Deposition of large organic particles (macrodetritus) in a sandy beach system (Puck Bay, Baltic Sea)*

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Abstract

The aim of this study was to evaluate the amount of organic macrodetritus deposited on the sandy shores of the southern Baltic, and to determine the type of washout material and their chemical composition (carbon and nitrogen).

Over 900 samples of macrodetritus (particles retained on a 0.5 mm sieve) were collected from seven sampling locations along a 120 km stretch of coastline in Poland at monthly intervals in 2002. Analysis of the C and N content of several categories of detritus supplied information about seasonal changes in and the ageing of algal debris, and indicated that the amount of carrion is constant; the latter is apparently always metabolised very rapidly. The annual deposition of macroalgal

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detritus on this coast was estimated at 15 000 tonnes fresh weight, that is around 75% of the primary production of filamentous macroalgae in Puck Bay.

In comparison with the amounts of kelp deposited on sandy beaches in South Africa (Griffiths & Stenton-Dozey 1981), the massive seaweed washouts on Mediterranean beaches (Morand & Briand 1996), or the deposition of algal mats in the northern Baltic (Norkko & Bonsdorff 1996a), the quantities of macrodetritus on the shore in the study area are average, even allowing for the fact that the Baltic Sea is highly eutrophic (HELCOM 2005).

1. Introduction

Drifting algal mats have recently become a problem in shallow, eutrophic seas worldwide (Morand & Briand 1996). On the one hand, the excess organic matter washed ashore or deposited on the seabed enhances the growth rates of suspension feeders (Duggins et al. 1989), while on the other it can create local hypoxia events that are followed by changes in zoobenthos abundance, species composition and the food web (Norkko & Bonsdorff 1996b). The adverse consequence of beach detritus for coastal tourism is obvious (Balance et al. 2000, Malm et al. 2004). Marine plant detritus plays an important role in the global carbon cycle and exceeds three-fold the amount of carbon stored in living marine plants (Mann 1988, Cebrian & Duarte 1995, Duarte & Cebrian 1996). Coastal marine waters are the key areas of plant detritus production and storage (Smith & Hollibaugh 1993). Owing to their permeability, sandy shores have been shown to be very efficient converters of organic matter (Boudreau et al. 2003). To understand the importance of sandy shores in the turnover of organic matter, it is necessary to have a knowledge of detritus production and its biomass. This paper presents quantitative data regarding the deposition of macroscopic detritus on the sandy shores of the southern Baltic. The aim is to answer the following questions:

- How much macrodetritus is washed ashore in a seasonal cycle?
- How much of the production is deposited?
- What type of material does the macrodetritus washout consist of?
- What is the chemical (C/N) composition of different detritus categories?

2. Material and methods

Seven locations along Puck Bay were examined monthly for the presence of macrodetritus throughout 2002. Additionally, two sites (Gdynia and Hel) were investigated at irregular intervals. Each locality consisted of a stretch of beach 100 m long. In each stretch ten 20×20 cm squares were marked at

10 m intervals along the drift line. The upper 5 cm sand layer was removed from each square and placed into plastic bags. In the laboratory, these samples were rinsed in tap water on a 0.5 mm screen in order to remove sand and fine particles. The remaining large particles were sorted into seven categories, counted, weighed wet, and then dried at 60°C to constant dry weight (dw). Measurements of air and sea temperature and salinity were taken at each sampling site. Samples were collected from swash and ground water to determine the amounts of total suspended matter (TSM) and particulate organic matter (POM) (Kotwicki et al. 2005).

Sub-samples of all possible types of macrodetritus were collected throughout the year and analysed for their C & N contents. Samples were acidified in HCl for 10 h to remove calcium carbonate, according to the procedures in Kramer et al. 1994, and analysed using a CHN analyser EA1108. The samples were homogenised before C and N analysis. Throughout this paper, the various forms of detritus are characterised by their C/N weight ratios.

Macrodetritus was collected daily from swash water (0.5 m depth) at the Sopot sampling site in June 2004. Every morning, ten swash water samples (1 dm^3) were collected from the same location on the beach and sieved on a 0.5 mm screen. The remaining algae were weighed to within 0.1 g with an ornithological field balance (Pesola).

The PRIMER (2004) software package was used to calculate multivariate statistics based on the Canberra distance and the Bray-Curtis similarity index on a double-square-root-transformed data matrix.

For the calculations of organic matter deposited onshore and concentrated at the coast, the beach area was taken to be the area between the water line and the first zone of vegetation on the dune. The drift line, where most of the detritus is deposited, was considered to be the 5 m-wide band next to the water line. The swash water zone is the shallow, 10 m-wide water zone next to the water line with an average depth of 0.5 m.

3. Study area

The waters of Puck Bay are brackish, microtidal, and eutrophic. Pelagic primary production in the bay is approximately 190 g C m^{-2} (Witek 1995). According to the scale developed by Brown & McLachlan (1990), the beaches studied here are of intermediate character with medium to fine sand (Table 1). The swash water salinity ranges from 3 to 8 PSU, and its temperature varies seasonally from 0 to 25°C (Table 2). The sources of detritus were identified using data from Pliński & Wiktor (1987), and Kruk-Dowgiałło & Ciszewski (1994). The euphotic zone up to the sandy sediments in the bay was regarded as a source area for filamentous algae production (Urbański & Szymelfenig 2003).

Table 1. Characteristics of the sandy beach at Sopot

Sopot beach characteristics	Value	Source
mean grain size fraction of sand	0.25–0.5 mm	
water content in sand in submerged zone	21% ww	
weight of 1 cm^3 of dry sand	1.82 g	
volume of 1 g of dry sand	0.6 cm^3	Kotwicki 2004
beach slope	3 to 4%	
seasonal changes in beach width	from 20 to 60 m	
exposure rate (Brown & McLachlan 1990, scale)	moderately exposed (18)	
organic matter content in sand (% dry weight)	0.03 to 0.3%	Urban-Malinga 2003
bacteria biomass in sand in the swash zone	1 μg C g^{-1} of sand	Jankowska 2002
meiofauna biomass range	1 to 4 g C m^{-2}	Kotwicki 2004
consumption of organic matter in swash zone	2 to 15 kg fresh biomass m^{-2} $year^{-1}$	Urban-Malinga 2003
decomposition rate of *Zostera marina* in swash zone	12 to 20% dw day^{-1}	Jędrzejczak 2002a
decomposition rate of carrion (fish) in swash zone	0.1 to 0.3 g day^{-1}	Jędrzejczak 2002b

4. Results

What do the macrodetritus washouts contain?

The detritus content at the various localities along the bay differed. Those on the inner part of the bay had more *Zostera*, those on the open sea coast were dominated by shell and tree fragments, while algae were the most common component at Gdynia and Sopot (Fig. 1). The content of macrodetritus deposits changed markedly during the year. Filamentous algae dominated the spring deposits, *Zostera* did so in the autumn, and tree and shell debris were predominant in the winter on the Sopot beach (Fig. 2).

Table 2. Characteristics of swash water from the study area

Feature	Value	Source (own data, where no author is indicated)
swash water: 0 to 0.5 m depth, 0–10 m from the water line		
minimum to maximum swash water temperature	0 to 25°C	
period of ice cover	January–February	
salinity range in swash water	3 to 8 PSU	
mean total suspended matter (TSM) concentration in swash water	50 mg dm^{-3}	
mean total suspended matter (TSM) concentration in ground water	200 mg dm^{-3}	
mean particulate organic matter (POM) concentration in swash water	20 mg dm^{-3}	
mean particulate organic matter (POM) concentration in ground water	50 mg dm^{-3}	
water content in filamentous algae	89%	
organic P content in filamentous algae	0.03% ww	Kruk-Dowgiałło & Ciszewski 1994
organic N content in filamentous algae	0.137% ww	
mean organic matter content in filamentous algae (dw)	58%	
dry algae density (June)	10 g dw cm^{-3}	
wet algae density (June)	0.7 g ww cm^{-3}	
mean concentration of filamentous algae in swash water during the June bloom	0.732 to 3.240 g dw dm^{-3}	own data from 23 measurements, Sopot
estimated biomass of algae in swash water in summer	350 to 1600 tonnes dw	for 0.7 to 3.2 g dw dm^{-3}, for a 100 km length of coast, 10 m wide and 0.5 deep
percentage of organic carbon in dry weight of algae	25%	
production to biomass ratio (P/B) for filamentous algae in Puck Bay	2	Witek 1995

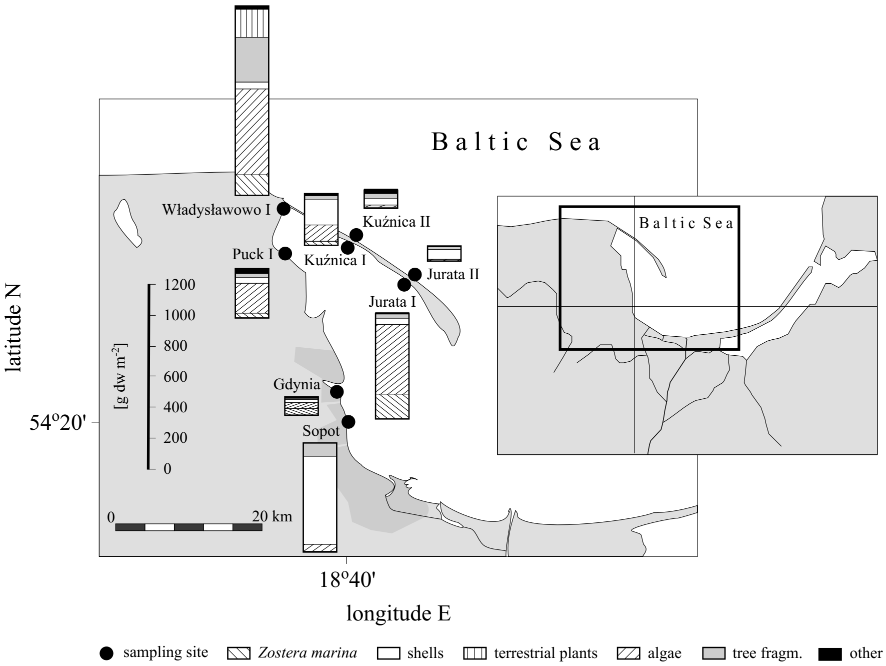

Fig. 1. Study area with sampling localities; the division of the coastline into units of similar deposition type

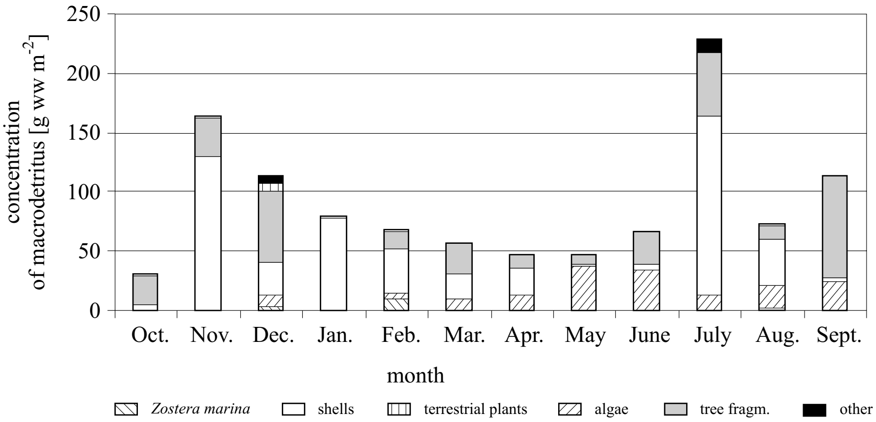

Fig. 2. Seasonal changes in the composition of macrodetritus deposits on the Sopot beach in 2003 (mean value from 10 replicates per month)

How much macrodetritus is washed ashore in a seasonal cycle?

Throughout the seasonal cycle the smallest deposits of detritus occur in winter (mean 34 g dw m^{-2}), the largest in spring and late summer (exceeding 100 g dw m^{-2}, Table 3). This pattern was repeated at all the localities (Fig. 3). The estimated amount of macrodetritus cast ashore from Puck Bay was calculated in this paper as the sum of the monthly mean biomass, and ranged from 1707 tonnes dw to 15 521 tonnes fresh weight (approximately 300 to 400 g C m^{-2} year^{-1}, Table 3). Similar calculations for the algae accumulated in the swash zone in summer produced a standing crop biomass range of 350–1600 tonnes dw for the study area (Table 2).

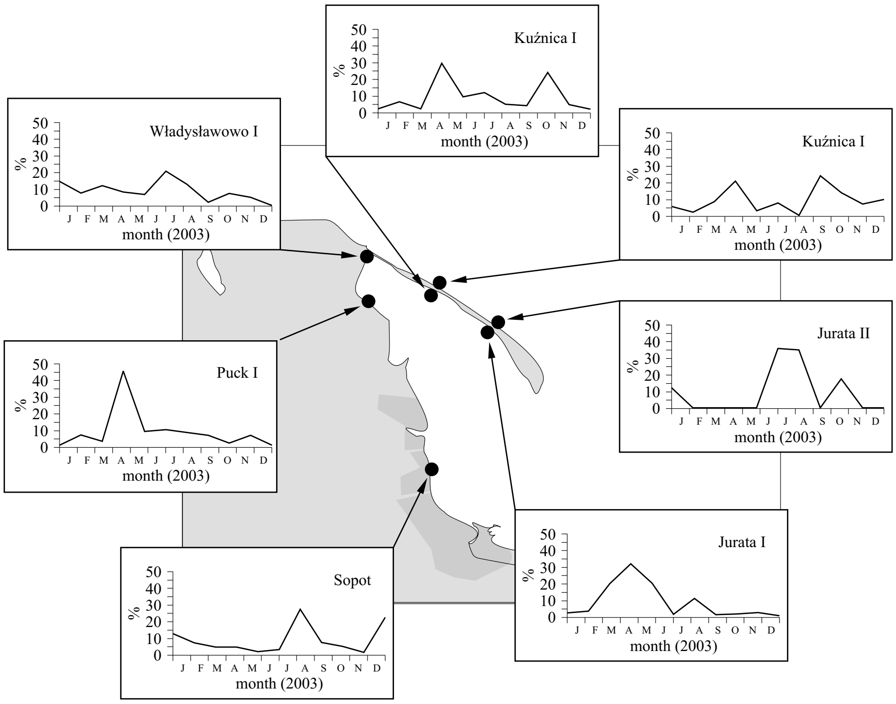

Fig. 3. Seasonality of macrodetritus deposition at the localities around Puck Bay, 2003

What are the C/N ratios of different detritus categories?

The quality of detritus varies among the categories. Refractory matter of wood and old shells were characterised by C/N ratios of more than 100, and freshly deposited carrion and filamentous algae by C/N ratios from 3 to 12 (Table 4). The C/N content changed seasonally within each category, and there were clear differences between the lowest values in the deposition season to the highest values after months of decomposition onshore. The widest range of values was noted for shell debris (C/N range of 20–716), whereas carrion values were constant (C/N range of 3–12; Fig. 4, Table 4).

Table 3. Estimated annual deposition of macrodetritus on the driftline from the study area

		Spring	Summer	Autumn	Winter		Estimated annual detritus deposition	Estimated detritus deposition		N	C	P
		Mean value [g dw m^{-2}]										
Coastal area 360 km^2	Coast length [km]	March–May	June–August	September–November	December–February	Annual deposition	5 m wide drift zone [tonnes dw km^{-1}]	[tonnes dw per area]	[tonnes ww km^{-1}]	[tonnes N km^{-1}]	[tonnes C km^{-1}]	[tonnes P km^{-1}]
Sopot	10	73	238	180	171	662	33	331	276	0.4	3.8	0.08
Gdynia I	15	32	52	23	12	1119	9	134	74	0.1	1.0	0.02
Puck I	15	170	85	48	5	309	23	347	193	0.3	2.6	0.06
Władysławowo I	5	284	649	180	82	1195	30	149	249	0.3	3.4	0.07
Kuźnica I	10	123	85	108	13	330	16	165	137	0.2	1.9	0.04
Jurata I	10	373	226	45	26	669	33	335	279	0.4	3.8	0.08
Hel I	5	0	51	13	9	73	2	9	15	0.0	0.2	0.00
Jurata II	15	0	51	13	9	73	5	82	45	0.1	0.6	0.01
Kuźnica II	15	43	14	61	21	139	10	156	87	0.1	1.2	0.03
Total	100	1098	1451	670	347	3567	mean 17	1707	15521	22	171	5

Table 4. Carbon/Nitrogen (C/N) ratios in the main categories of macrodetritus on the driftline from the study area

Macrodetritus category	Detritus type	Mean	Min	Max	SD	Number of samples
		C/N ratio				
tree fragments	leaves	42.3	16.4	81.9	18.0	11
	fruits	31.6	21.0	49.1	8.9	12
	Pinus cones	98.9	73.5	148.6	22.4	9
	branches	78.1	34.8	152.1	39.1	15
	kernels & nuts	203.8	99.3	393.7	116.4	10
	beech mast	92.2	54.1	197.6	43.1	12
shells	*Mytilus*	23.8	20.1	30.3	3.2	9
	Cardium	182.7	28.8	716.2	226.3	8
	Mya	100.6	50.8	368.3	101.0	9
	Macoma	62.1	21.5	86.5	24.2	8
algae	*Cladophora*	15.8	8.9	31.7	9.8	5
	Fucus	21.9	21.9	21.9	–	1
	Furcellaria	8.5	6.0	10.1	1.5	5
	Pilayella	8.0	7.9	8.1	0.2	2
	Chara	12.9	10.1	17.2	3.7	3
	Enteromorpha	24.1	8.1	69.9	23.8	6
carrion	fish bones, feathers	4.0	3.1	12.1	2.4	14
terrestrial plants	reeds, grass, bushes	57.2	27.1	99.6	25.6	13
angiosperms	*Zostera marina*	17.7	14.6	27.5	4.7	7

What is the relation between the detritus source and the area of deposition?

With the exception of the sea grass meadows, the major sources of macrodetritus (Table 5) are more or less evenly distributed along the coast of the bay (Kruk-Dowgiałło & Ciszewski 1994). The monthly detritus content was compared among all the localities with regard to the minimum, mean, maximum, and SD values for each of the seven categories. Multivariate analysis indicated that three groups of stations are similar with respect to more than 50% of the characteristics (Fig. 5). Jurata, an open-sea site, was the farthest distant from all the others, while Kuźnica, another open-sea site, was grouped with the semi-exposed Sopot site. All the other sites from the inner part of the bay were grouped together (Fig. 5). Daily fluctuations in detritus deposition are very pronounced. This was reflected in the swash water in Sopot, where variations in drifting algae concentrations ranged from 0 to 150 g ww dm^{-3} depending on the sampling location and the day of

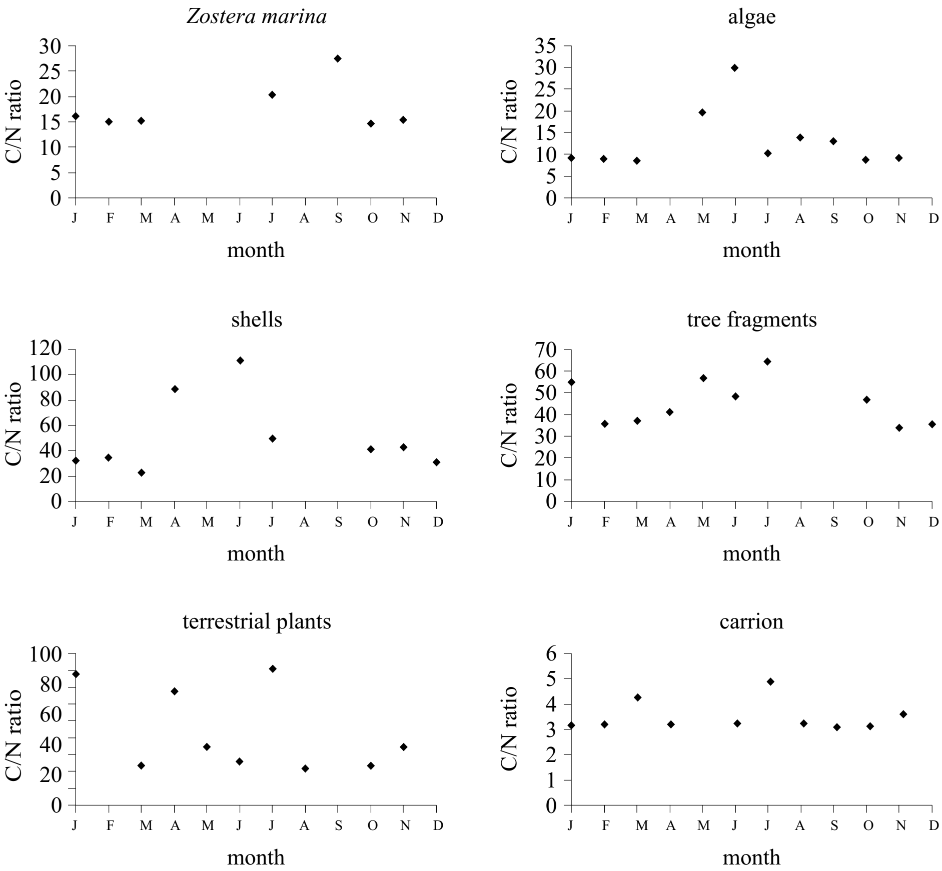

Fig. 4. Seasonal changes in the mean C/N weight ratio for the principal detritus categories on the Sopot beach, 2003 (the different scales illustrate better the changes in particular categories)

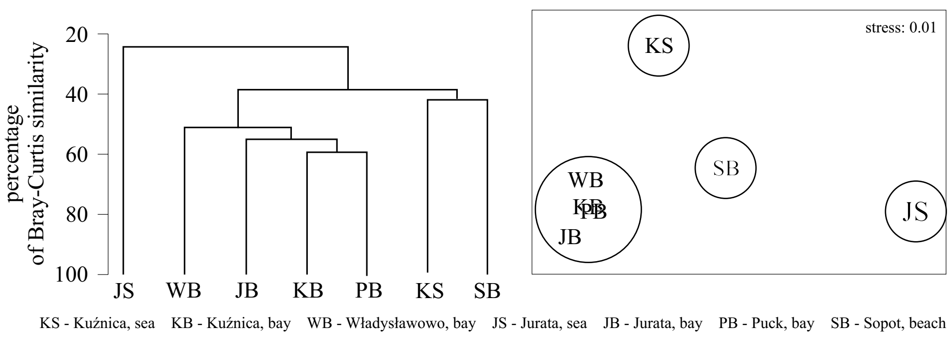

Fig. 5. The similarity of the localities as compared by the annual characteristics of macrodetritus

Table 5. Detritus sources in the study area; the area of the seabed within the euphotic zone is estimated at 324 km^2 (after Urbański & Szymelfenig 2003)

Detritus category	Detritus source	Production to biomass ratio	Mean biomass [g ww m^{-2}]	Remarks	Reference
tree fragments	*Pinus trees*			abundant at the dune top	
	Fagus trees			abundant between Sopot and Puck	
shells	*Macoma baltica*		26		Osowiecki 2000
	Mytilus edulis trossulus	1.6	204		Cuena Barron & Wołowicz 1981
	Mya arenaria		37	production of 50 000 tonnes	Osowiecki 2000
	Cerastoderma glaucum	0.84	45		Cuena Barron & Wołowicz 1981
algae	*Pilayella* & *Ectocarpus*	2	20	biomass estimated at 10 000 tonnes	Kruk-Dowgiałło & Ciszewski 1994
angiosperms	*Zostera marina*	1		biomass estimated at 200 tonnes	Kruk-Dowgiałło & Ciszewski 1994
	Potamogeton spp.	1		biomass estimated at 2300 tonnes	Kruk-Dowgiałło & Ciszewski 1994
carrion	coastal fish	0.5	0.1		Sapota & Skóra 1996
terrestrial plants	reeds, grass, bushes			along the most of the coast	

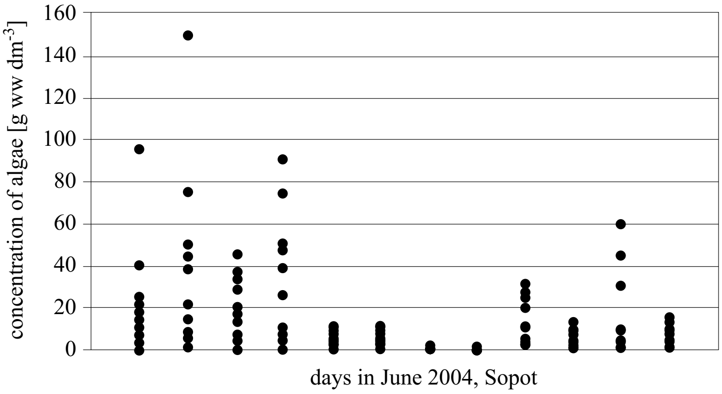

Fig. 6. Daily changes in drifting algae concentrations in swash water (10 samples of 1 dm^3 per day) on the Sopot beach, 2004

the bloom (Fig. 6). Daily fluctuations in macroalgae concentration in swash water and the consequent deposition were very pronounced and varied from 0 to 150 g fresh weight per dm^3 of water.

5. Discussion

Not many quantitative data are available on the amounts of macrodetritus deposited on shores. Deposition on South African and Californian sandy beaches littered with large kelp species has been estimated to range from 94 to 435 tonnes dw km^{-1} annually (Table 6). Antarctic island coasts received 18 tonnes ww km^{-1} yr^{-1} of brown algae (Zieliński 1981). Mediterranean beaches in France and Italy are littered with massive seaweed washouts ranging from 100 000 to one million tonnes of fresh weight (Morand & Briand 1996). Algal mats in the northern Baltic Sea exceed 400 g dw m^2 (Norkko & Bonsdorff 1996a). Compared to the values cited above, the amount of algae found on the shores of Puck Bay are average, even allowing for the fact that the area is highly eutrophic (HELCOM 2005). At present, the phytodetritus deposition on Puck Bay shores is estimated at about 75% of the annual macrophytobenthos production of the basin (filamentous algae production is estimated at 20 000 tonnes; Kruk-Dowgiałło & Ciszewski 1994). Shell debris deposition (estimated at 5000 tonnes) is about 10% of the annual Bivalvia production of the area (Table 5). The share of the local sea grass production that landed on the beach of an African bay was estimated at 19% (Ochieng & Erftenmeijer 1999).

The content of detritus collected for the present study indicates that a very small fraction of it is true litter (plastic, glass, metal, etc). Jóźwiak (1996) studied litter along the Polish coast and recorded an average of five

Table 6. Examples of macrodetritus deposition on sea shores (for calculations of dry weight to wet weight, a figure of 20% was taken for seagrass and 10% for filamentous algae)

Detritus	Original value	Recalculated [tonnes ww km^{-1} yr^{-1}]		Reference
kelp, South Africa	1200–2179 kg m^{-1} yr^{-1}	1200–2179	240–436	Griffiths & Stenton-Dozey 1981
kelp, Antarctic Island	18 tonnes dw km^{-1} yr^{-1}	90	18	Zieliński 1981
filamentous algae during bloom, Sopot beach	50 gC m^{-2} d^{-1}	900	90	Kotwicki et al. 2002
filamentous algae, Swedish Baltic coast	240 g dw m^{-2}	2400	240	Pihl et al. 1999
litter, plastic, South Africa	43 to 164 g m^{-1}			Madzena & Lasiak 1997
seaweed, general	0.2 to 400 kg m^{-2}	200 to 400 000	20 to 40 000	Morand & Briand 1996
mangrove leaves, Florida	3.1 g dw m^{-2} d^{-1}			Dawes et al. 1999
filamentous algae, Finland	440 g dw m^{-2}	4400	440	Norkko & Bonsdorff 1996a
kelp, White Sea	1 m^3 ww m^{-2}			Tzetlin et al. 1997
seagrass, Kenya	6800 tonnes dw/9.5 km	3573	714	Ochieng & Erftemeijer 1999
plastic and wood debris, Caribbean	1.7 to 11 kg m^{-2}			Debrot et al. 1999
filamentous algae	25 tonnes ww km^{-1}			Kędra & Urbański 2005
all kinds of marine organic debris		155	17	this paper, mean value

plastic items per 100 m of coast. This density is too low to be detected by the sampling method applied in the current study. Heavily littered with various kinds of debris, the beach at Curaçao contained up to 11 kg of debris m^{-2} (Debrot et al. 1999). Organic detritus washed ashore usually consisted of algae, both filamentous and kelp (Griffiths & Stenton-Dozey 1981, Eiloloa & Stigebrandt 2001), or sea grass (*Zostera, Posidonia* – Table 6). The abundant shell debris in several localities around Puck Bay had apparently been processed and redeposited, since Polish quartz sands are poor in carbonate (Urban-Malinga & Opaliński 2001). Abundant wood debris and terrestrial plant remains were a clear indication that there should be lignin in the shallow sea sediments, but biogeochemical studies of the bay did not confirm its presence. The River Vistula (Wisła) is the main contributor of terrigenous matter to the area (Witek 1995). The chemical content of fine-grained organic suspensions indicated that algal matter was the main source of POM in coastal waters (Kotwicki et al. 2005). The C/N ratio in the Puck Bay suspensions and surface sediments also confirmed the dominant role of algae as a supplier of organic matter to the seabed (Maksymowska et al. 1997, 2000).

Concern about drifting algal mats contaminating bathing beaches and shallow benthic communities has led to studies on the removal of algae and its processing for agricultural purposes (Eyras et al. 1998). However, observations have indicated that algae deposits on open shores are often redistributed daily by wind and waves (Kiirikki & Blomster 1996, Eiloloa & Stigebrandt 2001). That is why there is hardly any relation between the areas where detritus originates and is deposited. The key elements in Baltic macroalgal mat growth and displacement were identified as exposure, wind pattern, and the salinity gradient between bottom and surface waters (Eiloloa & Stigebrandt 2001). Furthermore, no direct links between point sources of nutrients and algal mat accumulation were detected (Eiloloa & Stigebrandt 2001).

The turnover rate and decomposition of stranded detritus is difficult to assess despite the numerous papers dealing with algal and seaweed decay in semi-experimental conditions (litter bag methods, Jędrzejczak 2002a). On recreational beaches the grinding of macrodetritus by walkers could become an important element in organic matter processing (Węsławski et al. 2000). Filamentous algae have been reported to decay rapidly onshore under summer conditions (a loss of mass of up to 40% in the first week, Kristensen & Hansen 1995, Paalme et al. 2002, Salovius & Bonsdorff 2004). Sea grass is more resistant, with 20% of its biomass surviving after 100 days (Jędrzejczak 2002b). Shells, leaves, and wood debris are ground mechanically, since their very high C/N ratio indicates their refractory character. Carrion and fresh algae are efficiently 'recycled' by numerous sandy beach bacteria, dominated by protein and lipid consumers (Podgórska & Mudryk 2003).

The biomass of macrodetritus washed ashore from the bay is estimated at 22 tonnes of N year^{-1}: this is less than the N supply from fine particles present in the swash zone (estimated at 96 tonnes of N year^{-1}, Kotwicki et al. (2005)). In all, the organic matter (suspended fine particles and macrodetritus) processed in the sandy beach system supplies the bay with 118 tonnes of N, which is equivalent to the contribution from a human population of 27 000 (at 4.4 kg N per person year^{-1}; Schwartz 2004). This amount is negligible in a eutrophic area that receives over 119 kilotonnes of N year^{-1} from Vistula river discharge (HELCOM 2005).

The deposition of allochthonous matter to the bottom of the bay was estimated at 68 g C m^{-2} year^{-1} (Witek 1995). If primary production in the area is assumed to be 190 g C m^{-2} year^{-1} (Witek 1995, Wasmund et al. 2001) and 30% of it ends up on the seabed (Heiskanen & Tallberg 1999), then the rate of deposition will be 68 + 63 = 131 g C m^{-2} year^{-1}. Present estimates indicate that 350 g C m^{-2} year^{-1} is deposited in the coastal narrow belt (100 km long and 10 m wide = 1 km^2). Assuming the area of the bottom within the euphotic zone to be 300 km^2 (Urbański & Szymelfenig 2003), the swash zone contributes roughly 1% of the carbon pool accessible to the benthic biota of the bay.

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