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Threats to a Temperate Kelp Forest Species, *Ecklonia cava*, through Tropical Fish Herbivory Associated with Sea Surface Warming in the East China Sea

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Abstract: Kelp forests in Korean waters, mainly consisting of *Ecklonia cava*, provide ecologically and economically important ecosystems. However, they are severely threatened by increasing sea surface temperature (SST). In 2023, an unusually high SST was observed in the northern East China Sea, where the average SST from August to November 2023 was found to be 1.1 °C higher than the average SST during the same period over the last two decades. Our photo images and videos reveal increasing feeding on *E. cava* populations by tropical herbivore rabbitfish (*Siganus canaliculatus*, *Siganus fuscescens*) associated with the impact of increasing SST. Given the fall reproductive peak of *E. cava* population, increased herbivory by tropical rabbitfish could have a significant adverse impact on the composition of temperate kelp forests.

Keywords: macroalgae; *Siganus*; rabbitfish; sea surface temperature; climate change; northern East China Sea

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Ecklonia cava Kjellman 1885 is a perennial endemic species with limited distribution, only appearing in the coastal areas of Korea and Japan [1,2]. *Ecklonia cava*-dominated kelp forests play an important role in the production of coastal fisheries, as they provide habitat and spawning grounds for a variety of marine organisms [3–5]. However, *E. cava* populations have been declined over the last several decades because sea surface temperature (SST) around the Korean Peninsula, particularly in the East China Sea, is rising rapidly due to global warming (Figure 1) [6–10]. Hyperthermal conditions caused by global warming can have negative effects on the metabolism, photosynthesis, growth, and survival of *E. cava* [8,11,12].

Between November 2022 and 2023, we observed significant physical damage to the *E. cava* population in the southern part of the Korean Peninsula (Maemul-do, 34°38′ N, 128°34′ E; Geomun-do, 34°02′ N, 127°19′ E) (Figures 1 and 2A,B). This study was conducted at an approximate depth of 8 m at each study site, which is a depth where the *E. cava* biomass was found to be the highest. A 30 m transect line was installed and *E. cava* density and morphological length were measured more than 30 times using a 50 cm × 50 cm quadrat. While the length of *E. cava* stipes (i.e., the stem part) showed no significant difference between the years in each site, the length of *E. cava* blades (i.e., the leafy part), in particular the longest blade length, showed a significant decrease (supplementary Figure S1). Video footage from 2023 recorded several schools of rabbitfish (Figure 2B) grazing through the *E. cava*-based kelp forest, eagerly feeding on *E. cava* blades (supplementary Videos S1 and S2). Detailed video analysis revealed their preference to consume the sorus (i.e., the reproductive structure) of mature blades while leaving behind torn blades and the stipes (Figure 2A). However, there was no evidence recorded of rabbitfish feeding activity (i.e., bite marks, torn blades) in *E. cava* individuals in 2022 (Figure 2C,D).

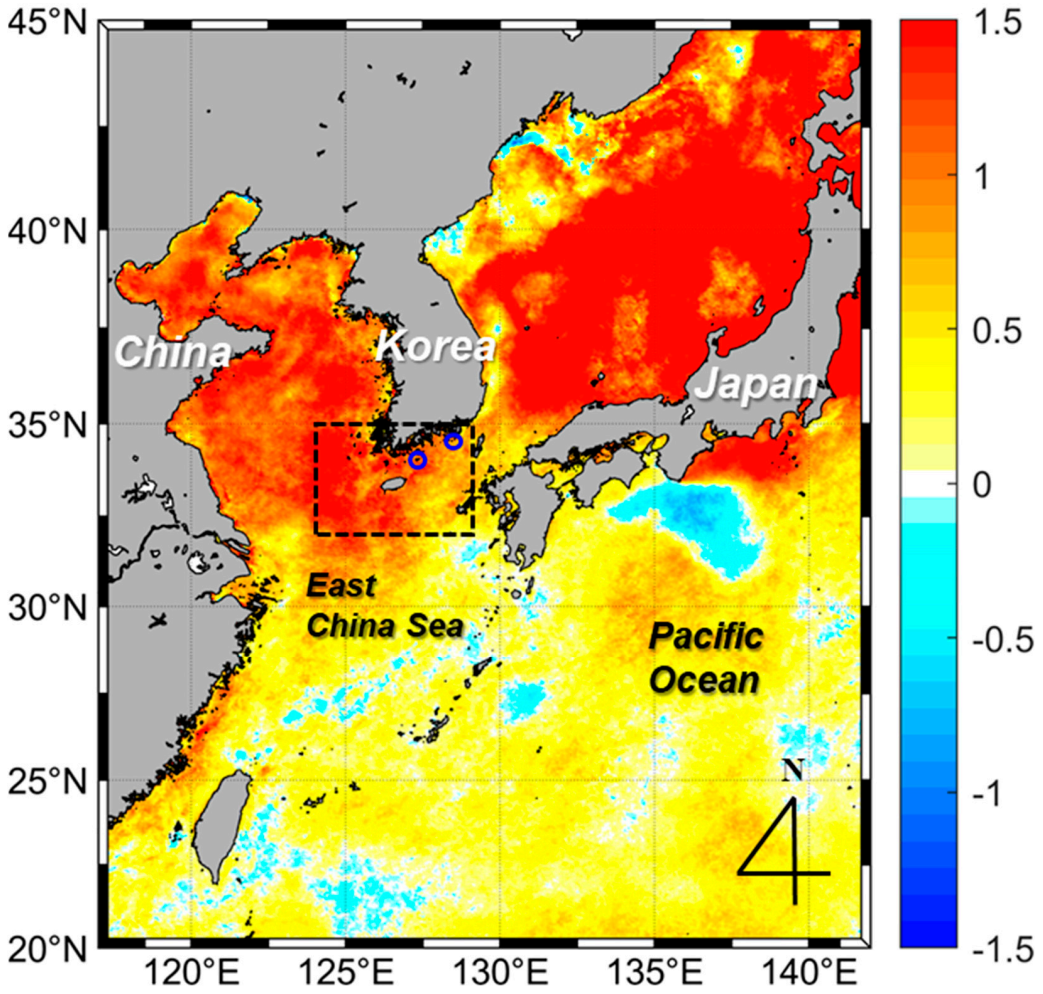

Figure 1. A map of study sites and the sea surface temperature anomaly averaged from August to November 2023 using a 21-year mean value around the East China Sea and the Korean Peninsula. The study sites are indicated by blue circles; the sea surface temperature anomaly (°C) is indicated by a color gradient from blue to red; the study area used for sea surface temperature analysis is indicated by a dashed box.

The species of rabbitfish observed were identified as *Siganus canaliculatus* (white-spotted spinefoot) and *Siganus fuscescens* (mottled spinefoot). These species are primarily tropical or subtropical, frequently appearing in the southern parts of Korean waters, including Jeju waters, which is currently the northernmost limit of their distribution [13–16]. In Jeju waters, they spawn in July and August when water temperature reaches its annual maximum while, in fall, their occurrence drops to less than 10% of that of the spawning season [15]. Reports from Japanese waters on the feeding behavior of *S. fuscescens* indicate the highest feeding rate at water temperatures of 26–29 °C [17]. Further studies showed a significant drop in the feeding rate in water temperatures below 20 °C and showed no indications of any feeding activity below 17.5 °C [18,19]. During the winter season, the rabbitfish remained within the macroalgal patch off the inshore areas without migrating and feeding [20]. Thus, the reproduction and feeding strategies of these species seem strongly related to water temperature.

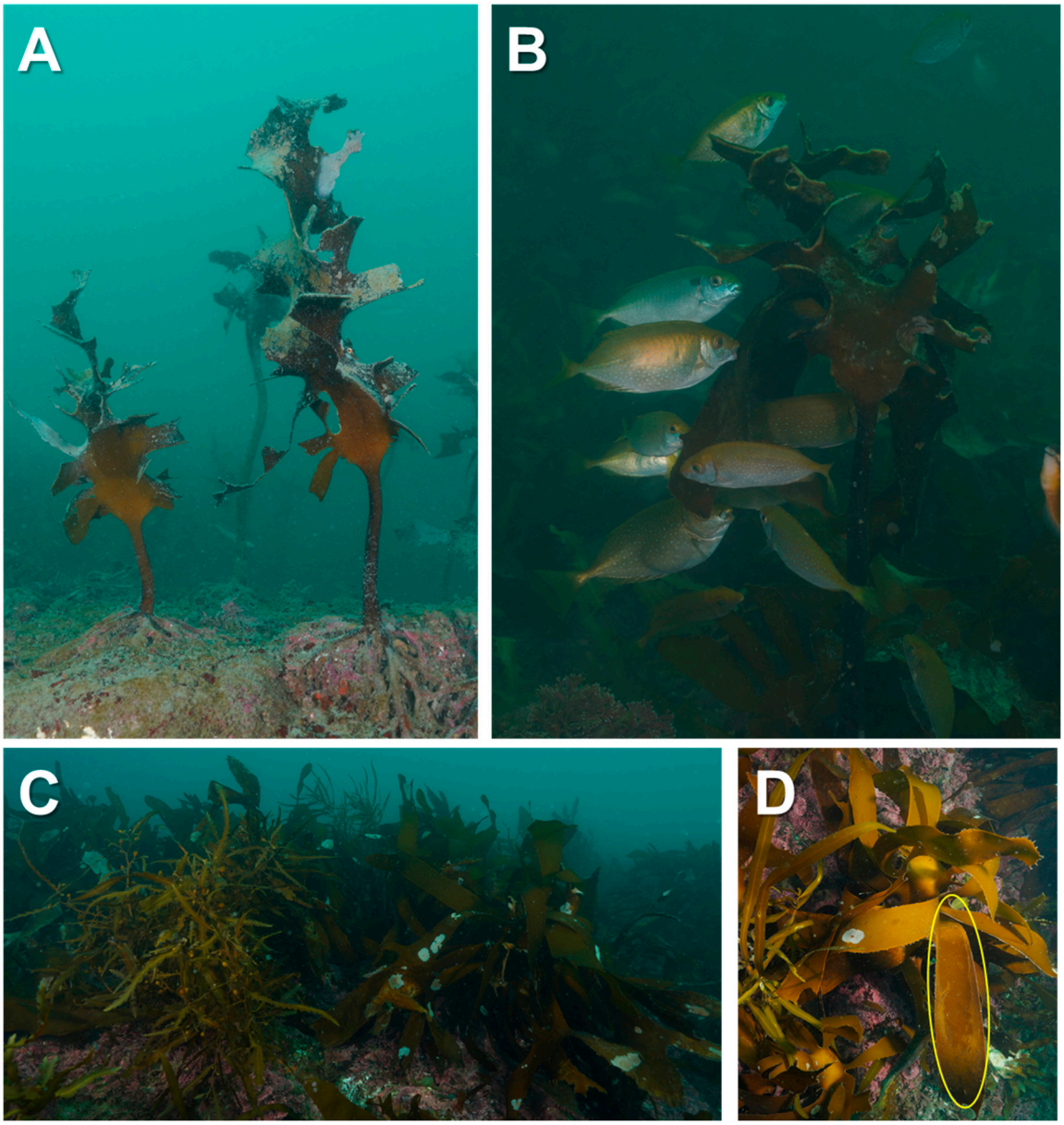

Figure 2. Photographic images of *Ecklonia cava* and *Siganus canaliculatus*. (**A**) *E. cava* with severe feeding damage (i.e., bite marks) in Maemul-do (November 2023), (**B**) *E. cava* and *S. canaliculatus* in Geomun-do (November 2023), (**C**) a healthy *E. cava* population in a kelp forest in Geomun-do (November 2022), and (**D**) *E. cava* blades with sorus (see yellow ellipsis) in Geomun-do (November 2022).

The significant increase in rabbitfish feeding on local kelp forests coincides with the sea surface warming around the northern East China Sea and the Korean Peninsula, which was recorded along with a strengthened positive SST anomaly from August to November 2023 (Figure 1). The mean satellite-derived SST value (from Moderate Resolution Imaging Spectroradiometer, MODIS) averaged from August to November during the 21-year (2003–2023) period in the study area was 23.4 °C, while the mean SST value in 2023 was 24.5 °C. The abnormal warming in the study area that occurred was a positive increase of 1.1 °C, which is approximately 0.8 °C higher than the global mean (Figure 1). Seawater temperature (data from the Korea Hydrographic and Oceanographic Agency) measured in situ in Geomun-do from August to September 2023 also showed the highest value (daily average of 26.8 °C, maximum of 28.3 °C) since 2007, as well as 3.2 °C higher compared to the value of the same period in

2022 (supplementary Figure S2). Overall, this dramatic damage of the *E. cava* population driven by the high activity and intensive grazing of rabbitfish is likely to be associated with the significant increase in SST in 2023. On the other hand, *E. cava* has been reported to have the lowest growth at high elevated temperatures (>25 °C), so the summer season of 2023 would have been even more adverse for this species [1,11]. In addition, high pressure of herbivory potentially will inhibit *E. cava* reproduction, as the maturation of *E. cava* with sorus is known to peak around October and spore release occurs during the fall season in Korean waters [21].

So far, large-scale mortality of the *E. cava* population around the Korean Peninsula has been reported due to typhoon occurrence and to herbivores such as gastropods and echinoderms; however, the impacts of tropical herbivore fish on the population in this region have not yet been reported [21,22]. The evidence in overgrazing of temperate kelp species by tropical herbivory has already been identified in Japan and in the Mediterranean, but information on specific mechanisms that facilitate this shift is still scarce [23,24]. Our observation indicates that not only is there an increase in seasonal water temperature but there is also an increase in tropical fish (i.e., *S. canaliculatus*, *S. fuscescens*) herbivory that may possibly hinder the maintenance of the population size by causing the loss of sorus before the reproduction season of kelp species (*E. cava*). Finally, the combined effects of global warming and invasive herbivory are likely to accelerate the decline of endemic *E. cava*.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/d16050253/s1, Figure S1: Comparison of *Ecklonia cava* stipe and blade lengths, respectively; Figure S2: Seawater temperature from August to November 2022 and 2023 in Geomun-do, Korea; Video S1: A video recorded in November 2023 of *Ecklonia*-dominated kelp forest and feeding activity of *Siganus canaliculatus* in Maemul-do, Korea; Video S2: A video recorded in November 2023 of *Ecklonia*-dominated kelp forest and feeding activity of *Siganus canaliculatus* in Geomun-do, Korea.

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