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Marine mucilage in the Sea of Marmara and its effects on the marine ecosystem: mass deaths

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Abstract: In April of 2021, there was a massive explosion of marine mucilage in the Sea of Marmara, as a result, many invertebrates of marine communities suffered mass mortality. We summarize our results about the devastating effect of mucilage bloom on mass deaths in the Sea of Marmara. The phenomena were lethal to the pelagic fishes and crustaceans, and individuals were impacted severely smothered by mucilage or anoxia. Mucilage accumulations have shown their effectiveness in many areas around the Kapıdağ Peninsula. Misakça, Şirinçavuş, Narlı, and Tatlısu regions, where mass death cases occurred, were selected as study areas, and these areas are characterized as shallow and calm waters. In total, 10164 dead individuals belonging to eighteen families were observed in the coastal area. *Atherina* sp. was the most affected species with an abundance of 3040 dead ind·100 m^{-2}, because of the spawning period in the coastal zone. Most of the species that died were pelagic, and *Engraulis encrasicolus*, *Spicara* sp., *Trachurus trachurus*, and *Sardina pilchardus* also suffered massive mortality. Due to insufficient wave action and tidal currents, mucilage was also identified at depths 5-30 m. In the following years to come, mass deaths in the Sea of Marmara are likely to have adverse effects, particularly on the food web.

Key words: Marine ecology, mucilage phenomenon, fishery management, fishing mortality, Mediterranean

1. Introduction

Global warming, seasonal changes, and human influence substantially affect the biological and chemical structure of marine water (Goffart et al., 2002). Mucilage formation in seas was described as the aggregation of organic materials that are produced by several marine organisms under special trophic and seasonal conditions (Innamorati et al., 2001). The process of mucilage formation starts with extracellular secretions by phytoplankton. The majority of these secretions consist of heteropolysaccharides (Svetličić et al., 2011). After excreted, heteropolysaccharide fibrils begin to form microgels which in time form macroaggregates known as marine snow (Ricci et al., 2014). These macroaggregates stick to detritus, suspended particles, microplastic particles, etc., and form a mass that we call marine mucilage (Chin et al., 1998; Turk et al., 2010; Svetličić et al., 2011; Ricci et al., 2014). The first mucilage event was reported in 1729 in the Adriatic Sea and have been reported in different areas ever since, including the Aegean Sea, east China Sea, the Tyrrhenian Sea, the Ligurian Sea, and the Sea of Marmara (Fonda-Umani et al., 1989; Gotsis-Skretas, 1995; Lorenti et al., 2005; Schiaparelli et al., 2007; Aktan et al., 2008; Fukao et al., 2009). Sea temperatures, oxygen availability, hydrodynamic regime, and meteorological factors have often been considered factors favoring mucilage events (Degobbis et al., 1999; Danovaro et al., 2009). Eutrophication originating from the river discharges and municipal sewage was asserted as the main factor causing mucilage events (Penna et al., 2004; Türkoğlu and Öner, 2010). While an increase in mucilage was noted at the beginning of the century (Precali et al., 2005), more recent reviews put forth no evidence for an overall increasing trend in the frequency of these events in the Mediterranean area (Zingone et al., 2021). The process of degradation of organic matter uses up oxygen; thus, hypoxia and even anoxia may occur. As a result of this, mucilage causes trophic disruption, oxygen deficiency and mass mortalities (Gray et al., 2002). Mucilage can reach huge dimensions and cover hundreds of kilometers of coastline (Fogg, 1995). Mucilage may cover the sea bottom or form a layer at the level of the pycnocline, the so-called 'false benthos' (Sieburth et al., 1987). As a result of problems to fisheries, aquaculture, recreation, tourism and public health, social and economic losses are inevitable (Rinaldi et al., 1995; Danovaro et al., 2009). Mucilage events had negative effects on many benthic organisms such as crustaceans, molluscs, macroalgae, sea urchins, gorgonians (Stachowitsch et al., 1990; Rinaldi et al., 1995; Özalp, 2021) and fish populations (Taylor et al., 1985; Kent et al., 1995; Regner, 1996; Giani et al., 2005), also

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affecting the growth of mussel populations (Cornello et al., 2005) and in Dardanelles (Turkey) even threatening the developmental level, health status and life of coral habitats (Özalp, 2021). Mass mortality of benthic organisms due to hypoxia was observed on the sandy-muddy bottom at depths of 20-25 m in the Gulf of Trieste (Adriatic Sea) (Stachowitsch, 1984) where marine mucilage is negatively affected as well as pelagic fishery (Giani et al., 2005).

The first mucilage in Turkey was observed in the mid-autumn of 2007 along the northeastern part of the Marmara Sea. Neither hypoxia nor anoxia and fish deaths were recorded in that period, but it was noticed that sedimentation of the dense aggregates had a negative effect on the benthic ecosystem (Aktan et al., 2008). It has been revealed that diatoms and environmental conditions are related to mucilage formation in the Marmara Sea (Aktan et al., 2008; Tüfekçi et al., 2010; Balkis et al., 2011; Balkıs et al., 2013). Years later, mucilage reappeared in the Sea of Marmara in November 2020 and began collecting on the surface in April 2021. The phytoplankton composition changed in the mucilage formation, and previously unobserved species became dominant (Balkis-Ozdelice et al., 2021; Ergul et al., 2021). The mucilage incident adversely affected the maritime operations (Uflaz et al., 2021), fishing activities (Yıldız and Gönülal, 2021) and benthos (Topçu and Öztürk, 2021) in the Sea of Marmara. The phenomenon reached frightening dimensions after approximately two months (Figure 1). Many invertebrates' mass death was determined in coastal and deep water. This impact was commonly lethal for the fishes and crustaceans.

In this study, with regular field studies and underwater observations, we sought to understand how and to what extent the marine ecosystem was affected by mucilage summarizing its devastating effect on aquatic ecosystems in the Sea of Marmara. Although different aspects of mucilage events in the Sea of Marmara have been investigated before (Aktan et al., 2008; Tüfekçi et al., 2010; Balkis et al., 2011; İşinibilir-Okyar et al., 2015; Keleş et al., 2020; Kalkavan, 2021; Uflaz et al., 2021; Yıldız and Gönülal, 2021), the mass deaths are presented for the first time in the current study. In addition to serious fish deaths in the coastal zone, we highlight a much more intense accumulation of mucilage on the benthos.

2. Materials and methods

This study was carried out on the coasts of the Kapıdağ Peninsula (Figure 2) during the mucilage event that occurred in the Sea of Marmara between April 2021 and May 2021. According to the assessment of the "Urban Wastewater Treatment Regulation", this area is defined as a sensitive area (Republic of Turkey Ministry of Environment and Urbanization RTMEU, 2017). Previous studies confirm that this region is sensitive to ecological changes (Tüfekçi et al., 2010).

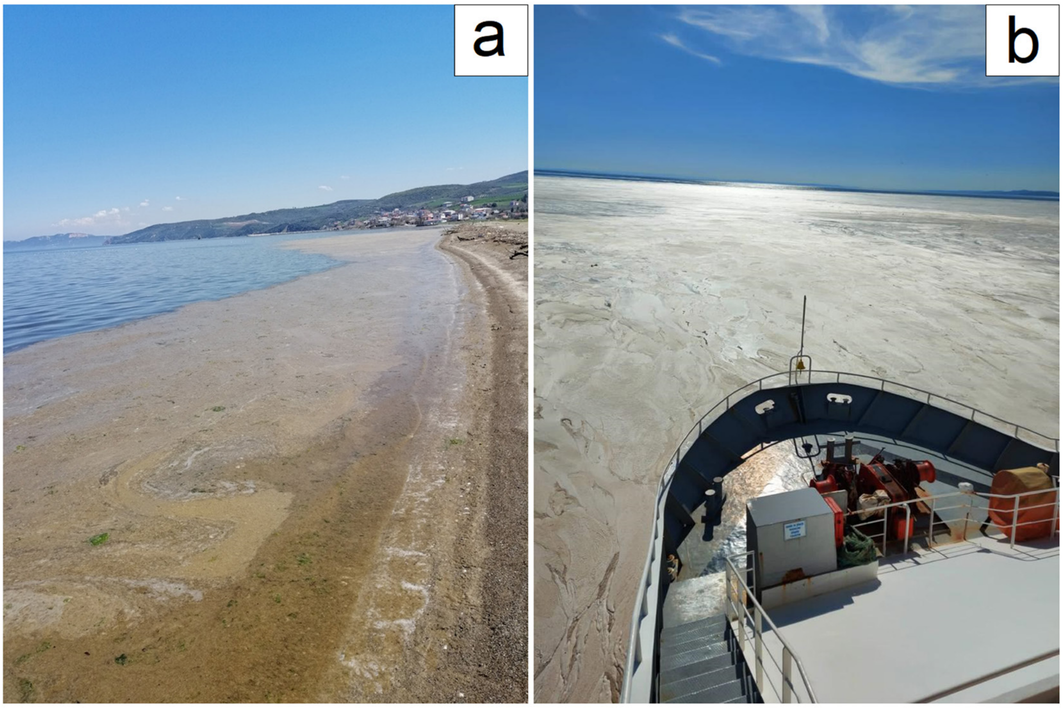


Figure 1. Mucilage aggregation examples on the water surface in the Sea of Marmara, a) on April 23, 2021, on the coast of Misakça and b) on May 25, 2021, in Erdek Harbor.

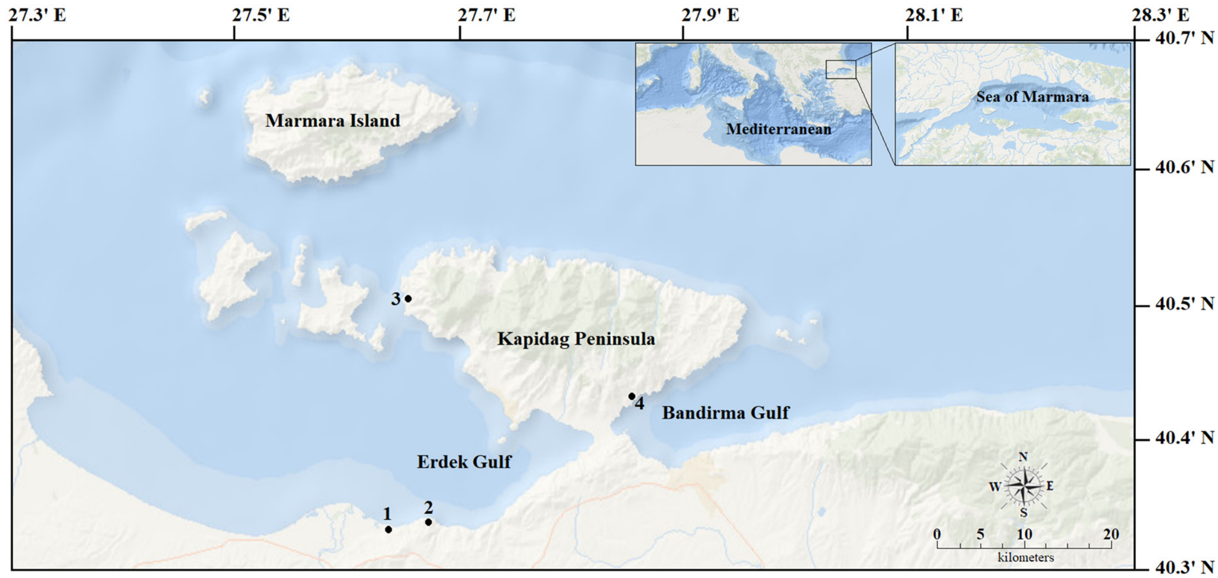


Figure 2. Regional map and sampling stations in the southern of Sea of Marmara (1: Misakça, 2: Şirinçavuş, 3: Narlı, 4: Tatlısu)

During the mucilage event (from November 2020 to July 2021), there was only one case of mass death attributed to mucilage formation between 22 and 25 April. During this period, surveys were done for four days in a row at each station. In the following days, underwater observations continued, but no new mass death cases were detected. Between 22 and 25 April, dissolved oxygen (DO) and sea surface temperature (SST) were measured daily with YSI® ProDss multimeter as water quality parameters. After the massive deaths, these parameters were followed for a long time. Chlorophyll-a (Chl-a) concentrations were estimated from Sentinel 3 satellite images, using the OC4Me Maximum Band Ratio, a polynomial and semianalytical algorithm, developed by Morel et al. (2007). The mass mortalities and benthic changes were monitored regularly by SCUBA diving. For these purposes line transects, quadrat, and visual count methods were used underwater (English et al., 1997) with the following procedures respectively: a distance of 1000 m along the coastal line was pointed by a handheld GPS (Garmin eTrex® 10). The area between the points was defined as a study line and divers swam at a depth of 2-4 m along this line parallel to the shore. To prevent adverse effects on research results, as far as possible, all dead individuals were collected (Figure 3). The smaller and dense specimens were captured using the quadrat method (1 × 1 m), whereas the larger and rare specimens were collected using the line transect method (1000 m). The latter procedure allowed us to search in a larger area. The photographic camera GoPro HERO 9 inside the housing Cyber-Shot (Marine Pack) was recording during dive time. This allowed us to analyze after the dive how the species were affected. Operation details (date, monitoring duration, etc.) and observation data (count, density, location of invaders) were noted on underwater data forms.

Dead individuals transferred to tanks were classified and were identified at species level according to the main references.[1] The abundance dead (ind·100 m^{-2}) was computed and standardized to a scanned area for each station, considering the systematic classification of specimens. Sampling locations and operation details are given in Table 1.

3. Results

The mucilage event in 2020-2021 reached huge dimensions and covered areas of hundreds of kilometers of coastline in the study area. As shown in Figure 2, although the mucilage was mainly found in the illuminated area close to the sea surface, some of it surfaced during the decomposition stage and covered the sea surface like a blanket. Mucilage formation was observed up to 30 m from the surface in the Sea of Marmara, and the highest density occurred between 5 and 25 m depths during dives. The degree of coverage varied among locations and depending on weather conditions, such as wind, current and waves. Chordates were more affected than Arthropods and the gills filaments of all dead fishes we studied were completely covered by mucilage. For more detailed information, please see our video on mass deaths in Supplementary file S1.

Table 2 shows the taxonomic classification of the affected taxon in the study area. In total, 10164 dead individuals belonging to eighteen families were observed

[1] Froese R, Pauly D (2020). FishBase. [online]. Website www.fishbase.org [accessed 18 Jun 2021].

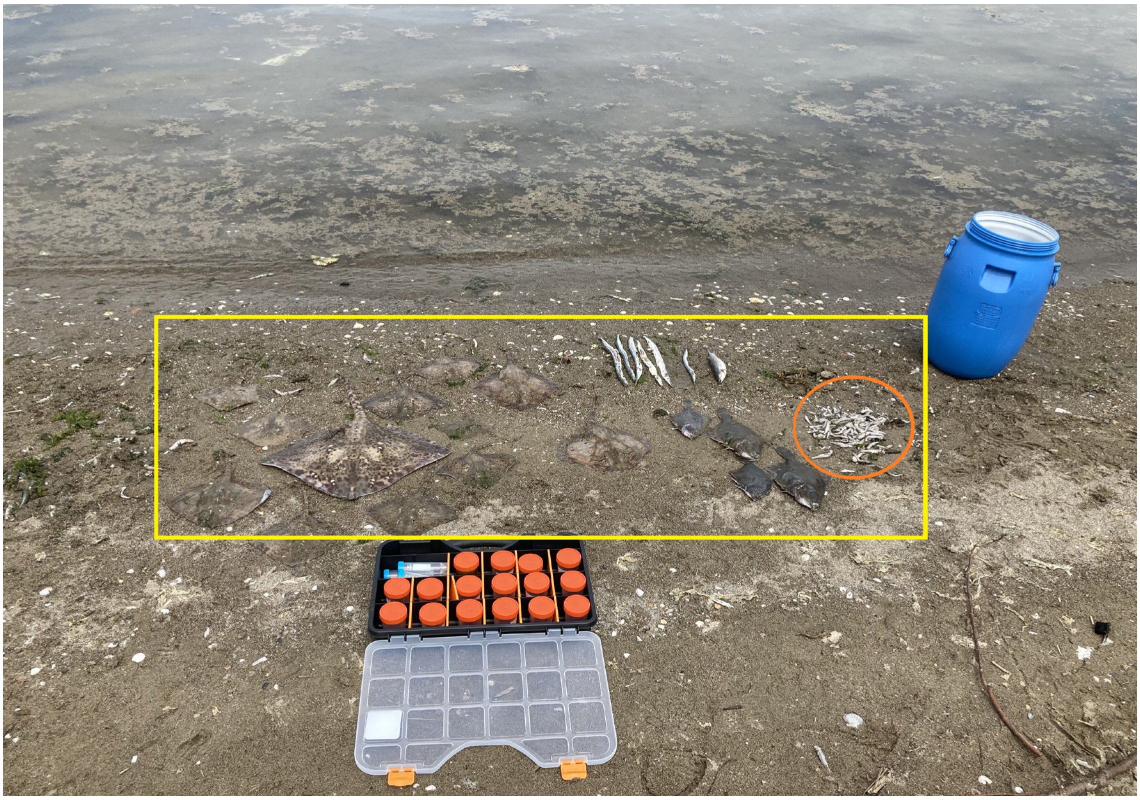


Figure 3. Some dead species were collected during sampling. The orange circle indicates *Atherina* sp., and the yellow square indicates other affected species.

Table 1. Sampling locations and operation details between 22 and 25 April 2021.

Sampling stations	Sampling methods	Target species class*	Scanned area per station (m^2)
1) Misakça (40°18'36.2"N 27°39'55.6"E)	Line transect (1 km × 4 m)	Larger/Rare	4000
2) Şirinçavuş (40°18'54.2"N 27°42'28.3"E)	Quadrat (1 × 1 m)	Smaller/Dense	60
3) Narlı (40°28'42.9"N 27°41'18.0"E)			
4) Tatlısu (40°24'43.0"N 27°55'48.8"E)			

*Targeting species were identified in Table 2.

in the coastal zone. The abundance of dead taxa by stations are detailed in Table 3. The highest mortality was recorded in Misakça, followed by Narlı, Şirinçavuş, and Tatlısu. *Atherina* sp. was the most affected taxon with 3040 dead ind·100 m^{-2}, followed by *Engraulis encrasicolus*, *Spicara* sp., *Trachurus trachurus*, and *Sardina pilchardus*. The abundance of the crustaceans was also quite high, with dead *Carcinus aestuarii* and *Palaemon elegans* seen more than some fish species.

Although demersal species were common in the Sea of Marmara, the proportion of demersal species was low (7%), while most of (93%) the species who died were pelagic. Most of the individuals affected by mucilage were juveniles or subadults. Twenty-five percent of the dead

Table 2. Taxonomic classification of dead taxon.

Kingdom	Phylum	Class	Order	Family	Genus	Species*
Animalia	Arthropoda	Malacostraca	Decapoda	Carcinidae	*Carcinus*	[b] *Carcinus aestuarii* Nardo, 1847
				Palaemonidae	*Palaemon*	[a] *Palaemon elegans* Rathke, 1836
				Polybiidae	*Liocarcinus*	[b] *Liocarcinus vernalis* Risso, 1827
				Xanthidae	*Xantho*	[b] *Xantho poressa* Olivi, 1792
	Chordata	Actinopterygii	Atheriniformes	Atherinidae	*Atherina*	[a] *Atherina* sp.
			Beloniformes	Belonidae	*Belone*	[b] *Belone belone* Linnaeus, 1760
			Clupeiformes	Clupeidae	*Sardina*	[a] *Sardina pilchardus* Walbaum, 1792
				Engraulidae	*Engraulis*	[a] *Engraulis encrasicolus* Linnaeus, 1758
			Mugiliformes	Mugilidae	*Mugil*	[b] *Mugil* sp.
			Perciformes	Carangidae	*Trachurus*	[a] *Trachurus trachurus* Linnaeus, 1758
				Mullidae	*Mullus*	[b] *Mullus* sp.
				Sparidae	*Spicara*	[a] *Spicara* sp.
				Uranoscopidae	*Uranoscopus*	[a] *Uranoscopus scaber* Linnaeus, 1758
			Pleuronectiformes	Pleuronectidae	*Platichthys*	[b] *Platichthys flesus* Linnaeus, 1758
			Scorpaeniformes	Scorpaenidae	*Scorpaena*	[a] *Scorpaena porcus* Linnaeus, 1758
				Triglidae	*Trigla*	[b] *Trigla lyra* Linnaeus, 1758
		Elasmobranchii	Rajiformes	Rajidae	*Raja*	[b] *Raja clavata* Linnaeus, 1758
			Myliobatiformes	Dasyatidae	*Dasyatis*	[b] *Dasyatis pastinaca* Linnaeus, 1758
Total	2	3	10	18	18	18

* Targeting species class were categorised [a]; smaller/dense, [b]; larger/rare

species had an economic value because they are caught as a target in fisheries (Figure 4). *Atherina* sp., *C. aestuarii*, *Dasyatis pastinaca*, *Liocarcinus vernalis*, *P. elegans* and *Raja clavata* are not a commercial target species per se; these are captured as by-catch in shrimp beam trawl, purse seine or gill net.

The DO level measured at all stations was lethal for many vertebrata and crustacea. DO ranged between 2.39 and 4.6 mg·L^{-1} (saturation 24.01% and 45.13%, respectively) between stations (Table 4). Chl-a level ranged between 7.34 and 52.06 mg·m^{-3} between stations (Figure 5), while the SST values ranged between 14.5 and 15.6 °C among the stations (Table 4).

4. Discussion

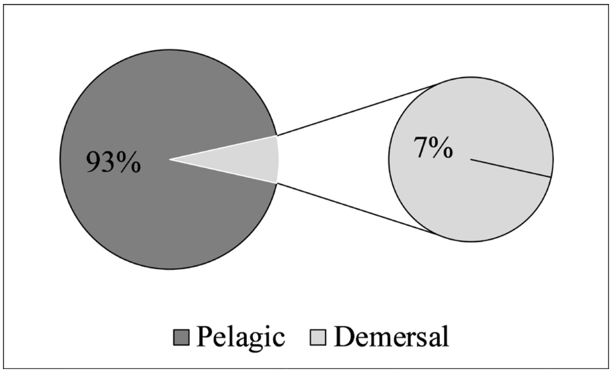
Mucilage did not occur in the Sea of Marmara for the first time. Its occurrence is not unique to the area, the event in 2020-2021 was defined as one of the worst mucilage outbreaks ever (Savun-Hekimoğlu and Gazioğlu, 2021). In this period, Ergul et al. (2021) reported that the ecological quality of the Sea of Marmara decreased significantly and the phosphate concentrations increased relatively. The formation of mucilage causes further ecological degradation and the results of this degradation can be destructive to marine life (Precali et al., 2005), in some cases even mass deaths can occur (Gray et al., 2002).

The mass mortalities can be explained first by directly clogging the gills by mucilage. Most documented mass mortality events verified the smothering of marine assemblages by mucilage accumulating in the gills and causing lesions (Fedra et al., 1976; Taylor et al., 1985; Stachowitsch et al., 1990; Kent et al., 1995). (DO) is essential to many forms of marine life including fish, invertebrates, bacteria and plants. Oxygen enters the water by direct absorption from the atmosphere and is also produced in the sea by phytoplankton (and phytobenthos) (Allan, 1995). The thick mucilage layer limits the interaction between water and the atmosphere by covering the surface and can cause oxygen depletion in the water. This creates an anoxic, or oxygen-depleted, environment where fish and other organisms cannot survive (Sha et al., 2021). DO levels below 3 mg·L^{-1} (about 28%-32%) are usually considered hypoxic and are a concern for marine organisms and marine environments. Lower nonlethal DO levels can negatively impact fish health and reduce appetite and growth (Gray et al., 2002). The low oxygen levels (down to 24%) measured at all stations may point that hypoxia occurs in the study area. According to the

Table 3. Species subjected to mass death due to mucilage and their abundance (dead ind·100 m^{-2}) by stations.

Species*	Misakça	Şirinçavuş	Narlı	Tatlısu	Total
Chordata (Phylum)					
[b,2] *Atherina* sp.	3976.67	2938.33	3615.00	1633.33	3040.83
[b,1] *Belone belone*	0.55	0.30	0.90	0.08	0.46
[a,2] *Dasyatis pastinaca*	-	-	0.03	-	0.01
[b,1] *Engraulis encrasicolus*	456.67	225.00	603.33	113.33	349.58
[b,1] *Mugil* sp	0.98	0.45	1.05	0.10	0.64
[a,1] *Mullus* sp	0.55	0.20	0.30	0.43	0.37
[a,1] *Platichthys flesus*	0.28	0.10	0.68	0.08	0.28
[a,2] *Raja clavata*	0.48	0.23	0.55	0.18	0.36
[b,1] *Sardina pilchardus*	161.67	85.00	63.33	181.67	122.92
[a,1] *Scorpaena porcus*	30.00	15.00	23.33	5.00	18.33
[a,1] *Spicara* sp	363.33	178.33	278.33	70.00	222.50
[b,1] *Trachurus trachurus*	156.67	91.67	211.67	56.67	129.17
[a,2] *Uranoscopus scaber*	61.67	5.00	18.33	15.00	25.00
[a,1] *Trigla lyra*	0.10	0.15	0.23	0.03	0.13
Arthropoda (Phylum)					
[a,2] *Carcinus aestuarii*	4.03	1.80	2.43	0.78	2.26
[a,2] *Liocarcinus vernalis*	0.53	0.45	0.40	0.08	0.36
[a,2] *Palaemon elegans*	5.00	3.33	1.67	1.67	2.92

* Economical value; [1] commercial, [2] noncommercial; Habitat; [a] demersal, [b] pelagic



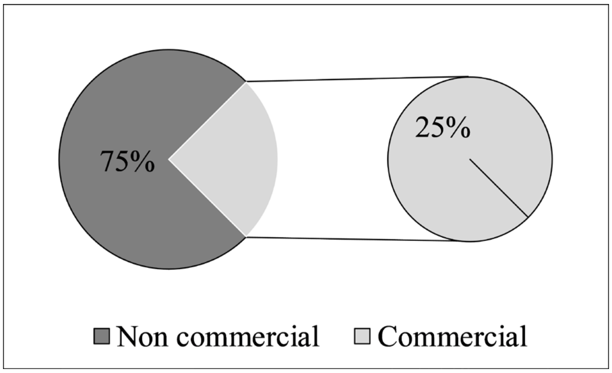


Figure 4. Percentage of species that died due to mucilage by habitat and commercial value.

daytime DO measurements, we did not find anoxic conditions; however, massive deaths may have occurred suddenly at the onset of darkness and night due to the cellular respiration of dinoflagellates (Vicente et al., 2002). Oxygen concentrations decline dramatically due to the exceptional use of oxygen at night (Pitcher and Probyn, 2016), and anoxia may develop (Vicente et al., 2002) and sudden fish deaths may occur at nighttime (Pitcher and Jacinto, 2019). We obtained nonanoxic oxygen measurements with photosynthesis activities that probably started with daylight. On the other hand, healthy animals like fish would have escaped from the anoxic zone, but the mucilage was so dense on the surface and spread over a wide area that we think may have made it difficult to escape. Both gill clogging and anoxia could have caused fish mortality, and the combination of these two impacts may be the explanation for such a massive event in the Sea of Marmara.

The mucilage effect on the ecosystem is also related to the hydrodynamical factors such as flows, waves

Table 4. Physico-chemical characteristics of seawater in the stations on 22 and 25 April 2021.

Water parameters	Misakça	Şirinçavuş	Narlı	Tatlısu
[a] Chlorophyll-a ($mg{\cdot}m^{-3}$)	52.06	33.69	29.14	7.34
[b] Dissolved oxygen ($mg{\cdot}L^{-1}$)	2.39 (24%)	3.32 (33%)	3.5 (35%)	4.6 (45%)
[b] Sea surface temperature (°C)	15.6	15.3	15.1	14.5

[a] estimated from Sentinel 3 satellite images
[b] represents a single measurement at a depth of 0-1 m at each station on the sampling day. Saturation percentages are given in parentheses.

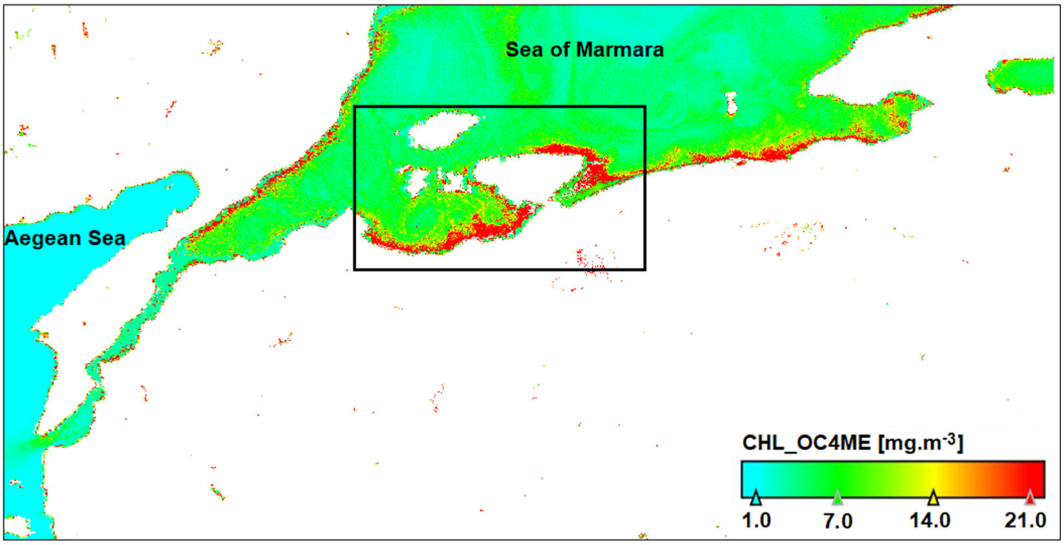


Figure 5. Sentinel 3 imagery of the chlorophyll-a concentration in the study area on April 22, 2021.

and seafloor morphology (Devescovi and Ivesa, 2007). The marine ecosystem in the İzmit, Gemlik, Erdek and Bandırma basins in the Sea of Marmara is vulnerable to current pressures due to insufficient flow (Gerin et al., 2013). The mucilage was primarily concentrated in shallow areas characterized by insufficient flow and low slope (Gulf of Erdek and Bandırma) and continued to exist for a long time in these areas. High Chl-a concentrations in stations where deaths are seen indicate eutrophic deterioration (Red deposits in Figure 5). As a result of hydrodynamic factors, mucilage persisted in the study area for a long time, resulting in differences in death densities between stations. The station Misakça had the lowest oxygen value, the highest chlorophyll value along the highest number of dead animals. The opposite situation is also valid for the station Tatlısu, where the lowest death densities were observed (Table 3, Figure 4).

Shallow waters (0-2 m) of the Gulf of Erdek are used as a nursery area by juveniles of the *Atherina* sp. which was the most dominant (47.7 % of the total number of fishes) (Keskin, 2007). *E. encrasicolus* and *S. pilchardus* are the common species in the region after the *Atherina* genus (Keskin, 2007). Mortality density by species is also thought to be related to their abundance in the region. Reproduction and recruitment processes during the mucilage period of the genus *Atherina* seem to have contributed to the increase in mortality. *Atherina* genus moves to shallow water to reproduce in the spring months, which coincide with the spawning season (Creech, 1992; Boudinar et al., 2016).

Massive deaths, especially in pelagic species, raise concerns about the deterioration in the food chain. Fish species may migrate towards areas with high biomass of foods if they cannot find forage on the sites they currently inhabit. The changes in the marine ecosystem caused by mucilage may disrupt the distribution and phenology of fish larvae, affect the recruitment and production of fish stocks, with indirect effects on food web structures and ecosystem-level changes (Brander, 2010). Considering the effects of mucilage on the food web and benthic ecosystem, the mass occurrence of mucilage could be considered a devastating threat for natural resources and marine ecosystems in the area, as has been determined in this study.

Since the Mediterranean is a semienclosed sea, the expected impacts of climate change are seen on ecosystems more intensely than in other oceanic regions (Siokou-Frangou et al., 2010). As a result of these changes, SST continues to increase all over the Mediterranean, this increase was mainly at the highest level in the Sea of Marmara, with an average of up to 2.2 °C above the previous temperatures.[2] Although for some years the mucilage events appeared to increase in frequency in the Adriatic Sea (Degobbis et al., 1999) and generally follow the temperature increase (Danovaro et al., 2009), they have become less frequent and, at least over the last 30 years there has not been any evidence of an increase in the Mediterranean Sea (Zingone et al., 2021). Preventative studies are better than cures for the marine ecosystem (Verma et al., 2020), but they are both costly and time-intensive. By experiencing the visible effects of climate change, the habitual practices must overhaul and initiate a full-scale effort to adapt. In other words, it is to adopt approaches that will allow mucilage to return to its natural course and solve the problem permanently. "Marmara Sea Protection Action Plan", consisting of 22 items, has been initiated in the Sea of Marmara, and its effects need to be scientifically monitored and evaluated both in the short and long term. The better way to prevent mucilage is to improve knowledge about mucilage through further investigations because the actual causes of the mucilage events observed from time to time in the area seem not to be unclear. Good practices towards improving marine water quality are needed and could be useful to mitigate these phenomena. Government authorities (either local or national) can lead the development of a strategy but need to involve all critical stakeholders, including academics, citizens, and businesses (both informal and formal).

5. Conclusion

The current study focused on the effects of mucilage on the marine ecosystem due to mass deaths, and this is what sets this study apart from all other studies. Whereas it is impossible to estimate the definite cause of the deaths due to a lack of background information, the available evidence points to suffocation due to gill obstruction by mucilage or low oxygen levels or the combined effects. Environmental, hydrodynamic, and hydro morphological characters make Gulfs of Erdek and Bandırma susceptible to mucilage and its adverse effects. Contrary to popular opinion, mucilage events in the Adriatic Sea are less frequent nowadays, while it is a matter of curiosity what the trend will be in the Sea of Marmara. Considering the effects of mass deaths on the food web and benthic ecosystem, in the coming years, adverse effects due to mucilage and mass deaths are likely to be seen in the Sea of Marmara. The mass deaths and observed effects on marine ecosystems emphasize the immediate need to find a solution to the problem. Monitoring ecological changes, data collection, and implementing marine pollution management strategies are necessary for the Mediterranean Sea and the Sea of Marmara. Actually, though marine mucilage has nowadays received considerable attention and research efforts have increased, more information is needed to predict the phenomenon and understand its effects. We believe that this study will contribute to understanding the effect of marine mucilage on aquatic life on a global scale. We predict that unless the problems are resolved, the mucilage events will continue to adversely affect the marine ecosystem and fisheries in the Sea of Marmara.

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Supplementary file

A1. Underwater video recording of mass fish deaths due to mucilage https://drive.google.com/file/d/1HPaFiDHZp32Aqp_F3tlqnzJ7MRM-ROpy/view?usp=sharing

[2] National Centers for Environmental Information (2021). Analysis of Mediterranean SST trends. [online]. Website www.ceam.es/ceamet/SST/SST-trend.html [accessed 18 Jun 2021].

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