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Gone with the Wind: Disappearance of *Ulva*-Driven Green Tides with Super Typhoons in Jeju Waters, South Korea

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Abstract: Jeju Island, located in the northern East China Sea, is experiencing a rapid rise in water temperature due to climate change. This has led to the increased activity of subtropical species and extreme fluctuations in coastal ecosystems, such as macroalgal blooms and coral bleaching. Additionally, the region is experiencing more frequent and intense typhoons. This study investigated the green tides caused by *Ulva*, particularly *Ulva ohnoi*, a subtropical species, and the effects of typhoons on these blooms through photographic analysis of the Jeju coastline. The study area was consistently covered by *Ulva* species every August from 2020 to 2022. Super typhoons struck Jeju Island every September during the study period, with wind speeds exceeding 20 m/s. In 2020 and 2022, the green tides largely dissipated following the typhoons. This ironic outcome highlights how climate-driven increases in subtropical *Ulva* biomass are being mitigated by the increasing frequency of super typhoons. However, despite the impact of super typhoon Chanthu in September 2021, there was no significant reduction in the *Ulva* bloom area. This anomaly may be attributable to the dominant easterly wind system in 2021, as the study area faces east, preventing the typhoon from influencing the distribution of *Ulva* blooms. These findings suggest that the wind intensity and direction of annual typhoons play a critical role in determining the resolution of green tide outbreaks.

Keywords: macroalgal bloom; climate change; disturbance; wind direction; northern East China Sea

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Jeju Island, South Korea, located in the northern East China Sea, is a biological hotspot with very high marine biodiversity due to a wide range of marine species found in both temperate and subtropical waters [1–3]. However, in recent decades, the island has experienced continuous outbreaks of green tides caused by *Ulva* species along its coast, posing a threat to the coastal ecosystem [4,5]. Unlike thin and tubular *Ulva* species such as *U. prolifera*, which has caused the world's largest green tides in the Yellow Sea of China [6,7], the predominant species at Jeju Island are foliose types such as *U. australis* (=*U. pertusa*) and *U. ohnoi* [4,5,8]. In 2014, we discovered a massive blade of *U. ohnoi* at Jeju Island measuring approximately 4.0 × 4.0 m, which was photographed despite parts of the thallus missing (Figure 1). *Ulva ohnoi* is a key species in summer macroalgal blooms, known for its higher thermal tolerance and subtropical nature [9,10].

In Shiheung (33°28′31″ N, 126°54′48″ E) on Jeju Island, green tides occur annually, resulting in large accumulations of *Ulva* biomass in coastal areas and decomposing in the upper intertidal zone (Figure 2). Although efforts are made to collect this biomass, they are insufficient (Figure 2). To monitor the green tides in Shiheung, in situ photographs were taken monthly at low tide from August to October over a 3-year period (2020–2022) using a drone (DJI Mavic 2 Pro), covering the same area of approximately 40 ha. Then, these images were composited into orthomosaic images using Metashape (Agisoft LLC, St. Petersburg, Russia) (Figure 3). The distribution of *Ulva* was determined using the maximum likelihood algorithm in ENVI Classic software (NV5 Geospatial Solutions, Inc., USA) based on the orthomosaic images.

Figure 1. Image of *Ulva ohnoi* found at Jeju Island in March 2014. The quadrat in the center of the image measures 50 × 50 cm.

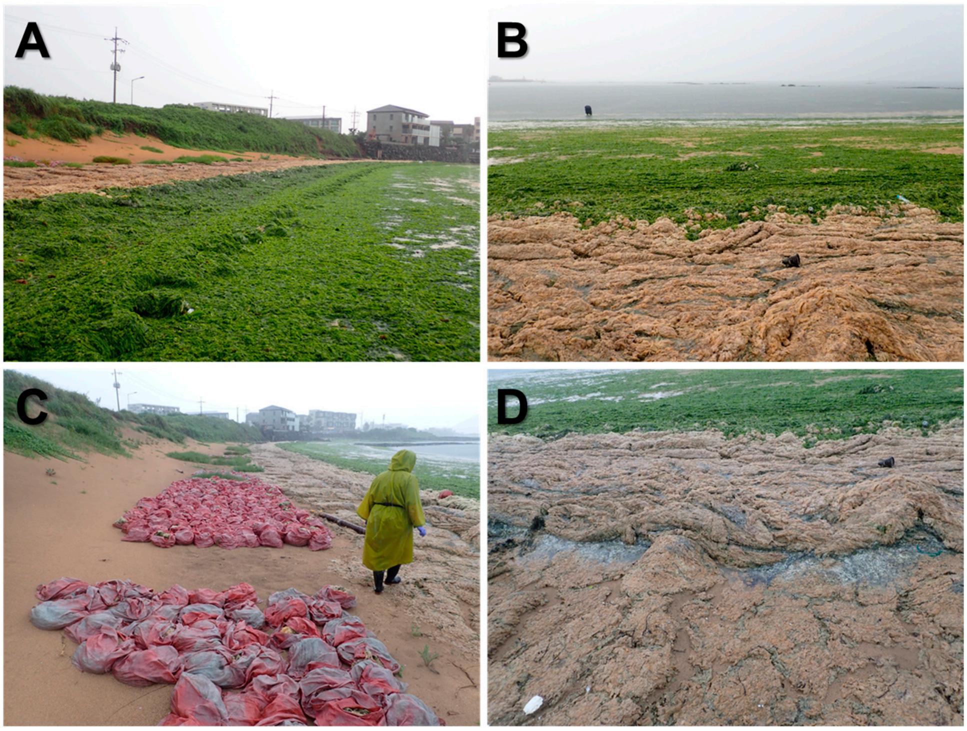

Figure 2. Green tide in Shiheung, Jeju Island. (**A**) *Ulva* mats along the shoreline. (**B**) Fresh mats in the upper section and decomposed ones in the lower section. (**C**) Sacks of *Ulva* collected for removal. (**D**) Accumulated and decaying *Ulva* biomass.

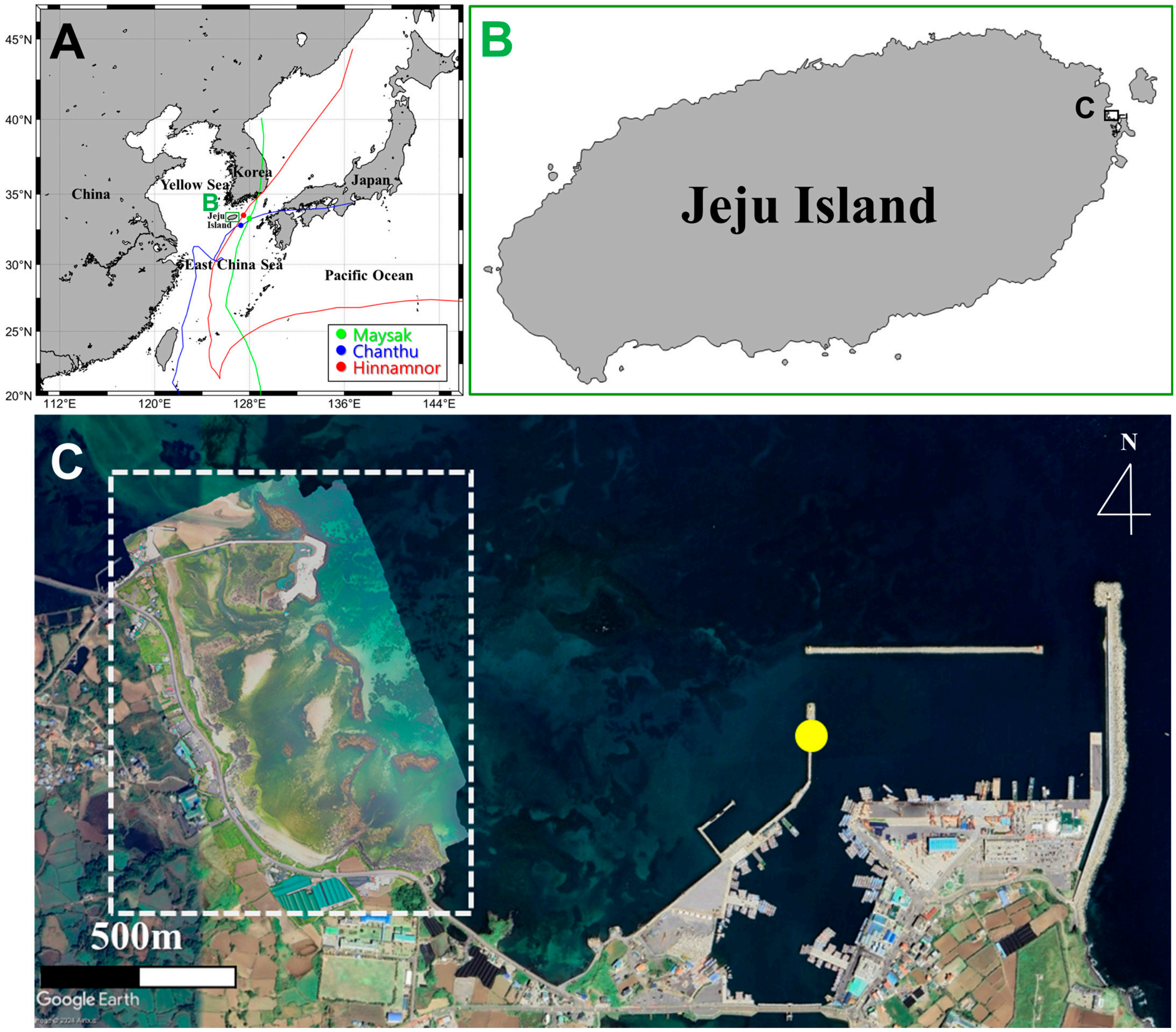

Figure 3. Map of the study site. (**A**) Typhoon tracks affecting Jeju Island, Korea, from 2020 to 2022. Each colored circle indicates the point when the typhoon was closest to Jeju Island. (**B**) A map of Jeju Island, Korea. (**C**) Shiheung, located in the western part of Jeju Island (Source: Google Maps; Imagery ©2024 TerraMetric. Map data ©2024). The white dashed box indicates the study site, and the yellow circle marks the wind observation point from the Korea Hydrographic and Oceanographic Agency.

During the study period, the area of *Ulva* blooms in Shiheung peaked each August, covering more than 40% of the total study site (Figures 4 and 5). In 2020 and 2022, the green tide area exceeded 23 ha in August but sharply decreased to less than 3 ha in September and remained low through October (Figures 4 and 5). In contrast, in 2021, the green tide covered 17.3 ha in August and remained at 15.9 ha until October, with large areas of *Ulva* continuously observed throughout the study area (Figures 4 and 5). Although the thalli of *U. ohnoi* are fragile and easily torn by waves and tides [5], they remain near the coast, apparently due to inward-facing currents and slow coastal water velocities [11,12]. The *Ulva* at the study site was widely distributed not only around rocks but also on sandy beaches, to which it cannot attach, suggesting that it continues to grow offshore while rolling within shallow areas [13].

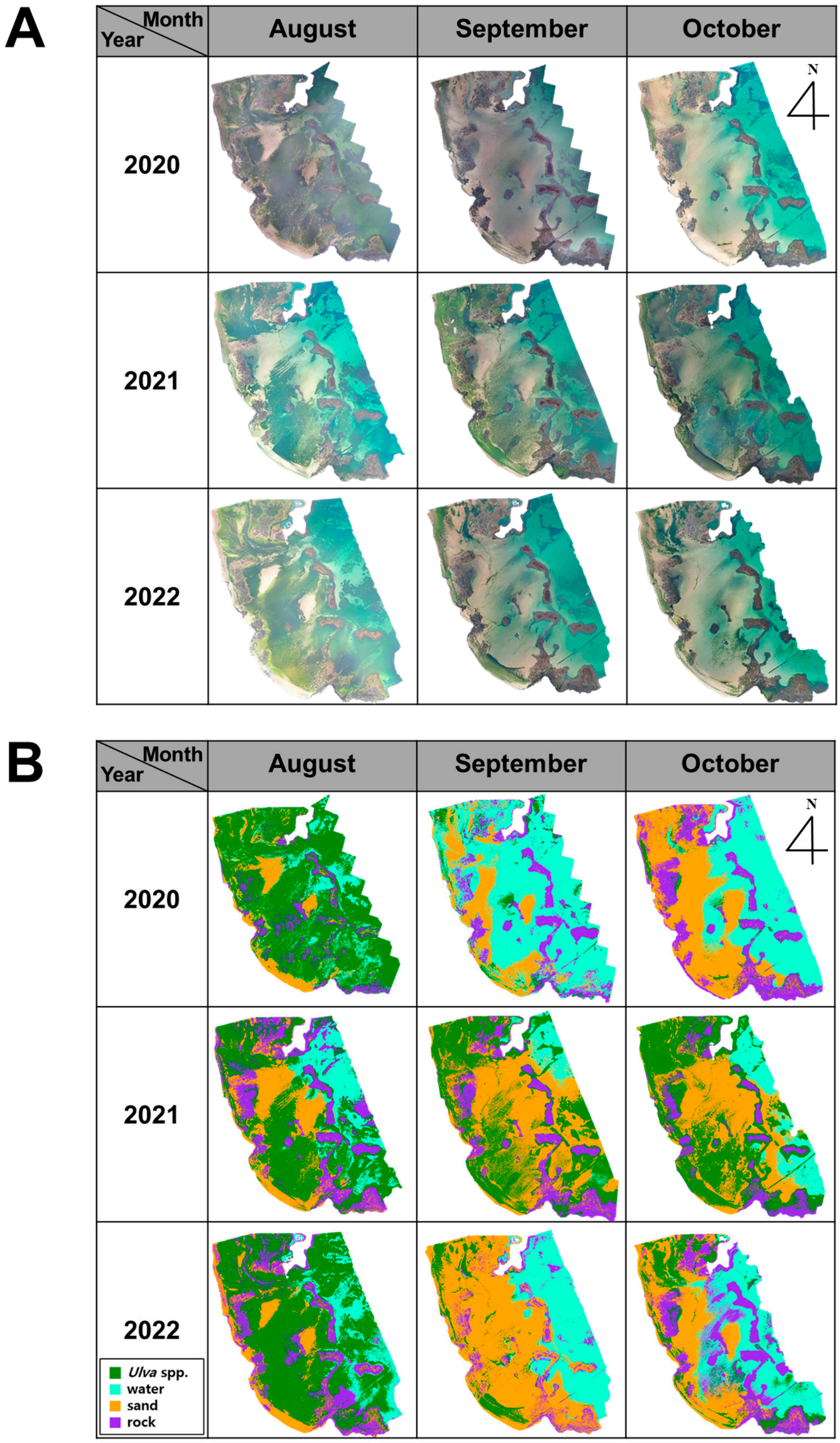

Figure 4. (**A**) Monthly orthomosaic images of Shiheung from August to October 2020–2022. (**B**) Object classification images derived from (**A**). Drone images were taken on 21 August, 18 September, and 18 October 2020; 26 August, 7 September, and 9 October 2021; 13 August, 26 September, and 22 October 2022.

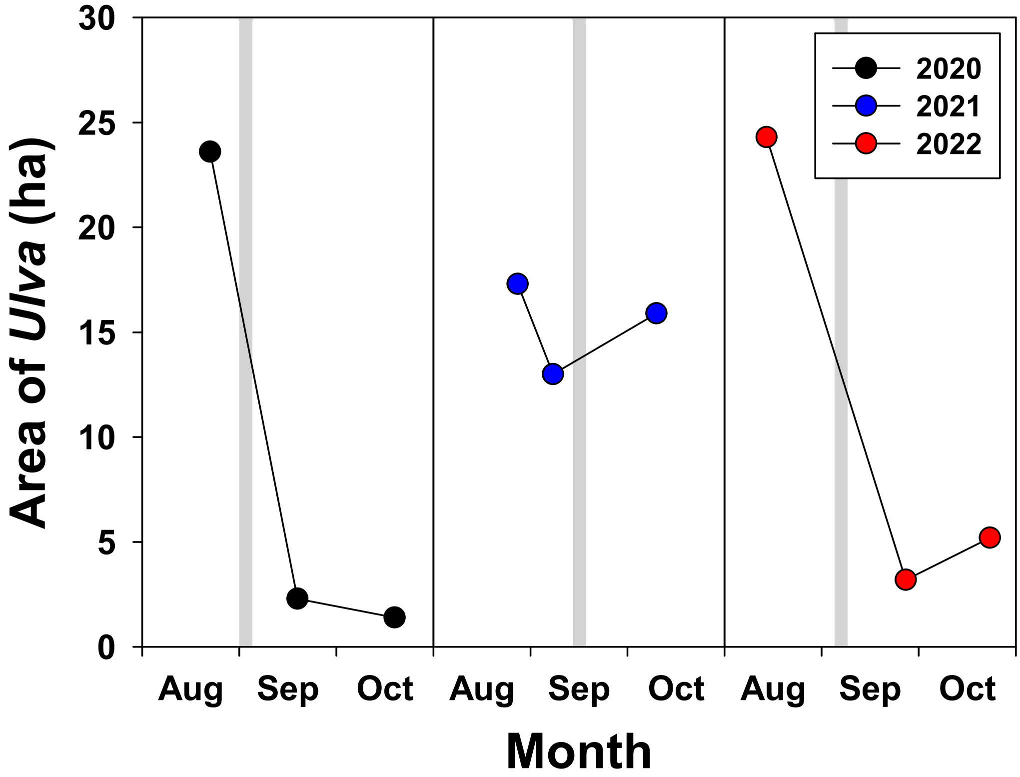

Figure 5. The distributional area of *Ulva* in Shiheung from August to October 2020–2022. The gray box indicates the 5 days of maximum impact of each typhoon (from 31 August to 4 September 2020; from 15 to 19 September 2021; from 4 to 8 September 2022).

Meanwhile, climate change is intensifying the impact of tropical cyclones (also known as typhoons in the northwestern Pacific Ocean) on the East China Sea, including on Jeju Island, which can act as a major disturbance to coastal ecosystems [14]. Elevated carbon dioxide levels and climate change increase the likelihood of typhoons reaching category 3 or higher on the Saffir–Simpson Hurricane Wind Scale (SSHWS) from tropical oceans [15,16]. In fact, during the study period, the site experienced very intense typhoons (category 4–5 on the SSHWS) every September, with major disturbances caused by Typhoon Maysak (category 4) in 2020, Typhoon Chanthu (category 5) in 2021, and Typhoon Hinnamnor (category 5) in 2022 (Figures 3 and 6). Wind speed and direction measurements near the study site during the 5 days of peak typhoon impact showed consistent northwesterly winds of 20 m/s or more in 2020 and 2022, while easterly winds of the same speed prevailed during the 2021 typhoon (Figure 6).

Photographs from September 2020 and 2022 visually demonstrate dissipation of the green tide, when strong westerly winds from the typhoons pushed the *Ulva* biomass out of the study area and into the deeper open sea to the east (Figure 4). These *Ulva* species can photosynthesize within the intertidal zone, allowing them to grow and survive [13]. However, once swept into the deeper subtidal zone, they sink and die, as they are not buoyant and cannot reach the water surface to receive the minimum irradiance required for photosynthesis. In contrast, in September 2021, intense typhoon impacts were evident, but the easterly winds, blowing in the opposite direction of the open sea, prevented the *Ulva* biomass from escaping the bay. As a result, the algae spread even across the sandy beach in October (Figure 4).

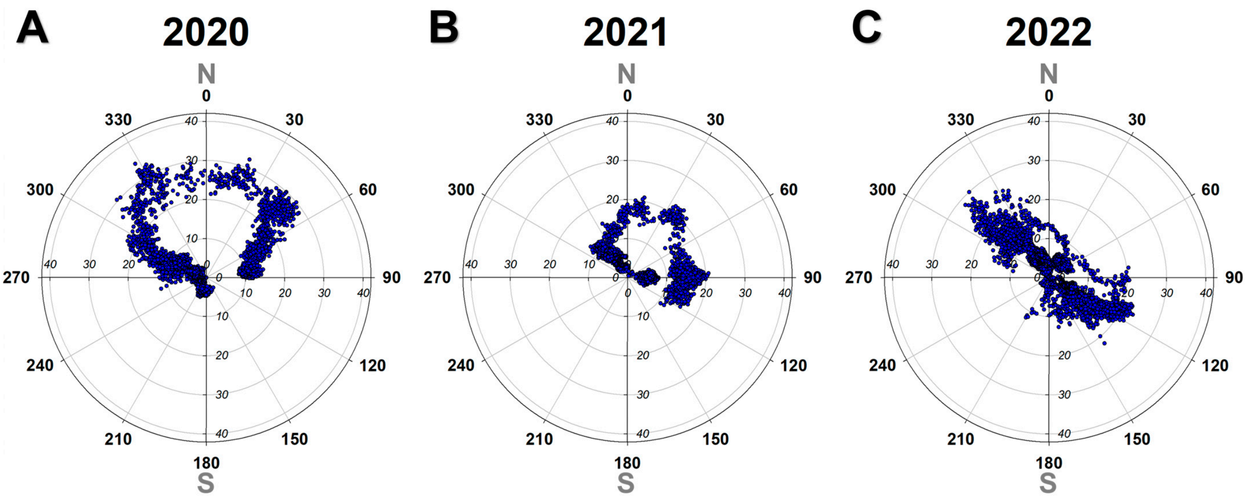

Figure 6. Wind direction and speed of typhoons near the study site during the 5 days of maximum impact from 2020 to 2022 (data from the Korea Hydrographic and Oceanographic Agency). (**A**) Maysack, (**B**) Chanthu, (**C**) Hannamnor. The gray capital letter and bold number indicate wind direction (unit: °) and italic number present wind speed (unit: m/s).

Over the past few decades, macroalgal blooms from *Ulva* and *Sargassum* in the East China Sea have shown a distinct increase in relation to climate change [17,18]. Outbreaks of *Ulva* green tides have also been occurring at Jeju Island since the 2000s. While studies have investigated the species and causes of these tides, there is a lack of research on the number and distribution of occurrences [4,8,11,19]. Seawater temperatures in the northern East China Sea, including around Jeju Island, have been rising more rapidly in recent years, particularly during the winter season. Additionally, the number of periods with high temperatures exceeding 20 °C is on the rise [20–23]. Given that the optimal growth temperature for *U. ohnoi* and *U. australis*, the primary species causing macroalgal blooms in the study area, ranges between 10 and 30 °C [10,13], it is likely that rising winter water temperatures are sustaining the green tides along the Jeju coast, while the high summer temperatures are exacerbating these macroalgal blooms to their peak. Additionally, the frequency and intensity of typhoon activity around the Korean Peninsula have increased since the 1970s, significantly increasing the risk to local communities [24,25]. However, studies on typhoon-related impacts on coastal ecosystems on Jeju Island have largely focused on changes in subtidal, kelp-dominated ecosystems [14].

This study highlights a paradoxical situation where green tides, exacerbated by elevated summer temperatures, are counterbalanced by increasingly frequent and intense typhoons, driven by climate change. This suggests that the development of benthic distributions, such as *Ulva* blooms induced by climate change, may be highly dependent on the presence and wind direction of large-scale disturbances. Consequently, the coastal biodiversity and benthic community structure may undergo dramatic, stage-wise transformations in response to typhoon impacts.

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