Beach wrack of the Baltic Sea

Environmental aspects of beach wrack removal

EUROPEAN UNION

EUROPEAN REGIONAL DEVELOPMENT FUND

WITH FINANCIAL SUPPORT OF THE RUSSIAN FEDERATION

Beach wrack of the Baltic Sea: Environmental aspects of beach wrack removal

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Content

Foreword

Beach wrack – what is it?

There was some debate over the terms used to describe material that is washed offshore by the sea and deposited onto our beaches. Dozens of terms in national languages of the Baltic countries exist and often the various terms are colloquial, some are used interchangeably even on a local level and others in several different countries. The terminology does not seem so important at first glance; however, it plays a major role in the discussion when it comes to processing the material, e.g., with or without litter.

Extensive literature search allows us to identify two terms that are most used: beach cast and beach wrack. Both refer to the material that can be found all over the world in the swash zone, in lines along the foreshore and sometimes at the back of the beach, especially after storms. The amount and composition vary depending on the season, coastal landform, offshore substrates (determining algae/seagrass growth), currents, tidal forces, wind and wave action.

We therefore propose the following interpretation for better understanding our reports: beach cast as an umbrella term for all washed up material consisting of beach wrack as the largest component, terrestrial debris, litter and living animals that inhabit it, but excluding materials such as sand, stones or pebbles. Also, beach wrack as purely the marine organic component of beach cast that originates from the sea, e.g., torn off seagrass, macro- and microalgae, shells, dead fish etc.

Since it is very difficult to collect "pure beach wrack" from the beaches by machines without sand, we additionally refer that this is "collected beach wrack" if this is mentioned relating to the processing in our reports.

"As long as we have to compete with wide, pristine and white catalogue beaches, we have to present our beaches to tourists in the same way" (quote from a German spa manager Markus Frick, Island of Poel). Meeting the public expectations of 'clean' recreational beaches is an ongoing challenge for coastal communities. There is no doubt that beach wrack (cf. inbox) as a natural part of coastal ecosystems is often regarded as a nuisance, particularly when it lands unexpectedly and in large quantities on beaches. It can cover beaches for weeks, rotting to a smelly soup that leaches back into the water. Consequently, beach wrack can be an annoying problem particularly to those whose economies rely on beach tourism. During the summer season, it is already being regularly removed as part of expensive beach cleaning routines in most touristic regions along the southern and western Baltic Sea coast. But again, and again, the question is raised: what can be done with all the collected biomass that is invariably at differing stages of decay and comprises of 50-80% sand? Could it be used as a resource rather than being disposed as a waste?

The discussion about beach wrack treatment is not new, having been pursued, mostly on a local basis, during various past projects. Some solutions have already been found and applied, but they remain local and fragmented. Local authorities are trying hard to independently find affordable, legal, and worthwhile use options for this biomass, but are being restricted by regulatory barriers, the resources that can be spent, a lack of knowledge and cooperation.

We, the partnership of the EU-project CONTRA (**CO**nversion of a **N**uisance **T**o a **R**esource and **A**sset; 2019-2021) recognised from the outset that beach wrack management is not straightforward and needs a wide-ranging concept that transcends the boundaries of municipalities, regions and countries. Consequently, within the CONTRA project we gathered the knowledge and built the capacity required to exploit the potential of the usage of beach wrack for the whole Baltic Sea region.

The challenge of beach wrack removal is to find a balance between public demand for ‘clean’ beaches, environmental protection, and the economy. To address this and to balance opposing interests, the CONTRA conducted a comprehensive evaluation of all perspectives relating to beach wrack management on national as well as on international levels. The project consortium comprised of public authorities, businesses, academia, and NGOs from six countries (Denmark, Germany, Estonia, Poland, Sweden, Russia) covering marine systems, coastal tourism, sustainable development, as well as administrative structures of the Baltic Sea region.

Different aspects of beach wrack removal and usage have been studied thoroughly. A set of seven case-studies have been described in detail, including an overview of the applicability of the concept. Additionally, ideas for sustainable options for pollution and nutrient remediation of the Baltic Sea have been put forward.

The results of our work are presented in four thematically in-depth analyses (main reports) focusing on:

- **Socioeconomics**
- **Ecology**
- **Business**
- **Technology**

A "**Tool kit**", covering practical aspects of beach wrack management, provides guidance for local and regional decisions makers. It serves both as a reference, as well as a decision aid to help practitioners convert current beach wrack management schemes into more sustainable solutions.

Additional reports/documents relating to beach wrack management are available on our project website at https://www.beachwrack-contra.eu/, including:

- **Legal aspects of beach wrack management in the Baltic Sea region**
- **Policy brief “Towards sustainable solutions for beach wrack treatment”**

With the help of this information, we hope that you - coastal authorities, enterprises, researchers - are inspired to adopt beach wrack treatment strategies that are environmentally sound as well as socially and economically worthwhile.

You are invited to join the “Beach Wrack Network” (https://www.eucc-d.de/beach-wrack-network.html) founded for the exchange between experts, practitioners, and policy makers about beach wrack issues within the Baltic Sea Region and beyond.

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Institute of Biological Sciences, Aquatic Ecology
University of Rostock, Germany
Lead Partner on behalf of the CONTRA consortium

1. Introduction

This report No 3.2 "Environmental aspects of beach wrack removal" is one of the outputs of the project CONTRA (**CO**nversion of a **N**uisance **T**o a **R**esource and **A**sset; 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 the experts from the CONTRA Project Partners. It represents the results obtained from the studied beaches located in the 6 countries: Germany, Denmark, Russia, Sweden, Estonia, and Poland.

The report covers main ecological aspects related to beach wrack ecology and beach management with focus on sandy beaches. Chapter 2 gives an overview of the studied areas, the research activities carried out, and the used methodology. The natural cycle of beach wrack is described in chapter 3. There, we view the seasonality in amounts and composition of beach wrack in selected managed and unmanaged beaches. The fate of beach wrack on the natural beaches including shoreline residence, aeolian dispersal and decomposition is also discussed. We also highlight the problem of litter on the beaches and in beach wrack. Different aspects of beach management such as noise pollution, disturbing wildlife, mechanical disturbance, compacting effects, and other effects potentially related to beach cleaning are covered in chapter 4.

2. Material and methodology

2.1. Study areas

The Baltic Sea is one of the largest semi-enclosed, brackish seas with a surface area of 349,644 km^2. It occupies a basin moulded by glacial erosion during the last few ice ages, and by post-glacial rebound of the area. It continued to evolve after the last de-glaciation (roughly 10,000–15,000 years ago) and the physicochemical properties of its water have undergone remarkable shifts over a relatively short period of time. The contemporary ''ecological age'' of the Baltic Sea is just about 8,000 years (Feistel et al., 2008). The Baltic Sea is very shallow, with a maximum depth of 460 m and an average depth of 60 m. The coastline length is about 8,000 km, and the configuration of the Baltic Sea is rather complex. The most distinct difference is between the North and South - the coasts of Sweden and Finland are highly fretted and mostly rocky, whereas those of the southern Baltic are mostly gently sloping and straighter. The main coastal features in the Baltic Sea region are sand or gravel spits, dunes, lagoons, wetlands, salt marshes, and cliffs cut in a variety of sediments (Łabuz, 2015; Figure 2.1.1).

Sandy beaches are the most attractive and important for tourism. Therefore, in the public beaches where beach wrack is abundant, it is usually seen as a nuisance which should be removed. Therefore, a managed beach is defined as beach from where beach wrack is removed for touristic purposes on a regular basis at least for some period of the year. Country-wise, the presence of sandy beaches and their management level is very different (Table 2.1.1). The management rate of sandy beaches is the highest in Poland and Sweden, where about 25% and 35% of all sandy beach ecosystems are managed. However, this country level information is sometimes very general or missing at all. For example, the share of managed beaches is currently not fully known in Denmark and even rough estimations are hard to provide. Overall, there are 174 Blue Flag Beaches in Denmark, which are either managed or monitored in regular basis. However, the total number of managed beaches is probably higher in Denmark (Table 2.1.1).

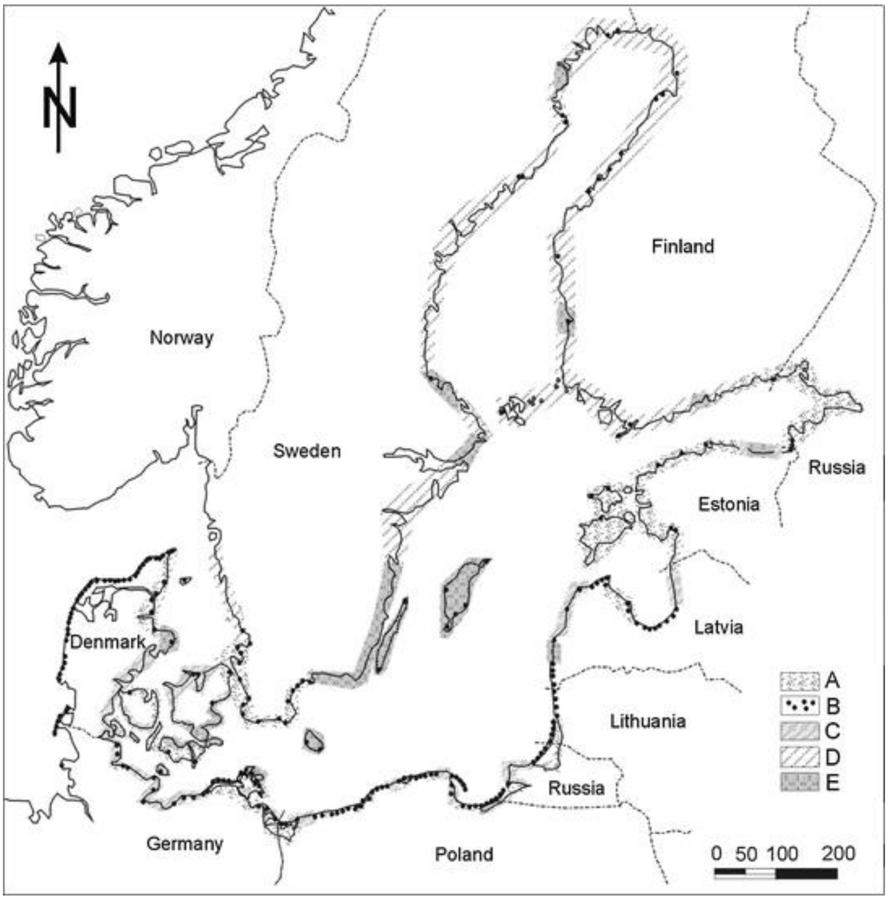


Figure 2.1.1. Coastal types in the Baltic Sea region: soft moraine cliffs (A), sandy barriers and sandy dunes (B), rocky cliffs (C), skerries (D), low coast, meadows, organic/ wetlands (E). Redrawn from Łabuz (2015).

Table 2.1.1. 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 length, km	Length of sandy beaches, km	Length of managed beaches, km	Number of managed beaches
Estonia	3,780	ca. 600	about 20	about 20
Russia (Kaliningrad)	145	ca. 145	a few km-s (varies from year to year)	a few (varies from year to year)
Poland	528	ca. 465	about 120	about 120
Germany	2,582	ca. 1,692	about 53	about 24
Denmark	8,750	sandy beaches and saltmarshes prevail	at least 1,800 km (coastal protection)	over 174
Sweden	3,218	ca. 350	about 100	about 25

Within CONTRA, fieldwork was carried out on sandy beaches of the Baltic Sea in six countries: Denmark, Sweden, Germany, Poland, Russia (Kaliningrad) and Estonia. At least one managed and one unmanaged beach was chosen in every country for the comparison of different beach wrack management practices, and to better highlight the impact of beach wrack removal on the ecosystem. In total, fieldwork was carried out in 19 beaches: 9 were managed and 10 represented natural conditions (Table 2.1.2, Figure 2.1.2).

Table 2.1.2. List of the studied beaches with coordinates and management status.

Country	Beach name	Site	Start coordN	Start coordE	End coordN	End coordE
Estonia	Kakumäe	Unmanaged	59.45048	24.57585	59.44966	24.57517
Estonia	Kakumäe	Managed	59.45048	24.57585	59.45140	24.57604
Russia	Filinskaya	Unmanaged	54.94815	20.01876	54.94792	20.02026
Russia	Zelenogradsk	Managed	54.96697	20.49298	54.96742	20.49437
Russia	Zelenogradsk	Managed	54.96366	20.48044	54.96401	20.48178
Russia	Filinskaya	Unmanaged	54.94751	20.02273	54.94741	20.02442
Sweden	Ekerum	Unmanaged	56.47244	16.33314	56.47438	16.33354
Sweden	Böda	Managed	57.27366	17.05592	57.27340	17.05591
Sweden	Kyrkertop	Managed	57.14590	17.03580	57.14551	17.04035
Denmark	Køge	Managed	55.44867	12.19875	55.44961	12.19861
Denmark	Nyborg	Unmanaged	55.30947	10.82031	55.30878	10.82142
Denmark	Køge	Unmanaged	55.44603	12.19969	55.44694	12.19939
Germany	Poel	Managed	54.00651	11.24845	54.00645	11.24842
Germany	Poel	Unmanaged	54.00691	11.24912	54.00661	11.24831
Germany	Kühlungsborn	Managed	54.09212	11.41820	54.09219	11.41818
Germany	Kühlungsborn	Unmanaged	54.41229	11.41911	54.09230	11.41911
Poland	Puck	Managed	54.72270	18.41697	54.72281	18.41393
Poland	Rzucewo	Unmanaged	54.69298	18.47191	54.69466	18.47238
Poland	Rzucewo	Unmanaged	54.69015	18.46921	54.69313	18.47203

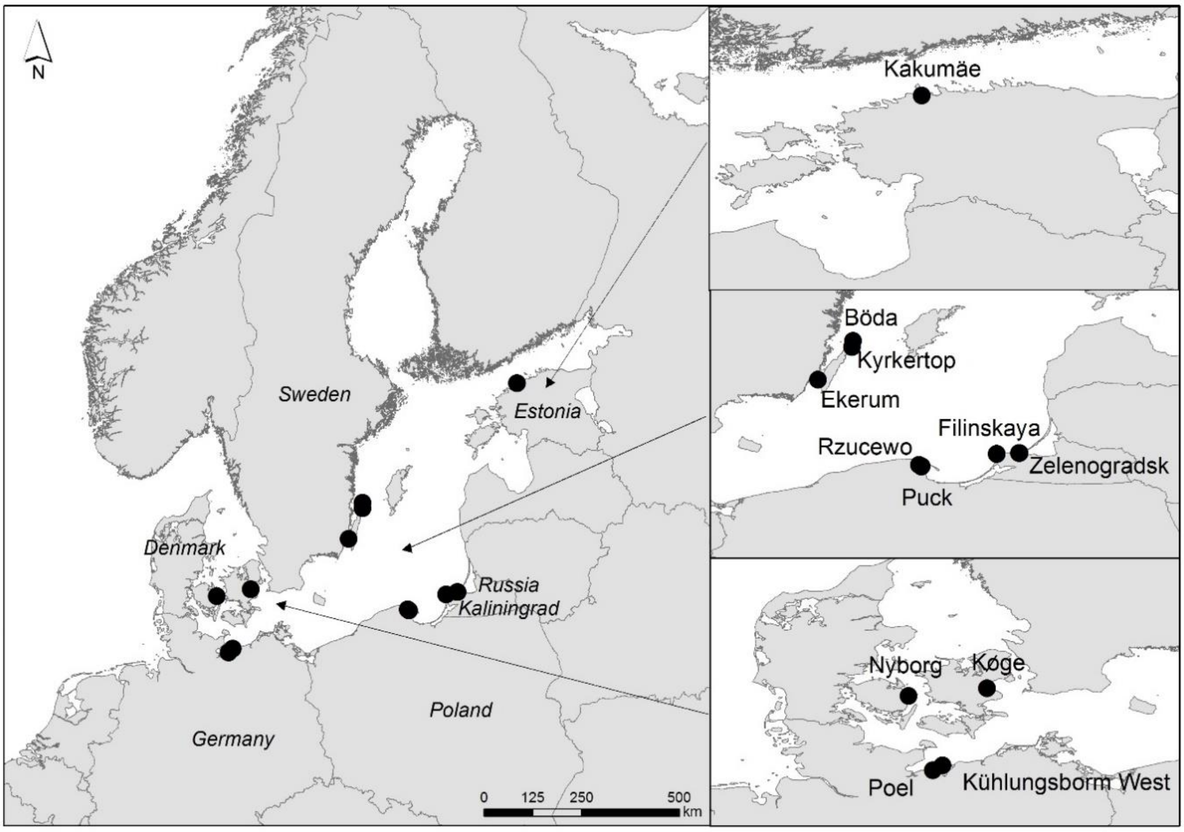


Figure 2.1.2. Location of the beaches where beach wrack studied were done within the project CONTRA.

2.1.1. Estonia

The total length of the Estonian coastline is 3,780 km, of which 1,242 km is on the mainland and the rest represents the islands. The Estonian coastline is very indented and straight coastline sections occur only in the eastern part of the Gulf of Finland and in the eastern part of the Gulf of Riga (including Pärnu beach). Different coastal types can be distinguished along the Estonian coast: cliffs (5%), scarps (short sections between other shore types), till (35%), gravel (11%), sand (16%), silt (31%) and artificial (2%; breakwaters, protecting walls, berms) (Tõnisson et al., 2013). Most of the sandy beaches are rather sheltered, located between peninsulas and typically less than 1 km long (e.g., Kakumäe, Võsu, Kuressaare beach). Long sandy beaches are found in the Pärnu Bay and in the eastern part of the Gulf of Finland (e.g., Narva-Jõesuu). The total number of managed beaches in Estonia is around 20 and the total length of managed stretches (where beach wrack is removed for touristic purposes during some period of year) is around 20 km.

2.1.1.1. Kakumäe beach

Kakumäe beach includes stretches of both managed and unmanaged beaches. It is a small and narrow sandy beach located in Tallinn, the capital city of Estonia, about 15 km form the city centre. The width of the beach (normal water level) is about 15-20 m, and next to beach are trees. Compared to the other beaches in Tallinn, Kakumäe is not the most popular among tourists and is mainly visited by locals all year round.

Photo 2.1.1. Kakumäe beach, managed section in 14.07.2019 (T. Paalme).

Photo 2.1.2. Kakumäe beach, unmanaged section in 15.10.2019 (T. Möller).

Total length of the managed beach section is around 500 m (Photo 2.1.1). The beach is managed between May and September, when needed, and the beach wrack is removed using a tractor. On a sunny summer day, the number of visitors may reach up to 3,000. The unmanaged beach section in Kakumäe is around 300 m long (Photo 2.1.2).

2.1.1.2. Pärnu beach

Pärnu beach is most popular in Estonia (Photo 2.1.3). Located in the Pärnu Bay, in the mouth of Pärnu River and within the limits of Pärnu city (around 40,000 inhabitants), it is one of the most favoured summer vacation destinations. The managed beach section is around 1,8 km long and it is managed daily in May-September. In the Pärnu Bay, only management effect studies (noise/ scare/ sand compaction) were performed.

Photo 2.1.3. Pärnu beach in 18.08.2020 (T. Möller).

2.1.2. Russia/Kaliningrad

The length of the shore coastline of the Kaliningrad Oblast in Russia is about 145 km, most of which is sandy beach. The width of the beaches in different areas vary between 10-75 m. There four major morpholithodynamic segments of the Kaliningrad Oblast coastline are: Russian part (25 km) of the Vistula Spit (shared with Poland), Russian part (47 km) of the Curonian Spit, and western (37 km) and northern (36 km) shores of the Sambia Peninsula. The shores on the spits are in a form of sandy beach with foredunes, and at some locations as an erosional terrace. The height of the Sambia Peninsula foredune and abrasion edge is from 5-7 m (near Zelenogradsk and Baltiysk) to 50-55 m (around the Cape Taran). The coasts of the Kaliningrad Oblast suffer from coastal erosion and cliff abrasion. Nearly half of the sea coastline in the Kaliningrad Oblast (73 km) is under erosion, and the rest is subject to alternating processes of accumulation and erosion (Karmanov et al., 2018). There are some federal resorts (Zelenogradsk and Svetlogorsk-Otradnoye), seaside resort settlements (Baltiysk, Yantarnyy, Donskoye, Poinerskiy, Primorye, Kulikovo) and some conservation areas (e.g., the National Park "Curonian Spit") in the Kaliningrad Oblast. However, only a few kilometres of the seaside are managed as public beaches.

The research under the CONTRA project was carried out on the unmanaged beach of Filinskaya Bay and on managed Zelenogradsk Beach. In addition, beach wrack presence was remotely monitored using a webcam in the western part of the Otradnoye beach and some observations for direct effect of beach management were carried out on the Yantarny Beach.

Photo 2.1.4. Filinskaya Bay, unmanaged beach in 06.09.2019 (J. Gorbunova).

Photo 2.1.5. Zelenogradsk beach, managed beach in 15.07.2020 (J. Gorbunova).

2.1.2.1. Filinskaya Bay

Filinskaya Bay is situated on the northern shore of the Sambia Peninsula east of Cape Taran. The bay is more than a kilometre long: the western part of the bay is pebbly, and the eastern part of the bay sandy beach with occasional boulders. The width of the beach is 10-40 m and the back of the beach is vegetated with grass and bushes. During the summer season (June-August), a lifeguard post operates on the beach. There is only a slipway for small boats. Compared to other beaches, the Filinskaya beach is not very popular among tourists, since the only way to get there is by a private car. The city of Kaliningrad is about 50 km away. The beach is not cleaned and there are no beach wrack or garbage collection activities. However, Filinskaya Bay is one of the sites in the Kaliningrad oblast where beach wrack is often washed ashore due to the closeness to the perennial algae growth area near the Cape Taran (Volodina, Gerb, 2013), and specific hydrodynamic conditions (Photo 2.1.4).

2.1.2.2. Zelenogradsk beach

The beach stretches along the town of Zelenogradsk for several kilometres. The total length of the managed beach sections is about 0.5 km. Part of the managed beach is aligned with a promenade.

There are some bank protection groins at a distance of 50 m from each other. Depending on sea level variations and dynamics of sand accumulation versus erosion, beach width varies between 1 and 25 m. There is no vegetation on the managed part of the beach. Another stretch of the managed beach is located in the eastern part of Zelenogradsk, where the Curonian Spit begins. The width of the beach is up to 35 m. In the back of the beach, a vegetated dune can be found. Zelenogradsk beach is one of the most popular in the region (Photo 2.1.5). The population of the city of Zelenogradsk is around 16,000. However, since the Zelenogradsk beach is one of the nearest beaches to Kaliningrad (with a population of about 500,000) with good transport accessibility, a large number of holidaymakers arrive in nice summer days. Beach cleaning is carried out from time to time by hand. In fact, the need to collect beach wrack from the Zelenogradsk beach appeared only a couple of times during the CONTRA project. Apparently, due to specific hydrodynamic conditions and bottom sediment structure, beach wrack is rarely washed ashore there.

2.1.2.3. Otradnoye beach

Otradnoye beach is situated on the northern shore of the Sambia Peninsula near the Otradnoye village. The beach is not cleaned, and there are no beach wrack and garbage treatment activities. The western part of the Otradnoye beach is located along the bank protection wall made of concrete and there is no vegetation on this part of the beach. There are also some bank protection groins. Depending on the sea water level, the beach width varies from 0 to 15 m. The western part of the Otradnoye beach, along with Filinskaya bay, is to one of the sites in the Kaliningrad Oblast where beach wrack is washed ashore more frequently in comparison with most of the other seaside. To monitor beach wrack, a webcam was installed there (Photo 2.1.6).

Photo 2.1.6. Otradnoye beach, unmanaged beach (left) and installed web camera for beach wrack movement observations (right) in 23.03.2020 (J. Gorbunova).

2.1.2.4. Yantarny beach

Yantarny beach is situated on the western shore of the Sambia Peninsula in the Yantarny settlement. The length of the managed part of the Yantarny beach is 1,300 m. The beach has an average width of 116 meters, and it consists of fine sand. This beach has a Blue Flag certification (www.blueflag.org). It is the only beach in the region where mechanical cleaning is routinely carried out using a cleaning machine. The sand is sifted with a separator several times a week. The mesh diameter used is 1 cm and 0.5 cm, depending on the sand humidity. The cleaning depth is up to 20 cm (Photo 2.1.7). During the cleaning procedure, all the beach litter retained by the separator, including algae, is removed. The collected waste is transported to the municipal landfill. However, on this seaside part of the beach, beach wrack (algae) emissions are usually small and rare.

Photo 2.1.7. Yantarny beach, managed beach in 25.08.2020 (J. Gorbunova).

2.1.3. Poland

The Polish Baltic coast in the southern Baltic is around 530 kilometres long and it extends from Swinoujscie in the west to Krynica Morska on the Vistula Spit in the east. About 85% of the Polish shore is relatively straight and it is formed of loose sediments. There are plenty of sandy beaches around 35 m wide on average and aligned with dunes of different types. In addition, soft Quaternary moraine cliffs stretch for 65 km along the Polish coast.

The shallow waters of the Gulf of Gdansk, and in particular the Puck Bay, are the most productive areas along the Polish coast. Puck Bay creates specific Baltic micro-habitats with low salinity and high influx of freshwater from rivers and groundwater sources (Kotwicki et al., 2014). The euphotic zone is a source area for filamentous algae and vascular plants production. According to the scale developed by Brown and McLachlan (1990), the beaches in Puck Bay area are of intermediate character with medium to fine sand. The swash water salinity ranges from 3 to 8 PSU and its temperature varies seasonally from 0 to 25°C. The macrophyte community is more abundant than in other parts of the Baltic Sea (Kruk-Dowgiałło, 1996). Reed habitats are found on the banks of lagoons and lakes and also along the Puck Bay.

Photo 2.1.8. Managed beach in Puck (IOPAN).

Photo 2.1.9. Rzucewo beach representing the natural conditions in southern Baltic Sea, Poland (IOPAN).

2.1.3.1. Puck beach

Puck is a small town located on the west coast of the Puck Bay. Near the city centre there is a managed city beach stretching about 200 m between the fishing and yacht harbours. The total length of the beach is 300 meters. The guarded swimming area on the sandy beach is 100 meters long and 30 meters wide. In Puck beach, beach wrack is manually removed daily from May to September. Each collection takes about 1.5 hours and is performed before 8:00 a.m. The collected material is sorted to separate the recyclable waste (plastic, glass) and the beach wrack is transported to the municipal waste disposal plant. The beach is not cleaned from October to April. The managed beach is clearly different from the unmanaged one, and it is characterized by a flattened beach profile and a lack of vegetation (Photo 2.1.8).

2.1.3.2. Rzucewo beach

The beach in Rzucewo is 4.5 km south-east from Puck. The sandy area is very narrow (3-5 m) and nearby dune vegetation includes grasses, bushes, and trees (Photo 2.1.9). Beach wrack thickness in this unmanaged area can be more than 1 m.

2.1.4. Germany

The German Baltic Sea coast has a total length of approximately 2,582 km, whereof 637 km is allocated to Schleswig-Holstein and the rest 1,945 km is the part of Mecklenburg-Western Pomerania (as given by the Federal State of Mecklenburg-Vorpommern, 2010). As the sampling sites during the CONTRA project located within the Mecklenburg-Western Pomerania, only this federal state will be considered. The coastal length of Mecklenburg-Vorpommern subdivides between 377 km of outer shoreline and 1,568 km long inner shoreline of boddens and lagoons with islands and peninsulas (Figure 2.1.3).

Due to its primal glacial shape, the coast of Mecklenburg-Western Pomerania is very complex, especially in the external coastline, which frequently alternates between steep cliff sections (128 km) and flat coastal sections (248 km) (Gurwell, 2008) (Figure 2.1.4).

For sampling areas, sites at Poel and Kühlungsborn West were chosen. Poel is an island, which is connected to the mainland by a drivable dike. The sampling site is located north of Poel at the beach “Am Schwarzen Busch”, which is exposed to the open sea and therefore impacted by wind and currents. Kühlungsborn is divided into two parts. Kühlungsborn Ost is mainly used for leisure and yachting, and the second beach is Kühlungsborn West, where the sampling was performed. Here, connected to the managed beach area, an accessible natures reserve is located.

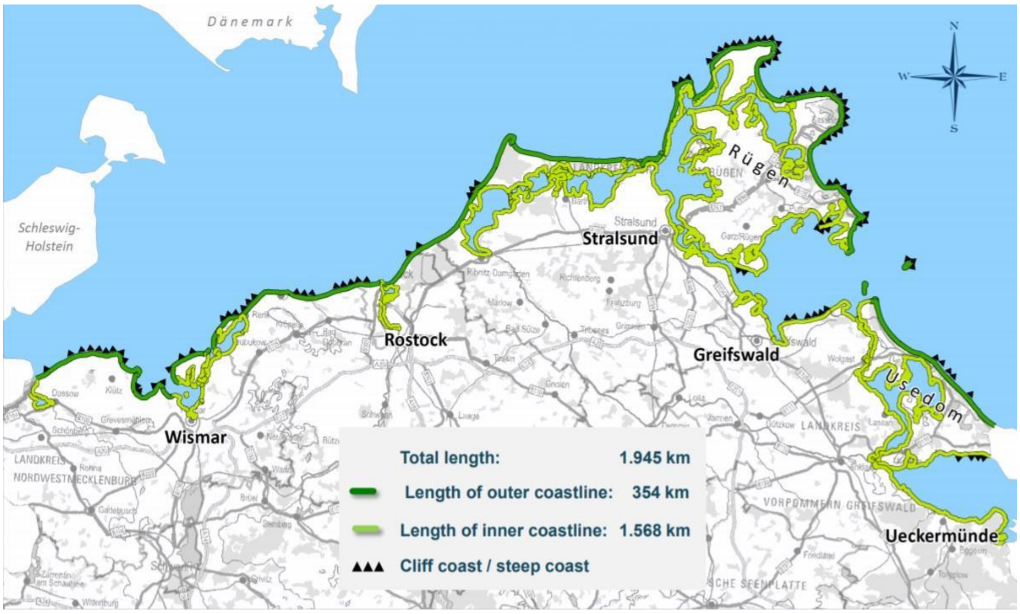


Figure 2.1.3. The coastline of Mecklenburg- Western Pomerania (by Frank Weichbrodt, Mecklenburg-Western Pomerania, Ministry of Agriculture and Environment Germany).

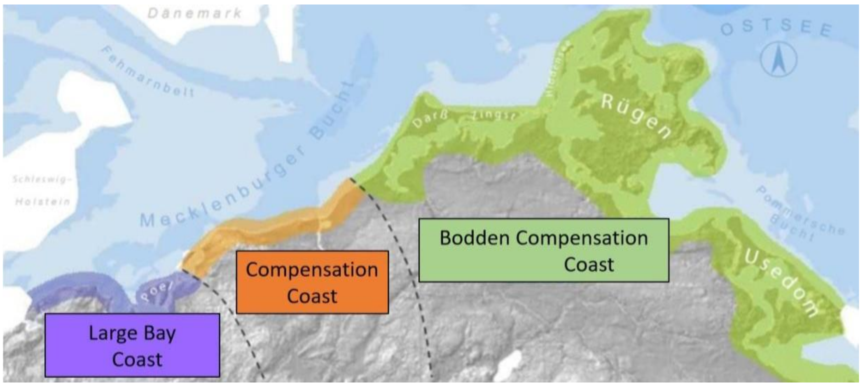


Figure 2.1.4 Morphological coastal types in Mecklenburg- Western Pomerania ("Regelwerk Küstenschutz Mecklenburg-Vorpommern", Ministry of Agriculture and Environment, July 2010).

2.1.4.1. Island of Poel

The island of Poel has an area of 37 km². The coastline of Poel is 11 km long, whereof the sampled beach "Am Schwarzen Busch" is in the northern part of the island. The beach includes a managed area for tourists along the main promenade. To the west/southwest, the unmanaged beach area and a dog beach continues. These two beach areas are clearly defined by the groins in the sea. The managed area extends to about 1 km in length. The beach width varies depending on wind conditions and sea level, but according to one year of samplings, it is between 30 - 40 m. The sampling was performed both within the managed and unmanaged areas.

Photo 2.1.10. "Am Schwarzen Busch" beach at Poel with very low water level in 01.07.2019. The unmanaged zone is to the left of the groin and the managed area is to the left (P.-K. Schätzle).

Photo 2.1.11. "Am Schwarzen Busch" beach at Poel with high-water level in 14.10.2019 with large amounts of seagrass washed ashore (P.-K. Schätzle).

A characteristic feature of the beach "Am Schwarzen Busch" is its white middle-grained sand (0.2-0.3 mm) with a gentle slope towards the Baltic Sea. Because of its sandy bottom and the shallow water, it provides a good habitat for the eelgrass *Zostera marina*, which is growing in large quantities in front of the coast. These occurrences mainly determined the species composition of beach wrack washed ashore around Poel during the year of study (Photos 2.1.10, 2.1.11).

Beach cleaning is performed between April and October, depending on the landing amounts of beach wrack. The regular management starts early in the morning (around 5 to 7 a.m.) every day during the season. The beach is cleaned with tractors and mounted forks in front or behind the vehicle. The collected beach wrack is then transferred to a flatbed truck and carted off to the interim storage. Here, beach wrack is collected and deposited for dewatering. A drainage underneath the collection area derives the sewage into large tanks. It is disposed separately as special sewage. The dried beach wrack is sieved to remove the sand and subsequently used for the production of soil fertilizers/conditioners (Hanseatische Umwelt, Sandhagen; project partner). The extracted sand is returned to the beach.

2.1.4.2. Kühlungsborn West

The beach of the town Kühlungsborn has a total length of approximately 6 km. Out of this, 3.5 km belongs to the area of Kühlungsborn Ost and 2.5 km belongs to Kühlungsborn West. The main part of Kühlungsborn Ost is used as leisure area and yachting with an almost 4 km long promenade and other tourist attractions. In the eastern area there is a marina for boating. At the main beach there is a 240 m long sea-bridge (pier). At the end of the west beach, an accessible nature reserve "Riedensee" continues towards the managed area. Sampling was performed both within the managed and unmanaged area. The two areas could be clearly defined by a small creek, the "Riedenbach". The managed area extends to about 5 km in length, with the unmanaged areas continuing to the west and to the east. The beach width varies depending on wind conditions and sea level, but according to one year of samplings, it is between 10 - 20 m.

The main characteristic of the beach Kühlungsborn West is its rocky shore (Photo 2.1.12). There is a graduate slope into the Baltic Sea, with a high euphotic zone within the beach area. Therefore, a lot of algae find ideal conditions for growing. Opposite to Poel, the beach wrack of Kühlungsborn mainly consists of red, green, and brown algae. Eelgrass is randomly found, mostly washed ashore from sandier areas in the surroundings after storm events.

Beach management is performed between April and October, depending on the beach wrack accumulations. The management starts early in the morning (around 6 – 8 a.m.) every day during the season. The beach is cleaned with tractors and mounted forks in front or behind the vehicle. Where the beach wrack is transported to, and what it is used for after collecting, is so far unknown. On some occasions it was simply pushed back into the sea or towards the unmanaged area.

Photo 2.1.12 Kühlungsborn West beach with mean water level in 11.05.2020 with low amounts of mixed green and red algae washed ashore. Behind the groin, the Riedenbach discharges into the Baltic Sea, the unmanaged beach area lies behind the groin (P.-K. Schätzle).

2.1.5. Denmark

Total length of the Danish coastline is more than 8,000 km, which includes the Baltic Sea coastline to the East and the North Sea coastline to the West (Kinze et al., 2018). The Danish coastal types consist of cliffs and sandy beaches. Cliffs are primarily on the western side of Jutland, where high winds and waves from the North Sea carve the shore. In the Sealand area adjacent to the Baltic Sea, sandy beaches, and calmer waters can be found. Brackish water from the Baltic Sea is mixed with highly saline oceanic water from Kattegat around Sealand. This contrast between seawater and brackish water causes salinity variations between 7-33 ‰ along the Danish coastline. Water temperature on the sea surface varies from 0-2 °C in the winter to up to 18 °C in the summer, whereas the bottom temperature varies from 4 to 12°C.

2.1.5.1. Køge beach

Køge municipality has a total of 60.000 residents. The municipality manages two different beaches, where the focus has been on the managed beach in the southern part of Køge. An unmanaged beach area lies next to it. The southern beach has been nourished with 70,000 m^3 of sand to create a wider beach for tourists (Koegekyst.dk, 2021). These two beaches are separated from each other by a mole that was constructed to prevent coastal erosion in the area. The managed beach is partly owned by Køge municipality and a private landowner. The unmanaged beach is owned by another landowner. The two beaches are ca. 900 meters long and on average 100 meters wide. The both beaches, managed and unmanaged, are studied in the CONTRA project (Figure 2.1.5, Photo 2.1.13). The Køge Bay (990 km²) usually accumulates high amounts of algae and eelgrass (Køge Technical, 2020). The bay borders with 21 municipalities (mst.dk 2021). The water in the Køge Bay is shallow, 10-15 meters deep in average. The Køge managed beach is cleaned in the summer months and beach wrack is removed after storms or when high amounts of wrack are washed up to the beach.

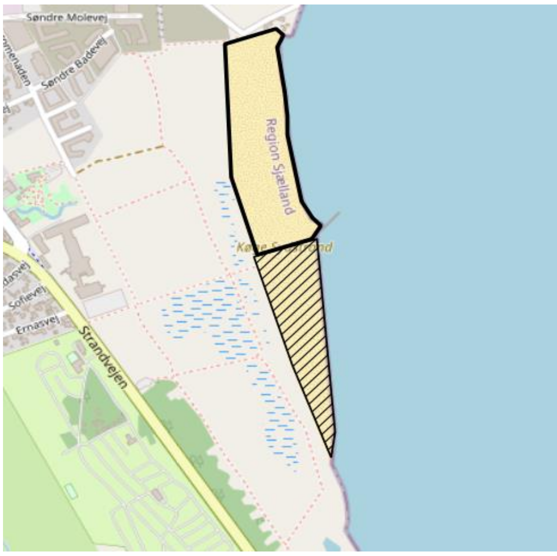


Figure 2.1.5. Køge beach is divided into unmanaged (dashed) and managed area.

Photo 2.1.13. Køge beach (T. Busk).

2.1.5.2. Nyborg

Photo 2.1.14. Nyborg beach in June 2020 (T. Busk).

Nyborg is a town (population ca. 17,000) close to the Storebælt (Great Belt) bridge connecting the islands of Funen and Sealand. There is a large water exchange through the strait and the coast is rather exposed. The examined beach lies close to the Nyborg city and is frequently visited by the residents and tourists in the summer. The beach wrack typically includes high amounts of bladderwrack and red algae. Nyborg beach is unmanaged, and the beach wrack is only removed by waves and tidal currents, which are intense in this exposed area. The studied beach is up to 90 meters wide and 200 meters long. Compared to Køge beach, Nyborg beach is less sandy with more rocks (Photo 2.1.14).

2.1.6. Sweden

The 6 km-long Öland Bridge connects the mainland Kalmar with the island of Öland, which is Sweden's second largest island. Measuring approximately 1,400 km^2, the island has over 70 nature reserves and ca. 500 km of coastline. While there are about 24,600 year-round inhabitants on the island, the number of visitors exceeds one million during the summer season (in July-August). Öland's popularity is undoubtedly justified as it is covered with orthoceratite limestone formations, forestry areas with the Great Alvar fauna, and fields hosting hundreds of bird and wildlife species. Most of Öland's beaches have the Blue Flag status outlined by the EU.

2.1.6.1. Ekerum beach

Ekerum beach is a partly managed beach as old beach wrack deposits are laying on the shore throughout the year. Ekerum Camping (considered as the "whole family's paradise") it is situated in Kalmarsund, 20 km north of Ölands Bridge. Lying on the front of the camping site, the beach is approximately 600 m long (Photo 2.1.15). The area is very scenic with a variety of trees. This well-equipped camping area has a plenty of facilities and it serves many visitors each year, both campers and daily visitors.

Photo 2.1.15. Ekerum beach in Öland (W. Hogland).

2.1.6.2. Böda Sand beach

Böda Sand beach is located on the east coast of the second-largest island of Sweden – Öland. Stretching for almost 20 km along the Böda bay, it is Öland's longest sandy beach. The managed (between March and November) Böda Sand beach is one of Sweden's most popular beaches. In fact, it is well known not only in Sweden but also throughout Europe. It features light, fine sand throughout its extent. The sea is shallow and calm, and the absence of stones appeals to both children and adults (Photo 2.1.16). There is a large camping ground with many amenities in the beach.

Photo 2.1.16. Böda Sand beach in Öland (W. Hogland).

Photo 2.1.17. Kyrketorps beach in Öland (W. Hogland).

2.1.6.3 Kyrketorps beach

Böda Riviera Kyrketorps beach is located near a pine forest (Photo 2.1.17). There are two camping sites (Böda Riviera Kyrketorps and Böda Sand camping) located in the Böda Bay close to the sea. Böda Riviera Kyrketorps Camping is fully equipped with many facilities, and it is located on the northernmost part of the Öland, about 70 km from the bridge to Kalmarsund. Beaches at both camping sites are managed between March and November.

2.2. Fieldwork and sampling

Depending on specific task, fieldwork and sampling was carried out on daily, weekly, monthly, quarterly, or annual basis (Table 2.2.1, Table 2.2.2). Sampling in wintertime was carried out when and where it was possible.

The study areas for most of the parameters were the same and the areas were monitored during the full fieldwork season. Permanent reference points were used to ensure that the same sites were monitored for all surveys. The study area covered the beach section between water edge to the back of the beach (up to vegetation) in 100 m length (Figure 2.2.1). In every study area, parameters such as beach width, slope, and primary use of the beach (tourism, public area, etc.) were recorded.

Table 2.2.1. Sampling schedule in the study areas. M - managed beach, UM - unmanaged beach, MP - management time period (mostly May-September), UP - unmanaged period (mostly October-April). X - research activities, * - possible additions.

Activity	**Daily**	**Weekly**	**Monthly**	**Quarterly**	**Annually**	**M**	**UM**	**MP**	**UP**
Beach wrack (BW) landings (amounts)			X			X	X	X	X
Beach wrack biomass and algal species composition			X			X	X	X	X
Meiofauna in sediment					X	X	X	X	
Macrofauna in sediment					X	X	X	X	
Residence time of beach wrack	X	X				X	X	X	X
Aeolian dispersal			X			X	X	X	X
Natural degradation of beach wrack			X				X	X	X
Natural degradation experiment			X				X	X	X
Greenhouse gas measurements		X					X	X	

Organic matter content				X		X	X	X	X
Nutrient content of beach wrack sediments					X	X	X	X	
Nutrient release from beach wrack					X		X	X	
Hazardous substances within sediment and algae					X	X	X	X	
Beach litter			X			X	X	X	X
Management activities					X	X	*	X	
Sand compaction and granulometry			*		X	X	*	X	
Noise pollution			X			X	*	X	
Scare effect			X			X	*	X	

Table 2.2.2. Fieldwork activities carried out in different countries in 2019 and 2020. X – fully carried out, * - supportive information.

Activity	GE	DK	SWE	POL	RUS	EST
Beach wrack (BW) landings (amounts)	X	X	*	X	X	X
Beach wrack biomass and algal species composition	X	X		X	X	X
Meiofauna in the sediment (swash zone)	*	*	*	X	*	*
Macrofauna in sediment (swash zone)	*	*		X	*	*
Residence time of beach wrack	X	*		*	X	X
Aeolian dispersal	X	*		*	X	*
Natural degradation of beach wrack			X			
Natural degradation experiment	*	*		X	*	X
Greenhouse gas measurements		X				
Organic matter content	*	*	*	X	*	*
Nutrient content of BW sediments	*	*	*	X	*	*
Nutrient release from BW	X			X		
Hazardous substances within sediment and algae	*	*	*	X	*	*
Beach litter	X	X	X	X	X	X
Management activities	X	*	*	*	X	X
Sand compaction and granulometry	X	*	*	*	X	X
Noise pollution	X	*		*	X	X
Scare effect	X	*		*	X	X

2.2.1. Beach wrack landings, biomass, and species composition

Beach wrack coverage estimations were carried out within a 100 m long beach section over the whole cross-shore area between the water edge (where possible) or from strandline to the back of the beach (Figure 2.2.1, 2.2.2). Width, thickness and length of beach wrack was determined both in new wrack and old wrack lines. If the wrack lay in several lines, the width of the stripes was summarized. The coverage was estimated as a percentage and coverage class was determined (Table 2.2.3). If the wrack was partly underneath the sand, the sand coverage information was also noted, and the amount of wrack underneath the sand was estimated. The algal composition was preliminarily estimated (the most distinctive species and algal groups) on the beach, biomass samples for more detailed analysis were collected.

Minimum of 3 biomass samples were taken with a 20 × 20 cm frame from fresh material (new wrack line). If old material (old wrack line) also existed, another 3 samples were taken from the older material (Figure 2.2.1, 2.2.2).

In the lab, the floral and faunal species were determined to the lowest possible taxonomical level. Animals were counted and sand was extracted. Samples were dried for 2 weeks at 60°C or 20 hours at 105°C and dry weight of each taxonomical group (and sand within the sample) was determined. Litter was protocolled if found.

Table 2.2.3. Indicative information for beach wrack coverage estimations.

Class	Coverage, %	Definition
0	0	No layer of wrack present
1	1-25	Thin: large areas of bare sand, wrack in small patches
2	26-50	Medium: more than half the area is bare sand, wrack in medium patches
3	51-75	High: less than half of the area is bare sand, wrack in large patches
4	>75	Extreme: little bare sand is evident, most wrack in large mounds

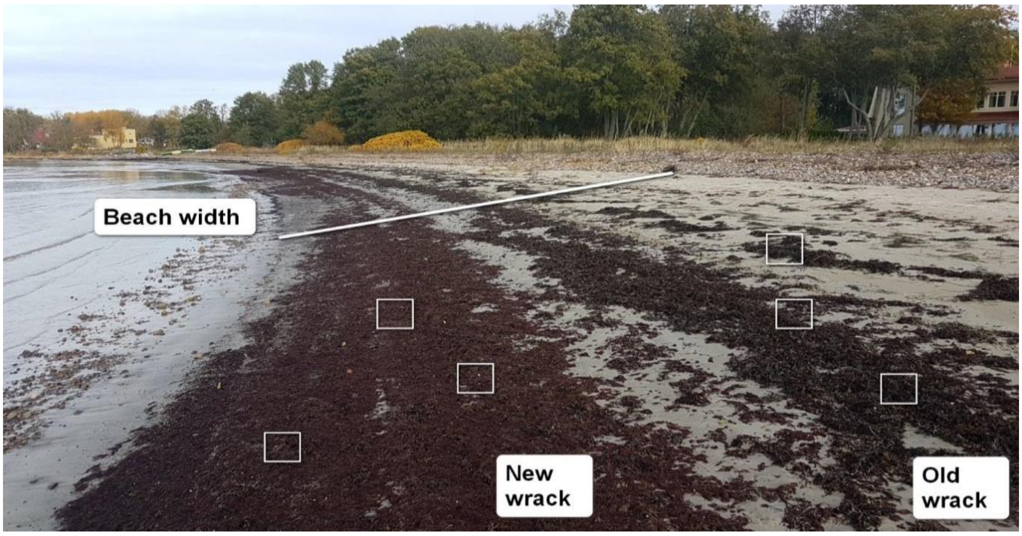


Figure 2.2.1. Example of placement of biomass samples (3 frames from fresh material, 3 frames from older material). Beach wrack was estimated and litter from the water's edge to the back of the beach (in beach width) was collected along the 100 m beach length (Kakumäe beach, 15.10.2019; T. Möller).

Figure 2.2.2. Example of the studied beach transect. Each transect was 100 m long and its width was measured from the foredune to the water. Beach wrack lines were differentiated by their position: old wrack closer to the dune, new wrack close to the waterline. Both from new and old wrack, three samples

were randomly taken within the 100 m beach stretch, which were subsequently examined for species composition and sand content in the lab (Ch. Porsche and P.-K. Schätzle).

2.2.2. Meiofauna in sediment

The material was similarly collected from managed and unmanaged beaches. 3 subsamples were taken from a shallow sublittoral (0.5 m depth) and 3 replicates were taken at the water line (in case of unmanaged beach - directly from the water line under the new beach wrack). In total, 6 samples were taken from one site/beach. The samples were taken using a tube or syringe, pressed into the sediment so that at least 10 cm of the sediment was collected. The sediment was transferred to a container of appropriate capacity and preserved using alcohol or formaldehyde. 99% alcohol was applied twice - as much as the water volume above the sediment. Formaldehyde was added until 4% of the final concentration was obtained. All further analyses were carried out in the laboratory of the IOPAN following the regular meiofauna analysis procedure.

2.2.3. Macrofauna in sediment

The macrozoobenthic inventory included taxonomic identification (to the lowest possible taxonomic unit), determination of abundance for individual taxa and their biomasses. Sampling and analysis of the samples was performed in accordance with the standard procedures of marine biological research used in the international monitoring of the Baltic Sea (HELCOM, 1999; HELCOM, 2015). The taxonomic classification together with the nomenclature was based on the World Register of Marine Species (WoRMS, 2018). Samples were collected monthly from April 2019 to March 2020 from the shallow sublittoral - both from managed and unmanaged beach areas. The samples including 3 replicates from both areas were collected using a small Ekman-type grab (Eckman grab) with a 250 cm^2 surface area from up to 10 cm depth. Samples were pre-washed on a 0.5 mm mesh sieve.

Sediment samples for biological analyses were preserved with 4% solution of formaldehyde. Appropriately labelled (with date, collection site, etc.) samples were used for further laboratory analysis. These were for determining the macrozoobenthos taxonomic composition, as well as abundances and biomasses (formalin wet weight) of individual taxa. Prior to sorting, the material sample was washed through a 0.5 mm mesh sieve to rinse off excess preservative. The material was then transferred to petri dishes and sorted into individual taxa using a stereo microscope. The results of the obtained qualitative (taxonomic composition) and quantitative (abundance and biomass) analyses of macrozoobenthos were recorded in the database.

Methodology of data analysis

The species structure was described based on seasons frequency/constancy index for each taxon.

The index of constancy indicates the presence of a given taxon within the biocoenosis (expressed as a percentage): $C = (n / N) \times 100\%$; where: C - taxon constancy index, n - number of samples containing the taxon, N - number of all samples.

Depending on the determined rate of constancy, taxa can be divided according to the scale described by Tischler (1949):

- 0-25% accidental species; very rare
- 25-50% rare species; accidental
- 50-75% constant species; constant
- 75-100% absolutely constant species.

Dominance for a given area, was determined as % of total abundance/biomass for each taxon.

2.2.4. Residence time

For estimating residence time, different approaches were used:
- using the help of locals (taking pictures on their beach visits) (e.g., in Estonia);
- installing wildlife trail cameras on site.

From the pictures the general coverage/change in coverage of beach wrack was estimated on the same basis as described in the methodological section 2.2.1 (Beach wrack landings).

2.2.5. Aeolian dispersal

Aeolian dispersal was estimated monthly at the unmanaged beach on a 1 m^2 quadrant on the dune (if present) or on the vegetated border in the upper part of the beach (Photo 2.2.1). The area exposed to winds was chosen, i.e., without hedges, cliffs, barriers, or buildings in front or in the back of the study site. A higher vegetation (e.g., marram grass/ beach grass (*Ammophila arenaria* (L.)) area was chosen. Every visit, the same quadrant was reviewed for density and height of branches. All the beach wrack was collected for further estimations of wet weight, dry weight, and composition (samples analysed as described under beach wrack biomass sampling). Special experiments were carried out in Germany (Poel beach), Estonia (Pärnu beach) and Russia (Filinskaya beach).

Photo 2.2.1. Placement of a sampling frame; within the frame all the biomass was counted for aeolian dispersal analyses (Poel beach, 27.07.2019, P.-K. Schätzle).

Photo 2.2.2. Example of material used in degradation experiment (Myriophyllum spicatum) (T. Möller)

2.2.6. Degradation

Decomposition of beach wrack was estimated both experimentally and by observation of natural degradation. The degradation experiment was carried out in July 2019 – February 2020 on Rzucewo beach (Poland) and in August 2019 – August 2020 in Kõiguste Bay (Estonia). Natural decomposition was observed in more detail on Rälla beach which is located on the southern part of Öland in Sweden. In this area, the forest reaches the beach and beach wrack lines are common. Fieldwork was also carried out in Denmark, Germany, and Russia, but due to some losses of experimental gear and differences in analysis methods, these results are not presented within this report.

Mesh bags used in degradation experiments were made of ordinary fiberglass mesh (mesh size ~4 × 4 mm) (Estonia, Photo 2.2.2) or of similar material (mesh size 2 × 2 mm) (Poland, Photo 2.2.3). The selected mesh sizes allowed access of fauna to the wrack material. Suggested size of the mesh bags was ~A5. Bags were numbered and labelled for recording. Three replicate mesh bags were used for each sampling occasion.

Photo 2.2.3. Degradation experiment setup in the Rzucewo beach, Poland (T. Kijewski).

The analysed algal material originated from the new wrack and approximately 100 ml of algae was used per litter bag. Wet weight, species composition and proportions were determined. Algae was placed into the bags and closed by sewing. In addition to algae that went to the litter bags, the same number of algal samples (~100 ml) were taken for determining wet weight - dry weight constant (5-10 samples). The samples were dried for 10 days at 60°C or 20 hours at 105°C.

The sample bags were anchored on the specific study sites at least in 2 locations:

- on the sediment (in back of the beach, where it is assumed that the experiment in not flushed away by waves) (Estonia)
- submerged in the water (in the areas which are under water also in low tide) (Estonia, Poland)
- buried in the sediment (10 cm deep) (Poland)

The samples were removed from the experimental sites after a specified time interval. The samples were packed separately (e.g., in zip-locked bags) and transported into the lab for further analysis. The algae were removed from the bag and dried to constant weight; the decomposition rate was calculated accordingly. The results were expressed as percentage of remained dry weight of wrack compared to the initial weight.

2.2.7. Greenhouse gas measurements

The measurement of greenhouse gases (GHG) was performed with a portable Gasmet analyzer (Model DX4030). The Gasmet equipment has been modified to be used in biological field studies. The Gasmet was installed with gas-tight tubes that are connected to a chamber (with dimensions 15 cm height and 25 cm diameter) (Figure 2.2.3). The chamber was further attached to rings (25 cm diameter) and placed on the beach wrack or sand for GHG measurements. A similar procedure was applied for measurements in the water, except that the chamber was connected to a floating board (Figure 2.2.3). The Gasmet includes an integrated pump that samples about 2 L of air, which flows through an inlet into a high sensitivity sensor that simultaneously detects CO_2 and CH_4. Afterwards, the air is pumped out. The Gasmet can be powered by an external battery and therefore it can be used for extended time in the field (up to ca. 4 hours). The data from the measurement was processed using the Calcmet software running on an external laptop. Therefore, it was possible to simultaneously track for concentration, time of analysis, and view the sample and reference spectra ("Gasmet DX4015: Gasmet.com," 2021).

Figure 2.2.3. Gasmet machine in use at Køge beach; closed chambers with tubes for the air flow to Gasmet are seen.

The Gasmet measures every 5 seconds. During the experiment, the chamber was left closed for measurements for 10 minutes. After the measurement, the chamber was lifted up so that the machine could be reset and closed again for new measurements. Three 10 min measurement replicates for sand, new beach wrack (NW), old beach wrack (OW) and water were performed. The GHG measurements were not performed when neither OW nor NW was available on the beach. The NW and OW was scarcely available on the managed beaches in summer since the beach wrack was routinely removed. This made the measurements difficult.

The GHG was measured monthly from July 2020 to January 2021. The GHG fluxes were studied by plotting the measured CO_2/CH_4 values over time. Linear regression was applied to calculate the efflux of CH_4 and CO_2 as the function of time (Figure 2.2.4). The efflux was expressed as mmol m^{-2} d^{-1}.

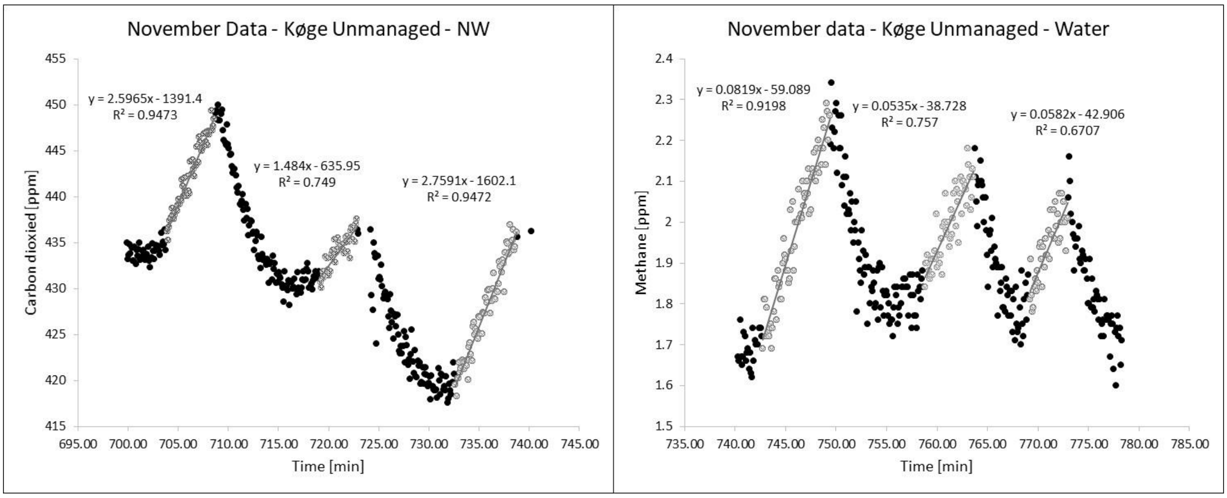


Figure 2.2.4. Gasmet measurements with time. Linear regression shows the efflux of CO_2 and CH_4, the data are from November, and from new wrack (NW) for CO_2 and water for CH_4.

2.2.8. Organic matter content

The samples were taken along transects from high water level to the vegetation/dunes. If possible, the sediment samples were taken also from underneath the beach wrack. Minimum 3 locations per transect were sampled. The suggested locations were:

- at the bare sand behind the wrack area
- underneath the "old wrack"
- underneath the "new wrack"
- flushing area.

The samples for organic matter content of sediment were taken at all stations in triplicates both on managed and unmanaged beach areas. The samples were collected with plastic tubes (2 cm in diameter) down to 5 cm in the sand and put into suitable plastic containers. The samples were deep-frozen (-20 °C) until further analysis. If the samples were analysed within one week, they were stored at 4 °C.

For laboratory analysis the deep-frozen sediment samples were melted to room temperature and put into previously measured and numbered crucibles. Samples were dried at 60 °C for 10 days and then kept in the desiccator for 12 hours. The dried samples were weighed and burned at 500 °C for 4 hours. After the ignition and cool down, the samples were kept in desiccator for 12 hours to stabilize the weight. After that, the samples were weighted. The loss of ignition was presented in % to dry weight of the sediment and the results of 3 samples from the same location were averaged.

2.2.9. Chemical substances from sediment and beach wrack

Analysis of chemical substances included mercury (Hg), nutrients; bisphenol A (BPA), 4-tert-octylphenol (4t-OP) and 4-nonylphenol (4-NP).

Sediment samples were collected from the beach (under the wrack and sand without contact with wrack), and from the sea (sediments close (up to 2 m) to the coastline). An upper layer of up to 5 cm was collected. For all chemical analyses, samples in 2 polyethylene bags or containers for each site were collected (in total, 6 bags per beach). Each bag contained approximately 150 g of sample. The samples were collected using rubber gloves and polyethylene or ceramic tools. The tools were regularly placed in 3M HNO_3 acid reagent of high purity and washed up with deionized water to avoid contamination with heavy metals and trace elements. During transport, the samples were stored in a dark, cold place (e.g., in portable cooler or ice box). The samples were stored in -20 °C until further analysis.

Samples for methylmercury (MeHg) were stored in -20 °C. Samples for Hg, nutrients, BPA, 4t-OP, 4-NP were freeze-dried and homogenized for further analysis. Some of the samples were transported frozen with dry ice to avoid multiple freezing-defreezing.

Sample preparation for XRF analysis requires an absolute homogenisation; therefore, a ball was used for this purpose. Homogenisation in a ceramic mortar and pestle was also possible, but the grinding fineness needed to be comparable to the one obtained with a ball mill. Minimum of 15 ml (but preferably 20-25 ml) of dried and homogenized material was used for XRF analysis and 17 g for mercury, nutrients, BPA, 4t-OP and 4-NP analysis. All further analyses were carried out in the laboratory of the IOPAN according to the regular analysis procedure.

Beach wrack was collected from the same place on the beach where sand "under the wrack" and "fresh" algae from the sea was taken. Beach wrack was sorted based on the dominating species. Each dominating species was packed into two separate plastic bags. Rubber gloves were used in gathering of the material. The samples were stored like the sediment samples.

- Samples for methylmercury (MeHg), one bag with dominate species from each sampling area was stored in -20°C. 400 g of wet sample was needed for the analysis.
- For the rest of the analyses, the procedure was the same for each dominate species as in the case of sediments (freeze dried and homogenised).

2.2.10. Beach litter

Sampling was carried out both in managed and unmanaged sites at least once a month between April and October (in April-March where possible). In the chosen study areas, a 100 m long transect situated along the new and old beach wrack was investigated. All litter items along the transects (transect width=wrack line width) were removed and recorded in the protocol. All the visible litter items (meso and macro litter) were also counted and collected within the remaining sampling unit. The collected litter was disposed into a garbage container or to a dumpsite. Beach litter was categorized based on EU Commission decision 2017/848 in the following categories: artificial polymer materials, rubber, cloth/textile, paper/cardboard, processed/worked wood, metal, glass/ceramics, chemicals, food waste, and “undefined”.

2.2.11. Management activities

Management activities on the managed beaches (where fieldwork was carried out) were recorded according to the questionnaire compiled under the CONTRA project (see also Hoffmann et al., 2021ab). The questionnaire included the following questions:

- Location and name of the beach, total length of the managed beach
- How long is the distance travelled with vehicles in total?
- Do people pay charge to visit the managed beaches?
- During which months is the beach wrack removed?
- Frequency of beach cleaning: weekly, daily, hourly?
- Did the period always remain the same or, was beach wrack sometimes removed in other months too, e.g., after a storm event?
- For the investigated site, was it a small, medium, large, or extreme quantity of beach wrack landing (+ sand) at the time of investigation? E.g., a small, medium, large, extreme of monthly total (in comparison to the previous investigations in 2019)
- Where was the beach wrack collected from?
    - The whole beach
    - A section of beach: 0-5m from water line
    - A section of beach: 5-10m from water line
    - The water
- How is beach wrack usually removed from the beach?
    - Specially designed beach cleaning machine
    - Tractor with pitchfork or bucket
    - Tractor with rake
    - Suction or vacuum pump
    - By hand
    - From water with amphibious vehicle
- Depth of the cleaned sand lane or the rake lengths used (e.g., length of the tines of the pitch forks)
- Participating staff: how many people were involved, what did they do?
- For beach wrack volume estimation: How many trailers were filled up? How large (length and width) were the trailers?
- How many times the vehicles drove back and forth?

- How was the collected sand dealt with? (was the sand separated by sieving? directly at the beach?)
- After collection, was the beach wrack stored? Where? Does the municipality have a dedicated storage facility for beach wrack?
- Typically, what percentage was made up of rubbish? How was manmade rubbish dealt with?
- How was the beach wrack handled after collection?
    - Transported to a municipality waste disposal plant;
    - Moved to another area of beach and left to decompose;
    - Moved to another area of beach as a coastal protection measure;
    - Transported for spreading on agricultural land;
    - Transported to a municipality composting facility;
    - Transported to a bio-energy plant.

Additional information on details and pictures of the participating vehicles and trailers was added when possible.

2.2.12. Sand compaction

Sand compaction investigations were conducted between April to October 2020 in up to three managed beaches per country. For each investigated site, the sediment grain size samples were also gathered and analysed via sieving through a set of sieves with graduated mesh sizes according to DIN EN ISO 17892-4. Samples were collected on the same day as the cleaning and when not possible (management activities was not daily), shortly after (e.g., day after).

A minimum of five samples per beach were collected covering the following locations:

- within a lane (width and height of the lane is needed)
- next to the lane (distance to the lane is needed)
- within a beaten track (width of the lane is needed)
- undisturbed areas (e.g., in front of a dune)

The sediment was manually wetted with Baltic Sea water to keep bulk density core intact. For this, a metal or plastic ring (diameter about 10 cm, height about 10 cm) was placed on the sand and filled with water, allowing it to wet naturally for some minutes. Using the appropriate tools, an undisturbed flat horizontal surface in the sand with a spade at the defined depth (around 10 cm) was prepared. The ring was pushed or gently hammered into the sand. Sand around the ring was excavated and the ring together with sand was sealed and gently removed. After sampling, the wet weight was measured, and the sample was dried to constant weight within the ring as described for biomass sampling.

Bulk density was calculated as follows: soil volume equals ring volume Therefore, the ring volume (in cm^3) was calculated: Volume = 3.14 x r^2 x ring height. The empty ring itself was weighed in grams (W_1). Dry sand together with ring was weighed (W_2) and dry soil weight was calculated accordingly: DW (g)=W_2-W_1.

Based on the gained values, bulk density (g/cm^3) was calculated: Density = dry soil weight (g) / soil volume (cm^3). Bulk density is usually expressed in megagrams per cubic metre (Mg/m^3) but the numerically equivalent units of g/cm^3 and t/m^3 are also used (1 Mg/m^3 = 1 g/cm^3 = 1 t/m^3) (Cresswell and Hamilton, 2002).

2.2.13. Noise nuisance

Noise nuisance was studied between April and October 2020 at least at one managed beach per country. Noise levels were determined using mobile phones with mobile applications. Ambient noise level was recorded, and five different measuring points based on distances to the cleaning vehicle/noise were chosen: 4 m, middle, end of the beach, in the dunes. Up to 10 measurements of sound pressure level in decibels (dB) were taken at each point.

2.2.14. Scare effect

Scare effect was studied between April and October 2020 at managed, and when possible, also at an adjacent unmanaged beach section. The activity of all bird species and all other scared animals were counted before, during, and after the management. Escape distance in meters, returning period and species were estimated based on visual observations. Furthermore, differences between people and machine scaring effects were determined when possible.

3. Natural cycle of beach wrack

Sandy shores consist of three units: surf zones, beaches, and dunes. This geomorphic system is also known as a littoral active zone. Beaches and dunes act together as a protective buffer against storms and sea level rise. The most characteristic feature of sandy shores is sand and its movement – wave and wind-induced sand movement can be up to 20 m (from the shoreline up to the landward edge of the active dunes). Two ecologically distinct systems are found in sandy shores: (1) marine beach/surf zone ecosystem that is inhabited by marine biota, which is strongly affected by wave energy, and (2) terrestrial dune system that is inhabited by terrestrial plants and animals, which is strongly influenced by wind action. These systems mutually influence each other. Besides sand movement, beach wrack is another viable part which links these systems.

In this chapter we provide a short introduction to various ecological aspects related to sandy beach ecosystems, including beach wrack amounts, beach wrack associated species composition, seasonality, residence time, decomposition, aeolian dispersal, nutrients, hazardous substances, and litter - based on research carried out in 2019-2020 in different beaches around the Baltic Sea.

3.1. Amount of beach wrack

The amount of beach wrack is the central question regarding beach management and building a business model based on beach wrack use. However, the information on beach wrack quantities is generally lacking. As it has been suggested e.g., by Blue Flag program (www.blueflag.global): "Algal vegetation or natural debris must be left on the beach. … Natural disposal by tides and waves at the beach is accepted, as long as it does not create a nuisance". The accepted level of beach wrack on the public beaches is highly dependent on the general knowledge of beach ecosystems functioning. The project CONTRA reports (Hoffmann et al., 2021ab) provide a more detailed overview of the public acceptance and tolerance regarding the amount of beach wrack on the beaches both in touristic high- and low seasons.

Information regarding beach wrack landings across the Baltic Sea both on a local and a large scale is scarce. However, research carried out under the CONTRA has given important baseline information for different areas and forms a solid base for further investigations. Based on primary predictive models of beach wrack accumulation areas during the late autumn period across the Baltic Sea region, some hot-spot areas (production up to 4,000 g per m^2 per month) were noted in Kattegat area, west and east coast of Sweden, southern coast of Finland, west coast of Estonia and Gdansk Bay (Figure 3.1.1, Kotta et al., 2020). Production hotspots were sporadically found also on the east coast of Finland, reaching up to 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 0-1,000 g per m^2 per month) (Kotta et al., 2020).

Beach wrack landings are highly seasonal – our observations under the CONTRA confirmed that the largest amounts of beach wrack commonly reached the beaches with autumn storms at the end of vegetative season. However, when interpreting the results, it must be considered that the end of 2019 and the winter of 2020 were extremely warm and stormy, and no ice nor snow-cover formed in that period. Secondary periods of higher beach wrack landings were noted around May-June and in August (see also 2.2.4 Residence time).

Depending mostly on the nearby dominating benthic habitats, exposure to currents, winds and waves, the amount of beach wrack varied greatly between the studied beaches during the project CONTRA. For instance, at the beach of Poel in Germany that has a northern to north-westerly exposure to the open Baltic Sea, the amount of old beach wrack randomly exceeded the amount of new beach wrack. Within the new beach wrack there were large variations, and not only in terms of seasonality. A large influence pertains to the currents which are mainly driven by wind, e.g., several peaks in beach wrack volumes were observed during summer 2019 (Figure 3.1.2, 3.1.3) Figure 3.1.4 illustrates the sudden changes in the coastal morphology as well as the variable sea water levels at the beach of Poel. During the periods of low water levels and smaller waves, the amount of landed wrack was usually lower than in times with higher water levels and waves. Especially on unmanaged beaches, the amount of old wrack usually exceeded the amount of new wrack. On unmanaged beaches the old wrack accumulates within the area of the foredunes, and due to the protected area, it is often not removed over several weeks. The new wrack is influenced more by wind and wave action: after seasonal or sudden storm events correlating with a higher water level and exposure to waves, the new wrack might have residence times from few hours to up to several days or even weeks. Further information about beach wrack residence times will be given in the next chapter 3.3. "Movement on the beach".

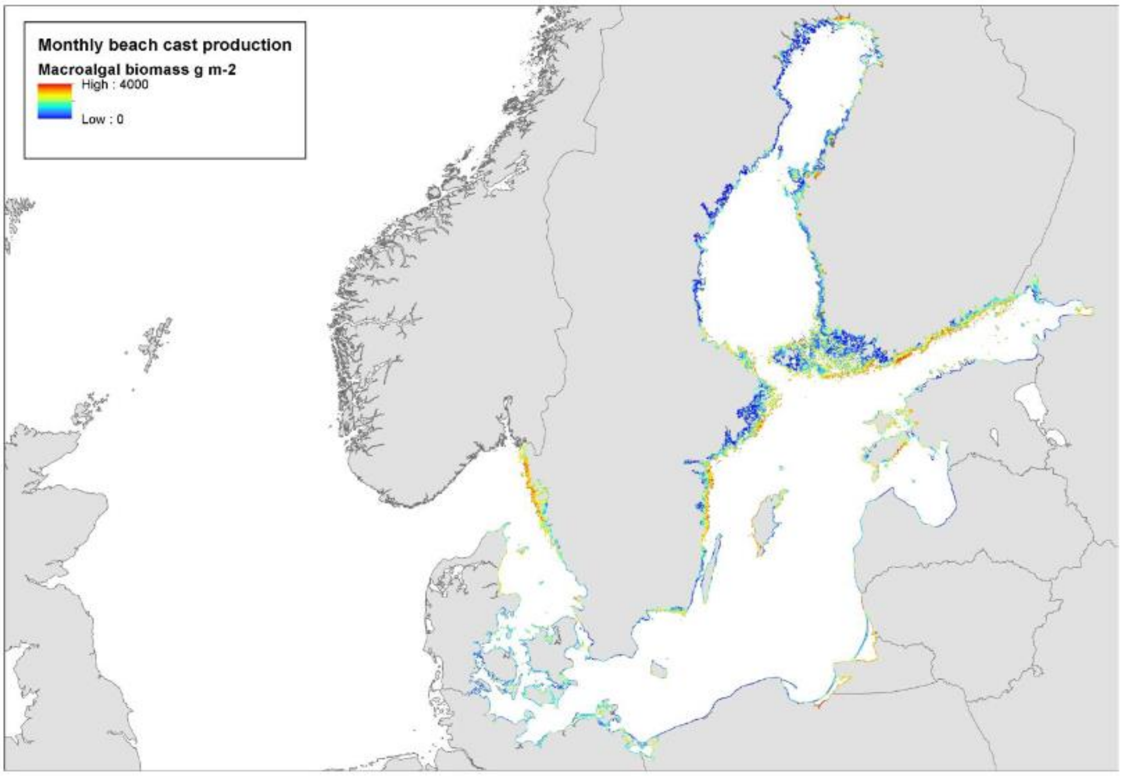


Figure 3.1.1. Monthly beach-cast production potential across the Baltic Sea in late autumn (redrawn from Kotta et al., 2020).

In our study the largest amounts were noted on the beaches of Poland and Denmark, where the beach wrack amount per 100 m long beach section was estimated as high as 203 m³ (Rzuzewo, Poland, unmanaged beach), 140 m³ (Køge, Denmark, unmanaged), 124 m³ (Nyborg, Denmark, unmanaged) and 87 m³ (Køge, Denmark, managed) (Figure 3.1.2, 3.1.3). In other areas the respective landings were usually less than 30 m³ of beach wrack per 100 m long beach section. On some beaches beach wrack amounts were negligible year-round, e.g., on Puck beach (Poland, managed) and on unmanaged section of Kühlungsborn West (Germany) where the amounts stayed mainly below 1 m³ (Figure 3.1.2, 3.1.3).

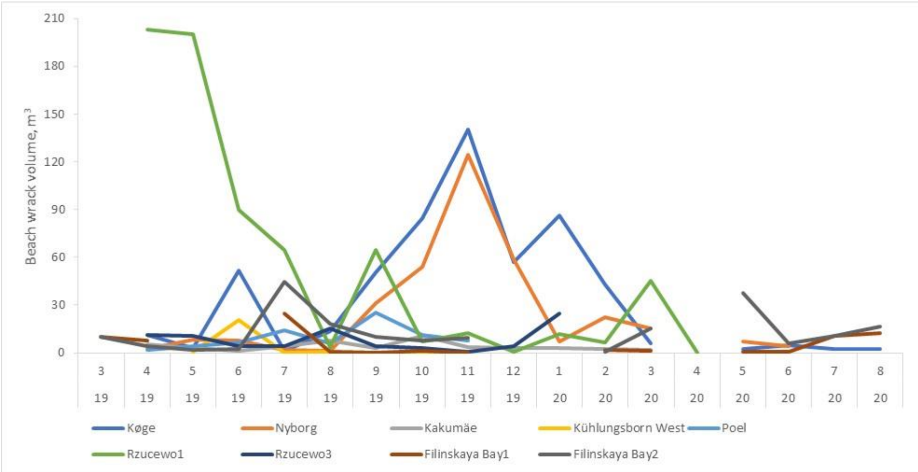


Figure 3.1.2. Temporal variations in beach wrack amounts (volume, m³) on the studied managed beaches from April 2019 to August 2020. The amounts are presented per 100 m long beach section.

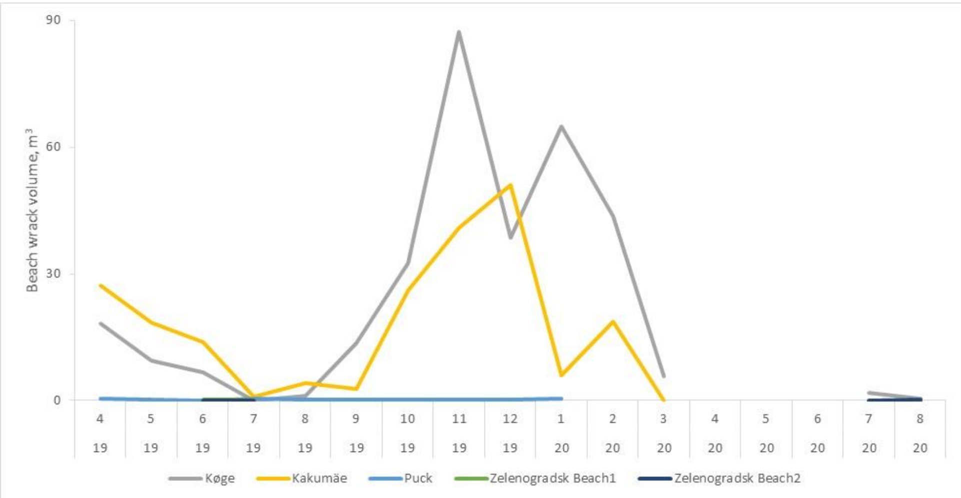


Figure 3.1.3. Temporal variations in beach wrack amounts (volume, m³) on the studied unmanaged beaches from April 2019 to August 2020. The amounts are presented per 100m long beach section.

Regarding the management status of the beaches during the touristic season from April to October, beach wrack quantities varied greatly. At the Island of Poel and on the beach of Kühlungsborn West (both Germany), no beach wrack was found during the study period. One of the probable reasons was that the activities under the CONTRA study were performed in early morning around 7-8 a.m., but the municipal waste disposal of beach wrack (e.g., at Poel) was done already at around 5 a.m. The management was carried out daily during the touristic high season. The collected beach wrack was removed with heavy cleaning machines and sometimes roughly cleaned from sand within the shallow water (chapter 4: Effect of management on sandy beaches).

Therefore, by the time of sampling for CONTRA the beaches have been already cleaned up of beach wrack. This is the reason why there are no data for managed beaches in Germany. In general, these kinds of problems are needed to be considered when managed beaches are sampled. Figure 3.1.2 shows that the management activities were carried out irregularly and according to needs in Køge (Denmark) and on Kakumäe beach (Estonia).

On most beaches, and especially on unmanaged ones, the amount of new wrack exceeds the old wrack amounts. The exceptions were the beaches of Rzucewo (Poland, unmanaged), Køge (Denmark, managed) and Kakumäe (Estonia, both managed and unmanaged). It is noticeable that on the Danish beaches beach wrack volumes were higher than in the other countries. On Danish beaches, the old wrack consisted mainly of eelgrass, faunal parts, and land plants, some of them of unidentifiably origin (Figure 3.1.4, chapter 3.2. Species composition). In the bay area of Køge, the growth conditions for eelgrass are favoured by the shallow and sheltered waters, where the eelgrass is not exposed to physical damage or rip-off by waves and currents as it occurs in more exposed areas (e.g. the beach of Poel in Germany).

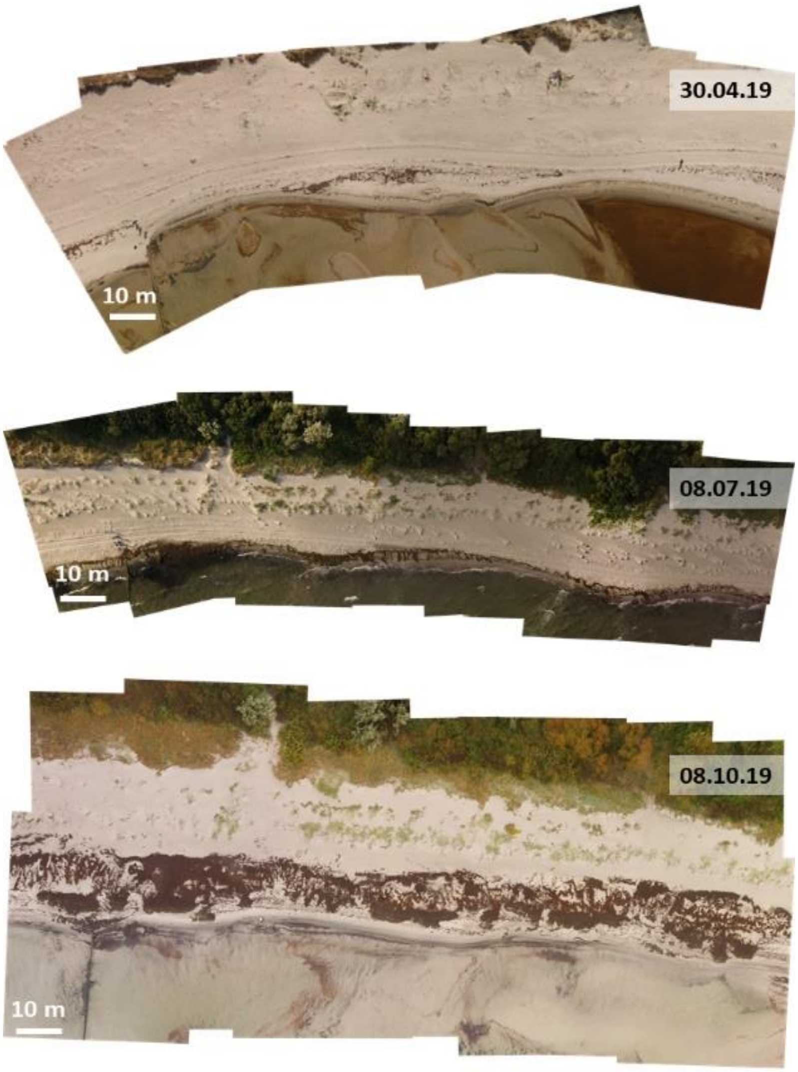


Figure 3.1.4. Beach wrack amounts on the studied unmanaged beach of Poel. The second photograph was taken after a storm event during in July. All the photographs present a 100 m long beach section. Imaging was done using a DJI drone flying at an altitude of 30-40 m (Ch. Porsche and P.-K. Schätzle)

Beach wrack amount on Kakumäe beach (Estonia) was consistent throughout the year. On the unmanaged beach the differences between season and off-season were random and beach wrack load was consistently high. The amounts were also high year-round at the managed beach, except during the period from July to September. In the sheltered beaches of Kakumäe the amounts of old beach wrack were generally higher than the amounts of new wrack. The high volumes (around 40 m^3 of beach wrack per 100 m long beach section) of new wrack were observed in some cases (see also chapter 3.3 Residence time).

Precise estimation of beach wrack abundance using drone imaging technology was tested on the beaches of Poland and Germany (Figure 3.1.4). However, because a remarkable amount of beach wrack can be buried under sand, the effectiveness of using such drones in estimating the amount of beach wrack was not sufficient. Therefore, the use of drone images for coverage estimations was used as supportive information within the CONTRA.

Table 3.1.1 gives an overview of abundance of beach wrack on all examined beaches with their respective management statuses. The management activities were carried out on daily or weekly basis. The exception was Kakumäe beach (Estonia), where the management activities were carried out in June-July 2019 and the management frequency was lower compared to other regions. Thus, on Kakumäe beach the managed beach had a higher coverage of beach wrack than on the unmanaged sections. Also, the managed beach of Køge (Denmark) had a similar volume of beach wrack although being managed. According to our observations, the coverages and amounts of beach wrack did not necessarily had cross dependencies (Figures 3.1.5, 3.1.6). Sometimes it was also hard to estimate the coverages and amounts as the beach wrack was partly buried underneath the sand and in that case the estimations depended on the fieldworkers opinion.

Table 3.1.1. Average beach wrack volume (BW vol), average dry weight of new wrack (NW dw), old wrack (OW dw) and combined total wrack dry weight (TW), and average coverage on the beach. M - managed beaches, UM - unmanaged.

Land	**Beach**	**Manage-ment**	**BW vol [m^3]**	**NW dw [kg/m^2]**	**OW dw [kg/m^2]**	**TW dw [kg/m^2]**	**Coverage [%]**
Denmark	Køge	M	24.30	0.68	1.90	1.65	38.93
	Køge	UM	35.01	1.37	0.90	2.28	62.00
	Nyborg	UM	24.66	1.41	1.10	2.35	52.62
Estonia	Kakumäe	M	17.50	3.62	7.04	9.19	22.25
	Kakumäe	UM	4.04	3.44	5.14	8.30	16.33
Germany	Poel	UM	8.41	1.13	0.75	1.88	8.47
	KüBo_W	UM	1.83	0.61	0.73	0.78	1.49
Poland	Puck	M	0.26	0.09	0.10	0.10	0.94
	Ruzcewo1	UM	46.27	0.44	7.82	8.02	35.25
	Ruzcewo3	UM	7.64	14.67	15.77	23.67	51.00
Russia	Filinskaya1	UM	4.21	2.14	1.50	2.28	1.63
	Filinskaya2	UM	11.36	6.06	2.21	6.84	4.36
	Zelenogradsk1	M	0.17	1.83	0.50	1.67	0.24
	Zelenogradsk2	M	0.06	0.22	0.00	0.22	0.31

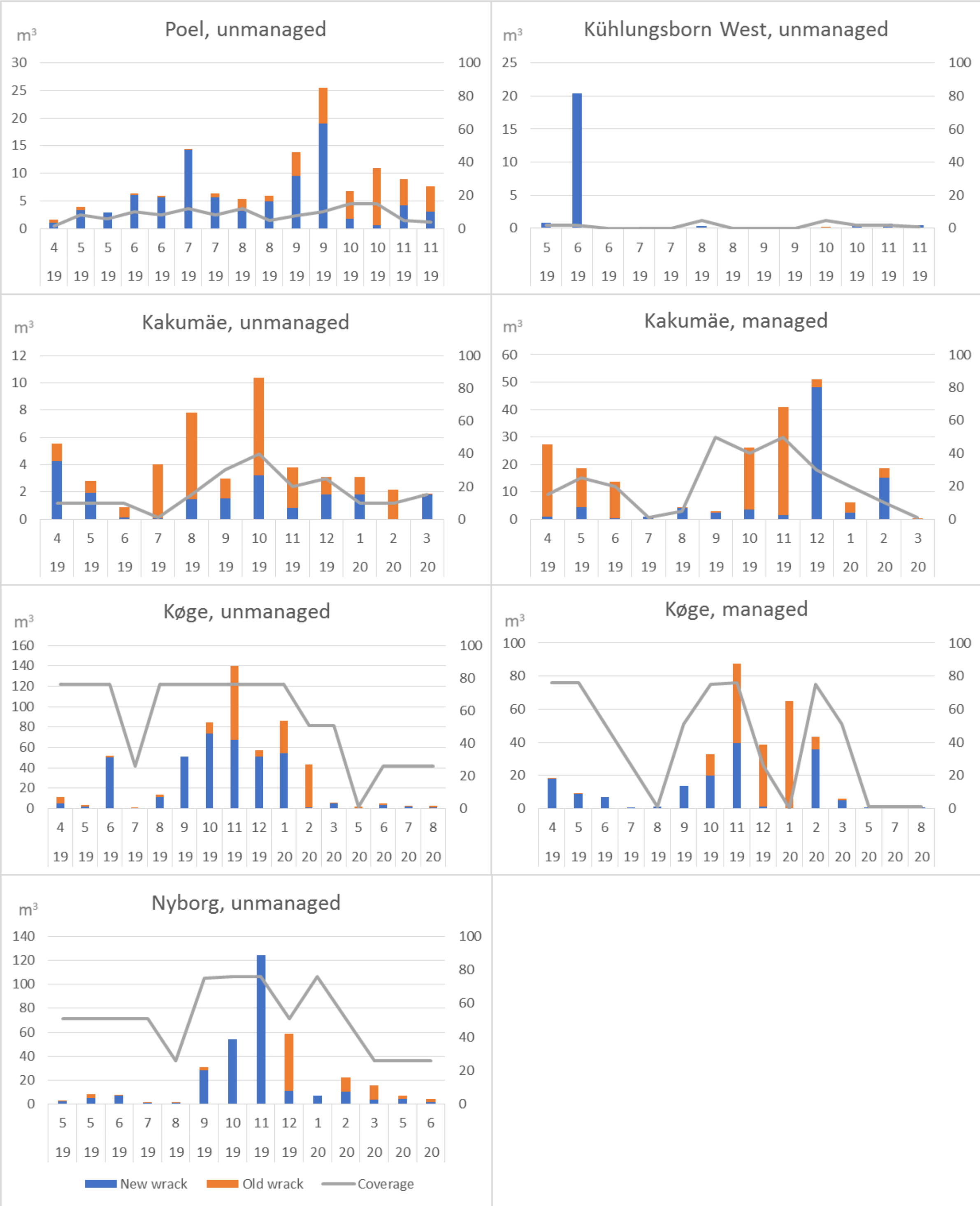


Figure 3.1.5. New and old beach wrack volume (m³) and coverage (%, line) on the studied beaches in Germany (Poel, Kühlungsborn West), Estonia (Kakumäe) and Denmark (Køge, Nyborg) between April 2019 and August 2020.

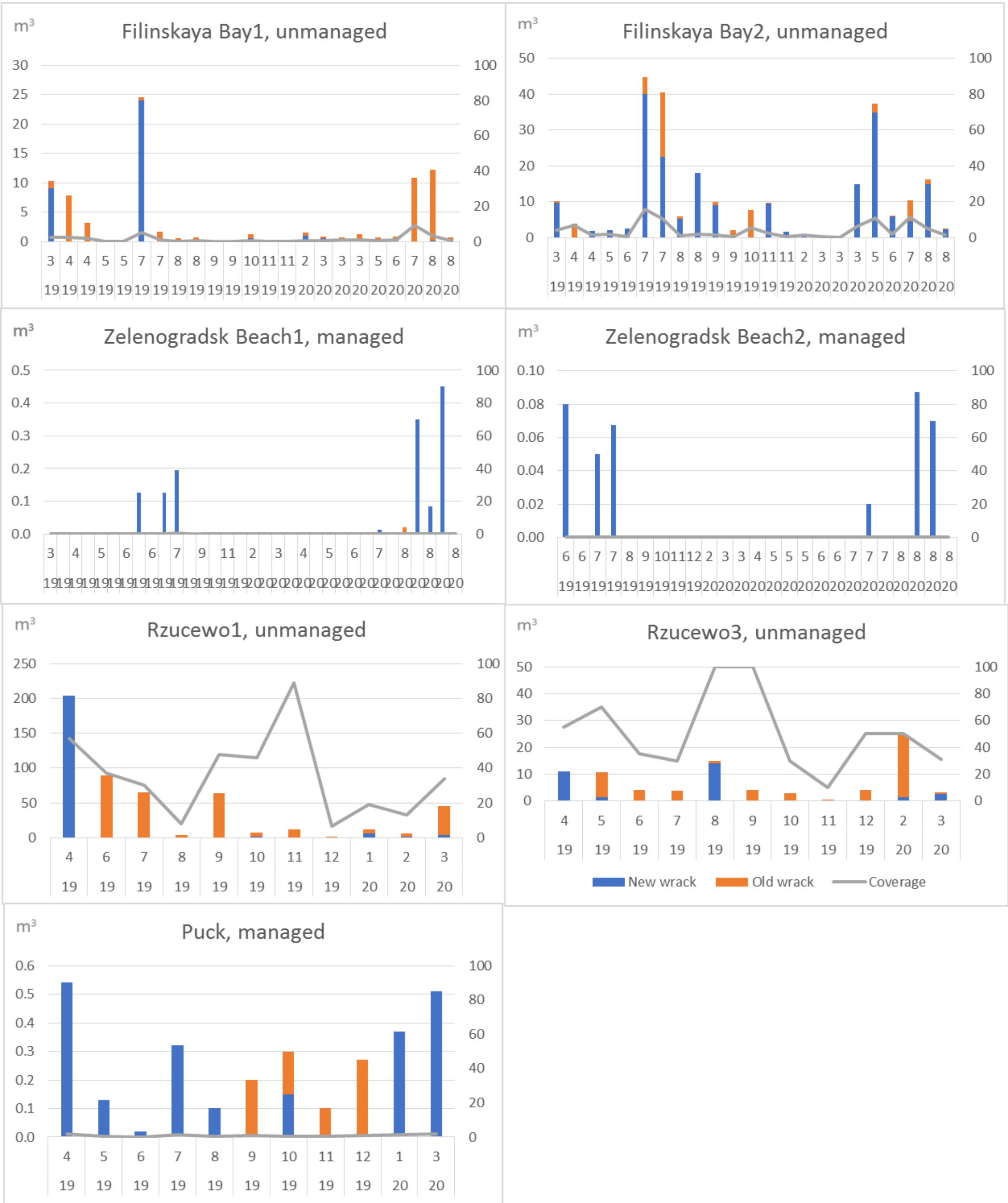


Figure 3.1.5. New and old beach wrack volume (m³) and coverage (%, line) on studied beaches in Russia (Kaliningrad Oblast - Zelenogradsk, Filinskaya) and Poland (Rzucewo, Puck) between March 2019 and August 2020.

3.2. Species composition

The Baltic Sea offers a habitat for about 530 macrophytes and algal species, 1,900 invertebrate species, 240 fish species and 5 mammal species (HELCOM 2012). However, the biodiversity of beach wrack composition on each beach is most dependent on nearby prevailing marine benthic habitat types and dominating algae and macrophytes species (e.g., Torn et al., 2016). With greater storms and intensified water activity the material can be carried to the beaches also from a further distance, but this is rare. In general terms, compliance between the samples of beach wrack and submerged vegetation is hydrodynamically possible if the alongshore currents are weak and the material on the beach originates from the adjacent sea areas. The higher wave events have been proven to have a significant effect on the thickness and the amount of beach wrack, no significant influence on the species number was noted (Suursaar et al., 2014).

Coastal structure and morphology do influence the species composition of beach wrack. In the vicinity of rocky areas, a higher proportion of macroalgae is detached from rocks during storms and therefore resulting their dominance in an algal beach wrack. On sandy shores the seagrass and other higher plants prevail in beach wrack. Structure of wrack also depends on different buoyancy of the species caused by their diverse morphology.

Species composition showed a great variability through the participating countries (Figures 3.2.1-.3.2.6). The differences in the species composition slightly varied between new and old wrack. One of the differences was significant decrease in the abundance of species belonging to phylum Chlorophyceae. Specimens belonging to this taxon in the Baltic Sea region are annual filamentous algae which degrade quickly. Due to degradation, especially within the old wrack, there can be a confusion between green and brown algae, land plants and other material being integrated into the beach wrack.

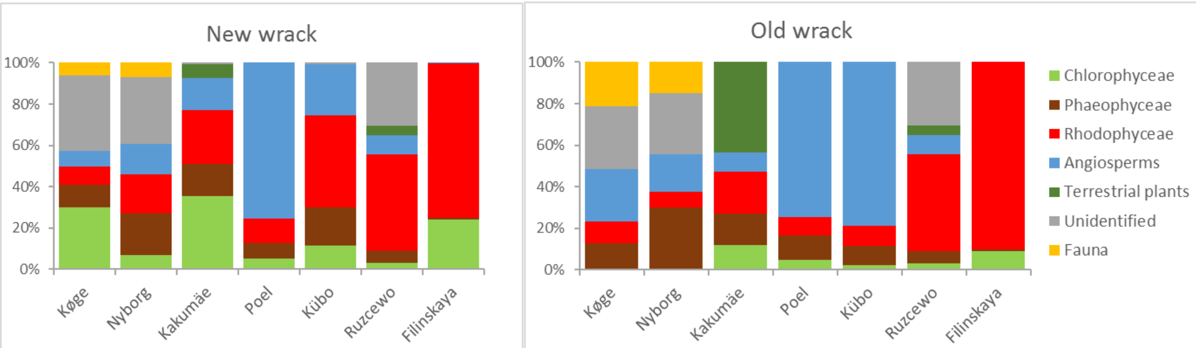


Figure 3.2.1. Species composition in beach wrack during the CONTRA from April 2019 to August 2020.

In Germany, the angiosperms (mainly *Zostera marina*) are the dominant species in beach wrack. Eelgrass *Zostera marina* is also common in beach wrack in Denmark. This reflects the natural habitat of *Z. marina*: both countries are in the western Baltic Sea, where the sea water salinity is higher than in the other countries in the eastern Baltic Sea. Also, soft-bottom benthic habitats are dominating. *Z. marina* needs clear and shallow waters, with a sandy substrate for their rooting. In a way, this species acts as an ecological engineer (Wright and Jones, 2006, Boström et al., 2014; Schubert et al., 2015).

In Poland, Estonia, and Russia, Rhodophyceae had a greater proportion in beach wrack composition. Phaeophycean were evenly distributed within the wrack of the investigated beaches. Angiosperms were randomly found on these surveyed beaches of Poland, Estonia, and Russia, but this depended on nearby benthic habitats. Also, in Estonia there are some regions where eelgrass is the dominant species in beach wrack. At the beach of Poel, Germany, the main beach wrack species was *Z. marina*. Further on, at Kühlungsborn West, where the beach is sandy with some rocky parts, beach wrack consisted of different macroalgal species. Seagrass was only randomly found. However, the angiosperms may occur within the old wrack of Kühlungsborn during summertime. After heavy storms, the seagrass amount was higher in Kühlungsborn West, indicating the possible distant origin of seagrass (e.g., Poel, distance approximately 25 km). With the Salzhaff on its way, the currents, and winds favour long-distance transportation of the seagrass. Import to Kühlungsborn West might come from any area if the currents are favouring (Gosselck and Schabelon, 2007).

In sheltered bays, such as Kakumäe, Estonia, the wrack composition was highly heterogeneous. On Kakumäe beach in total 131 taxa were described within the beach wrack during the one-year period, including 74 faunal and 57 floral species. In terms of origin, land-based fauna and sea-based flora dominated in the beach wrack (40 and 39 taxa, respectively). In total 34 marine-origin faunal species were recorded. Among others, remains of 18 terrestrial floral species were recorded. In addition to the natural part, beach wrack can also contain artificial items such as litter. Dominant species in the Kakumäe beach wrack were *Fucus vesiculosus, Furcellaria lumbricalis, Zostera marina, Phragmites australis, Ceramium tenuicorne, Vertebrata fucoides* and *Cladophora glomerata* reflecting the heterogeneity of nearby benthic habitats. For e.g., Puck Bay (Poland), the dominant species 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 were located close to overgrown dunes). On the exposed beaches of Kaliningrad Oblast in total 14 taxa of macroalgae and seagrasses were registered from beach wrack. Excluding the sand (which was on average 39% of wet weight of beach wrack samples), the biomass of macroalgae was on average 95%.

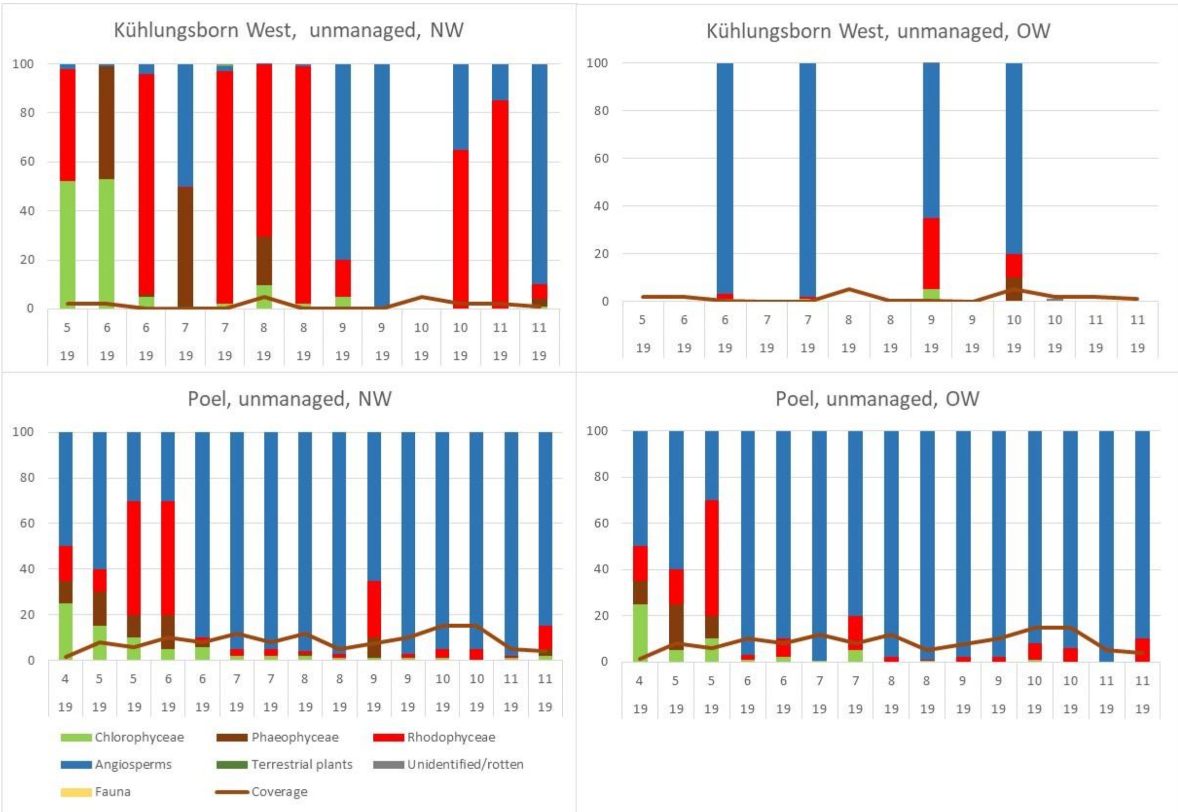


Figure 3.2.2. Species proportion (%) on "Am schwarzen Busch" (Island of Poel) and "Kühlungsborn West" (Germany) during the period from April to November 2019. Line indicates total beach wrack coverage (%). NW – new wrack, OW – old wrack. Missing values represent times without wrack accumulation.

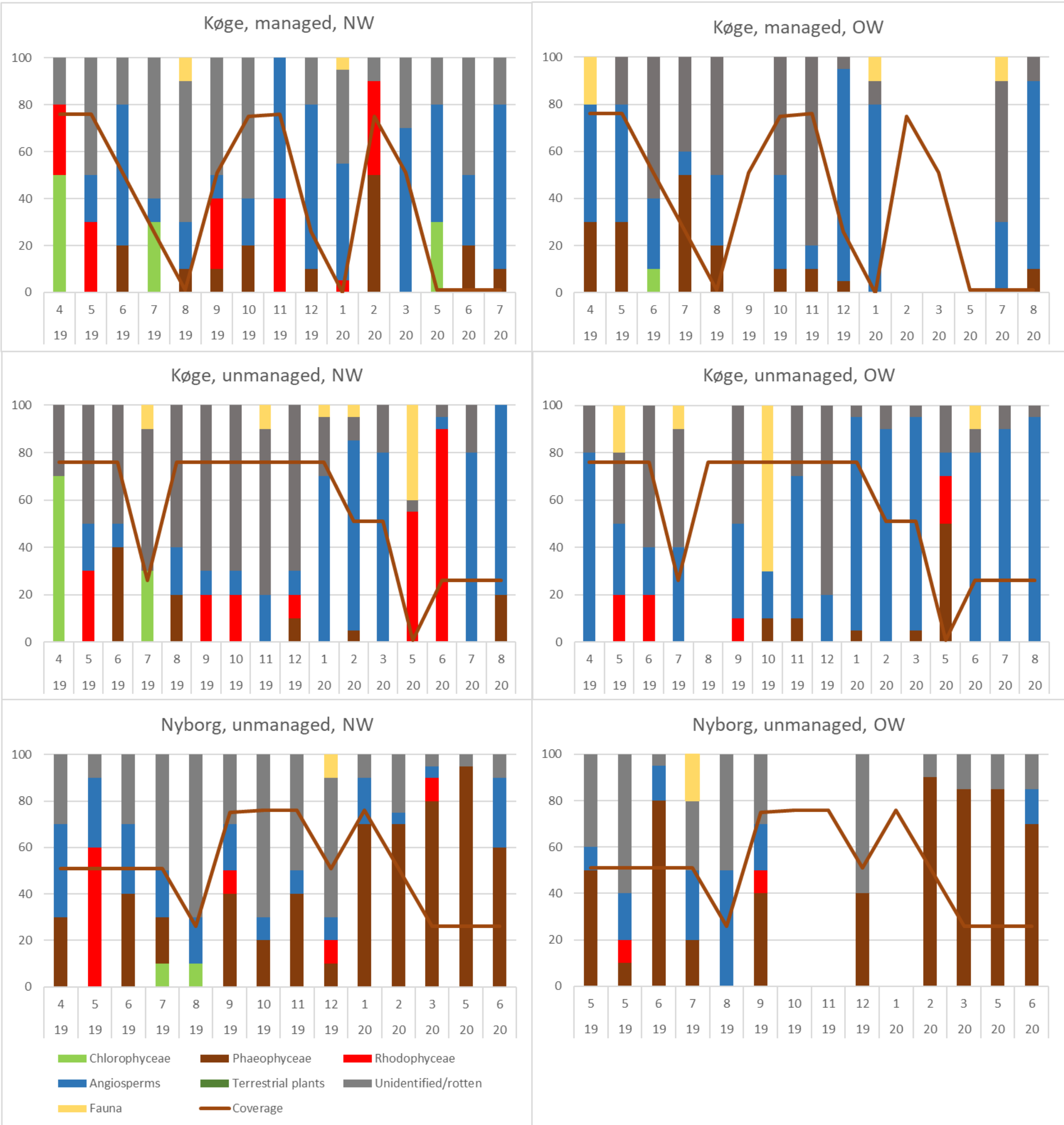


Figure 3.2.3. Species proportion (%) variations in Denmark beaches, the Køge and Nyborg, between April 2019 and August 2020. Line indicates total beach wrack coverage (%). NW – new wrack, OW – old wrack. Missing values represent times without wrack accumulation.

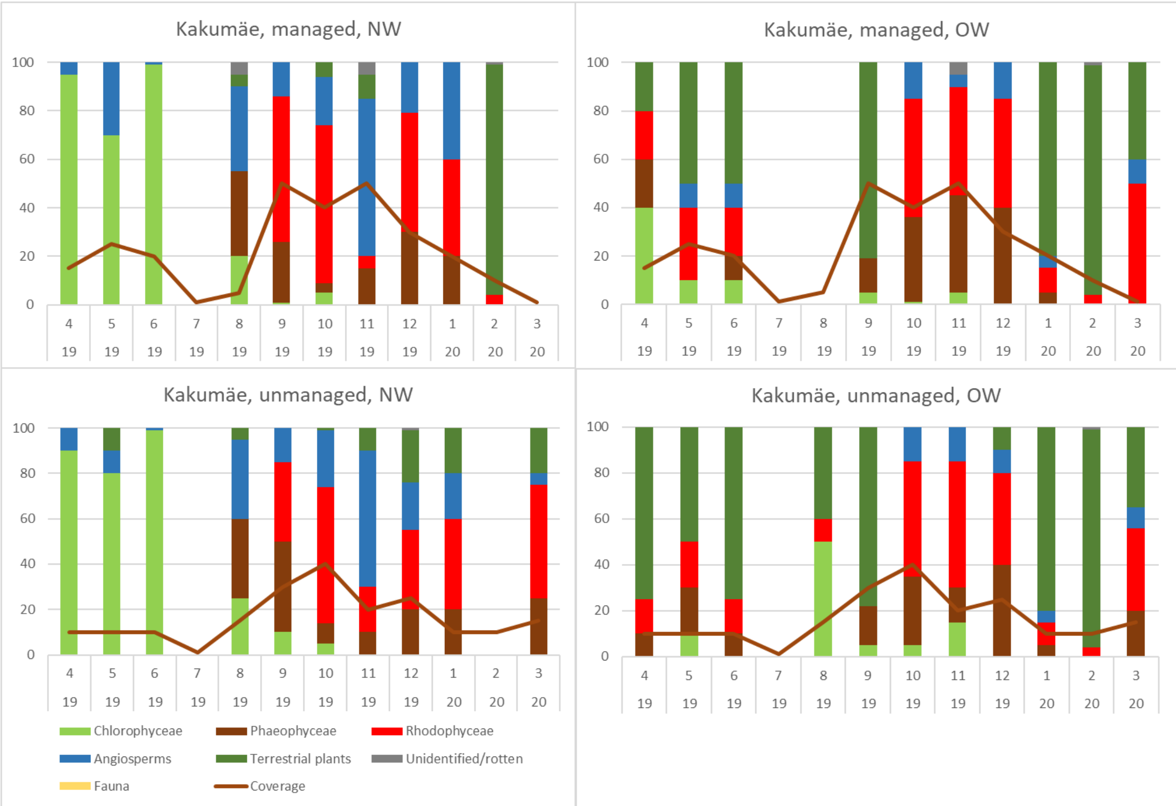


Figure 3.2.4. Species proportion (%) variations on Kakumäe beach sections in Estonia in period from April 2019 to March 2020. Line indicates total beach wrack coverage (%). NW – new wrack, OW – old wrack. Missing values represent times without wrack accumulation.

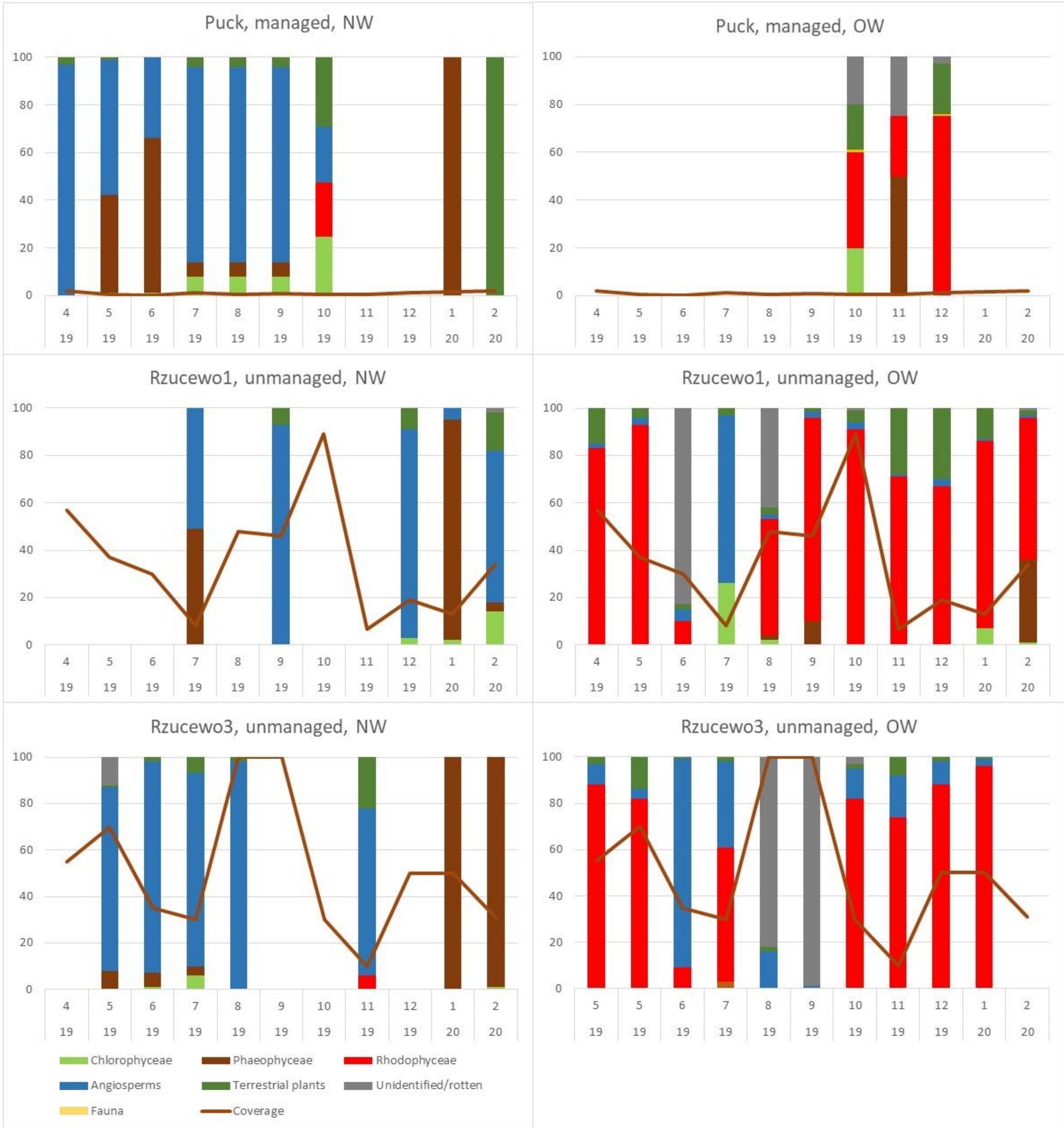


Figure 3.2.5. Species proportion (%) variations on Polish beaches, Puck and Rzucewo, over the period from April 2019 to February 2020. Missing values represent times without wrack accumulation.

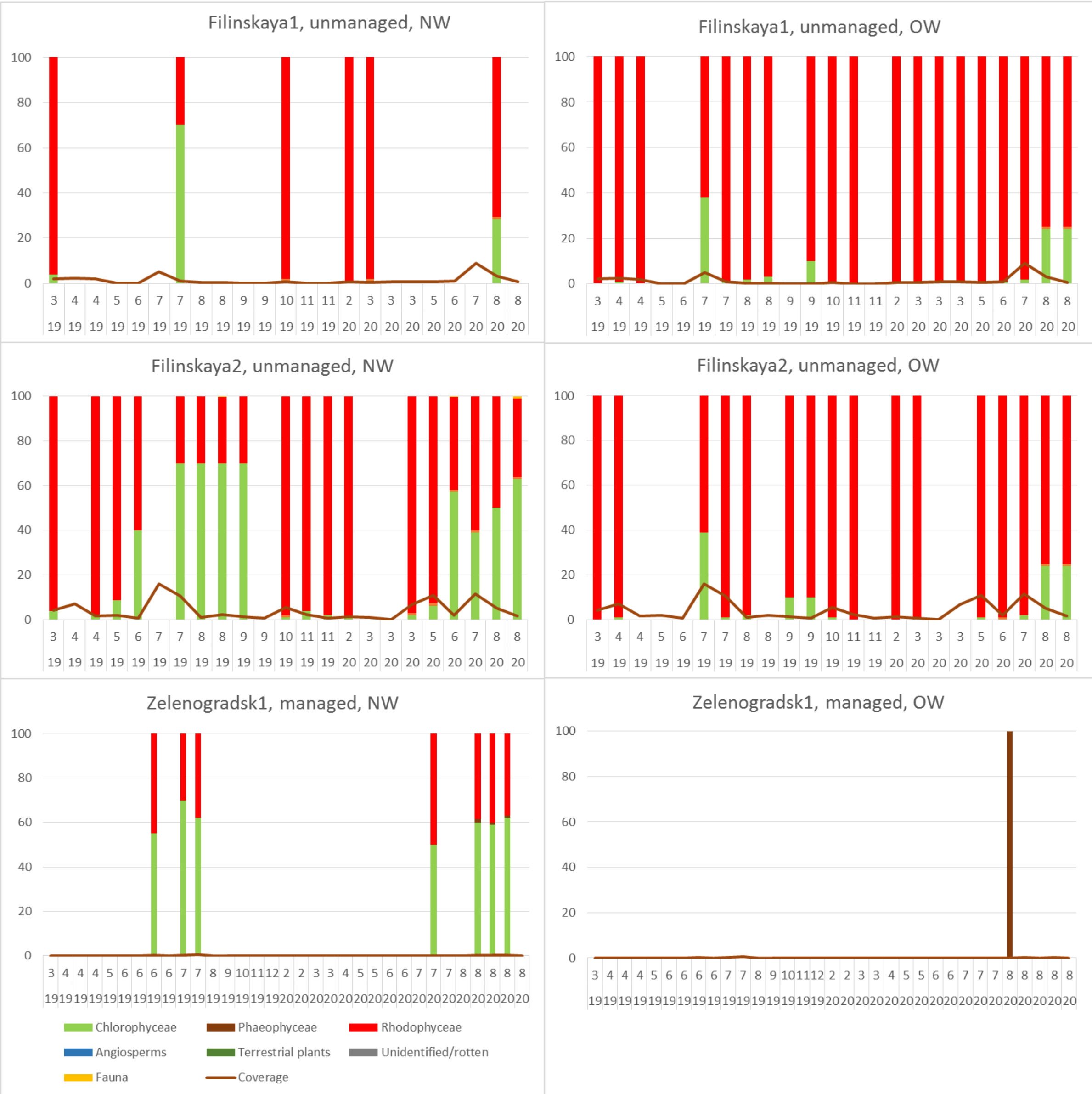


Figure 3.2.6. Species proportion (%) variations on Russian beaches (Kaliningrad Oblast), Filinskaya and Zelenogradsk, during the period from March 2019 to August 2020. Missing values represent times without wrack accumulation.

Beach wrack fauna

More detailed beach wrack analysis was conducted in the beaches of Russia, Estonia, and Poland. In Poland, beach wrack meiofauna was studied more thoroughly and in Estonia the terrestrial invertebrates related to beach wrack were investigated.

Russia (Kaliningrad)

Beach wrack with *Furcellaria lumbricalis* often contained epiphytic organisms (*Mytilus edulis*, *Amphibalanus improvisus*, Bryozoa). The biomass of *Mytilus edulis* was comparable to that of algae. Old beach wrack sometimes contained many larvae and imago of Diptera in summer, but their biomass was not significant.

Poland

The marine macrofaunal composition was studied in more detail at two beaches of Poland: Puck beach represents the managed and Rzucewo represents the unmanaged beach. A comparison of macrofauna from managed and unmanaged beached is presented in section 4.2.1. 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 (due to their belonging to the meiofauna, they were not taken into consideration in the further analysis of macrozoobenthos). 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 a 1 mm mesh but will be retained by a 32 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 favourable 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.

Estonia

Representatives of two phylum Mollusca and Arthropoda were found in the collected beach wrack 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. The only crustacean terrestrial *Oniscus asellus* (common woodlouse, class Malacostraca, order Isopoda), occurred in a wide range of habitats, mainly under stones and on rotting wood. But they can also live within beach wrack.

Among the arachnids, some species on spiders (*Walckenaeria vigilax*, *Oedothorax apicatus*, *Erigone longipalpis*) and mites (not assigned to species) occurred. Spiders *Walckenaeria vigilax* and especially *Erigone longipalpis* are typical to this habitat. It can be assumed that all the species of mites are more widespread than in the limited seashore area, but among them also some habitat-specific species may occur.

Springtails (Cl. Entognatha, Subcl. Collembola) were numerous, but not assigned to the species. These are omnivorous, free-living organisms that prefer moist conditions. They do not directly engage in the decomposition of organic matter but contribute to it indirectly through the fragmentation of organic matter and the control of soil microbial communities. These species are very characteristic in such habitats.

Representatives of the following orders of insects were found in the samples: Heteroptera (Hemiptera, Homoptera), Psocoptera, Neuroptera, Colepotera, Diptera (Brachycera, Nematocera), and Hymenoptera (parasitoids). Typical species among the bugs were *Saldula pallipes* (a species of shore bug in the family Saldidae) and some species from genus Sigara – a genus of water boatmen in the family Corixidae of which most live in fresh water, but some species within this genus are halophiles. Not typical species, probably accidentally on beach, was

Acanthosoma haemorrhoidale (Hawthorn shield bug, usually living on plants).

Among Coleoptera, typical species of this biotope are from genus Agonum sp., mid-sized to smallish wet-loving beetles throughout their life cycle; genus Cercyon with species *C. sylvestris*, *C. haemorrhoidalis*, *C. marinus*, *C. littoralis* (belongs to water scavenger beetles Hydrophilidae, prefer predominantly terrestrial habits but frequently associated with decaying plant and animal matter); *Laccobius minutus* (belonging to water scavenger beetles, Hydrophilidae); *Oxyomus sylvestris* (a species of aphodiinae dung beetle, family Scarabaeidae). Adults occur in all types of decaying organic matter. Most of rove beetles (family Staphylinidae) are predators of insects and other invertebrates, living in forest leaf litter and other decaying plant matter. They are also commonly found under stones and around freshwater margins. Almost 400 species are known to live on ocean shores that are submerged at a high tide. Rove beetles are known from every type of habitat in which beetles occur, and their diets include just about everything except the living tissues of higher plants. All the other beetle species found have accidentally entered this habitat. These are 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*.

Among Diptera many larval stages of the gnatmidge (Nematocera) and fly (Brachycera) species were found. Chironomidae can be found in almost any aquatic or semiaquatic habitat, many species in the genus are marine. They are found in the intertidal zone of seashores. Representatives of other Nematocera family Dixidae or meniscus midges are also aquatic but not typical to this biotope. The larvae live in unpolluted, standing fresh waters, just beneath the surface film, usually amongst marginal aquatic vegetation. Hymenoptera species may be typical parasitoids for insect species living in this biotope. The other encountered species appear as occasional guests. These were: Psocoptera, Aphidodea, Homoptera and Neuroptera (*Chrysoperla carnea*, *Hemerobius lutenscens*).

3.3. Movement on the beach

3.3.1. Shoreline residence

Variability in wrack supply on sandy beaches can be explained through interactions between wave exposure, coastal topography and seasonality (Barreiro et al., 2011, Suursaar et al., 2014).Beach wrack transformation on the beach could happen for several reasons: stay on the beach for a long time, flushing back to the sea, covering under the thickness of sand or small pebbles (potentially followed by flushing to the sea), the wind-wave dispersal along and inland the beach (Figure 3.3.1). The residence time of wrack on the beach is an important factor for the terrestrial ecosystems functioning, recreation resource characteristics and management options.

Beach wrack residence time was investigated during the CONTRA Project by studies at respective sites in Germany, Estonia, and Russia (Table 3.3.1, 3.3.2). For this purpose, photographs were regularly taken at the selected sites (by a photographer or a web camera). The images made it possible to assess the presence or absence of beach wrack at the time, the degree of its coverage, and thereby the residence time.

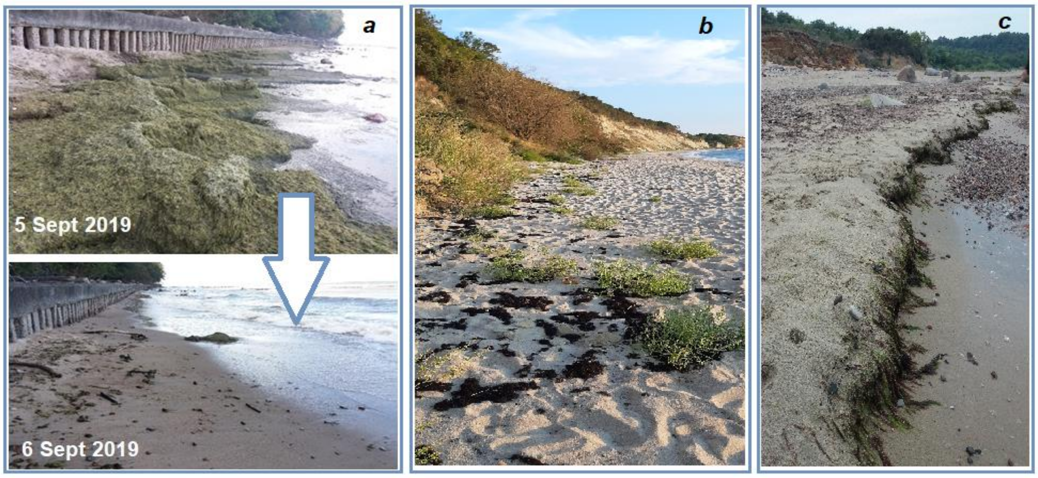


Figure 3.3.1. Beach wrack can undergo different transformation ways: flushing back to the sea (a), disperse inland by wind and waves (b), buried under the sand (c) (J. Gorbunova).
Table 3.3.1. Beach wrack photo-monitoring parameters of the beaches of Germany, Estonia and Russia.

Table 3.3.2. The results of beach wrack photo-monitoring on the beaches of Germany, Estonia and Russia.

Country	Site	Observed beach width	Coordinates		Observation period		Observation frequency	Way of the observation	The total number of images
		m	N	E	Start	End			
GE	Vilm Island (North)	0-5.8	54°19'05"	13°31'53"	25.09.2020	13.01.2021	2-6 times/month	Photographer	13
EST	Kakumäe beach (Managed)	5-60	59°26'59"	24°34'31"	15.04.2019	16.03.2020	1-14 times/month	Photographer	72
EST	Kakumäe beach (Unmanaged)	5-55	59°27'05"	24°34'34"	15.04.2019	16.03.2020	1-14 times/month	Photographer	71
RU	Otradnoye beach (Western part)	0-18	54°56'39"	20°07'17"	01.11.2019	21.02.2021	3-6 times/day	Webcam	1761

Country	Site	Days when BW was observed on the beach	Estimated BW coverage			Residence time of BW on the beach		
			1-9%	10-49%	50% and more	Min	Max	Average
		% of all observed days	% days of BW observed			days	days	days
GE	Vilm Island (North)	92	50	33	17			
EST	Kakumäe beach (Managed)	90	7	90	3	*BW was on the beach all the time period of observations until it was removed during cleaning (6, 86&214 days)*		
EST	Kakumäe beach (Unmanaged)	100	3	97	0	*BW was on the beach all the time period of observations (336 days)*		
RU	Otradnoye beach (Western part)	50	49	41	10	1	25	6

Vilm Island, North (Germany)

The studies were carried out from 25.09.2020 to 13.01.2021 in the northern part of Vilm Island (Photo 3.3.1). Photographs were taken 2-6 times a month (Table 3.3.2). Beach wrack coverage in the studied period at Vilm Island is shown in Figure 3.3.2. Beach wrack was found in 92% of the observed days. Among these days, beach wrack coverage was low (1-9% coverage of the beach area) in 50% of time, medium coverage (10-49% of the beach area) occurrence was 33%; and significant coverage (50% and more of the beach area) occurred in 17% of the days. The complete absence of wrack was observed under the conditions of beach flooding due to the extreme high water level on 14.10.2020.

Photo 3.3.1. Vilm Island, North (Germany, P.K. Schätzle)

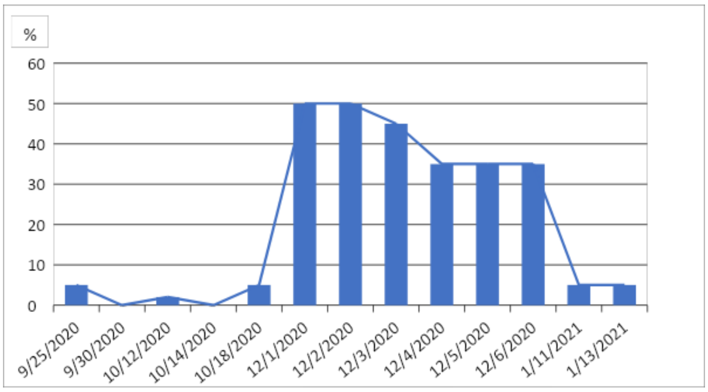


Figure 3.3.2. Variations in beach wrack coverage (September 2020 – January 2021) in Vilm Island, North (new wrack).

Kakumäe Beach, managed and unmanaged areas (Estonia)

The studies were carried out from 15.04.2019 to 16.03.2020 on Kakumäe beach in its managed and unmanaged areas (Photo 3.3.2, 3.3.3). Photographs were taken 1-14 times a month (Table 3.3.1). It should be noted that the width of the Kakumäe beach is quite large - up to 60 m in the managed area and up to 55 m in the unmanaged zone. Complete flooding of the beach has never been observed during the study. The smallest registered beach width was 5 m.

Beach wrack coverage in the studied period at different areas of Kakumäe beach is shown in Figure 3.3.3. Long beach wrack residence time is typical for Kakumäe beach. In the unmanaged area the wrack was on the beach over the entire period of observations (336 days) and cleaning in the managed area it was until being removed (up to 214 days). Beach wrack was found in 90% of the observed days in the managed area of the beach and in 100% in the unmanaged area. Long-term presence of wrack on the Kakumäe beach triggered its overgrowth with vegetation. Growth of terrestrial plants on beach wrack was observed from late May 2020. The plants were removed with beach wrack in July 2020 on the managed area and they were present until mid-September 2020 on the unmanaged area. Beach wrack coverage was 10-45% of the beach area in on most observation days.

Photo 3.3.2. Kakumäe Beach, managed area (Estonia) (03.07.2019, T. Paalme)

Photo 3.3.3. Kakumäe Beach, unmanaged area (Estonia) (03.07.2019, T. Paalme)

Figure 3.3.3. Variations in beach wrack coverage (April 2019-March 2020) on Kakumäe Beach (100 m long beach section). In 2019 the first beach wrack cleaning activity took place in middle of July and there were 3-4 cleaning efforts.

Otradnoye Beach, western part (Russia)

The western part of Otradnoye Beach is one of the sites where beach wrack is frequently cast ashore in the Kaliningrad Oblast (Russia). Beach wrack residence time was assessed using remote monitoring by a webcam. The webcam images covered a section of the beach with a length of about 40 m and a width of 15-20 m (Figure 3.3.4). Observations were carried out from 01.11.2019 to 21.02.2021, 6 times a day in summer and 3 times a day in winter (Table 3.3.1).

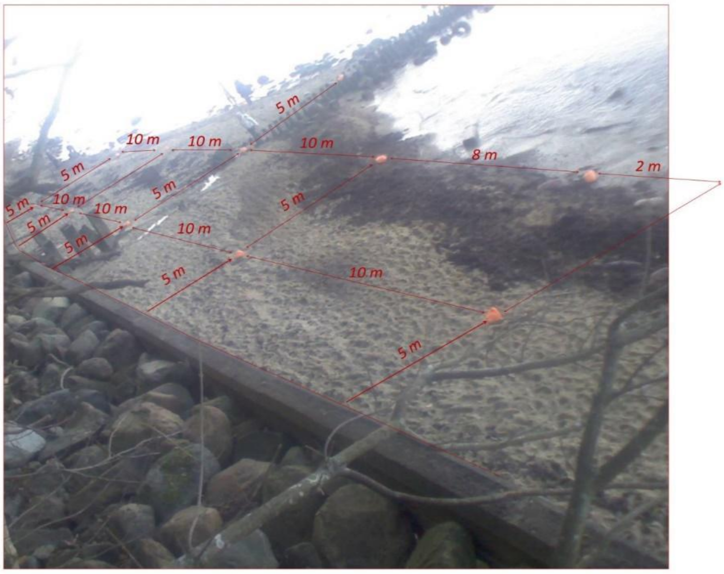


Figure 3.3.4. The webcam image with spot distance markers, the western part of the Otradnoye beach.

Beach wrack coverage in the studied period at Otradnoye Beach is shown in Figure 3.3.5. Beach wrack was found in 50% of the observation days. Beach wrack coverage was low (1-9% of the beach area) in 49% cases, medium (10-49% of the beach area) in 41% cases, and significant (50% and more of the beach area) in 10% of the days.

The residence time of beach wrack varied greatly, but it was often limited to a few days on Otradnoye beach. The residence time ranged from 25 days to less than one day, average residence time was less than 6 days during the observation period.

Beach wrack residence time was associated with the strength and direction of wind and waves. Otradnoye beach is situated in the northern coast of the Sambian Peninsula. Beach wrack usually remains on the beach in the conditions of winds of eastern and southern directions. Flushing of the beach wrack was due to winds of northern and western directions of significant strength. The waves flood the beach and wash the wrack away (Figure 3.3.6).

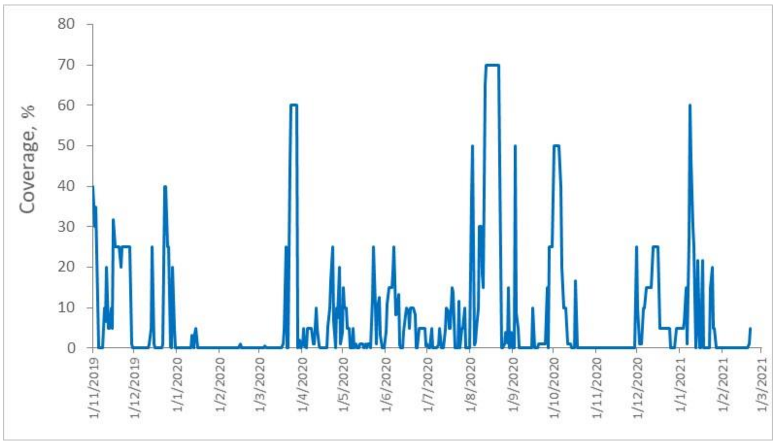


Figure 3.3.5. Variations in beach wrack coverage (November 2019-February 2021) on unmanaged Otradnoye Beach (40 m long beach section).

Generally, the main condition for beach wrack accumulation is the sequence of two events: the drift of algae to the water's edge and the subsequent rapid decrease in sea level, while the beach wrack is trapped on the beach.

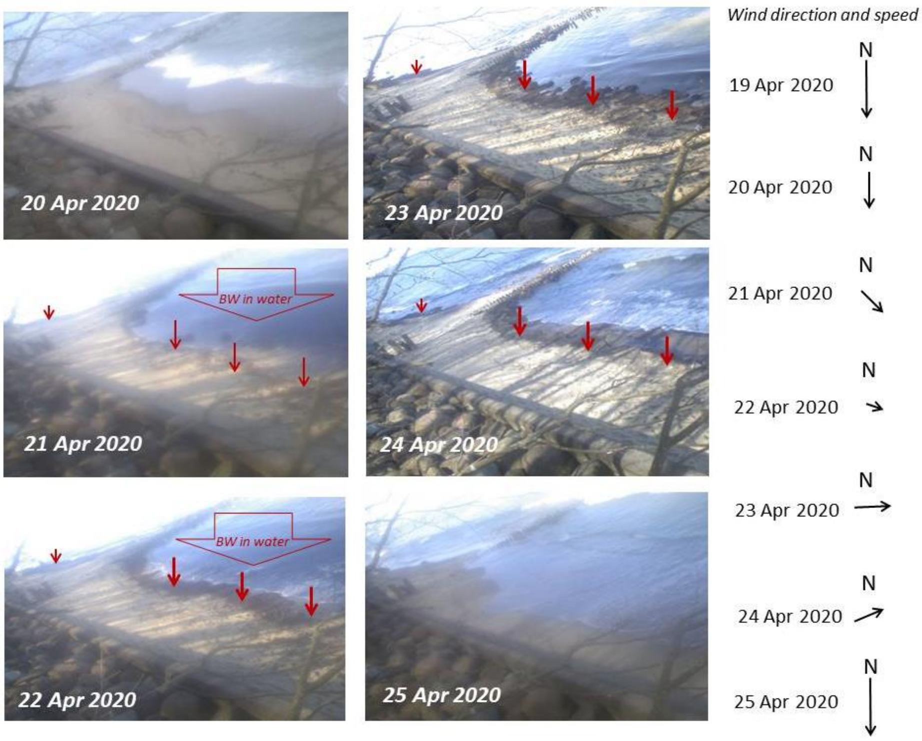


Figure 3.3.6. A typical example of beach wrack accumulation and flushing due to winds (the western part of the Otradnoye beach, northern exposure of the coastline). The arrows indicate the direction and strength of the wind (the weather station is located at a distance of 5 km, https://rp5.ru).

Undoubtedly, the small width (up to 18 m) of the Otradnoye beach provided the conditions for beach wrack to wash out of into the sea more easily. However, of the 238 days when the wrack was absent on the beach, only 18% of the days featured beach flooding. Thus, flooding was not the only reason for the absence of wrack. A total or partial washout of beach wrack back to the sea was observed on the other beaches of the Kaliningrad Oblast (Figure 3.3.7). Regular and long-term studies of the wrack residence time were carried out only on the Otradnoye beach. However, according to the spatial observations, it can be assumed that the short residence time of beach wrack is typical for most of the beaches of the Kaliningrad Oblast.

Figure 3.3.7. A typical example of beach wrack flushing left – the eastern part of Zelenogradsk beach, right – the eastern part of Filinskaya Bay (J. Gorbunova).

The spatial variations of beach wrack residence times occur due to the hydrodynamic conditions and characteristics of the coastline. As the studies have shown, beach wrack residence time varies greatly on different beaches of the Baltic Sea. For example, a long-term presence of wrack is typical for Kakumäe Beach (Estonia). Wrack was on the beach during the whole period of observations (336 days) in the unmanaged area. Wrack was observed in the managed section of the beach until it was removed during the beach clean-up.

A short beach wrack residence time was observed at Otradnoye Beach (Russia). The residence time ranged 1-25 days and in average it was less than 6 days. The short residence time of beach wrack is typical for most of the beaches of the Kaliningrad Oblast (Russia).

Conclusions

It is necessary to consider the peculiarities of the wrack residence time on the different beaches to plan management activities. Short residence time can be a limiting factor for a successful beach wrack harvesting. To improve efficiency, it is necessary to apply special measures in such conditions. For example, a possible solution can be the use of webcam observations on a potentially profitable seashore to coordinate the harvesting activities. This can be relevant for Kaliningrad Oblast and other areas with short beach wrack residence time. For the beaches with a long wrack residence time, it might be an important component of the natural terrestrial ecosystem (as a source of nutrients for beach plants, food or shelter for invertebrates). This must be considered when planning management activities. It may be helpful to establish special protected areas on the beach.

3.2.2. Aeolian dispersal of beach wrack

Many studies have shown the importance of beach wrack for marine environment and the functioning of beach ecosystems (Polis and Hurd, 1996, Ince et al., 2007, Barreiro et al., 2013). This includes the fact that algae thrown ashore are a component of fertilizer for dune vegetation in the process of coastal dune formation (Walter, 1975).

Figure 3.3.9. Influence of beach wrack accumulation on vegetation (J. Gorbunova)

Figure 3.3.10. Beach wrack in the vegetation of the back-beach, Filinskaya Bay (08.02.2020, J. Gorbunova).

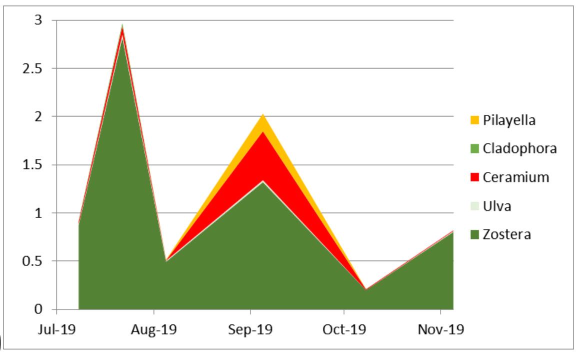
At the same time, only a part of the beach wrack that reaches the shoreline enters the food web of the terrestrial dune ecosystem. On some Baltic beaches the wrack residence time is often limited to a few days (see section 3.3.1). It is also a common situation that most of the wrack could be flushed back to the sea. To be valuable for the vegetation of the beach, the wrack must not only reach the coastline, but also drift across the beach to a zone of vegetation (Figure 3.3.9).
Aeolian dispersal accompanied with potential wave dispersal of beach wrack was investigated during the CONTRA by measurements at the respective sites in Germany, Estonia, and Russia (Table 3.3.3). The study included the estimation of the amount of beach wrack that has been accumulated in the beach wrack catcher. The catcher contained thickets of beach vegetation to trap the wrack with an area of 1 m^2.

In Filinskaya Bay, Russia, the observed amount of beach wrack in the vegetation varied from 0 to 200 g/m^2 in dry weight. The largest amount (100-200 g/m^2) was found in February and March 2020 (Figure 3.3.10). This is most likely associated with storms when wind and waves throw algae towards the back of the beach. The winter of 2019/2020 was mild, there was no stable snow cover and 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 area in Cape Taran (Volodina and Gerb, 2013). The beach in the bay is gently sloping and does not have dunes. The vegetation zone is at the back of the beach at a 25-45 m distance from the sea line. A total of 380 g/m^2 (dry algae weight) were harvested during the study period, which can be considered an annual input of beach wrack into the vegetation thickets in Filinskaya Bay.

The species composition of algae in the wrack that were sampled in the vegetation zone was limited to 5 species at the sites in Germany, Estonia, and Russia (Table 3.3.3). Seasonal dynamics of species composition of algae from new wrack collected near the water line and in beach vegetation zone was compared with each other (Figure 3.3.11). The main algae species in both the new wrack and in the wrack from vegetation zone was *Zostera marina* at Poel Beach (Germany). Filamentous algae were found only in wrack from the water edge (Figure 3.3.11). In Estonia, only fragments of *Fucus vesiculosus* were found in June 2020. No vegetation of beach wrack origin was found during the managed period in August and September 2020 (Table 3.3.3).

Table 3.3.3. Wrack amount (wet weight – WW and dry weight – DW) in the vegetation zone of the beaches of Germany, Estonia, and Russia.

Study area						Trap/"beach wrack catcher"						Drifted beach wrack biomass		
Country	Unmanaged beach	Date	beach slope ca. [°]	dune slope ca. [°]	beach width [m]	Species_I	Number	Height [cm]	Species_II	Number	Height [cm]	WW [g]	DW [g]	composition (% species)
GE	Poel	08.07.2019	30	50	25.03	*Ammophila arenaria*	72	70	*Cakile maritima*	1	20	12.33	10.48	*Zostera marina* 100%
GE	Poel	24.07.2019	30	50	28.33	*Ammophila arenaria*	74	66	*Cakile maritima*	1	15	10.44	9.28	*Zostera marina* 100%
GE	Poel	05.08.2019	30	50	31.56	*Ammophila arenaria*	83	80	*Cakile maritima*	1	10	20.58	19.68	*Zostera marina* 100%
GE	Poel	05.09.2019	30	50	34.66	*Ammophila arenaria*	107	78.5	*Cakile maritima*	1	7	22.74	4.41	*Zostera marina* 100%
GE	Poel	08.10.2019	30	50	31.96	*Ammophila arenaria*	94	76	*Cakile maritima*	1	6	15.73	3.27	*Zostera marina* 100%
GE	Poel	05.11.2019	30	50	26.36	*Ammophila arenaria*	71	58.5	*Cakile maritima*	1	4.8	3.29	0.54	*Zostera marina* 100%
EST	Pärnu	18/06/2020	10	35	38	*Leymus arenarius*	57	56	*Salix sp*	18	86	0.3	0.2	*Fucus vesiculosus* 100%
EST	Pärnu	31/8/2020	10	35	45	*Leymus arenarius*	55	70	*Salix sp*	18	95	0	0	0
EST	Pärnu	24/9/2020	10	35	40	*Leymus arenarius*	54	68	*Salix sp*	18	96	0	0	0
RU	Filinskaya Bay	06.09.2019	30	0	38	*Phragmites australis*		120	-			1.47	0.98	*Furcellaria lumbricalis* 100%
RU	Filinskaya Bay	24.09.2019	30	0	35	*Phragmites australis*		120	-			1.18	0.87	*Furcellaria lumbricalis* 100%
RU	Filinskaya Bay	15.10.2019	30	0	42	*Phragmites australis*		120	-			3.18	1.34	*Furcellaria lumbricalis* 100%
RU	Filinskaya Bay	01.11.2019	30	0	29	*Phragmites australis*		120	-			1.04	0.85	*Furcellaria lumbricalis* 100%
RU	Filinskaya Bay	17.11.2019	30	0	37	*Phragmites australis*		120	-			2.75	1.74	*Furcellaria lumbricalis* 100%
RU	Filinskaya Bay	08.02.2020	30	0	30	*Phragmites australis*	~250	120	-			425.03	105.38	*Furcellaria lumbricalis* 95%, *Fucus vesiculosus* 4%, *Cladophora sp.* 1%
RU	Filinskaya Bay	13.03.2020	30	0	25	*Phragmites australis*	~250	120	-			1082.34	198.45	*Furcellaria lumbricalis* 98%, *Fucus vesiculosus* 1%, *Cladophora sp.* 1%
RU	Filinskaya Bay	23.03.2020	30	0	30	*Phragmites australis*	~250	120	-			132.45	23.19	*Furcellaria lumbricalis* 100%
RU	Filinskaya Bay	23.05.2020	30	0	30	*Phragmites australis*	~350	50-120	*Lathyrus maritimus*, *Atriplex sp.*	3	10	65.12	18.35	*Furcellaria lumbricalis* 100%
RU	Filinskaya Bay	20.06.2020	30	0	35	*Phragmites australis*	~350	50-120	*Lathyrus maritimus*, *Atriplex sp.*, *Cakile maritima*	5	20	12.64	8.15	*Furcellaria lumbricalis* 99%, *Polysiphonia fucoides* 1%
RU	Filinskaya Bay	19.07.2020	30	0	35	*Phragmites australis*	~400	50-150	*Lathyrus maritimus*, *Atriplex sp.*, *Cakile maritima*, *Honckenya peploides*	10	30	16.12	9.07	*Furcellaria lumbricalis* 94%, *Fucus vesiculosus* 4%, *Cladophora sp.* 1%, *Polysiphonia fucoides* 1%
RU	Filinskaya Bay	07.08.2020	30	0	40	*Phragmites australis*	~400	50-150	*Lathyrus maritimus*, *Atriplex sp.*, *Cakile maritima*, *Honckenya peploides*	20	30	18.24	11.95	*Furcellaria lumbricalis* 84%, *Fucus vesiculosus* 15%, *Polysiphonia fucoides* 1%
RU	Filinskaya Bay	25.08.2020	20	0	35	*Phragmites australis*	~400	50-150	*Lathyrus maritimus*, *Atriplex sp.*, *Cakile maritima*, *Honckenya peploides*	20	30	5.31	2.98	*Furcellaria lumbricalis* 86%, *Fucus vesiculosus* 10%, *Zostera marina* 3%, *Polysiphonia fucoides* 1%

a)


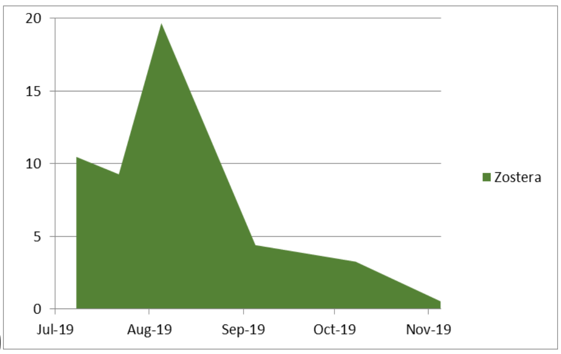
b)


Figure 3.3.11. Seasonal dynamics of species composition: a) new wrack near the water line (dry weight of algae in the ejection spot, kg/m^2), b) drifted wrack in the beach vegetation zone (dry weight in grams per 1 m^2 of thicket), Poel Beach, Germany.

Furcellaria lumbricalis dominated throughout the year in the wrack in the beach vegetation zone in Filinskaya Bay, Russia (Figure 3.3.12.b). At the same time, *F. lumbricalis* formed most of the biomass of the new wrack that located near the water line from October 2019 to June 2020. During the rest of the year, filamentous algae *Cladophora*, *Ulva* and *Vertebrata* prevailed (Figure 3.3.12.a). Also, in the thickets of vegetation, a relatively large amount of *Fucus vesiculosus*, up to 15% of the total weight of the wrack, was found. At the same time, the share of *F. vesiculosus* was very small in the new wrack located near the water line (less than 1%), the same applied to *Z. marina*. So far, the vegetation of *F. vesiculosus* and *Z. marina* has not been registered within the Russian sector of the southeastern part of the Baltic Sea. Presumably, they were brought in small amounts by currents from the surrounding marine areas (Volodyina and Gerb, 2013).

Based on our observations, a preliminary conclusion can be drawn: different species of algae are subject to varying degrees of aeolian and wave dispersal across the beach. For example, *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* do not stick together much. 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* spp.). This kind of increased buoyancy can help them to drift ashore (Barreiro et al., 2011). At the same time, the filamentous algae (*Cladophora*, *Ulva*, *Vertebrata*), when dried, strongly stick together and form dense mats along the coastline where they were cast by waves. These algae were almost never found inland of the beach in the vegetated zone.

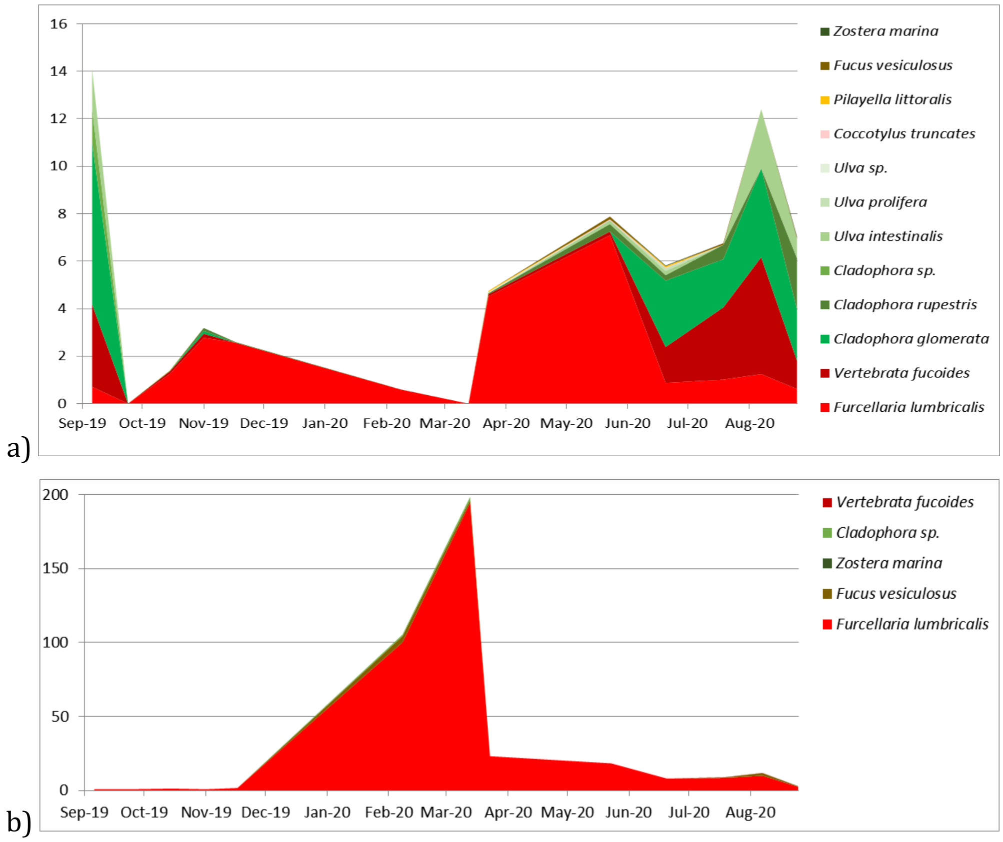


Figure 3.3.12. Seasonal dynamics of species composition: a) new wrack near the water line (dry weight of algae in the ejection spot, kg / m^2), b) drifted wrack in the beach vegetation zone (dry weight of algae in grams per 1 m^2 of thicket), Filinskaya Bay, Russia.

Conclusions

A detailed understanding and quantification of aeolian and wave dispersal of beach wrack in the beaches requires additional extensive scientific research. However, it is possible to draw some preliminary conclusions that are significant for the CONTRA project in order to provide some recommendations for management options:

- beach wrack can accumulate in the beach vegetation zone and on some beaches, it contributes to the allochthonous nutrient input into terrestrial ecosystems. This is important for species growth and diversity of dune vegetation on these beaches.
- different species of algae in beach wrack are involved to a varying degree in this process. Most of the filamentous algae do not disperse back to the beach due a rather dense, compact structure and they consolidate at a more or less short distance from the water line. In opposite, several perennial species (e.g., *Fucus vesiculosus*, *F. lumbricalis*) have a branchy structure of the thallus with higher air resistance after drying and therefore they can be more easily carried by the wind.
- as an example from the seaside of the southeastern Baltic, it was revealed that beach wrack accumulation in the beach vegetation zone was the most intensive in the late autumn, winter, and early spring. In summer, the accumulation was smaller. Apparently, this is due to increased storm activity during the autumn-winter period. Also, the changes in algae species composition of the beach wrack in the different seasons may have a contribution. The proportion of filamentous algae increases up to 85-90% in summer. Many species are opportunistic, and their abundant vegetation is partly caused by the Baltic Sea eutrophication. The beach wrack, which mostly consists of filamentous algae, has a rather dense, consolidated structure. The aeolian dispersal of such a wrack is smaller and its significance for the terrestrial beach vegetation zone is apparently low. The wrack can be flushed back to the sea, which further contributes the eutrophication of coastal waters. Therefore, the removal of wrack in certain seasons when cleaning the beach can be justified. This can contribute to the improvement of the water quality in the Baltic Sea, and the harvested wrack can be used to benefit economic activities, dunes restoration, etc. (see Report WP5). Thoughtful seasonal planning of beach clean-up allows to partially avoid conflicts of interest between the beach ecosystem and the tourism industry, for which summer is the high season.

Beach management planning should consider the fact that for some of the beaches the wrack can be a significant source of nutrients for dune vegetation. However, for some beaches, seasonal beach clean-up can help to avoid conflicts of interest between the beach ecosystem and the tourism industry.

3.2.2.1. Degradation

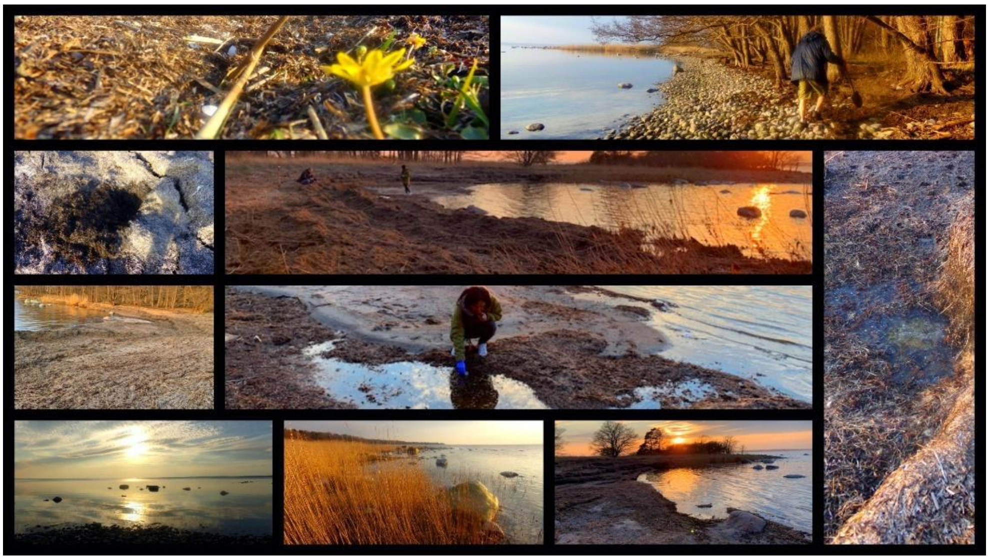
Degradation of the landed algae and seagrass is a natural process of beach ecosystems. Therefore, we summarize our results on natural decomposition, decomposition rate on land and in water, and greenhouse gas emissions from decaying beach wrack on the beach.

3.2.2.2. Natural decomposition of beach wrack in sheltered bays

beach morphology and storm events differentiate beach wrack accumulation. High amounts of beach wrack together with long residence time are most specific to sheltered bays. Natural decomposition varies due to changes in weather conditions and in particular, due to wind speed and direction. On some occasions beach wrack deposits cover beaches in more than 1 m thick layer, providing an important ecological and biogeochemical implications for the coastal ecosystem. Beach wrack contributes to coast protection by reducing erosion of the coast due to waves and global warming induced sea-level rise. It recycles nutrients to the coastal environment, supplies nutrients to dune vegetation and provides direct and indirect food sources by its biodiversity (Crawley et al., 2009; Mellbrand et al., 2011).

Within the CONTRA project, a beach in the western Öland, the Rälla beach, was used to study the means of natural decomposition processes. The beach is mainly covered by decomposing algae (Figure 3.3.13a and 3.3.13b). The most common species of macroalgae and seagrass in beach wrack were: *Fucus vesiculosus, Fucus serratus, Furcellaria lumbricalis, Vertebrata fucoides, Ceramium tenuicorne, Rhodomela confervoides* and *Zostera marina*. Beach wrack deposits were mainly cast to the beach during winter storms, but also during other high-water situations. The Rälla beach is temporarily flooded by brackish seawater from the Baltic improving the nutrient conditions but also resulting in a relatively high concentration of NaCl in the soil, which affects the composition of plant species. Thus, the soil conditions are rich in nutrients stimulating vegetation with high nutrient demand and the monocultures (Figure 3.3.13, 3.3.14).

A



B

Figure 3.3.13. Rälla beach in 29.03.2020 (A) and 05.07.2020 (B) (V. Sachpazidou)

Figure 3.3.14. Decomposition of seaweed on Rälla beach. The wrack causes a strong stench due to lack of oxygen, large quantity of wrack and high temperatures in the preceding days. A large amount of phytoplankton covers the entire length of Rälla´s coastal front; the decomposing seaweeds have cast up on the shore of popular tourist destinations in Öland and turn the sea water brown (20.07.2020, W.Hogland).

The areas closest to the sea were not colonized by plant species and only covered by layers of algae with different decomposition stages (Figure 3.3.14). It must be noted that this vegetation survey was carried out at the end of August 2020, and some of the species with early growth had already disappeared. The vegetation study did not include grass and Carex species, mosses or algae.

The lower parts of the vegetated segments of the beach were mainly covered by monocultures of *Atriplex littoralis* and *Chenopodium album* (Table 3.3.4). In the upper zones of the beach the substrate consisted of decomposed organic soil substrate and the species diversity was somewhat higher there. *Urtica dioica* was abundant also *Calystegia sepium Lamium purpureum* and *Galeopsis tetrahit* were found. Also, single specimens of *Achillea australis* and *Scorzoneroides autumnalis*, and some individuals of *Salix repens* occurred. In moist parts, *Phragmites australis* was abundant. At the edge of the forest Rälla Tall, in the areas that normally are not flooded, adult species of *Quescus robur* and *Alnus glutinosa* were common, as well as some individuals of *Salix caprea*.

Photo 3.3.4. The established vegetation on Rälla beach (V. Sachpazidou).

In July 2020, decomposition of the thick algal layer in the shallow waters of the Rälla beach caused a particularly unpleasant odour. The decomposition of algae occurred in conditions with a of lack of oxygen in the wrack. Large quantity of the wrack and high air temperatures favoured the emissions of the strong odour that emerged on the beach. The chemical components that end up in the bay (mainly nitrogen and phosphorus compounds) usually originate from entrapment of fertilizer residues on the fields, while rain and rivers flushes them into the sea and causes eutrophication.

The amount of wrack accumulating on the Rälla beach varied among the sites and times during 2020. Some locations consistently received large accumulations of beach wrack, but there were also sites that received minimal amounts of wrack. We estimated that it will take a long time for such beach wrack landings to disappear. In recent years it has been a recurring phenomenon with increasing intensity. Ekerum's inland forest is bordered with the Baltic Sea. The combination of strong winds, excessive humidity and the presence of forest species communities form the conditions in the Rälla beach coastal area. Ekerum's upland forest community includes the beach forest sandy soil "Rälla".

The depth profile of the Rälla beach wrack 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. Evaluation of the samples was performed in regard to metal concentrations (Figure 3.3.15), moisture and organic content. Zinc concentration varied between 115–290 mg/kg with the lowest values near the waterline and the highest values at 140 m from the water edge. Organic content showed the smallest variance, the observed values varied between 95–99% and moisture content decreased gradually with increasing distance from the waterline. 80% of moisture content was noted near the waterline and 25% was observed at 120 m distance from the waterline. The analysis package was performed according to 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.

Table 3.3.4. List of species growing on beach wrack piles in Öland, Sweden. The abundance was estimated as: 1 – rare, 2 – frequent, 3 – abundant. Information regarding habitat and flowering is adapted from the Jepson Herbaria of the University of California database .https://ucjeps.berkeley.edu/ (in 3 May 2021).

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

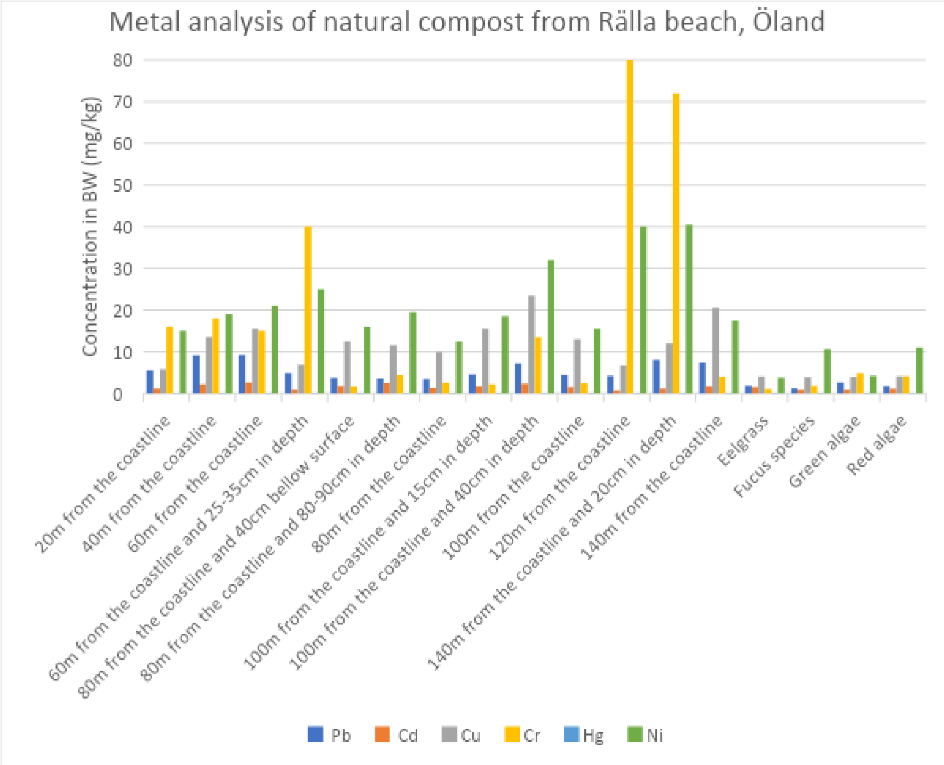


Figure 3.3.15. Heavy metal (Pb, Cd, Cu, Cr, Hg, Ni) distribution in beach forest Rälla beach wrack natural compost from the coastline up to the forest.

3.2.2.3. Degradation in water and on land

Residence time and decomposition rate are strongly related to each other in beach wrack management. Marine macrophytes directly enhance the abundance of sandy beach fauna through provision of food and habitat and therefore the residence time (degradation process duration) on the beaches is an important factor for the local faunal assemblages (e.g., Ince et al., 2007).

Litter bag experiments were carried out in Poland and Estonia. Degradation rates of the selected species groups (filamentous algae, higher plants, perennials) in different environments (submersed in the water, in a beach above the sediment or buried in the sand) were examined for up to one year in 2019-2020. The experiments were performed with species which were characteristic for the study area (Table 3.3.5). In Poland, the wrack deposits on the Rzucewo beach are mainly composed of the seagrass *Zostera* and the filamentous algae *Pilayella* or *Ectocarpus*, which are difficult to distinguish in the wrack. In Kõiguste Bay (Estonia) both higher plants and perennial algae together with filamentous algae were found in the beach wrack. While the Baltic Sea hosts both attached and loose-lying forms of *Furcellaria*, the attached form was used in this experiment.

It appeared that the degradation of beach wrack was significantly influenced by decomposition time, species composition, and placement of the wrack on the beach. In both sites (Estonia, Poland), significant weight loss occurred within the first month when 14 to 85% of initial dry weight was lost (Figures 3.3.16, 3.3.17). After four or more months, the changes in the remaining biomass were minor. The results are in accordance with previous studies. For instance, short-term studies have shown that the major loss of weight of beach wrack may be over within the first 10 days (Jędrzejczak, 2002a, Lastra et al., 2014).

As expected, filamentous algae decomposed more rapidly compared to higher plants or perennials. Rapid decline of biomass of filamentous species during the first months were followed by a decrease more than 90%. More surprisingly, *Furcellaria* showed a considerably high decomposition rate despite a relative sturdy thallus. In Estonia, *Fucus* was the most resistance to decay. The *Fucus* lost 60% of initial biomass during the year, while *Furcellaria* lost 99% and *Myriophyllum* lost 98% (Figures 3.3.18, 3.3.19).

Table 3.3.5. Initial species composition in experimental setup.

Site	Group	Species composition
Poland, Rzucewo beach	Higher plants	*Zostera marina* 100%
	Filamentous algae	*Pylaiella littoralis* and/or *Ectocarpus confervoides* 100%
Estonia, Kõiguste bay	Higher plants	*Myriophyllum spicatum* 90% *Cladophora glomerata* 10%
	Perennials	*Fucus vesiculosus* 58% *Furcellaria lumbricalis* 40% *Vertebrata fucoides* 2%

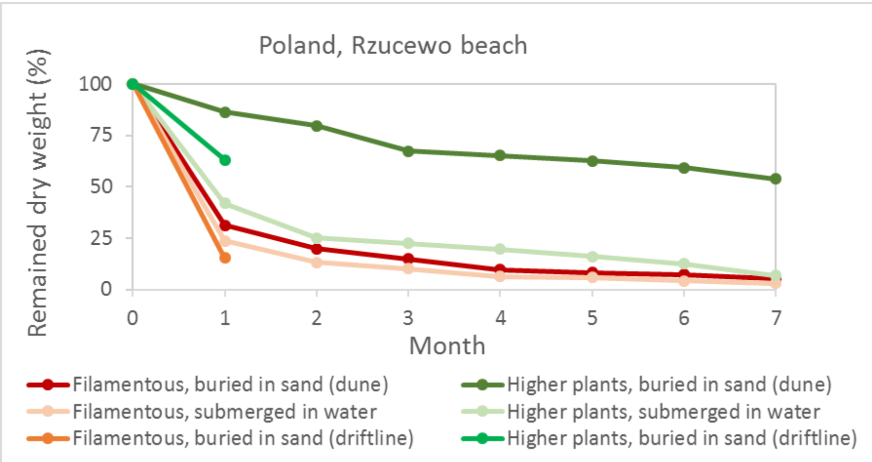


Figure 3.3.16. Variations in average proportion of remained initial dry weight of filamentous algae (*Pylaiella littoralis* and/or *Ectocarpus confervoides*) and higher plants (*Zostera marina*) from July 2019 to February 2020.

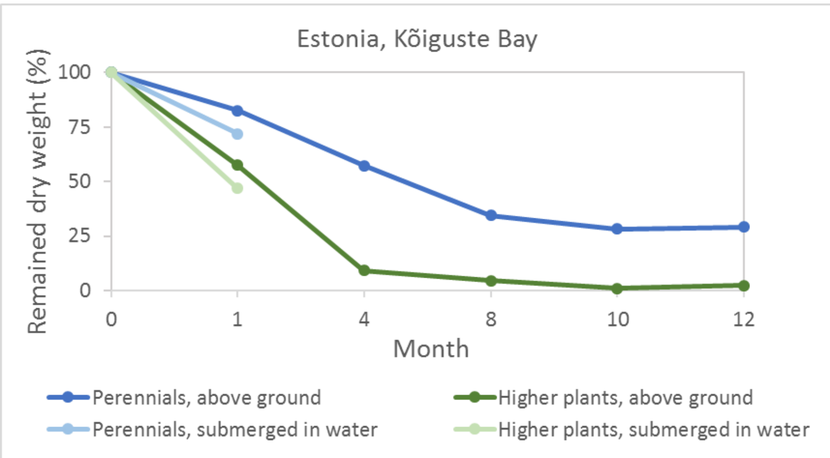


Figure 3.3.17. Average proportion of remained initial dry weight of perennials (mainly *Fucus vesiculosus* and *Furcellaria lumbrialis*) and higher plants (mainly *Myriophyllum spicatum*) from August 2019 to July 2020.

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 wrack above the sediment or buried in the sand (Figures 3.3.16, 3.3.17). 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 *Zostera* submersed in water was similar to the degradation rate of filamentous algae, the species showed significantly higher resistance when buried in the sand (Figure 3.3.16).

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

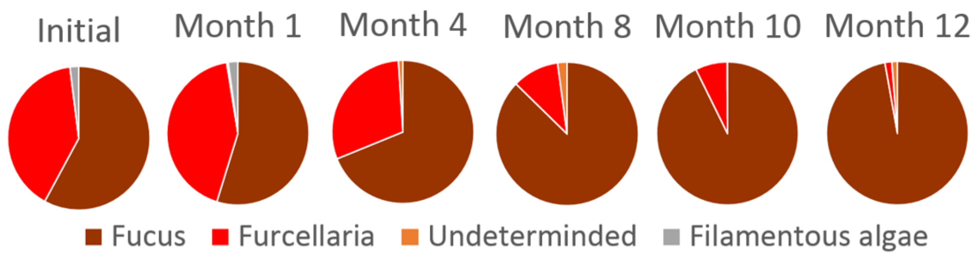


Figure 3.3.18. Average proportion of species groups in beach wrack (initially dominated by perennials *Fucus vesiculosus* and *Furcellaria lumbricalis*) used in the degradation experiment carried out in Estonia.

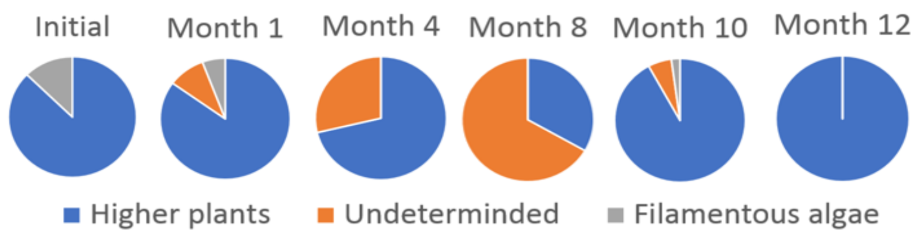


Figure 3.3.19. Average proportion of species groups in beach wrack (dominated by higher plant *Myriophyllum spicatum*) used in the degradation experiment carried out in Estonia.

Conclusions

The Baltic Sea is a seasonally varying system with large variations 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 with maximum rates when the algae decayed in a wet environment (Lastra et al., 2015).

3.2.2.4. Greenhouse gas emission

The decaying beach wrack may contribute substantially to global greenhouse gas emissions (this report, Liu et al., 2019). For instance, beach wrack composed of *Zostera nigricaulis* and *Amphibolis antarctica* can be substantial sources of CO_2 (but not CH_4) during the decomposing process. Liu et al. (2019) reported the biomass loss which coincided with the CO_2 emissions followed a double exponential model ($R^2 > 0.92$). The initial flux rate was 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 the 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 the Køge case below). 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 per year, which is equivalent to the annual emissions of 0.63–9.19 million Chinese citizens (Figure 3.3.20, Liu et al., 2019).

The greenhouse gas CH_4 has a 25 times larger greenhouse warming potential than CO_2 and in coastal ecosystems its emission depends on salinity (0–35 psu) with the most intense CH_4 emission at intermediate salinity levels (9–18 psu) (Misson et al., 2021). The CO_2 and CH_4 emissions in beach wrack also depended 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 beach wrack deposited on the sand. Intense wave action contributes to the fragmentation of the macrophytes tissues, which accelerate the rates of degradation and greenhouse gases emission.

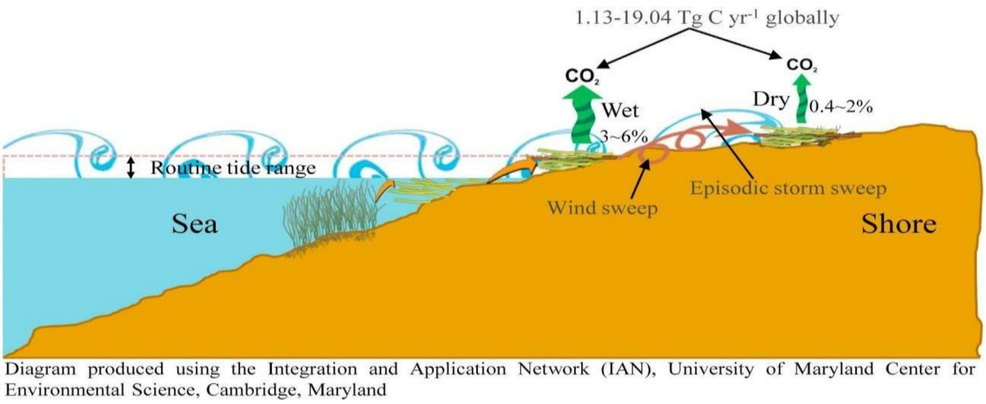


Figure 3.3.20. The scheme of greenhouse gas emissions from beach wrack (redrawn from Liu et al., 2019).

In the Baltic Sea region, the studies on greenhouse gas emission from beach wrack have been rare. Under the CONTRA project these measurements were carried out monthly from July 2020 to January 2021 on a beach in Køge, Denmark. The efflux is expressed as mmol per m^2 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 was noted from the results (Figure 3.3.21). The high summer temperatures of 20 °C corresponded with high CO_2 emissions in August, especially on the Køge unmanaged beach. Measurements of lower emissions in January were in correspondence to lower temperatures. The CO_2 emission reached the highest rates in August in the new wrack and sand (9,346-6,722 mmol m^{-2} d^{-1}) in the Køge unmanaged beach. It was followed by the pile of beach wrack (7,131 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 gathered in the back of the managed beach after clean-up in summer. Missing values correspond to lack of either new or old beach wrack, or non-detectable emissions. Compared to CH_4 emission

(3-109 mmol m^{-2} d^{-1}), the emission rates of CO_2 were generally higher ranging from 331 to 9,346 mmol m^{-2} d^{-1} for all measured sites, i.e., in new wrack, old wrack, sand and water (Figure 3.3.24). CH_4 and CO_2 showed temporal variation and temperature-dependent emissions. The emission of CH_4 was higher in summer compared to winter. 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 3.3.24). Emissions of CH_4 in the water was always higher compared to the emissions from sand, new wrack, and old wrack, which was either not detectable or very low. On managed sites the emissions of CH_4 were in general higher than on unmanaged sites, especially in water emission measurements. Uptake of CH_4 was observed only once during the sampling period (in July) for the new wrack on the unmanaged beach.

To provide an assessment of total greenhouse gases emissions, we converted the CH_4 emissions into CO_2 equivalents (based on 25-factor greenhouse warming potential), summed the CH_4 and CO_2 emissions and finally transformed the emissions according to the area of each beach and a location (new wrack, old wrack, sand, water). Køge managed beach had a total emission of 44 tons with the largest contribution from water, sand, and pile of accumulated beach wrack (~280 m^3) (Table 3.3.8). The beach cleaning by using tractors while the beach wrack was pushed back to the water can explain the high emissions both in the water and in the sand. The tractors mixed the beach wrack with the sand and caused higher fragmentation of the material, degradation, and greenhouse gas emissions. This sand mixing effect was not observed on the unmanaged beach. On the unmanaged beach the newly deposited beach wrack had the highest emission that can be 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 is needed.

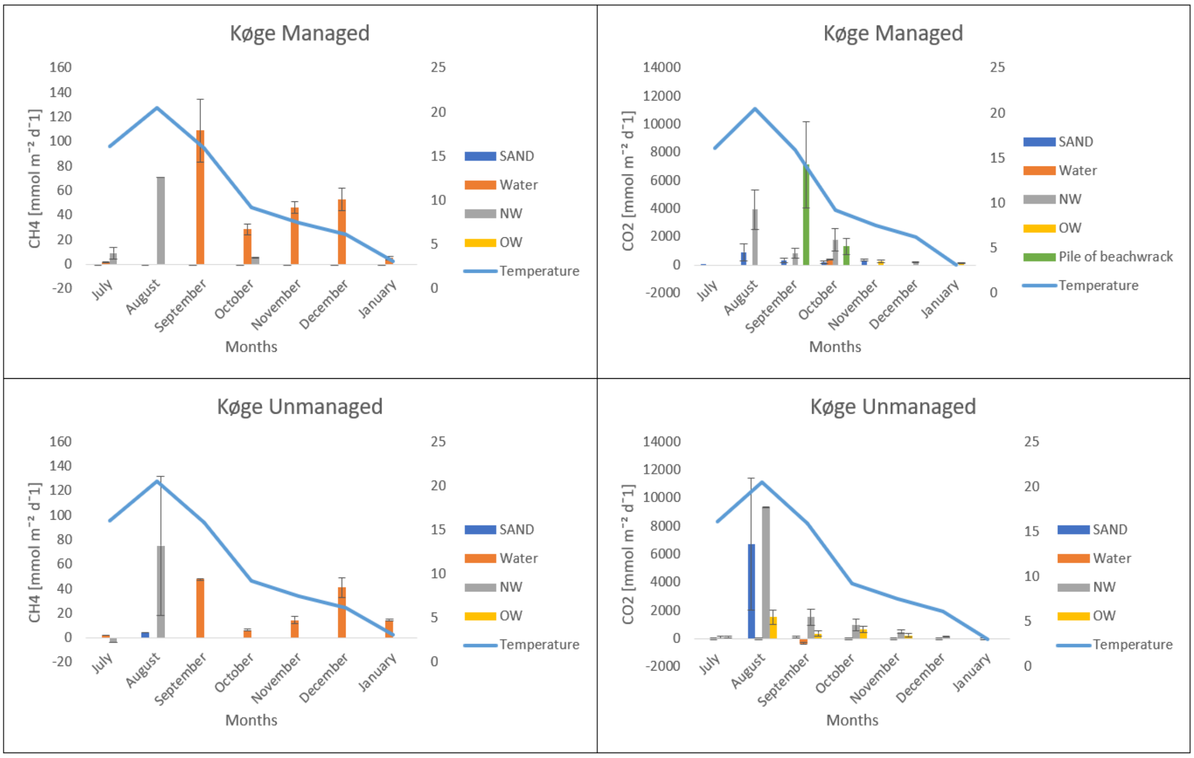


Figure 3.3.21. Monthly greenhouse gas emissions from July 2020 to January 2021 in the sand, new beach wrack (NW), old beach wrack (OW) and water on Køge (Denmark) managed and unmanaged beaches. The blue line represents the average air temperature in the sampling day.

Table 3.3.8. Estimated total emission in CO_2 equivalents (tons) for 7-month measurements of the greenhouse gases CO_2 and CH_4 on 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

Conclusions

Greenhouse gas emission from the beach wrack is an important parameter that needs more thorough studies. Such estimations are needed for coastal carbon budgets to better understand the changes in coastal environment. The information can also be used in beach management, eutrophication problems, wrack accumulation, and climate change-related problems. As was shown by Liu et al. (2019), the relocation of the beach wrack regarding moisture content is important. For instance, it is possible to reduce atmospheric CO_2 emissions simply by relocating beach wrack from water's edge up to a drier dunes area. Currently, relocating and piling up the beach wrack is a common practice on some beaches of the Baltic Sea. However, our study has shown that this material should not be compiled into large piles, since weather conditions such as rain and temperature may accelerate organic degradation. Therefore, the management of beach wrack in the Baltic Sea should take this relocation effect into account in the future. More detailed studies on greenhouse gas emissions of such beach wrack relocations are needed. Current management practices may not be optimal in some cases when greenhouse emissions are considered.

3.4. Nutrient availability and organic matter

Drifting algal mats have recently become a serious problem in shallow, eutrophic seas worldwide. On one hand, the excess organic matter washed ashore or deposited on the seabed enhances the growth of suspension feeders, while on the other it can create local hypoxia events that are followed by changes in zoobenthos abundance, species composition and the food web. Marine plant detritus plays an important role in the global carbon cycle and exceeds three-fold the amount of carbon that is stored in living marine plants. Coastal marine waters are the key areas of plant detritus production and storage. Owing to their permeability, sandy shores are efficient converters of organic matter. To understand the importance of sandy shores in the turnover of organic matter, it is necessary to study detritus production and its biomass (Kotwicki et al., 2005).

The detritus content at various locations along the Puck Bay differed. On the city beach inside the Puck Bay, there was less beach wrack than on the unmanaged beach. Beach wrack biomass at the P1 station located in Puck did not exceed 1.25 kg / m^2 (December 2019) wet weight of macroalgae, while at the station RZ3 (Rzucewo), wet weight of macroalgae was up to 28.8 kg/m^2 new wrack in spring, and 27.8 kg/m^2 old wrack in October. Dominant species in beach wrack at the Puck Bay (station P1) were *Zostera marina, Potamogeton pectinatus* and *Pylaiella* sp. At the stations located in Rzucewo, beach wrack was dominated by *Potamogeton pectinatus, Zostera marina* and land plants (the stations are located close to overgrown dunes). Together with the species composition of the plants, macrofauna community was analysed. Macrofauna organisms were numerous both on Puck and Rzucewo beach in spring and summer 2019. On Puck (station P1) larvae Chironomidae were present, and on Rzucewo (RZ3) larvae Chironomidae and Oligochaeta were found. Shells of Bivalvia (*Cerastoderma glaucum, Mya arenaria, Mytilus trossulus, Limecola baltica*), *Amphibalanus improvisus* and Gastropoda were recorded every time. On Puck (station P1), fewer shells (under 0.4 grams) were recorded in comparison with the stations in Rzucewo (up to 24.6 grams). The largest number was found at Rzucewo: stations RZ1 in spring 2019 (24.6 grams) and RZ3 on drift line (13.6 grams) in late autumn.

REDOX potential

One of the important factors which was measured during the sampling campaign was redox (oxidation-reduction) potential. Redox reactions are vitally important for major element cycling, sorption processes, trace element mobility and toxicity, most remediation schemes, and life itself. Results of the *in-situ* measurements in surface and pore water show significant oxygen depletion in the warm period and lower annual oxygen levels in the area impacted by algae (Figure 3.4.1). Moreover, the results of the measurements indicate that oxygen consumption during algae decomposition influences an area on a wider scale than just the algae wrack, also causing oxygen depletion in unimpacted pore waters.

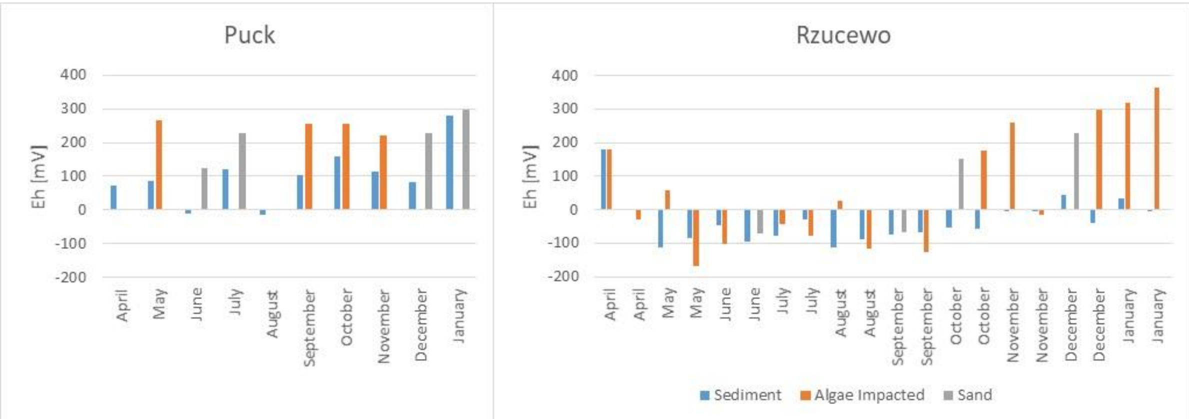


Figure 3.4.1. Change of the of redox potential [Eh] for managed (a) and unmanaged (b) sites in Poland.

Nutrients in surface and porewaters

Nutrient concentrations were highly variable in all types of studied waters without clear spatial or temporal trends (Table 3.4.1). In some months very high concentrations were observed. This can indicate an intense decomposition of marine detritus or delivery of nutrients from land (natural or anthropogenic). Concentrations of phosphates and ammonia were usually higher in pore water and nitrate was lower in the water column (Table 3.4.1). This is rather typical for the coastal zone. Phosphate concentrations in pore water taken under detritus at the beach were higher compared to those obtained in the water column. In stations P1 and Rz1 they were in many cases higher than the average phosphate concentration in pore waters from the gulf.

Ammonia concentrations measured from pore water from the beach were approximately comparable to those measured from the gulf (Table 3.4.1). Nitrate+nitrite concentrations in pore water from beach were either higher (Rz1) than in the water column, or similar (Rz3). Only in pore water from beach at R2 nitrite was absent or the concentration was low (from July to November).

Table 3.4.1. Nutrient concentrations in the study area in Poland (Puck beach stations P1, and Rzucewo beach stations Rz1 and Rz3, data since April to November 2020).

		n	mean	median	min.	max.	Q25	Q75	SD	RSD
water	PO_4^{3-} (mmol/L)	24	1.7	0.7	0.2	10.0	0.3	1.6	2.5	147
pore water		22	11.7	4.5	0.2	50.5	0.8	21.7	14.2	121
pore water from beach		21	12.7	4.5	0.2	50.6	1.9	18.3	15.6	123
water	NO_3^- + NO_2^- (mmol/L)	24	5.8	1.3	0.1	80.8	1.1	2.0	16.3	282
pore water		22	1.2	0.4	0.0	16.4	0.1	0.8	3.4	290
pore water from beach		21	4.0	1.5	0.0	15.2	0.6	6.8	5.1	128
water	NH_4^+ (mmol/L)	24	29.8	3.6	0.5	584.5	1.7	7.5	118.4	397
pore water		22	113.2	85.2	9.3	344.8	49.6	152.6	92.4	82
pore water from beach		21	233.2	43.4	2.7	1772.4	26.6	211.9	436.3	187

Carbon, total nitrogen, total phosphorus, and water extractable phosphorus in wrack

In most cases at all stations within a given month, Ctot, Ntot and Ptot content in detritus decreases in the following order: wrack from water>wrack from surface layer of beach sand>wrack from deeper layer of beach sand (Figure 3.4.2). The same pattern also occurs for water extractable forms of nitrogen and phosphorus (the most labile forms) (Figure 3.4.3). This reflects the gradual decomposition of organic matter after deposition on the beaches. The labile forms of phosphorus make up 18 to 73% (49 ± 165%) of total phosphorus and the lowest values are in the detritus collected from the deeper layers of the beach sediment (Figure 3.4.3). The share of labile forms of nitrogen in total nitrogen ranges from 0.04-8.21% (1.58 ± 2.6%). The increase in this share (Figure 3.4.4) indicates nitrification.

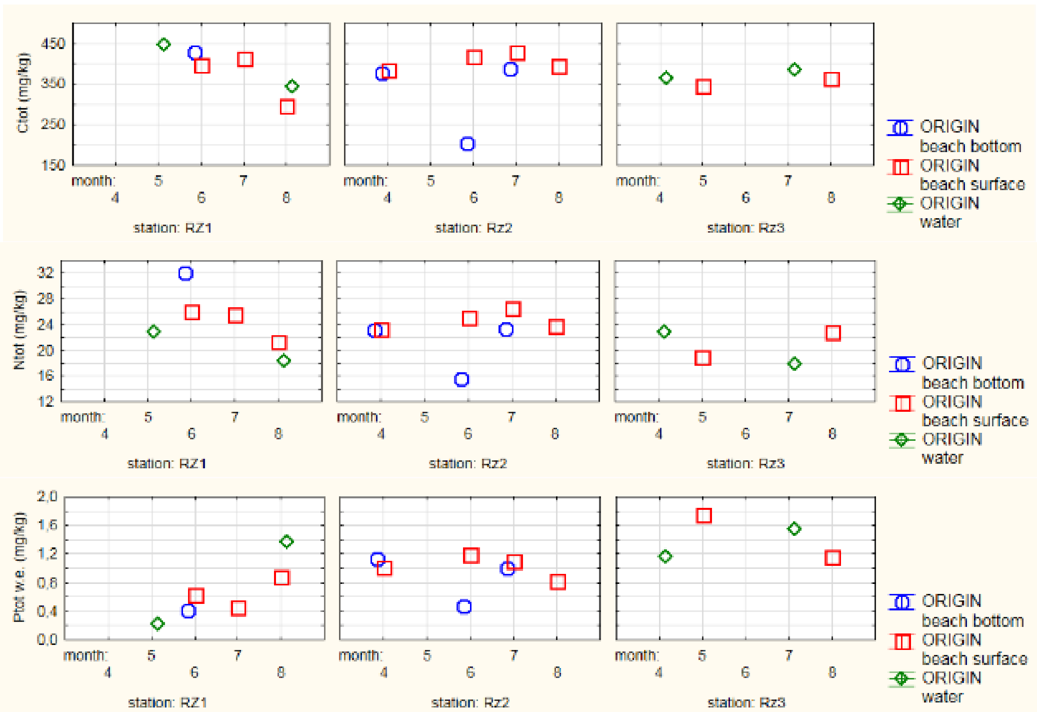


Figure 3.4.2. Seasonal and spatial variability of carbon (Ctot), nitrogen (Ntot) and phosphorus (Ptot) in wrack sampled from surface water and from two layers of sediment at three stations in Poland, Rzucewo beach.

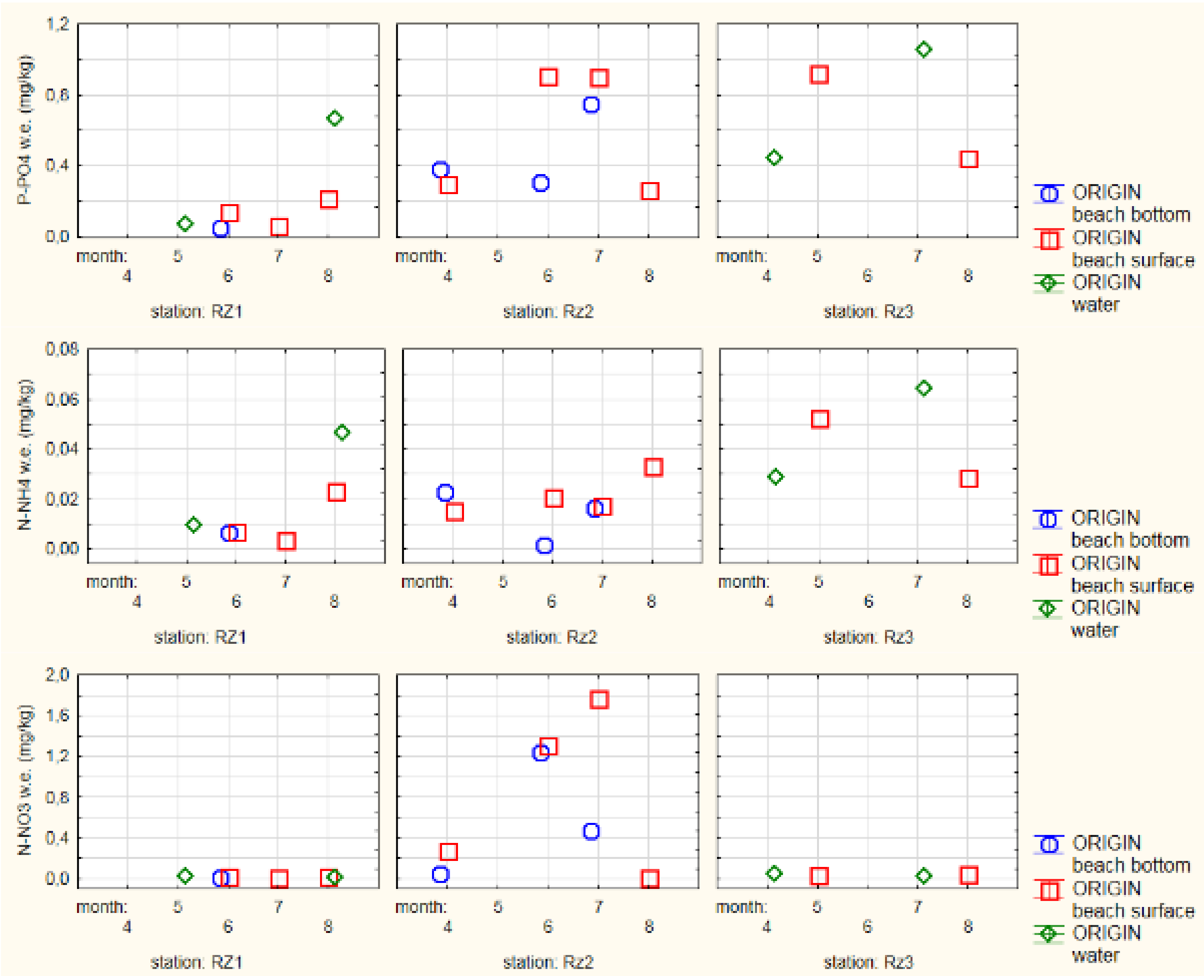


Figure 3.4.3. Seasonal and spatial variability of water extractable forms of phosphorus and nitrogen in wrack sampled from surface water and two layers of sediment at three stations in Poland, Rzucewo beach.

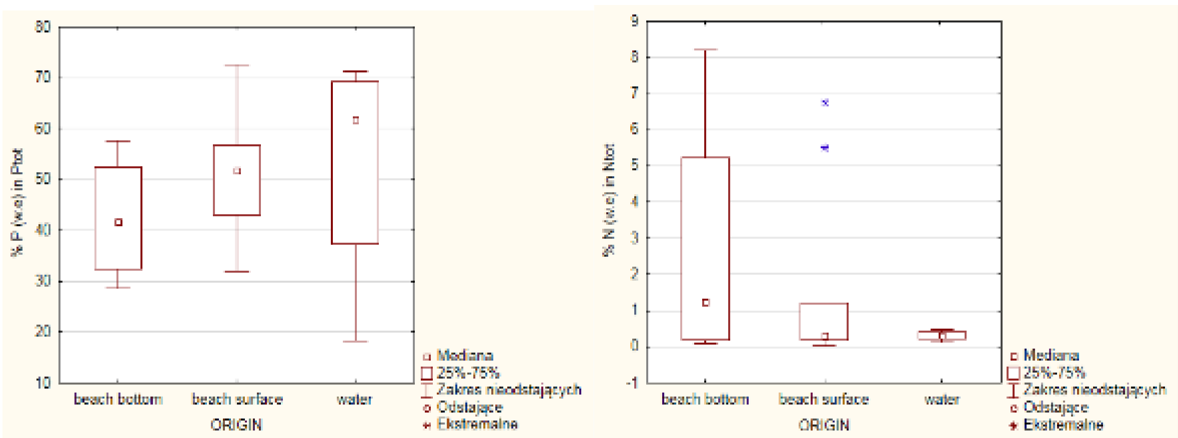


Figure 3.4.4. Percentage of water extractable forms of phosphorus and nitrogen in total forms in wrack from water and beach.

Conclusions

Using beach wrack removal, it is possible to remove significant amount of nutrients from the marine environment. Rough estimates show that for 1 tonne dry weight of detritus from the beach the weight of total phosphorus ranges from 1 to more than 2 kg, and in nitrogen it ranges between 16 and 32 kg. Such a load delivered to sea water can be responsible for the production of 1 to 2 tonnes of phytoplankton biomass.

3.5. Hazardous substances

In shallow coastal waters with extensive sea meadows, macrophytobenthos constitutes an important element of the ecosystem, both in terms of ecosystem functioning and biomass. During storms some of the plants forming the meadows are detached from the bottom of the sea and washed up on the shore/beaches. Shoring also includes floating filamentous algae, such as *ectocarpace* (i.e., *Pylaiella littoralis*) and green algae such as Enteromorpha, which are not the part of underwater meadows, but can be transported from offshore areas. Along most of the coast, the beach cast does not unduly affect the people who live near the coast. However, in certain areas, the amount of permanently trapped wrack is considerable. This creates problems not only for nearby inhabitants and local authorities, who are responsible for maintaining the beaches, but also for the local beach ecosystem.

Seagrass and algae wrack release several constituents during decomposition, which alter the coastal biogeochemical cycles and influence organisms. This includes nutrients and dissolved organic carbon, which will affect flora and microbial activity, and heavy metals (in polluted systems) – which creates risks for biota. Also, emission of volatile components from decaying plant material might constitute a risk for human health (H_2S, Hg^0, ^{137}Cs), as well as for the climate (methane).

Within the CONTRA project concentrations of heavy metals, methylmercury, nutrients, Bisphenol A (BPA), Nonylphenols (NP), octylphenols (OP), Polycyclic aromatic hydrocarbons (PAHs) and Polychlorinated biphenyls (PCB) were investigated in the beach wrack, sediment, and water in the coastal areas of Poland.

Mercury

Anthropogenic mercury remains a problem in the aquatic environment. Based on the sedimentary records in the Baltic Sea, its levels exceed 5-fold the Hg levels coming from natural sources (i.e., hydrothermal processes and rock weathering). Recently, emission of this metal to the environment has substantially decreased (HELCOM and SYKE 2008). This resulted in noticeable decrease of mercury concentration in macrophyta in the Polish coastal zone of the southern Baltic. 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 mercury 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 current patterns and coastline configuration, large quantities of macrophytobenthos gather in the coastal zone or end up as beach cast. During the summer season in the Gulf of Gdańsk the amount of beached seagrass and algae wrack ranges from several dozen to up to 800 tons on a 1 km long beach section (Filipkowska et al., 2008, Weinberger et al., 2020). A median Hg total concentration 7.6 ng g^{-1}dw has been calculated; 1 km long beach segment may receive 6 g of mercury per season. Analyses of coastal erosion in the southern Baltic show that ca. 39% of the Polish coast is accumulative (Dubrawski et al., 2008).

This means that about 200 km of the coastline favours phytobenthos accumulation. During summer season, benthic plants on Polish beaches alone may contain from 0.05 up to 1.2 kg mercury (Bełdowska et al., 2015).

A recent study performed within the CONTRA project in the Bay of Puck (sheltered part of Gdańsk Bay) indicated that the concentration of mercury was lower on the managed beach (P1) and higher on the unmanaged site, where decomposing wrack was collected (Rz1 and Rz2) (Figure 3.5.1). However, in the unmanaged station (Rz3), the concentration of mercury in living algae were similar to those at managed site. This indicates that although biological material accumulates Hg at the same rate and is characterized with the same mercury concentration in both sites, accumulation does not stop after landing. Decomposing beach wrack in the 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. Another explanation is that mercury is captured from the atmosphere, where it originates from local sources. This means that unmanaged beaches may not only transfer mercury from beach cast via accumulation in algae and subsequent release, but additionally enhance mercury flux to the beach from other local sources.

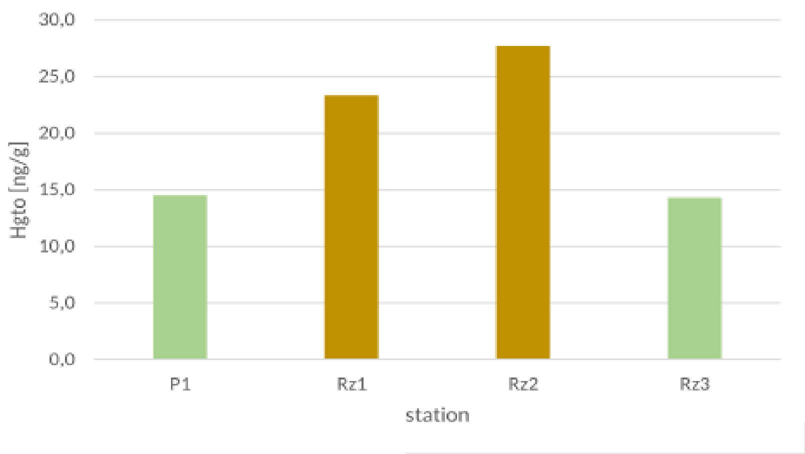


Figure 3.5.1. Total mercury concentration in alive algae at managed site (P1), decaying beach wrack at unmanaged site (Rz1, Rz2) and alive algae at unmanaged site (Rz3).

Decaying algae at the unmanaged site represent two regimes. At Rzucewo, station Rz1, beach cast is located in the surf zone, and wrack is constantly wetted by seawater. At station Rz2, beach cast is located higher on the beach, and the algae mat is dry. Vertical profiles of mercury differ at those stations (Figure 3.5.2). In Rz1 station, concentration of Hg is significantly lower in the deeper layer, as compared to the surface, while in Rz2 station, a slight decrease of mercury concentration is observed in the top layer of dried beach cast. Possible explanation is that the wet algae, although dead, constantly filter and accumulate mercury from the coastal water. Lower concentration in the bottom layer may indicate release of accumulated mercury into porewaters in its bioavailable, dissolved form. The situation in dry beach cast at Rz2 is different, where no leaching to porewaters occurs due to lack of water percolation through the system. There, the re-emission of mercury occurs in the top layer via volatilization into the atmosphere due to direct sunlight and elevated temperature.

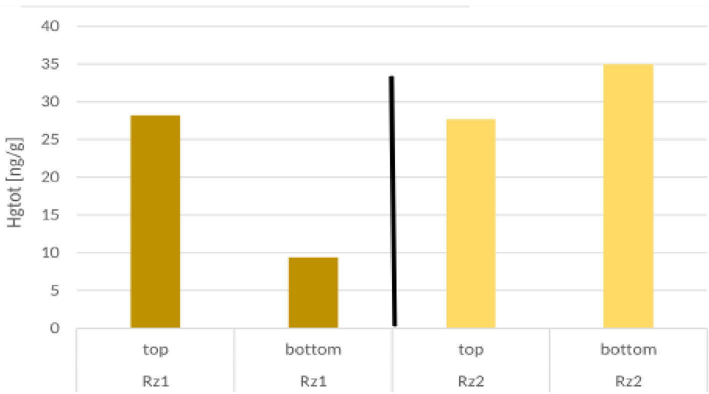


Figure 3.5.2. Total mercury concentration in top and bottom layers at unmanaged station, in wet (Rz1) and dry (Rz2) decomposition regimes.

The above-described hypothesis is supported by a speciation analysis. In station Rz2, mercury speciation was similar in top and bottom layers (Figure 3.5.3). In station Rz1, however, a speciation shift occurred. The easily soluble fraction Hgads1 rises significantly in the bottom layer compared to the top layer. Also, formation of an insoluble HgS fraction occurred, which is associated to mercury sulphide. This confirms that mercury in the algae and obtained in the process of surf filtration is transformed into more soluble forms during beach cast decomposition. Some of it is transferred to porewaters (in the form of Hg ads1), while the remaining mercury reacts with the hydrogen sulphide (which appears in the bottom layers of decomposing algae in anoxic conditions), forming a fraction of HgS, associated with cinnabar and mercury associated with other metal sulphides. This creates two threats for the coastal zone – constant flux of bioavailable mercury to porewaters, and accumulation of HgS. HgS is stable in anoxic conditions but could oxidize and return to the coastal zone in more bioavailable form after storms that remove beach wrack layer.

Methylmercury

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 that favour methylation processes and production of MeHg are anoxic, and also prefer the presence of high contents of organic matter and specific microorganisms. All of those conditions occur in the beach wrack. Results from the measurements of MeHg in sediments and sand do not give a definite answer whether the BW promotes the production of MeHg or not. For station Rzucewo (unmanaged site) in June 2019, the highest concentration of MeHg (20 pg g^{-1} dw) was measured in algae impacted beach sand. The concentrations were lower in the unimpacted areas (8 pg g^{-1} dw) and in the sediments collected from the water (5 pg g^{-1} dw). However, in July 2019, higher concentration occurred in the sediments collected from water (45 pg g^{-1} dw) in comparison to algae impacted beach sand (6 pg g^{-1} dw) and unimpacted sand (<LOD). In case of the managed beach in Puck, both in June and July 2019, MeHg was detected only in sediments and at low concentrations (8-10 pg g^{-1} dw). The concentration was below the detection limit (<LOD) in the sand from beach.

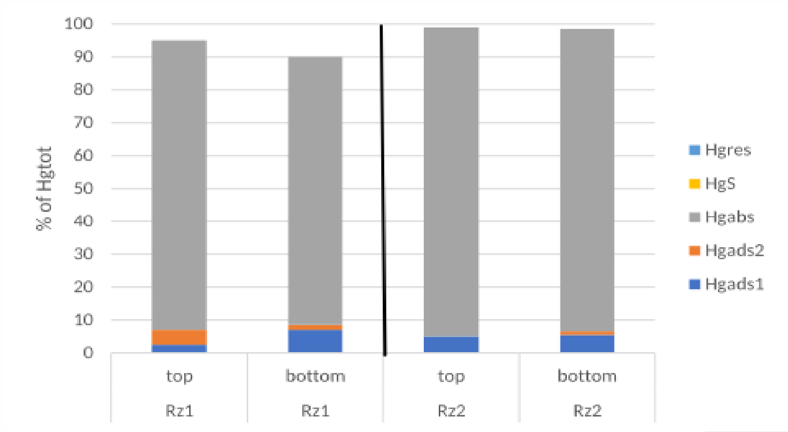


Figure 3.5.3. Mercury speciation in decaying algae at unmanaged station in top and bottom layers: Rz1 – wet decomposition; Rz2 – dry decomposition

Heavy metals

Heavy metals are natural elements of Earth's crust, but their discharge to the environment due to anthropogenic activity overwhelms their natural pathways. The most toxic heavy metals that pollute the Baltic Sea are 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 chains. Consequently, they can pose a threat to humans as well (Zaborska et al., 2019). The concentration of heavy metals in sediments does not exceed the thresholds values given in Journal of Laws (Laws, 2002) and HELCOM core indicators. However, a magnitude higher Zn concentration was observed in the beach wrack analysed on the unmanaged beach in comparison to sediments (Figure 3.5.4).

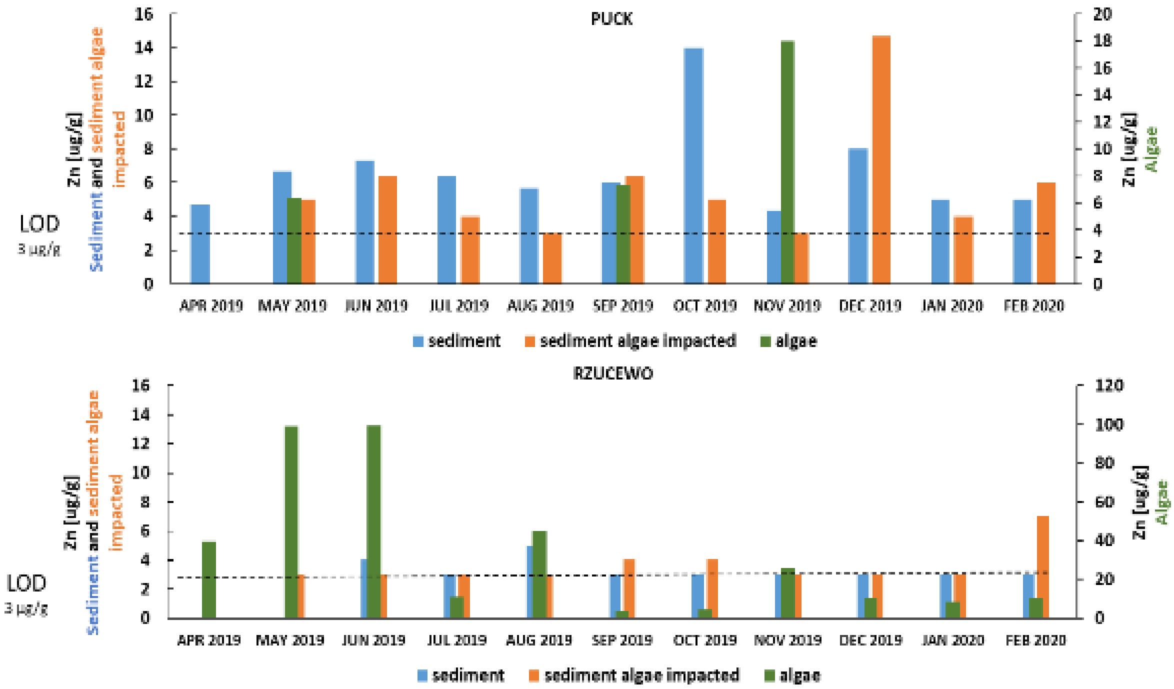


Figure 3.5.4. Zinc concentrations from in situ measurements in sediments with and without the impact of algae on managed (PUCK) and unmanaged beach (RZUCEWO).

Also, chromium (Cr) concentrations deserve further investigations. The observed Cr levels in sand from the managed beach (Puck), sand impacted with algae (Rzucewo1 + Rzucewo3) and in sediments from both areas were rather different (Figure 3.5.5). The measurements indicated 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 wrack decomposition. Although the data for chromium are only available from one sampling campaign (July 2019), the preliminary results suggest that BW can be a source of metals to the coastal environment.

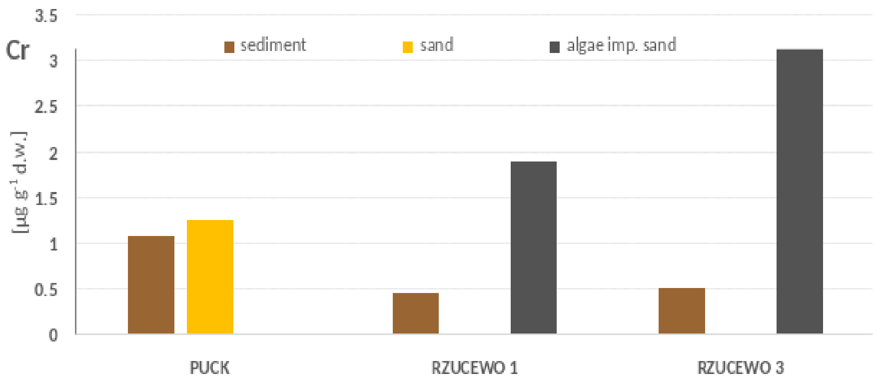


Figure 3.5.5. Chromium concentrations in sediments with and without the impact of algae on managed (PUCK) and unmanaged beach (RZUCEWO) in July 2019.

Organic contaminants

Organic pollutants persist in the environment, they are toxic, tend to bio-accumulate in the biota and undergo biomagnification along the trophic chain. Therefore, they can be transported over long distances. For a long time, the focus was on persistent organic pollutants (POPs), Polychlorinated Biphenyls (PCBs) and Polycyclic aromatic hydrocarbons (PAHs), which are routinely monitored according to law. Pharmaceuticals and alkylphenols like Bisphenol A, nonylphenols and octylphenols are pollutants which are not commonly monitored during routine monitoring programmes, but nevertheless they have the potential to enter the environment and to cause adverse ecological effects. The threshold values for water samples are presented e.g., in Journal of Laws in Poland (2011) and in the HELCOM core indicator (Zaborskaet al., 2019).

Seven polychlorinated biphenyls (PCB 28, 52, 101, 118, 138, 153, 180) and sixteen polycyclic hydrocarbons PAHs (fluorene (FLN), phenanthrene (PHE), anthracene (ANT), fluoranthene (FLT), pyrene (PYR), benzo(a)anthracene (BAA), chrysene (CHR), B(b+k)fluoranthene (BKF), benzo(a)pyrene (BAP), dibenzo(a,h)anthracene (DBA), benzo(g,h,i)perylene (BP), and indeno(1,2,3-c,d)pyrene (IND), Naphthalene (NAP), acenaphthene (ACE), and acenaphthylene (ACY)) were analysed in sediments, beach sand and algae samples. These were collected in July 2019 in two stations in Rzucewo and in Puck. In case of Σ7 PCBs the concentration levels varied from <LOQ (1.1 ng g^{-1} dw) to 81.8 ng g-1 dw in algae and beach wrack and from 2.3 to 17.0 ng g^{-1} dw in sediments and beach sand (Figure 3.5.6). None of the obtained concentrations exceeded the threshold value of 127 ng g^{-1} dw (CCME, 2012). PCBs was detected in algae and beach wrack samples from the unmanaged station R3 with concentrations 33 and 81.8 ng g-1 dw, respectively. In beach wrack from station R1 and floating algae from stations R1 and P the concentrations of PCBs were low (<LOQ) (Figure 3.5.6). The concentrations were higher in the unimpacted sand sediments and sands samples than in the impacted samples.

The concentrations of Σ16 PAH varied from 1,237 to 21,708 ng g^{-1} dw in algae and beach wrack and from 128 to 2,590 ng g^{-1} dw in sediments and beach sand. Similar to PCBs, the highest concentration was detected in beach wrack from unmanaged sites in Rzucewo. In the case of sediments and sand samples, concentration in impacted sand was generally lower than in the not impacted samples (Figure 3.5.6).

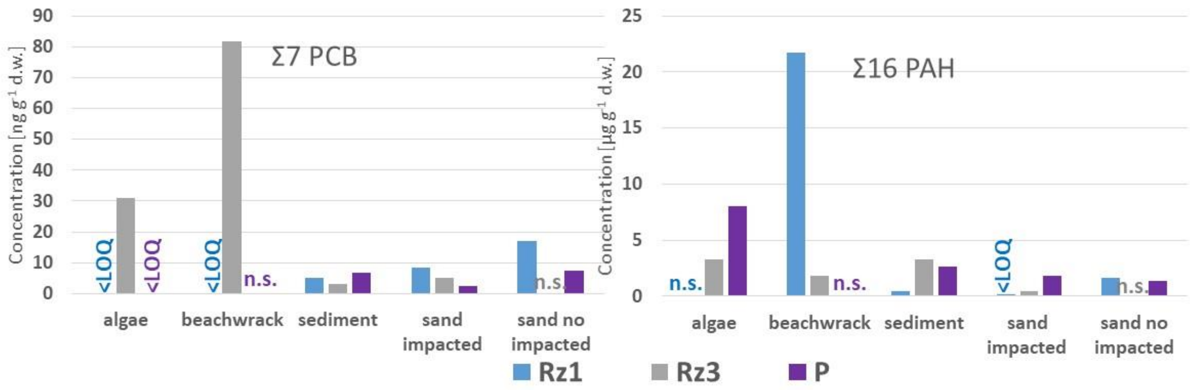


Figure 3.5.6. Concentrations of Σ7 PCBs and Σ16 PAHs in July 2019 in stations Rz1, Rz3 and P. n.s.- no sample, <LOQ - below Limit of Quantification.

Results of the PCBs and PAHs show that beach wrack can cumulate those contaminants. High concentration of PCBs in R3 station was probably connected with unknown point source pollution. Close to this station, fishermen moored their boats and put them on land, which can be an additional source of the pollution. On the other hand, results from impacted and unimpacted sand suggest that beach wrack adsorb PAHs and PCBs from the beach and their concentrations are lower in impacted regions. However, cumulated contaminants sooner or later will be released into the environment. The fate of PCBs and PAHs in the investigated region is more complicated than suspected and should be investigated in the future.

Bisphenol A is widely used in the production of synthetic materials and epoxide resins. It can be found in many daily used products like food packs. BPA can be dangerous for living organisms because it can interfere with the functioning of their hormonal system (Staniszewska et al., 2016). The concentration of BPA in porewater samples from Rzucewo and Puck exceeds the threshold value 150 ng L^{-1} described by HELCOM (2018a) in all analysed samples from May to August 2019. Concentrations from the samples from October and November were generally below the threshold value. The results suggest that BW can be an important source of Bisphenol A. Moreover, results from the BW analyses show that the concentration of BPA was higher in cold seasons (October-November). This may suggest that degradation of BW, which is more intensive in warm period, helps to release contaminants to the pore water.

Other compounds that can affect the environment are nonylphenols and octylphenols. NPs and OPs are used in industry for production of surface-active agents and synthetic materials. The threshold value for the porewater was calculated from the HELCOM core indicator (300 ng L^{-1} for NP and 10 ng L^{-1} for OP). The threshold value was exceeded for OP in 76% of the samples. The threshold was not exceeded in NP.

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), is a group of xenobiotics which have a significant impact on the hormonal, reproductive and other important systems and organs.

Bisphenol A and 4-nonylphenol were identified in all samples, the 4-*tert*-octylphenol in 80% of samples (4-t-OP was not identified in the July samples). The highest concentration was observed for BPA (average 214.3; median 45.4 ng g^{-1} dw) and for 4-NP (average 82.3; median 61.3 ng g^{-1}

dw). Maximum concentration of BPA was 1,704.5 ng g^{-1} dw. The lowest concentrations were determined for 4-t-OP (average 49.3, median 17,9 ng g^{-1} dw).

The maximum average concentration per station was recorded in station Rz1 (BPA 450.7, 4-t-OP 74,1 and 4-NP 107.8 ng g^{-1} dw) and the lowest references in station P1 (40.6, 16.6, 68.5 ng g^{-1} dw respectively). Variability of concentration depended on season and it was the highest in autumn (Figure 3.5.7).

Our research indicated that the microalgae may have a potential to accumulate bisphenol A, 4-tert-octylphenol and 4-nonylphenol. This can result in pollution of beaches exposed to dead plants because of transfer of dangerous compounds up the food chain.

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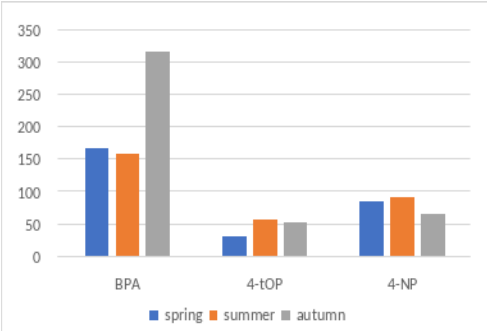

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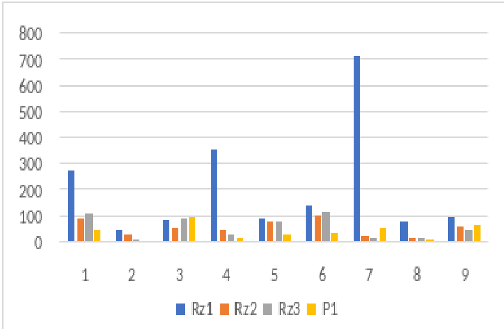

Figure 3.5.7. Concentrations of bisphenol A (BPA), 4-tert-octylphenol (4-t-OP) and 4-nonylphenol (4-NP) ng g^{-1} dw depending on season (A) and on season and station (B).

Conclusions

Based on the obtained results, beach wrack can release contaminants accumulated by algae during their lifetime from seawater and sediments. Studies on mercury additionally indicated that beach wrack deposited on beaches continues to accumulate dissolved substances from seawater. Contaminants are released to the coastal zone during decomposition of organic matter, partly via groundwater, which returns to the sea, and partly to atmosphere via volatiles. Due to presence of large quantities of organic matter and because the contaminants were already absorbed by marine plants and algae, enhanced bioavailability of contaminants occurs - compared to seawater where they came from. The process is cyclic: the contaminants are removed from the seawater and sediments by marine plants and algae in the distant offshore areas. In the Puck Bay, this area included the entire bay and the Gulf of Gdańsk. Then, they are washed ashore, building up the metal and organic contaminants pool in these areas. During decomposition, bioavailable forms of contaminants are released to the coastal zone, where biota can absorb it and transfer them up to the food chain. Breaking this link, by removal of beach wrack after deposition, can result in the depuration of the ecosystem.

3.6. Litter

Litter consists of items that have been made or used by people and deliberately discarded or unintentionally lost in the sea or on the beaches. Such materials can be transported into the marine environment from land by rivers, surface flushing, sewage systems or winds. Marine litter can be found in all coastal components (beaches, sea surface film, water column, seafloor and biota) and close to populated areas and in remote areas alike (Figure 3.6.1, Galgani et al., 2013).

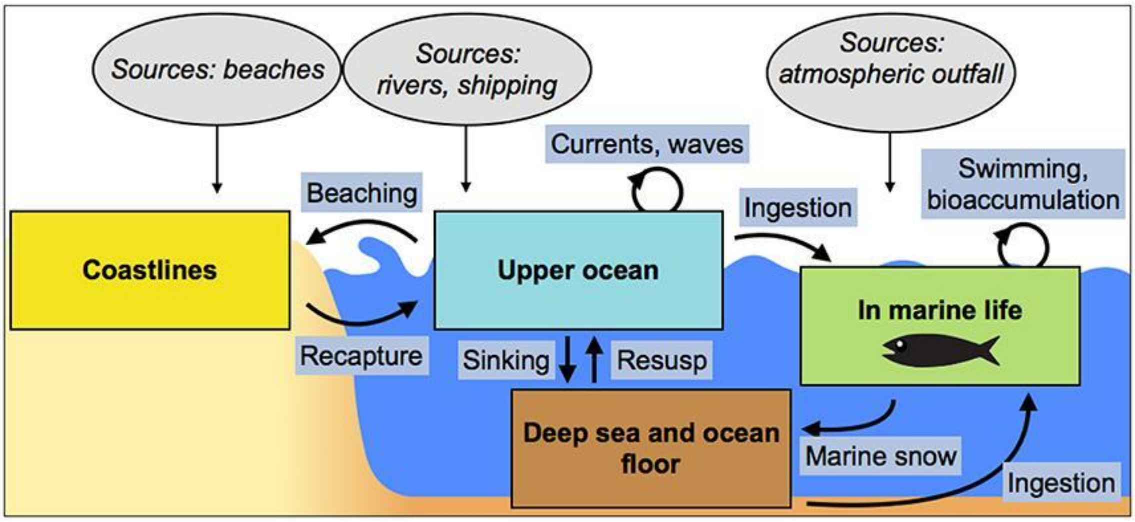

Figure 3.6.1. A scheme of litter system in the sea (redrawn from Hardesty et al., 2017).

Presence of litter in the marine environment and on the beaches is a globally increasing problem. Beach litter can be either of marine origin (carried to the beach via currents), or of land-based origin (left to the beach by visitors or carried by winds). From the beach the litter can further move into the water environment, inland or can be ingested by birds and animals. Beach litter has a significant environmental, economic and psychological negative effect (e.g., Galgani et al., 2019; Wyles et al., 2016). Within beaches the litter directly affects the beach ecosystems and calls for an effort by municipalities to keep the beaches clean. Nevertheless, it is easier to remove the litter from the beaches than from other marine components (e.g., organisms).

The amount of beach litter varies greatly across the globe, but all the coastal regions are already somehow affected. In the Mediterranean Sea, which is the most polluted sea in Europe in terms of litter, contamination can be over 6,000 items (in size >2.5 cm) per 100 m long beach section (Vlacogianni et al., 2019). The Baltic Sea region is currently considered to be a relatively clean area in Europe. Nevertheless, the average amounts of litter items per 100 m of beach section are estimated to be around 50-300 (HELCOM, 2018bc).

Presence of litter within beach wrack is an important aspect to consider, e.g., in selection of options for further beach wrack processing. Therefore, the quantity of litter needs to be studied locally. On the beaches the litter can be removed either separately or together with the beach wrack. There is also a great variety in litter nomenclature, material, hazardousness, size (Table 3.6.1) and origin. The presence of litter just makes beach wrack a more complicated raw material (GESAMP, 2016, Veiga et al., 2016). While large and visible litter items can be easily removed by hand-picking, the smaller items are entangled or buried into the beached algal material and are difficult to remove. Microlitter and nanolitter on the beach wrack need a more specific approach.

Table 3.6.1. Size classes of marine litter (according to GESAMP, 2016).

	Size
Megalitter	> 1 m diameter
Macrolitter	2.5 cm to 100 cm
Mesolitter	0.5 cm to 2.5 cm
Microlitter	0.1 µm to 0.5 cm
Nanolitter	< 0.1 µm

Macrolitter

In total 2,289 litter items were removed from the 19 study areas over the period April 2019-March 2020. 1,326 litter items originated from the managed beach sections and 963 from the unmanaged beach sections.

Throughout the study period, the largest number of litter items were collected from the chosen beaches in Estonia and Poland where the record catches were 127 and 116, respectively. Both records originated from the managed beach sections. On the studied beaches in Denmark, Sweden, Germany, and Kaliningrad the number of 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 considered 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 these previous findings – both in managed and unmanaged beaches the share of plastic among other litter materials was 72% (Table 3.6.2). For other materials (metal, glass, and rubber), there was little difference between managed and unmanaged beaches.

Table 3.6.2. The share of litter materials on managed and unmanaged beaches visited within the CONTRA.

	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/cardboard	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

The most common findings were cigarette remains, plastic pieces, food containers, candy wrappers, plastic bags, plastic bottle caps, glass fragments, glass bottles, glass jars, pieces of plastic rope, plastic foam sponges, metal caps and pull tabs (Table 3.6.3, 3.6.4, Figures 3.6.3, 3.6.4). Out of 82 litter categories under the UNEP nomenclature, 56 categories were recorded on the studied beaches. The findings are in accordance with earlier similar studies (e.g., Addamo et al., 2017) showing that most of the litter on the public beaches is related to simple leisure activities and originate from land-based sources. Large number of cigarette remains on the unmanaged beaches is mostly based on the findings from the Kakumäe unmanaged beach – the beach is located within the city, and it is popular year-round. Other studied unmanaged beaches are located further away from the densely populated areas and the share of cigarette remains on those beaches was considerably lower. Based on observations, the size of litter items was mostly below 10 cm. Presence of large and heavy objects of size larger than 1 m (e.g., tyres, mattresses, wooden pallets) was observed only in few times. The monthly variation in litter varied greatly, especially on the managed beaches of Estonia and Poland. However, the occurrence patterns were rather unclear (see the next 10 subfigures in figure 3.6.2).

Table 3.6.3. Most common litter items found within 19 studied beaches.

UNEP code	Material	Item	Sum	%
PL11	Artpoly	Cigarette remains	593	25.9
PL24	Artpoly	Other (pieces, parts, unknown etc.)	377	16.5
PL06	Artpoly	Food containers, candy wrappers	160	7.0

PL07	Artpoly	Plastic bags (opaque and ear)	125	5.5
PL01	Artpoly	Bottle caps and lids	114	5.0
GC07	Glass	Glass or ceramic fragments	104	4.5
GC02	Glass	Bottles and jars	97	4.2
PL19	Artpoly	Rope	70	3.1
FP01	Artpoly	Foam sponge	69	3.0
ME02	Metal	Bottles caps, lids and pull tabs	63	2.8
PC05	Paper	Other	53	2.3
WD06	Wood	Other	52	2.3
CL01	Textile	Clothing, shoes, hats, and towels	37	1.6
PL04	Artpoly	Knives, forks, spoons, straws, stirrers, (cutlery)	29	1.3
PC03	Paper	Cups, food trays, food wrappers, cigarette packs, drink containers	26	1.1
FP04	Artpoly	Foam (insulation and packaging)	25	1.1
PL08	Artpoly	Toys and party poppers	24	1.0
ME03	Metal	Aluminium drink cans	20	0.87
ME06	Metal	Foil wrappers ME	20	0.87
PL21	Artpoly	Strapping	19	0.83
RB01	Rubber	Balloons, balls, and toys	18	0.79
ME10	Metal	Other (specify)	16	0.70
PL02	Artpoly	Bottles < 2 L	14	0.61
RB05	Rubber	Inner tubes and rubber sheet	13	0.57
WD03	Wood	Ice-cream sticks, chip forks, chopsticks, and toothpicks	12	0.52
OR03	Organic	Fruit, food, pastry, candy, and ice cream	10	0.44
PC01	Paper	Paper (including newspapers and magazines)	9	0.39
PL03	Artpoly	Bottles, drums, jerry cans and buckets > 2 L	9	0.39
PL16	Artpoly	Sheeting (tarpaulin or other woven plastic bags, palette wrap)	9	0.39
CL04	Textile	Rope and string	8	0.35
PC02	Paper	Cardboard boxes and fragments	8	0.35
CL06	Textile	Other	7	0.31
ME08	Metal	Fragments	7	0.31
OT05	Other	Other	7	0.31
PC04	Paper	Tubes for firework	7	0.31
PL10	Artpoly	Cigarette lighters	7	0.31
PL05	Artpoly	Drink package rings, six-pack rings, ring carriers	6	0.26
ME09	Metal	Wire, wire mesh and barbed wire	4	0.17
RB02	Rubber	Footwear (flip-flops)	4	0.17
RB06	Rubber	Rubber bands	4	0.17
GC01	Glass	Construction material (brick, cement, pipes)	3	0.13
GC08	Glass	Other (specify)	3	0.13
RB04	Rubber	Tyres	3	0.13
FP02	Artpoly	Cups and food packs	2	0.09
OR02	Organic	Faeces (excrement)	2	0.09
PL18	Artpoly	Monofilament line	2	0.09
PL20	Artpoly	Fishing net	2	0.09
WD04	Wood	Processed timber and pallet crates	2	0.09
CL05	Textile	Carpet and furnishing	1	0.04
FP05	Artpoly	Other	1	0.04
OT01	Other	Paraffin or wax	1	0.04
PL22	Artpoly	Fibreglass fragments	1	0.04
RB03	Rubber	Gloves	1	0.04
RB08	Rubber	Other	1	0.04
WD01	Wood	Corks	1	0.04
WD05	Wood	Matches and fireworks	1	0.04

Table 3.6.4. Most common litter items on the studied managed and unmanaged beaches. Different colours indicate different materials (plastic, metal, glass and ceramics, wood, paper).

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 sponges	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

Our findings indicated that most of the litter items on the beaches were related to beach wrack – in total 44.8% of litter were found together with old wrack (i.e., within old wrack line), 25.9% was found together with new wrack (new wrack line) and 29.3% was found from the remaining beach area. There are some variations between the beaches (Figure 3.6.5), but the general pattern indicated that litter and beach wrack moves together and similarly, especially on the unmanaged beaches.

The survey carried out under the CONTRA (Hoffmann et al., 2021ab) included questionnaire regarding the littering of the beaches. Out of 23 municipalities who participated the survey, 8 had no data regarding the amount of litter within beach wrack, 3 estimated it to be zero, 7 estimated the amount of litter to 1-5% and 5 municipalities estimated the amount of litter within beach wrack to 5-10%. These very general estimations were often based on assumptions. However they indicate that in many cases there is a lack of such information on municipality level. The amount of litter estimated to 5-10% of beach wrack is also rather high and reflects the high pollution level of our beaches.

Microlitter

Within the CONTRA project we did not focus on meso and microlitter, but its presence was determined from the biomass samples collected from the Kakumäe beach (Estonia) and in the Filinskaya Bay (Kaliningrad Oblast, Russia). While mesolitter are litter items in size of 5-25 mm length or diameter, microlitter is in size < 5 mm. On Kakumäe beach, out of 129 analysed biomass samples 55 (in total 43%) contained some pieces of still visible microlitter pieces in the 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 was estimated that on average 1 m^3 of beach wrack contained about 0.06 m^2 of polyethylene.

When beach wrack is removed for beach cleaning purposes, it is removed together with some sand (chapter 4). According to recent studies on microlitter pollution on the 12 beaches in southern Baltic Sea (Polish coast) the amount of microplastic varied between 76 and 295 items per kg of dry sediment. Fibres and plastic fragments were the dominant microplastic types (Urban-Malinga et al., 2020). The amount of nanoplastic on the Baltic Sea sandy beaches is currently unknown. Based on the share of plastic pollution and microplastic on the beaches, using beach wrack directly as a fertilizer on the agricultural fields cannot be recommended because microplastic pollution on agricultural fields can pose risks (Nizzetto et al., 2016, Henseler et al., 2019, Gavigan et al., 2020). However, food security issues connected to microplastic pollution in agriculture are not sufficiently studied yet.

Figure 3.6.2. Number of litter items on the studied beaches. Management activities and study period (month, year) are indicated.

Figure 3.6.3. Typical litter from a managed beach, example from Kakumäe, Estonia (T. Möller).

Figure 3.6.4. Examples of litter items found together with beach wrack in Kakumäe, Estonia (T. Möller).

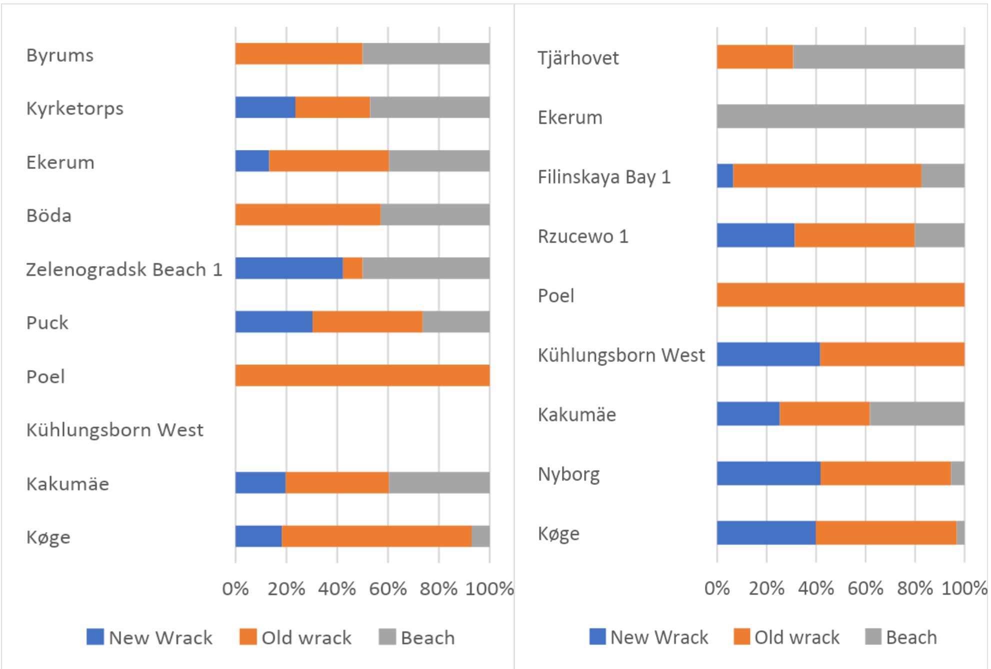

Figure 3.6.5. Share of beach litter findings (%) associated with new wrack, old wrack or occurring on the remaining beach section on managed (left) and unmanaged (right) beaches.

Conclusions

The largest share of litter material on managed beaches was comprised of plastic (72%) with most common items being cigarette remains, food containers, candy wrappers and other plastic pieces.

The majority of the litter on managed beaches is related to leisure activities and originate from land-based sources.

Throughout the study period and among all the studied beaches, the largest number of litter items per 100 m long beach section was collected from the beaches of Estonia (127 items) and Poland (116 items). Both the maximum values corresponded to managed beach sections. However, these managed beaches are also in the close vicinity of cities and are popular year-round. On other studied managed beaches (representing semi-rural areas) in Denmark, Sweden, Germany, and Kaliningrad the number of 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 considered to represent the good environmental status regarding beach litter.

Most of the macro and mesolitter found on the beaches were related to beach wrack lines, together with either old or new beach wrack. Microlitter was present both in beach wrack and in beach sediment. Out of 129 analysed biomass samples from the Kakumäe beach (Estonia) 43% contained some pieces of microlitter in size range of 1-5 mm.

Based on the surveys carried out within the CONTRA project (Hoffmann et al., 2021ab), nearly one third of the municipalities (8 out of 23) had no information regarding the amount of litter within beach wrack. This indicates a lack of information on the municipality level.

The amount of litter both within the algae and in sediment should be monitored on a local basis and taken into account when searching for possible uses of removed beach wrack. The amount and nature of litter can significantly affect and limit beach wrack treatment options.

4. Effect of management on sandy beaches

The increasing human activities on the beach and developments in the surrounding areas have led to the destruction of the typical flora and fauna (Davenport and 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 an uninfluenced sandy beach on the Baltic Sea coast. Few exceptions are the environmental protection areas, such as core zones of national parks and bird sanctuaries. For example, the extent of sandy beaches on the German coastline is estimated at 450 km, of which 351 km is influenced by tourism, and only 22 km are designated as "natural sandy beach without any human influence" (Schumacher, 2008).

As clean beaches are increasingly desirable, they are being cleaned more and more to remove nuisance biomass and waste (CONTRA report Hoffmann et al., 2021ab). The frequency and type of cleaning activities are adapted to local conditions, weather conditions and the expected amounts of beach wrack (chapter 3). There are two main types of beach cleaning procedures: mechanical and manual. Mechanical beach cleaning is defined as litter and/or organic material removal using automatic machines that rake or sieve the uppermost layer of sand. Manual cleaning means people picking up litter by hand, which interferes less with nature, but it is also carried out less because of high personnel costs.

Natural sandy beaches usually have a narrow area of sand close to the sea, which is flattened by waves and sea level variations. Landward to this zone, there can be a zone of vegetated dunes that are only occasionally swept by high floods. Usually, managed beaches have much less vegetation, lower biodiversity, fewer "natural" dunes, and much flatter topography than unmanaged beaches (Schumacher, 2008). Many of such beaches are nourished with additional sand during autumn-spring months, or the sand is moved from one place to another with machines to widen the sandy zone. Thus, the beaches that are very popular, are also morphologically modified and their ecosystem characteristics are altered as well 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. Therefore, it traps and stabilizes sediments on the beachfront (Ahrendt, 2019; chapter 3). This could reduce erosion and loss of sand in the swash zone. Despite this potential importance of beach wrack, the corresponding studies are surprisingly scarce for the Baltic Sea coast (chapter 3). The protective effect from hydrodynamic forces has not been studied as well.

In case of large quantities of beach wrack, its removal could decrease the nutrients and pollutants release at the beach. This can help control the eutrophication and pollution of the Baltic Sea (section 3.4-3.5). Furthermore, parallel removal of beach wrack and litter is good for wildlife (section 3.6). However, the ultimate impacts of such measures to the ecosystem of the Baltic Sea have not been thoroughly studied so far.

While the impacts of human activities on the beach ecosystem are generally known (or assumed), there is still a lack of complex ecological studies for the Baltic Sea coast. Therefore, the CONTRA project was initiated to start with a comparative study in six different countries and corresponding study sites. In this chapter, the different chemical, biological and mechanical levels of effects on sediments and fauna caused by mechanical cleaning are evaluated and discussed. For a better description of these impacts, managed and unmanaged beaches were compared that are otherwise similar in their habitat structures (section 2.1).

4.1. Biological disturbance on beach infauna

Wrack removal does not only remove the unwanted material, but it deprives the ecosystem of valuable nutrient input and removes the food and habitat for wrack-associated fauna. The removal of beach wrack has been shown to have a serious impact on the wrack-associated fauna with a 2-3-fold decrease in species richness (Dugan et al., 2003). Our results within the CONTRA project also indicated to a lower species richness and lower quantity of macrofauna on the managed beaches. The macrofaunal composition was studied in more detail on the two beaches of Poland: Puck beach (P1) represents the managed and Rzucewo (R3) represents the unmanaged beach. The Puck Bay is a managed beach located within the city of Puck (number of habitats around 11 000). Between May and September, a 0-5 m wide beach section (from the waterline) is cleaned by hand on a daily basis. Total length of the beach is 1,8 km and the managed section is 400 m long. The beach in Rzucewo is located 4.5 km south-east from Puck. The sandy area is narrow (3-5 m), and the nearby dune vegetation includes grasses, bushes, and trees.

Both in managed (Puck, P1) and unmanaged (Rzucewo, R3) areas a total of 21 species or taxa belonging to the macrofauna were found. Also some epiphytic organisms such as *Amphibalanus improvisus* barnacles and 3 taxa that belong to the meiofauna - Nematoda, Turbellaria and Collembola (the latter belongs to meiofauna and is not taken into consideration in the macrozoobenthos analysis) were found. The frequency and dominance of occurrence of macrofaunal taxa in the managed area is summarized in Table 4.1.1.

Table 4.1.1. The frequency and dominance of macrofaunal taxa at the managed area Puck Bay, Poland.

	Puck, PL, managed area			
Taxa	**frequency [%]**	**Occurrence frequency**	**percentage [%]**	**Abundance dominance**
Oligochaeta	100	absolutely constant	39.4	absolutely dominant
Polychaeta				
Hediste diversicolor	100	absolutely constant	1.0	
Marenzelleria viridis	50	constant	3.0	
Pygospio elegans	17	accidental	0.6	

Manayunkia aestuarina	8	accidental	0.5	
Bivalvia				
Limecola balthica	67	constant	0.1	
Cerastoderma glaucum	75	absolutely constant	6.5	subdominant
Mya arenaria	58	constant	0.1	
Mytilus edulis	--	--	--	--
Gastropoda				
Hydrobidae	75	absolutely constant	33.5	absolutely dominant
Theodoxus fluviatilis	--	--	--	--
Crustacea				
Rhithropanopeus harrisi	8	accidental	0.3	
Corophium volutator	33	rare	0.1	
Corophium multisetosum	100	absolutely constant	0.3	
Corophium juv.	50	constant	0.2	
Gammarus salinus	8	accidental	0.1	
Gammarus zaddachi	--	--	--	--
Gammarus deubeni	--	--	--	--
Gammarus juv.	17	accidental	0.1	
Heterotanais oerstedti	50	constant	0.4	
Cyathura carinata	--	--	--	--
Idotea sp.	8	accidental	0.1	
Chironomidae	100	absolutely constant	13.9	absolutely dominant
Number of taxa	16			

There were 16 taxa in total in the managed area, 6 of them were considered absolutely constant, although only 3 – Oligochaeta, Hydrobidae, Chironomidae - can be considered as dominant taxa in the overall abundance of the site's community. Representatives of the bivalve molluscs *Cerastoderma glaucum* and Polychaeta *Marenzelleria* spp formed a relatively large, significant component in the total macrofaunal abundance at the managed site. The frequency and dominance of macrofaunal taxa in the unmanaged area is summarized in Table 4.1.2.

Table 4.1.2. The frequency and dominance of macrofaunal taxa at unmanaged area.

	Rzucewo, PL, (R3), unmanaged area			
Taxa	**frequency [%]**	**Occurrence frequency**	**percentage [%]**	**Abundance dominance**
Oligochaeta	100	absolutely constant	54.2	absolutely dominant
Polychaeta				
Hediste diversicolor	100	absolutely constant	1.9	
Marenzelleria viridis	58	constant	1.3	
Pygospio elegans	17	accidental	2.2	
Manayunkia aestuarina	8	accidental	0.4	
Bivalvia				
Limecola balthica	83	absolutely constant	0.7	
Cerastoderma glaucum	75	absolutely constant	2.1	
Mya arenaria	33	rare	0.2	
Mytilus edulis	25	rare	0.1	
Gastropoda				
Hydrobidae	67	absolutely constant	28.5	absolutely dominant
Theodoxus fluviatilis	17	accidental	0.1	
Crustacea				

Rhithropanopeus harrisi	33	rare	0.3	
Corophium volutator	33	rare	0.9	
Corophium multisetosum	17	accidental	0.1	
Corophium juv.	17	accidental	0.1	
Gammarus salinus	17	accidental	0.1	
Gammarus zaddachi	8	accidental	0.1	
Gammarus deubeni	8	accidental	0.1	
Gammarus juv.	58	absolutely constant	0.2	
Heterotanais oerstedti	17	accidental	0.4	
Cyathura carinata	25	rare	0.2	
Idotea sp.	--	--	--	--
Chironomidae	100	absolutely constant	5.8	subdominant
Number of taxa	20			

There were 20 taxa in total recorded in the unmanaged area (Table 4.1.2), 7 of them were considered absolutely constant, although only 3 – Oligochaeta, Hydrobidae, Chironomidae - can be considered as dominant taxa in the overall abundance of the site's community. *M. viridis*, *L. balthica* and *Gammarus* spp were constant species at the unmanaged site with relatively high abundance compared to the other taxa. The total macrofaunal abundance in the unmanaged area was almost double the values recorded at the managed station (Table 4.1.3). Oligochaetes dominated in abundance at both stations, ahead of Hydrobidae and Chironomidae.

Table 4.1.3. Average abundance [indiv./m^2] and biomass [g/m^2] of particular taxa in managed (P1) and unmanaged (R3) sites.

	Average abundance [indiv./m^2]		**Average biomass [g/m^2]**	
Station Taxa	**P1**	**RZ3**	**P1**	**RZ3**
Oligochaeta	9124.4	20328.3	2.571	6.131
Polychaeta				
Hediste diversicolor	222.2	712.8	4.331	31.892
Marenzelleria viridis	695.6	491.4	1.942	0.249
Pygospio elegans	140.0	826.7	0.197	0.272
Manayunkia aestuarina	106.7	160.0	0.011	0.005
Bivalvia				
Limecola balthica	21.7	255.3	1.802	15.825
Cerastoderma glaucum	1506.7	797.0	32.383	23.726
Mya arenaria	24.8	60.0	2.231	15.198
Mytilus edulis		15.6		0.863
Gastropoda				
Hydrobidae	7760.0	10696.7	24.817	22.513
Theodoxus fluviatilis		40.0		1.097
Crustacea				
Rhithropanopeus harrisi	80.0	103.3	3.329	8.260
Corophium volutator	33.3	341.7	0.054	0.801
Corophium multisetosum	76.7	26.7	0.160	0.024
Corophium juv.	35.6	33.3	0.006	0.005
Gammarus salinus	13.3	26.7	0.055	0.236
Gammarus zaddachi		40.0		1.500
Gammarus deubeni		40.0		0.768
Gammarus juv.	20.0	81.9	0.015	0.089

Heterotanais oerstedti	84.4	153.3	0.017	0.609
Cyathura carinata		80.0		0.284
Idotea sp.	13.3		0.001	
Chironomidae	3213.3	2160.6	0.350	0.600
Total mean:	23172.0	37471.3	74.27	130.95

In terms of biomass, representatives of Bivalvia and Gastropoda dominated, as these were weighed together with shells. However, the biomass of *H. diversicolor* (Polychaeta) (absolutely dominant) and the other bivalve representatives *L. balthica* and *M. areanaria* in the unmanaged region was significantly higher than in the managed one.

The observed seasonal changes reflect the natural life cycle of individual macrobenthic components, with peaks in abundance in late spring and fall (Figure 4.1.1). Monthly changes in total macrofaunal abundance are due to changes in abundance of the dominant taxa, although some other, less abundant taxa can show a similar pattern of seasonal change (see details in Table 4.1.4 and Table 4.1.5).

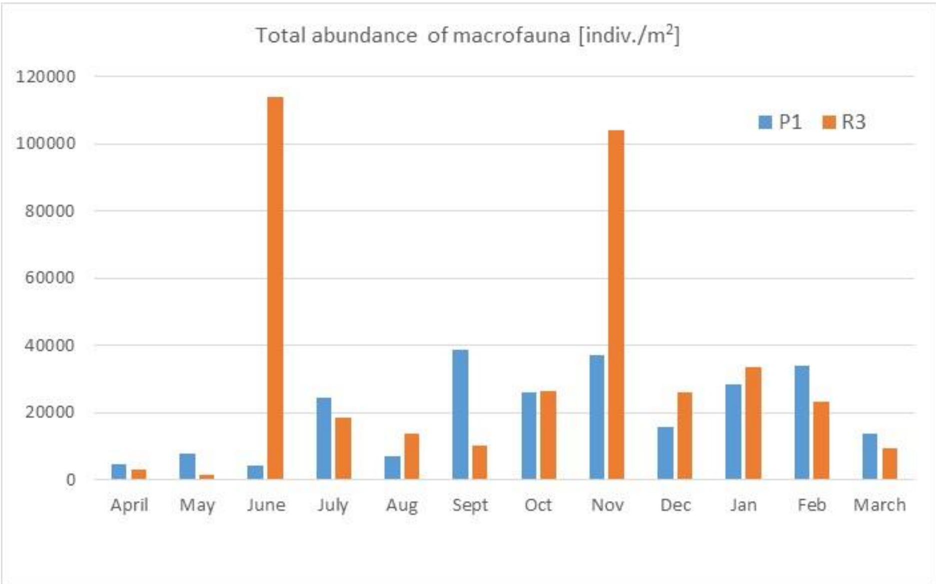

Figure 4.1.1. Seasonal changes in total macrobenthic abundance in managed Puck (P1) and unmanaged Rzucewo (R3) areas in Poland.

Table 4.1.4. Monthly changes in average abundance [indiv./m^2] of particular macrofaunal taxa in the managed area (station P1).

Taxa / Date	**30.04.19**	**24.05.19**	**26.06.19**	**15.07.19**	**27.08.19**	**23.09.19**	**30.10.19**	**20.11.19**	**28.12.19**	**30.01.20**	**21.02.20**	**19.03.20**
Oligochaeta	4333	7413	2587	11827	1733	4520	16333	14333	7987	12787	19040	6600
Polychaeta												
Hediste diversicolor	27	227	147	93	40	173	160	93	293	387	533	493
Marenzelleria viridis	0	0	0	0	0	0	53	173	1373	827	507	1240
Pygospio elegans	0	0	0	0	0	0	0	0	27	0	253	0
Manayunkia aestuarina	0	0	0	0	0	0	0	0	0	0	107	0
Bivalvia												
Limecola balthica	0	13	13	0	0	13	13	0	27	27	40	27
Cerastoderma glaucum	0	0	0	5533	373	6653	27	587	80	67	133	107
Mya arenaria	0	0	0	0	0	67	13	40	13	13	13	13
Mytilus edulis	0	0	0	0	0	0	0	0	0	0	0	0
Gastropoda												
Hydrobidae	0	0	0	320	3827	26547	1453	10067	3000	10867	10667	3093

Theodoxus fluviatilis	0	0	0	0	0	0	0	0	0	0	0	0
Crustacea												
Rhithropanopeus harrisi	0	0	0	0	0	80	0	0	0	0	0	0
Corophium volutator	0	0	40	67	0	13	0	0	0	0	0	13
Corophium multisetosum	53	13	27	173	53	40	53	293	13	80	93	27
Corophium juv.	0	0	0	107	13	13	27	0	40	13	0	0
Gammarus salinus	13	0	0	0	0	0	0	0	0	0	0	0
Gammarus zaddachi	0	0	0	0	0	0	0	0	0	0	0	0
Gammarus deubeni	0	0	0	0	0	0	0	0	0	0	0	0
Gammarus juv.	0	27	0	13	0	0	0	0	0	0	0	0
Heterotanais oerstedti	0	13	0	120	0	187	53	80	53	0	0	0
Cyathura carinata	0	0	0	0	0	0	0	0	0	0	0	0
Idotea sp.	0	0	0	0	13	0	0	0	0	0	0	0
Chironomidae	13	27	1333	6067	840	507	7600	11533	2920	3187	2453	2080

Table 4.1.5. Monthly changes in average abundance [indiv./m^2] of particular macrofaunal taxa in the unmanaged area (station R3).

Station R3 Taxa	**30.04. 19**	**24.05. 19**	**26.06. 19**	**15.07. 19**	**27.08. 19**	**23.09. 19**	**30.10. 19**	**20.11. 19**	**28.12. 19**	**30.01. 20**	**21.02. 20**	**19.03. 20**
Oligochaeta	2440	520	10688 0	13700	4933	4067	17773	25280	12653	27413	19600	8680
Polychaeta												
Hediste diversicolor	80	547	1187	140	27	173	453	3080	1440	707	613	107
Marenzelleria viridis	0	0	0	0	0	13	13	1787	667	880	13	67
Pygospio elegans	0	0	0	0	0	0	0	1493	160	0	0	0
Manayunkia aestuarina	0	0	0	0	0	0	0	160	0	0	0	0
Bivalvia												
Limecola balthica	0	293	1107	60	13	0	53	520	347	80	40	40
Cerastoderma glaucum	0	27	2720	0	40	267	120	2827	1133	27	13	0
Mya arenaria	0	13	0	0	13	0	0	173	40	0	0	0
Mytilus edulis	0	0	0	20	13	0	0	0	0	0	13	0
Gastropoda												
Hydrobidae	0	0	0	0	4800	893	7133	59960	8373	1547	2467	400
Theodoxus fluviatilis	0	0	0	0	0	13	0	67	0	0	0	0
Crustacea												
Rhithropanopeus harrisi	40	0	0	0	0	253	0	80	40	0	0	0
Corophium volutator	0	0	1040	60	253	0	0	0	0	13	0	0
Corophium multisetosum	0	0	0	0	40	0	0	0	0	0	13	0
Corophium juv.	0	0	0	0	13	0	0	53	0	0	0	0
Gammarus salinus	40	0	0	0	0	0	0	0	0	13	0	0
Gammarus zaddachi	40	0	0	0	0	0	0	0	0	0	0	0
Gammarus deubeni	40	0	0	0	0	0	0	0	0	0	0	0
Gammarus juv.	80	13	93	160	13	160	0	53	0	0	0	0
Heterotanais oerstedti	0	0	0	0	0	280	0	0	27	0	0	0
Cyathura carinata	0	0	0	0	0	0	0	160	67	13	0	0
Idotea sp.	0	0	0	0	0	0	0	0	0	0	0	0
Chironomidae	40	0	773	4100	3640	4173	907	8173	920	2720	293	187

Conclusions

The total macrofaunal abundance in the unmanaged area was almost two times higher than it was recorded at the managed station. The unmanaged region had higher biodiversity and more taxa than the managed region. Biomass of *H. diversicolor* (Polychaeta) (absolutely dominant) and the bivalve representatives *L. balthica* and *M. areanaria* in the unmanaged region was significantly higher than in the managed one. This occurred due to a large amount of organic matter, which provided an excellent food source and a possible breeding site. On the other hand, increased organic matter may also cause temporary oxygen deficiency. Therefore the higher abundance of macrofauna in the unmanaged region mainly occurred due to the presence of opportunistic species that are adapted to live in adverse environmental conditions. In addition to *H. diversicolor* and *L. baltica*, insect larvae of Chironomidae and benthic Oligochaetes were the examples of such species. The observed seasonal changes reflect the natural life cycle of individual macrobenthic components with peaks in abundance in late spring and fall. Such seasonality was observed in both areas.

4.2. Mechanical disturbance

Due to frequent and regular traffic (e.g., cleaning, backfill), beaches are gradually transformed into larger areas of sand, while smaller sand hills and newly formed dunes are flattened (Schumacher, 2008). For mechanical cleaning, heavy vehicles such as sieving machines pulled by tractors are commonly used (Figure 4.2.1). This may lead to compaction of the sediments/soils due to the sheer weight of the machinery (Gheskiere et al., 2005). The sediment is compacted especially in the sensitive swash area, where beach wrack is preferably removed. The sediments are also 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 of the disturbance of beach ecosystems through recreational driving on beaches is well-known (Houser et al., 2013). Sand-dwelling microorganisms and invertebrates are hampered as their dwelling tubes are destroyed. They are not able to live in the swash area, and they have to retreat to the undisturbed sections of the beach, if possible (section 4.1). This in turn affects the abundance and biodiversity of the species that feed on the inhabitants of beach wrack infauna by depriving them of their food source (Defeo et al., 2008, section 3.2).

Figure 4.2.1. Beach Wrack removal in Sweden in 2020 (Kalmar) using heavy machinery (W. Hogland).

The presence of machines and corresponding noise/scare effect can disturb wildlife like birds even if the disturbance last only a short time.

Dugan et al., (2003) found that the “cleaned” areas of 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 and the topography is flattened. Dunes, beach wrack and vegetation act as barriers that slow down the wind-induced movement of sand (section 3.3.1/3.3.2). The disappearance of these features may prevent the further formation of dunes. As the beaches become flatter and wider, the abundance and diversity of vegetation decreases, as vegetation requires more stable sand to root. In a 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 a compost layer to build up dunes, or installing sand catching fences can counteract this effect (as shown in Case study 4 within CONTRA; CONTRA report Chubarenko et al., 2021).

4.2.1. Sand removal

An important aspect regarding mechanical disturbance due to beach wrack removal is removal of sand from the beach ecosystems. Analysis of biomass samples collected from Kakumäe beach (Estonia) showed that the sand proportion in total dry weight of beach wrack that is removed from the beach can be as high as 97%, with an average of 58%. On average the share of sand in new wrack was 61.5% (±25.8) and in old wrack it was 53.9% (±33.1) (Figure 4.2.2). In our study it yielded an average of 2.5 kg of sand (dry weight) per 1 m^2 that was removed together with beach wrack from new wrack line and to 4.1 kg of sand per old wrack line. The maximum values reached up to 21.8 kg of sand removal per m^2. Such high values were observed both in old and new wrack (Figure 4.2.3). The smallest amounts of sand were removed together with old wrack d winter period, where the old wrack mostly consisted of the remnants of reed *Phragmites australis*.

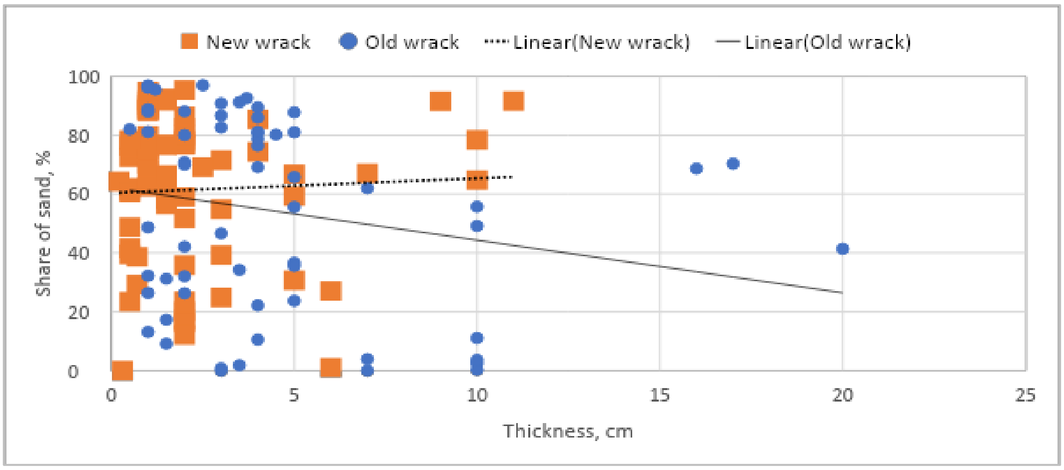

Figure 4.2.2. The share (%) of sand in removed beach wrack on Kakumäe beach (Estonia) in relation to beach wrack thickness (cm) and age status. The share is calculated based on dry weights.

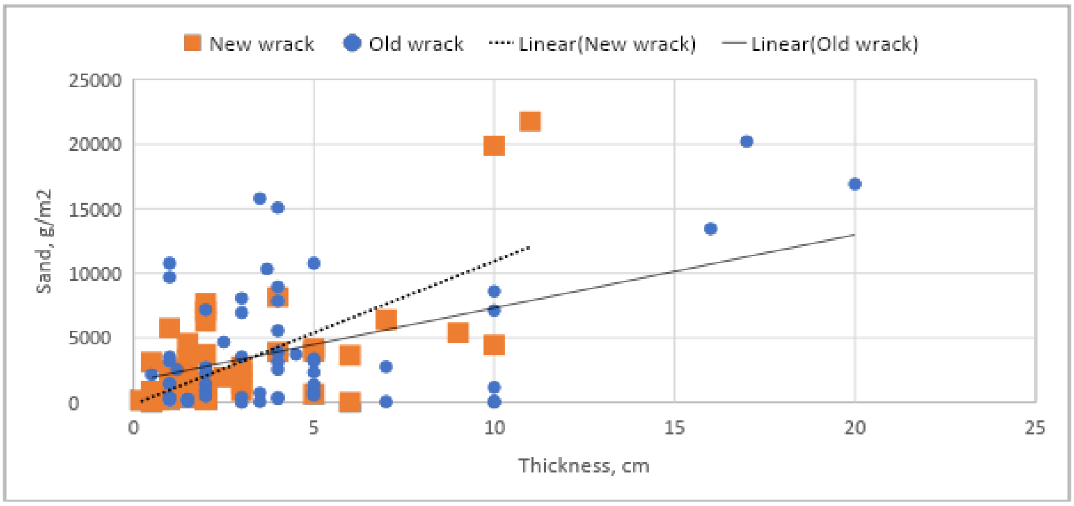

Figure 4.2.3. Amount of removed sand (dry weight, g/m^2) on Kakumäe beach (Estonia) in relation to beach wrack thickness (cm) and age status.

4.2.2. Compaction of sediments and soils

Sand compaction and its potentially negative impact on beach ecosystems was discussed in a comprehensive review of Speybroeck et al., (2006). They highlighted this as a side-effect of beach stabilization measures, such as beach nourishment. Although the findings from this review article can be applicable on a broader scope, research specifically focusing on compaction due to mechanical beach wrack removal are scarce.

Therefore, the compaction of sand was investigated during the CONTRA by several bulk density measurements at respective sites in Denmark, Germany, Russia, and Estonia (Table 4.2.1). In sandy soils, bulk density can be 1.6 g/cm^3, whereas in aggregated loams and in clay soils it can be as low as 1.1 g/cm^3 (Richardson and Jackson, 2017). The bulk density is affected by the structure of the soil (i.e., looseness or compaction), as well as by its swelling and shrinkage characteristics, which depend on clay content and wetness of sediment. However, at beaches with medium sand the lower bulk density values could indicate a stronger sand compaction.

Our results (Table 4.2.1) showed the strongest compaction in the swash area, and it decreases in the lanes of the machines and in the “undisturbed areas” in front of the dunes. In the swash zone the sand was permanently and strongly compacted mostly due to high moisture and wave motion. Very likely, not only weight of the machinery contributed to the sediment compaction, but also the walking of people. This so-called footfall load compaction of the sand and may cause lower biodiversity of the infauna (Schumacher, 2008).

In the back area of the beach, the sand was much more loosely bedded. Therefore, the results largely depended on exact sample placement. Also, some of the sand was churned up 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 was a common practice, these beaches were also included in the investigations, which, however, complicated the interpretation. In comparison to fine-textured clay-rich soils, coarse sandy soils of sandy beaches are considered less prone to soil compaction related issues, such as persistent structural changes affecting water and air infiltration capacity (Nawaz et al., 2013).

Despite these interpretation problems, results indicated that differences between undisturbed areas and travelled tracks existed, even if only slightly. Further studies should include a more detailed comparison with natural/undisturbed beaches. It is likely that temporary vital structures e.g., of burrowing invertebrates may be destroyed by overdrive of heavy machinery and use of sediment forks in beach cleaning (Table 4.2.3). Moreover, numerous studies on the environmental impact of beach nourishment have shown that compaction negatively affects the diversity of beach inhabiting invertebrates (Speybroeck et al., 2006).

Table 4.2.1. Bulk density values [g/cm^2] of sediment samples (medium sand: 0.2-0.3 mm grain size) taken at different positions at the respective sites in Denmark, Germany, Russia, and Estonia in summer 2020.

			Coordinates				Bulk density [g/cm^3]		
Country	Date	Site	N	E	Description	n	Value	Mean	SD
DK	29.07.2020	Køge Managed	55° 26'53.9	12° 11'54.5	from top of sand	4		1.52	0.07
DK	29.07.2020	Køge unmanaged	55° 26'49.5	12° 11'56.9	from top of sand	4		1.48	0.06
DK	24.08.2020	Køge Managed	55° 26.933'	12° 11.913'	From 5 cm below top sand	4		1.49	0.04
DK	24.08.2020	Køge unmanaged	55° 26.830'	12° 11.951'	From 5 cm below top sand	4		1.49	0.06
GE	30.06.2020	Warnemünde managed	54°10.530'	12°04.457'	footpath through people	1	1.33	1.34	0.02
GE	07.07.2020	Kühlungsborn West managed	54°09.133'	11°43.233'	footpath through people	1	1.33		
GE	01.07.2020	Poel "Am Schwarzen Busch" unmanaged	54°00.421'	11°24.588'	footpath through people	1	1.36		
GE	30.06.2020	Warnemünde managed	54°10.529'	12°04.453'	next to (tyre print) lane	1	1.55	1.43	0.10
GE	07.07.2020	Kühlungsborn West managed	54°09.129'	11°43.230'	next to (tyre print) lane	1	1.42		
GE	01.07.2020	Poel "Am Schwarzen Busch" unmanaged	54°00.426'	11°25.023'	next to (tyre print) lane	1	1.34		
GE	30.06.2020	Warnemünde managed	54°10.506'	12°04.496'	within (tyre print) lane	1	1.42	1.48	0.07
GE	07.07.2020	Kühlungsborn West managed	54°09.126'	11°43.229'	within (tyre print) lane	1	1.46		
GE	01.07.2020	Poel "Am Schwarzen Busch" unmanaged	54°00.426'	11°25.025'	within (tyre print) lane	1	1.57		
GE	30.06.2020	Warnemünde managed	54°10.506'	12°04.496'	undisturbed (next to dune)	1	1.38	1.54	0.15
GE	07.07.2020	Kühlungsborn West managed	54°09.123'	11°43.223'	undisturbed (next to dune)	1	1.69		
GE	01.07.2020	Poel "Am Schwarzen Busch" unmanaged	54°00.413'	11°25.013	undisturbed (next to dune)	1	1.55		
RU	25.08.2020	Yantarny Managed	54° 52'03	19° 55'58	footpath through people	3		1.69	0.03
RU	25.08.2020	Yantarny Managed	54° 52'04	19° 55'58	1 m next to (tyre print) lane	3		1.65	0.04
RU	25.08.2020	Yantarny Managed	54° 52'04	19° 55'58	within (tyre print) lane	4		1.46	0.10
RU	25.08.2020	Yantarny Unmanaged sector	54° 51'58	19° 55'58	undisturbed (in front of the dune)	3		1.53	0.02
EST	08.07.2020	Kakumäe managed according to needs	59.45048	24.57585	next to water	1	1.52		
EST	08.07.2020	Kakumäe managed according to needs	59.45048	24.57585	next to beaten track	2		1.64	0.08
EST	08.07.2020	Kakumäe managed according to needs	59.45048	24.57585	within beaten track	1	1.57		
EST	08.07.2020	Kakumäe managed according to needs	59.45048	24.57585	undisturbed (near dune)	1	1.64		
EST	09.07.2020	Pärnu managed daily	58.37467	24.49323	next to water	1	1.70		
EST	09.07.2020	Pärnu managed daily	58.37467	24.49323	next to beaten track	1	1.68		
EST	09.07.2020	Pärnu managed daily	58.37467	24.49323	beaten track	2		1.62	0.05
EST	09.07.2020	Pärnu managed daily	58.37467	24.49323	undisturbed (near dune)	1	1.64		

4.2.3. Effect on abundance and biodiversity

Besides the aforementioned disturbance-related impacts, the removal of beach wrack (BW) itself potentially affects beach biodiversity. According to various studies summarized by Defeo et al. (2008), the BW cover of the beach and the abundance of shorebirds were positively correlated to each other. In addition, the general loss off dune vegetation contributes to increased nestling mortality of dune nesting bird species (Watson et al., 1996). Nests are abandoned with a higher frequency due to disturbances, especially on the areas that lack protective vegetation, which in turn increases the risk of nestling predation. There is a controversy regarding the impacts of driving on dune breeding bird populations in the heavily affected coastal areas (e.g., in Australia, Great Britain, and South Africa) (Watson et al., 1996, Weston et al., 2014). In fact, on beaches with beach cleaning hardly any breeding activity occurs. As noted by Defeo et al. (2008), a ban of off-road vehicles on beaches would have a positive effect on the coastal bird populations. However, whether this will be enough to bring the sensitive shorebird species back remains questionable due to the overall increase in 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 and McLachlan, 1990). Beach wrack constitutes a 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 have found that removal of beach wrack can lead to a decrease in diversity, abundance and total biomass of beach inhabiting meio and macrofauna, including macro invertebrates (section 4.1). Some studies have also pointed out the existence of bottom-up effects in beach wrack harvesting. Therefore, macrofaunal species at higher trophic levels including shore birds may be negatively affected as well (Orr, 2013). Dugan et al. (2003) concluded that recovery of beach ecosystems from disturbances such as beach wrack removal towards an ecological status similar to undisturbed conditions might take years. This seems to be particularly valid for species at higher trophic levels, including shore birds. A modelling study by Orr (2013) showed that shore bird populations on western Scottish beaches may need up to 20 years to recover from a decline caused by BW harvesting.

Within the CONTRA project, four study areas on the Baltic Sea coast of Mecklenburg-Vorpommern and Schleswig-Holstein (Germany) were chosen to investigate the impacts on wildlife: Zingst, Haffkrug, Island of Poel (Timmendorf) and the nearby Island of Langenwerder (a bird sanctuary as a reference area for natural conditions; Figure 4.2.4). The investigations of bird behaviour were planned for four days per site and beach category (unmanaged/managed), each lasting between two and four hours. This time interval covered the cleaning activities, as well as a half-hour period before and after clean-up. The studies were performed within the summer months of July and August 2020 and the results were presented in two theses (state examination and bachelor) of Julia Teich and Marina Manzel (Teich, 2021; Manzel, 2021; in German, University of Rostock).

Figure 4.2.4. Four study sites for wildlife observations off the German Western Baltic Sea coast.

Beach wrack coverage varied considerably from site to site. The lowest coverage was at Zingst beach, with little differences between the managed (0.5-3%) and the unmanaged beach section (2-2.5%) (data not shown). The unmanaged beach section in Haffkrug also had a low degree of BW cover (2%), while the managed section was slightly more covered at approx. 5%. The highest BW cover with two-three times higher values was estimated on Langenwerder (55-70%). These values were also reflected in beach wrack biomass amounts (Figure 4.2.5). The highest values were measured on Langenwerder where about half of the total biomass (1.1 kg/m^2) was in the old beach wrack. New wrack biomass was the lowest in Zingst (0.05 kg/m^2). It was 0.4 kg/m^2 in Timmendorf, while three- and four-times higher amounts were found in Haffkrug and Langenwerder, respectively.

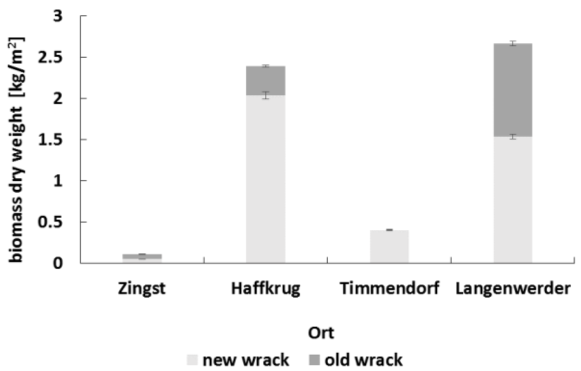

Figure 4.2.5. Mean biomass values [DW=dry weight in kg/m^2; n=3] of old and new beach wrack at the unmanaged beach sites of Zingst (23.07.20), Haffkrug (17.08.20), Timmendorf (25.08.20) and the reference site (bird reserve) of Langenwerder (25.08.20). No old beach wrack was found in Timmendorf. (Germany).

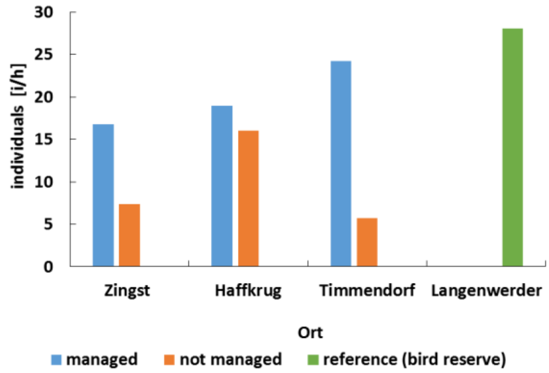

Figure 4.2.6. Bird individuals per hour [i/h] and beach area within 1-4 days (n=1-4) in July and August 2020. Total duration and absolute numbers of individuals: Zingst managed: 10.6h, i=178; Zingst unmanaged: 10.3h, i=76; Haffkrug managed 2h, i=38; Haffkrug unmanaged 2h, i=32; Timmendorf managed 2.4h, i=57; Timmendorf unmanaged 2.63h, i=15; Langenwerder 4.45h, i=125.

Figures 4.2.5 and 4.2.6 show that the beach wrack coverage/amounts were not necessarily correlated with the presence of birds that could feed on beach wrack fauna. With a total of 416 individuals counted, the share of cultural followers/synanthropic species amounted to 84.84% of all observed birds (95 individuals), which prefer likely other food sources. The cultural followers dominated with 89% (i=416) in the managed and unmanaged sites (Table 4.2.1). Individuals of other sensitive shorebird species (i=79) which are susceptible to disturbance and depend on beach wrack infauna, as well as the vulnerable species in the Red List, have only been observed in the reference area.

This tendency of reflecting more natural conditions for the wildlife in the areas without human influence was also confirmed by the presence of individuals per site (Figure 4.2.7) or biodiversity values (Figure 4.2.8). The highest bird individual presence with 28.1 [i/h] and biodiversity with 1.9 [H'] was found in the reference area. The lower biodiversity values at the managed and unmanaged beach sections reflect the low number of species and the dominance of two Larinea species *L. ridbundus* and *L. argentatus*. Surprisingly, the lowest values were counted at the unmanaged sites with 8.2 [i/h] and 1.4 [H'] in total. This could be explained by an attraction effect of foraging on managed beaches.

Especially in case of cultural followers/synanthropic species, beach wrack with its infauna is a less attractive food source than the organic residues from human food, which is richer in fat, protein and calories. In addition, for the birds, this food is easier to access e.g., from rubbish bins, which are mainly found at managed, touristic areas. It was also observed that the flies that were flushed out of beach wrack due to the mechanical cleaning attracted swallows *Delichon urbica* (Hirundinidae).

When beach wrack was dumped into large piles at the border to unmanaged areas, it became even more attractive for the birds to forage. The studies performed in Denmark, Russia, and Estonia confirmed the results from the German investigations (Table 4.2.2) that the observed bird species belonged to the cultural followers and showed an adapted behaviour to the cleaning activities. Flying hunting birds such as swallows (Hirundo sp.) or ground-feeding birds like wagtails (Motacilla sp.) benefited from the beach cleaning and followed the machines.

Table 4.2.1. 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.); 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 and 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

4.2.4. Corresponding noise/scare effect on wildlife

The "cultural followers" birds of the managed and unmanaged sites were optimally adapted in their feeding and distancing behaviour to the anthropogenic impact (Figure 4.2.8, 4.2.9). 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 4.2.10). More than one third of the observed individuals showed neither response to mechanical activities (Figure 4.2.8) nor were they affected by walkers or dogs (Figure 4.2.10). 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 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 decreases. It was observed that some species/individuals were even attracted by the cleaning (Figure 4.2.8, Table 4.8). According to Becker-Carus (2004), birds are able to learn through operant conditioning. In this case, the birds learned that food is increasingly available during beach cleaning (i.e., positive consequence). This positively reinforced the behaviour of staying near the cleaning vehicles or to follow the tracks on the sand.

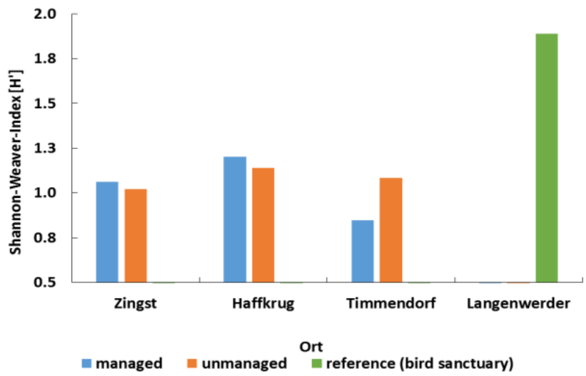

Figure 4.2.7. Biodiversity at the different sites at German beaches according to Shannon-Weaver indices; managed in total (H=1.31), unmanaged in total (H'=1.42) and reference area (H'=1.89).

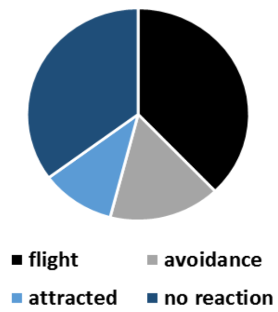

Figure 4.2.8. Individual reactions (i=37) exposed to cleaning (n=4) regardless vehicle type, site and time (Germany). Only *Larus ridbundus* (i=24) and *L. argentatus* (i=13) were considered as they were present at all sites.

Our results showed that besides the presence of humans, beach cleaning activities can have a direct, short-term influence on bird behaviour (Figure 4.2.8, 4.2.9, Table 4.2.2). However, the vehicles represent a multisensory stimulus, which means that different and complex senses of birds were affected. The machines emit a certain level of sound (Table 4.2.3, 4.2.4) 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 (Table 4.2.4).

Table 4.2.2. Overview of all bird species and their behaviour observed at beaches in Denmark, Russia, and Estonia during beach cleaning activities in summer 2020

country	date	managed beach	comments	birds	count	behaviour
DK	29.07.2020	Køge	Before tractor*	*Corvus cornix*	5	
			Before tractor*	*Chroicocephalus ridibundus*	1	
			Before tractor*	*Larus canus*	1	
			After tractor*	*Chroicocephalus ridibundus*	1	
			After tractor*	Motacilla sp.	5	birds flies after the tractor to collect insects from
			After tractor*	Hirundo sp.	25	the sand being turned.
DK	24.08.2020	Køge	Before tractor	No birds observed	0	
			After tractor	*Larus argentatus*	1	
			After tractor	Hirundo sp. / Motacilla sp.	many	lots of flies comes from the sand and birds collect them and flying right behind the tractor.
RU	25.08.2020	Yantarny	Before cleaning machine (15 min)	Columba sp.	7	
			During cleaning machine (60 min)	Columba sp.	8	
			After cleaning machine (15 min)	Columba sp.	6	
RU	25.08.2020	Filinskaya Bay	unmanaged; 15 min observation	Laridae	28	
EST	18.06.2020	Pärnu	jeep & small tractor	Crow	2	flew away when the machine came and returned straight after the machine had gone a bit further
EST	09.07.2020	Pärnu	jeep & small tractor	Crow	2	walking near water. When the cleaning machine came, they escaped. 3 minutes after machines had gone, a crow returned.
EST	18.08.2020	Pärnu	no machinery	Crow	2	walking & flying nearby
EST	31.08.2020	Pärnu	no machinery, few humans	*Haematopus ostralegus*	1	walking
			(10 people within 30 minutes)	*Corvus cornix*	8	walking
				Hirundo rustica	2	flying by

* tractor driving 1 hour for beach cleaning then an excavator is used to push the beachwrack closest to the water into the water. Unknown how long the excavator drives.

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 certain loudness level, the difference of 10 dB is perceived as a doubling of loudness. However, the results should be considered as approximate and preliminary, as determination via diverse mobile phone microphone recordings, short measurement duration and a non-standardised measurement technique was used.

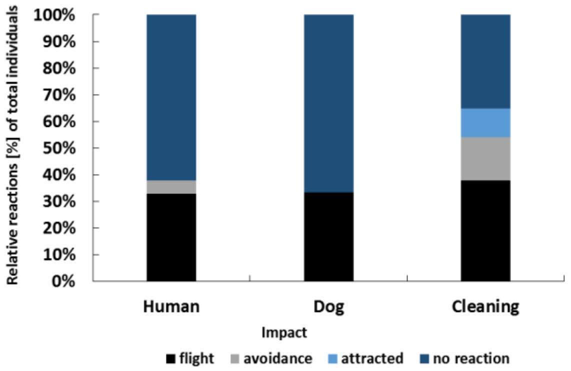

Figure 4.2.9. Responses of bird individuals (i=201) exposed to the three different effects: human(s)/walkers (i=122), dog(s) (i=42) and cleaning activities (i=37) for all study days (n=1-4) and beach sections (n=7, Germany).

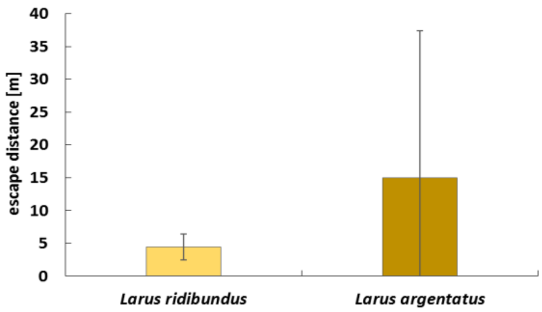

Figure 4.2.10. Mean distances [m] to cleaning vehicles leading to escape for individuals (i=37) of the *Larus ridibundus* (i=24) and *Larus argentatus* (i=13), present at all machine cleanings (Tab. 2).

Table 4.2.3. Overview of machines and their details on possible impacts on the beach ecosystem observed during the German studies.

site	date	kind of machine	company	model	type of use	(learning) weight [kg]	Measured lane tyre width [cm]	Measured mean lane depth [cm]	Charging volume [m^3]
Zingst	23.07.2020	Beachcleaner	Kässbohrer AG	Beachtech 3000	cleaning	3200	214		4.7
		tractor	Case IH	ICU MXU 110	dragging	5680	n.g.	10	-
Haffkrug	17.08.2020	tractor with front loader and rear rake	Massey Ferguson	6100er series	cleaning	~ 4700	60	3	-
		tractor 2 +	Massey Ferguson	7600er series	dragging the trailer	~ 6200	60	3	-
		trailer	Claas	unknown	BW removal	~7500	n.g.	n.g.	44.3
Timmendorf	before Easter each year	Beachcleaner +	Kässbohrer AG	Beachtech 2000	"basic cleaning"	1800	n.g	n.g.	1.5
		tractor	unknown	unknown	dragging	n.g.	n.g.	n.g.	-
Timmendorf	25.08.2020	Tractor with silo tongs and cultivator	John Deere	6320 Premium	cleaning	4550	50	13.2	-
		lorry	Mercedes	Unimog	BW removal	5430	45	11.3	~19.2

Table 4.2.4. Noise measurements [dB] of different beach cleaning activities in Denmark, Germany, Russia, and Estonia measured with mobile phone microphones and respective Apps (e.g., "Sound meter" Denmark, "Decibel Meter – Tools Dev. 2.9.8", Germany). Measurements were performed with different sample intervals [s] and distances [m] to the machine noise.

							Noise [dB]			
country	date	site	cleaning machine	description	sample [s]	n	Max	Min	Mean	Mean without ambient noise
DK	29.07.2020	Køge	tractor with rake	before tractor (= ambient noise)	10	9	71	45	54	
				during tractor front	5	1	85	80	82	28
				during: tractor left side	5	1	86	81	83	29
				during: tractor right side	5	1	84	78	80	26
				during: tractor behind	5	1	87	66	79	25
				tractor driving by	NA	4	86	56	73	20
DK	24.08.2020	Køge	tractor with rake	before tractor (= ambient noise)	10	10	81	47	62	
				tractor 10 meter distance	10	3	85	71	81	18
				tractor 4 meter distance	10	3	87	74	81	19
GE	23.07.2020	Zingst		ambient noise	30	1	62	52	59	
			Beach Cleaner + tractor*	driving by	30	1	80	55	64	6
GE	17.08.2020	Haffkrug		ambient noise	30	1	61	52	58	
			tractor with rear rake*	driving by	30	1	76	56	66	9
GE	25.08.2020	Timmendorf		ambient noise	30	1	65	51	58	
			tractor with silo tongs and cultivator*	driving by	30	1	74	53	69	11
RU	25.08.2020	Yantarny	cleaning machine	distance of 80 m (=ambient noise)	60	1	72	64	67	
			(mesh Ø 1 to 0.5 cm)	distance of 1 m	60	1	96	91	92	25
			(depth 20 cm)	distance of 2 m	60	1	83	78	80	13
				distance of 4 m	60	1	84	77	82	15
				distance of 20 m	60	1	83	78	81	14
				distance of 40 m	60	1	83	79	80	13
EST	31.08.2020	Pärnu	no machinery	ambient noise	10	5	37	45	40	
EST	18.06.2020	Pärnu	jeep and small tractor	ambient noise	10	1	50	70	56	
			with rakes	distance of 4 m	10	1	68	80	75	19
				distance of 30 m	10	1	55	67	63	7
				distance of 100 m	10	1	44	55	47	[-9]
				distance of 300 m	10	1	60	71	67	11
EST	09.07.2020	Pärnu	jeep and small tractor	ambient noise	10	5	58	81	72	
			with rakes	distance of 4 m	6	1	72	81	78	7
				distance of 10 m	6	3	65	80	73	1

* control table 4.2.3 for more details about the machines

Conclusions

As it was shown by Zielinski et al. (2019) and confirmed by this study, the mechanical removal of beach wrack is not the only source of disturbance on managed beaches in comparison to pristine beaches. However, many of such previous studies did not attempt to eliminate all other possible influence factors. Nevertheless, more precise information on the relative impact on beach ecosystems of different human activities would be useful for the development of beach management plans in order to minimize negative environmental impact.

Our results (and especially those obtained from the sandy beaches of Germany) showed that the absence of beach cleaning did not cause a significant increase in biodiversity and numbers of individuals on unmanaged beaches. However, this contrasted with the reference area (bird sanctuary), that represented natural conditions, higher biodiversity and possibly less sand compaction - which is already absent in the unmanaged sites. We conclude that anthropogenic effects such as landscape change and massive human presence have already lead to reduction in biodiversity and presence of flora and fauna. Beach cleaning contributes to ecosystem change, but on the studied managed beaches in Germany it was not the main trigger of environmental change.

Summary

Beach wrack landings

Information regarding beach wrack landings across the Baltic Sea both on a local and larger scale is scarce. However, research carried out under the CONTRA project has given important baseline information and forms a solid foundation for further investigations. Based on the primary predictive models of beach wrack accumulation areas during the late autumn period across the Baltic Sea region, hot-spot areas (production up to 4,000 g per m^2 per month) were found in the Kattegat area, western and eastern coasts of Sweden, along the southern coast of Finland, western coast of Estonia and in the Gdansk Bay (Kotta et al., 2020). Production hotspots were sporadically also found along the eastern coast of Finland up to the northernmost parts of the Bothnian Bay, as well as on the shores of St. Petersburg. The remaining areas of the Baltic Sea had a lower beach-cast production potential (approximately 0-1 kg g per m^2 per month) (Kotta et al., 2020).

Beach wrack landings are highly seasonal – our observations under the CONTRA confirmed that the largest amounts of beach wrack reach the beaches with autumn storms at the end of vegetative season. However, the end of 2019 and winter 2020 were extremely warm and stormy with no ice cover, and this should be taken into account when interpreting the results. Other periods of higher beach wrack landings can be noted in May-June and in August.

Depending mostly on the nearby dominating benthic habitats, exposure to currents, wind and waves the amount of beach wrack varied greatly between the studied beaches during the CONTRA project. The largest amounts were found on the beaches of Poland and Denmark, where the beach wrack amount per 100 m long beach section was estimated as high as 203 m^3 at Rzuzewo (Poland, unmanaged), 140 m^3 (Køge, Denmark, unmanaged), 124 m^3 (Nyborg, Denmark, unmanaged) and 87 m^3 (Køge, Denmark, managed). In other areas the respective landings were usually less than 30 m^3 of beach wrack per 100 m long beach section. On some beaches beach wrack amounts were negligible year-round, e.g., on the Puck beach (Poland, managed) and unmanaged section of Kühlungsborn West (Germany), where the wrack amounts were mainly below 1 m^3.

Beach wrack species composition

The biodiversity of beach wrack composition mostly depended on nearby prevailing marine benthic habitat types and dominating algae and macrophytes (e.g., Torn et al., 2016). With greater storms and intensified water activity the material can be carried to the beaches also from a further distance, but this is rather rare. In general terms, compliance between the samples of beach wrack and submerged vegetation is possible when the alongshore currents are weak and the material on the beach originates from the adjacent sea areas. The higher wave events have been proven to have a significant effect on the thickness and the amount of beach wrack, however, no significant influence on the species number was noted (Suursaar et al., 2014).

The geomorphology of the coast can also influence the species composition of the beach wrack. Near rocky areas, a higher proportion of macroalgae, which are detached from the rocks during storms, leads to their dominance in an algal beach wrack. On sandy shores, seagrass and other higher plants dominate. However, the wrack structure also depends on the buoyancy of species due to their specific morphology.

Species composition showed great variability through the studied beaches and differences in the composition slightly varied between new and old wrack. A significant decrease from new to old wrack occurred in the abundance of species belonging to phylum Chlorophyceae. Specimens belonging to this taxon in the Baltic Sea region are annual filamentous algae which degrade quickly. Due to degradation, especially within the old wrack, there is a likelihood of confusion between green and brown algae, land plants, and other material being integrated in beach wrack.

On the beaches of Germany and Denmark the angiosperms (mainly *Zostera marina*) are dominant species within the beach wrack. This reflects the natural habitat of *Z. marina*: both countries are in the western Baltic Sea where the salinity is higher than along the coasts of countries in the eastern Baltic Sea region. Also, soft-bottom benthic habitats dominate there.

In Poland, Estonia, and Russia, Rhodophyceae had a greater proportion in beach wrack composition. Phaeophycean were evenly distributed within the wrack of the investigated beaches. Angiosperms were randomly found on these surveyed beaches of Poland, Estonia, and Russia, but this depended on nearby benthic habitats. In Estonia there were regions where eelgrass was the dominant species in the beach wrack.

Residence time

Beach wrack residence time spatial variations substantially differed due to variations in hydrodynamic conditions and characteristics of the coastline. Beach wrack residence time varied greatly on different beaches of the Baltic Sea. For example, the long-term presence of wrack is typical for Kakumäe beach in Estonia. Beach wrack was on the beach during the whole study period (336 days) in its unmanaged section. Wrack was observed in the managed section of the beach until it was removed during the cleaning. However, a short period of beach wrack residence was observed at Otradnoye beach in Russia. The residence time ranged between 1-25 days and in average it was below 6 days. The short residence time of beach wrack is typical for most of the beaches of Kaliningrad Oblast (Russia).

It is important to take into account the peculiarities of the wrack residence time to plan management activities. Short residence time can be a limiting factor for a successful beach wrack harvesting. To improve efficiency, it is necessary to apply special measures in such conditions. For example, a possible optimization solution could be the use of webcam observations to coordinate harvesting activities (relevant for Kaliningrad Oblast and the other areas with short beach wrack residence time). At the same time, for beaches with a long natural wrack residence time the wrack can be an important component of the terrestrial ecosystems, for example, as a source of nutrients for beach plants or food, or a shelter for invertebrates.

Aeolian dispersal

A detailed understanding of the mechanisms of aeolian and wave dispersal of beach wrack on the beaches requires some additional research. However, it is possible to draw some preliminary conclusions that are significant for the CONTRA project to make some recommendations for management options:

- beach wrack can accumulate in the beach vegetation zone and contribute into the allochthonous nutrient input into terrestrial ecosystems on some beaches. This is important for growth and diversity of dune vegetation on these beaches.
- different species of algae in beach wrack are differently involved in this process. Most of the filamentous algae do not disperse back to the beach due a rather dense, compact structure and they consolidate at a short distance from the water line. However, several perennial species (e.g., *Fucus vesiculosus*, *Furcellaria lumbricalis*) have a branchy structure of the thallus with higher air resistance after drying and therefore more easily carried by the wind.
- on the south-eastern Baltic study sites it was found that beach wrack accumulation was the most intensive in the late autumn, but also in winter and in early spring. The accumulation was smaller in summer. Apparently, this was due to increased storm activity during these seasons, and due to changes of algae species composition of the beach wrack in the different seasons. The proportion of filamentous algae increases up to 85-90% in summer. Many species are opportunistic and their abundant vegetation is partly caused by the Baltic Sea eutrophication. The beach wrack, which mostly consists of filamentous algae, has a rather

dense, consolidated structure. The aeolian dispersal of such wrack is smaller and its significance for the terrestrial beach vegetation zone is apparently smaller, too. The wrack could be flushed back into the sea, which can lead to further eutrophication of coastal waters. Therefore, the removal of such a wrack from the beach is justified in certain seasons. This can contribute to the improvement of the water quality in the Baltic Sea, and the harvested wrack can be used to benefit economy, dunes restoration, etc. (see CONTRA-Report Chubarenko et al., 2021). Thoughtful seasonal planning of beach clean-up allows to partially avoid conflicts of interest between the beach ecosystem and the tourism industry.

Beach management planning should take into account the fact that for some beaches the wrack can be a significant source of nutrients for dune vegetation.

Degradation

The litter bag experiments carried out in Poland and Estonia examined the degradation rates of the selected species groups (filamentous algae, higher plants, perennials, characteristic for the study area) in different environments (submersed in the water, in a beach above the sediment or buried in the sand) for up to one year in 2019-2020.

The degradation of beach wrack was significantly influenced by decomposition time, species composition, and placement of the wrack on the beach. In both sites (Estonia, Poland), significant weight loss occurred within the first month when 14 to 85% of initial dry weight was lost. After four and more months the changes in remaining biomass were minor. The results were in accordance with some previous short-term studies showing that the major loss of weight of beach wrack may occur within the first 10 days (Jędrzejczak, 2002a, Lastra et al., 2014). As expected, filamentous algae decomposed more rapidly compared to the higher plants and perennials. Rapid decline of biomass of filamentous species during the first months were followed by a gradual decrease up to the 90% level. More surprisingly, *Furcellaria* showed a considerably high decomposition rate despite of relative sturdy thalli. In Estonia, *Fucus* was the most resistant to decay. *Fucus* lost 60% of initial biomass during one year, while *Furcellaria* lost 99% and *Myriophyllum* lost 98%.

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 placement of wrack above the sediment or buried in the sand. The decline of plant material buried in sand in the driftline was faster compared to the wrack that was buried in the sand near dunes. While the degradation of *Zostera* submersed in water was similar to the degradation rate of filamentous algae, the species showed significantly higher resistance when they were buried in the sand.

The Baltic Sea is a seasonally varying system 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, with maximum rates obtained when algae decayed in a wet environment (Lastra et al., 2015).

Greenhouse gas emission during the beach wrack degradation process is an important research topic that requires more studies. This information is very valuable for composing the present-day coastal carbon budgets to better understand and map the coastal changes, study beach management options, general eutrophication issues and climate-related issues of wrack accumulation. As was demonstrated by Liu et al. (2019), the location of the beach wrack in regard to moisture content is important as it is possible to reduce atmospheric CO_2 emissions e.g., by relocating beach wrack from the water's edge to drier dune areas. At present, 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 very large piles, since certain weather conditions such as rain and high temperature may trigger organic degradation. Therefore, the relocation of beach wrack to drier dune areas should consider this effect in the future management of beach wrack. More detailed studies regarding the emissions of greenhouse gases of such beach wrack relocations is needed. Some management practices, such as transport of beach wrack back to the water by tractors may not be advised in some cases when greenhouse gas emissions are a concern.

Nutrient availability

Nutrient concentrations varied highly in time and space. In some months very high nutrient concentrations were observed. This can be an indication of intense decomposition of marine detritus or delivery of nutrients from land (natural or anthropogenic sources). Concentration of phosphate and ammonia in pore water were usually higher and concentrations in nitrate were lower than in water column, what is typical for the coastal zone. Phosphate concentrations in pore water under the detritus at the beach were higher compared to that obtained in the water column.

In most cases at all stations within a given month, Ctot, Ntot, and Ptot content in detritus decreased in a following order: wrack from water> wrack from surface layer of beach sand> wrack from deeper layer of beach sand. The same pattern also occurred for water extractable forms of nitrogen and phosphorus (the most labile forms). This reflects gradual decomposition of organic matter after deposition to the beaches. The labile forms of phosphorus made up 18 to 73% (49 ± 165%) of total phosphorus and the lowest values were in the detritus collected from the deeper layers of the beach sediment. The share of labile forms of nitrogen in total nitrogen ranged from 0.04 to 8.2% (1.6 ± 2.6%). This increase occurred due to nitrification processes.

It is possible to remove a significant amount of nutrients from the marine environment by removing beach wrack. Rough estimates show that for 1 t dry weight of organic material collected, the weight of total phosphorus ranges from 1 to more than 2 kg, and in nitrogen from 16 to 32 kg. Such a load delivered to the sea can be responsible for 1-2 t phytoplankton biomass production.

Hazardous substances

In shallow coastal waters with extensive sea meadows, macrophytobenthos constitutes an important element of the ecosystem, both in terms of functioning and biomass. During storms some of the plants forming the meadows are detached from the bottom of the sea and washed up on the shore/beaches. The shoring also includes floating filamentous algae, such as e.g., *Pylaiella littoralis* and green algae such as Enteromorpha, which are not the part of underwater meadows, but can be transported from offshore areas. In most of the coast, the beach wrack does not affect much the people who live nearby. However, in certain areas large beach wrack entrapments occur. This creates problems not only for local inhabitants and authorities, who are responsible for maintaining the beaches, but also for the local beach ecosystem.

Seagrass and algae wrack release several constituents during decomposition, which alter the coastal biogeochemical cycles and influence the organisms. This includes nutrients and dissolved organic carbon, which affect flora and microbial activity, and heavy metals – which creates risk for biota. Also, emission of volatile components (H_2S, Hg^0, ^{137}Cs) from decaying plant material might constitute a risk for human health, as well as for the climate (methane).

A recent study performed within CONTRA in the Bay of Puck (sheltered part of Gdańsk Bay) indicated that the concentration of mercury on managed beaches (where a few living algae occurred) was lower than in the unmanaged sites, where decomposing wrack was collected. However, in the unmanaged station, concentration of mercury in live algae was similar to those at managed areas. This indicates that although biological material from the bay accumulates Hg at the same rate and is characterized with the same mercury concentration in both sites, accumulation does not stop after wrack 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 pathway could be mercury capture from atmosphere, where it occurs due to low emission from local sources. This means that unmanaged beaches may not only transfer mercury from beach cast via accumulation in live algae and subsequent release, but additionally enhance mercury flux to the beach from other local sources.

Also, chromium concentrations deserve further investigations. The observed difference between Cr levels in sand from the managed beach (Puck) and from sand impacted with algae (Rzucewo) were significant. The measured values indicated 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 wracked algae decomposition. Although the data for chromium were only available for one sampling campaign (July 2019), the preliminary results suggest that beach wrack can be a source of metals to the coastal environment.

Results of PCBs and PAHs show that beach wrack can accumulate those contaminants, too. High concentrations of PCBs at R3 station were probably connected to an unknown pollution source. Close to this station, fishermen moored their boats and put them on the land, which can be an additional source. On the other hand, results from impacted and unimpacted sands suggest that beach wrack adsorb PAHs and PCBs from the beach and their concentration are lower in the impacted regions. However, the accumulated contaminants sooner or later will be released back to the environment. The fate of PCBs and PAHs in the investigated region is more complicated than suspected and should be further investigated.

Based on the obtained results, we can confirm that 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 released to the coastal zone during decomposition of organic matter, partly into the groundwaters, which are returning to the sea, and partly to atmosphere via volatiles. Presence of large quantities of organic matter and the fact that the contaminants were already absorbed by marine plants and algae results in enhanced bioavailability of the contaminants, as compared to the seawater where these contaminants came from. The process is cyclic – the contaminants are removed from the seawater and sediments by marine plants and algae in the areas that locate at a considerable distance from the coastal zone. In case of the Puck Bay, this included the entire bay and Gulf of Gdańsk. They are then washed ashore, 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 food chain. Breaking this chain by removal of beach wrack after deposition can result in the depuration of the ecosystem.

Litter

Presence of litter in the marine environment and on beaches is a global problem. Beach litter can be of marine origin (that is carried to the beach by currents and waves) or of land-based origin (e.g., left to the beach by visitors or carried by winds). From beaches the litter can move either into the water environment, move towards inland, or be ingested by birds and animals. Beach litter has significant environmental, economic, and psychological negative effect (e.g., Galgani et al., 2019; Wyles et al., 2016). Litter directly affects the beach ecosystems and brings more responsibilities to municipalities in order to keep the beaches clean. Nevertheless, it is easier for humans to remove the litter from the beaches than from other marine ecosystem components.

The most widespread litter material on the studied managed beaches was plastic (72%) with most common items being cigarette remains, food containers and candy wrappers. Our findings suggest that most of the litter on managed beaches is related to leisure activities and originate from land-based sources.

Throughout the study period, the largest number of litter items were collected from Estonian and Poland's beaches where the record "catches" were 127 and 116 items per 100 m of beach section, respectively. Both records originated from managed beach sections. These managed beaches were close to city centres and were very popular among year-round. On other studied managed beaches (representing semi-rural areas) in Denmark, Sweden, Germany, and Kaliningrad the number of litter items remained mostly under 20 items per 100 m of beach section. This up to 20 litter items per 100 m beach section is considered to represent good environmental status regarding marine litter.

Most of the macro- and mesolitter found on the beaches was related to beach wrack lines and found either together with old beach wrack or in the new beach wrack. Microlitter occurred both within the beach wrack and in the beach sediment. Out of 129 analysed biomass samples from Kakumäe beach, Estonia, 43% samples contained some microlitter items in size range of 1-5 mm. In the Filinskaya Bay, Russia, out of 109 processed samples, 28% contained mesolitter. 77% of the findings were pieces of polyethylene.

The amount of litter both within the algae and in the sediment should be monitored on a local basis and taken into account when searching for further uses of the removed wrack. The amount and nature of litter significantly affects the treatment and possible further uses of beach wrack.

Mechanical disturbance

Disturbance effects due to beach management to the beach macro and meiofauna was studied on the beaches of Poland. The total macrofaunal abundance in the unmanaged area was almost double of what was recorded at the managed station. The unmanaged region had higher biodiversity and more taxa than the managed region. Biomass of *H. diversicolor* (Polychaeta) (absolutely dominant) and the bivalve representatives *L. balthica* and *M. areanaria* 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 provides an excellent food source and 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. baltica*, are insect larvae of Chironomidae and benthic Oligochaetes. The observed seasonal changes reflected the natural life cycle of individual macrobenthic components with peaks in abundance in late spring and fall, what was observed in both areas.

As already mentioned by Zielinski et al. (2019) and confirmed by our studies, the mechanical removal of beach wrack is not the only source of disturbance on managed beaches in comparison to the pristine beaches. In agreement with this, more information on the impact of different human activities on beach ecosystems would be useful for the development of beach management plans, minimizing a negative environmental impact and enlarging the protected areas.

Our studies showed (and specifically regarding the sandy beaches of Germany) that the absence of beach cleaning was not associated with a significant increase in biodiversity and numbers of individuals on unmanaged beaches. However, this contrasts with the reference area (bird sanctuary) that reflected the "real" natural situation with higher biodiversity and less sand compaction. We concluded that anthropogenic effects such as landscape change/development and massive human presence have already lead to a decreased biodiversity of flora and fauna. Although beach cleaning contributed to the whole ecosystem change, it was not the main trigger of changed environment on the studied managed beaches in Germany.

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