Title

Quantitative mapping of kelp forests (*Laminaria* spp.) before and after harvest in coastal waters of the Shiretoko Peninsula, Hokkaido, Japan

Authors

Kenji Minami · Naoki Tojo · Hiroki Yasuma · Yusuke Ito · Takahiro Nobetsu · Shin-ichi Fukui · Kazushi Miyashita

Affiliations and addresses

K. Minami : Faculty of Fisheries Science, Hokkaido University, Minato-cho 3-1-1, Hakodate, Hokkaido 041-8611, Japan

N. Tojo : Marino-Forum 21, Taito 4-8-7, Taito, Tokyo 110-0016, Japan

H. Yasuma : Graduate School of Fisheries Science, Hokkaido University, Minato-cho 3-1-1, Hakodate, Hokkaido 041-8611, Japan

Y. Ito : Forestry and Fisheries Dependence, Hiroshima Agriculture, Motomachi 10-52, Naka-ku, Hiroshima, Hiroshima 730-8511, Japan

T. Nobetsu : Shiretoko Nature Foundation, Shiretoko National Park Nature Center, Iwaobetsu 531, Shari-cho, Hokkaido 099-4356, Japan

S. Fukui · K. Miyashita : Field Science Center for Northern Biosphere, Hokkaido University, Minato-cho 3-1-1, Hakodate, Hokkaido 041-8611, Japan

Corresponding Author

Kenji Minami

tel: +81 138 40 8885; fax: +81 138 40 8885; e-mail: kminami@fish.hokudai.ac.jp

E-mail addresses

K. Minami (kminami@fish.hokudai.ac.jp)

N. Tojo (bering.raven@gmail.com)

H. Yasuma (yasuma@fish.hokudai.ac.jp)

Y. Ito (y-itou85593@pref.hiroshima.lg.jp)

T. Nobetsu (nobe@shiretoko.or.jp)

S. Fukui (s-fukui@fsc.hokudai.ac.jp)

K. Miyashita (miyashi@fish.hokudai.ac.jp)

Regional terms

Japan; Hokkaido; Shiretoko peninsula

Abstract

In the Shiretoko Peninsula, a World Natural Heritage site, the sustainable management of kelp forests has drawn public attention because of the economic and ecological importance of kelp. We spatially estimated the distributions of kelp forests in the Shiretoko Peninsula before and after harvest. Field surveys were conducted in coastal waters (23.74 km^2) at the ends of July and August 2008, immediately before and after harvest. Data on the presence or absence and thickness of the kelp forests were collected via acoustic observation. The data were interpolated using geostatistical methods. Before harvest, the kelp forests were continuously distributed over 5.64 km^2 (thickness 33–132 cm), especially near the north part of the study area. After harvest, they were sparsely distributed over 2.73 km^2 (thickness 35–105 cm). In the southern part of the study area, the influence of harvests was observed as declines in forest area. In addition, relatively thickly forested areas formed the majority of the part most likely to be harvested. Selective harvesting for area and size was confirmed though quantitative mapping of kelp forests. The quantitative mapping of both the distribution and harvest of kelp forests was successful.

Keywords

Distribution · Echo surveys · Geostatistical analysis · Harvesting · Kelps

Introduction

Kelp forests provide valuable fishery products in Japan. In particular, *Laminaria* spp. products from the waters of northeastern Hokkaido, Japan, are considered highly valuable because of their superior quality [1]. Kelp harvesting is an active fisheries industry in Japan, and kelp forests play important ecological roles in the coastal waters [2]. The primary production of kelp forests is as high as that of terrestrial vascular plants, such as mature rain forests (approximately 1300 g C m^{-2} $year^{-1}$), and kelp forests are considered to be major primary producers in coastal ecosystems [3]. Due to these economic and ecological contributions, fisheries scientists and environmental managers regard the relationship between kelp distribution and kelp harvesting as important information for the sustainability of coastal area.

The quantification of harvest efforts and identification of harvest locations are key for sustainable fisheries management in coastal area. However, the long coastline has historically made kelp surveys difficult, so information on kelp distribution is limited. The large spatial extent around coastal area has also made difficult traditional fishery surveys such as diving or shipboard observations [4]. Direct tracking of local individual fishers is almost impossible over such a large and complex area [5].

In recent years, integrated methods using acoustic observations with echosounder and geostatistical analyses have been suggested as practical survey and quantification methodologies for the mapping and ecological study of seagrass and seaweed beds in coastal waters [5-7]. Acoustically transmitted ultrasonic sound waves travel through the water and continuously measure the reflections of objects (echoes) such as fish schools and the sea bottom [8]. To estimate the horizontal distribution of kelp forests, data obtained from acoustic observations with echosounders have been geostatistically interpolated using kriging [9]. Geostatistical interpolation can estimate the abundance of a target plant with statistical references based on values such as the thickness or density of the target, and has been applied to both terrestrial and aquatic plant distributions [6, 10, 11]. The combination of acoustic observation and geostatistical interpolation would be an effective method for conducting a quantitative mapping study of kelp forest distribution along coastal area.

In the present study, we estimated kelp forest distributions before and after harvest on the eastern side of the Shiretoko Peninsula, located in northeastern Hokkaido, Japan, using acoustic observation and geostatistical analysis. The Shiretoko Peninsula was registered by UNESCO as a World Natural Heritage site in July 2005, because of its unique ecosystem and diverse ecological interactions (Fig. 1). In its coastal waters, *Laminaria ochotensis* Miyabe and *L. diabolica* Miyabe, which are perennial plants [12], form dense kelp forests [13, 14]. In Shiretoko Peninsula, because the kelp forests grow thick most in summer [12], kelps are harvested in that season. Especially, on the eastern side of the Shiretoko Peninsula, the annual harvest of *Laminaria* spp. is approximately 600 tonnes in dry weight [15], and kelp forest distribution is closely tied to the kelp harvest. We observed the presence or absence and measured the thickness from the sea bottom to the top of the kelp forests using acoustical techniques. Then we geostatistically interpolated these data and estimated the area of the forests and the change in their distribution due to harvesting activities. Based on these results, the Shiretoko Peninsula kelp fisheries were evaluated from a viewpoint of ecological sustainability.

Materials and methods

Data collection

Field surveys were conducted in the coastal waters of the Shiretoko Peninsula on 23–24 July 2008 before harvest and 21–22 August 2008 after harvest (Fig. 1). Harvesting period in 2008 was from 26 July to 20 August. The sea conditions at the surveys were smooth sea. The survey area (23.74 km^2) was defined as the region from Shiretoko Cape (44°01.14'N 145°12.19'E) to Rausu (44°1.03'N 145°11.93'E), in waters of less than 30 m depth, corresponding to the depth limits for *L. ochotensis* and *L. diabolica*, which are 18 and 25 m, respectively [16, 17]. The survey cruise ran orthogonally or parallel to the shoreline at about 400–800 m intervals, except when evading shallow areas, set net fisheries, or aquaculture. The route taken after harvest followed the same path as well as possible. The ship’s speed was 4–6 knots to avoid cavitation around the transducer and to ensure the detection of small (<1 m) kelp forests. The speed was stayed almost constant. In this study, we considered that the vessel motion didn’t almost affect the amplitude of sea bottom, because of the ship speed, the sea condition and the survey depth.

The sampling equipment used to detect and measure kelp forests consisted of an acoustic component and a differential GPS (Trimble) linked to a laptop PC. The acoustic component consisted of a BL550 echosounder (Sonic) with a 200 kHz, 3° single-beam transducer that generated continuous pulses (pings) every second (Table 1). The sound speeds in July and August were 1496 m/s and 1511 m/s, respectively. At the sound speeds, the vertical resolutions of the pulse in July and August were 6.0 cm. The measurement range of the BL550 was set to 30 m. The transducer was mounted off the side of the research vessel at a depth of 0.5 m. The BL550 digitized the intensity of the echo with user-defined parameters from level (Lv.) 1 (weak) to Lv. 255 (strong). In this study, we set the echo via the PC that operated the onboard system, and we saved the intensities in digital data to the PC. Onboard or underwater video observations were conducted to distinguish kelp from other algae (Fig. 2). While conducting the observations, we stopped the vessel. Data from other algae were excluded from the analysis. Underwater video observations were also conducted to confirm the change in kelp forest distribution from harvesting activities at Shiretoko Cape, Aidomari, and Rausu, representing the north (44°19.53' N 145°20.70' E), middle (44°12.45' N 145°20.16' E), and south (44°8.76' N 145°16.52' E) areas, respectively.

Detection of kelp forest echoes

Detected echoes were categorized into three groups: kelp forest, sea bottom, and seawater (Fig. 3a). Echoes from solid targets such as the sea bottom are strong, while echoes from seawater are weak because of the absence of objects to reflect the transmitted supersonic waves (Fig. 3b). Echo categorization was made by validating acoustic data using an underwater video camera (Fig. 1). Based on these categorizations, detected echoes with intensities equal to Lv. 255 were categorized as sea bottom, and those with intensities of less than Lv. 255 were categorized as kelp forest or seawater. All echoes with intensities of less than Lv. 4 were categorized as seawater. The thickness of kelp forests was measured between Lv. 255 and Lv. 4. We excluded detected objects that measured less than 30 cm in thickness from the analyses to avoid possible confounding with the acoustic dead zone, which was calculated based on pulse length and local bathymetry [18]. For the same reason, abrupt bathymetric changes, such as near large rocks (≥30 cm) or steep slopes were excluded from analyses when detected. In addition, acoustic observations from 32 randomly selected sites were compared to *in situ* kelp forests using a ROV as a post survey validation. We confirmed that mean errors of thickness measurements were less than the vertical resolution of the BL550 (6.0 cm, [19]).

Spatial estimation of kelp forests using geostatistical analysis

We evaluated spatial autocorrelations within the processed kelp forest data as horizontal distribution trends, then estimated the area and thickness of kelp forests by kriging [9, 10]. The observed spatial autocorrelations in the experimental semivariograms (γ) were calculated as

$$\gamma = \frac{1}{2n_c}\sum_{\alpha=1}^{n_c}\left[z\left(\mathrm{X}_\alpha + h\right) - z(\mathrm{X}_\alpha)\right]^2 \tag{1}$$

where n_c is the number of these pairs, z is the values at locations i and $i + h$ of the detected kelp forest, and h is the lag, which is the distance between pairs of data points at specific locations [20].

We focused on spatial aspects of kelp forest over the Shiretoko coastal shelf, rather than the dynamics of individual plants. Hence, the minimum resolution for semivariogram analyses corresponded to the unit of distance among forest patches. The center of each kelp forest patch was defined based on the statistical quantile of the upper fifth percentile of the measured thickness frequency distribution. The general intervals among the defined centers of kelp forest were obtained from the average nearest neighbor distance among the center points (85 m).

The best-fit theoretical semivariograms were selected from the obtained experimental semivariograms using the maximum likelihood algorithm for before and after harvest (Fig. 4, [20]). A spherical model was used as the function, as this made fewer assumptions in the model parameters and achieved a better fit than other model candidates in pilot analyses. First, to calculate theoretical semivariograms with minimum spatial bias from the survey design, the sampling circles needed to include data from at least two transect lines. Therefore, we used values of γ within 1700 m of each location for model fitting. Then the model parameters (range, partial sill, and nugget) were obtained from the selected best-fit models. Range is the maximum distance across which spatial autocorrelation exists in kelp distribution and is a vector in which the partial sill is observed. The partial sill is the maximum variability, which depends on the distance between pairs of data points at specific locations. The nugget is the value of γ, which is the variability within a lag including random error. Using these parameters of the theoretical semivariograms, kelp forest distributions before and after harvest were compared.

Kelp forest distribution was analyzed from two different aspects: the presence or absence of forests or forest patches, and the variation in thickness within or among existing forest patches. Here, we describe the horizontal distribution properties of kelp forests and discuss the causal mechanisms of their biological distribution [9, 10, 20]. We applied a two-stage approach to predict the presence or absence of kelp forest and then estimate the thickness of existing forests in each subarea. In the first stage, the probability of kelp occurrence was predicted using probability kriging with the best-fit theoretical semivariogram based on the γ of occurrence [20]. To calculate the γ of occurrence, the thickness of the subsampled kelp forests (n = 15 000), including absence data (thickness = 0 cm), was first normal-score transformed [20]. The presence

(≥0.5 probability) or absence (<0.5 probability) of kelp forest was determined based on the interpolated probability of occurrence. The interpolation was validated according to concordance rate, calculated in the manner of leave-one-out cross-validations (LOOCVs, [20, 21]). Then all of the observed presence or absence values were compared to predictions. In the second stage, the thickness of the kelp forest was estimated using ordinal kriging based on the best-fit theoretical semivariogram of thickness based on the γ of thickness [20]. To calculate the γ of thickness, the z values of the thickness subsamples were natural-log transformed, using only presence data (thickness ≥30 cm). The interpolation of thickness was validated using LOOCVs, and the root mean square errors (RMSEs) were evaluated. Kelp forest areas were calculated and compared before and after harvest. The calculations and interpolations above were made using ArcGIS ver. 9.3 (Environmental Systems Research Institute, ESRI).

Results

Detected kelp forests

Before harvest, 4,279 of 15,000 pings along the survey transect represented echoes from kelp forests. The measured thickness ranged from 30 to 140 cm with an average (± SD) of 64 ± 25 cm. In contrast, after harvest, 4,383 of 15,000 pings were echoes from kelp forests. The measured thickness ranged from 30 to 121 cm with an average of 57 ± 22 cm. The average thickness of the kelp forest before harvest was 7 cm thicker than that after harvest. Also, 3.5% of the kelp forests before harvest were thicker than the maximum thickness of forests after harvest.

Semivariograms

The semivariogram parameters indicated differences in spatial trends in the occurrences of kelp forests before and after harvest (Fig. 5a). The partial sill before harvest (12.66×10^{-2}) was two times larger than that after harvest (5.51×10^{-2}). Conversely, the range after harvest (1,679 m) was four times longer than that before harvest (413 m). These differences in semivariogram parameters indicate that the occurrence of kelp forests before harvest was more horizontally variable, with patches or gaps [22, 23], than that after harvest. On the other hand, the nugget increased by 7.03×10^{-2} from before harvest (6.14×10^{-2}) to after harvest (13.17×10^{-2}). This increase in nugget may indicate that the complexity of occurrence on a small scale (< lag 85 m) increased after harvest, although it may also suggest potential observation errors during the survey.

Again, the semivariogram parameters of thickness of the kelp forest did not differ before and after harvest (Fig. 5b). The ranges before and after harvest were the same (224 m). The partial sills and nuggets were also almost the same. These results indicate that trends in the thickness of the kelp forest did not change with harvesting activities.

Distribution of the kelp forests

The interpolated kelp forest is shown in Fig. 6. Overall, kelp forests were larger and thicker before harvest than after harvest. Before harvest, the kelp forests were continuously distributed along the coastline from Shiretoko Cape to Aidomari and were especially obvious near the Shiretoko Cape. From Aidomari to Rausu, the kelp forests were sparsely distributed. The distribution area of kelp forests before harvest from Shiretoko Cape to Rausu was 5.64 km^2, which was 24% of the analyzed area (23.74 km^2). The estimated thickness of kelp forests before harvest ranged between 33 and 132 cm. The most widely distributed thickness was 77 cm (0.21 km^2; Fig. 7a). However, kelp forests after harvest were continuously distributed from Shiretoko Cape to Pekinnohana and were sparsely distributed from Pekinnohana to Aidomari. They were not distributed from Aidomari to Rausu. The estimated thickness after harvest ranged between 35 and 105 cm, and the most widely distributed thickness was 58 cm (0.13 km^2; Fig. 7b). The concordance rates with LOOCVs for the presence or absence predictions before and after harvest were 80% and 79%, respectively. The RMSEs of the estimated thicknesses before and after harvest were 23 cm and 20 cm, respectively.

These results indicate that the distributions of kelp forest were changed by harvesting activities. In the region from Shiretoko Cape to Pekinnohana, the horizontal distribution did not change but the thickness was reduced. In the region from Pekinnohana to Aidomari, the continuous distribution changed to a sparse distribution, and the thickness was also reduced. Furthermore, in the region from Aidomari to Rausu, sparsely distributed areas before harvest had a very low distribution after harvest. Overall, the dimension of kelp forest decreased by 2.91 km^2 over the harvesting season and the thickness was also reduced. The post-harvest dimension was half that before harvest.

As in the acoustic observations, changes in kelp distribution were also observed with underwater video. At Shiretoko Cape, kelp forest was present before and after harvest, whereas little was observed after harvest at Aidomari and Rusa.

Discussion

This is the first quantitative mapping to reveal the relationship between kelp forest distribution and harvesting activity using acoustic observation and geostatistical analysis. The distributions of kelp forest over a 23.74 km^2 area before and after harvest were successfully measured under a set transect. Acoustic observation of various aquatic plants have been conducted [24, 25], but, in most cases, the observations covering areas of over 10 km^2 are limited to a study of seagrass beds in Ajino Bay [26]. Additionally, the observations have not quantitatively mapped the distribution change by harvest, environmental transformation, and others. The present study is therefore notable as one of the pilot applications of the distribution change of kelp forests using acoustic based on high resolution data. Based on the high-resolution data from across the study area, statistically valid estimations were made of the kelp forest. Spatial change in the distribution of the kelp forests in harvest season was also statistically analyzed.

The semivariogram indicated that the spatial autocorrelations of the presence or absence of kelp forest were attenuated in the harvesting season, and that the complexity of forest over a small scale (< 85 m) increased in that season. In contrast, thickness remained almost unchanged during the harvesting season. This may be attributable in part to the harvest method. In Shiretoko Peninsula, kelp is harvested with a tool called a makka, a long pole with bifurcated front edge. Using it, a fisher aboard a boat wrenches the kelp from the sea bottom [27], uprooting approximately 1 m^2 of kelp and dramatically changing the distribution at that precise location from presence to absence. At the same time, however, the fisher is in constant motion and the next harvest is likely to be a distance away from the first, resulting in a complex, mosaic distribution that gradually fills back in and disappears over the harvesting season. In addition, the harvesting season lasts only 1 month. It is thought that the kelp grows little during the harvesting season, and that the thickness also changes little.

Regional changes in kelp forest were estimated by comparing the distributions before and after harvest (Fig. 8). In the region from Shiretoko Cape to Pekin-nohana, only a small area was removed. In the southern region of Pekin-nohana, the forest largely disappeared. Kelp-processing facilities called bannya are scattered along the coast of the Shiretoko Peninsula. Each fisher has a base bannya, from which the fisher embarks on the harvest and returns to process the harvest. Nearly all bannya are located in the southern region of Pekin-nohana. Given fuel costs, the kelp forests in southern regions are of value to fishers. Thus, harvesting activity is preferentially conducted in the southern region, explaining why the forests in this region largely disappeared during harvesting season.

After harvest, the overall thickness of the kelp forest was reduced compared to that before harvest (Table 2), and thicker areas in particular decreased. In the study region, *L. ochotensis* and *L. diabolica* kelp forests are perennial plants [12] whose value on the market is highest when they are two or more years old, at which point they are also taller than younger plants. Therefore, the fishers in Shiretoko Peninsula mainly harvest such kelp, leaving younger plants for future harvests. As a result, thicker kelp forest in particular decreased during the harvesting season.

Various artifactual and ecological factors will alter the distribution of kelp forests in the coastal waters. The grazing impact of benthic herbivores such as sea urchin (*Strongyloceentrotus* spp.) has been discussed as a possible determinant of change in the area covered by kelp forests in various North pacific waters [15]. In winter, drift ice physically scrapes the kelp forests from the rocks along the shore in northeastern Hokkaido, Japan [1]. If a lot of drift ice has come to shore in Shiretoko Peninsula, it is known that the distribution of kelp forests dramatically decrease. The quantitative mapping is probably effective in estimating the causal relationships that determine the distribution change of kelp forests. Further, quantified information on the distribution change of kelp forests is not only of practical use to fisheries scientists and environmental managers but is also important for the sustainability of the marine ecosystem in coastal water. Our method using acoustic observation and geostatistical analysis make it possible for fishers to visually understand the relationship between distribution and harvesting activity, which is important for understanding the condition of the resource and for facilitating its sustainable utilization [28, 29]. As discussed above, the integrated analysis based on this study is probably effective in estimating the sustainable management of kelp forests. Continued surveys and the application of analytical methods such as those used in this study will provide time-series information to reveal the ecological and anthropogenic mechanisms determining kelp forest distribution along the coast waters. The information may allow to better sustainable management of kelp forests.

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Fig. 1 Study area and survey transect line of before and after harvest. Gray area along coast indicates study region. Study region stretches from Shiretoko Cape to Rausu. Solid lines indicate where measurements were made. Open circles mark points where underwater video was used for validation

Fig.2 Examples of underwater images of **a** kelp, **b** seagrass and **c** sargassum by ROV

Fig. 3 Echogram of **a** kelp forest and **b** bare ground detected with BL-550. Black line is the top of the kelp forest. White line is the sea bottom; the bottom of the kelp forest. The region between the lines is estimated as the kelp forest. The color bar indicates acoustic intensity

Fig. 4 An example of an experimental semivariogram. Circles comprise the experimental semivariogram. The solid line represents the theoretical semivariogram

Fig. 5 Semivariograms of the **a** occurrence and **b** thickness of kelp forests. Open circles indicate experimental semivariogram before harvest. Cross marks indicate experimental semivariogram after harvest. Solid line represents theoretical semivariogram before harvest. Dashed line represents theoretical semivariogram after harvest

Fig. 6 Maps of kelp forest distribution **a** before and **b** after harvest in 2008. Thickness estimation was overlapped with presence or absence estimation. Color bar indicates estimated thickness of kelp forest

Fig. 7 Frequency distributions of estimated thicknesses **a** before and **b** after harvest

Fig. 8 Spatial change in kelp forest by harvesting activities around **a** Shiretoko cape, **b** Pekin-nohana and **c** Aidomari. Black region indicates decreased area. Gray region indicates non-decreased area

Title: 知床半島における漁前後のコンブ場の分布推定

Authors and Affiliations:

南憲吏（北大院水）

東条斉興（マリノフォーラム 21）

安間洋樹（北大院水）

伊藤祐介（広島農水）

野別貴博（知床財団）

福井信一（北大フィールド科セ）

宮下和士（北大フィールド科セ）

Abstract:

コンブ場は、沿岸の漁業や生態系において重要な役割を果たしている。本研究では、知床半島沿岸（24.21 km^2）において音響手法によるコンブ漁前後の分布を推定した。調査は、2008 年の漁直前の 7 月下旬と直後の 8 月下旬に実施した。推定された漁前後の分布面積（厚み）は、それぞれ 5.64 km^2（33-132 cm）、2.73 km^2（35-105 cm）であった。調査海域の南側で多く減少し、厚みも低くなっていた。こうした変化は、南側中心のコンブ漁と厚みのあるコンブ場での収穫によるものと考えられた。

Fig. 1

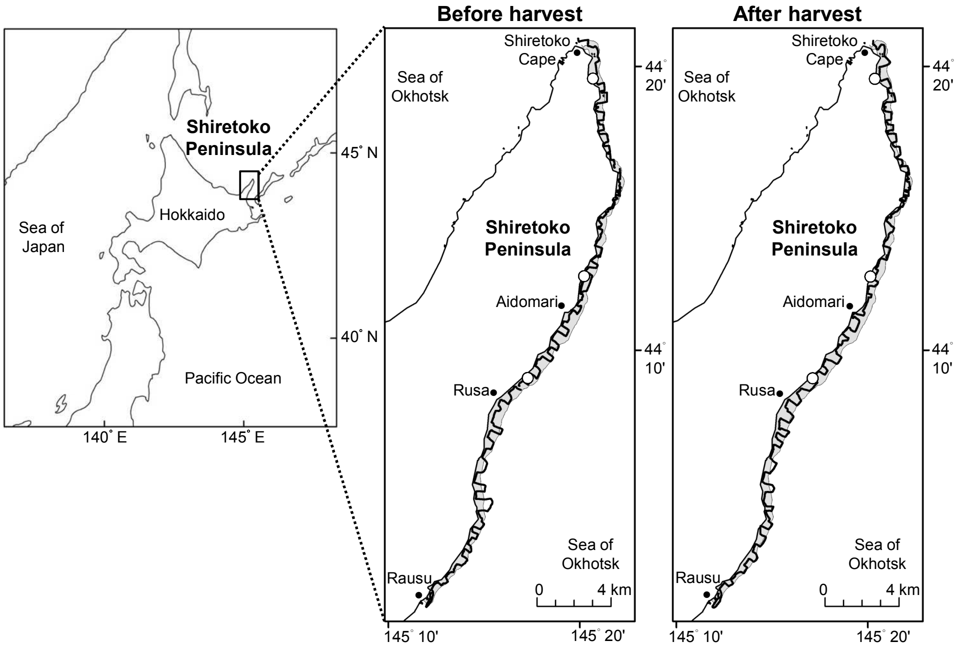

Before harvest
After harvest
Shiretoko Peninsula
Hokkaido
Sea of Japan
Pacific Ocean
45° N
40° N
140° E
145° E
Shiretoko Cape
Sea of Okhotsk
Aidomari
Rusa
Rausu
0
4 km
44° 20'
44° 10'
145° 10'
145° 20'

Fig. 2

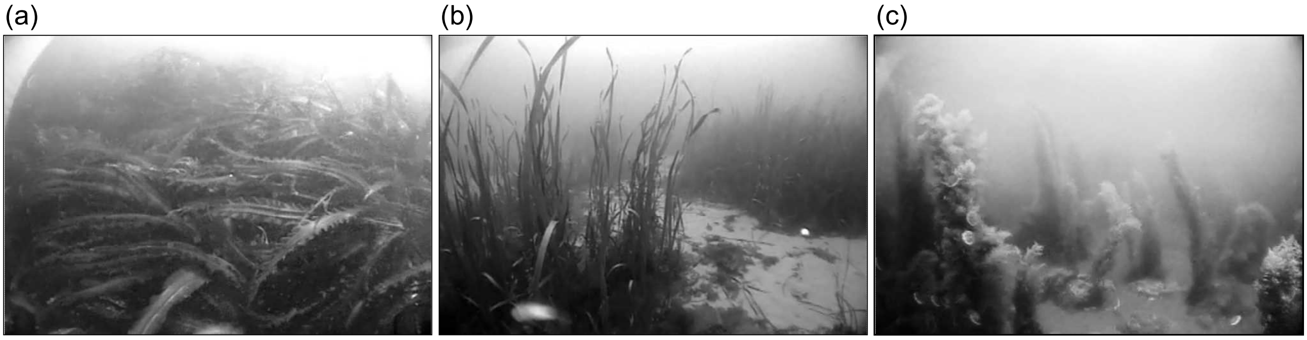


Fig. 3

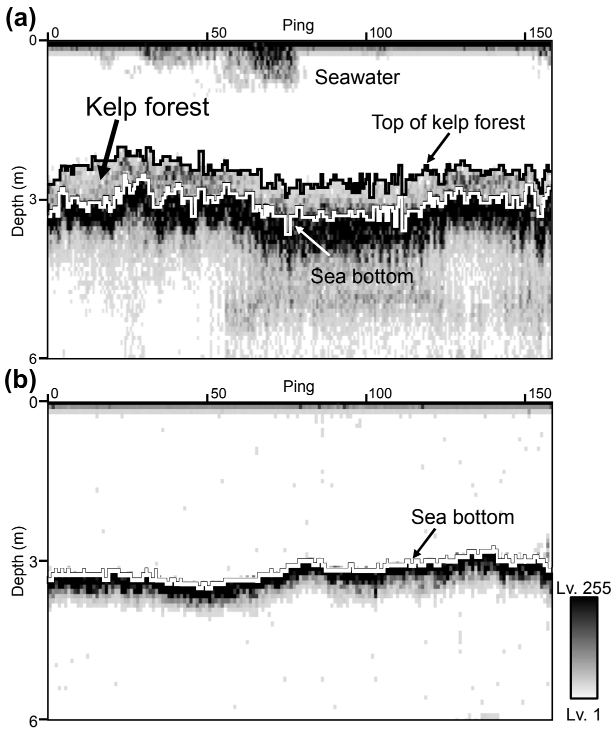

(a)
Ping
0
50
100
150
Seawater
Kelp forest
Top of kelp forest
Depth (m)
0
3
6
Sea bottom
(b)
Ping
0
50
100
150
Sea bottom
Depth (m)
0
3
6
Lv. 255
Lv. 1

Fig. 4

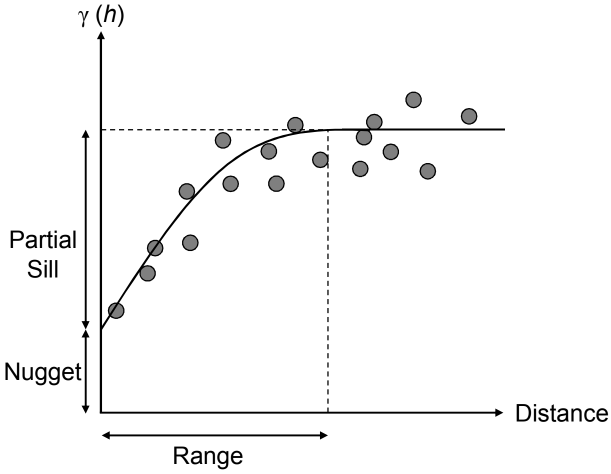


Fig. 5

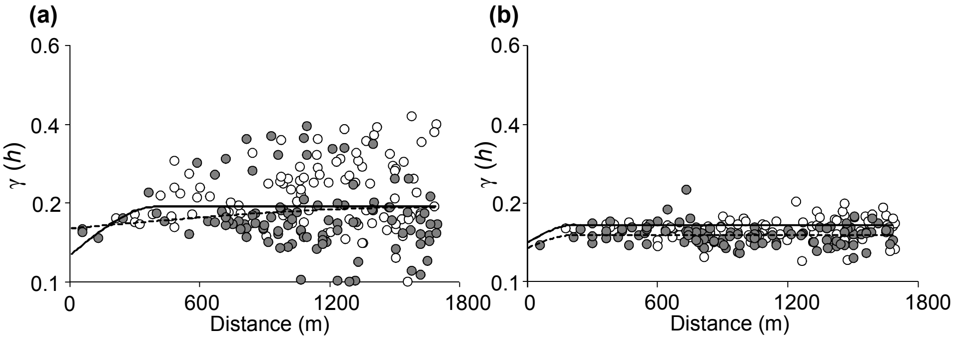
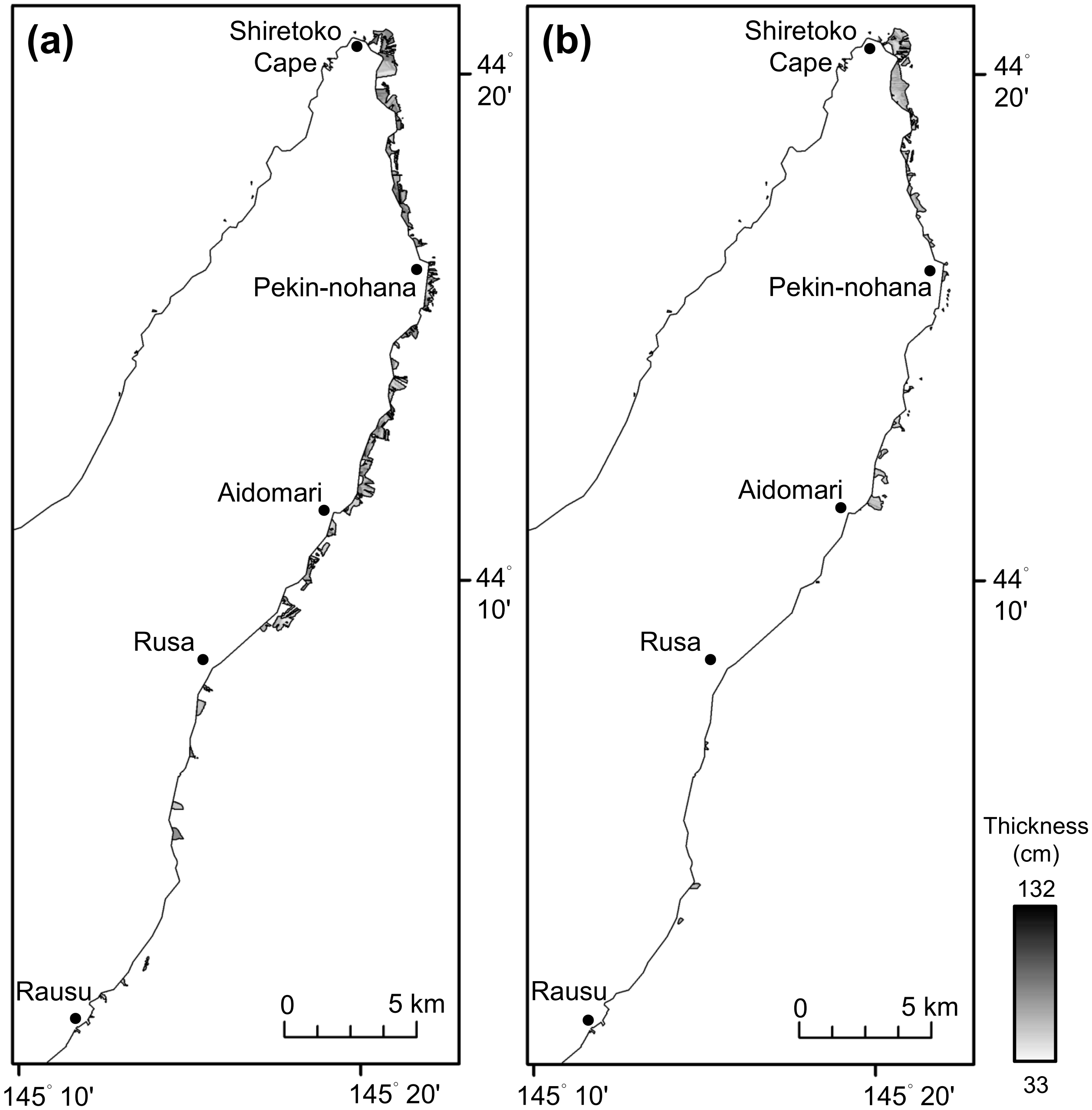
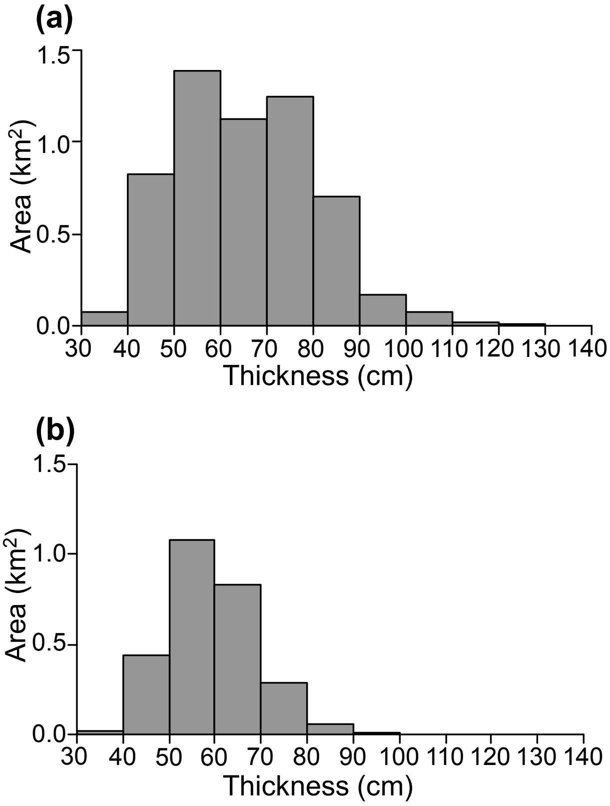

(a)
0.6
0.4
0.2
0.1
γ (h)
0
600
1200
1800
Distance (m)
(b)
0.6
0.4
0.2
0.1
γ (h)
0
600
1200
1800
Distance (m)

Fig. 6



(a)
Shiretoko
Cape
Pekin-nohana
Aidomari
Rusa
Rausu
0
5 km
44° 20'
44° 10'
145° 10'
145° 20'
(b)
Shiretoko
Cape
Pekin-nohana
Aidomari
Rusa
Rausu
0
5 km
44° 20'
44° 10'
145° 10'
145° 20'
Thickness
(cm)
132
33

Fig. 7



(a)
1.5
1.0
0.5
0.0
Area (km²)
30 40 50 60 70 80 90 100 110 120 130 140
Thickness (cm)
(b)
1.5
1.0
0.5
0.0
Area (km²)
30 40 50 60 70 80 90 100 110 120 130 140
Thickness (cm)

Fig. 8

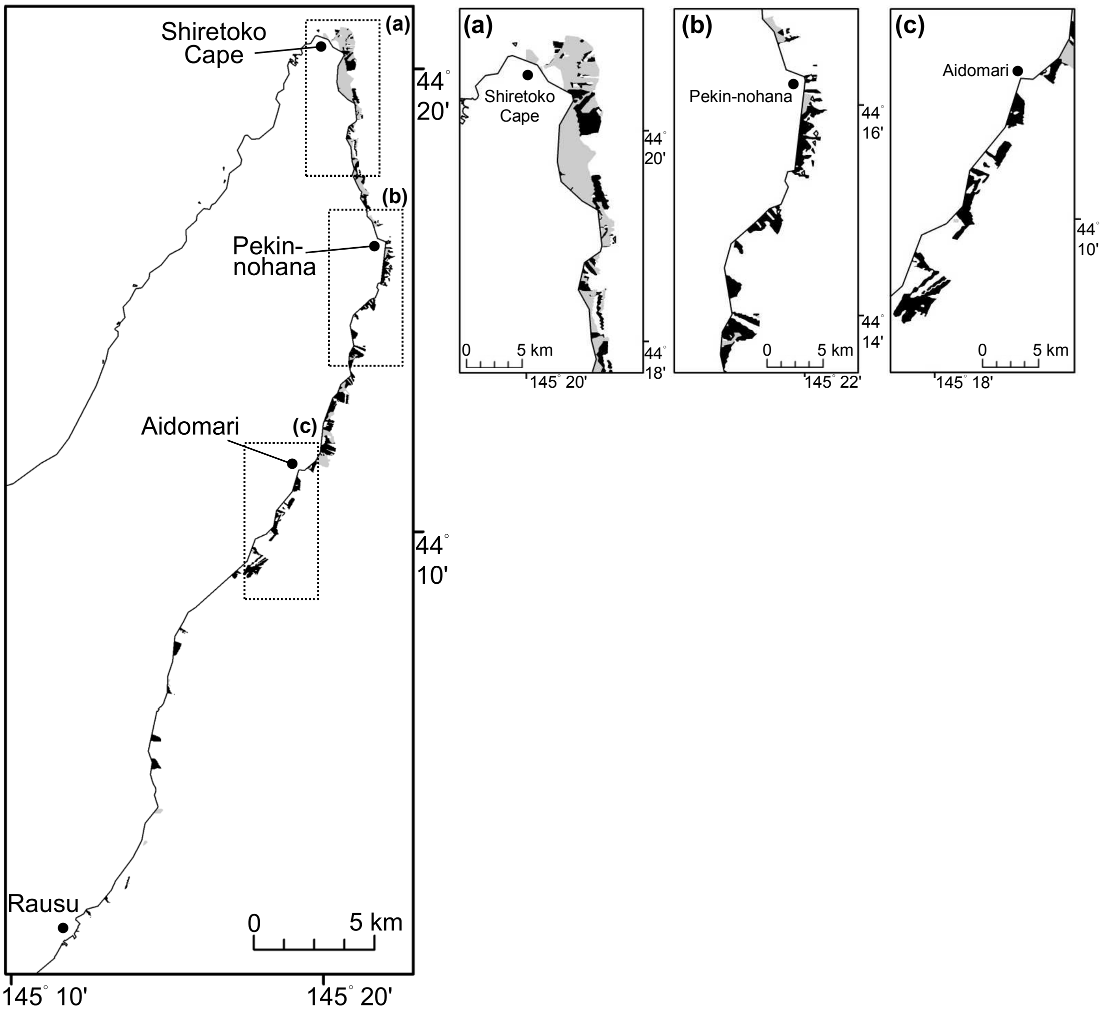

Shiretoko Cape
(a)
44° 20'
(b)
Pekin-nohana
Aidomari
(c)
44° 10'
Rausu
0
5 km
145° 10'
145° 20'
(a)
Shiretoko Cape
44° 20'
44° 18'
0
5 km
145° 20'
(b)
Pekin-nohana
44° 16'
44° 14'
0
5 km
145° 22'
(c)
Aidomari
44° 10'
0
5 km
145° 18'

Table 1 Setting for the echo sounder (BL550) with 200 kHz transducer

Variable	Specification
Transducer	T-129
Frequency (kHz)	200
Beam type	Single
Beam width (degrees)	3
Pulse duration (μs)	80
Ping rate (s)	1

Table 2 Change in kelp forest distribution by harvesting in 2008

Thickness (cm)	Frequency (%)	
	Non-decreased area	Decreased area
30 – 40	31	69
40 – 50	54	49
50 – 60	78	22
60 – 70	74	26
70 – 80	23	77
80 – 90	9	91
90 – 100	4	96
100 – 110	4	96
110 – 120	0	100
120 – 130	0	100
130 – 140	0	100