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Growth variation in long blade kelp *Saccharina longissima* in eastern Hokkaido, Japan

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Abstract: *Saccharina longissima* (Naga-konbu in Japanese) is distributed in shallow Pacific coastal areas from eastern Hokkaido (Kushiro and Nemuro) to Chishima Island. It is a commercially important Laminariacean kelp species in this area. The variations in the blade size of *S. longissima* (age 1+) were analyzed in Habomai, eastern Hokkaido, Japan. The fisheries cooperative association of Habomai in Nemuro monitored the blade size of the kelp in the harvest grounds along more than 15 km of coastline in May and June from 2000 to 2014. The monitoring data showed that the blade weight varied among years, and the growth of blade weight was greater in 2002 and 2009 then the other years. The kelps had a poorer growth of the blade in 2001, 2011 and 2013. Correlation analysis revealed that the coefficients between the blade weight in May and the monthly mean water temperature in spring to autumn in the previous year were negative but positive in winter to spring in the same year. Generalized linear regression model (GLM) analysis of the blade weight in May also revealed that the growth models including only monthly mean water temperature (January, April, July and October in the previous year, January, April during in the same year) and longitude effectively estimated the variation of the annual mean weight. Correlation analysis also revealed that the mean wet weight of *S. longissima* in May represents the growth condition of the kelp of the year, and it is useful for predicting the annual fisheries production in this area. These results suggested that the weight growth of *S. longissima* is affected by the ambient water temperature both in the previous and the same years. High temperature in the preceding autumn and extremely low temperature in the preceding winter to spring reduce the blade weight in the summer harvest season. Therefore, the increasing trends of water temperature in recent years may be one of the factors decreasing the fisheries production of the kelp in eastern Hokkaido.

Key words: *Saccharina longissima* (Naga-konbu), *Laminariacean* kelp, growth, water temperature, eastern Hokkaido

Introduction

Seaweeds, including kelps, are fundamental species of the coastal ecosystem, serving as a nursery, refuge, forage and spawning habitat for many organisms (Steneck *et al*., 2002). In addition, kelp species have especially high growth rates, and wild harvest and culture of Laminariacean kelp species are important for the fishing industry in the Pacific coastal areas, such as northern Japan (Mizuta, 2003). *Saccharina longissima* (Naga-konbu in Japanese) is one of those kelp species, which grows up to more than 10 m in blade length (**Fig.1a**). *S. longissima* used to be classified as *Laminaria longissima* (Miyabe), but

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most *Laminaria* species including this species were taxonomically reorganized into the genus *Saccharina* through a multi-gene molecular investigation (Lane *et al*., 2006; Yotsukura, 2010). The kelp is distributed in shallow Pacific coastal areas (**Fig.1b**) from eastern Hokkaido (Kushiro and Nemuro) to the Chishima Islands. Its distribution area is under the influence of the cold Oyashio current, and the water temperature varies seasonally from sub-zero to 20°C. This kelp is the main harvested species in eastern Hokkaido (**Fig.1c, d**), mostly used for tsukuda-ni (preserved food cooked with sweetened soy sauce) and kelp rolls, making use of its soft texture, whereas other kelp species with harder blades are widely used for broth. The annual total fishery production of the kelp species in Kushiro and Nemuro, where *S. longissima* is the main harvested species, is around 10 thousand tons in dry weight, with a gradual decreasing trend in recent years (**Fig.2**, Hokkaido Regional Agricultural Administration Office, 2017). A similar trend is seen in other kelp species in other areas in Hokkaido. Akaike (2017) suggested that there is a high probability change of the marine environment has affected the production of kelp species in Hokkaido. The present study focused on determination of the environmental factors affecting the variation in the growth and fisheries production of *S. longissima* (Miyabe) in eastern Hokkaido, Japan.

Materials and methods

The fisheries cooperative association of Habomai has been monitoring the blade size of the *S. longissima* in May and June in its harvest grounds along more than 15 km of coastline in Nemuro, eastern Hokkaido (from 43.30°N, 145.67°E to 43.39°N, 145.82°E, **Fig.3**). In each monitoring, one to 20 sporophytes of the kelp were collected using long handle gears in 28 to 40 locations, and the blade length, maximum width and the wet weight of the kelp were measured. The variations in the blade size of the kelp over age 1+ (2^{nd} year sporophyte) from 2000 to 2014 were analyzed in this study. *S. longissima* is a perennial species, and the kelp over age 1+ is targeted for fisheries harvest using long handle gears between June and October. Thin bladed sporophytes identified as less than age 1+, were excluded from the calculative analysis. The

Fig. 1. *Saccharina longissima*. (a): overview of sporophytes, (b): lower intertidal to upper subtidal habitats, (c) and (d): drying process on artificial stone fields.

incongruous sporophytes, with unknown collection sites and unusual weight to length ratio, were also excluded from the analysis.

Effects of environmental factors on the blade weight in May were estimated using correlation analysis. Blade weight was used for the representative variable of *S. longissima* size in the correlation analysis. Monthly average water temperature in Kushiro, monthly mean daylight hours and wind speed in Nemuro in the previous and same years were used as the environmental factors in this analysis. Moreover, the effects of water temperature on the blade weight in May were estimated using a generalized linear regression model (GLM) because the correlation analysis revealed that only coefficients between the blade weight in May and the mean water temperature had significant trends throughout the years (see Result and Discussion). To avoid the multi-collinearity of the mean water temperature among successive months, monthly mean water temperature for January, April, July and October, which were selected as the representative months of each quarter of the year, were used as the dependent variables for the GLM analysis. In addition, GLM analysis was also performed between the mean blade weight in May and the monthly mean water temperature, with a significant correlation with the former ($P < 0.05$). But January in the previous year and January, March in the same year were excluded to avoid multi-collinearity (see Results and Discussion). Longitudes of the sampling sites were also used as explanation variables for locations in these models. Dependent variables (blade weight in May) were assumed to follow the gamma distribution (log link). Model selection based on Akaike's information criterion (AIC) was then performed, and those with the minimum AICs were regarded as the best fit model. Monthly mean water temperature in Kushiro was calculated from the temperature of the intake water for the experimental facilities of Hokkaido National Fisheries Research Institute (Kushiro Laboratory), Japan Fisheries Research and Education Agency (42.949° N, 144.442° E), which is located 100 km west of the study area in Habomai. Monthly average daylight hours and wind speed were obtained from the Automated Meteorological Data Acquisition System (AMeDAS) in Nemuro (43.331°N, 145.586° E). Relationships between mean blade weight in May and June, the mean blade weight in May and fisheries production of kelp species in Nemuro (Hokkaido Regional Agricultural Administration Office, 2017) were analyzed for each site using a correlation analysis. In the correlation analysis, blade weight and fisheries production were transformed logarithmically. The significance of the correlation coefficients was tested by Pearson's

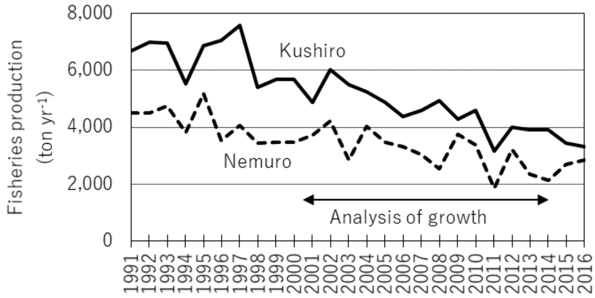

Fig. 2. Fisheries production of kelp species in eastern Hokkaido (Kushiro and Nemuro). *Saccharina longissima* is assumed to contribute about 70 % of the fisheries production of kelps in this area. Values are in dry weight.

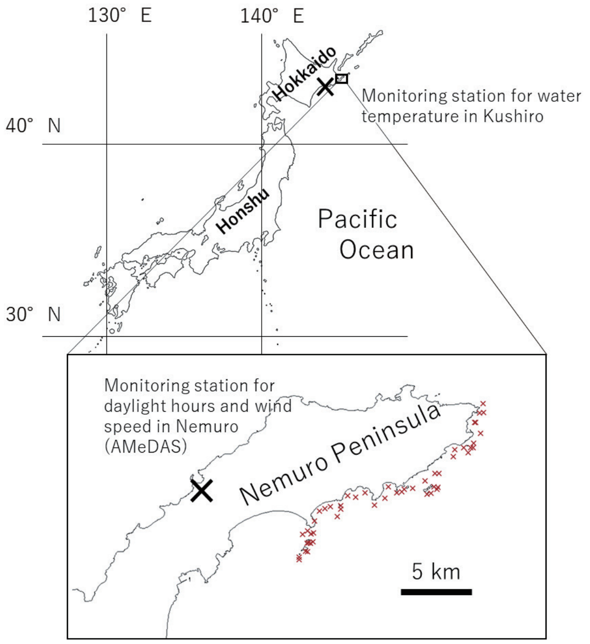

Fig. 3. Monitoring sites for *Saccharina longissima* in Habomai area and monitoring stations for water temperature in Kushiro and daylight hours and wind speed in Nemuro, eastern Hokkaido, Japan.

product-moment correlation, and P < 0.05 was considered statistically significant.

Results and discussion

From the 15 year monitoring data, 4,149 sporophytes and 469 site mean blade weights and 4,543 sporophytes and 396 site mean blade weights were used for the analysis for May and June, respectively, in this study of *S. longissima*. The monitoring data showed that the blade weight in May varied among years (**Fig.4**). Overall, mean of the blade weight in May was 703 ± 174 gWW (grams wet weight ± standard deviation (SD)). The mean blade weight in May was heavier in 2002 and 2009 than the overall mean + SD, whereas the mean weight was lighter in 2001, 2013 and 2011 than the overall mean - SD. Correlation analysis revealed that coefficients between the blade weight in May and monthly mean water temperature displayed certain trends throughout the years (**Fig.5 and 6**); the correlation coefficients between the mean blade weight in May and the mean water temperature in the previous spring to autumn were negative (r = -0.28 to -0.08), and those between the mean blade weight in May and the mean water temperature in winter and spring in the same year were positive (r = 0.33 to 0.48). The mean blade weight in May had a significant

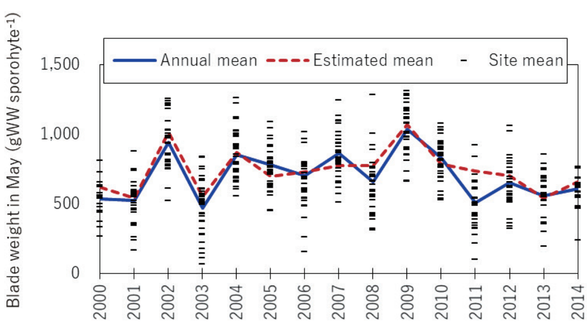

Fig. 4. Monitored and estimated blade weight of *Saccharina longissima* in May in Habomai area, eastern Hokkaido, Japan. Values are in wet weight (WW). Dashed line shows the estimated weight by the model including longitudes and monthly mean water temperatures (January, April, July, October during same year and January, April during same year).

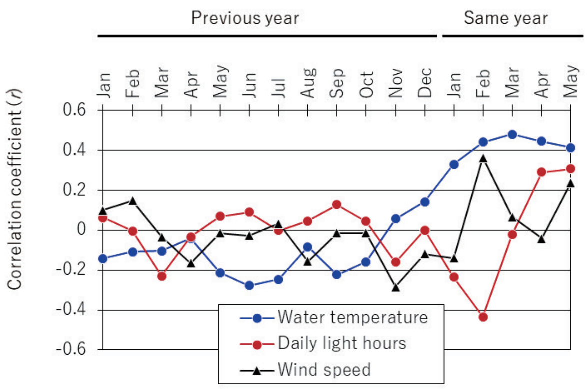

Fig. 5. Variations in correlation coefficient between site mean blade weight of *Saccharina longissima* in May and monthly mean water temperature, daylight hours and wind speed.

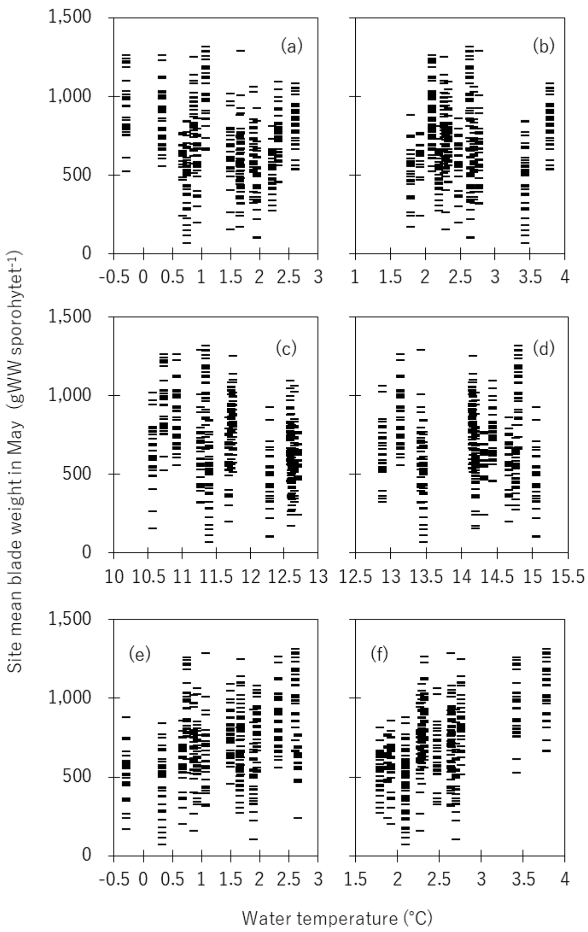

Fig. 6. Relationships between site mean blade weight of *Saccharina longissima* in May and monthly mean water temperature. (a): January, (b): April, (c): July, (d): October in the previous year, (e): January, (f): April in the same year.

correlation with the mean water temperature, except for in April, August and November in the previous year. The mean blade weight in May was significantly correlated with the mean daylight hours in March (r = -0.23), September (0.13), and November (-0.16) in the previous year and January (-0.24), February (-0.43) and April (0.29) in the same year. The mean blade weight in May was also significantly correlated with monthly mean wind speed in January (r = 0.10), February (0.15), April (-0.16), August (-0.16), September (-0.18), November (-0.28), and December (-0.12) in the previous year and January (-0.14) and March (0.36) in the same year. However, unlike water temperature, neither the daylight hours nor the wind speed showed correlative tends with the blade weight throughout the years.

The GLM analysis of the blade weight in May revealed that the model including water temperature in February, May-July, September, and December in the previous year and February and April in the same year was the best fit model, with the smallest AIC value of 6,329 (**Table 1**). The model including only water temperature of each quarter of the year and longitude also had a smaller AIC value (6,347) than the null model (6,513), and it effectively estimated the variation of the mean weight in May (**Fig.4**). In this model, the mean blade weight in May had a negative GLM coefficient with the quarterly mean water temperature in April to October in the previous year and positive coefficients in January and April in the same year, which was similar to the trend shown in the correlation coefficient analysis. The GLM coefficient of the longitude was positive both in the best model and the model including only water temperature and longitude.

Overall, mean of the blade weight in June was 1,038 ± 210 gWW. The mean weight in June ranged between 716 ± 169 gWW in 2014 to 1,385 ± 252 gWW in 2009. The per site mean blade weight in June was positively correlated with the blade weight in May, with a correlation coefficient of 0.45 (**Fig.7**), and the mean blade weight in May was positively correlated with fisheries production of the kelp in Nemuro, with a correlation coefficient of 0.58 (**Fig.8**). These results revealed that the blade weight of *S. longissima* in May remarkably represents the growth situation of the kelp of the year and is useful to predict the fisheries production in this area. This association

Table 1. Result of generalized linear model analysis of site mean blade weight of *Saccharina longissima* in May in Habomai, eastern Hokkaido Japan. Values of each variable represent mean estimate coefficient ± standard error. Check marks represent the independent variables included in each model.

Independent variables			Null model	Estimate coefficient	Full model	Best model	Estimate coefficient	Full(Best) model
Intercept				-141.70 ± 35.41	✔	✔	-144.89 ± 36.08	✔
Water temperature								
	Previous year	January					0.08 ± 0.03	✔
		Februrary		0.06 ± 0.04	✔	✔		
		March		0.05 ± 0.05	✔			
		April					-0.10 ± 0.03	✔
		May		-0.08 ± 0.03	✔	✔		
		June		-0.09 ± 0.03	✔	✔		
		July		0.06 ± 0.03	✔	✔	-0.09 ± 0.02	✔
		August						
		September		-0.04 ± 0.03	✔	✔		
		October		0.01 ± 0.04	✔		-0.08 ± 0.02	✔
		November						
		December		-0.07 ± 0.03	✔	✔		
	Same year	Januray					0.13 ± 0.02	✔
		Februrary		0.22 ± 0.05	✔	✔		
		March						
		April		0.20 ± 0.04	✔	✔	0.23 ± 0.03	✔
Longitude				1.02 ± 0.24	✔	✔	1.05 ± 0.25	✔
AIC			6,513		6,331	6,329		6,347

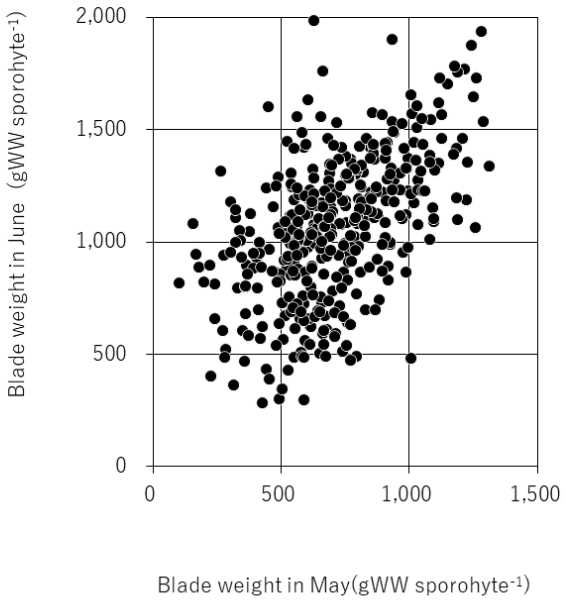

Fig. 7. Relationship between site mean blade weight of *Saccharine longissima* in May and June. Values are in wet weight (WW).

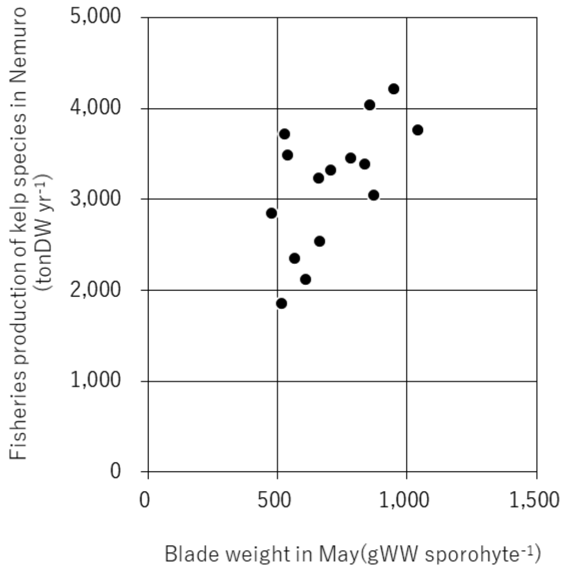

Fig. 8. Relationships between annual mean blade weight of *Saccharine longissima* in May and annual fisheries production of kelp species in Nemuro, where *S. longissima* was the main harvested kelp species. Blade weight and fisheries production are in wet weight (WW) and dry weight (DW), respectively.

occurred despite the fact that the fisheries production of the kelp was often affected by the number of days of harvest and fishermen (Shinada *et al.* 2014).

Growth status of the age 1+ sporophytes until May is an important factor in determining the fisheries production of the kelp in this area, and GLM analysis and correlation analysis feasibly revealed that the growth was affected by the ambient water temperature. High temperature in the previous autumn and extremely low temperature in the previous winter to spring reduced the blade weight of the kelp in the summer harvest season. Sasaki (1973) reported that regeneration of *S. longissima* sporophytes starts around November, with a daily growth rate of blade length ranging from 5 to 10 mm day-1 until March, and growth reaches the maximum of 68 mm day-1 during May and June. Early decrease of water temperature in the previous year might cause early start of regeneration of the sporophytes, and the growth of sporophytes might be enhanced by warmer conditions during winter and spring, when water temperature is below 4℃ in this area. Meanwhile, Kirihara *et al.* (2003) reported that the growing densities of age 1+ sporophytes of *S. japonica* in early summer were negatively related with the water temperature in the previous spring. Moreover, Shinada *et al.* (2014) concluded that dissolved inorganic nitrogen concentration in March and sea urchin (consumer of kelp) biomass were important for changes in first year biomass of *S. japonica* var. *ochotonids*, but there were no clear relationships between the kelp biomass and water temperature. These relationships between growth and biomass of *S. japonica* and water temperature were different from the results of our study probably due to the differences in species and age of kelps.

General trends in the blade weight variation in May was well-estimated by the models that included quarterly mean water temperature and longitude, but there was a large difference between the estimated and actual mean blade weight in 2011, during which the tsunami generated by the great east Japan earthquake hit this area with the wave height over 4.5 m (Japan Meteorological Agency, 2013). Disturbance caused by the tsunami might have damaged the blades and inhibited the kelp growth. In addition, drift ice physically scrapes off the kelps from the rocky substrates and causes declines in the fisheries production. However, intense drift ice increases the fisheries production of the kelp in the following year through creating a new substrate for the kelp (Sasaki 1973).

In the GLM analysis, longitude was shown to positively affect the blade weight in May. This may be explained by the ocean currents in the study area. In the coastal area of eastern Hokkaido, large amounts of nutrients are supplied by the first branch of the Oyashio current, which runs westward (Tanaka *et al*., 1991). Therefore, the faster growth of the sporophytes might be attributable to the higher nutrient supply in eastern part of the monitoring area, located upstream in the Oyashio current.

In conclusion, water temperature is an important environmental factor to determine the growth of *S. longissima*. In the sea off Kushiro (offshore of eastern Hokkaido), an upward trend in sea surface temperature (SST) is clear during autumn, in which regeneration of S. longissima sporophytes starts, both on a long-term basis and since the year 2000 (**Fig.9**, Global Environment and Marine Department, Japan Meteorological Agency, 2017). In addition, since 2000, SST during the spring growing season of *S. longissima is* frequently below the grand mean from 1981 to 2010. This trend in water temperatures may be one of the factors decreasing the growth and the fisheries production of the kelp in eastern Hokkaido, and there is a concern that the deterioration of the kelp fisheries may be aggravated if the present water temperature trend persists.

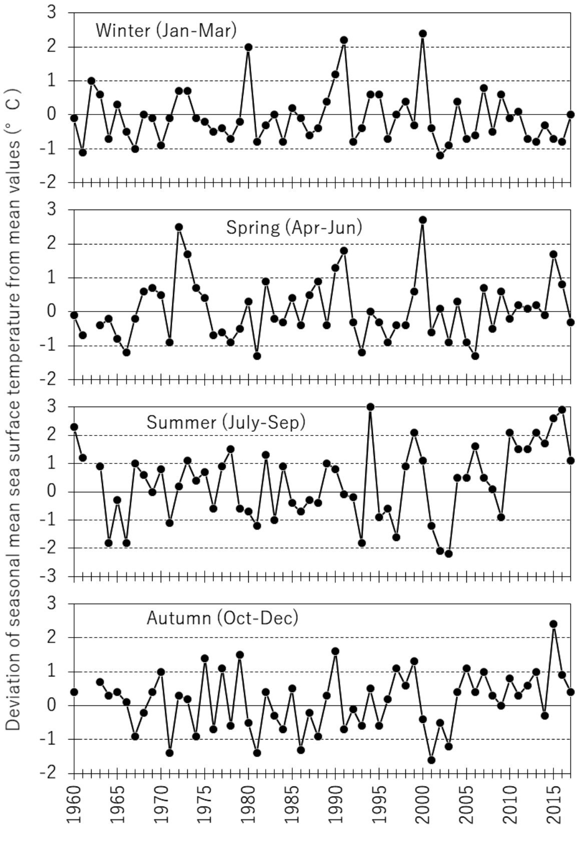

Fig. 9. Deviation of seasonal mean sea surface temperature from the grand mean values in sea off Kushiro (offshore of eastern Hokkaido, Japan). The grand mean values for each season were calculated from the seasonal mean sea surface temperature from 1981 to 2010. Data was obtained from Global Environment and Marine Department, Japan Meteorological Agency (2017).

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Yotsukura N., 2010: The hierarchy of Laminariales in Japan. *Algal Resources*, **3**, 193-198. (in Japanese with English abstracts)

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(1) Sasaki S., 1973: Studies on the life history of *Laminaria angustata* var. *longissima (M.) Miyabe*. Hokkaido Kushiro Fisheries Experimental Station, Kushiro, 141pp.

This paper was published in 1970s when this species increasingly became of high fisheries importance around eastern Hokkaido, Japan. The author summarized the life history of *Laminaria angustata* var. *longissima (M.) Miyabe*., which has been recently renamed as Saccharina longissima. This paper includes the studies about the life history of two seasonal germinal groups in winter and summer to provide information for stock enhancements, the importance of suspended culture, reviewing position of the *S. longissima* in Japanese kelp fisheries with evaluating the factors affecting its fisheries production such as the floating ice. Some parts of these studies were published in Journal of Hokkaido Fisheries Experimental Station in Japanese. Although the marine and social environments for *S. longissima* fisheries have markedly changed since 1970s, intensive studies such as one done by Sasaki (1973) have not been conducted since then.

(2) Yotsukura N., 2010: The hierarchy of Laminariales in Japan. *Algal Resources*, **3**, 193-198.

This paper reviews the hierarchy of laminarialean algae which has been proposed by molecular phylogenetic analyses. There is a variety of laminarialean species in Japan's coastal areas where some species including *Saccharina longissima* are harvested or cultured on a large scale. These species have been classified based on morphological characteristics although there are variations in its morphology among its growth stages and environmental conditions. Author enumerated 37 laminarialean species belonging to 7 families in Japan.