Journal of Marine Science and Technology, Vol. 25, No. 3, pp. 343-351 (2017)
DOI: 10.6119/JMST-016-1229-1

VERIFICATION OF ECHOSOUNDER MEASUREMENTS OF THICKNESS AND SPATIAL DISTRIBUTION OF KELP FORESTS

Huamei Shao[1], Kenji Minami[2], Hokuto Shirakawa[2], Takashi Maeda[3], Toshiaki Ohmura[4], Yoshikazu Fujikawa[5], Norishige Yotsukura[6], Masahiro Nakaoka[7], and Kazushi Miyashita[2]

Key words: acoustic, kelp forests, spatial distribution, thickness.

ABSTRACT

Acoustic methods can be used to assess seaweed meadows. The accuracy of the methods is a key factor in the estimation of seaweed distribution and conditions. We obtained and verified thickness and spatial distribution values measured using an echosounder. We determined the thickness of seaweed growing in the coastal waters off Higashidoori-mura, Aomori, Japan on June 5-6, 2013. Acoustic data were collected using an on-board quantitative echosounder at 120 kHz. The thickness was also directly measured at 14 points. The root mean square error (RMSE) of the thickness determined by the acoustic and direct methods was calculated. A survey to determine the spatial distribution was performed in Miyako-shi, Iwate on July 18, 2014. The estimated spatial distribution was determined from the thickness data collected by the acoustic method of varied transect lines by changing transect orientation and intervals. The kelp forest distribution was also observed directly at 106 points. Then, the concordance rates of the visual observations and estimated spatial distribution were obtained. The RMSE of the acoustic and directly measured thickness of the kelp forests (*Saccharina japonica*), was 0.06 m, similar to the vertical resolution of the echosounder. The concordance rate between the acoustic and directly measured values was 92% when the maximum transect interval was 21 m. Smaller transect intervals yielded higher accuracy. High accuracy for the thickness and acoustically derived spatial distribution were obtained by the acoustic method when suitable thresholds were used, which has important applications for the evaluation of seaweed stands.

I. INTRODUCTION

Seaweed stands have primary production rates similar to those of tropical rainforests and provide nutrients and habitats for numerous invertebrates and fish in shallow waters; hence, they play a critical ecological role in coastal waters (Mann, 1973; Mann, 1982; Steneck et al., 2002). Kelp forests distributed along cold-water rocky subtidal marine coastlines supply fisheries products and are important food sources, especially in Asia (Okazaki, 1971; Mabeau and Fleurence, 1993). However, reductions in seaweed populations and the disappearance of kelp forests have occurred in coastal waters worldwide because of increasing water temperatures, threats from herbivores, and overfishing (Mann, 1977; Watanabe and Harrold, 1991; Steneck et al., 2002; Fujita, 2010; Feehan et al., 2012; Jueterbock et al., 2013). In Japan, continuous monitoring of the current conditions and distribution characteristics of seaweed is critical to guide strategies to address these problems (Fisheries Agency, 2007; Kirihara and Fujikawa, 2011). A range of countermeasures has been implemented in an attempt to tackle these problems, and seaweed monitoring across a large area is required to evaluate their success (Fisheries Agency, 2007; Norderhaug and Christie, 2009). The continuous monitoring of the spatial distribution and condition of kelp forests, which can vary significantly over a large area, is necessary for effective ecosystem conservation and sustainable economic use.

The spatial distribution of seaweed can be determined by direct observation and remote sensing. Direct observation generally refers to visual observations by divers or from ships and via images taken by underwater cameras. Acoustic methods and images taken from satellites/airplanes are usually used for remote sensing. Visual observations are costly and require more time and

Paper submitted 05/06/16; revised 10/07/16; accepted 12/29/16. Author for correspondence: Huamei Shao (e-mail: hmshao@affrc.go.jp).
[1] *Seikai National Fisheries Research Institute, Stock Enhancement and Aquaculture Department, Nagasaki, Nagasaki, Japan.*
[2] *Field Science Center for Northern Biosphere, Hokkaido University, Hakodate, Hokkaido, Japan.*
[3] *Hakodate Fisheries Research Institute, Hokkaido Research Organization, Hakodate, Hokkaido, Japan.*
[4] *Iwate Fisheries Technology Center, Kamaishi, Iwate, Japan.*
[5] *Division of Fisheries Infrastructure Aomori Prefecture, Fisheries Bureau, Aomori, Aomori, Japan.*
[6] *Field Science Center for Northern Biosphere, Hokkaido University, Sapporo, Hokkaido, Japan.*
[7] *Field Science Center for Northern Biosphere, Hokkaido University, Akkeshi, Hokkaido, Japan.*

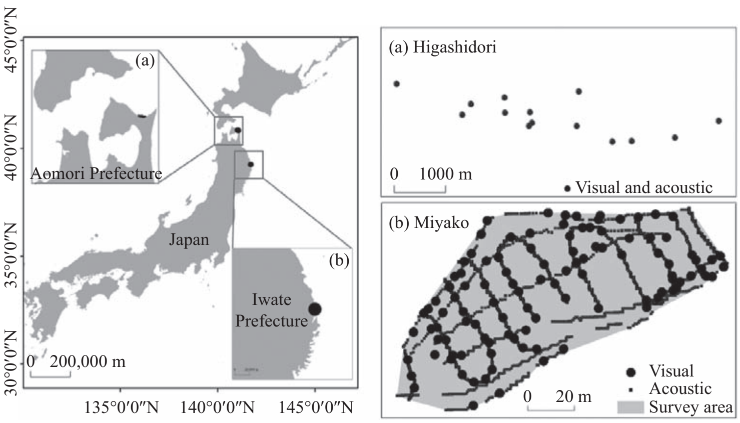


Fig. 1. Survey areas for verification of the (a) thickness and (b) spatial distribution of kelp forests along the Japanese coastline. Large circles represent the direct observation points from a survey boat, and small squares represent acoustic observation points.

effort, and thus are difficult to apply to surveys over wide areas. Images from satellites/airplanes can be obtained in a short period over a large area; however, this method is limited by cloud coverage, sea surface roughness and water clarity in subtidal areas (Vis et al., 2003). The acoustic method has been suggested as an effective and quantitative method to assess seaweed and seagrass meadows over wide areas. In recent years, various types of acoustic equipment, such as side-scan sonars, multi-beam sonars, and echosounders have been used (Komatsu et al., 2002; Sabol et al., 2002; Brown et al., 2005; Sabol et al., 2009; Minami et al., 2010; Paul et al., 2011). Side-scan sonars provide maps of seagrass distribution and qualitative changes in coverage, and multi-beam sonars additionally acquire canopy height data (Pasqualini et al., 1998; Komatsu et al., 2003). The use of echosounders to detect canopy heights under survey lines has also been reported (Sabol et al., 2009). As the leaves of kelp do not have obvious gas bubble and backscattering strength of which are weaker than seabed and stronger than seawater. Thus the boundary of kelp forests could be detected by acoustic method based on the change of backscattering strength, and the thickness is possibly extracted. The spatial distribution of kelp forests in coastal waters was estimated using a geostatistical method based on echosounder data obtained along transect lines (Minami et al., 2010; Shao et al., 2013). In addition, if the echosounders are calibrated each time before surveys, the backscattering strength of the same substance in the water is the same, and the thickness of the kelp forest can be accurately measured in each survey. Individual differences caused by visual observations could be eliminated by conducting continuous long-term annual surveys using the acoustic method. The seasonal variation in biomass of Sargassum beds recorded using a quantitative echosounder was reported recently (Minami et al., 2015). Echosounders could also potentially be used in the future to measure the backscattering strength to determine kelp biomass, which is important for evaluation and management of coastal fisheries activities.

However, there have been few attempts to evaluate thickness and spatial distribution data obtained using the acoustic method e.g., comparing the thickness and percentage of correct classification of kelp or bare ground (concordance rate) with direct observations. As the accuracy of these data affects the ecological and economic evaluation of seagrass and seaweed meadows, the objectives of this study were to obtain the rate of concordance between acoustic and direct methods in an area of kelp forests and to suggest options for improving data accuracy. We focused on two aspects: thickness and spatial distribution. As kelp leave do not have obvious gas bubble thus backscattering strength is weaker than gas bubble including seaweed, for example, *Sargassum* species. Moreover, varied species of kelp have specific characteristics themselves and the backscattering probably be different as the varied density and characteristics of the shapes. Thus, in this study one species among kelp, *Saccharina japonica* was considered as the target and analyzed, other species of seaweed which grow with it are also analyzed for comparison of varied species possibly extracted by acoustic method with the adaptive threshold value of backscattering strength. Thus, the survey for thickness was conducted in areas where *Saccharina japonica* dominated, and the root mean square errors (RMSEs) of the thickness of the kelp forests determined from the acoustic method (acoustic thickness) and that from the direct method (direct thickness) were calculated. Then, we examined the factors affecting the accuracy and the possible methods to improve this accuracy. For spatial distribution, the survey was conducted in an area where *S. japonica* was thriving and dominant. As spatial distribution of kelp forests is the objective of the study, thus random samples are preferred for the estimation based on unbiased data. For determination of acoustic survey lines, transect should be chosen to cross the shortest axis in order to minimize the time interval spent travelling between them when no information is available about spatial structure of the fish stock (Simmonds and Maclennan, 2005). Kelp forests don't migrate like fishes and they often distribute depending on the water depth as the light is necessary for the growth (Bearham et al., 2013). Water depth detection and discussion of accuracy along with varied transects orientation, parallel or perpendicular to isobath are necessary. Thus concordance rate of visual obser-

Table 1. Echosounder parameters.

KCE-300 (Sonic Co.)	
Frequency (kHz)	120
Pulse length (ms)	0.6
Beam width (degree)	8.5
Sampling frequency (kHz)	20
Ping rate (s^{-1})	5

vations and the estimated spatial distributions using kriging interpolation based on acoustic data obtained along transect lines with different transect intervals and orientations were obtained, and we discuss the reasons and approaches for improving this method.

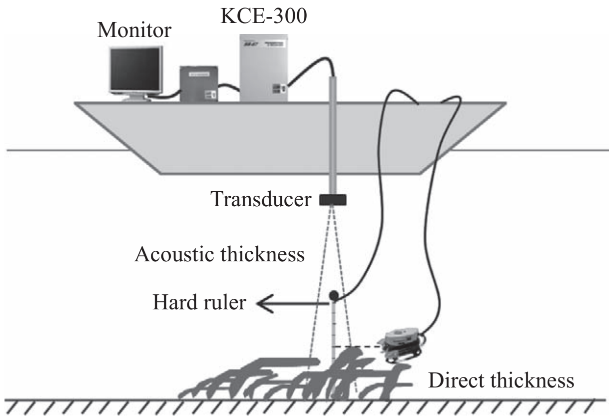


Fig. 2. Set-up used for direct and acoustic thickness measurements. The line with short slashes represents the sea bottom; the dark grey figures above the sea bottom represent kelp; The acoustic equipment consisted of a transducer, transmitter and receiver connected to a monitor on the boat.

II. METHOD

1. Thickness Verification

1) Field Survey

The survey of thickness was conducted in coastal waters off Higashidoori-mura, Shimokita Peninsular, Aomori Prefecture, Japan on June 5-6, 2013 (Fig. 1). Sea desertification resulting from the disappearance of seaweed has been reported in Aomori, and the volume of kelp harvest has decreased in recent years, which makes continuous monitoring more critical (Kirihara and Fujikawa, 2011). Due to the influence of sea desertification, in addition to flourishing kelp (*S. japonica*), forests of low thickness also exist in this area, which is useful for verification of the acoustic method for determining thickness. We measured and compared the thickness inferred acoustically using a quantitative echosounder with the thickness directly obtained from visual observations via an underwater camera.

2) Thickness Measurements

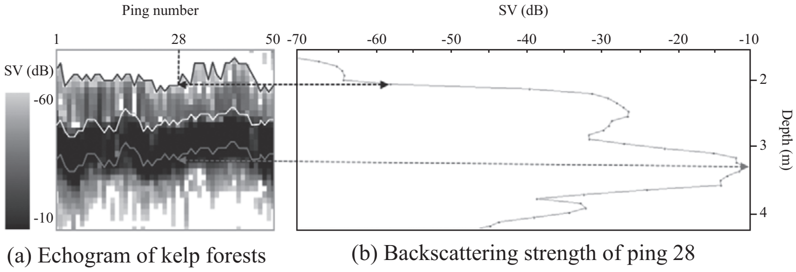
The acoustic and direct thicknesses were measured at 14 points where seaweed forest was found (Fig. 2). The acoustic thickness was collected by an on-board quantitative echosounder (KCE-300, Sonic Co., Tokyo) at 120 kHz on a small survey boat. The quantitative echosounder consisted of a transducer, transmitter and a receiver connected to a monitor. The transducer transmitted five pulses per second, and the pulse length was set to 0.6 ms. The vertical resolution was 3.75 cm (Table 1). Water temperature and salinity was collected by a compact CTD (Alec Electronics Co. Kobe), sound speed was 1,498 m/s.

The direct thickness of the seaweed forest was recorded at 14 measurement points using a remote operated vehicle (ROV; Global Environment Solutions Co.) and a 2-m hard ruler. The hard ruler was a stick pasted by tape entirety and held in position with weights at the bottom and a float at the top. Maintaining it in a vertical position, the ruler was dropped into the water to the sea bottom three times at each measurement point. We controlled the ROV to make the encounter to the harder ruler, and the hard ruler would be taken out of water until maximum thickness values of kelp forest could be readable from the videos recorded by ROV three times.

3) Thickness Analysis

Echograms of the backscattering strength were obtained from the echosounder and analyzed using the Echoview software program (Ver. 4.9, Myriax Co.). Analysis started after the calibration. The detected echoes were categorized into three groups according to location type: kelp forest, sea bottom, and seawater. Echoes from solid targets such as the sea bottom are strong, while echoes from seawater are weak due to the absence of objects to reflect the transmitted supersonic waves. We defined the strongest response as sea bottom, and the lower line of the kelp forests was defined as being 45 cm above the seabed based on the detected dead zone calculated from the pulse length (Ona and Mitson, 1996). Maximum difference in the volume backscattering strength (Sv) of two adjacent cells in each ping above the lower line was defined as the threshold between the seawater and kelp. Average Sv value of the lower cell of 900 pings in each point for all kelp points in the survey area was calculated to be -60 dB, which was considered as the threshold value between sea water and kelp forests. Then the upper line of the kelp forests signal was picked depend on this value. The acoustic thickness of the kelp forest was defined as the distance between the lower and upper lines (Fig. 3).

The acoustic thickness was extracted as the average of the values measured at 2 m intervals along all transect lines to compensate for the movement of the boat caused by the waves when the thickness was measured directly. The direct thickness was obtained from videos recorded by an underwater camera. The maximum values were read to a precision of 4 cm, which corresponded to the minimum difference, because it was the closest readable value of the vertical resolution of the echosounder (3.75 cm). Three maximum values were obtained at each measurement point, and the mean was calculated. In addition, the dominant genus of the seaweed was recorded based on the videos taken by the underwater camera. The thicknesses measured



(a) Echogram of kelp forests (b) Backscattering strength of ping 28

Fig. 3. Extracted threshold of kelp forest. (a) Echogram of kelp forest from a visual observation point. The horizontal axis is pings with time, and the vertical axis is water depth. The solid bars denote the range of the backscattering strength: black is strongest (-10 dB), and grey is weakest (-60 dB). The black solid line denotes the upper line, the grey solid line is the sea bottom, and the white solid line between the bottom and upper line is the lower line. (b) One-ping backscattering strength of kelp forest. The horizontal axis is backscattering strength, and the vertical axis is water depth.

using the direct method were considered the true values; then the RMSE was calculated using the following formula:

$$RMSE = \sqrt{\frac{1}{n}\sum\nolimits_{i=1}^{n}\left(y_i - x_i\right)^2}$$

where n is the number of observation points, y_i is the acoustic thickness, and x_i is the direct thickness.

2. Verification of Spatial Distribution

1) Field Survey

The survey of spatial distribution was conducted in coastal waters off Miyako city, Iwate Prefecture, Japan on July 18, 2014 (Fig. 1). This area was chosen, because the kelp forest is dominated by thriving *S. japonica*. Winds are generally not strong in the area, and the sea surface is comparatively calm compared with other areas where kelp grows, which facilitates the collection of directly measured data and increases the quality of acoustic data, as which is less affected by waves. In addition, the water visibility is comparatively high, which is beneficial to visual methods. Furthermore, northeast Japan, especially Iwate Prefecture was seriously affected by the Tohoku Earthquake that occurred off the Pacific coast in 2011, and resource evaluations and strategies to support recovery are important in the wake of the earthquake. The kelp in this area is a key economic resource and is not currently monitored extensively. We estimated the spatial distribution based on acoustic data and obtained the concordance rate of the spatial distribution and visual observations at the site.

2) Survey Method

Data on the presence/absence and thickness of the kelp were collected via acoustic observations along transects using the same KCE-300 echosounder used for the thickness verification employing a fisheries boat traveling at a speed of 3-4 knots. The echosounder settings were the same as those used in the survey of thickness (Table 1). Water temperature and salinity was collected by the compact CTD which was used in the survey for thickness verification. Sound speed was calculated as 1,512 m/s of this survey. Transects were set parallel and perpendicular to the coastline by visual and acoustic observation at 20-40 m intervals. The survey ended when kelp was no longer discernible from bare ground, where the water depth was approximately 10 m. Shallow areas where the water depth was less than 2 m were avoided due to the danger of the boat bottom hitting rocks. In addition, the occurrence of kelp forest was confirmed approximately every 10 s by visual observations using a box-shaped hydroscope with glass at the bottom. We obtained viable data from 236 points.

3) Spatial Distribution Analysis

Geostatistical analysis has been used for the ecological study of varied vegetation on the land or in the sea (Minami et al., 2010; Singh and Das, 2014; Minami et al., 2015). The spatial distribution of kelp forests in the present study was estimated by geostatistical analysis using ArcGIS (Ver.10.1, Environmental Systems Research Institute, ESRI) based on the extracted acoustic thickness data along transect lines. The influences of rocks, slopes and other small-sized seaweed such as red algae were considered to be less than 20 cm in the survey areas; thus, values less than 20 cm were considered bare ground, and values greater than 20 cm were considered kelp forest. The probability of kelp occurrence was predicted using probability kriging with the best-fit theoretical semivariogram based on the threshold of occurrence using acoustic data. An occurrence probability greater than 0.5 was considered a kelp forest area, and that less than 0.5 was considered bare ground area (Johnston et al., 2001). The best-fit theoretical semivariograms were selected from the obtained experimental semivariograms using the maximum likelihood algorithm. A spherical model was used as the function, because it makes fewer assumptions in the model parameters and achieves a better fit than do other model candidates in pilot analyses (Burrough and Mcdonnell, 1998). The spherical model is one of the most commonly used model in geostatistical analysis (Wackernagel, 2003). This model shows a progressive decrease of spatial autocorrelation until some distance, beyond which autocorrelation is zero. Equation of the mathematical model is as below.

$$\gamma(h) = \begin{cases} c\left[\dfrac{3h}{2a} - \dfrac{1}{2}\left(\dfrac{h}{a}\right)^3\right] & 0 \le h \le a \\ c & a < h \end{cases}$$

Table 2. Comparison of thickness values obtained by the direct and acoustic methods.

No.	Direct thickness (m)	Acoustic thickness (m)	ΔThickness(m)	Main species
1	0.20	0.15	0.05	*S. japonica*
2	0.20	0.22	0.02	*S. japonica*
3	0.24	0.37	0.05	*S. japonica*
4	0.24	0.27	0.03	*S. japonica*
5	0.28	0.35	0.07	*S. japonica*
6	0.31	0.31	0.00	*S. japonica*
7	0.32	0.38	0.06	*S. japonica*
8	0.37	0.39	0.02	*S. japonica*
9	0.40	0.32	0.08	*S. japonica*
10	0.45	0.55	0.10	*S. japonica*
11	1.32	1.36	0.04	*S. japonica*
12	1.50	1.57	0.07	*S. japonica*
13	2.00	2.12	0.12	*S. japonica*
14	2.00	2.47	0.47	*S. fulvellum*

where c is the sill value, h is the distance between two locations (lag), a is the range of the model. Lag size was taken as the average nearest neighbor distance among the center points, which were obtained from the upper 5^{th} percentile of the measured thickness. Lag number was calculated as half of the transect interval divided by lag size.

To examine the accuracy of the different interval lengths, total and partial transect lines were selected, with transect intervals ranging from 21 to 164 m. The spatial distribution was estimated for the following 10 patterns:

(1) all transect lines, maximum transect interval of 21 m;
(2) six transect lines parallel to the coastline, maximum transect interval of 33 m;
(3) side and middle transect lines parallel to the coastline, maximum transect interval of 37 m;
(4) side and neighboring transect lines parallel to the coastline, maximum transect interval of 53 m;
(5) side transect lines parallel to the coastline, maximum transect interval of 72 m;
(6) 11 transect lines perpendicular to the coastline, maximum transect interval of 30 m;
(7) six transect lines perpendicular to the coastline, maximum transect interval of 40 m;
(8) bordered and middle transect lines perpendicular to the coastline, maximum transect interval of 72 m;
(9) side and neighboring transect lines perpendicular to the coastline, maximum transect interval of 96 m; and
(10) side transect lines perpendicular to the coastline, maximum transect interval of 164 m.

The lag number was calculated based on the transect interval and lag size. The spatial distribution of the kelp forest was estimated based on the lag size and number respectively. First, the presence/absence of kelp forest was determined by probability kriging; second, the concordance rate with direct observations was analyzed; and finally, the concordance rates of different intervals were compared. The concordance of the spatial distribution with direct observations was further examined by measuring the distances from the discordant positions to the edge of kelp forest patches and calculating the mean distance of the 10 patterns.

III. RESULTS

1. Thickness Verification

Among all 14 survey points, the predominant species was *S. japonica* at 13 points, with the remaining point composed of mainly *Sargassum fulvellum*, whose community was clearly thicker than those of the other kelp forests. The acoustic thickness ranged from 0.15 to 2.47 m, with a mean of 0.78 m, and the thickest site (2.47 m) was the *S. fulvellum* forest (Table 2). In comparison, the direct thickness ranged from 0.20 to 2.00 m, with a mean of 0.70 m. The acoustic thickness was 0.08 m thicker than the direct thickness, and the RMSE was 0.14 m. The acoustic thickness of the *S. japonica* forests ranged from 0.15 to 2.12 m, with a mean of 0.65 m. In comparison, the direct thickness ranged from 0.20 to 2.00 m, with a mean of 0.63 m. The average acoustic thickness of *S. japonica* forests points was 0.03 m thicker than the direct thickness, and the RMSE was 0.06 m, which was smaller than when the *S. fulvellum* forest was included with the *S. japonica* forests.

2. Verification of Spatial Distribution

For the visual observations using a box-shaped hydroscope with glass at the bottom at 107 points, the occurrence rate was 83.2%. There were 89 points of kelp-covered ground (mainly composed of *S. japonica*) and 18 points of bare ground. In comparison, the occurrence rate of the acoustic data was 80.1%, and there were 1,299 points of kelp-covered ground and 323 points of bare ground. The rate of concordance between the visual and acoustic observations was 91.5% for all data, 92.1% where there was kelp forest (82 points of accordance, 7 points

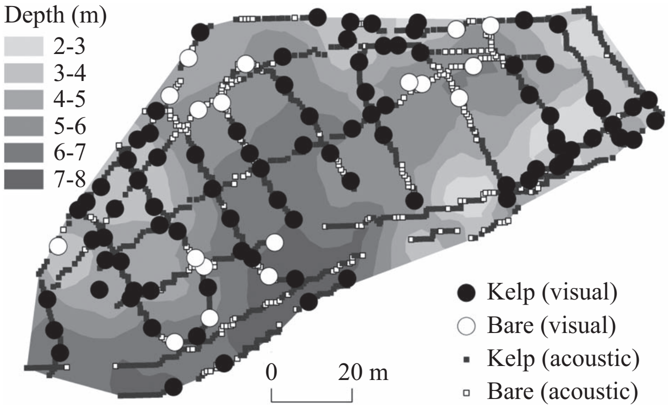


Fig. 4. Visual observations and acoustic results at different water depths.

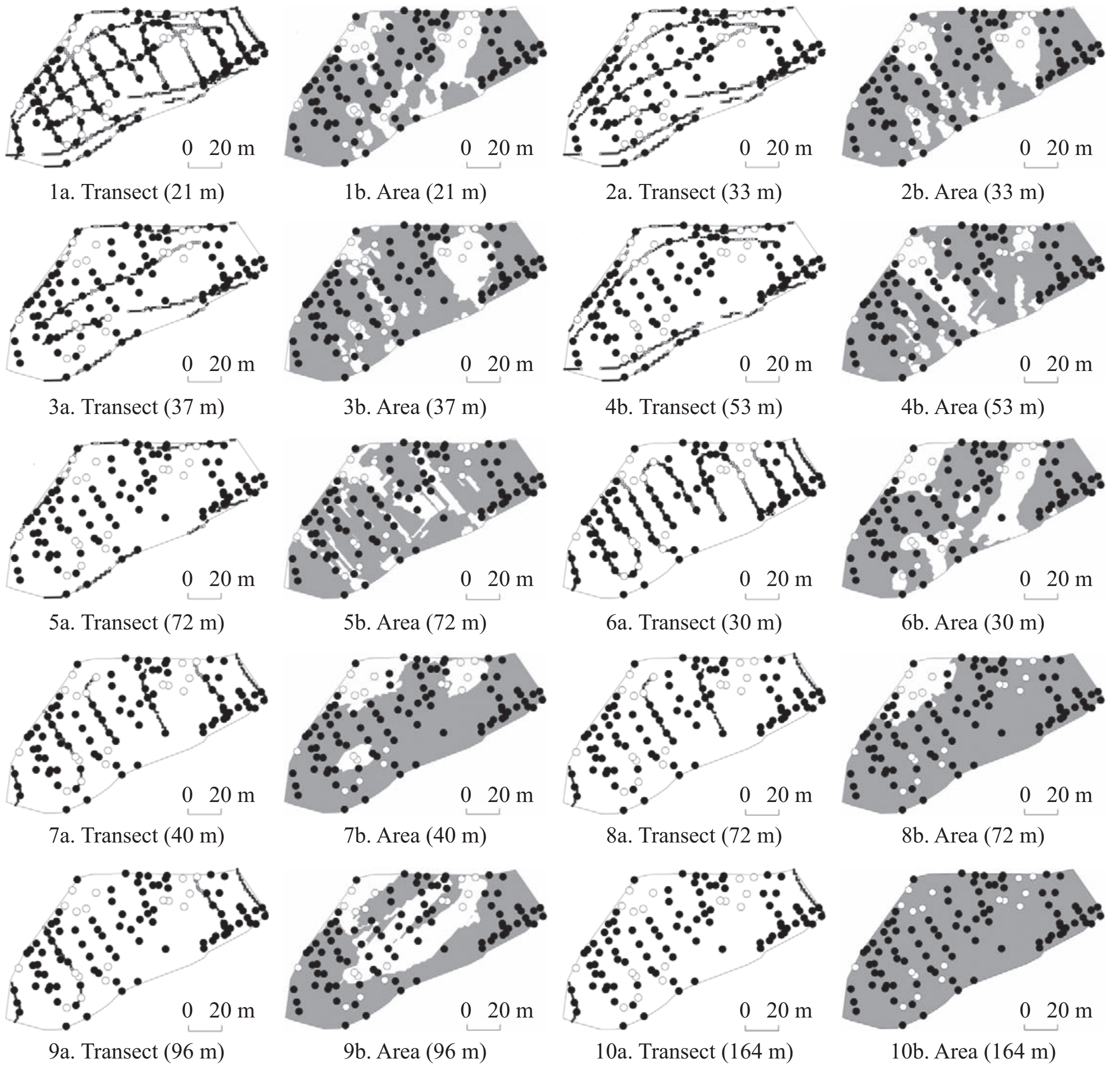


Fig. 5. (a) Visual and acoustic observations along transect lines for varied transect intervals. Large hollow circles represent bare ground and solid circles represent kelp ground by visual observations; small hollow squares represent bare ground and solid squares represent kelp ground by acoustic method. (b) Visual observations and spatial distributions for varied transect intervals. Hollow circles mean bare ground and solid circles represent kelp ground by visual observations; grey areas represent kelp ground estimated by acoustic method. (1)-(5): Transect lines parallel to coastline with maximum intervals from 21 m to 72 m; (6)-(10): Transect lines perpendicular to coastline with maximum intervals from 30 m to 164 m.

Table 3. Concordance rates of visual observations and spatial distributions for varied transect intervals. Average distance = Average distance of discordant positions to patch edges. No. 1-5: transect lines parallel to coastline; No. 6-10: transect lines perpendicular to coastline.

Pattern no.	Kelp area (m^2)	Occurrence rate	Concordance rate	Average distance (m)	Maximum interval (m)
1	6493	71%	92%	1.6	21
2	6694	76%	91%	2.0	33
3	6908	78%	89%	1.6	37
4	6936	78%	85%	2.7	53
5	6993	79%	76%	2.9	72
6	6210	70%	89%	4.3	30
7	7163	81%	83%	3.9	40
8	7869	89%	79%	9.1	72
9	5873	66%	79%	4.5	96
10	8864	100%	83%	12	164

of discordance), and 88.9% where there was bare ground (15 points of accordance, 2 points of discordance). The thickness determined by the acoustic method was less than 1.6 m, which was in the range of the directly observed thickness values. When arranged by water depth, the occurrence rate of kelp forest was 85% for a water depth less than 3 m, 93% for 3-4 m depths, 77% for 4-5 m depths, 54% for 5-6 m depths, 80% for 6-7 m depths, and 58% for 7-8 m depths. Although the occurrence rate decreased with increasing water depth, no well-defined relationship was observed with depth. The results from the acoustic and visual observations are shown in Fig. 4.

The area of distribution was 6,493 m^2 based on the kriging method, which was 71% of the survey area (8,864 m^2) (Fig. 5 (1b)). From the distribution map, we observed that the kelp forests were continuous communities; hence, kelp forests were widely distributed in the survey area. The rate of concordance between the estimated spatial distribution and visual observations was also greater than 90% when all acoustic data for which the maximum transect interval was 21 m were analyzed. This rate was similar to the concordance rate of the acoustic and visual observations along transect lines, which was 92%, approximately 90%.

The concordance rates of the spatial distribution and visual observations for different transect intervals increased from 76% to 92% for transect intervals decreasing from 164 to 21 m (Fig. 5 and Table 3). Although the concordance rate was the same for transect intervals increasing from 72 to 96 m but increased for intervals increasing from 96 to 164 m, the occurrence rate differed significantly between the acoustic data along the transect lines and the visual observations. High accuracy was obtained in the acoustic data when the transect intervals were less than 53 m regardless of whether the transect lines were perpendicular or parallel to the isobaths; the concordance rates were greater than 80%, and the occurrence rates were similar between the visual observations and acoustic method.

On the spatial distribution map of all analyzed data, all of the discordances occurred at points where the distance from the edge of kelp patches was less than 4 m, and 67% of the discordances occurred less than 2 m from the edge of the kelp patches and generally occurred at the edge of the patches. The average distances of discordant points to patch edges increased with increasing transect interval for transect lines both parallel and perpendicular to the coastline (Table 3). Thus, discordances tended to occur near the edge of kelp patches, and the trend became less defined with increasing transect interval.

IV. DISCUSSION

The kelp forests in the survey area in Aomori were composed of mainly *S. japonica* at 13 measurement points. The RMSE of the direct and acoustic thickness was 6 cm. Although this was slightly larger than the vertical resolution (3.75 cm) of the echosounder, the survey was conducted in the sea, and the thickness of the kelp forests possibly varied due to currents and movement of the boat, while the thickness was being recorded by both the acoustic and direct methods; these are considered to be the main reasons for the differences between the directly measured and acoustic thicknesses. In addition, this difference was small because many kelp forests had thicknesses greater than 1 m. Thus, the measurement of acoustic thickness using an echosounder is a suitable method with high accuracy.

For verification of the acoustic thickness values, there was one measurement point composed mainly of *S. fulvellum*, which has air-filled structures. The RMSE of all 14 measurement points (including the *S. fulvellum* point) was 0.16 m, which was significantly larger than the value for only the kelp forests. The accuracy decreased when the two seaweed types were analyzed together using the same backscattering threshold. The backscattering strength of *S. fulvellum* is much stronger than that of *S. japonica* because of the air-filled structure of the latter (air has a high backscattering strength) (Xavier, 2010). Hence, the errors increased when *S. fulvellum* patches were analyzed using the backscattering strength with *S. japonica*. To increase the accuracy of the acoustic thickness, different values of backscattering strength should be used depending on the species.

The height of the dead zone above the sea bottom for separation was 45 cm, since the survey was conducted using an echosounder with a 6-ms pulse length. The size of the dead zone increases when a larger pulse length is used and decreases when the pulse length is smaller; thus, correction values should be calculated to compensate for the dead zone to increase the accuracy. However, for stands of flourishing seaweed, the seaweed can be effectively detected and evaluated using larger pulse lengths. When detailed information is required for areas where kelp forests are sparse or other small-sized seaweeds exist, a smaller pulse length is essential. However, it is difficult to reduce the pulse length, because to detect shorter pulse of the echoes require wide bandwidth of the receiver and it is more vulnerable to noise. To overcome noise it is helpful to generate more power in the transmission, but there are limitations in both the electronics and the sound levels that can be transmitted in the water (Simmonds and Maclennan, 2005). Thus the pulse length should be chosen carefully based on the characteristics of the survey area and objectives of the survey. In this study, the thickness of the kelp was greater than 15 cm, and the influences of rocks, slopes and other small seaweeds were considered negligible. The threshold value for excluding the influences of these factors should be selected based on the sea bottom conditions at the survey locations. The vertical resolution of the echosounder was lower than the RMSE; thus, increasing the resolution would not be expected to increase the accuracy. For surveys in calm waters e.g., lakes and sheltered bays, if higher accuracy is required, a high vertical resolution may be important; on the other hand, if the survey area is in choppy water, the RMSE will probably not be reduced even if a high resolution is used. The echosounder resolution should be selected carefully before collecting data in survey areas with variable conditions in order to obtain high accuracy.

The kelp forests in the survey area in Iwate were widely distributed. The rate of concordance between the spatial distribution and visual observations was greater than 90% when the maximum transect interval was 21 m, which was similar to the concordance rate between the acoustic and visual observations. The spatial distribution of kelp forests can be estimated with high accuracy using the acoustic method when suitable transect lines are selected. Although only kelp area and bare ground area were verified in this study, the thickness of the kelp forests was also obtained, and the acoustic method using an echosounder is useful for estimating both the thickness and spatial distribution, which is important for resource evaluation in kelp forest areas.

The concordance rates indicated that the accuracy increased with a decrease in the transect interval in our survey area, which is consistent with other studies (Minami, 2010; Shao, 2013; Minami et al., 2015). Higher concordance rates were found near the transect lines. When the maximum transect interval was less than 53 m, and the number of transect lines was greater than or equal to 4, the concordance rates of the spatial distribution and observations did not decrease rapidly with a decreasing interval and were higher than 80%. The concordance rates decreased to less than 80% when the number of transect lines decreased to 2 and the transect interval was greater than 53 m. Thus, 53 m was probably the threshold distance that was narrower than most kelp patches and the suitable interval for evaluating kelp forests with higher accuracy in the survey area. When the transect interval was narrower than most of the kelp patches, the accuracy showed no significant increase when the transect interval was reduced.

On the spatial distribution maps, differences between the acoustic and directly observed values tended to occur at the edges of kelp patches. This is because the edge of kelp forests is not clearly defined. Although differences in the standard values between the direct and acoustic methods may contribute to the discordance, the kelp forests in the study area were continuous, and the average thickness was calculated every 2 m along the transect lines to reduce the discordance. Hence, to reduce the difference between the acoustic and directly measured values and to obtain higher accuracy using the acoustic method, narrow transect intervals are essential for small patches where kelp forests are sparse; in contrast, wide transect intervals can be chosen for large patches where kelp forests are flourishing. Since adding survey transect lines increases the cost and effort, the most suitable transect interval should be selected for higher accuracy and efficiency.

No significant differences between the acoustic and directly observed values were found regardless of whether the transect lines were perpendicular or parallel to the isobaths, since the survey area was in shallow coastal waters and the sea bottom was comparatively flat. For acoustic surveys in areas where the sea bottom has a steep slope, transect lines perpendicular to isobaths can decrease the acoustic dead zone caused by the pulse angle and water depth (Ona and Mitson, 1996). However, for seaweed surveys in coastal areas, the seaweeds generally grow in shallow areas and the sea bottom does not usually have a steep slope; thus, the difference between acoustic and directly measured values should be small. In addition, when small survey boats travel perpendicularly to the isobaths i.e., perpendicularly to the coastline, there are often many nets and cages for fisheries activities near the coastline, which can be dangerous. Thus, transect lines parallel to the coastline are more suitable for seaweed surveys in these shallow coastal waters. We did not observe that the occurrence rate of kelp forests decreased rapidly with increasing depth, as the survey areas were in shallow coastal waters where the water depth was less than 10 m. However, for survey areas where the seaweed distribution decreases quickly with water depth due to the decreasing strength of the sunlight (Bearham et al., 2013), appropriate methods taking into account the factors that vary with water depth should be used. Thus, survey transect lines orientation should be decided based on the survey area and distribution condition of seaweed. In summary, the acoustic method using an echosounder is a suitable method for measuring the thickness of kelp forests, and the appropriate backscattering strength should be used when different species possessing different features are present. A high concordance rate for the spatial distribution was observed when the transect interval was less than 53 m, and suitable transect intervals should be applied according to the characteristics of the area and aims of the survey. Seaweed thickness and spatial distribution data collected using the acoustic method with an echosounder are important for resource evaluation and ecological and economic studies of both kelp forest and seaweed areas. High levels of accuracy in the biomass estimation of kelp forests can be achieved by selecting the optimal backscattering strength for the echosounder.

ACKNOWLEDGEMENTS

I really appreciate the assistance of Shiriyazaki and an anonymous fisheries cooperative association in Miyako. I also thank Mr. Maruoka of Sonic Corporation and the members of the Marine Ecosystem Change Analysis Laboratory for their assistance. This research was supported by the Environment Research and Technology Development Fund (S9) of the Ministry of the Environment, Japan and a Grant-in-Aid for Scientific Research (No. 23380108). I am also grateful to the anonymous referees of this manuscript.

REFERENCES

Bearham, D., M. A. Vanderklift and J. R. Gunson (2013). Temperature and light explain spatial variation in growth and productivity of the kelp *Ecklonia radiata*. Marine Ecology Progress Series 476, 59-70.

Brown, C. J., A. Mitchell, D. S. Limpenny, M. R. Robertson, M. Service and N. Golding (2005). Mapping seabed habitats in the Firth of Lorn off the west coast of Scotland: evaluation and comparison of habitat maps produced using the acoustic ground-discrimination system, RoxAnn, and sidescan sonar. Ices Journal of Marine Science 62, 790-802.

Burrough, P. and R. Mcdonnell (1998). Optimal interpolation using geostatistics. Principles of geographical information systems. PA, B. New York, Oxford University Press, 132-161.

Feehan, C., R. E. Scheibling and J. S. Lauzon-Guay (2012). Aggregative feeding behavior in sea urchins leads to destructive grazing in a Nova Scotian kelp bed. Marine Ecology Progress Series 444, 69-83.

Fisheries Agency (2007). Isoyake Taisaku Guideline. Tokyo, Suisancho.

Fujita, D. (2010). Current status and problems of isoyake in Japan. Bulletin of Fisheries Research Agency, 32.

Johnston, K., J. M. V. Hoef, K. Krivoruchko and N. Lucas (2001). Using ArcGIS geostatistical analyst. New York, ESRI.

Jueterbock, A., L. Tyberghein, H. Verbruggen, J. A. Coyer, J. L. Olsen and G. Hoarau (2013). Climate change impact on seaweed meadow distribution in the North Atlantic rocky intertidal. Ecology and Evolution 3, 1356-1373.

Kirihara, S. and Y. Fujikawa (2011). An attempt to recover kelp bed by fishermen divers on an urchin-dominated barren ground on the coast of Shiriya, Aomori Prefecture, Japan. Fisheries Engineering, 48.

Komatsu, T., C. Igararashi, K. Tatsukawa, M. Nakaoka, T. Hiraishi and A. Taira (2002). Mapping of seagrass and seaweed beds using hydro-acoustic methods. Fisheries Science 68, 580-583.

Komatsu, T., C. Igarashi, K. Tatsukawa, S. Sultana, Y. Matsuoka and S. Harada (2003). Use of multi-beam sonar to map seagrass beds in Otsuchi Bay on the Sanriku Coast of Japan. Aquatic Living Resources 16, 223-230.

Mabeau, S. and J. Fleurence (1993). Seaweed in food-products - biochemical and nutritional aspects. Trends in Food Science & Technology 4, 103-107.

Mann, K. H. (1973). Seaweeds-Their productivity and strategy for growth. Science 182, 975-981.

Mann, K. H. (1977). Destruction of kelp-beds by sea-urchins-cyclical phenomenon or irreversible degradation. Helgolander Wissenschaftliche Meeresuntersuchungen 30, 455-467.

Mann, K. H. (1982). Ecology of coastal waters : a systems approach. Berkeley, University of California Press.

Minami, K. (2010). Spatial estimation of sea forest distribution using acoustic method. Ph.D. unpublished, Hokkaido University.

Minami, K., A. Hamano, N. Tojo and K. Miyashita (2015). The estimation of seasonal biomass change of the *Sargassum* bed in Kuruminose, Yamaguchi, Japan, by an acoustic method. Marine Acoustic Society of Japan 42, 1-10.

Minami, K., H. Yasuma, N. Tojo, S. Fukui, Y. Ito, T. Nobetsu and K. Miyashita (2010). Estimation of kelp forest, *Laminaria* spp., distributions in coastal waters of the Shiretoko Peninsula, Hokkaido, Japan, using echosounder and geostatistical analysis. Fisheries Science 76, 729-736.

Norderhaug, K. M. and H. C. Christie (2009). Sea urchin grazing and kelp revegetation in the NE Atlantic. Marine Biology Research 5, 515-528.

Okazaki, A. (1971). Seaweeds and their uses in Japan. Tokyo, Tokai University Press.

Ona, E. and R. B. Mitson (1996). Acoustic sampling and signal processing near the seabed: The deadzone revisited. Ices Journal of Marine Science 53, 677-690.

Pasqualini, V., C. Pergent-Martini, P. Clabaut and G. Pergent(1998). Mapping of *Posidonia oceanica* using aerial photographs and side scan sonar: Application off the Island of Corsica (France). Estuarine Coastal and Shelf Science 47, 359-367.

Paul, M., A. Lefebvre, E. Manca and C. L. Amos(2011). An acoustic method for the remote measurement of seagrass metrics. Estuarine Coastal and Shelf Science 93, 68-79.

Sabol, B. M., J. Kannenberg and J. G. Skogerboe (2009). Integrating acoustic mapping into operational aquatic plant management: a case study in Wisconsin. Journal of Aquatic Plant Management 47, 44-52.

Sabol, B. M., R. E. Melton, R. Chamberlain, P. Doering and K. Haunert (2002). Evaluation of a digital echo sounder system for detection of submersed aquatic vegetation. Estuaries 25, 133-141.

Shao, H. (2013). Spatiotemporal analysis of kelp forest distribution characteristics in sea desertification areas using acoustic and direct sensing method. Master unpublished, Hokkaido University.

Shao, H., Y. Ito, K. Minami, H. Yasuma and K. Miyashita (2013). Spatial estimation of the kelp forest (*Laminaria* spp.) distributions in coastal waters of Osatsube Hokkaido, Japan, using acoustic method and geographic information system, GIS/Spatial Analyses in Fishery and Aquatic Sciences. Newsland, 133-150.

Simmonds, J. and D. Maclennan (2005). Fisheries Acoustics. Oxford, UK, Blackwell Science Ltd.

Singh, T. P. and S. Das (2014). Predictive analysis for vegetation biomass assessment in Western Ghat Region (WG) using geospatial techniques. Journal of the Indian Society of Remote Sensing 42, 549-557.

Steneck, R. S., M. H. Graham, B. J. Bourque, D. Corbett, J. M. Erlandson, J. A. Estes and M. J. Tegner (2002). Kelp forest ecosystems: biodiversity, stability, resilience and future. Environmental Conservation 29, 436-459.

Vis, C., C. Hudon and R. Carignan (2003). An evaluation of approaches used to determine the distribution and biomass of emergent and submerged aquatic macrophytes over large spatial scales. Aquatic Botany 77, 187-201.

Wackernagel, H. (2003). Multivariate geostatistics: An introduction with applications. Heidelberg, Springer-Verlag Berlin Heidelberg.

Watanabe, J. M. and C. Harrold (1991). Destructive grazing by sea-urchins *Strongylocentrotus* spp. in a central California kelp forest: Potential roles of recruitment, depth and predation. Marine Ecology Progress Series 71, 125-141.

Xavier, L. (2010). An introduction to underwater acoustics: Principles and applications. Heidelberg, Springer.