental disturbances than macrofauna. The studies carried out under the CONTRA project showed that the mean meiofauna abundance in the managed area was almost three times higher than that in the unmanaged site, and taxa considered sensitive to oxygen lack were found mainly in the managed area.

### Sand content

One important aspect regarding beach wrack removal is also removal of sand from the beach ecosystems. The sand content within beach wrack varies greatly, based on our studies in Kakumäe, Estonia, the sand content in removed beach wrack was on average 58 % with maximum values of 97 %. In our study it equaled to average of 2.5 kg of sand (dry weight) per 1 m² that was removed together with beach wrack from new wrack line and to 4.1 kg of sand on avareage per old wrack line. The maximum values reached up to 21.8 kg of sand removal per m². The high content of sand within the beach wrack is one argument in favor of shortening the management period and intensity. This removes valuable sand from the beach, which, in addition to the loss of surface area, plays an important role in coastal protection.

### Machinery for beach wrack removal

Whenever possible (depending on the cleanable beach area and beach wrack loads) the beach wrack should be removed by hand (rake) and/or using specially developed no-motorized carts. Surely this can be done in areas where the beach wrack loads are rather low and the managed area is also small. For example the Kuressaare beach in Saaremaa, Estonia, where a 400 m long beach section is managed daily by hand and according to needs in period April-October. In areas where such approach is not applicable, mostly tractors built for agricultural activities are used. However, when using heavy machinery, it is important to really adapt the cleaning activities to the needs and to limit the number, distances and time spent travelling back and forth. The machines should be in good order and e.g. oil leaks/droppings should be prevented in the first place. Furthermore, when using rakes, it is important not to let them penetrate too deeply into the soil (not deeper than 10 cm) to avoid the constant rearrangement of deeper sediment layers. As this is where most of the material lies, the main cleaning is commonly done in the splash zone. However, as this zone is the most fragile part of the beach ecosystem, travelling and cleanings should be kept to a minimum.

### Moving the beach wrack – to where?

The common practices of beach wrack removal include pushing the beach wrack back into the water or collecting it into piles nearby the managed beach. In case of such practice especially case-studies Wracover, Wrack4Coast and FERTIWRACK (CONTRA-report Chubarenko et al., 2021) show another approaches for the possible use of beach wrack. When piling up biomass on the beach for storage, care should be taken to ensure that these piles are not too high and, if necessary, aerated/remixed to prevent anoxic conditions and thus increased emissions of e.g. green house gases. Furthermore, it would be advisable to observe the water leaking out after raining. In principle, large quantities of biomass layered on top of each other should be avoided for long periods.

# Acknowledgement

We are thankful to all who contributed their time and energy to the compilation of the CONTRA activities and this report. Jane Hofmann, Jens Almqvist and Boris Chubarenko provided valuable ideas in the process of compiling the report. Case-study representatives Sara Hillbom Guizani, Timo Garrels, Steffen Aldag, Katarzyna Jankowska, Alicja Kupczyk contributed into chapter 5 (ecosystem services).

University of Tartu, Estonia is especially grateful to Mati Martin, Tiina Paalme, Greta Reisalu, Jonne Kotta, Hanna-Eliisa Luts, Karolin Teeveer, Nataliia Yarmola, Martin Teeveer, Kaire Kaljurand, Kiran Liversage, Maria Põldma, Kristiina Tiivel, Marge Simo, Jekaterina Jefimova and Kaie Maennel. Estonian Environmental Investment Centre co-financed the project (project no 15658).

ABIORAS, Russia acknowledges Aleksey Grave, Alexander Kileso and Dmitriy Domnin for the co-operation.

We acknowledge deeply all the experts who contributed in the assessment of ecosystem services related to sandy beaches management (chapter 5), list of experts is given below.

| Name | Country | Authority | Background | Involvement in CONTRA |
|---|---|---|---|---|
| Erik Kristensen | Denmark | University of Southern Denmark | Marine ecology | no |
| Thomas Busk | Denmark | University of Southern Denmark | Ecology | yes |
| Reimo Rivis | Estonia | University of Tallinn | Geology | no |
| Georg Martin | Estonia | University of Tartu | Benthic ecology | yes |
| Kaire Torn | Estonia | University of Tartu | Marine biology | yes |
| Tiia Möller | Estonia | University of Tartu | Marine biology | yes |
| Mareike Hannes | Germany | REM Consult | Urban planning | yes |
| Hendrik Schubert | Germany | Rostock University | Marine ecology | yes |
| Jana Woelfel | Germany | Rostock University | Marine ecology | yes |
| Diana Vaiciute | Lithuania | Klaipeda University | Ecology | no |
| Marija Katarzyte | Lithuania | Klaipeda University | Ecology | no |
| Martynas Bucas | Lithuania | Klaipeda University | Marine biology | no |
| Gregorz Siedlewicz | Poland | Institute of Oceanology of the Polish Academy of Sciences | Marine chemistry | yes |
| Jan Marcin Weslawski | Poland | Institute of Oceanology of the Polish Academy of Sciences | Marine ecology | yes |
| Lech Kotwicki | Poland | Institute of Oceanology of the Polish Academy of Sciences | Coastal ecology | yes |
| Sergey Aleksandrov | Russia | Atlantic Research Institute of Marine Fisheries and Oceanography | Aquatic ecology | no |
| Aleksey Grave | Russia | Shirshov Institute of Oceanology of Russian Academy of Sciences | Engineering | yes |

| Name | Country | Authority | Background | Involvement in CONTRA |
|---|---|---|---|---|
| Andrey Sokolov | Russia | Shirshov Institute of Oceanology of Russian Academy of Sciences | Mathematical modelling | no |
| Boris Chubarenko | Russia | Shirshov Institute of Oceanology of Russian Academy of Sciences | Coastal oceanography | yes |
| Dmitriy Domnin | Russia | Shirshov Institute of Oceanology of Russian Academy of Sciences | Geography | yes |
| Ekaterina Zhelezova | Russia | Shirshov Institute of Oceanology of Russian Academy of Sciences | Coastal systems | no |
| Julia Gorbunova | Russia | Shirshov Institute of Oceanology of Russian Academy of Sciences | Aquatic ecology | yes |
| Valentina Bobykina | Russia | Shirshov Institute of Oceanology of Russian Academy of Sciences | Geomorphology | yes |
| Laura Ferrrans | Sweden | Linnaeus University | Environmental engineering | no |
| Varvara Sachpazidou | Sweden | Linnaeus University | Aquatic ecology | yes |
| William Hogland | Sweden | Linnaeus University | Environmental science | yes |
| Therese Lindquist | Sweden | Morbylanga municipality | Environment and climate strategy | no |
| Kristin Bertilius | Sweden | Municipality of Borgholm | Wetland biology | no |
| Frank Schmieder | Sweden | Swedish University of Agricultural Sciences | Biochemistry | no |
| Gunnar Cervin | Sweden | University of Gothenburg | Marine botany | no |

# References

**Addamo, A.M., Laroche, P., Hanke, G.** (2017) Top Marine Beach Litter Items in Europe, EUR 29249 EN, Publications Office of the European Union, Luxembourg, 2017, ISBN 978-92-79-87711-7, doi:10.2760/496717, JRC108181

**Almqvist, J., Bretz, T., Fondahn, Å.** (2021) Beach wrack in a business environment: Guidance and inspiration towards increased resource utilization based on innovative treatment options, Report of the Interreg Project CONTRA, Kristianstad, 40 pp. https://www.beachwrack-contra.eu/business-environment

**Ahtiainen, H., Öhman, M.C.** (2014) Ecosystem Services in the Baltic Sea. Valuation of Marine and Coastal Ecosystem Services in the Baltic Sea. Nordic Council of Ministers

**Barreiro, F., Gómez, M., Lastra, M., López, J., de la Huz, R.** (2011) Annual cycle of wrack supply to sandy beaches: effect of the physical environment. Mar Ecol Prog Ser 433:65–74. https://doi.org/10.3354/meps09130

**Barreiro, F., Gómez, M., López, J. Lastra, M., de la Huz, R.** (2013) Coupling between macroalgal inputs and nutrients outcrop in exposed sandy beaches. Hydrobiologia 700, 73–84. https://doi.org/10.1007/s10750-012-1220-z

**Becker-Carus, C.** (2004) Lernen. In: Allgemeine Psychologie. Eine Einführung. Elsevier, Spektrum München, Heidelberg: 313–367 [in German]

**Bełdowska, M., Jędruch, A., Słupkowska, J., Saniewska, D., Saniewski, M.** (2015) Macrophyta as a vector of contemporary and historical mercury from the marine environment to the trophic web. Environmental Science and Pollution Research 22(7): 5228–5240

**Brown A.C., McLachlan A.** (1990) Ecology of sandy shores, Elsevier, Amsterdam, 328 pp.

**Burkhard, B., F. Kroll, S. Nedkov, F. Müller** (2012) Mapping supply, demand and budgets of 913 ecosystem services. In: Ecological Indicators 21: 17–29

**Burkhard, B., Petrosillo, I., Costanza, R.** (2010) Ecosystem services – bridging ecology, economy and social sciences. Ecological complexity 7(3), 257–259. DOI: 10.1016/j.ecocom.2010.07.001

**Chubarenko, B., Schubert, H., Woelfel, J.** (Eds.) (2021) Case studies for innovative solutions of beach wrack use: Report of the Interreg Project CONTRA, Rostock, 81 pp. https://www.beachwrack-contra.eu/case-studies-report

**Concalves, G.R., Andriolo, U., Pinto, L., Bessa, F.** (2019) Mapping marine litter using UAS on a beach-dune system: a multidisciplinary approach. Science of the Total Environment 706: 135742. DOI: 10.1016/j.scitotenv.2019.135742

**Costanza, R., d'Arge, R., de Groot, Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M.** (1997) The value of the world's ecosystem services and natural capital. Nature 387: 253–260

**Crawley, A., Kline, D.I., Dunn, S., Anthony, K., Dove, S.** (2010) The effect of ocean acidification on symbiont photorespiration and productivity in *Acropora formosa*. Glob Change Biol 16: 851–863. Global Change Biology. 16. 10.1111/j.1365-2486.2009.01943.x

**Davenport, J., Davenport, J. L.** (2006) The impact of tourism and personal leisure transport on coastal environments: A review. Estuarine, Coastal and Shelf Science 67: 280–292

**Defeo, O., McLachlan, A., Schoeman, D.S., Schlachter, T., Dugann, J., Jones, A., Lastra, M., Scapini, F.** (2009) Threats to sandy beach ecosystems: A review. Estuarine, Coastal and Shelf Science 81: 1–12

**Dubrawski, R., Zawadzka, E., Gawlik, W., Bistram, K.** (2008) Stan morskiej strefy brzegowej na podstawie wybranych wyników monitoringu brzegów morskich z lat 2004–2006." Inżynieria Morska i Geotechnika 1: 15–27 [in Polish]

**Dugan, J.E., Hubbard, D.M.** (2010) Loss of coastal strand habitat in Southern California; the role of beach grooming. Estuaries and Coasts 33 (1): 67–77. Doi: 10.1007/s12237-009-9239-8

**Dugan, J.E., Hubbard, D.M., McCrary, M.D., Pierson, M. O.** (2003) The response of macrofauna communities and shorebirds to macrophyte wrack subsidies on exposed sandy beaches of southern California". Estuarine, Coastal and Shelf Science 58: 25–40

**Feistel, R., Nausch, G., Wasmund, N.** (2008) State and evolution of the Baltic Sea, 1952–2005: a detailed 50-year survey of meteorology and climate, physics, chemistry, biology, and marine environment. John Wiley & Sons

**Filipkowska, A., Lubecki, L., Szymczak-Zyla, M., Kowalewska, G., Zbikowski, R., Szefer, P.** (2008) Utilisation of macroalgae from the Sopot beach (Baltic Sea). Oceanologia 50(2): 255–273

**Galgani, F., Hange, G., Werner, S., De Vrees, L.** (2013) Marine litter within the European Marine Strategy Frameworki Directive. ICES Journal of Marine Science 70 (6) 1055–1064. doi:10.1093/icesjms/fst122

**Galgani, L., Beiras, R., Galgani, F., Panti, C., Borja, A.** (2019) Editorial: Impacts of marine litter. Frontiers in Marine Science. https://doi.org/10.3389/fmars.2019.00208

**Gavigan, J., Kefela, T., Macadam-Somer, I., Suh, S., Geyer, R.** (2020) Synthetic microfiber emissions to land rival those to waterbodies and are growing. PLoS ONE 15(9): e0237839. https://doi.org/10.1371/journal.pone.0237839

**GESAMP** (2016) Sources, fate and effects of microplastics in the marine environment: Part 2 of a global assessment. A report to inform the Second United Nations Environment Assembly, 220 (Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection, London, U.K.)

**Gheskiere, T., Vincx, M., Weslawski, J.M., Scapini, F., Degraer, S.** (2005) Meiofauna as descriptor of tourism-induced changes at sandy beaches. Marine Environmental Research 60: 245–265.

**Hackney, C.T.** (1987) Factors affecting accumulation or loss of macroorganic matter in salt marsh sediments. Ecology 68, 1109–1113.

**HELCOM** (2018a) HELCOM Thematic assessment of eutrophication 2011–2016. Baltic Sea Environment Proceedings No. 156" Available at: http://www.helcom.fi/baltic-sea-trends/holistic-assessments/state-of-the-baltic-sea-2018/reports-and-materials/

**HELCOM** (2018b) Economic and social analyses in the Baltic Sea region – HELCOM Thematic assessment 2011–2016

**HELCOM** (2018c) HELCOM Thematic assessment of hazardous substances 2011–2016. Baltic Sea Environment Proceedings n°157.Available at: http://www.helcom.fi/baltic-sea-trends/holistic-assessments/state-of-the-baltic-sea-2018/reports-and-materials

**HELCOM** (2018d) HELCOM thematic assessment of biodiversity 2011–2016. Available at: http://www.helcom.fi/baltic-sea-trends/holistic-assessments/state-of-the-baltic-sea-2018/reports-and-materials

**HELCOM** (2012) Checklist of Baltic Sea Macro-species. Baltic Sea Environment Proceedings No. 130

**HELCOM, SYKE** (2008) Waterborne inputs of heavy metals to the Baltic Sea. HELCOM Indicator Fact Sheets HELCOM, PLC-Group HELCOMData Consultant SYKE.

**Henseler, M., Brandes, E., Kreins, P.** (2019) Microplastics in agricultural soils: a new challenge not only for agro-environmental policy? Conference paper: 172nd EAAE Seminar, May 28–29, 2019 At: Brussels, Belgium

**Hofmann J., Banovec M.** (2021a). Socioeconomic impacts of beach wrack management: Report of the Interreg Project CONTRA. Rostock. 54 pp.

**Hofmann J., Banovec M., Stybel N., Lovato M.** (2021b) (in preparation) Public Awareness of beach wrack in the Baltic Sea Region (title subject to change). Report of the Interreg project, Rostock. https://www.beachwrack-contra.eu/acceptance

**Houser, C., Labude, B., Haider, L., Weymer, B.** (2013) Impacts of driving on the beach: Case studies from Assateague Island and Padre Island National Seashores. Ocean & Coastal Management 71: 33–45

**Ince, R., Hyndes, G.A., Lavery, P., Vanderklift, M.** (2007) Marine macrophytes directly enhance abundances of sandy beach fauna through provision of food and habitat. Estuarine Coastal and Shelf Science 74 (1–2). Doi: 10.1016/j.ecss.2007.03.029

**Janke, K., Kremer, B.P.** (1993) Strand und Küste. Tiere, Pflanzen, Lebensräume. Kosmos, Stuttgart. [in German]

**Jędrzejczak, M. F.** (2002) Spatio-temporal decay 'hot spots' of stranded wrack in a Baltic sandy coastal system. Part I. Comparative study of the pattern: 1 type of wrack vs 3b each sites. Oceanologia 44 (4), 491–512

**Journal of Laws** (2002). M. o. E. Polish Goverment. Poland. Ord. 16.04.2002.

**Kotta, J., Jänes, H., Paalme, T., Peterson, A., Kotta, I., Aps, R., Szava-Kovats, R., Kaasik, A., Fetissov, M.** (2020) GoA 2.1. Assessing the PanBaltic potential of macroalgae cultivation and of harvesting wild stocks. Interreg Baltic Sea Region, GRASS

**Kotwicki, L., Weslawski, J.M., Raczynska, A., Kupiec, A.** (2005) Deposition of large organic particles (macrodetritus) in a sandy beach system (Puck Bay, Baltic Sea)." Oceanologia 47(2): 181–199

**Łabuz, T.A.** (2015) Environmental impacts—coastal erosion and coastline changes. The BACC II Author Team, Second Assessment of Climate Change for the Baltic Sea Basin, Regional Climate Studies, pp 381–396. DOI 10.1007/978-3-319-16006-1_20

**Lastra M., López J., Neves G.** (2015) Algal decay, temperature and body size influencing trophic behaviour of wrack consumers in sandy beaches. Marine biology 162, 221–233

**Liu., S., Trevathan-Tackett, S.M., Ewers Lewis, C.J., Olliver, Q., Jiang, Z., Huang, X., Macraedie, P.** (2019) Beach-cast seagrass wrack contributes substantially to global greenhouse gas emissions. Journal of Environmental Mangement 231: 329–335, 10.1016/j.jenvman.2018.10.047

**McLachlan, A., Defeo, O.** (2018) The ecology of sandy shores. Third edition. Elsevier Inc.

**Misson, G., Mainardis, M., Marroni, F., Peressotti, A., Goi, D.** (2021) Environmental methane emissions from seagrass wrack and evaluation of salinity effect on microbial community composition. Journal of Cleaner Production. 285: 12546. doi.org/10.1016/j.jclepro.2020.125426

**Mellbrand, K., Hambäck, P.** (2010) Coastal niches for terrestrial predators: A stable isotope study. Canadian Journal of Zoology. 88. 1077–1085. 10.1139/Z10-074

**Möller, T., Woelfel, J., Beldowski, J., Busk, T., Gorbunova, J., Hogland, W., Kotwicki, L., Martin, G., Quintana, C.O., Sachpazidou, V., Schmieder, F., Schubert, H., Schätzle, P.-K., Taevere, T., Torn, K.** (2021) Environmental aspects of beach wrack removal, Tallin, 104 pp. https://www.beachwrack-contra.eu/removal

**Müller, F.** (2005) Indicating ecosystem and landscape organisation. Ecological Indicators 5 (4), 280–294

**Müller, F., Bicking, S.Ahrendt, K., KinhBaca; D., Blindow, I., Fürst, C., Haase, P., Kruse, M., Kruse, T., Ma, L., Perennes, M., Ruljevic, I., Schernewski, G., Schimming, C.-G., Schneider, A., Schubert, H., Schumacher, J., Tappeiner, U., Zeleny, J.** (2020) Assessing ecosystem service potentials to evaluate terrestrial, coastal and marine ecosystem types in Northern Germany – An expert-based matrix approach. Ecological Indicators 112: 106–116

**Nizzetto, L., Futter, M., Langaas, S.** (2016) Are agricultural soil dumps for microplastics of urban origin? Environ. Sci. Technol. 2016, 50, 20, 10777–10779. https://doi.org/10.1021/acs.est.6b04140

**Nordstrom, K. F., Jackson, N.L., Korotky, K.H.** (2011) Aeolian sediment transport across beach wrack. Journal of Coastal Research, 59: 211–217. https://doi.org/10.2112/SI59-022.1

**Orr, M., Zimmer, M., Jelinski, D,E., Mews, M.** (2005) Wrack deposition on different beach types: spatial and temporal variation in the pattern of subsidy. Ecology 86:1496–1507

**Orr, K.K.** (2013) Predicting the ecosystem effects of harvesting beach-cast kelp for biofuel. Dissertation. University of the Highlands and Islands, Scotland

**Ortega, C.P.** (2012) Chapter 2: Effects of noise pollution on birds: A brief review of our knowledge – Efectos de la Polución Sonora en Aves: una Breve Revisión de Nuestro Conocimiento. Ornithological Monographs 74: 6–22

**Polis, G.A, Hurd, S.D.** (1996) Linking marine and terrestrial food webs: allochthonous input from the ocean supports high secondary productivity on small islands and coastal land communities. The American Naturalist 147

**Richardson, M.D., Jackson, D.R.** (2017) Chapter 8 – The Seafloor, In: Applied Underwater Acoustics, Neighbors T. H.& Bradley D. (eds.), Elsevier Springer: 469–552

**Schumacher, S.** (2008) Sandstrände der deutschen Ostseeküste – Gefährdung, Schutz und Ökologie der Wirbellosen. Hochschule Anhalt Fachbereich Landwirtschaft, Ökotrophologie und Landespflege, In: IKZM-Oder Berichte 5, EUCC – Die Küstenunion Deutschland e.V. (Hrsg.) Rostock: 150 pp. [in German]

**Šilc, U., Küzmič, F., Caković, D., Stešević, D.** (2018) Beach litter along various sand dune habitats in the southern Adriatic (E Mediterranean). Marine Pollution Bulletin 128. DOI: 10.1016/j.marpolbul.2018.01.045

**Speybroeck, J., Bonte, D., Courtens, W., Gheskiere, T., Grootaert, P., Maelfait, J.-P., Mathys, M., Provoost, S., Sabbe, K., Stienen, E.W.M., Lancker, V.V., Vincx, M., Degraer, S.** (2006) Beach nourishment: an ecologically sound coastal defence alternative? A review. Aquatic Conservation: Marine and Freshwater Ecosystems 16, 419–435

**Suursaar, Ü., Torn, K., Martin, G., Herkül, K., Kullas, T.** (2014) Formation and species composition of stormcast beach wrack in the Gulf of Riga, Baltic Sea. Oceanologia, 56, 673–695

**Szefer, P.** (2002) Metals, Metalloids and Radionuclides in the Baltic Ecosystem. Amsterdam, Elsevier.

**Torn, K., Martin, G., Suursaar, Ü.** (2015) Beach wrack macrovegetation index for assessing coastal phytobenthic biodiversity. Proceedings of the Estonian Academy of Sciences, 2016, 65, 1, 78–87doi: 10.3176/proc.2016.1.08

**Urban-Malinga, B. Zalewski, M. Jakubowska, A., Wodzinowski, T., Malinga, M., Pałys, B., Dąbrowska, A.** (2020) Microplastics on sandy beaches of the southern Baltic Sea. Marine Pollution Bulletin, Volume 155, 111170, https://doi.org/10.1016/j.marpolbul.2020.111170.

**Van Loon, W., Hanke, G., Fleet, D., Werner, S., Barry, J., Strand, J., Eriksson, J., Galgani, F., Gräwe, D., Schulz, M., Vlachogianni, T., Press, M., Blidberg, E., Walvoort, D.,** (2020) A European Threshold Value and Assessment Method for Macro Litter on Coastlines. EUR 30347 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-21444-1, doi:10.2760/54369, JRC121707

**Veiga, J.M., Fleet, D., Kinsey, S., Nilsson, P., Vlachogianni, T., Werner, S., Galgani, F., Thompson, R.C., Dagevos, J., Gago, J., Sobral, P., Cronin, R.** (2016) Identifying Sources of Marine Litter. MSFD GES TG Marine Litter Thematic Report;JRC Technical Report;EUR28309; doi:10.2788/018068

**Vlacogianni, T., Skocir, M., Constantin, P., Labbe, C., Orthodoxou, D., Pesmatoglou, I., Scanella, D., Spika, M., Zissimopolous, V., Scoullos, M.** (2019) Plastic pollution on the Mediterranean coastline: generating fit-for-purpose data to support decision-making via a participatory-science initiative. Science of the Total Environment. 711:135058 doi: 10.1016/j.scitotenv.2019.135058

**Volodina, A.A., Gerb, M.A.** (2013) Macrophytes of the coastal zone of the Russian sector of the southeastern part of the Baltic Sea (Kaliningrad Oblast). Izvestiya KGTU, No. 28, pp. 129–135. [ in Russian]

**Walter, G.** (1975) Globular vegetation: ecological and physiological characteristics. In: Tundras, meadows, steppes, extratropical deserts. M.: Progress. Vol. 3. 428 p.

**Watson, J.J., Kerley, G.I.H., McLachlan, A.** (1996) Human activity and potential impacts on dune breeding birds in the Alexandria coastal Dunefield. Landscape and Urban Planning 34: 315–322

**Weinberger, F., Paalme, T., Wikstrom, A.** (2020) Seaweed resources of the Baltic Sea, Kattegat and German and Danish North Sea coasts. Botanica Marina 63(1): 61–72.

**Weston, M.A., Schlacher, T.A., Lynn, D.** (2014) Pro-Environmental Beach Driving is Uncommon and Ineffective in Reducing Disturbance to Beach-Dwelling Birds. Environmental Management 53, 999–1004

**Wyles, K. J., Pahl, S., Thomas, K., Thompson, R.** (2016) Factors that can undermine the psychological benefits of coastal environments: exploring the effect of tidal state, presence, and type of litter. Environment and Behavior. 48(9) 1095–1126. DOI: 10.1177/0013916515592177

**Zaborska, A., Siedlewicz, G., Szymczycha, B., Dzierzbicka-Glowacka, L., Pazdro, K.** (2019) Legacy and emerging pollutants in the Gulf of Gdansk (southern Baltic Sea) – loads and distribution revisited. Marine Pollution Bulletin 139: 238–255