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<b>Citation</b>	Fisheries Science, 76(5), 729-736 <a href="https://doi.org/10.1007/s12562-010-0270-2">https://doi.org/10.1007/s12562-010-0270-2</a>
<b>Issue Date</b>	2010-09
<b>Doc URL</b>	<a href="http://hdl.handle.net/2115/45110">http://hdl.handle.net/2115/45110</a>
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<b>Type</b>	article (author version)
<b>File Information</b>	FS76-5_729-736.pdf



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**Title:**

**Estimation of kelp forests *Laminaria* spp. distributions in coastal waters**

**of the Shiretoko Peninsula, Hokkaido, Japan, using echosounder and geostatistical analysis**

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**Abstract** Sustainable management of the kelp forests of the Shiretoko Peninsula, a World Natural Heritage site, is necessary due to kelp's ecological and economic importance. The objectives of this study were to estimate the area of kelp forests and to clarify their spatial characteristics in coastal waters of the Shiretoko Peninsula. Data on the presence/absence and thickness of kelp forests were collected via acoustic observation on transects over about 80 km using an echosounder at 200 kHz. Acoustic data were geostatistically interpolated, and the areas covered by kelp forests were estimated. Differences in kelp distribution between the eastern and western sides of the peninsula were compared. The total area of kelp forest was 3.88 km<sup>2</sup> (eastern area: 3.49 km<sup>2</sup>; western area: 0.39 km<sup>2</sup>). The range of thickness of the kelp forests was 34–91 cm. Many kelp forests in the eastern area were thick (>78 cm) and distributed continuously, while kelp forests in the western area were sparsely distributed.

**Keywords** Acoustic observation · Geostatistical analysis · Kelp forests · Shiretoko Peninsula

## Introduction

The Shiretoko Peninsula, located in northeastern Hokkaido, Japan, 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 the coastal waters around Shiretoko Peninsula, *Laminaria ochotensis* Miyabe and *L. diabolica*

Miyabe form dense vegetation of kelp forests, which are considered to be the “forests of the sea” [1, 2].

Kelp forests play important ecological and economic roles in the coastal waters of the Shiretoko Peninsula

[3]. The primary production of kelp forests is as high as that of terrestrial vascular plants, such as mature

rain forest (approximately  $1300 \text{ g C m}^{-2} \text{ yr}^{-1}$ ), and kelp forests are considered to be the high primary

producers in coastal ecosystems [4]. The coastline of the Shiretoko Peninsula is over 100 km long, so the

primary production of the kelp forests along the coastline is presumably considerable. Also, kelp forests

provide valuable fishing resources in Japan [5]. *Laminaria* spp. products from the coastal waters of the

Shiretoko Peninsula are especially regarded as some of the best and most valuable products in Japanese

markets because of their superior quality [6]. Due to these ecological and economic contributions,

environmental and fisheries managements to sustain the kelp forests in the coastal waters of the Shiretoko

Peninsula is needed.

Mapping and quantification of kelp forest distribution along the coast of the Shiretoko Peninsula is a

practical first step toward sustainable kelp forest resource management. However, the extent of the coastal

area of the Shiretoko Peninsula has made kelp surveys difficult, so information on distribution is limited.

Spatial variability in kelp harvests from the Shiretoko coast has been reported. The annual harvest of

*Laminaria* spp. from the eastern side of the peninsula is approximately 600 tons in dry weight, but harvests from the western side of the peninsula are approximately 0 ton [7]. It is difficult to quantify the spatial variability of kelp forests over large areas using traditional survey designs and analyses. Traditional surveys of sea forest including kelp of Shiretoko Peninsula have been conducted mainly by diving or from onboard observations [8]. These direct methods have advantages for species identification and for obtaining detailed information on the growing conditions of kelp forests, but such methods are highly consumptive of time and resources when attempting to cover large and presumably complex areas such as the Shiretoko coast [9].

In recent years, integrated methods using acoustic observations via 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 [9, 10]. An echosounder transmits ultrasonic sound waves through the water and continuously measures the reflections of objects (echoes) such as sea bottoms and fish schools during surveys [11]. Since acoustic observation via echosounder continuously measures echoes, researchers are not required to frequently change the echosounder setting or to take many direct sample records during surveys. Acoustic observations have already been applied to several studies of seaweed and seagrass beds [12-14]. For the estimation of horizontal distribution of kelp forests, data obtained from acoustic observation via echosounder were geostatistically interpolated using kriging [15]. Geostatistical interpolation has been applied in the past to both terrestrial and aquatic plant distribution studies [10, 16]. Geostatistical interpolations can estimate the abundance of target plants with statistical references based on values such as the thickness or density of the target [17]. For mapping and

precise quantifications with objective validations, the application of geostatistical interpolation procedures using reasonable amounts of data from acoustic observations presents a practical methodology. The combination of acoustic observation and geostatistical interpolation would be an effective method for conducting a quantitative mapping study of the kelp forest distribution along the coast of the Shiretoko Peninsula.

In this study, the objective was to estimate the distribution of the kelp forests of the Shiretoko Peninsula using acoustic observation and geostatistical analysis. We observed the presence or absence and measured the thickness (Height) of kelp forests using acoustic technique observations, and we then geostatistically interpolated these acoustic data and estimated the distribution of the forests. The distributions of kelp in eastern and western areas were compared, and the distribution characteristics of the kelp forests of the Shiretoko Peninsula were evaluated from an ecological standpoint.

## **Materials and methods**

### Data collection

Field surveys were conducted in the coastal waters of the Shiretoko Peninsula from 11 to 15 August 2007 before kelp forests declining due to fisheries harvest and seasonal deterioration (Fig. 1, [18]). The analytical subareas, the eastern area (23.74 km<sup>2</sup>) and the western area (19.58 km<sup>2</sup>), were defined by the border at the Shiretoko Cape (44°01.14'N, 145°12.19'E; Fig. 1). The survey areas were set in water less

than 30 m in depth, corresponding with the depth limits for *L. ochotensis* and *L. diabolica*, which are 18 m and 25 m, respectively (Fig. 1, [19, 20]). The survey cruise ran orthogonally or parallel to the shoreline at about 400 – 800 m intervals, unless evading shallow bottom, set net fishery and aquaculture areas. The ship's speed was 4-6 knots to avoid cavitations around the transducer and to certainly detect small (< 1 m) kelp forests during the survey.

Sampling equipment to detect and measure kelp forests consisted of an acoustic component and a differential GPS (Trimble Co.) linked to a laptop PC. The acoustic component consisted of a BL550 echosounder (Sonic Co.) with a 200-kHz, 3° single-beam transducer that generated continuous pulses (pings) every second (Table 1). The vertical resolution of the pulse was 6 cm. The transducer was mounted off the side of the research vessel at a depth of 0.5 m. The BL550 digitizes 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 of the sea bottom to be equal to Lv. 255. Position report data (latitude and longitude) were stored on the hard drive of the PC that operated the onboard system. Onboard or underwater video observations (n = 83) were conducted to distinguish kelp forest from other algae, echoes from forests appeared in echogram. Data of other algae were excluded from analysis.

#### Detection of kelp forest echoes

Detected echoes were categorized into three groups: kelp forest, sea bottom, and seawater (Fig. 2a). Echoes from solid targets such as the sea bottom are strong, while echoes from seawater are weak due to the



absence of reflection objects for the transmitted supersonic sound (Fig. 2b). 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 echoes 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 (Fig. 2b). The thickness of the kelp forest was measured between Lv. 255 and Lv. 4. We excluded detected objects less than 30 cm in thickness from analyses to avoid possible confounding with the acoustic dead zone, which was calculated based on pulse length and local bathymetry [21, 22]. For the same reason, detected of abrupt bathymetry changes, such as near large rocks ( $\geq 30$  cm) or steep slope, were excluded from analyses. Additionally, acoustic observations in 34 randomly selected sites were compared to in-situ kelp forest using ROV as a post survey validation. We confirmed mean errors with less than a BL550 vertical resolution (6 cm).

#### Estimation of the distribution of kelp forests using geostatistical analysis

We evaluated spatial autocorrelations within processed kelp forest data as horizontal distribution trends, then estimated the area and thickness of kelp forests by kriging [15, 17]. The observed spatial autocorrelations in the eastern and western area experimental semivariograms ( $\gamma$ ) were calculated as

$$\gamma(h) = \frac{1}{2n} \sum_{i=1}^n (z_{(i+h)} - z_{(i)})^2, \quad (1)$$

where  $n$  is the number of these pairs,  $z$  is the values at locations  $i$  and  $i+h$  of the detected kelp forest.  $h$  is the

lag, which is the distance between pairs of data at specific locations [23].

This study focused on the spatial aspects of kelp forest over the Shretoko coastal shelf instead of the dynamics of individual plants. So, 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 (the upper 5 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 obtained experimental semivariograms using the maximum likelihood algorithm for each subarea (Fig. 3, [23]). A spherical model was used as the function because it makes fewer assumptions in the model parameters and because it confirmed 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  $\gamma$ s within 1700 m distance from 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 at specific locations. The nugget is the value of  $\gamma$ , which is the variability within a lag including random errors. Using these parameters of the theoretical semivariograms, kelp forest distributions between eastern and western areas were compared.

Kelp forest distribution was analyzed from two different aspects: (1) presence or absence of the forests

or forest patches and (2) the variation of thickness within or among the present forests patches. We will describe the horizontal distribution properties of kelp forests and discuss the causal mechanism of biological distribution [17, 23, 24]. We applied a two-stage approach to predict the presence or absence of kelp forest and then estimate the thickness of present 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  $\gamma$  of occurrence [23]. To calculate  $\gamma$  of occurrence, the thickness of the subsampled kelp forests ( $n = 15,000$ ) including absence data (thickness = 0 cm) was first normal-score transformed [23]. The presence ( $>0.5$  probability) or absence ( $<0.5$  probability) of the kelp forest was determined based on the interpolated probability of occurrence. The interpolation of presence or absence of kelp forests was validated by concordance rate, calculated in manner of leave-one-out cross-validations (LOOCVs, [23, 25]). Then, all of the observed presence or absence 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  $\gamma$  of thickness [23]. To calculate  $\gamma$  of thickness, the  $z$  values of the thickness subsamples were natural-log transformed, using only presence data (thickness  $\geq 30$  cm). The interpolation of thickness was validated using LOOCVs, then the root mean squares of errors (RMSEs) were evaluated.

Kelp forests area were calculated and compared between the eastern and western areas. The calculations and interpolations above were made using ArcGIS ver. 9.2 (Environmental Systems Research Institute, Inc., ESRI).

## Results

### Detected kelp forests

In the eastern area, 2,717 of 15,000 pings were echoes from kelp forests detected along the survey transect.

The measured thickness ranged from 30 to 108 cm with an average ( $\pm$ S.D) of 53 ( $\pm$ 13) cm (Fig. 4).

However, in the western area, 1,330 pings of 15,000 were echoes from kelp forests. The measured thickness ranged from 30 to 78 cm with an average of 44 cm ( $\pm$ 18, *S.D.*; Fig. 4). The maximum thickness of the kelp forest in eastern areas (108 cm) was 30 cm thicker than in western areas (78 cm). Also, 10% of the kelp forests in the eastern area were thicker than the maximum thickness of forests in the western area.

### Semivariograms

The semivariogram parameters indicated differences in spatial trends in occurrence of kelp forests between the eastern and western areas (Fig. 5a, Table 2a). The partial sill in the eastern area ( $5.74 \times 10^{-2}$ ) was 22 times larger than that in the western area ( $0.26 \times 10^{-2}$ ). Conversely, the range in the western area (1697 m) was three times longer than that of the eastern area (530 m). These differences in semivariogram parameters indicate that the occurrence of kelp forest in eastern areas are more horizontally variable with patches or gaps [26, 27] than that in western areas.

Again, the semivariogram parameters of thickness of the kelp forest were different between the eastern

and western areas (Fig. 3b, Table 2b). Eastern area was characterized by smaller partial sill ( $1.07 \times 10^{-2}$ ) and larger range (370 m) than that of the western area (partial sill =  $1.68 \times 10^{-2}$ , range = 223 m). These results indicate relatively uniform thickness among present forest patches in the eastern area compared to the western area. On the other hand, the nugget in the eastern area ( $9.43 \times 10^{-2}$ ) was approximately two times larger than that in the western area ( $5.69 \times 10^{-2}$ ). The difference in nugget may indicate that the thickness of kelp forests within patches is more stochastically variable in the eastern side relative to the western side, though it may also suggest potential observation errors during the survey.

#### Distribution of the kelp forests

The interpolated kelp forest is shown in Figure 6. Overall, kelp forests in the eastern area were larger and thicker than they were in the western area. Kelp forests in the eastern area extended farther offshore compared to those in the western area. The total area of the kelp forests surveyed was 3.88 km<sup>2</sup>. In the eastern area, kelp forests were continuously distributed along the coastline and were especially obvious near the Shiretoko Cape. The distributed area of kelp forests in the eastern region was 3.49 km<sup>2</sup>, which was 15% of the analytical area (23.74 km<sup>2</sup>) in eastern side of Shiretoko Peninsula. The estimated thickness of the eastern forests ranged between 34 and 91 cm, with most falling below the 64 cm range, which accounted for 90 % of all kelp forests (Fig. 7a). The 10% of kelp forests that were over 64 cm thick made up an area of 0.34 km<sup>2</sup> and was patchily distributed over the entire eastern area. In the western area, kelp forests were sparsely distributed. The area of western kelp forest was 0.39 km<sup>2</sup>, which was 2% of the analytical area

(19.58 km<sup>2</sup>) in western side of Shiretoko Peninsula. The estimated thickness of the western forests ranged from 34 to 75 cm (Fig. 7b), with little forest over 64 cm thick. The concordance rates with LOOCVs for the prediction of presence or absence were 99% for both subareas. The RMSEs of the estimated thickness in eastern and western areas were 18 and 12 cm, respectively.

## **Discussion**

This study is the first quantitative study of coastal kelp forests over an area of 43.3-km<sup>2</sup> area using acoustic observations and geostatistical analysis. The thickness of kelp forests was successfully measured under a set transect. Acoustic observations of various aquatic plants have been conducted [12-14], but detailed observations covering areas of over 10 km<sup>2</sup> are limited to a study of seagrass beds in Ajino Bay [28]. The present study is therefore notable as one of the pilot applications of the acoustic method. Based on the high-resolution data from across the study area, statistically valid estimations were made of the kelp forest. Spatial variability in the distribution of the kelp forests was also statistically analyzed.

The kelp forests along the eastern side of the peninsula were relatively thick and horizontally continuous, while those along the western side were sparse (Figs. 6 and 7). The spatial variability in occurrence of forest patches along the eastern side was larger than it was along the western side, and the spatial variability in thickness along the eastern side was more continuous than it along western side, as indicated in the semivariograms (Fig. 5). Structurally complex kelp forests provide fish and phytal animals with suitable refuges from advection and predators and also attracts a variety of other fauna [29-33]. The horizontal and

vertical structure of the eastern side probably enhances the diversity of fauna and ecological relationships. Conversely, the ecosystem on the western side might be simpler, but the sparse patches of kelp forests may provide locally valuable habitats to organisms.

These spatial characteristics of the kelp forests are probably a consequence of the differences in ecological setup between the eastern and western sides of the Shiretoko Peninsula. The difference in the thickness of kelp forests between the eastern and western sides was caused by the difference in species that formed the forests. The major species on the eastern side of the peninsula are *L. ochotensis* and *L. diabolica*, but only *L. ochotensis* is observed in the western areas [1, 2]. The different species composition of kelp forests on the eastern and western sides of the peninsula may be a cause of the observed spatial differences in forest thickness and future field validation of species composition is recommended.

The observed differences in vegetated area between the eastern and western sides of the Shiretoko Peninsula corresponded with the harvest of *Laminaria* spp. on the peninsula [7]. The grazing impact of benthic herbivores such as sea urchin (*Strongylocentrotus* spp.), which influences the variability in marine environments, has been discussed as a possible determinant of change in the area covered by kelp forests in various North Pacific waters [7]. On Rishiri Island, located in northern Hokkaido, the distribution of kelp forests declined due to intense grazing by *Strongylocentrotus nudus*, which was influenced by changes in water temperature [34]. The coastal sea off the Shiretoko Peninsula is one of the major *Strongylocentrotus* spp. habitats, so the distribution of the kelp forest along the peninsula would be influenced by *Strongylocentrotus* spp. More than 10 times the number of *Strongylocentrotus* spp. have been found on the western side of the peninsula than on the eastern side [7]. Grazing impacts associated with environmental

variability is most likely one of the controlling factors of the continuity of kelp forests in coastal waters along the Shiretoko Peninsula.

One of the most dramatic changes in the marine environment in the Shiretoko Peninsula comes from drift ice reaching the shore from January to March. The ice physically scrapes the kelp forest from the rocks along the shore. The harvest of *Laminaria* spp. declines in coastal waters along Nemuro, located in the east of Hokkaido, in years experiencing intense drift ice [6]. From 2000 to 2007, the total annual duration for which drift ice reached western areas was approximately 30 days longer than the duration for which it reached eastern areas (The Drift Ice Condition Chart of the ICE Information Center, Japan). These spatial differences in drift ice distribution potentially influence the foliated areas of kelp forests in the study area.

As discussed above, various ecological factors will alter the distribution of kelp forests in the coastal waters of the Shiretoko Peninsula. The integrated analysis based on this study is probably effective in revealing the causal relationships that determine the distribution of kelp forests in this area. Quantified information on kelp forest distribution is not only of practical use to local fishers but is also important for the sustainability of the marine ecosystems of the peninsula. Conducting further study efforts that integrate direct species sampling with estimates of kelp forest primary production along the Shiretoko Peninsula will provide practical information for the assessment of ecology. Continuous spatial and temporal monitoring of ecologically important kelp forests will provide essential information to fishers and managers for the future sustainability of the coastal waters of the Shiretoko Peninsula.



## Acknowledgments

We thank the Fisheries Cooperation Association of Rausu and the Sonic Corporation for their support in conducting this study and researcher Y. Fukuda and boatman K. Sudou for their kind advice and assistance.

This study was supported by the Ministry of the Environment, Japan.

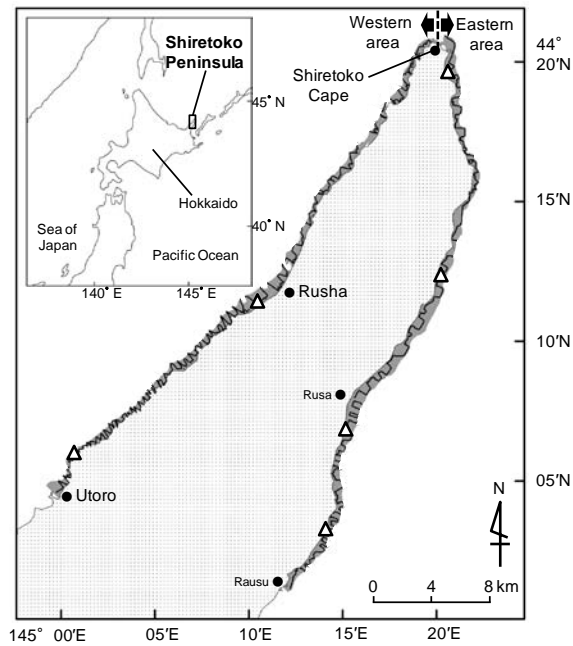
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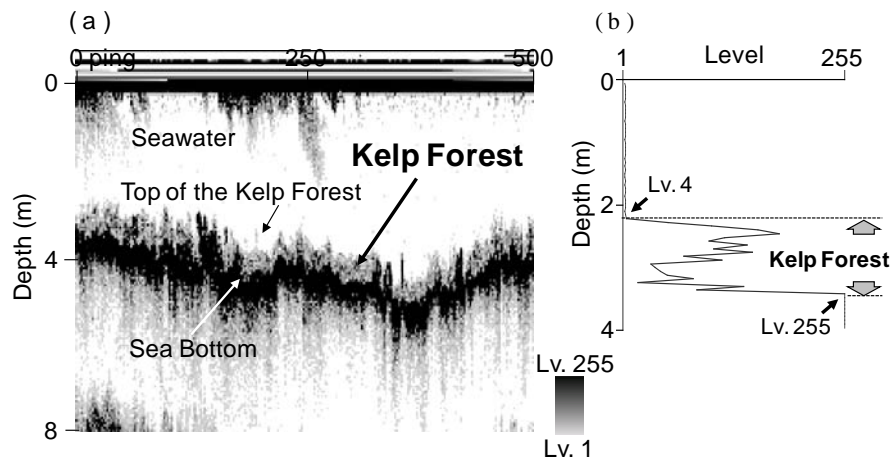
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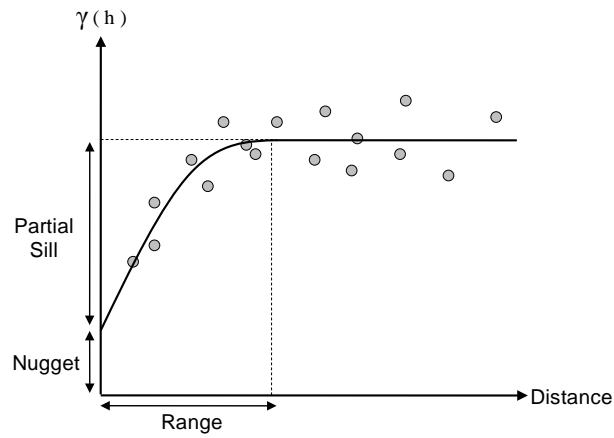
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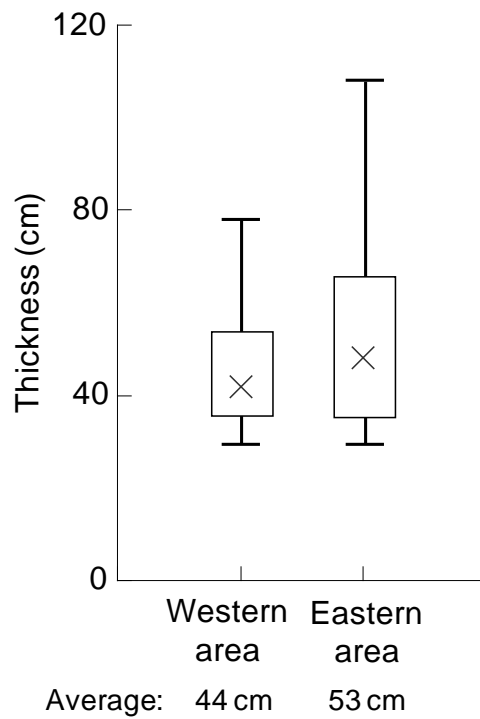
**Fig. 1** Study area and survey transect line. Light shaded area is the study area. Solid lines are measurement lines. Dashed line indicates the boundary line between the eastern and western area ( $145^{\circ} 12.19' E$ ,  $44^{\circ} 01.14' N$ ). The eastern area is from Shiretoko cape to Utoro. The western area is from Shiretoko cape to Rausu. Open triangle is the validation point of the kelp forest using underwater video



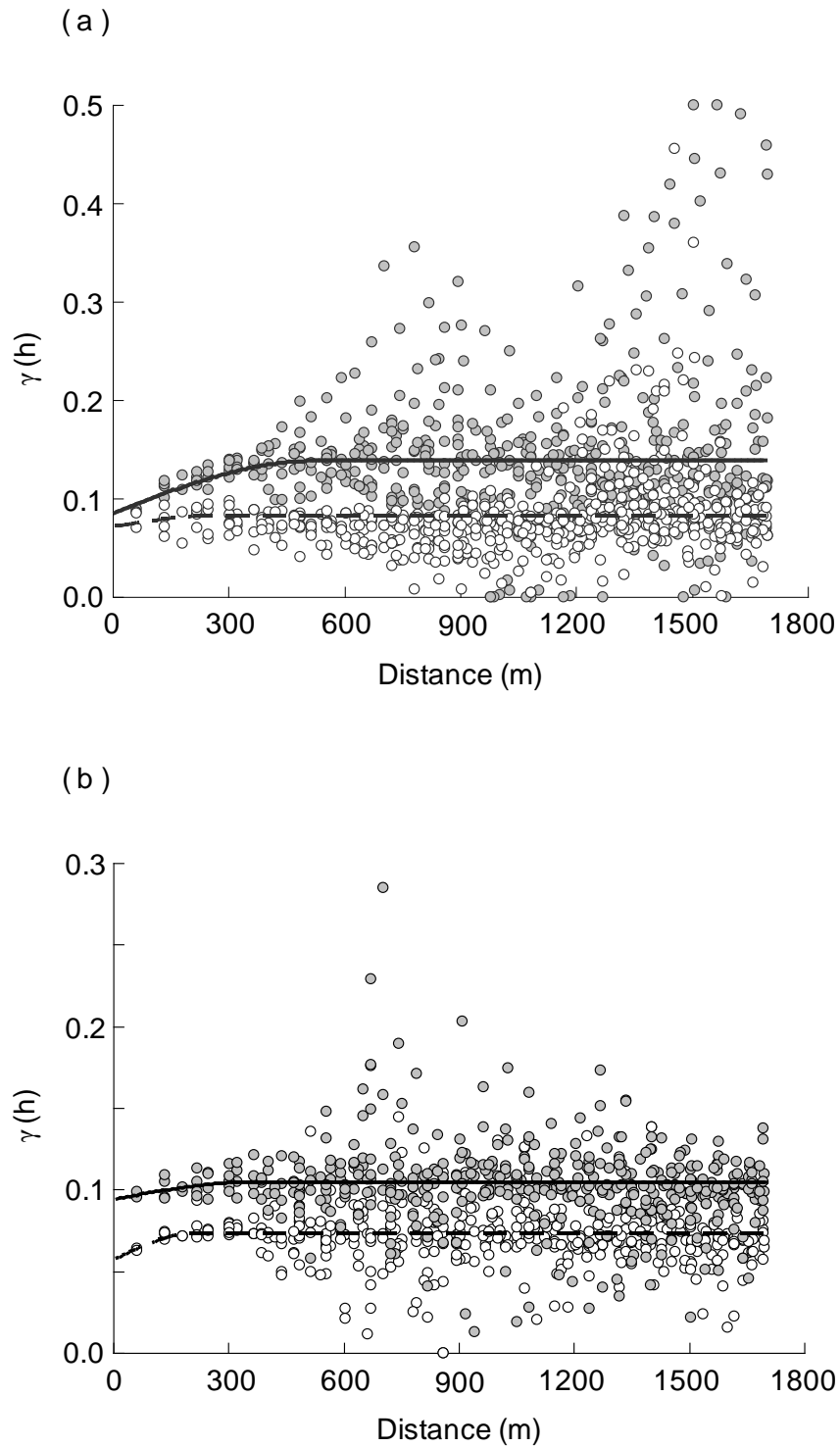
**Fig. 2** (a) Detected kelp forest with echosounder. Black line is the top of the kelp forest. White line is the bottom of the kelp forest. The region, which is between the lines, is estimated as the kelp forest. The color bar indicates echo level. (b) An example of one ping of the kelp forest. Dashed lines are the boundaries between the kelp forest and sea water or between the kelp forest and sea bottom



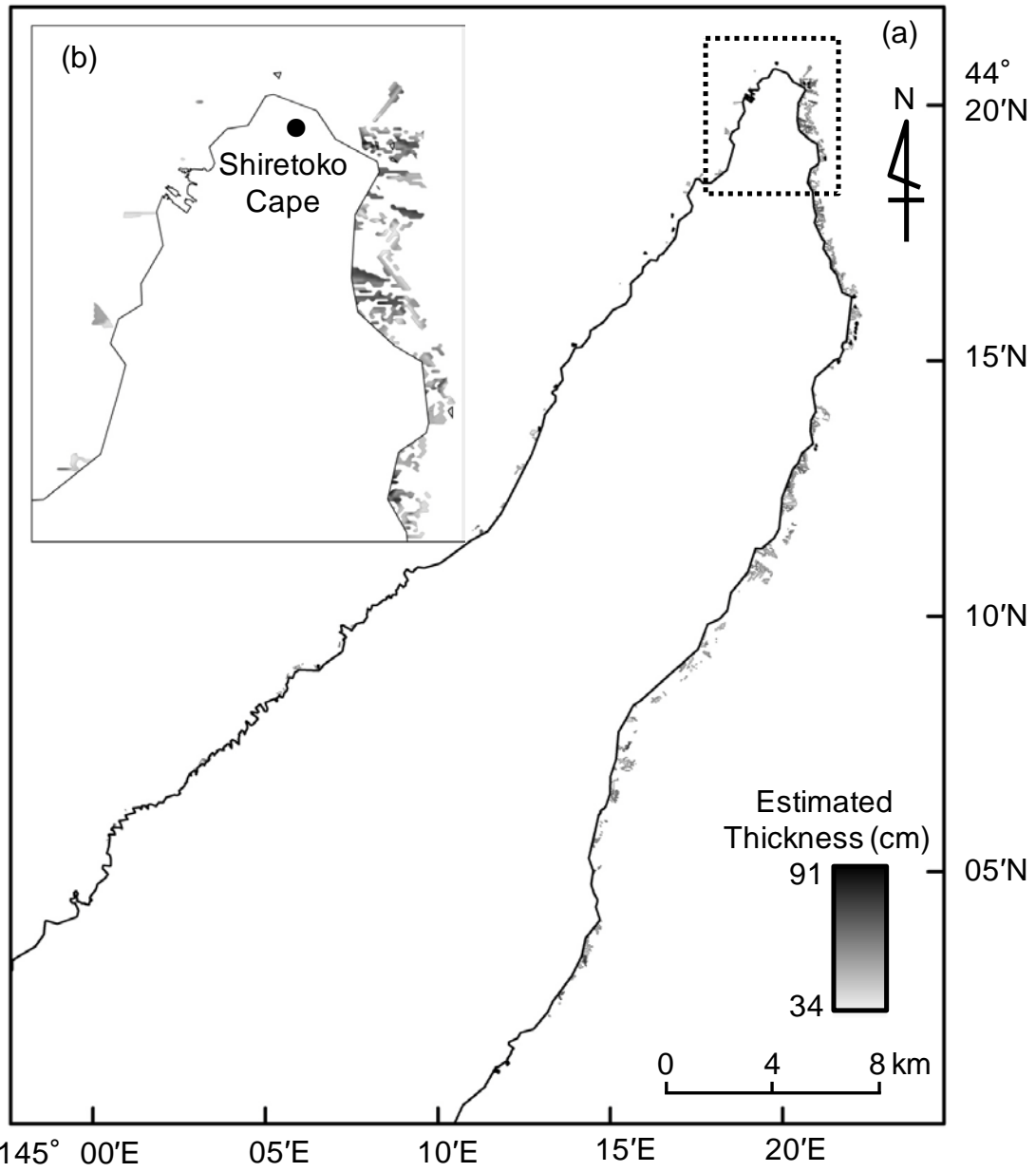
**Fig. 3** An example of experimental semivariogram. Closed circles compose the experimental semivariogram. The solid line represents the theoretical semivariogram



**Fig. 4** Box plot of measured kelp forest thickness data in eastern and western areas. The upper and lower portions of the boxes are the third and first quartiles of thickness, respectively. The vertical bar indicates the minimum and maximum values. The cross mark in the box represents the average

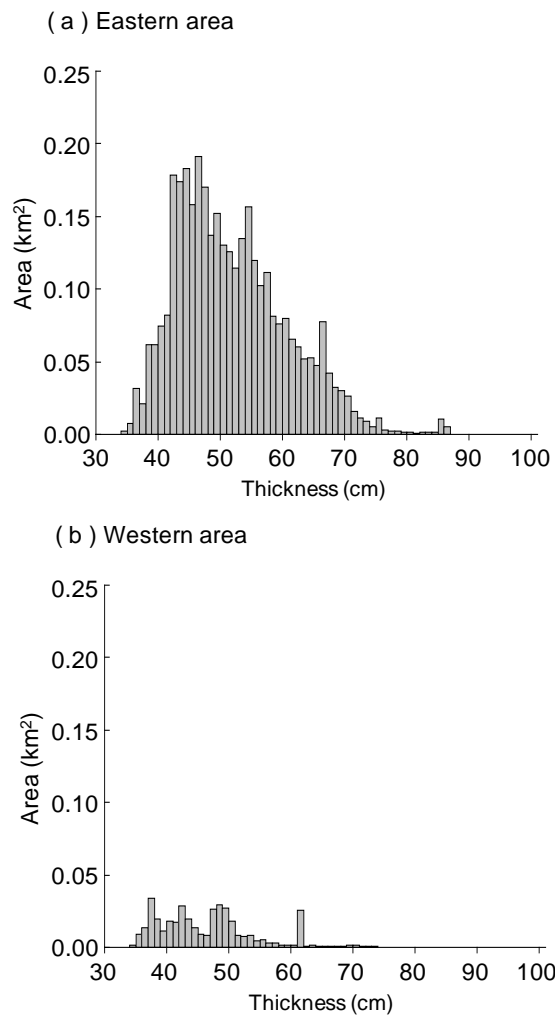


**Fig. 5** Semivariograms of (a) the occurrence of kelp forest and (b) the thickness of the kelp forest. Closed circles compose the experimental semivariogram in the eastern area. Open circles compose the experimental semivariogram in the western area. The solid line represents the theoretical semivariogram in eastern area. The dashed line represents the theoretical semivariogram in western area



**Fig. 6** (a) Map of kelp forest distribution. Thickness estimation was overlapped with presence or absence estimation. (b) Close up view of Shiretoko cape (dashed region)





**Fig. 7** Frequency distributions of thickness estimated in (a) the eastern

**Table 1** Acoustic specifications of the BL550 echosounder

Transducer	T-129
Frequency (kHz)	200
Beam type	Single
Beam width (degrees)	3
Vertical resolution (cm)	6
Ping rate (s)	1

**Table 2** Parameters of theoretical semivariograms of the occurrence and the thickness of the kelp forest in the eastern and western areas

	The occurrence		The thickness	
	Eastern area	Western area	Eastern area	Western area
Lag (m)	85	85	85	85
Range (m)	530	1697	370	223
Partial Sill	$5.74 \times 10^{-2}$	$0.26 \times 10^{-2}$	$1.07 \times 10^{-2}$	$1.68 \times 10^{-2}$
Nugget	$7.96 \times 10^{-2}$	$7.52 \times 10^{-2}$	$9.43 \times 10^{-2}$	$5.70 \times 10^{-2}$