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Spatial Distribution of Pine Pollen Grains Concentrations as a Source of Biologically Active Substances in Surface Waters of the Southern Baltic Sea

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Abstract: Pine pollen is a very important component of the marine environment: it is a valuable source of both carbon and macro- and microelements, and it is also a major food resource for many marine organisms. Its characteristic optical properties distinguish it from other suspended particulate matter (SPM), but it can also distort measurements of the latter. Hence, it affects a range of sea water properties as well as a number of key biogeochemical processes taking place in the marine environment. Pollen concentrations were determined with satisfactory accuracy in samples of sea water taken from selected stations in the southern Baltic Sea in May 2018. This paper aims to highlight the spatial differentiation of pollen levels in southern Baltic surface waters and to show that pollen in May is a significant, hitherto overlooked, source of a great many substances essential for the ecosystem's functioning. Our measurements indicated that pollen was present over the entire area of the southern Baltic studied. Spatially, its concentrations in surface waters differed very widely. Very high levels were recorded both very close to the shore and a long way from it. Any analysis of the influence on the ecosystem of the various substances that pollen brings to the water must take into account the ratio of the concentration of pollen to that of other SPM in the ecosystem. This study showed that even a small concentration of SPM in the central Baltic means that pollen grains can periodically supply substances key to the ecosystem's functioning. In many areas, pine pollen can make up as much as ca. 50% of the SPM in the 1.25–250 µm size range.

Keywords: pine pollen grains; southern Baltic surface water; LISST-100X; organic matter; allochthonous carbon; particle size distribution; suspended particulate matter

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1. Introduction

The Baltic Sea is an inland, shelf sea, surrounded by the Scandinavian peninsula in the north and east, continental Europe in the south and the Danish islands in the west. It is connected to the North Sea through the Danish Straits, Kattegat and Skagerrak, which are shallow waters, so the exchange of Baltic water with the World Ocean is extremely limited. Consequently, every substance that enters Baltic waters has a major impact on the functioning of the whole ecosystem. Scientists have been studying the principal biogeochemical cycles taking place in the Baltic Sea for a long time [1–4]. A great many models have been developed to describe the influx of different substances into Baltic waters and how they are transformed [5–10]. In order to describe precisely how these substances influence key processes in the Baltic, we need first to define precisely all their sources and the magnitudes of their fluxes. The results of the present study show that there is a very important source, hitherto overlooked, supplying very considerable amounts of substances that have a huge impact on how the Baltic ecosystem functions. We are talking here of pine pollen, vast quantities of which reach the Baltic in spring, mostly on the wind from the pine forests that cover very large areas of the coastlands surrounding the sea () [11–14]. The aerial transport of pine pollen is the upshot of complex natural forces associated with the climate, biosphere and geomorphology. Features of the weather, such as wind speed and direction, temperature, insolation, precipitation and air humidity, greatly influence the concentration and dispersal of pollen in the air and also its deposition on the sea surface. It is known that pine pollen can be carried considerable distances by the wind from its point of origin [15–23]. Hesselman [24] demonstrated that pine pollen from Scandinavian forests had been carried over distances of 30–35 km; Szczepanek et al. [25] showed that pollen collected in Kraków had been transported 100 km; Dyakowska [26] reported that pine pollen had been found at distances of 600–1000 km from pine forests; and Campbell et al. [27] recorded pine pollen in the Canadian Arctic as having come from as far away as 3000 km. Pollen grains can also be transported over long distances and re-deposited by flowing waters (rivers entering the sea or marine currents). Hence, the presence of large concentrations of pollen even in central regions of the Baltic is nothing unusual. That pollen is present in the entire Baltic is confirmed by the results of the very latest satellite research, reported by Hu et al. [28], in which the authors of the present paper participated.

Pollen is visible on the water surface as a yellow film. Its concentrations in the Baltic are sometimes so large that they actually form a conspicuous yellow layer on the surface (Figure 1a,b). The ability of pollen to float on the water as soon as it has landed is due to its distinctive structure, which contains two air sacs. How pollen reaches the Baltic from pine forests and its effect on this sensitive ecosystem has never yet been studied. Likewise, the problem of the presence of pollen in the Baltic and the methods of measuring it in an aquatic environment have only recently begun to be addressed: just a few papers have been published on the subject to date [28–31]. The first of these papers describes the method of measuring pollen concentrations (a component of suspended particulate matter SPM) and gives in situ values from Baltic coastal waters near Ustka (Poland). Even these very first measurements in sea water show that during the pine pollen season, surface water concentrations of pollen can be very high. Locally, it can even be the dominant component of SPM in the Baltic. The second paper describes the validation of a method for measuring pollen levels with an LISST100 instrument in the laboratory, confirming that this method for counting pollen grains in the sea is highly efficient. Lienart et al. [31] show that pine pollen in the Baltic Sea can be an important source of food for local organisms, including invertebrates. Finally, Hu et al. [28] describe a method for the remote detection of pollen in Baltic waters using satellite methods. The maps in that paper show that pine pollen is present over almost the entire Baltic Sea. The deposition of pine pollen in the water substantially alters the concentration and composition of TSM. Much research has shown that this organic suspension of pine pollen is also an important source of macroelements for aquatic ecosystems [32–37]. Our own studies show that this is also the case in the Baltic. It is therefore very likely that even minimal amounts of pollen are crucial to the ecosystem's functioning.

(a) (b)

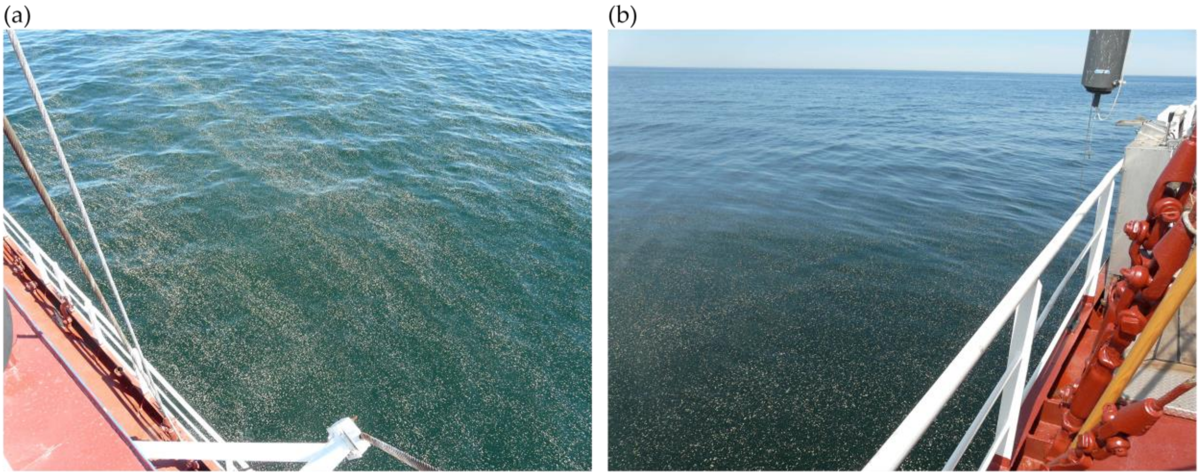

Figure 1. (**a**,**b**) Floating on the water of the Baltic Sea (from the deck of the ship).

Considering the above arguments, the objective of this work is to estimate the concentration of pine pollen grains in surface waters of the southern Baltic Sea. In addition, we want to answer the following questions: how high pollen concentrations can be found in the waters of the southern Baltic and where large concentrations of this pollen were observed. Finally, we want to show that pollen grains are an important source that provides very significant amounts of various substances that have a huge impact on how the Baltic ecosystem functions.

Because pine trees are extremely widespread across the northern hemisphere [11], and its pollen can be transported on the wind over considerable distances, we can assume that the issues discussed in this paper do not apply only to the Baltic. Similar phenomena can be expected in other parts of the world during the pine pollen season. For example, amounts of pine pollen have been measured in the USA: in the waters of the Gulf of Maine [38], Wisconsin lakes [32], Oregon [39] and the Mississippi River [40].

2. Materials and Methods

This research was carried out in the southern Baltic Sea during the pine pollen season. Grains of pine pollen were sampled during a research cruise on board the r/v 'Oceania' in 2018. The exact locations of the measurement stations are shown on Figure 2; the map shows all the measurement stations—those marked in yellow are stations where concentrations of pine pollen were recorded in the seawater. Samples for analysis were taken at 36 measurement stations. The properties of the water samples at each station are listed in Table 1. The water samples were taken from the sea surface layer with a horizontal bathometer and immediately analyzed using a LISST-100X instrument (Sequoia Scientific Inc., Bellevue, WA, USA). Some of the water from the same samples was used for determining chlorophyll a and SPM concentrations. The water transparency (Secchi depth) was measured from on board the ship using a 30 cm diameter white disc.

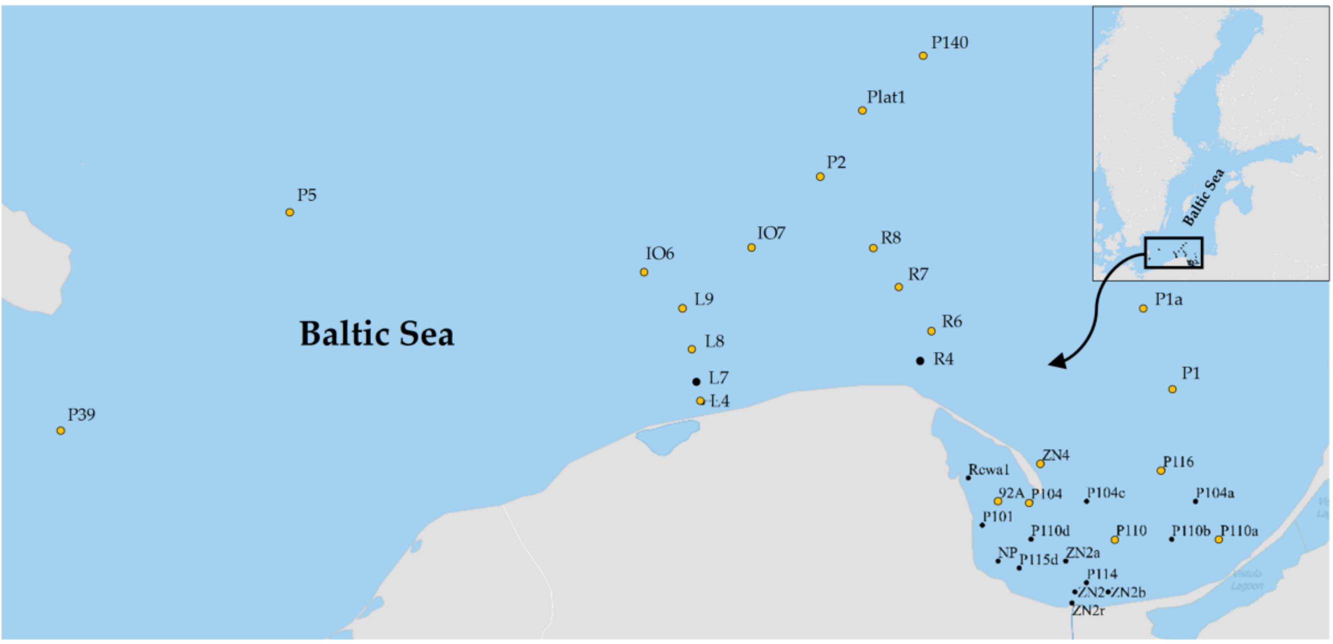

Figure 2. Location of sampling stations in May 2018 in the southern Baltic Sea (large concentrations of pollen grains were indicated by yellow).

Table 1. Characteristic of sampling stations used in this study.

Data	Station	Geographic Coordinates		Secchi Depth (m)	SPM(g m^{-3})	Chlorophyll a (mg m^{-3})
		Latitude (°N)	Longitude (°E)			
14 May 2018	P104	54.58	18.79	6.0	2.41	2.40
14 May 2018	P110	54.50	19.11	5.0	1.99	2.20
15 May 2018	P104c	54.58	19.00	5.0	8.11	4.00
15 May 2018	P116	54.58	19.00	5.5	2.91	3.10
15 May 2018	P1	54.65	19.29	6.5	2.31	2.30
15 May 2018	P1a	54.83	19.32	5.5	1.63	3.50
16 May 2018	P140	55.00	19.23	4.0	4.04	8.40
16 May 2018	Plat1	55.55	18.39	5.0	4.11	4.30
16 May 2018	P2	55.43	18.16	7.5	1.52	3.00
16 May 2018	P39	55.29	18.00	8.5	1.90	1.10
17 May 2018	P5	54.74	15.11	7.5	2.11	2.70
17 May 2018	NP	54.45	18.67	4.0	4.01	4.70
18 May 2018	P115d	54.44	18.75	4.0	2.69	2.03
18 May 2018	P101	54.53	18.61	4.0	1.86	1.14
18 May 2018	Rewa1	54.63	18.55	4.5	1.54	1.14
18 May 2018	92A	55.21	15.98	6.0	2.07	3.20
20 May 2018	ZN4	54.45	18.66	5.5	2.15	3.70
20 May 2018	P110d	54.50	18.79	7.0	2.08	2.50
20 May 2018	ZN2	54.38	18.96	1.5	10.32	39.30
20 May 2018	ZN2r	54.33	18.94	bd	15.42	34.29
21 May 2018	P114	54.40	19.00	2.0	5.89	6.68
21 May 2018	ZN2b	54.38	19.08	3.0	3.81	6.68
21 May 2018	ZN2a	54.45	18.92	6.5	3.86	3.34
21 May 2018	P110a	54.58	18.66	3.5	3.85	6.10
21 May 2018	P104a	54.58	19.42	7.0	1.70	1.40
21 May 2018	P110b	54.50	19.33	5.0	1.33	1.62
22 May 2018	R4	54.88	18.37	14.0	0.94	0.50
22 May 2018	R6	54.66	18.83	6.5	1.62	1.70
22 May 2018	R7	54.50	18.79	5.5	2.16	3.00
22 May 2018	R8	54.38	18.95	5.5	2.29	2.50
23 May 2018	L4	54.50	19.51	14.0	0.73	0.60
23 May 2018	L7	54.83	17.53	9.0	0.85	0.90
23 May 2018	L8	54.58	19.41	7.0	0.70	0.60
23 May 2018	L9	54.88	18.36	8.0	0.51	0.47
23 May 2018	IO6	54.95	18.41	11.0	0.51	0.35
23 May 2018	IO7	55.04	18.30	6.5	1.00	1.07

In the ship's laboratory, the LISST-100X was used to measure the volume concentration of pollen grains and the total volume of SPM (size range: 1.25–250 μm) in the sea water samples. The measurements were made in a special chamber containing 100 mL of the water sample. The measurement data were recorded with the LISTST-SOP program (the measurements were averaged). During the measurements, the magnetic stirrer built into the chamber had to be activated to prevent errors due to the pine pollen grains rising rapidly to the surface of the sample, and hence, to avoid underestimating the pollen concentration in the sea. The speed of the stirrer was adjusted to other organic substances suspended in the water samples in order not to damage their cells and not to influence the SPM concentration. Background measurements were made using deionized water every day prior to starting the actual measurements of pollen concentrations. The method of estimating pine pollen and SPM concentrations in the 1.25–250 μm size range in the aquatic environment was described in detail in Pawlik and Ficek [29] and validated in Pawlik and Ficek [30].

The total suspended particulate matter (SPM) concentration in water (expressed in g m^{-3}) was obtained by weighing its dry mass, collected gravimetrically on a CF/F Whatman glass filter from a specified volume of water, in accordance with the method described in Stavn et al. [41] and Woźniak et al. [42]. Prior to filtration, the filters were heated for 4 h at 450 °C, then rinsed with pure deionized, particle-free water (to prevent loss of filter material during the filtration of the main sample), then dried and initially weighed. Immediately after sampling, the sea water was filtered on board ship under a pressure not exceeding 0.4 atm. The volumes of sea water samples varied from 500 to 3000 mL, depending on the water's turbidity (on the water's particle content). After the water sample had been filtered, the filter was rinsed with 50 cm^3 of deionized water to remove sea salt from it, which might otherwise cause the SPM content to be overestimated. The filter was then placed in a desiccator for 24 h and stored in a freezer for subsequent laboratory analysis. To determine the total mass of SPM in the water, the appropriately prepared filters were weighed three times on a precision balance (Radwag AS 60/C/2; accuracy 0.01 mg).

Chlorophyll a concentrations in sea water were obtained spectrophotometrically by measuring the absorbance in a 90% acetone extract [43] on a HITACHI U-3900H, Tokyo, Japan instrument using a 2 cm cell. Then, 47 mm diameter Whatman GF/F filters (Maidstone, Kent, UK) were used for these measurements. Immediately after sampling, the sea water was filtered on board the ship under a pressure not exceeding 0.4 atm. The volume of filtered water was made dependent on its suspended organic matter content.

Since pollen degrades rapidly in water, we analyzed its chemical composition in pollen collected during the pine pollen season from trees growing in forests along the southern Baltic coast. Each measurement was performed in triplicate, and the results were averaged.

Total phosphorus was determined spectrophotometrically with ammonium molybdate (UV-VIS, Hitachi U-5100, Tokyo, Japan). Pollen samples (0.5 g) were digested in a solution of 65% nitric acid (V) and 30% H_2O_2 Suprapur (Merck, Lowe, NJ, USA) in a microwave mineralizer (ETHOS EASY, Milestone connect, Sorisole (BG), Italy). After mineralization, the samples were made up to 50 mL with deionized water. The phosphorus contents of the solutions thereby obtained were measured.

The concentrations of carbon and nitrogen were measured in an elemental analyzer (CHNS Flash Smart 4000 Series—Thermo Scientific, Waltham, MA, USA). This analysis was based on gas chromatography: the chromatographic column separated the combustion reaction products at a temperature of ca. 1800 °C in an atmosphere of oxygen or helium carrier gas. The separate analytes were detected using a thermal conductivity detector (TCD) which, by generating electric signals, gave the percentage content of the elements after data processing in the Eager Xperience program [44]. The calibration was performed using a methionine standard $C_5H_{11}NO_2S$.

3. Results and Discussion

The measurements under discussion in this paper were made during a cruise between 14 and 23 May 2018. The suspended particulate matter (SPM) and chlorophyll a concentrations, together with the transparency of the sea water, were measured at selected stations. These data are listed in Table 1. The SPM concentrations ranged from 0.51 to 15.42 g m^{-3}, the chlorophyll a levels were from 0.35 to 34.29 mg m^{-3}, and the Secchi depth was from 1.5 to 14.0 m.

At the same stations, pine pollen concentrations were measured using an LISST-100X instrument according to an original methodology developed by the authors of this paper [29,30]. This yielded the spatial variability in the pollen distribution. This was the first time that pollen grain concentrations were measured in the Baltic Sea on such a large scale. The measurements showed that practically the whole study area was covered with pollen. Figure 3 shows that substantial pollen concentrations were recorded not only in the coastal zone but also at considerable distances from the shore, except in areas where terrestrial runoff was mixing with sea water. Pollen levels were high even at stations such as P5, P140 and Plat1, respectively, located 83.5, 79.7 and 66.6 km from the nearest land.

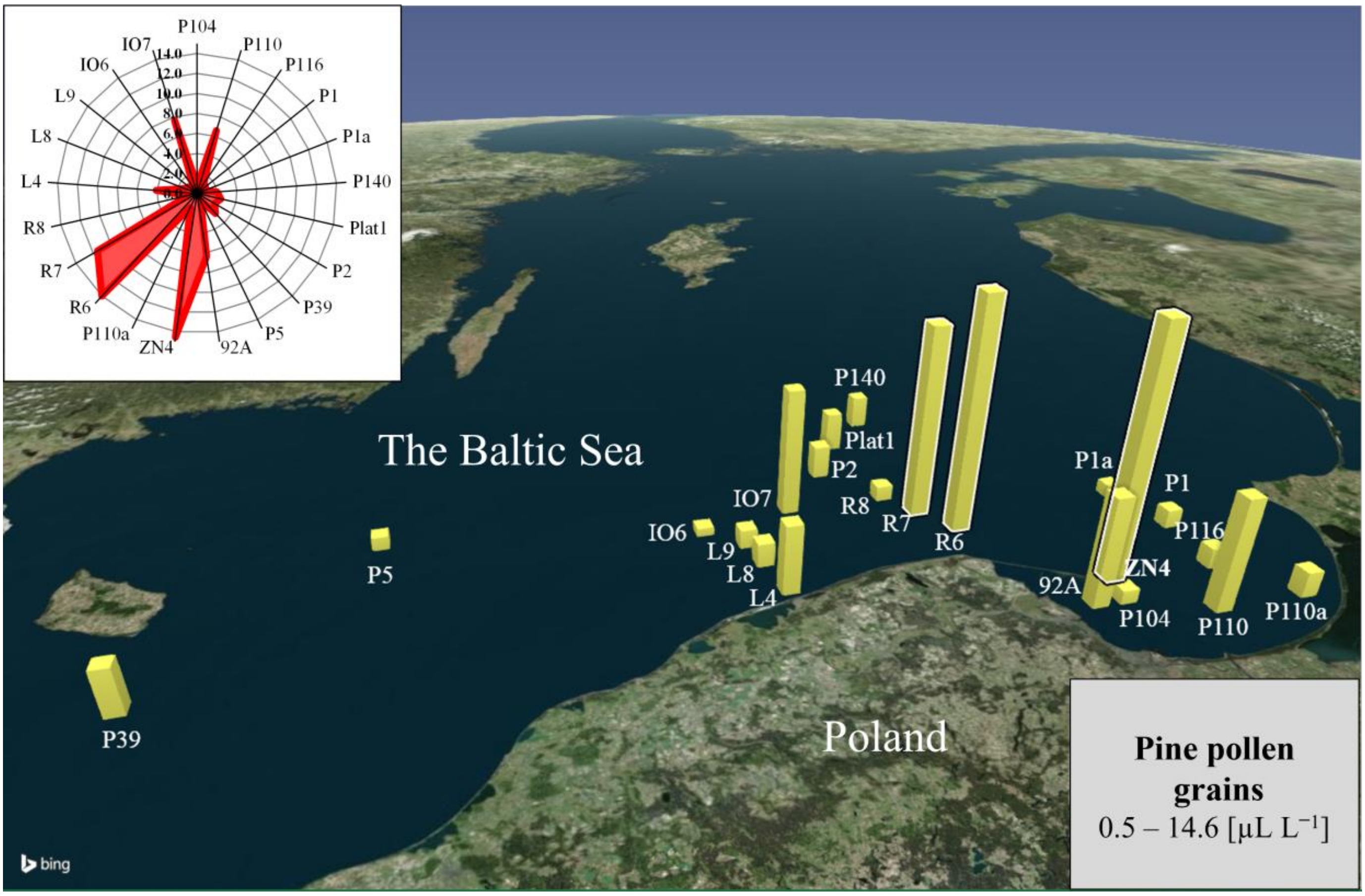

Figure 3. Spatial distribution of concentration of pine pollen grains in May 2018 in (μL L^{-1}).

Spatially, the pollen concentrations varied very widely: they could be very high or low even at stations quite close to each other. For example, at the open sea stations R7 and R8, ca. 10 km apart, the respective concentrations were 11.49 μL L^{-1} and 0.98 μL L^{-1}, while at stations 92a and P104, ca. 7.8 km apart in the Gulf of Gdańsk, the respective concentrations were 6.4 μL L^{-1} and 0.8 μL L^{-1}.

No statistically significant relationships were found between the pollen concentration and chlorophyll a concentration, salinity (riverine inflow) or water temperature (upwellings). Low coefficients of determination (R^2 = 0.0065, 0.0003 and 0.0095, respectively) indicate a lack of correlation between these quantities (see Figure 4).

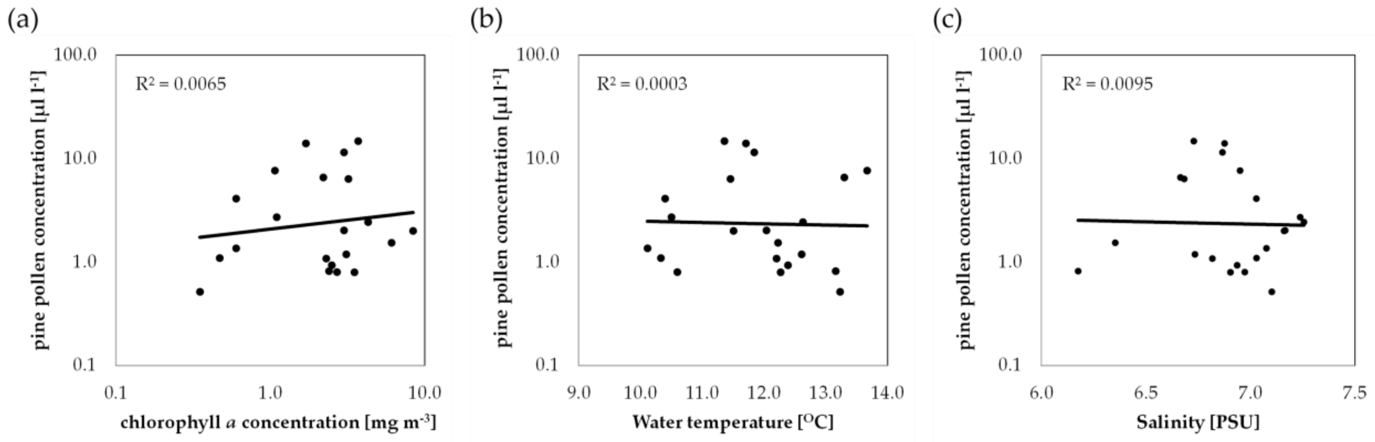

Figure 4. Relationships between pine pollen concentration measured by LISST-100X and (**a**) chlorophyll a concentration; (**b**) water temperature; (**c**) salinity.

This was treated as compelling evidence that these parameters had no effect on the pollen concentrations in the study area and confirmed the conjecture that such a wide distribution of pollen resulted from the combined effects of wind and sea currents.

The importance of pollen reaching the Baltic Sea environment varies greatly and without doubt depends on the amounts of suspended matter in the deposition area. SPM levels in Baltic surface waters are fairly large but highly variable. The study that Woźniak et al. [42] carried out in the southern Baltic in 2006–2009 yielded SPM values from ca. 0.36 to 15.7 g m^{-3} (average 2.42 g m^{-3}). The high concentrations and considerable variability of SPM are also corroborated by satellite data from the SatBałtyk System (www.satbaltyk.pl, accessed on 5 December 2022). The maps in this system show very high levels of these substances in the coastal zone and in the bays and lagoons. In the central Baltic, these concentrations are many times lower. The measurements we made during the cruise in May 2018 confirmed the variability of SPM (min. = 0.51, max. = 15.42, average 3.03 g m^{-3}).

The great spatial variabilities of pollen and SPM concentrations mean that absolute pollen concentrations are not an adequate reflection of the role of compounds supplied together with the pollen to different parts of the Baltic environment. A far better index for analyzing the effect of pollen deposition is the ratio of pine pollen grains relative to the total suspended matter in the surface water layer. The 2018 LISST measurements of the ratio of the volume of pollen to that of 1.25–250 µm SPM are shown on Figure 5. This shows that a large proportion of SPM consists of pollen not only in offshore waters but also over very large areas of the central Baltic. A 30% content of pollen in SPM is nothing unusual, and in places, this figure can rise to 50%. For example, at station P39, Plat1 and P2 in the central Baltic, pollen levels were minimal (appropriately 2.7, 2.4 and 2.0 µL L^{-1}), but because the overall SPM concentration was low, the percentage was very high (appropriately 49.2, 34.2 and 29.1%). The same was applied at stations P104 and P116 in the Gulf of Gdańsk. However, at station ZN4, quite close to P104, we recorded the opposite situation: pollen concentrations were very high (14.7 µL L^{-1}), but its percentage in the SPM was not (13.9%). The magnitude of the proportion of pollen in SPM can be linked with the role of pollen grains in the aquatic environment. To examine the biological role of pollen in the aquatic environment, the contents of carbon C, nitrogen N and phosphorus P were measured in pollen acquired from pine trees growing close to the Baltic shore. The levels of these elements were as follows: 47.66% C, 0.32% P and 2.50% N (see Table 2). These results indicate that pollen is an important source of elements for the Baltic Sea and other aquatic ecosystems, as confirmed by other authors [32,37,45–47].

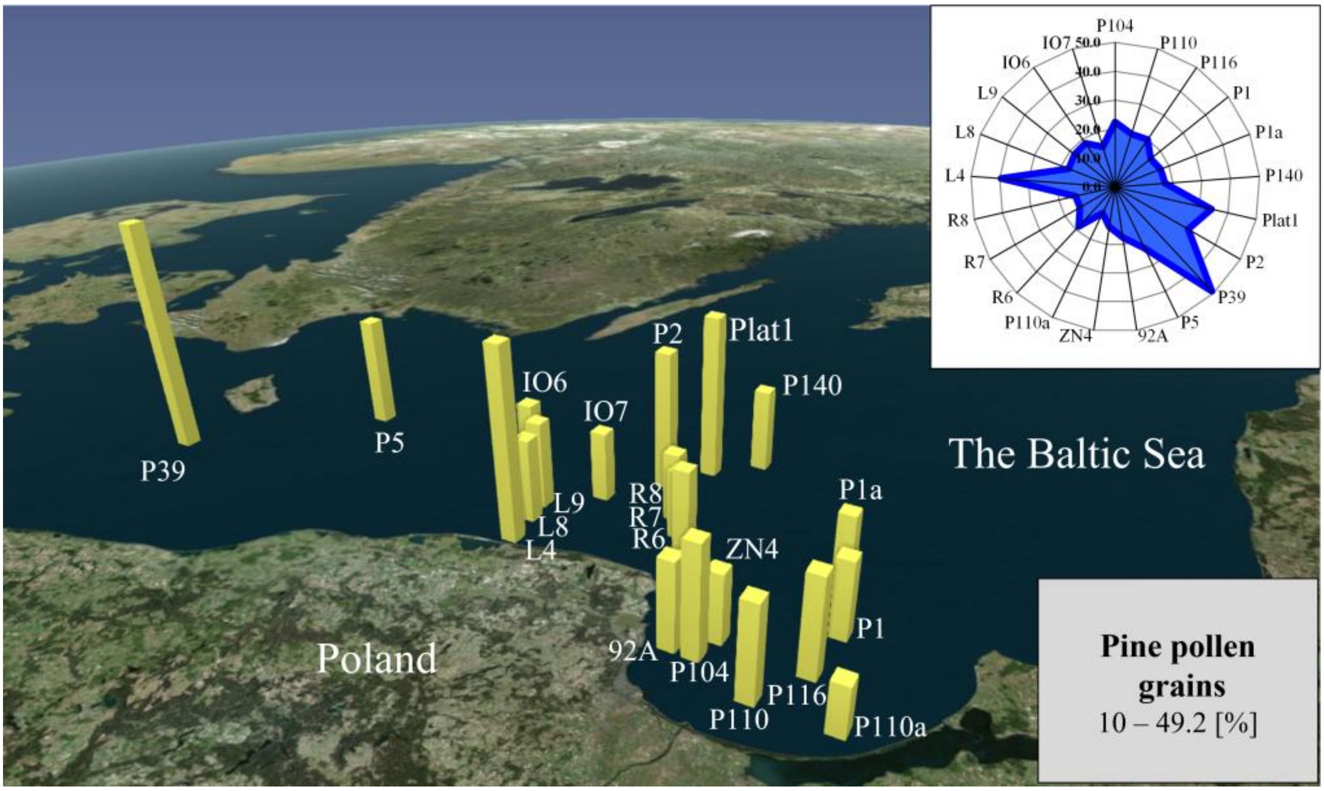

Figure 5. Relative concentration of pollen grains in suspension in surface layer of water measured in May 2018 (the ratio of the number of pollen grains to the total number of suspended particles in size range from 1.25 to 250 μm).

Table 2. Selected chemical characteristics of pine pollen grains (*Pinus sylvestris*).

Component	Content % of a Component/an Element in Dry Mass	References
cellulose	3.60% 2.00%	[48] [49]
sporopollenins	19.60% 21.90%	[48] [49]
C	47.66% 50.79% 49.50% 50.00%	own research [47] [40] [32]
P	0.32% 0.34% 0.30% 0.30%	own research [47] [47] [46]
N	2.50% 2.24% 2.00–2.40%	own research [47] [45]
S	0.26%	[47]
K	0.94%	[47]
Mg	0.15%	[47]
Ca	0.05%	[47]

What is more, once a pollen grain hits the water, the dissolved molecules are very rapidly flushed out into the surrounding water. Indeed, the majority of water-extractable macro-nutrients in pollen (>80%) may be flushed out within a few hours in both terrestrial [50] and aquatic ecosystems [37], subsequently to be incorporated, redistributed and transformed by micro-organisms [37,51]. Studies have shown (see Table 2) that pine pollen contains mainly carbohydrates and proteins, while the sporopollenins that make up the fire-proof walls of the grains consist of n-alkanes and aliphatic carbohydrates [52–54]. Other elements, such as sulfur, potassium, magnesium and calcium, are present in very much smaller amounts. The precise chemical composition of a pine pollen grain is given in Table 2. The C:P and C:N ratios in pollen (>30) are similar to those in terrestrial organic matter, such as leaf litter. A laboratory study by Rösel et al. [37] shows that during the initial phase of decomposition of the pollen grain once this is in the water, the excess of carbon in relation to P and N falls very abruptly. This indicates the very high bioavailability of this allochthonous particulate organic matter (POM). In the next phase, the level of organic carbon drops suddenly, while dissolved N and P accumulate in the water surrounding the pollen grain.

The papers by Rösel et al. [37] and Filipiak [47] show that the presence of SPM, rich as it is in carbon, nitrogen and phosphorus, has a marked impact on marine life. One can anticipate that the appearance of pollen will have a major effect on low-nutrient waters but a more moderate impact in SPM-richer waters. Therefore, the appearance in low-nutrient waters of even small amounts of pollen can significantly enhance the availability of these essential elements in the water. As we stated above, pollen introduces a great deal of carbon to the ecosystem. Woźniak et al. [42] demonstrate that carbon makes up ca. 25.2% of the SPM in southern Baltic waters. Table 2 shows that pollen contains around twice as much carbon in relation to the non-pollen SPM in the southern Baltic. Moreover, this carbon is rather easily flushed out when pollen is deposited in the water.

Pollen fallout is particularly important for the central Baltic Sea, the surface waters of which usually contain only small amounts of essential nutrients by the end of spring. It is easy to notice that pine pollen has a direct influence on nutrient concentration in Baltic waters. The inputs of nitrogen and phosphorus is a main reason of the Baltic Sea eutrophication, which is one of the main threats to the Baltic Sea ecosystem. The pine pollen rain, though short-lived, can raise nutrient levels in the water and substantially modify the cycles of organic matter, nutrients and energy. Pollen grains entering the water have the potential, within a short time, to supply nutrients and energy to the internal nutrient cycles in the water and also the microbial loop. This has been demonstrated by Doskey [32], Graham et al. [36] and Rösel et al. [37]. Other studies [55–57] show that pollen grains are an excellent microbial substrate and habitat. A variety of heterotrophic bacteria and aquatic fungi in the water decompose POM (e.g., [37,51,58,59]), including the chemically almost indestructible intracellular walls of pollen grains [16,58]. This greatly influences the composition and activity of microflora, particularly in macroscopic organic aggregates [60–62] and enhances the productivity of the ecosystem by introducing pollen-derived nutrients into the trophic web [36,37,63–65]. Pollen deposition directly supplies organic matter to the entire Baltic Sea, which may have a major impact on the macro- and microelement cycles, e.g., those of carbon, phosphorus, nitrogen, iron, potassium, magnesium, calcium, manganese and zinc [47]. Pine pollen rains act as instantaneous pulses of nutrients, which are rapidly incorporated and just as quickly utilized in the trophic web. Rösel et al. [37] suggested that blooms of algae may be associated with the short-lived but highly intensive fallout of tree pollen. The present study shows that the composition of pine pollen and the ability of pollen rains to rapidly introduce nutrients to the trophic web make pollen an ideal medium promoting the growth of algal blooms [37]. Pollen is an easily assimilable, digestible and nutritious food for fungi, bacteria, protozoa and various groups of invertebrates, which suggests that pollen is of importance to the intra- and inter-ecosystem cycle of nutrients [47]. The activity of organisms increases the nutrient turnover [66,67]. The biomass transfer that they bring about can also affect other trophic levels, as is the case in lakes, in which the influx of coniferous tree pollen was found to have altered the communities of zooplankton, phytoplankton and littoral periphyton [33].

4. Conclusions

The paper discusses the analysis of the absolute and relative concentrations of pine pollen in southern Baltic Sea waters. This shows that the spring fallout of pollen, hitherto not analyzed, constitutes a significant input of organic matter to this ecosystem. Pollen levels in Baltic surface waters, measured during the 2018 pollen season, varied from 0.5 to 14.7 $\mu L\ L^{-1}$, which is 10–49.2% of SPM in the 1.25–250 μm size range. Because pollen is an important source of essential nutrients to this marine ecosystem, the instantaneous pulses of pollen supplied to the water in spring play a crucial part in the biogeochemical cycles of carbon and nutrients in the sea. The potentially large amounts of organic carbon and nutrients supplied by pollen grains can replenish these resources in the ecosystem. This is particularly important when other levels of other resources in the water are limited. The local enrichment of waters in nutrients, such as carbon, nitrogen and phosphorus, can buffer the varying availability of autochthonous resources. Being an excellent substrate and microbiological habitat, pine pollen is a readily available source of food for marine organisms. Hence, it is a major resource of allochthonous organic matter carried by the wind to Baltic waters. Analysis of the magnitudes of these pollen fluxes supplied to the Baltic would be highly desirable, given the worsening eutrophication and expanding anoxic zones in this sea, which is characterized by a very restricted exchange of water with the world ocean.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to the fact they will be a part of Ph.D. thesis.

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Conflicts of Interest: The authors declare no conflict of interest.

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