Water temperature characteristics and the maintenance of Sargassum piluliferum (Fucales, Phaeophyceae) in Namako-ike Lake, Kami-Koshiki-shima Island, Kagoshima Prefecture, Japan

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Abstract: In the southern Japanese coastal area affected by the Kuroshio Current, seaweed beds consisting of brown macroalgae has been reduced owing to increases in water temperature and damage from grazing by herbivorous animals. Kami-Koshiki-shima Island, located in western part of Kagoshima Prefecture, contains landlocked brackish-water lagoons, and Sargassum piluliferum is a dominant species in Namako-ike Lake, located in one of these lagoons. In this study, seawater temperature in Namako-ike Lake and neighboring waters was measured in 2014 in order to elucidate the factors contributing to the maintenance of the S. piluliferum populations. The annual average seawater temperature in 2014 was 19.5 °C in Namako-ike Lake, with the highest water temperature recorded in July, 2014 at 35.6 °C and the lowest water temperature recorded in March, 2014 at 6.6 °C. These results suggest that S. piluliferum has tolerance to high water temperature in Namako-ike Lake, which is far higher than in surrounding sea areas. The lack of herbivorous animals in the lake is suggested to be the main factor contributing to the maintenance of the S. piluliferum population rather than an increase in water temperature. In order to maintain the S. piluliferum population, it is necessary to continue monitoring the organisms growing in Namako-ike Lake in cooperation with local residents.

Keywords: biomass, Koshiki-shima, Namako-ike Lake, Sargassum piluliferum, temperature

Introduction

The Koshiki-shima Archipelago is located 40 km west of the Satsuma Peninsula in Satsumasendai City, Kagoshima Prefecture, Japan, and comprises three inhabited islands and many other uninhabited islands. The total length of the chain of islands is 40 km (Aramaki et al. 1976). Koshiki-shima Islands have a variety of shore landscapes (e.g., coastal cliffs, sand banks, and ria coasts). In addition, these islands were designated as a Prefectural Nature Park in 1990 because of their superior natural resources and scenery, such as the laurel forests growing from the coast to the ridge at an altitude of 600 m (Ministry of Environment of Japan 2014). Furthermore, this area has important natural environments such as habitats of rare bird species, lake groups separated by a sandbar, and populations of Quercus phillyraeoides (Ministry of Environment of Japan 2014; National Printing Bureau 2015). Namako-ike Lake is the largest lake in the national park at 2,200 m in length, 550 m in width, and an area of 560 m². Namako-

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ike Lake is separated from the open sea by a sandbar, but some seawater can move into the lake under the sandbar, and pitch differences affect the surface of the lake depending on the sea tide. Because open seawater cannot pass over the sandbar into Namako-ike Lake owing to daily surges and high and low tides, the animals and plants in the lake represent a specific population that is completely isolated from the open sea by gravel (Kagoshima Prefecture 1990).

A total of eight species of large marine algae and marine flowering plants were reported to inhabit Namako-ike Lake in 1990 (Kagoshima Prefecture 1990); subsequently, a comprehensive survey identified a total of 30 species of marine plants in the lake in 2003 and 2006 (Shimabukuro et al. 2012). In particular, the brown alga *Sargassum piluliferum* (Turner) C. Agardh was found to be growing throughout almost the entire area of the lake, representing the largest distribution area of all marine plant communities with respect to biomass in this lake (Shimabukuro et al. 2012).

However, a state of ISOYAKE (i.e., unusual decreases in the algae population) is a continuous chronic condition in the sea area outside of Koshiki-shima Island. The main factors contributing to ISOYAKE are sedimentation of the floating mud, grazing pressure by animals, and calm of seawater flow induced by artificial structures; however, the quality of the water environment such as water temperature plays a major role in this effect (Fisheries Agency 2015).

In Namako-ike Lake, water temperature, dissolved oxygen levels, salinity, and nutrient levels were measured in May and November of 2003 (Shimabukuro et al. 2012). However, these measurements only represent single points in time, and do not reflect seasonal variations. Therefore, in this study, water temperature was measured throughout the year in order to elucidate the factors contributing to the maintenance of seaweed beds in this lake. Determining the environmental factors contributing to the population maintenance of brown macroalgae in the lake may provide valuable information for preventing the ISOYAKE state in the surrounding sea area.

**Study Sites and Methods**

This study was conducted in Namako-ike Lake located in the northern part of Kami-Koshiki-shima Island, Satsuma-sendai City, Kagoshima Prefecture, Japan (Figs 1 and 2).

**Water temperature:** A water temperature data logger (Tidbit V2, UTBI-001, Onset Computer Corporation) was installed at about 2 m below sea level in the quay of Naka-Koshiki Port (Fig. 1: T1) from January until the end of December 2014, and water temperature was measured at 1-hour intervals for comparison to water temperature variations of Namako-ike Lake. The water temperature of Namako-ike Lake was...
measured in a similar manner, and the same type of data logger was placed in the west bank in the middle of the sea 2 m under this lake (Fig. 1: T2). In addition, annual air temperature data of Namako-ike Lake over the survey period were obtained from the homepage of the Meteorological Agency of Japan (http://www.jma.go.jp/jma/menu/menureport.html) for Naka-Koshiki, Satsuma-sendai City, Kagoshima Prefecture.

Thallus length and density of *S. piluliferum*: The two sites chosen for measuring thallus length and density of *S. piluliferum* were the same research sites used in a previous study conducted in 2003 (Shimabukuro et al. 2012) (Fig. 1: P1, P2). We installed three square-shaped frames (50×50 cm) at each site and counted the number of thalli of *S. piluliferum* in the frame, the number of branches on each thallus, and the maximum length of the thallus; the data were collected on November 1, 2013.

In addition, we surveyed the algal vegetation by visual observation in two sites outside of Namako-ike Lake (Fig. 1: P3, November 1, 2013; Fig. 1: P4, November 2, 2013), for comparison with the vegetation of Namako-ike Lake.

**Results**

**Temperature:** The annual (January to December 2014) average water temperature of Namako-ike Lake was 19.5 °C, whereas the average water temperature of Naka-Koshiki Port was 21.1 °C. The annual average air temperature of Naka-Koshiki was 18.2 °C (Fig. 3).

The mean water temperature of Namako-ike Lake of the summer season (July to September), when the temperature is highest, was 28.1 °C, and the maximum water temperature recorded was 35.6 °C (at 15:00 on July 28, 2014). Furthermore, in July 2014, the water temperature of Namako-ike Lake was greater than 30 °C throughout most of the day over a 23-hour period (from 20:00 of July 29 to 18:00 of July 30, 2014). The mean water temperature of Naka-Koshiki Port in the summer season (July to September) was 26.6 °C, and the mean air temperature of Naka-Koshiki in this period was 26.1 °C (Fig. 3).

The mean water temperature of Namako-ike Lake in the winter season (January, February, and December 2014) was 10.8 °C, and the lowest water temperature recorded was 7.3 °C (at 1:00 on January 12, 2014). Furthermore, water temperatures below 10 °C were reported for a consecutive period of 70 hours (from 15:00 on January 16 to 12:00 on January 19, 2014) in Namako-ike Lake. The water temperature of Naka-Koshiki Port did not drop below 10 °C in the winter season. The mean air temperature of Naka-Koshiki in the winter season was 10.0 °C, and the lowest air temperature recorded was 2.5 °C (at 0:00 on January 20, 2014) (Fig. 3).

The relationships between the annual water temperatures of Namako-ike Lake and Naka-
Koshiki Port, and between the annual water temperature of Namako-ike Lake and the air temperature of Naka-Koshiki are shown in Fig. 4-A, B. The relationships were linear, with high \( R^2 \) values (water temperature of Namako-ike Lake and air temperature of Naka-Koshiki Port \( R^2 = 0.914, p < 0.05; \) water temperature of Namako-ike Lake and water temperature of Naka-Koshiki Port). C: Relationships of temperatures in the winter season (water temperature of Namako-ike Lake and air temperature of Naka-Koshiki). D: Relationships of temperatures in the winter season (water temperature of Namako-ike Lake and water temperature of Naka-Koshiki Port).

Thallus length and density of *S. piluliferum*:
The population of *S. piluliferum* was confirmed to be growing in the two experimental sites (Fig. 1-P1, P2) used in this study (Fig. 5). Table 1 shows the measurement results at the sites of P1 and P2 on November 1, 2013. For the site P1, the density of *S. piluliferum* shoots was \( 22.7 \pm 1.3 \) shoots m\(^{-2} \), the number of *S. piluliferum* main branches was \( 212.0 \pm 10.6 \) branches m\(^{-2} \), and the average plant length was \( 390.8 \pm 17.2 \) mm. *S. piluliferum* was found to be mature in site P1, because receptacles were arising from the axils of the branches. In experimental site P2, the density of *S. piluliferum* shoots was \( 24.0 \pm 2.3 \) shoots m\(^{-2} \), the number of main branches was \( 206.0 \pm 19.6 \) branches m\(^{-2} \), and the average plant length was \( 437.8 \pm 18.4 \) mm (mean \( \pm \) S.D.).
Visual observations of the flora outside of Namako-ike Lake (Fig. 1: P3, P4) revealed that the most dominant algae were Corallinaceae species, which covered the surfaces of rocks, and two small algae, *Dictyopteris undulata* Holmes and *Gelidium elegans* Kuetzing, which were found to be growing at small abundance on rocks. No *Sargassum* species, including *S. piluliferum*, were detected outside of Namako-ike Lake (Fig. 6).

**Discussion**

The population of *S. piluliferum* in Namako-ike Lake was formed in the same place, but the biomass of this species was slightly decreased when compared with reports from 10 years ago (Shimabukuro et al. 2012). There is no record of the initial colonization of *S. piluliferum* in Namako-ike Lake. Specimens of *S. piluliferum* were collected in Urauchi Bay, on the eastern side of Kami-Koshiki-shima Island (Fig. 1), in 1984 and were deposited in the Kagoshima Prefectural Fisheries Technology and Development Center (KFE-B67-42-67, 68); however, algal beds composed of brown macroalgae no longer exist along the shores of the Koshiki-shima Islands, now.

There is also a record of *S. piluliferum* growing in Arakawa, Ichiki-Kushikino City, Kagoshima Prefecture, near the Koshiki-shima Islands, on the western side of the Satsuma peninsula (Tanaka 1977). Since the cove of Namako-ike Lake closed in about 6,000 years ago, external seawater can only enter this lake through very fine gravel. Therefore, owing to sand filters about tens of meters in width, the animals and plants that routinely grow in the waters outside of the lake are not able to penetrate into the lake. It was thought that a large quantity of...
seawater flowed into Namako-ike Lake from outside when the seawall and sandbar collapsed because of typhoon Ruth in October of 1951 (Fujioka 1964). However, it is hard to imagine that the thalli and embryos of *S. piluliferum* would have flowed into Namako-ike Lake and thrived there during the typhoon, as October represents the time when this species is at the lowest levels in Kagoshima, Southern Japan.

*Apostichopus japonicus* (Japanese name: NAMAKO) was introduced into Namako-ike Lake, giving it its name, during transport along the Satsuma Domain from Omura Bay in Nagasaki Prefecture in the Edo Period, and was able to survive and reproduce (Editorial Committee of the Local History of Kami-Koshiki Village 1980). Because *S. piluliferum* was distributed over Omura Bay (Editorial Committee of Local History of Omura City 2013) (Fig. 1), *S. piluliferum* might also have been introduced in Namako-ike Lake along with *A. japonicus* to grow on the bay. However, this theory is only a speculation. Because not only *S. piluliferum* grows in Omura Bay, it is necessary to carefully investigate the populated route of *S. piluliferum* growing in Namako-ike Lake.

Seaweed beds have been in continuous decline since the 1960s, and the Kyushu west coast, including Kagoshima, has entered into a serious ISOYAKE state (Shinmura 1983, Kiriyama 2009). Seaweed bed including *S. piluliferum* has decreased in the southern Japan region due to warming of the seawater and feeding damage induced by grazers. Therefore, it is curious that *S. piluliferum* has maintained such an abundant population in Namako-ike Lake, which is adjacent to the ISOYAKE sea area.

The annual mean water temperature of Namako-ike Lake in 2014 was found to be 19.5 °C, and the mean water temperature of the Naka-Koshiki port of the open sea setting was 21.1 °C in this study. In general, the main factor contributing to warming of lake water is heat due to irradiation from the sun, whereas the main factors contributing to lowering the temperature of the lake water are infusion of water from the outside, such as from rivers, and evaporation from the surface of the lake owing to a night-cooling effect (Yoshimura 1976). However, Namako-ike Lake does not have an inflow of the inland water by the river, and only a slight amount of open seawater can pass through the sandbar into the lake. Therefore, because the highest water temperature reached 35 °C, and a water temperature greater than 30 °C continued for 16 hours in the summer (from 8:00, 23, Jul. to 0:00, 24, Jul.), Namako-ike Lake represents a more severe water temperature environment for *S. piluliferum* compared to the outside sea area.

In culture experiments, the upper temperature limit for growth of *S. piluliferum* was found to be 30 °C for adults (Haraguchi et al. 2005) and 32 °C for juveniles (Baba 2011). The branches and leaves of *S. piluliferum* growing in Namako-ike Lake are much thinner than those of this species growing in other sea areas (Shimabukuro et al. 2012). Owing to its isolation from external sources for a long period of time, *S. piluliferum* growing in Namako-ike Lake shows a characteristic unique morphology and physiology, suggesting that this population is becoming genetically differentiated from those growing in other coastal areas. Therefore, the population genetics of *S. piluliferum* inhabiting Namako-ike Lake should be clarified in future studies.

The main animals that cause feeding damage to seaweed beds in the area along the shore of Kyushu, Japan are the fish species *Siganus fuscescens* and *Calotomus japonicus* and the sea urchins *Anthocidaris crassispina* and *Diadema setosum* (Kuwabara et al. 2006; Fujita et al. 2008). As described above, animals from the adjacent sea area cannot invade Namako-ike Lake through the sandbar, but may have had an opportunity to invade following previous collapses of the sandbar and due to annual typhoons or high waves. However, the seawater temperature of Namako-ike Lake was 6.6 °C lower than that of the open sea area, where the minimum sea water temperature did not drop below 10 °C in the winter season, whereas the sea water temperature of the lake was continuously less than 10 °C for a period of 70 hours in 2014.

Experimental studies have demonstrated that the lower water temperature limit of *S. fuscescens* and *C. japonicus* is approximately 10 °C (Shimo et al. 2000), that of *A. crassispina* is 7 °C (Shimo et
al. 2000), and that of D. setosum is 9.3°C (Marine Ecology Research Institute 2011). These values represent the survival limit temperatures, whereas the temperature limits to be able to eat for the grazers of these species is a few degrees higher. Therefore, even if the animals that prey on S. piluliferum could enter Namako-ike Lake through some accident, they would likely not be able to survive in the lake through the winter season. When the authors observed in this lake, S. fuscescens and D. setosum did not exist.

The summer water temperature of Namako-ike Lake was the environment that was severe to grow it for the S. piluliferum physiologically, but the population of this species was maintained. Therefore, it is suggested that the herbivore-free environment of Namako-ike Lake is the main factor contributing to maintenance of the S. piluliferum population, and not water temperature, directly. In other words, the factor of decrease of seaweed bed in the Southwest Japan coast, was feeding damage by animals, rather than the high water temperature giving a physiological effect to the Sargassum bed including S. piluliferum.

The population of S. piluliferum inhabiting Namako-ike Lake represents a specific ecosystem in the landlocked brackish-water lagoon in Koshiki-shima Islands, and rarity value is very high. Closed wetlands, such as lakes, are protected from external environmental changes, but when a large change occurs, including invasion of introduced species and the inflow of large-scale sand, closed wetlands cannot be easily restored. Fishing and collections of biological samples for research purposes in Namako-ike Lake are managed by local residents, and it appears that consciousness of the lake resources has increased since this area has been designated as a national park in Japan. In order to better conserve these ecosystems in the future, it is necessary to accumulate basic knowledge about the animals and plants in Namako-ike Lake through research and to continue monitoring the organisms inhabiting the lake in cooperation with local residents.

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